Principles and Baseline Knowledge of Functionally Graded Aluminium Matrix Materials (FGAMMs): Fabrication Techniques and Applications

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Abstract. This paper discusses the main Functionally Graded Materials (FGMs) and their bulk fabrication techniques, their development, principles and applications. The fabrication processes considered include powder metallurgy (PM), sintering, squeeze casting, infiltration process, compocasting, centrifugal casting, stir casting, material prototyping. The paper provides an overview of the FGM processing parameters including reinforcement particles size and volume %, temperature, pressure (for PM), and stirrer and mould rotational speeds (for stir and centrifugal casting processes respectively). The paper notes that the FGMs are widely used in the following sectors: automotive, medical, aerospace, aviation, nuclear energy, renewable energy, chemical, engineering, optics electronics etc.

Introduction

This paper focuses on the concept of bulk functionally graded materials (FGMs) production technologies of aluminium alloys and composites, their processing parameters and applications. This study reviews the past and present status of major bulk FGMs production techniques. The aim is to identify simple and cheap methods of production that can enhance the mechanical properties of aluminium alloys for hydro turbine blade production. Aluminium deposits are vast in sub-Saharan Africa and their alloys can be sourced locally. Hydropower technologies can help in tackling the perennial power problems in the region.

Functionally Graded Material (FGM) is a group of composite materials that have exceptional properties due to exploitation of the individual properties of the constituent materials. The materials are characterised by gradual transitions in material composition and microstructure in a specific direction [1, 2]. The possibility of manipulating the constituent materials of a FGM to meet functional requirements, makes this group of materials unique [3]. However, this class of advanced materials also occur in nature. Materials such as bone, teeth etc. are examples of FGMs that occur in nature [1]. Fig. 1 shows the path of modern materials, starting from base natural materials to FGM. The concept of FGM was modelled from nature in the quest to solving engineering problems [4].

Pure metals have little significance in engineering applications due to their deficiencies related to functional requirements. Quite often the requirements are conflicting and this occurrence makes most material in their natural form less valuable from an engineering point of view. For instance, a part may require hardness and ductility to function properly in a given working environment. It is more or less impossible to have such a material existing naturally. In this kind of situation, two different materials may be combined with each having one of the required properties. The combined materials could be metal and metal, metal and non-metal or non-metal and non-metal, and during merging they may be in the same state or not. The properties of the parent material are the summation of the properties of the different materials that are combined. Table 1 shows various forms of material combination that can be made, and their limitations [5].
FGMs have properties that are functions of location in the material as represented by Fig. 2. These properties include chemical composition, microstructure, and atomic arrangement.
to disintegrate from the matrix and this failure process is called delamination [4, 6]. Functionally graded materials can be divided into two broad groups namely [2, 5]:

i. **Thin FGM** - Thin FGMs are relatively thin sections or thin surface coating, produced by physical or chemical vapour deposition (PVD/CVD), plasma spraying, self-propagating high temperature synthesis (SHS) etc.

ii. **Bulk FGM** - Bulk FGMs are produced using powder metallurgy technique, centrifugal casting method, solid freeform technology etc.

**Historical Background**

**Evolution of FGMs.** The FGMs were initially introduced as a class of advanced composite materials with a single continuous or discontinuous inclination in terms of microstructure and composition as shown in Fig. 3 [7, 8]. The FGM chemical and physical properties change trend is 3-dimensional [9]. Although, several theoretical works were carried out and reported on FGMs in the 1970s, the influence of these studies was not great due to inadequate and suitable manufacturing techniques. The development of present day FGMs started in 1972 in relation to the study of composites and polymeric materials when Bever and Duwez investigated the properties of global material and re-examined the potential use of graded composites [10, 11].

![Figure 3: Type of FGM structure: (a) continuous and (b) discontinuous [12].](image)

Shen and Bever submitted that variation of the chemical pattern of monomers, supramolecular structure or morphology and the molecular constitution of the polymers may influence the graduation of polymeric material. In this study, the material properties of chemical, mechanical, biomedical and transport and their applications were discussed. However, the study did not consider design, production and appraisal of the gradient of the structure [10]. The evolution of modern day FGMs started in the mid-1980s when Japanese engineers’ encountered difficulty in finding a material for a particular barrier in a hypersonic space plane project. The thermal working condition requirements for the barrier were 1000 K inside temperature and 2000 K outside temperature with a thickness less than 10 mm. This material necessity pushed the engineers to come up with FGM [13]. The first national symposium on FGMs was held in Sendai, Japan in 1990 [14].

FGM technology was a popular programme from 1987 to 1991 in Japan and numerous production techniques were advanced for FGMs processing. These initial manufacturing processes include chemical vapour deposition, self-propagating high temperature synthesis (SHS) self-propagating, plasma spraying, powder metallurgy and self-propagating high temperature synthesis (SHS) and galvanofoming. From 1991 to the present many new techniques have been developed and used. FGMs fabrication methods have been categorised differently by authors. In 1999, Miyamoto et al. classified the manufacturing processes into four main categories; melt, layer, preform and bulk processes as shown in Fig. 4 [15]. The delamination problem that is associated with composite materials was eliminated in FGMs. The sharp interfaces that are mainly responsible for the failure in composites were substituted with gradient interfaces resulting in smooth transition between the materials in contact [4, 16]. In 1985, the application of continuous texture control was
introduced. This was to enhance binding strength and reduce the thermal stress present in ceramic coatings and joints being prepared for recycling in rocket engines [13].

The FGMs concept spread to Europe and it has become a popular manufacturing process in Germany. A transregional Collaborative Research Centre (SFB Transregio) was established in 2006, funded and mandated to exploit the potentials of thermomechanically coupled manufactured graded monomaterials such as aluminum, steel and polypropylene [17].

![Figure 4: Classification of FGMs fabrication methods](image)

**Functional graded aluminium alloy matrix composites (FGAAMCs), Concepts and their Fabrication Techniques**

The combination of aluminium alloy and ceramic material processed by certain techniques such as squeeze and centrifugal casting processes form functional graded aluminium alloy matrix composites (FGAAMCs). The industrial application of FGMs is increasing rapidly in automotive, aircraft and aerospace [18-20]. This interest is orchestrated by the possibility of determining the chemical and physical properties through manoeuvring of microstructure. It is possible in the FGM manufacturing process to have a material with high wear resistance at a high temperature. For example, this can be achieved by reinforcing the matrix with adequate distribution of ceramic material along the mass of the part with the required bulk toughness kept intact [21]. Many investigative works have been performed on FGMs using aluminium matrix alloys and ceramic as reinforced materials. Examples of metal matrix materials are aluminum, brace, bronze, titanium and magnesium. Regarding reinforcements, the most common used are nitrides (BN, ZrN, TiN), carbides (SiC, TiC, ZrC), borides (ZrB₂, TiB₂, SiB₂), oxides (Al₂O₃, MgO, TiO₂, ZrO₂), silicides (MoSi₂) and fine particles of various intermetallics (Fe₃Al, FeAl, NiAl, Ni₃Al, Ti₃Al, TiAl) [22]. FGMCs of Al/SiCₚ have shown a lot of potential as engineering materials and have attracted material scientists and engineers. Since the Japanese engineers’ breakthrough in the hypersonic space plane project in the 1980s till now, researchers have been investigating different aspects of FGMs, from characterisation of FGMs to their production techniques and applications.

There are various methods of manufacturing FGMs and an overview is presented in Table 2. These methods are physical and chemical in form. The method to be applied depends on the type of the materials, available manufacturing equipment for FGMs and potential application [23]. The methods of FGMs production have witnessed tremendous development in the past two decades. This dynamism has led to the emergence of several attractive engineering materials with striking properties that have been applied in different sectors such as automotive and aviation sectors. The production methods are broadly categorised into as follows [9]:

**Constructive process** – this process involves total automation of the management of the compositional gradient through piling of more than one set up material selectively until a stratum of layer formation is created. This method allows for a large layer.
**Transport based process** – This process is suitable for cases were movement of materials is based on natural occurrence to form microstructural and compositional gradients during manufacturing of FGMs. The dynamism in FGMs manufacturing technologies is rapid and the classification is presented in Table 2.

<table>
<thead>
<tr>
<th>Method</th>
<th>Type</th>
<th>Group of FGM</th>
</tr>
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<tbody>
<tr>
<td>Vapour deposition technique</td>
<td>Chemical vapour deposition (CVD) and physical vapour deposition (PVD)</td>
<td>Thin surface coating</td>
</tr>
<tr>
<td>Powder metallurgy (PM)</td>
<td>Stepwise Compositional Control: powder stacking, sheet lamination and wet powder spraying Continuous Composition Control: Centrifugal Powder forming (CPF), impeller dry blending, centrifugal sedimentation, electrophoretic deposition and pressure filtration / vacuum slip casting</td>
<td>Bulk</td>
</tr>
<tr>
<td>Melting processes</td>
<td>Centrifugal casting, sedimentation casting infiltration processing thermal spray processing</td>
<td>Bulk</td>
</tr>
<tr>
<td>Material prototyping/solid freeform (SFF) Fabrication</td>
<td>Laser based processes: laser cladding, melting, laser sintering, selective 3D-printing and selective laser</td>
<td>Bulk</td>
</tr>
<tr>
<td>Other methods</td>
<td>plasma spraying, electrodeposition, electrophoretic, ion beam assisted deposition (IBAD), self-propagating high-temperature synthesis (SHS)</td>
<td>Thin coating</td>
</tr>
</tbody>
</table>

**Powder Metallurgy (PM).** Powder metallurgy (PM) is a metal manufacturing process that makes semi-finished or finished components from mixed or alloyed powders. This process involves the following steps: production of powder metal, metalloids, metal alloys or compounds; blending and mixing of powders, compaction; sintering; and, in some cases, repeating the operation [9, 28, 29]. PM, therefore, is the production and exploitation of metal powders. Particles whose size is less than 100 nm (1 mm) are referred to as powder [30]. Metal powders’ attributes depend on the following parameters: particle shape and size, particle size distribution, compressibility, apparent density, and flow rate. PM is known to be cost effective in the production of complex-shaped components as it minimises the application of secondary operations such as machining.

Notwithstanding the exceptional qualities of PM processes, porosity, production of parts with complex shape and features, and high strength are challenges [31]. There are pores in almost all of the PM parts and this has both advantages and disadvantages. One of the advantages is being able to produce self-lubricating bearings. The pores that are linked to the surface are impregnated with oil. However, the presence of voids in a part has serious effects on the thermal, mechanical, magnetic, physical, wear, and corrosion behaviour of that part [30]. The design engineer is always interested in material’s elastic constants such as Young’s modulus (E), shear modulus (G), and Poisson’s ratio (v). PM elastic constants are related by equation (1):

\[
E = 2G (1 + v)
\]

Beiss shows a relation between density (\( \rho \)) and Young’s modulus (E) in equation (2):

\[
E = E_o \left( \frac{\rho}{\rho_o} \right)^n
\]
Where $E_o$ is the pore-free material Young's modulus, and $\rho_o$ is the pore-free material density and $m$ is the exponent which is pore dependent, and ranges from 2.5 and 4.5.

Also, the PM materials mechanical properties are a function of the density [32, 33].

$$\frac{P}{P_o} = \left(\frac{\rho}{\rho_o}\right)^m$$  \hspace{1cm} (3)

Where, $P$ is the interest property, $P_o$ is the pore-free material value, $\rho$ is the material density, $\rho_o$ is the pore-free material density, and $m$ is an exponent the value of which depends on a given property.

PM is a technology that has a wide diversity in the manufacturing of automobile parts. In 2015 the Metal Powder Industries Federation (MPIF) PM received an award for excellence in design [34]. Some of the outstanding works listed in the award are: carrier and one-way rocker clutch assembly by GKN Sinter Metals; sector gear and fixed ring by Cloyes Gear & Products Inc.; variable valve timing (VVT) rotor adaptor assembly by GKN Sinter Metals; helical gear and spur pinion by Capstan Atlantic; powder metallurgy aluminum camshaft-bearing cap by Metal Powder Products Co., etc. Powder metallurgy is one of the key methods in the fabrication of functionally graded aluminium alloy and its composites, and several academic and industrial researches have been performed on this methodology.

Cylindrical specimens of iron powder-based graded products made from Distaloy SE powder having regions with varied carbon content, sintered by two methods, were investigated [35]. The sintering methods used are pressureless sintering and pressure-aided sintering, called Spark Plasma Sintering (SPS). Arising from this study, it was observed that:

i. Sintering by means of the SPS technique produced slightly lower shrinkage compared to conventional sintering.

ii. Microstructural studies of the manufactured products showed similar morphology of pores, with minor consequence of sintering techniques and parameters on pore size distribution.

iii. The SPS sintered products showed an increased number of large pores, compared to the conventional method.

iv. The SPS method cooling rate influenced the formation of numerous areas with bainitic structure causing an increase in outer layer hardness.

Investigative work was performed on the production of AlSi alloy with carbon nanotubes (CNTs) reinforcement for the purpose of obtaining FGM for engine piston ring applications. Wear and fatigue have been cited as the major cause of piston ring failure. FGMs fabricated by the PM process was seen as a solution to this problem, but existing manufacturing methods could only build cylinder specimens with limited gradients [37, 38] as cited by [36]. To address these limitations, new equipment was developed and then used to obtain an optimised AlSi-CNTs FGM for this purpose. This equipment permits the formation of varied continuous powder distribution along a given side of the sample. Various mechanical tests were carried out and discussed and including ultimate tensile and yield strengths, fatigue limit performance, tensile strain, and wear resistance tests. The results show that [36]: hot-pressing technique is good for the fabrication of AlSi-CNT FGM; the piston rings show varied gradient, about 2 wt.% of CNTs on the inner surface, 0 wt.% of CNTs in middle and 2 wt.% of CNTs on the outer surface of piston ring; AlSi-CNT FGMs provide better mechanical performance compared to AlSi unreinforced alloy; and, considering cost effectiveness, CNTs 2 wt.% gradient outer surfaces was considered best for piston ring material.

**Sintering Process.** Sintering is a PM consolidation process which is carried out alongside with the compaction process of FGM using hot pressing. Examples of sintering methods are spark plasma sintering (SPS), high frequency induction heating and electric furnace heating. The SPS sintering method was used in the production of HAP/Ti FGM and it was useful in stress relaxation of FGM [39]. Porosity is a measure of sintering effectiveness and sintering models have been created and analysed. Other factors that influence the behaviour of FGM fabricated by sintering methods are time, sintering atmosphere, temperature, and the isostatic condensation [40]. A study
on porosity using a sintered nickel/alumina (Ni/Al2O3) FGM revealed that porosity is directly related to the rate of shrinkage. Further, the study shows that a porosity reduction model is used to: check quality of particle-reinforced metal-ceramic FGM and predict changes in porosity reduction in particle dispersion development of FGMs [41, 42].

PM methods are continuously undergoing appraisal and modification for cost effectiveness, quality and suitability. According to Kieback et al. PM includes sedimentation, plasma spraying, electrophoretic deposition, slip casting, powder stacking, etc. as current FGMs manufacturing methods [37]. However, some of these methods produce sharp interfaces which lead to thermal expansion mismatch and residual thermal stresses. An example of such a PM method is sequential slip casting [43], but Po-Hua used sedimentation and vibration to scale up the production of aluminum and high-density polyethylene (Al-HDPE) FGMs to avoid thermal expansion mismatch and residual thermal stresses [44].

**Squeeze Casting.** Ghomashchi and Vikhrov in a review study categorised four basic steps in squeeze casting fabrication of FGMs: pouring of a calculated molten metal into the mould; closing the mould, pressure application; and, cast ejection [45]. However, there are other fundamental processes that are essential for quality squeeze casting. Other steps in the squeeze casting process of aluminium matrix FGM production include melting a specified metal, degassing, preheating of mould, pouring, and pressing. Regarding ceramic-metal functionally graded composite fabrication, further steps are particles preheating, addition of particles to the molten metal and stirring of the mixture.

The squeeze casting method produces finished or nearly finished castings with minor post production processes so as a result is considered to be a near net-shape manufacturing route. The pressure on the metal is released after solidification is completed. The applied pressure in squeeze casting enhances the bonding force between the matrix and the reinforcement, the wettability and solidification rate [46, 47]. Applying Clausius-Capeyron’s expression in equation (4) to a metallostatic pressure as high as 200 MPa increases the melting point of the metal [48]. Epanchistov stated that the eutectic point in the A-Si structure changes to a higher silicon content [49].

\[
\frac{\Delta T_f}{\Delta P} = T_f \frac{(V_l - V_s)}{\Delta H_f}
\]

(4)

Where \(T_f\) = equilibrium freezing temperature; \(V_l\) and \(V_s\) = specific volumes of the liquid and solid, respectively; and \(\Delta H_f\) = latent heat of fusion. A rough estimate of the effect of pressure can be determined by considering the liquid metal as an ideal gas and replacing the thermodynamic volume equation to have equation (5):

\[
P = P_o \exp \left( \frac{-\Delta H_f}{RT_f} \right)
\]

(5)

Where \(P_o\), \(\Delta H_f\) and \(R\) = constants.

Numerous research studies have been conducted in different parts of the world on aluminium and magnesium related metal matrix composites (MMCs) fabricated by the squeeze casting method. Over 700 journal articles published on MMCs research was reported in 2000 [45, 50]. The annual growth of the application of squeeze casting in aerospace, automotive, sport and leisure was put at 12 ± 15 % [51].

**Infiltration Method.** Infiltration is the process of metal matrix composites (MMCs) fabrication by means of ejecting a molten metal at a high pressure into a porous preform. Infiltration involves two stages: initiation of flow depicted by the dynamic wetting angle, and advancing the flow in the capillaries of the preform. The infiltration pressure threshold, \(P_0\), according to capillary law is [52]:

\[
P_0 = 6\lambda \gamma_v \cos \theta \left( \frac{V_p}{1-V_p}D \right)
\]

(6)

Where \(\theta\) is the contact angle; \(\lambda\) is the geometry depended factor; \(\gamma_v\) is the tension of liquid-vapour surface; \(D\) is the mean diameter; and \(V\) is the volume fraction of the particulates.
The combination of squeeze casting and infiltration involves preform. The fabrication of a preform has these basic steps: liquid powder processing, pressing and shaping and sintering of the preform. The principle behind preform is the blending of a ceramic powder slurry with a sacrificial organic pore forming agent (PFA) that is pyrolysable. The mixture is then pressed and heat treated to pyrolyse the PFA to form preform pores. Preform processing parameters include a pore forming agent (PFA), green sintering temperature and green pressing pressure. Cellulose particles (PC) and carbon fibres (PF) are examples of PFAs. Table 3 shows some PFAs and their sintering temperature.

Table 3: Sintering temperatures for different preform formation [53, 54]

<table>
<thead>
<tr>
<th>Ceramics</th>
<th>Pore forming additives</th>
<th>Sintering temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AO</td>
<td>PF</td>
<td>1500</td>
</tr>
<tr>
<td>AO</td>
<td>PC</td>
<td>1600</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>Glassy frit binder (AG)</td>
<td>1000</td>
</tr>
</tbody>
</table>

The study of the behaviour of FGMs characterised by pure aluminium reinforced with Al₂O₃ (50% volume) and B₄C particles with an average diameter of 30 μm was conducted. The composites were fabricated by pressure gas infiltration. The study observed that during monotonic loading, the composite materials measured 25% elongation to failure; the ultimate tensile strengths recorded were 120 MPa and 200 MPa for Al-Al₂O₃ and Al-B₄C composites respectively; the tensile failure of Al-Al₂O₃ was due to particle fracture while matrix porosity was responsible for the failure in Al-B₄C. Degradation of Young modulus, and density decrease were used to measure the internal damage propagation. In another experiment, ceramic preforms with the same porosity level were produced by sintering of RA-207LS Al₂O₃ powder [55]. The preforms’ porosity were based on polymer matrix cellular structure. Two types of pressure sources were used: pressure-vacuum infiltration (T = 720 °C, p = 15 MPa, t = 15 min), and gas-pressure infiltration (GPI) in an autoclave (T = 700 °C, p=4 MPa, t = 5 min). The study concluded that: ceramic-metal composites with interpenetrating of phases resulted from the two infiltration methods; GPI provided a higher degree of infiltration; and, better composites were obtained from preforms with the smallest pores. The flow of metal within the preforms depends on capillary size; the pressure variation along the capillary length; the metal liquid state preserving time within the capillary; and, the alloy viscosity dynamic. The study added that the composites produced by the GPI method are characterised by compressive strength, higher hardness, and an increase in Young’s modulus. Fig. 5 shows the GPI set up.

**Gas Pressure Infiltration**

![Figure 5: Schematic of GPI set up](image)

**Centrifugal casting.** The fabrication of FGMs by the centrifugal casting technique involves the filling of a spinning mould and the cast is allow to solidify before rotation is stopped [20, 56]. The rotation creates centrifugal force that pushes the molten metal against the wall of the mould to produce the desired shape. This technique was first used by Dimitri Sensaud DeLavaud, a Brazilian
in 1918 [56]. The method is used in the casting of metal such as functionally graded materials (FGMs), alloy steels, corrosion- and heat-resistant steels, aluminum alloys, copper alloys, etc. It also used in the production of non-metal such as ceramics, plastics, glasses, and practically every material that can be melted into liquid or slurries. In centrifugal casting of hypereutectic alloys such as A390-5%Mg, the outer periphery will be a fibrous form of silicon. The large primary silicon and large α-aluminum dendrites will migrate to the inner region since they have almost the same density. In the case of particles and slurry, the particles will migrate to the outer region. For a slurry-slurry system, the heavier slurry with the higher density will move towards the mould wall. The magnitude of the segregation depends on the speed of rotation. The force generated equation and other common basic expression in centrifugal casting process is as follows:

The angular velocity, \( \omega \);

\[
\omega = \frac{v}{r} = \frac{2\pi N}{60} \tag{7}
\]

Centrifugal force, \( F_c \), acting on the particle of mass \( m \) at distance \( r \);

\[
F_c = m \omega^2 r = m \frac{4\pi^2 N^2}{3600} \tag{8}
\]

The ratio of centrifugal force to gravitational force, \( G \), can be simplified as;

\[
G = \frac{F_c}{F_g} = \frac{r \omega^2}{g} = \frac{r \left( \frac{2\pi N}{6} \right)}{g} \tag{9}
\]

Thornton recommends 50 G to 100 G range of speed for metal mould and 25 G to 50 G range of speed for sand cast mould. Speeds that are too high can cause hot tears to outside surfaces and excessive stresses [57]. The magnitude of centrifugal force possessed by particles in a molten metal depend on the density and size of the particles. The denser and larger particles migrate to the mould wall. The Stokes equation is used to explain this process for spherical shaped particles as in equation (10).

\[
v = \frac{d^2 (\rho_p - \rho_l) g}{18 \mu} \tag{10}
\]

Where \( v \) is the particle velocity; \( d \) is the diameter of the particle; \( \rho_p \) is the particle density; \( \rho_l \) is the molten metal density; \( g \) is the gravitation force; and, \( \mu \) is the viscosity of the molten metal.

The centrifugal method can be categorised in different ways: it can be based on mould arrangement and mould angle inclination to either vertical or horizontal planes [56]; and, it can be according to liquidus temperature of the matrix alloy. There are two types of centrifugal methods of fabrication by liquidus [58]. The ex situ or solid-particle centrifugal method involves temperature below the liquidus temperature of the matrix material and addition of pre-fabrication reinforcement to the liquid matrix metal by infiltration, vortex or casting method; and the centrifugal in situ method which involves temperature above liquidus temperature of the matrix and the reinforcement is precipitated in the matrix melt during cooling and solidification. The in situ method advantages compared to the ex situ technique, namely, good wettability, homogeneous distribution of reinforcement and reinforcement materials, and thermodynamic stability in the matrix alloy [59, 60].

Although many metal-ceramics FGMs have been developed by the centrifugal method, it is still in the development stage because of the inadequate knowledge of particle distribution and control [61]. The significant processing parameters for gradient microstructure control are: mould temperature; crucible temperature; pouring rate; thermal gradient through the mould; velocity of mould rotation; solidification rate etc. Temperature circulation is difficult to estimate during centrifugal casting due to the mould’s fast rotation during pour and solidification. A schematic of a vertical centrifugal casting machine is shown in Fig. 6.
Presently, the centrifugal casting method is one of the cheapest and simplest FGM fabrication methods. Gravity or centrifugal casting is the most economical to run [61]. The properties of a material depend greatly on its microstructure. Centrifugal process parameters are used to manipulate microstructure formation. Centrifugal technique processing parameters include pouring and mould temperatures, speed of mould rotation, and particle size. The application of this method is vital in the fabrication of disc, ring, and pipe components and as result it has attracted several academic and industrial research grants.

Gomes et al. carried out a comparative analysis between the wear behaviour of Al–SiC<sub>p</sub> FGM and homogeneous Al–Si–Mg-20%SiC<sub>p</sub> composite [62]. They were subjected to the slide the nodular cast iron (NCI) and the Pin-on disc tests without lubrication using 5N as normal load. The study revealed that Al–SiC<sub>p</sub> FGM has lower wear coefficient than that of the homogeneous composite. This was attributed to the effects of SiC particles which serve as load-bearing elements. This shows that the presence of reinforcement particles in the matrix alloy enhances the wear resistance. However, it was demonstrated in other studies that the ratio of the matrix to reinforcement has a threshold that should not be exceeded. Exceeding the threshold can cause severe failure in the FGM matrix/reinforcement interface [63, 64].

Ramadan and Omer in their study produced functionally graded aluminum matrix composite (FGAMC) through the centrifugal casting method. In the FGAMC formation, Boron 1.2 % to 1.85 % by weight was dissolved in molten aluminum at 1400 °C through the addition of AlB<sub>2</sub> flake of 2.71 % to 4.20 % by weight. Centrifugal casting was carried out at 800 °C. It was reported in the results that two dissimilar regions were observed without smooth gradient as shown in Fig. 7, a zone (outer) with AlB<sub>2</sub> surplus and a zone (inner) with AlB<sub>2</sub> deficit. Further, the achievement of 64 % hardness and strength increase through the increase of reinforcement particles at the outer zone was reported [65].

Three samples of functionally graded rings were produced from aluminum A390 as a metal matrix alloy using centrifugal casting method by Rahvard et al. The three rings of A390 alloy had different amounts of Magnesium (Mg) of 0 %, 6 % and 12 % of weight Mg respectively. The effects of Mg volume variation on their mechanical and microstructural properties were investigated.
in the samples of the metal matrix. This was used to know the particles distribution in the matrix alloy. Also examined was wear resistance by the three ring samples and a comparison analysis was made. It was observed in the work that [66]:

i. The characteristics of A390 ring reinforced without Mg has the Si particles distributed in both inner and outer areas. This particle arrangement was attributed to the density of the primary Si being lower than that of the metal matrix alloy. This density difference will cause the particles to drift towards the inner region. However, the highest hardness was recorded in the outer region.

ii. The second sample which is A390 alloy with 6%Mg displayed different particle distribution performance. The density of Mg$_2$Si is far lower than the aluminum alloy liquid density. The difference in densities causes the Mg$_2$Si particles to move to the inner region with a higher velocity. Subsequently, a distinctive alteration between the zones is obtained. It was reported that the inner region performed better in terms of hardness and wear resistance.

iii. The third sample was 12%Mg ring with Mg$_2$Si as primary Mg$_2$Si reinforcement. The distribution was observed almost throughout the entire cross-section except for a narrow free reinforcement zone of 2mm thickness. The external layer was reported to possess the best performance for hardness and wear resistance.

The study of processing parameters like G number, caster and casting atmosphere influences on the cooling rate and microstructure formation were examined by Hisashi, Yoshimi and Yuko [67]. Samples of Al-Al$_2$Cu FGMs were produced through the centrifugal casting method at different casting conditions. The process parameters used were reinforcement volume fraction, pouring and mould temperatures, G number, mould diameter, degassing method, and cooling method. For experimental control and comparative analysis of the vacuum centrifugal casting, gravity casting was explored with the process parameters. Rod-shaped and pipe-shaped Al-Al$_2$Cu FGMs were produced by two kinds of vacuum centrifugal casters from Al-$33\text{mass}\%$Cu eutectic alloy. Also, the distribution of lamellar spacing in the FGMs was evaluated. The study revealed that:

i. The composition and microstructure in both rod-shaped and pipe-shaped FGMs samples were position dependent in the samples which are defined by production parameters such as cooling rate.

ii. The samples of FGMs produced under vacuum show a comparatively abrupt profile of distribution of the Al$_2$Cu volume fraction compared to samples produced under atmospheric gas. This was attributed to cooling rate distribution.

iii. There was a homogeneous distribution of cooling rate in smaller samples of FGMs compared to the larger samples. It was reported that G number and atmosphere influenced the cooling rate distribution and size of sample.

iv. It was observed that lamellar spacing is a function of position.

Babu et al. developed analytical theory used for two-dimensional dynamics simulations to engineer metal-ceramic FGM for a preferred composition gradient employing the centrifugal casting technique [61]. This work modelled the movement of ceramic particles in molten metal under centrifugal force and the combination of effects of solidification. The centrifugal method was used to produce FGM rings from the mixture of aluminum and silicon carbide (SiC) particles. Experimental results were to validate the simulation technique and then recommended for FGM composition gradient.

**Material Prototyping or Solid Freeform (SFF) Fabrication Method.** The dynamics of Material Prototyping or Solid Freeform (SFF) Fabrication Method method of material fabrication is very fast and has taken the centre stage of FGM production. Its benefits include production of complex shapes, fast production speed, material optimisation, not energy intensive, and fabrication of parts directly from CAD STL file. Five stages are involved in this method: CAD model data generation; CAD model data conversion to Standard Triangulation Language (STL) file; STL slicing into two dimensional cross section profiles; layer by layer deposition of component; and, removal and finishing operations [68, 69]. SFF technologies come in various types used in the fabrication of functionally graded materials. Prototyping technologies are still evolving with poor
surface finish and dimension accuracy challenges and current research efforts are being directed to these challenges.

**Stir Casting.** Stir casting simply means the blending of the melted matrix and particles before pouring the mixture into the mould as depicted by Fig. 8a. This is an aspect of the casting process that is vital for quality casting of FGAAMCs by melt casting. Stirring is employed to add and disperse the particles into the molten metal and to suspend the particles in the slurry. The introduction of particles into the matrix melt is an important step in FGMMCs fabrication and there are different methods to do this. These methods include: the insertion of particles restrained by inert gas carrier into the melt through injection gun; addition of the particles to the melt stream during pouring; use of a reciprocating piston to push particles into the molten metal; spray of particles along with atomised molten metal into a substrate; vortex method; distribution of particles in the molten metal by centrifugal process, etc. A complete set up of a stir casting facility is shown in Fig. 8b. The vortex method is known to be one of the best approaches to insert particles into the matrix melt, to distribute and suspend the particles in the slurry before it is cast. The stirring is introduced after the matrix has melted and the stirring is made vigorous in order to form a vortex at the surface of the matrix melt. The particles are then added to the matrix through the vortex and stirred for few minutes before the slurry mixture is cast. Stir casting is influence by certain parameters such as pouring temperature, stirring time, stirrer blade angle, pouring rate, and gating systems [70, 71].

**Compocasting.** A lot of methods have been proposed and used to improve wettability and some of the methods are use of wettability fluxes and agents, preheating, ceramic coating, and oxidation [72, 73]. However, some of these methods are expensive and add to the production cost. The addition of reinforcement particles to a semi-solid matrix at lower casting temperature is termed slurry casting or compocasting. This modified stir casting method is regarded as an economical technique to enhance wettability [74].

There is always a quest to improve thermal, mechanical and chemical properties of materials to form new materials to meet the present material demands. As a result, many of the production technologies that have been or are in use are undergoing appraisal and new ideas are being added. Compocasting is one the casting technologies that is undergoing review and its investigation and application is expanding. Gladston et al. fabricated AA6061-RHA\(\text{p}\) (rice husk ash particle) composite by compocasting technique. The study observed the formation of intergranular dispersion of particles and the improvement of macro hardness and ultimate tensile strength of RHA particles of FGMC [73]. The challenges of homogeneous distribution of SiCp particles and the non-uniform dispersion of coarse Si fibres in Al-Si alloys cause poor mechanical properties. These setbacks were eliminated by the use of an accumulative roll bonding (ARB) process which operates on the principle of compocasting technique [75]. The ARB schematic is shown in Fig. 9. It was revealed that this process produced a composite with evenly distributed Si and SiCp particles; finer and spheroidal Si particles; no Si and SiC particles free zone; minimised porosity; and, better matrix-particle bonding. The mechanical attributes of the composite were enhanced.
Combination of Methods. Some of these methods are combined for effective production of FGAAMCs. Sintering is a major step in PM and in some cases it is combined with centrifugal the casting process. The stir casting process can also combine with other casting processes such as centrifugal casting, gravity casting and ultrasonic casting. Kunimine et al. combined sintering and centrifugal casting processes to fabricate copper/diamond FGMs for grinding wheels application [76]. The study investigated the influence of fabrication parameters such as casting and sintering temperatures, and the holding time on microstructure of a copper/diamond FGM. The novel FGM production stages are as shown in Fig. 10.

Kunimine et al. study revealed that: preform thickness can be controlled by choosing combinations of sintering holding time and temperature; copper/diamond FGMs were produced under casting temperatures of 1393 K and 1373 K by centrifugal sintered-casting technique and diamond abrasive grain fractions were controlled by processing parameters; the amount of pores in copper/diamond FGMs structure serve as chip spaces and were appropriate for grinding wheels for
machining carbon fibre-reinforced plastic (CFRP) application and gyro-driving grinding wheel systems provided with copper/diamond FGMs grinding wheel drilled on CFRP plate precisely without burring and delamination.

Erdemir et al. combined two techniques, hot press and consolidation method, to fabricate a number of layers of Al2024/SiC FGMs. The study investigated the impact of SiC volume fraction on corrosion and wear resistance behaviour. The formation of FGMs of varied percentage of SiC (30 % to 60%) were used [77]. The study observed that: two layered FGMs with 50 wt.% SiC on outer layer composites showed excellent corrosion resistance in 3.5% NaCl solution; the macrohardness of Al2024/SiC FGM with 40 wt.% SiC was 225 Hv while 30 wt.% SiC measured 170 Hv; increase in SiC content in Al2024/SiC decreases wear rate while increase in the applied load increases wear loss. The study concludes that wear mechanism changes from adhesive wear to abrasive wear due to an increase in SiC particles content.

Effects of wettability and porosity in FGMs

**Wettability.** The spreading of a liquid around a solid surface is defined as wettability and it relates to the close contact between a solid and a liquid. The manner in which reinforcement particles are wet by melt is a measure of success of particle insertion into the casting in composite production. The addition of reactive elements, such as Zr, Ti, Mg, Ca, etc. to metal matrix stimulates wettability of matrix on particles. Young Dupre’s equation describes the bonding force relationship between the matrix and the particles in terms of contact angle ($\theta$) as shown is Fig. 1 as follows [78]: $\theta = 0^\circ$ (Perfect wettability); $\theta = 180^\circ$ (no wetting); $0 < \theta < 180^\circ$ (partial wetting).

![Figure 1: Schematic showing the contact angle between the solid phase and the liquid phase [70]](image)

Where $\gamma_{sv}$ is the solid–vapour; $\gamma_{sl}$ is the solid–liquid interfacial energy; and $\gamma_{lv}$ is the liquid–vapour interfacial energy.

A series of investigation on the influence of stirring casting on microstructure and wettability effects in FGAAMCs carried out by Hashim, Looney and Hashmi in which they carried out a series of wettability tests in aluminium FGAAMCs fabricated by stirring of semi-liquid slurry. A359 alloy, SiC$_p$ and magnesium were used as matrix, reinforcement, and wetting agent respectively [70]. The study had stirring rotational speed, impeller size, holding temperature and stirrer location in the melt as the relevant fabrication processing parameters. A variety of mechanical properties can be achieved through this process by varying these processing parameters. This is because mechanical properties of the FGAAMCs largely depend on the reinforcement type, size, and its distribution pattern, the particles wet level by the matrix, and the quantity of porosity. The technique was described as cost effective, however, this greatly depends on how the production technical challenges are resolved.

The influence of processing parameters (temperature and holding time) on the dispersion of particles in a matrix and the subsequent mechanical behaviours was studied [79]. The matrix and reinforcement used were Al-11Si-Mg and SiC$_p$ (40 µm) respectively fabricated by stir casting at a constant rotation speed of 450 rpm. The formation of dendrites was conspicuously observed and the particles were evenly distributed in the specimens prepared at 700 °C, 750 °C, and 800 °C. Coupled with no significant pore formation, particle clustering was not seen in the SEM image. However,
significant pores and particles clustering were found in the specimens prepared at 850 °C and 900 °C. This condition was credited to the high viscosity which induces low shearing melt rate.

Abrasive wear property of Al6082-SiC-Gr hybrid composites produced by stir casting was examined and compared with Al6082 alloy and Al6082–SiC composites [80]. The study reported that: Al-SiC-Gr hybrid composites had a better wear resistance performance than Al6082 alloy and Al6082-SiC composites; 16.4 % and 27 % wear enhancement was observed of 200 mm grit size of Al-SiC-Gr composite, as-cast and T6 heat treated respectively when 15N load was applied; 100 mm grit size of Al-SiC-Gr composite, as-cast and T6 heat treated respectively, were found to be 19.6 % and 26.9 % wear resistance improved respectively.

**Porosity.** In most engineering materials, porosities are regarded as defects and as such material are made dense to minimise porosity and to enhance mechanical properties in FGAAMCs. Porosity formation is caused by air bubbles in a matrix melt, vapour from surfaces of reinforcing particles, gas entrainment and hydrogen evolution, and shrinkage during solidification [81]. Research works have shown that the porosity in a FGMMC is also a function of casting processing parameters. A decrease in the amount of porosity in FGMMC means an increase in the Poisson ratio, damping capacity, Young’s modulus of elasticity and tensile and compressive strength. However, there are engineering and biomedical materials where porosity serves a useful purpose. Some of the engineering materials where porosity is useful are filters, catalyst supports and furnace lining bricks [82]. Applications of porous material includes solid oxide fuel cells porous electrodes, and isolating bacteria membranes used in bioreactors [83]. a series of production techniques have been invented and appraised to reduce porosity in cast FGMs and these include: vacuum casting, inert gas bubbling past the liquid metal, casting under pressure, compressing, rolling of material after casting to close the voids, and addition of hexachloroethane to melt.

**Applications areas of FGMs**

The FGM concept is described as a systematic process of bringing incompatible functions such as thermal, wear and corrosion resistance, toughness and machinability into a single part. This has expanded the application of FGMs in many sectors. Table 4 and Fig. 12 present FGMs application areas.

<table>
<thead>
<tr>
<th>Sectors</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering</td>
<td>Cutting tools, machine parts, engine components, etc.</td>
</tr>
<tr>
<td>Medical</td>
<td>Biomaterials: implants, artificial skin, drug delivery system</td>
</tr>
<tr>
<td>Energy</td>
<td>Thermionic and thermoelectric converters, fuel cells and solar batteries</td>
</tr>
<tr>
<td>Aerospace</td>
<td>Space plane nose, combustion chamber protective layer, body components etc.</td>
</tr>
<tr>
<td>Automotive</td>
<td>Crown of piston, cylinder liners, exhaust valves and valve seating</td>
</tr>
<tr>
<td>Nuclear</td>
<td>First wall of fusion reaction, fuel pellets</td>
</tr>
<tr>
<td>Optics</td>
<td>Optical fibre, lens</td>
</tr>
<tr>
<td>Chemical</td>
<td>Heat exchanger, heat pipe, slurry pump, reaction vessel</td>
</tr>
<tr>
<td>Electronics</td>
<td>Graded band semiconductor, substrate, sensor</td>
</tr>
</tbody>
</table>

Two FGMs in commercial status are high performer cutting tools, namely, tungsten carbide/cobalt and a razor blade of iron aluminum/stainless steel (FeAl/SS) FGM [15].
Conclusion

This paper presents an overview of the main FGMs bulk production techniques, their evolution, principles and applications. The fabrication processes include PM, sintering, squeeze casting, infiltration process, compocasting, centrifugal casting, stir casting, material prototyping. Despite the rapid development observed in all the techniques considered, challenges still abound in getting the desirable material without certain material attributes being a trade-off. The use of some of these techniques for mass production is challenging from cost of fabrication perspective. However, the combination of methods is seen as the most promising method of evolving new quality FGMs. Several FGAAMCs laboratory investigations have shown that the main processing parameters depend on the type of fabrication method used. However, reinforcement particle size, and casting temperature seem to be general while pressure, mould, and stirrer speed of rotational are for PM, centrifugal and stir castings respectively.

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References


