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Centrifugally Cast Functionally Graded Materials – A Review

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Abstract: *Functionally Graded Materials (FGMs) are a class of engineered materials characterized by a spatial variation of composition and microstructure aiming at controlling corresponding functional (i.e. mechanical, thermal, electrical, etc.) properties. The tailored gradual variation of microstructural features may be obtained through non-uniform distributions of the reinforcement phase(s) with different properties, sizes and shapes, as well as by interchanging the role of reinforcement and matrix materials in a continuous manner. Wide ranges of processing methods are considered on the production of FGMs. Centrifugal casting is one of the most effective methods for processing functionally graded materials (FGMs) made of aluminum, and it has been demonstrated that a compositional gradient can be obtained by using centrifugal casting to segregate phases with different densities. The addition of particles to the melt drastically changes the viscosity of the melt, and this has implications for casting processes. Microstructural evaluation, wear mechanisms, porosity, stress distributions, etc. of various metal-metal, metal-ceramic and ceramic-ceramic FGMs are discussed to expose an overall view for carrying future research. Finally the applications of FGMs in various fields, which are still facing new innovations are considered.*

Keywords: Functionally graded materials, Centrifugal casting, characteristics of FGM, Applications of FGM.

1. INTRODUCTION

A material whose composition, structure and morphology vary smoothly from one end to the other is recognized as Functionally Graded Materials (FGM). The concept of FGMs was first proposed in 1987 to develop heat resistant materials for air frame and the propulsion system of space planes.

FGMs exhibit gradual transition in the microstructure and/or the composition in a definite direction, the presence of which leads to variation in functional performance within the part through microstructural manipulation. FGMs possess a characteristic of tailoring of graded composition and micro structure according to the distribution of properties needed to achieve desired function which distinguishes it from the conventional materials. As we all know composite materials and cermets have been employed as a solution for the various engineering problems for the number of years. Though the development of new materials (FGMs) is due to mismatch occurs while applying them as a coating on the surface of the base material to withstand desired condition which leads to change in the properties like elastic modulli, thermal expansion and hardness. The gradual transition allows the creation of superior and multiple properties without any weak interface [1].

This idea is emulated from nature to solve engineering problem the same way artificial neural network is used to emulate human brain. The pioneering properties and functions cannot be achieved by traditional materials with homogeneity. FGM's multifunctional behavior and performance create scope for applications require advanced materials namely aerospace, automotive, biomedical,

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defenses, electronics, power engineering, etc. A FGM is used to join two different materials without stress concentration at their interface. A Sharp interface as in the composite material leads to the initiation of failure. FGMs replace this sharp interface with a gradient interface which produces smooth transition from one material to the next. Gradation in properties from one portion to another portion can be determined by material constituent composition. According to the material composition function specified, the volume fraction of one material constituent will be changed from 100% on one side to zero on another side, and that of another constituent will be changed the other way around as shown in Fig.1. The FGM helps to reduce stress, prevent peeling of the coated layer, prevent microcrack propagation, etc. For a component having a material region made of an FGM, its fabrication technology must be able to add different materials with certain volume fractions simultaneously for every pixel according to the specified composition function.

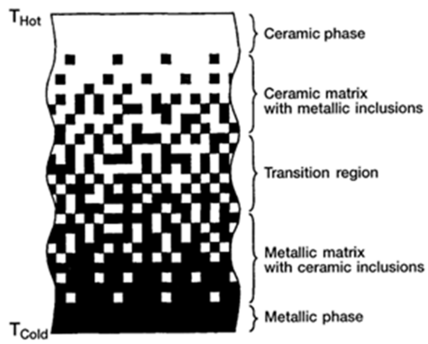

Fig.1. Structural view of continuously graded FGM.

The manufacturing process of a FGM can usually be divided into two steps. Initial one is building up of the spatially inhomogeneous structure called Gradation. Another is the transformation of this structure into a bulk material called Consolidation. In detail gradation process can be categorized into constitutive, homogenizing and segregating processes. Stepwise build up of the graded structure from precursor materials is constitutive process. Homogenizing is a process of converting sharp interfaces between two materials into a gradient by material support. Segregation starts with a macroscopically homogeneous material, which is converted into graded material by material transport caused by an external field (i.e. gravitational, electrical field, etc). Normally sintering and solidification follows gradation process. Graded structure is of two types namely continuous and step wise. In continuous type structure, change in composition and/or microstructure occurs continuously with position. Powder metallurgical processed FGMs follow discrete (or) step wise structure. In detail their microstructure feature changes in a step wise manner with interfaces existing between discrete layers. Continuous graded structures are to be produced by centrifugal casting [2].

In this paper centrifugal casting technique of FGMs are presented with their experimental investigation of various materials. Some research works on functionally graded materials in recent times are presented and the future research needs are proposed. This work clearly demonstrates various possibilities available in FGM research and useful to gain background knowledge. Also some applications of functionally graded materials are presented here.

2. Centrifugal Method of FGM

Centrifugal force can be used to create a gradient composition in a metallic melt that contains another solid phase. Generally, fabrication of FGMs by the centrifugal method is classified into two categories based on the melting temperature of the reinforcement particle. If the melting point is significantly higher than the processing temperature, the reinforcement particle remains solid in a liquid matrix. This method is named as a centrifugal solid-particle method (CSPM). A typical centrifugal casting setup is given below in Fig.2.

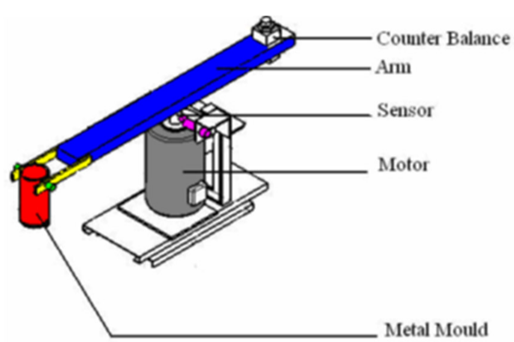

Fig.2. Vertical centrifugal casting setup.

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The selective reinforcement of the component surface obtained by CSPM results in a higher wear resistance in the outer surface as well as maintaining high bulk toughness. On the other hand, if the melting point of the reinforcement particle is lower than the processing temperature, centrifugal force can be applied during the solidification both to the reinforcement particle and to the matrix. This solidification is similar to the production of in situ composites using the crystallization phenomena, and this method is, therefore, named as a centrifugal in situ method (CISM). The formation mechanism of the compositional gradient during the fabrication of FGM by the centrifugal in-situ method in the A–B alloy is, 1) Partial separation of A and B elements in the liquid state occurs due to the density difference. 2) A compositional gradient is formed before the crystallization of the primary crystal. 3) The primary crystals in the matrix appear according to local chemical composition. 4) The primary crystals migrate because of density difference, and a further compositional gradient is formed [3].

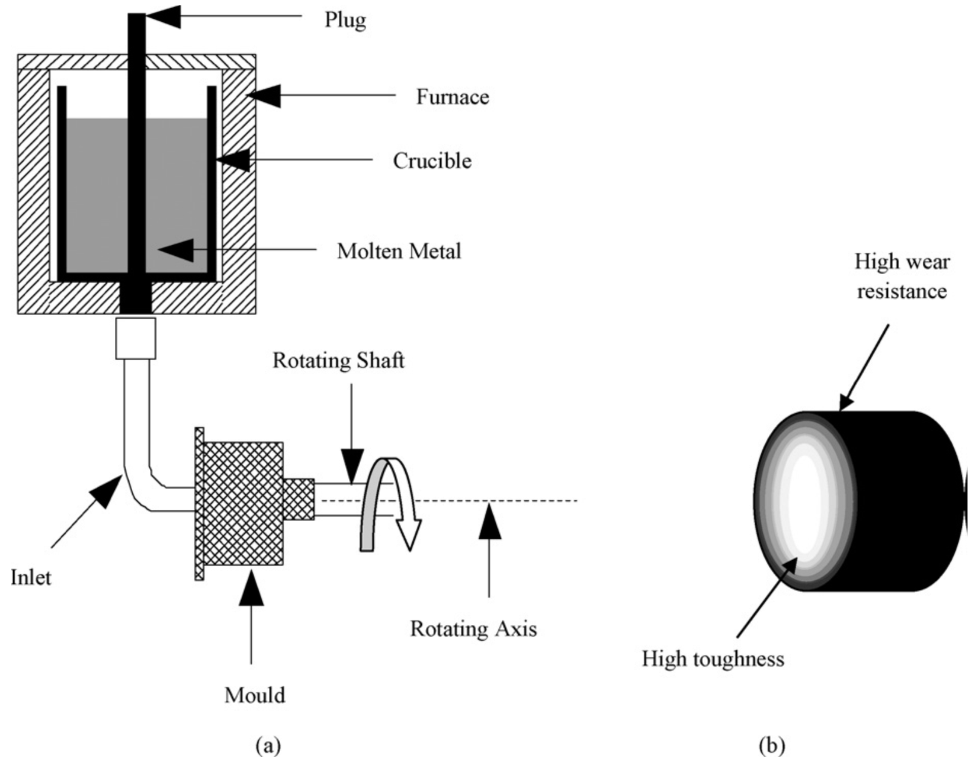

Fig.3. Schematic representation of: (a) the horizontal centrifugal casting process and (b) the final product obtained (**Al** - High toughness inner region and **SiC** – High wear resistance).

Usually, the density of the outer part of the FGM rings fabricated by the centrifugal in situ method is larger than that of the inner part of the ring. In general, steeper compositional gradient appears for the CSPM. Since the motion of the solid-particles under the centrifugal force is governed by stoke's law (Migration distance is greater for large particles). It is well known that, the mechanical properties depend on particle size distribution as well as the volume fraction of particles in particle reinforced or dispersion strengthened of any composite material. From the research works it is found that the extent of particle segregation and relative location of enriched and depleted particle zones within the casting are mainly dictated by the relative densities of the particle and liquid, teeming temperature, melt viscosity, cooling rate, particle size, solidification time and magnitude of centrifugal acceleration [4]. The effect of centrifugal casting technique on castings as compared to the traditional gravity casting work [5] concluded that the centrifugal effect may produce an increase in rupture strength by 50%, rupture strain by 300% and young's modulus by 20%. Also an important and interesting finding in this study is, higher the distance in relation to the rotation centre (higher centrifugal force) the bigger the increase in mechanical properties. Also the centrifugal effect on castings may be divided in three main features: centrifugal pressure, intrinsic vibration of the process, and fluid dynamics. The effect of each of these variables will be the responsible for the differences in both mechanical and/or metallurgical properties on the castings. A CSPM method shows the reinforcement position is heavily depends on the 'G' number during solidification. Centrifugal force magnitude 'G' is given by,

(1)

Where 'R' is the radius of the arm in meters, 'ω' is the arm rotational speed in rad/sec and 'g' is the acceleration due to gravity. From the consideration of different levels of centrifugal force and sizes of particle, a gradient in the FGM becomes steeper by increasing the 'G' number or by decreasing the mean volume fraction of particles [6].

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A commercially available Mg alloy, ZK60A [3] was used as a mater alloy to fabricate Mg based FGM with a mould temperature of 680°C with a cooling rate of 0.05°C/s. Results of EDX analysis showed that Zn concentration at each region was almost the same i.e., weak peaks at middle and inner region, while Zr exists only in the outer region as strong peaks. Graded distribution of Zr phase is enhanced with increasing the 'G' number. In case of hardness phenomena the maximum hardness value was attained at outer strong Zr phase region and it increased in the direction of centrifugal force. Al-Al_2Cu functionally graded material (FGM) ring was fabricated from Al-3 mass%Cu initial master alloy by CISM. In the case of Al-3mass%Cu alloy, the density of the primary α-Al crystal is larger than that of the molten Al alloy. Therefore, the solid α-Al phase migrates towards the outer periphery of the ring when the centrifugal force is applied in the early stage of solidification. Consequently, since the Cu concentration within the FGM ring monolithically increases towards the ring's inner position i.e., density and hardness increases toward inner region [4]. In the solidification, primary Si particles moved in the direction opposite to the direction of the 'G' force as the density is less than that of liquid aluminium. Also the hardness is mainly affected by the primary Si content along the polished specimen [7].

The fabrication of Al-5mass%Zr FGM [8] by CSPM shows that Al_3Zr particles are almost oriented normal to the applied centrifugal force direction. Also increasing centrifugal force resulted in a steep particles distribution and decreased thickness of the intermetallics rich area. Anisotropy of wear property of the current Al/Al_3Zr FGMs was diminished with decreasing the applied centrifugal force and thence decreasing the particle orientation. An enhanced wear resistance was achieved in the Al/Al_3Zr FGMs by controlling the distribution of both the orientation and the volume fraction of Al_3Zr particles. Also they concluded plastic deformation induced wear was the dominant wear mechanism.

The fabrication of Al-Si alloy pistons reinforced with SiC particles [9] locally at the head by centrifugal casting results the hardness values along the axis of piston gradually increased from the skirt to the head, which corresponds to the structure changing along the axis of the pistons. At a slurry temperature of 850°C, a mould temperature of 600°C and a rotation speed of 800rpm possessed the highest value of hardness with best wear resistance when compared with the piston fabricated by permanent gravity mould casting. A unidirectional solidification mould is employed in Al/Al_2O_3 FGM [10] shows most of the Al_2O_3 particles enriched in the external zone of the specimen under centrifugal force, and some assembled Al_2O_3 particles with low bulk density segregate to the inner reinforced zone of the cylinder. The mechanical properties of FGM were increased with increasing Al_2O_3 particles. Also the fracture surface of the FGM at the center was ductile nature and the outer was brittle nature. Hydraulic simulation experiments on vertical centrifugal casting machine with two different filling methods (top filling and bottom filling) and different kind of rotational velocities showed that in both top filling and bottom filling, liquids stick to back-wall of cavity or runner to filling due to the action of centrifugal force. Filling volume is rising with the increase of the filling time and rotational velocity of mold. Experiments on titanium alloy resulted that the bottom filling method is better than the top one, which can achieve stable filling, minimize turbulence and avoid drastic liquid collision [11].

An investigation on mullite-molybdenum graded cylinders reveals that the methodology of slurry preparation has a vital influence on the gradation of Mo along the radial direction. Hardness values proved the continuous compositional change from inner to outer surface of graded cylinders and the hardness became constant in outer surface of graded specimens due to formation of interconnected Mo structures [12]. Gao et al. investigated the solidification process during the centrifugal casting of FGMs numerically and validated results against the experimental results. During solidification, the particles move to the outer or inner direction of the mould under centrifugal field depending on the particle density relative to that of the melt. Solidification is induced from the outer wall of the mould by convective cooling while the inner wall is assumed to be adiabatic. The model was used to investigate the solidification process in centrifugal casting of Al/SiC FGMs in a cylindrical mould. Three factors can be identified to be responsible for creation of the particle concentration gradient: the geometrical nature of particle flow in the cylindrical mould, the angular velocity, and the solidification rate, which captures the desired gradient — it is the interruption of particle migration by the solidification front that creates gradients in the particle concentration. By optimizing processing conditions, such as the particle size, initial particle concentration, rotational speed of the mould, cooling rate and superheat, one can engineer a desired gradient in the solidified part [13]. Under a constant acceleration, the velocity (v of a spherical particle of size (R_p) may be estimated using stoke's law by,

$$v = \frac{2R_p{}^2(\rho_p - \rho_l)\gamma}{9\eta} \qquad (2)$$

Where, ρ_p and ρ_l are the densities of the particle and liquid and η is the viscosity of the liquid. From Eq. (2) it can be seen that a higher centrifugal force (acceleration) will result in a higher particle velocity, emphasizing the reinforcement gradient along the centrifugal direction. FGM cast at low centrifugal speed (1500 rpm) presented a smooth gradient on SiCp distribution, while FGM cast at higher centrifugal speed (2000 rpm) revealed a sharper gradient on the distribution of reinforcing particles. This gradient was controlled by the movement of the solidification front, blocking the mobility of SiC particles in the melt. For the aluminium based FGM composites, two-body abrasion wear, oxidative wear, adhesion and delamination are the main wear mechanisms identified [13].

3. Application of Functionally Graded Materials

Some of the applications of functionally graded materials are discussed below.

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a) In aerospace and Automotives

Space Shuttle utilizes ceramic tiles as thermal protection from heat generated during re-entry into the Earth's atmosphere. However, these tiles are prone to cracking at the tile / superstructure interface due to differences in thermal expansion coefficients. An FGM made of ceramic and metal can provide the thermal protection and load carrying capability in one material thus eliminating the problem of cracked tiles found on the Space Shuttle. The interest in graded materials like Aluminium/Silicon carbide (ceramic – metal) are focused primarily on the control of thermal stresses in elements exposed to high temperatures (to 1600°C) for instance aerospace structures and Cu/SiC for dynamic seal applications.

Thermal Barriers Coatings made up of ZrO_2 and NiCoCrAlY FGMs are very popular as thin layers protecting of aircraft engine components against the thermal shock (e.g. turbine blades). Boron additions to conventional titanium alloys have the potential to form lightweight, high modulus, dispersion strengthened, discontinuous-reinforced composite material structures enabling replacement for significantly more dense steel and nickel materials.

b) In Medicine

In dental implantation a more realistic FGM is usually composed of collagen hydroxyapatite (HAP) and titanium is used [14]. Porous hydroxyapatite (HA) scaffolds with a functionally graded core/shell structure was fabricated for biomedical applications [15]. TiO_2 has also been used in combination with hydroxyapatite for developing biomaterials for implants because of its favourable biological effects and improved corrosion resistance. TiO_2 is also frequently and successfully used to reinforce Al_2O_3 wear resistant coating on metal substrate [16].

c) In Defence

One of the most important characteristics of functionally graded material is the ability to inhibit crack propagation. Metal ceramic FGMs used in structures as fire retardant doors and penetration resistant materials for armour plates and bullet-proof vests. One of the available material compositions gradually shifts from titanium diboride to a combination of titanium and titanium diboride, combining the ceramic's ability to absorb energy with the toughness of a metal - ideal for vehicle armor solutions [15].

d) In optoelectronics

Piezoelectric and thermoelectric devices, high density magnetic recording media, in optical applications as graded refractive index materials in audio-video discs.

e) In Industry

A ceramic roller suitable for various hybrid bearing applications in industries made up of silicon nitride as base material. This material possesses excellent mechanical properties, ideal for load bearing applications. In many cases, entire components are made of tungsten carbide, for an application requiring wear resistant properties. With a gradient, the use of expensive carbides can be minimized; thus lowering the total cost of the component. Functionally graded metal matrix composites (FGMMCs), especially gradient particulate composites with aluminum matrix, have been used in important applications such as in electronic packaging industry, for brake rotor assemblies in automobile industry and as armor materials [16].

4. Future Scope

Many research works carried out in the metal-ceramic FGMs such as (Al/Al_2O_3, WC/Co, Mo/Mo_2C, Ni/Al_2O_3, ZrO_2/NiCr and WC/Ni) for their proposed application. Based on the research history it is clear that the FGM processing stated with the ceramic compounds. Up to now so many processing technologies were discussed on the metal-ceramic type for the applications like which required high temperature resistance and toughness with light weight material. In contrast metal-metal combination having only least research works it may be due to the simplicity in the production processes of ceramic-ceramic and metal-ceramic combination. With the consideration of industrial needs new FGM families and their processing methods are to be developed especially with respect to real applications.

5. Conclusion

Functionally graded materials are very important in engineering and other applications which requires special properties which are not satisfied by the conventional materials like naturally available materials, alloys and metal matrix composites. Also we have discussed so many processing routes for making them to the special applications. In this regard here we present some of the deficiencies related to

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each processing technique for the further improvement. Commonly all the processing routes start with powders of base. During the consolidation for the gradient forming step, due to the lack in management of sintering temperature and time distortion in the final part arises with unequal density. To overcome this, a prior sintering step is to be implemented before the production in order to reach the desired part of final density. Concerning with the electrophoretic deposition a modelling work should be carried out to know the kinetics of deposition prior to the production process also suspensions of aqueous are better than the non aqueous since those are cost effective and eco friendly.

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