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A Review of Functionally Graded Materials: Fabrication Processes and Applications

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Abstract

Functionally graded materials (FGMs) are materials that possess variance in properties across the geometry of the material. They are a class of materials developed from the existing knowledge of material alloying. This paper discusses the evolution and the background study of FGMs. The different FGMs processing techniques and their comparative advantages were discussed. Furthermore, the paper classified FGMs based on the principle of their manufacturing method. Various application areas of FGMs were discussed.

Keywords: Functionally graded materials, metal casting, alloying materials

1. INTRODUCTION

Pure metals have limited applications in engineering due to the demand for contradictory properties due to functionality requirements [1]. In engineering applications there is a need for materials with different properties which will enable them to perform optimally under service conditions. Such properties are non-existent or difficult to obtain in a pure metallic material. Therefore, two or more different metals, each of which possess one of the required properties for optimum performance, are combined to produce what is known as alloys. The importance of metals in day-to-day life and particularly in engineering cannot be overemphasised. These range from domestic to industrial applications, such as manufacturing and construction. The working condition of the metal during service as well as expected performance informs the choice of the metal to be selected for any particular engineering application. Owing to the less desirable properties of pure metals, metal alloys, such as aluminium alloys are generally preferred for engineering applications.

Aluminium in its raw form is abundant in nature, comprising about 8% of the earth's crust. Pure aluminium is of low strength and easily deforms under load. In engineering applications such as automobile components and aerospace designs, the use of aluminium alloys are employed due to their light weight and lower density compared to steel. Good thermal and electrical conductivity are also desirable properties of aluminium for electrical cable production and kitchenware. Alloying elements such as magnesium, manganese, copper, zinc, tin and silicon, when added to aluminium, enhance its properties thereby making it suitable for use in industrial as well as domestic applications. One of the most essential alloying elements for aluminium is silicon as it improves the cast-ability of aluminium metal. Alloys provide enhanced properties that are unique compared to those which are present in parent materials on their own. However, conventional alloys face constraints such as thermodynamic equilibrium limitations and thermal dissimilarities between alloying materials [1, 2]. These challenges, among others, have led to the development of unique materials known as functionally graded materials (FGMs).

Functionally graded materials are specialized types of advanced materials developed to withstand severe service conditions while performing at optimum during service. They are developed such that the properties, composition and features of the constituent elements of the material varies with respect to the location and dimension along the material [3, 4] as shown in Fig. 1. The composition, microstructure or the porosity gradient of the FGM can vary either continuously or discontinuously and can be specifically designed to provide specific functionality during service [5].

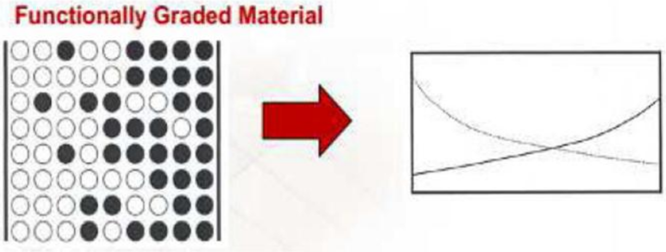

Fig. 1. Profile of FGM

Similar to conventional composite materials, the properties and characteristics of FGMs are different from those of the individual elemental materials which form the FGM. The property(ies) of the FGM are graduated across the volume of the material because of the dependability of the chemical composition, microstructure or atomic order of atoms, and of their position within the material [4, 6].

The need for FGMs arises from the desire to have materials which possesses the ability to retain their structural integrity during service when exposed to opposing conditions simultaneously from different ends. Interest in FGMs has increased over the years due to the advantages of FGMs over single component materials or alloys. One example of an advantage is the elimination of sharp boundaries which serve as stress concentrator regions that trigger failure in conventional composite materials, and substituting it with the gradient type boundaries, while also eliminating the thermodynamic limitations encountered in alloy applications [1, 7]. Furthermore, FGMs are unique in that they can be designed specifically for predefined applications [3, 4]. The ability to influence and manipulate the properties of composite materials for a specific engineering application makes the research into FGMs of immense importance.

2. BACKGROUND OF FGMs

Material development in the past focused on producing materials with homogenous properties which exhibit little or no property variance when finished and which are capable of producing optimum performance during service. However, arising from the limitations encountered in the application of conventional homogenous materials such as polymers, ceramics and metal alloys, the need for FGMs arose. The use of FGMs over the past few decades has witnessed tremendous growth both in the area of development and in the area of application, particularly in the aerospace, automobile and health sectors. Various manufacturing methods to produce FGMs have been developed over time, particularly in Japan between 1987 and 1991. The earliest form of fabrication methods in the thin group of FGMs were mostly in form of layer processing, examples of which included spraying, vapor deposition and self-propagating high-temperature synthesis (SHS). Powder metallurgy (PM) was employed in processing of bulk FGMs [1]. The use of conventional composites has not been successful in spacecraft and aviation applications. Continuous texture control was developed and adopted in 1985 to improve the binding strength and decrease the stress due to the rise in temperature in the ceramics coating of rocket engines [1].

Modern day FGMs were developed as a result of the challenges encountered by Japanese engineers in the mid-80s when building the frame of a space rocket because the material needed to be able to withstand opposing temperature extremes on opposite sides of the material. The inner and outer working temperatures of the materials were 1000 K and 2000 K respectively, while the material thickness was less than 0.1 cm [3, 8]. The success of that project kick-started evolution of modern day use of FGMs. This led to the first national symposium on FGMs which took place in 1990 in Japan [9]. At the turn of the new century, production processes of FGMs were already widespread, with FGMs finding their way into Europe, leading to the establishment of a trans-regional research centre in Germany in 2006. The centre was tasked with the exploitation of manufactured graded mono materials like steel and aluminium, joined thermally and mechanically [1].

3. GROUPS OF FGM

Depending on the geometry and the cross-sectional area of the material to be produced, FGMs can be categorized into two major groups, the thin and bulk FGMs.

3.1. Thin FGMs

These are usually in form of surface coating and have thin cross sections. The choice of surface deposition method employed in the manufacturing of thin FGM is dictated by the service requirements of the material. Various deposition techniques for thin FGMs include vapor deposition, plasma spraying, atomic layer deposition (ALD), electrodeposition, SHS, among others [1, 8, 10]. Thin FGMs are usually not suitable for applications with extreme service conditions.

3.2. Bulk FGMs

Bulk FGMs are those with thickness greater than 1 mm and whose functional properties vary with respect to the gradient profile of the material. Bulk FGMs are produced through different techniques such as the solid freeform (SFF), PM, metal casting (MC) among others

4. FGM CHARACTERIZATION

The characterization of FGM is often based on the variation of the structure and composition of the constituent materials which make up the graded material. These variations in turn influence the overall properties exhibited by the material during service. The literature generally groups FGM manufacturing processes into four major categories [1, 4, 11, 12], namely, bulk, layer, preform and melt processes as shown in Fig. 2.

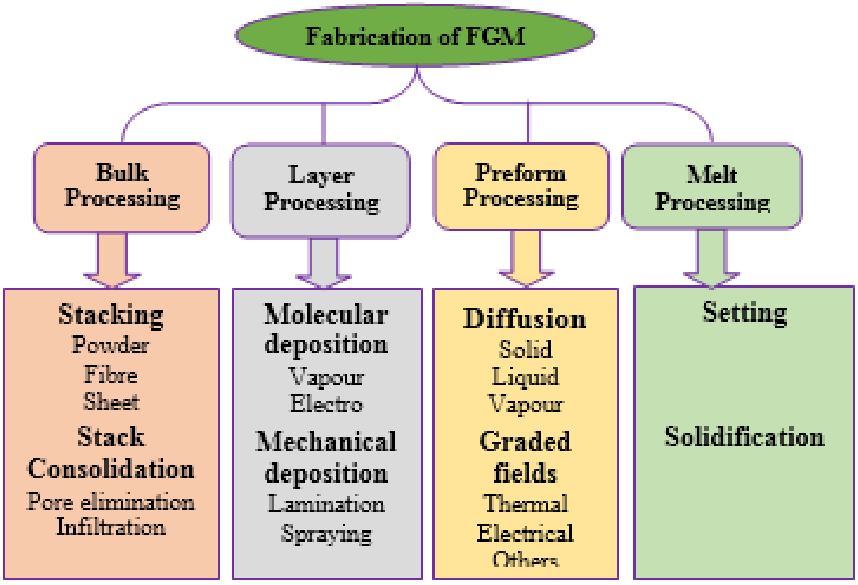

Fig. 2. FGM processing techniques [1]

5. FABRICATION PROCESSES OF FGMs

As discussed earlier, the choice of FGM fabrication technique is mainly influenced by both the desired service properties and the FGM group of the material to be produced.

5.1. Thin Group FGM Manufacturing Process

Thin FGM is usually produced through various deposition processes such as vapor deposition, atomic layer deposition, spray deposition, electrodeposition and laser deposition. The choice of deposition is dependent on the service required of the material.

5.1.1. Vapor Deposition Process

Vapor deposition techniques are used in producing thin FGMs. There are various types of vapor deposition techniques, which include but are not limited to, chemical vapor deposition, physical vapor deposition and sputter deposition. Vapor deposition techniques are excellent in deposition of a graded surface coating producing desirable microstructure. However, they are only efficient in producing thin FGMs, as they are relatively tedious and labor intensive. Furthermore, cost of production is comparatively high and toxic gases are given off as a by-product [13]. Other processing techniques for thin FGMs include SHS, plasma spraying, and ion beam assisted deposition (IBAD) [14].

5.1.2. Atomic Layer Deposition (ALD)

ALD involves a process of deposition of thin film metal and metal oxide deposition in Ångstrom scale (i.e. 10^{-10}) to produce an FGM. This is advantageous compared to other deposition techniques such as thermal spray and chemical vapor deposition [15]. The quest to develop semiconductors and capacitors with improved cycle performance has driven research interest in ALD. The ability to have control over the film thickness during deposition adds to the advantages of this process. Sun et al. [16] developed a Ti_2O-graphene functionally graded material for a super-capacitor using the ALD process. Ti_2O was deposited on the graphene material in nanoscale. When used as a super capacitor, Sun et al. [16] reported that the Ti_2O-G composites showed exceptional charge transfer conductivity and good ion diffusion with negligible deterioration in electrochemical performance compared to when pure graphene was used.

5.1.3. Spray Deposition

The spray deposition process of producing FGMs is a relatively recent technique that involves the use of inert gas to atomize liquid melt into fine droplets and then deposit the droplets on a metallic substrate. The process has been successfully applied to preparing ceramic particle reinforcement of metal matrix composites [17]. The spray deposition process eliminates challenges such as liquid aluminum particle rejection encountered during liquid state processing of composite matrix. Su et al. [18] developed a SiC particle Al-20Si-3Cu FGM using the spray deposition process coupled with a programmable control system. It was established that an increase in the SiC particle weight fraction in the as-deposited preform brought about an increase in the porosity and micro hardness of the material. Furthermore, as seen in Fig. 3, a homogenous distribution of the SiC particles in the as-deposited preform is observed across the material bulk in the longitudinal direction. Due to its advantages over other liquid state processing methods, spray deposition processing of FGM appears to be the preferred processing method for a wide range of FGMs.

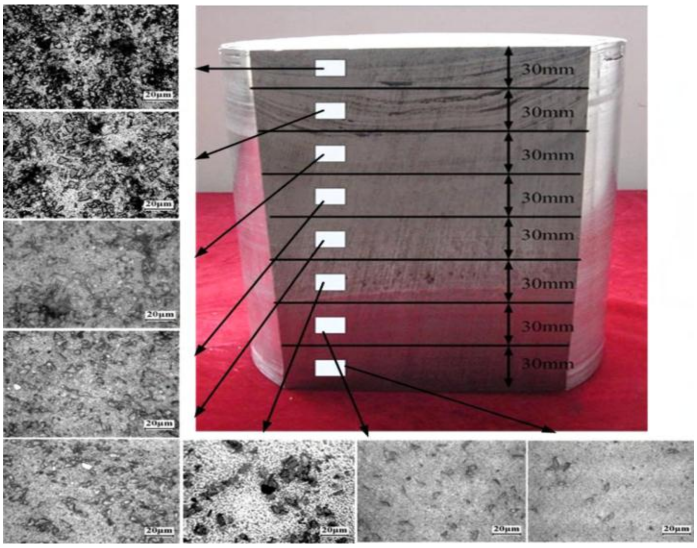

Fig. 3. Microstructure of the distribution of SiC particles in the FGM perform [18]

5.1.4. Electrodeposition

Electrochemicals as a form of surface coating have been considered as viable options in the manufacturing of FGMs [19], due to advantages such as uniform dispersal of allotting elements, continuous processing and reduced waste when compared to methods like the chemical vapour deposition (CVD) and physical vapour deposition (PVD) [20]. Some common factors that influence electrodeposited graded coatings are density of current, and particle loading in bath electrolyte [19, 20]. Torabinejad et al. [19] fabricated a functionally graded coating of Ni-Fe-Mn/Al_2O_3 70 μm thick on mild steel via the electrodeposition method. Two types of coatings were produced: one was synthesized by steadily reducing the duty cycle and keeping the frequency unchanged while the other was electrodeposited by steadily increasing the frequency while keeping the duty cycle unchanged. The effect of pulse parameters like frequency and duty cycles on corrosion and wear behaviour as well as the composition, microstructure and micro-hardness of the functionally graded nanocomposite coatings were examined. Torabinejad et al. [19] found that with the increase in frequency, chemical composition of the matrix in nanocomposite coatings remained unchanged across the cross-section. Additionally, the micro-hardness and wear resistance of the coating was enhanced due to refinement of the grains when frequency increased. Conversely, a decrease in the duty cycle resulted in a change in chemical composition across the coating cross-section. Other research work conducted using electrodeposition process can be found in the literature [21-23].

5.1.5. Laser Deposition (LD)

Laser deposition (or laser metal deposition) is a relatively new additive manufacturing process that can be adapted to making FGMs from three-dimensional computer-aided designs. Process parameters for laser deposition require optimization for the desired application. Mahamood and Akinlabi [24] produced a functionally graded titanium alloy composite. They obtained the optimized process parameters for all material combinations from an earlier study [25]. The FGM with optimized processing parameters for all the material combinations showed improved properties, whereas those without optimized parameters for all material blends did not [24].

5.2. Bulk Group FGM Manufacturing Process

Processing of bulk FGMs are usually energy intensive and slow and cannot be produced using deposition techniques such as vapor deposition [3]. The process of manufacturing bulk FGM is generally grouped into two: the gradation process and the consolidation process. The gradation process comprises the constitutive, homogenizing and the segregation processes. The constitutive process is based on a layered build-up of the FGM from its powdered form. This process has over time become viable economically and technologically owing to the innovation recorded in the automation industry. The homogenizing process eliminates the sharp interface which exists in the bulk FGMs by converting it into a gradient form through material transport. The segregation process uses external gravitation or electric fields to convert a material from a homogenous to a graded form [6, 8]. The bulk FGMs consolidation process follows the gradation process. This process involves the sintering and solidification of the powder material. Processing conditions for the material are chosen such that their gradient structure is not altered while unequal shrinkage is also mitigated [8]. Bulk manufacturing processes include PM, MC and SFF [3].

5.2.1. Powder Metallurgy (PM)

PM is a bulk manufacturing process which produces finished or semi-finished metal components from powder whose particle sizes are less than 0.1 cm. There are two main types of PM: stepwise compositional control (SCC) and continuous compositional control (CCC). In SCC, the microstructural properties of the material are observed to be in layered form across the cross-section of the material, whereas the CCC exhibits a position dependent composition and microstructure across material.

Generally, there are four main stages in PM processes: production, weighing and mixing of metal powder, stacking, compaction of the powdered metal and sintering [1, 8, 26] as shown in Fig. 4. The main process parameters in PM are powder mixture composition, shape, compacting pressure, particle size, and sintering temperature [6].

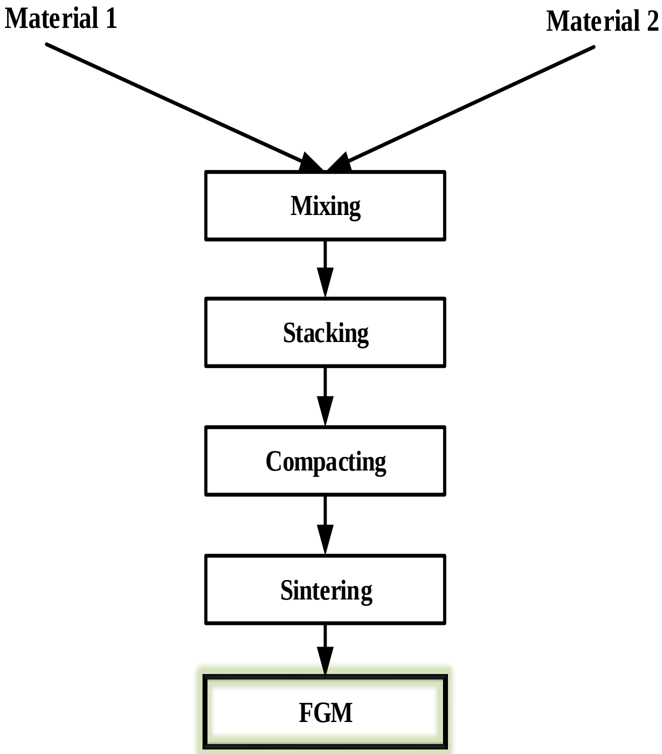

Fig. 4. Processes involved in powder metallurgy

5.2.2. Metal Casting (MC)

Examples of casting techniques applicable in the production of FGMs are slip casting, centrifugal casting, stir casting and the squeeze casting. Other casting techniques are sedimentation casting, sequential casting, controlled mold filling, infiltration, and directional solidification [6]. All of these are well documented in the literature although there is room for further research.

5.2.2.1. Slip Casting

A slurry solution made up of material particles, dispersing agents and water is poured into a spongy plaster mold as depicted in Fig. 5. As solidification occurs, the solid particles are drawn to the wall of the mold. An outlet valve attached to the base of the mold is released and the slurry is drained from the cast. The cast material is allowed to solidify and dry and the mold is then removed. The desired gradient of the material can be obtained by varying the composition and particle size of the material suspension during the casting process [27]. The slip casting process is similar to the slurry dipping process of fabricating FGM [6].

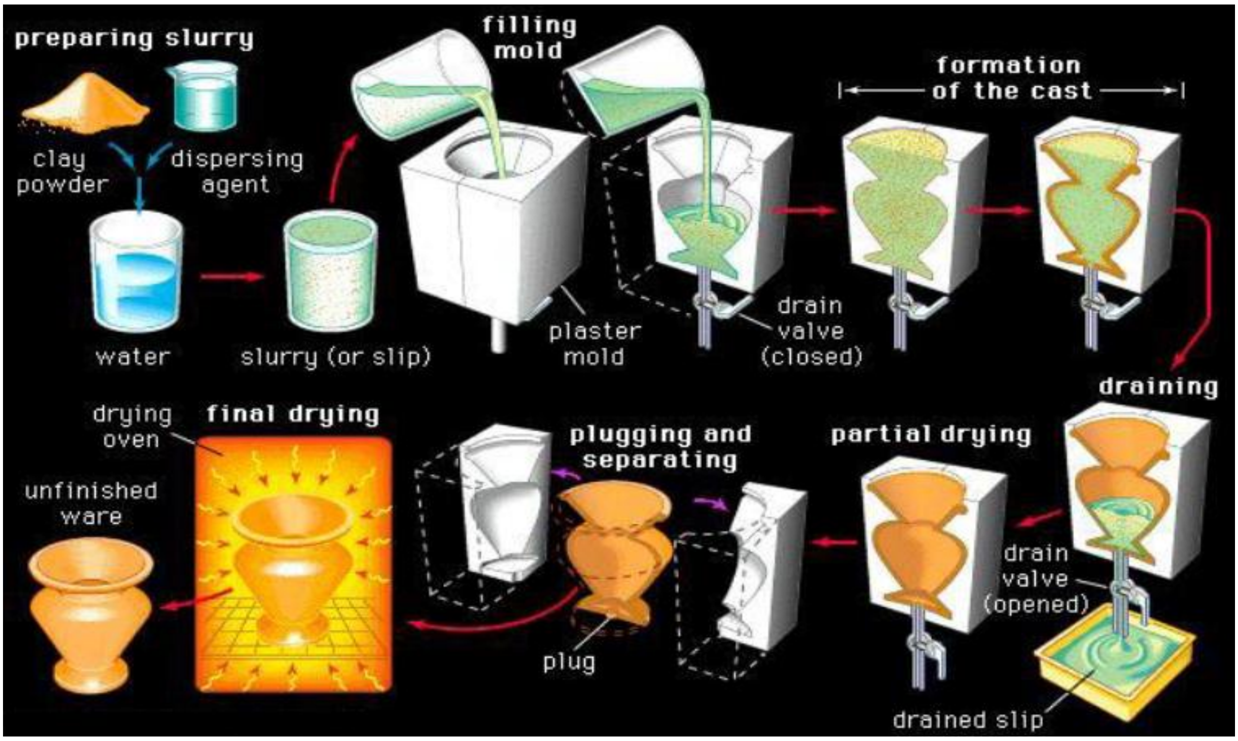

Fig. 5. Slip casting steps [28]

Katayama et al. [29] produced an Al_2O_3-W FGM with one of the materials containing oxidized powder of W while the other contained "as-received" W (not oxidized). The result showed that the Al_2O_3-W FGM, which contained as received W showed a distinct interface between the Al_2O_3 and the W particle, as shown in Fig. 6, whereas the Al_2O_3-W FGM with oxidized W showed a compositional gradient in its microstructure as seen in Fig. 7.

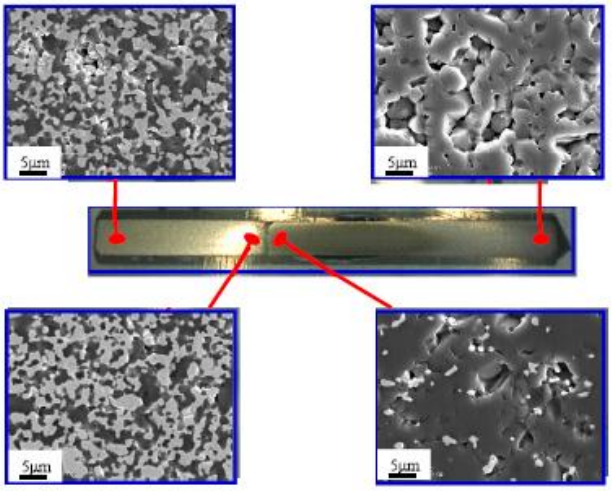

Fig. 6. Optical micrograph and SEM images of FGM of Al_2O_3-W with as-received W powder [29]

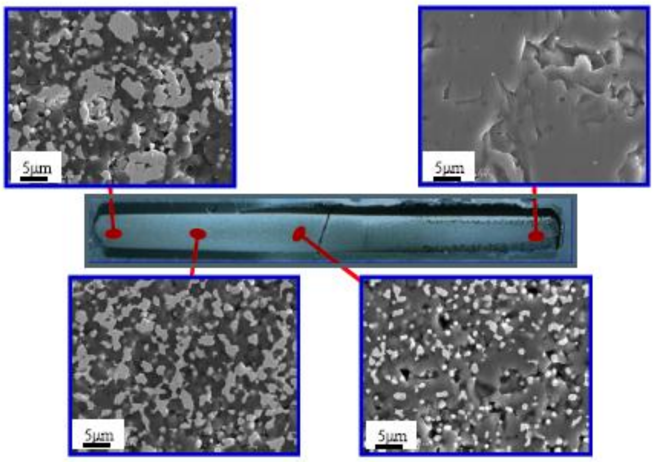

Fig. 7. Optical micrograph and SEM images of FGM of Al_2O_3-W with oxidized W powder [29]

The distinction observed in Fig. 6 is attributed to the difference in the densities of the powders. It is worth noting that the slip casting process is followed by a consolidation step to allow for a sintered material.

5.2.2.2. Centrifugal Casting

The centrifugal method of casting FGM uses a spinning mold in casting of the materials rather than using gravity force. The mold is mounted on a rotational shaft while the melt is poured into it [30] and allowed to solidify while the mold is still rotating [31, 32]. A typical centrifugal casting setup is shown in Fig. 8.

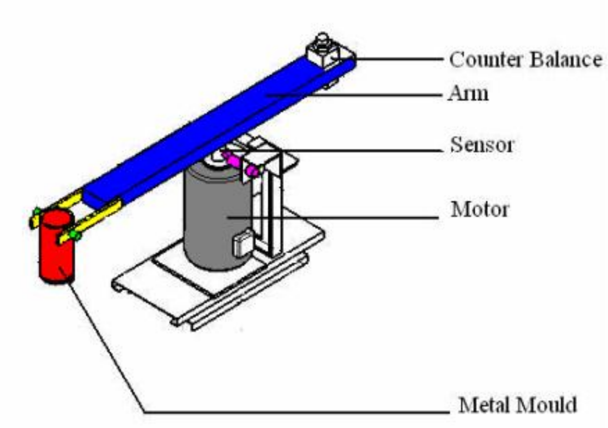

Fig. 8. Vertical setup of centrifugal casting [27]

Gradients formed through this method are largely dependent on the variance of the densities of the materials that make up the melt as well as the speed of rotation of the mold [3]. Gradient material produced through the centrifugal method is formed from a metallic melt which contains solid particles of secondary material(s) in varying concentration across the material. The melting temperature of the secondary particle (in solid phase) may be higher or lower than the temperature of the melt during casting. This phenomenon informs the two classifications of the centrifugal method namely, centrifugal solid particle method (CSPM) and the centrifugal *in situ* method (CISM). The former occurs due to the melt having a lower temperature compared to the melting temperature of the secondary particle, hence, the secondary particle remains in its solid state during solidification. The latter occurs when the melt has a higher temperature than the melting temperature of the secondary particle. As a result, the particle melts in the mix as the material solidifies under centrifugal action [27]. The centrifugal process offers continuous compositional graduation of the material and in the CSPM method, high wear resistance and material toughness is observed as seen in Fig. 9. The CISM method possesses advantages such as homogenous dispersion of reinforcing particles, good thermodynamic stability and good wettability compared to the CSPM method [33].

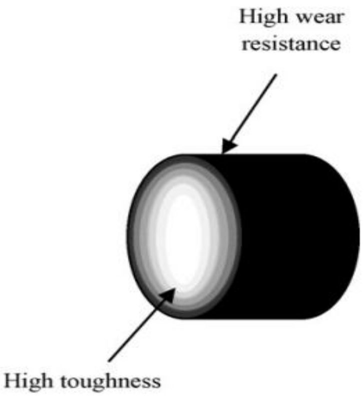

Fig. 9. Showing areas of high toughness and wear resistance for a CSPM processed material [27]

The geometry of the FGMs produced centrifugal method (CM) is limited to cylindrical shapes [3] and the types of gradients formed are limited due to the parameters involved in the formation of those gradients, namely, material densities and applied centrifugal force [6, 26]. Furthermore, the denser particle reinforcement tends to move towards the outer wall of the cast during the rotation of the mold [1]. This phenomenon is governed by Stokes law, which is expressed as:

$$v = \frac{d^2(\rho_{p-}\rho_l)g}{18\mu} \qquad (1)$$

Where v is the particle velocity, d is particle diameter, μ is viscosity of liquid metal, ρ_l is density of liquid metal and ρ_p is density of particle.

The basic expression of the centrifugal casting process of producing FGM is given as follows:

$$\omega = \frac{v}{r} = \frac{2\pi N}{60} \qquad (2)$$

Where ω is the angular force an N is speed in rev/min.

The centrifugal force that acts on particle is given as:

$$F_c = m\omega^2 r = m_p \frac{4\pi^2 N^2}{3600} \qquad (3)$$

Where F_c is Centrifugal Force, m_p is mass of particle an r is distance.

The difference in the densities of the melt and the reinforcing particle(s) results in a particle concentration gradient which is observed in the solidified FGM processed from CM [6] and a distinct gradient in composition is observed for FGMs produced through the CSPM method as opposed to those produced through the CISM method [27]

5.2.2.3. Stir Casting (SC)

The stir casting process of manufacturing FGMs involves the use of an automated stirrer to facilitate the desired dispersion of reinforcing particles in the melt before solidification takes place (Fig. 10). This can be applied to a mixture of two slurries or a slurry-particle combination. In addition to proper dispersion of the reinforcing particles within the mix [34], stirring also helps to keep the particles suspended in the slurry. Introducing the reinforcing particle into the melt is a vital stage in the SC process. There are various methods of introduction amongst which the vortex method yields the best output. This method involves the vigorous stirring of the melt until a vortex is formed in the melt and the reinforcing substances are introduced into the slurry through the vortex. Other stir casting methods are injection gun particle insertion, particle spraying into slurry, particle addition during pouring [1].

There are various factors which affect the quality of the FGMs produced through the stir casting process, including: stirring time and speed of rotation of stirrer in the melt. Brabazon et al. [35] observed that a homogenous particle suspension is obtainable in the melt when rotation speeds of 200 rpm are employed during the stir casting process. Other determining factors which influence quality are pouring rate, pouring temperature and angle of the stirring blade within the melt [1].

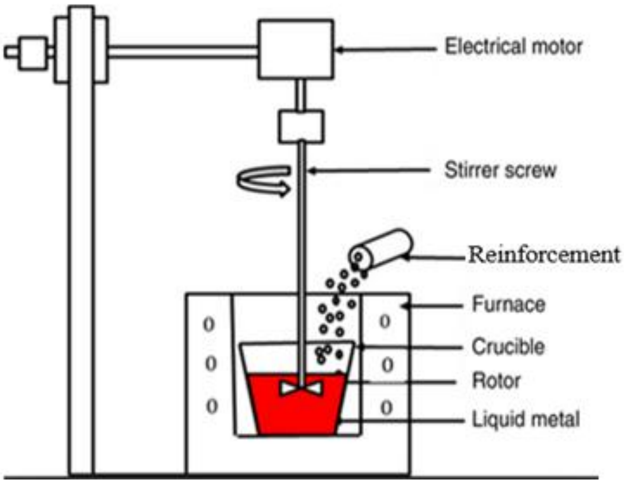

Fig 10 A schematic stir casting set up [1]

5.2.2.4. Squeeze Casting

The squeeze casting process of producing FGMs involves the melting and pouring of the material into a mold followed by addition of reinforcing particles and stirring to obtain uniform distribution and squeezing of the soft material through a die to obtain the finished material. This process usually requires minimal post-manufacture finishing as the material obtained is in near-finished form. Vital operations such as degassing, mold preheating, pouring and squeezing are performed to obtain quality casting for aluminium based FGM. Additional operations such as preheating of reinforcing substance, its addition to the melt and further stirring of the melt before squeezing are performed for a metal-ceramic FGM [1].

Reihani, [36] using the squeeze casting method, studied the influence of SiC reinforcing particles on the mechanical properties, ageing behaviour and wear properties of aluminium based material. It was concluded that a near pore-free cast with uniform dispersal of the SiC particles is obtainable through this processing technique. Furthermore, the material wear resistance and strength appear to increase while the ductility appears to decrease.

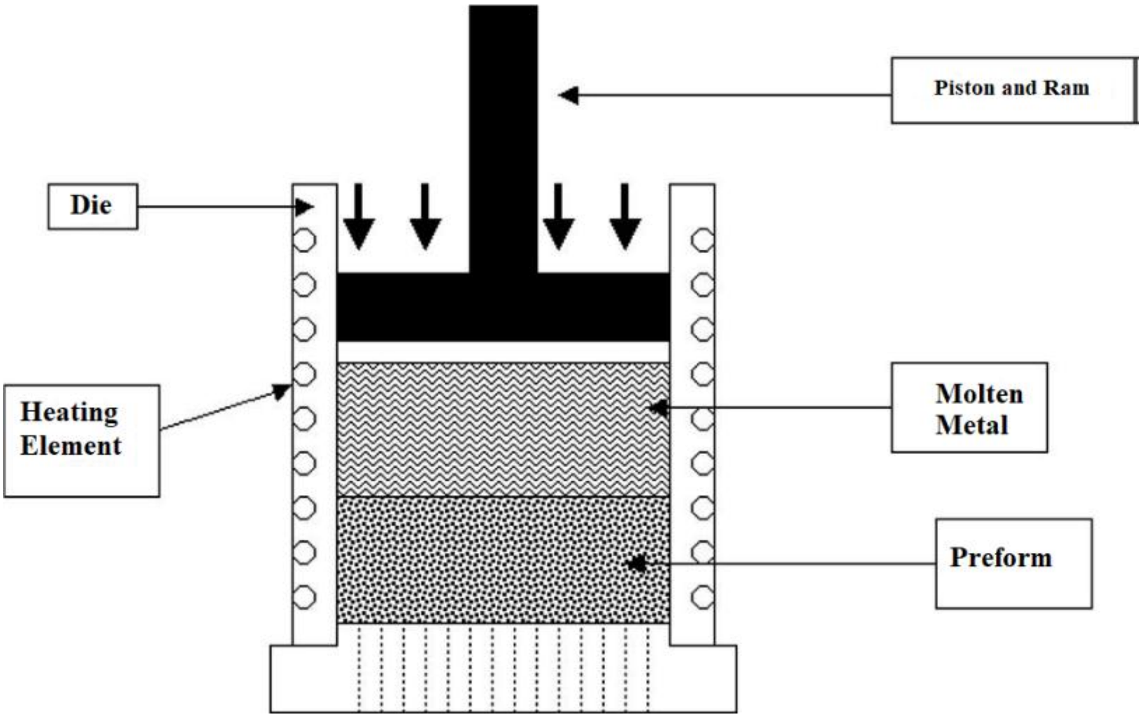

Fig. 11. Schematic diagram of the squeeze casting apparatus [36]

5.2.3. Other Fabrication Processes for FGMs

In addition to the above-mentioned fabrication processes, other types of fabrication processes that have been researched and are available in literature are listed in Table 1.

TABLE 1

OTHER FABRICATION PROCESSES FOR FGMS

Processing Techniques	Procedure	References
Sequential Casting	The sequential casting process or controlled mold filling, as used by [37] in the designing and processing of bimetallic aluminum alloys, involves pouring of different melted alloys which have similar solidification temperature ranges in succession into a mold to form a single FGM. The melt from the second material is poured into the mold containing the first melt whose solidification process is in progress. Formation of gradient structure across the material profile occurs as a result of forced thermal convection between the individual materials [6].	[6, 37]
Infiltration Technique	The infiltration process involves pouring of a melt into a porosity gradient refractory preform whose temperature is greater than that of the melt. The preform is produced from sintering of powdered materials [6].	[6]
Solid Freeform	Solid freeform processing, also referred to as material prototyping, is a software-based method with great research interest in the production of FGMs. The process involves five stages as described by [1, 3, 6], and offers advantages such as less energy consumption, manufacture of intricate profiles, direct manufacture from CAD STL data file as well as material optimization. Research is intensifying on how to improve on the surface finishing and dimensional accuracy of the FGM obtained through solid freeform processing.	[1, 3, 6]
Frictional Stir Casting	Frictional stir casting involves the plastic deformation of a bulk material by inserting a rotating tool on it and moving it along a desired path on the material [38]. Results obtained from this processing technique have been found to produce aluminum alloys with improved properties and microstructure [39, 40].	[38-40]
Electrophoretic Deposition	This is a low-cost deposition process capable of producing FGMs with intricate shapes. This technique is useful in producing multi-layered composite materials from simple equipment [41]. The process was used by Askari et al. [42] in producing a $Al_2O_3/SiC/ZrO_2$ FGM to be used for artificial bio implants.	[41, 42]

6. TRENDS IN FGM AND AREAS OF APPLICATION

Since the introduction of continuous texture control application of FGM in 1985, FGMs have found relevance in various engineering and non-engineering applications due to excellent in-service performance in extreme conditions. Applications in FGM have been able to blend properties which were, in the past, considered incompatible. Table 2 shows the various applications in which FGMs have been deployed.

TABLE 2

AREAS OF APPLICATION OF FGMS

Area of Applications	Uses
Aerospace	Due to the ability to withstand severe thermal differences during service, FGMs have been employed suitably for building of rocket engine parts as well as body parts for space plane [3]. Growth in aviation technologies have prompted demanded the service of materials with good thermal qualities and service durability. In the past, these qualities were sort for from artificial metal, ceramics or organic fiber composites[43].
Medical	Due to its similarities in microstructural arrangements in bio tissues like teeth and bones, FGM have been found as applications in the orthopedic and dental practice for production of biomaterials.
Manufacturing and Energy	Owing to high thermo-mechanical, properties FGM are used in the production of thermal barrier coatings and heat exchanger tubes for power plant. FGM also provide protective coating for turbine blades in turbine engines.
Automobile	FGMs have been used for automobile parts such as pistons, gears and exhaust valves
Defense	The ability to impede the spread of cracks within a material is a core property of FGM, as such, it has been found suitable in the production of armored plates for bulletproof vest and military helmets.
Electronics and optoelectronics	FGMs are used for optical fibers for wave high-speed transmission. Computer circuit boards (PCB) for cell phones.
Cutting tools	Tungsten carbide/cobalt and aluminum/stainless steel have found commercial success in being used as cutting tools [1].

7. OUTLOOKS OF FGMs

Over the years FGM has received huge research interest owing to its numerous advantages. However, the production and fabrication costs, especially with PM and techniques dependent on it, are relatively high. Furthermore, the production of semi-finished FGMs which still need further machining to obtain the desired geometry, pose a challenge. SFF offers a viable solution to the above challenges; however, more research works are needed on its performance to generate an all-inclusive database through characterization of FGM. Furthermore, with the rising interest in additive manufacturing techniques such as 3-D printing, the production of aluminum based FGM using 3-D printing can be exploited as a viable fabrication route for FGM.

8. CONCLUSION

This paper presents a general review of FGM, its evolution, manufacturing techniques and applications. The choice of manufacturing process is dependent on both the type of FGM and the required service properties of the material to be manufactured. Thin FGMs are usually fabricated through vapor and spray depositions. Bulk FGMs are mainly manufactured via the PM and MC processes. Despite the increase in research of FGMs, challenges of large scale production as well as trade-offs of certain material properties during production still exist and this hampers its deployment in manufacturing. Regardless of these challenges, FGM application areas will continue to increase in engineering material development.

REFERENCES

[1] W. S. Ebhota, A. S. Karun, F. L. Inambao, Principles and Baseline Knowledge of Functionally Graded Aluminium Matrix Materials (FGAMMs): Fabrication Techniques and Applications, *International Journal of Engineering Research in Africa*, Vol 26, pp. 47-67, 2016. https://doi.org/10.4028/www.scientific.net/JERA.26.47

[2] B. Craig, Limitations of Alloying to Improve the Threshold for Hydrogen Stress Cracking of Steels, in: *Hydrogen Effects on Material Behavior,* Proc. *of the 4th Internat. Conf. on the Effect of Hydrogen on the Behavior of Materials* (Wyoming, Sept. 12–15), pp. 223-230, 1989.

[3] R. M. Mahamood, E. T. Akinlabi, M. Shukla, S. Pityana, Functionally graded Material: an Overview, Proceedings of the World Congress on Engineering 2012 Vol III, WCE, July 4-6, London, UK, 2012.

[4] A. Bouzekova-Penkova A. Miteva, Aluminium-Based Functionally Graded Materials, Space Research and

Technology Institute, Bulgarian Academy of Sciences, 2014

[5] J. J. Lannutti, Functionally Graded Materials: Properties, Potential and Design Guidelines, *Composites Engineering,* Vol. 4, pp. 81-94, 1994. https://doi.org/10.1016/0961-9526(94)90010-8

[6] B. Kieback, A. Neubrand, H. Riedel, Processing Techniques For Functionally Graded Materials, *Materials Science and Engineering: A,* Vol. 362, pp. 81-106, 2003. doi10.1016/S0921-5093(03)00578-1.

[7] S. Wang, Fracture Mechanics for Delamination Problems in Composite Materials, *Journal of Composite Materials,* vol. 17, pp. 210-223, 1983. https://doi.org/10.1177/002199838301700302

[8] S. K. Bohidar, R. Sharma, P. R. Mishra, Functionally Graded Materials: a Critical Review, *International Journal of Research,* vol. 1, pp. 289-301, 2014.

[9] A. B. Makwana K. Panchal, A Review of Stress Analysis of Functionally Graded Material Plate with Cut-Out, *International Journal of Engineering Research and Technology,* vol. 3, pp. 2020-2025, 2014.

[10] K. A. Mumtaz N. Hopkinson, Laser Melting Functionally Graded Composition of Waspaloy® and Zirconia Powders, *Journal of Materials Science,* vol. 42, pp. 7647-7656, 2007. https://dspace.lboro.ac.uk/2134/3543

[11] Y. Miyamoto, W. Kaysser, B. Rabin, A. Kawasaki, R. G. Ford, *Functionally graded materials: design, processing and applications* vol. 5: Springer Science & Business Media, 2013.

[12] N. Oxman, S. Keating, E. Tsai, Functionally Graded Rapid Prototyping, in *Innovative Developments in Virtual and Physical Prototyping, CRC Press,.* Proc. 5th Internat. Conf. on Advanced Research in Virtual and Rapid Prototyping (VRAP), Leiria, Portugal, Sept. 28–Oct. 1, 2011, pp. 483-489,.

[13] J. Groves H. Wadley, Functionally Graded Materials Synthesis via Low Vacuum Directed Vapor Deposition, *Composites Part B: Engineering,* vol. 28, pp. 57-69, 1997. doi: 10.1016/S1359-8368(96)00023-6

[14] G. Knoppers, J. Gunnink, J. Van den Hout, W. Van Wliet, The Reality of Functionally Graded Material Products, in *Intelligent Production Machines and Systems:* First I* PROMS Virtual Conference, Elsevier, Amsterdam, 2005, pp. 467-474.

[15] S. M. George, Atomic Layer Deposition: an Overview, *Chemical Reviews,* vol. 110, pp. 111-131, 2009. doi: 10.1021/cr900056b

[16] X. Sun, M. Xie, G. Wang, H. Sun, A. S. Cavanagh, J. J. Travis*, et al.*, Atomic Layer Deposition of TiO2 on Graphene for Supercapacitors, *Journal of the Electrochemical Society,* vol. 159, pp. A364-A369, 2012. doi: 10.1149/2.025204jes

[17] S. K. Chaudhury S. C. Panigrahi, Role of Processing Parameters on Microstructural Evolution of Spray Formed Al–2Mg Alloy and Al–2Mg–TiO2 Composite, *Journal of Materials Processing Technology,* vol. 182, pp. 343-351, 2007. https://doi.org/10.1016/j.jmatprotec.2006.08.013

[18] B. Su, H. G. Yan, G. Chen, J. L. Shi, J. H. Chen, P. L. Zeng, Study on the Preparation of the SiCp/Al–20Si–3Cu Functionally Graded Material Using Spray Deposition, *Materials Science and Engineering: A,* vol. 527, pp. 6660-6665, 2010. https://doi.org/10.1016/j.msea.2010.06.090

[19] V. Torabinejad, M. Aliofkhazraei, A. S. Rouhaghdam, M. H. Allahyarzadeh, Electrodeposition of Ni–Fe–Mn/Al2O3 Functionally Graded Nanocomposite Coatings, *Surface Engineering,* vol. 33, pp. 122-130, 2017. https://doi.org/10.1080/02670844.2016.1151577

[20] S. A. Lajevardi, T. Shahrabi, J. A. Szpunar, Synthesis of Functionally Graded Nano Al2O3–Ni Composite Coating by Pulse Electrodeposition, *Applied Surface Science,* vol. 279, pp. 180-188, 2013. https://doi.org/10.1080/02670844.2016.1151577

[21] D. Gopi, E. Shinyjoy, M. Sekar, M. Surendiran, L. Kavitha, T. S. Sampath Kumar, Development of Carbon Nanotubes Reinforced Hydroxyapatite Composite Coatings on Titanium by Electrodeposition Method, *Corrosion Science,* vol. 73, pp. 321-330, 2013. http://dx.doi.org/10.1016/j.corsci.2013.04.021

[22] A. Sohrabi, A. Dolati, M. Ghorbani, A. Monfared, P. Stroeve, Nanomechanical Properties of Functionally Graded Composite Coatings: Electrodeposited Nickel Dispersions Containing Silicon Micro- and Nanoparticles, *Materials Chemistry and Physics,* vol. 121, pp. 497-505, 2010. doi: 10.1016/j.matchemphys.2010.02.014

[23] M. H. Allahyarzadeh, M. Aliofkhazraei, A. R. S. Rouhaghdam, V. Torabinejad, Gradient Electrodeposition of Ni-Cu-W(alumina) Nanocomposite Coating, *Materials & Design,* vol. 107, pp. 74-81, 2016. https://doi.org/10.1016/j.matdes.2016.06.019

[24] R. M. Mahamood E. T. Akinlabi, Laser Metal Deposition of Functionally Graded Ti6Al4V/TiC, *Materials & Design,* vol. 84, pp. 402-410, 2015. https://doi.org/10.1016/j.matdes.2015.06.135

[25] R. M. Mahamood, E. T. Akinlabi, M. Shukla, S. Pityana, *Process for manufacture of Titanium based Composites,* South Africa Patent 2014.

[26] S. A. CPM, B. Varghese, A. Baby, A Review on Functionally Graded Materials, *International Journal of Engineering and Science,* vol. 3, pp. 90-101, 2014.

[27] A. Saiyathibrahim, N. Mohamed, P. Dhanapal, Processing Techniques of Functionally Graded Materials—A Review, in *International Conference on Systems, Science, Control, Communication, Engineering and Technology*, 2015, pp. 98-105.

[28] *Ceramics Processing: Slip Casting*. Available: http://ceramics.org/wp-content/uploads/2014/04/Slip-Casting-Lesson-111.pdf

[29] T. Katayama, S. Sukenaga, N. Saito, H. Kagata, K. Nakashima, Fabrication of Al2O3-W functionally Graded Materials by Slipcasting Method, in *IOP Conference Series: Materials Science and Engineering*, 2011, p. 202023.

[30] Y. Watanabe, Y. Inaguma, H. Sato, E. Miura-Fujiwara, A novel Fabrication Method for Functionally Graded Materials Under Centrifugal Force: The Centrifugal Mixed-Powder Method, *Materials,* vol. 2, pp. 2510-2525, 2009. doi:10.3390/ma2042510

[31] A. Vieira, P. Sequeira, J. Gomes, L. Rocha, Dry Sliding Wear of Al alloy/SiCp Functionally Graded Composites: Influence of Processing Conditions, *Wear,* vol. 267, pp. 585-592, 2009. https://doi.org/10.1016/j.wear.2009.01.041

[32] W. S. Ebhota, A. S. Karun, F. L. Inambao, Centrifugal Casting Technique Baseline Knowledge, Applications, and Processing Parameters: Overview, *International Journal of Materials Research,* vol. 107, pp. 960-969, 2016. https://doi.org/10.3139/146.111423

[33] M. Hoseini M. Meratian, Tensile Properties of In-Situ Aluminium–Alumina Composites, *Materials Letters,* vol. 59, pp. 3414-3418, 2005. https://doi.org/10.1016/j.matlet.2005.06.006

[34] P. B. Pawar A. A. Utpat, Development of Aluminium Based Silicon Carbide Particulate Metal Matrix Composite for Spur Gear, *Procedia Materials Science,* vol. 6, pp. 1150-1156, 2014.

[35] D. Brabazon, D. Browne, A. Carr, "Mechanical Stir Casting of Aluminium Alloys from the Mushy State: Process, Microstructure and Mechanical Properties," *Materials Science and Engineering: A,* vol. 326, pp. 370-381, 2002.

[36] S. S. Reihani, Processing of Squeeze Cast Al6061–30vol% SiC Composites and their Characterization, *Materials & Design,* vol. 27, pp. 216-222, 2006. https://doi.org/10.1016/j.matdes.2004.10.016

[37] A. S. Karun, S. Hari, W. S. Ebhota, T. Rajan, U. Pillai, B. Pai, Design and Processing of Bimetallic Aluminum Alloys by Sequential Casting Technique, *Metallurgical and Materials Transactions A,* vol. 48, pp. 279-293, 2017. https://doi.org/10.1007/s11661-016-3824-9

[38] H. Sun, S. Yang, D. Jin, Improvement of Microstructure, Mechanical Properties and Corrosion Resistance of Cast Al–12Si Alloy by Friction Stir Processing, *Transactions of the Indian Institute of Metals,* Vol 71, pp. 1-7, 2018. doi: 10.1007/s12666-017-1232-5

[39] F. Y. Tsai P. W. Kao, Improvement of Mechanical Properties of a Cast Al–Si Base Alloy by Friction Stir Processing, *Materials Letters,* vol. 80, pp. 40-42, 2012. https://doi.org/10.1016/j.matlet.2012.04.073

[40] A. Tajiri, Y. Uematsu, T. Kakiuchi, Y. Tozaki, Y. Suzuki, A. Afrinaldi, Effect of Friction Stir Processing Conditions on Fatigue Behavior and Texture Development in A356-T6 Cast Aluminum Alloy, *International Journal of Fatigue,* vol. 80, pp. 192-202, 22015. https://doi.org/10.1016/j.ijfatigue.2015.06.001

[41] L. Besra M. Liu, A Review on Fundamentals and Applications of Electrophoretic Deposition (EPD), *Progress in Materials Science,* vol. 52, pp. 1-61, 2007.

[42] E. Askari, M. Mehrali, I. H. S. C. Metselaar, N. A. Kadri, M. M. Rahman, Fabrication and Mechanical Properties of Al2O3/SiC/ZrO2 Functionally Graded Material by Electrophoretic Deposition, *Journal of the Mechanical Behavior of Biomedical Materials,* vol. 12, pp. 144-150, 2012. doi: 10.1016/j.jmbbm.2012.02.029

[43] N. Cherradi, A. Kawasaki, M. Gasik, Worldwide Trends in Functional Gradient Materials Research and Development, *Composites Engineering,* vol. 4, pp. 883-894, 1994. https://doi.org/10.1016/S0961-9526(09)80012-9