Centrifugal Casting: A Potential Technique for Making Functionally Graded Materials and Engineering Components

T. P. D. Rajan, R. M. Pillai and B. C. Pai *

Functionally Graded Materials (FGM) are the emerging new class of advanced engineering materials, which exhibit gradual transitions in the microstructure and/or the composition in a specific direction, the presence of which leads to variation in the functional performance within a part. FGM are in their early stages of evolution and expected to have a strong impact on the design and development of new components and structures with better performance. Among the various processing routes available for FGM, centrifugal casting has become one of the simplest and cost-effective methods for producing large-size engineering components. The gradient in composition or microstructures can be tailored by varying the processing parameters. The gradation is formed mainly due to the density difference between the molten metal and phases or particles present in the system. This paper presents the principle and types of centrifugal casting, introduces the concept of functionally graded materials and then discusses on various studies carried out on FGM processing through centrifugal casting technique, followed by their structural characteristics, properties and component development. Ample scope exists for further development of new functionally graded materials systems and engineering components using this potential technique.

Keywords: Centrifugal Casting, Functionally Graded Materials (FGM), Metal Matrix Composites.

INTRODUCTION

The advancement of technology in the field of aerospace, automotive, defence, electronics, biomedical and power engineering has led to the need of advanced materials with multifunctional behaviour and performance. To an extent these demands have been contented by the emerging new concept of functionally graded materials (FGM). FGM exhibit gradual transitions in the microstructure and/or the composition in a specific direction, the presence of which leads to variation in the functional performance within a part. Among the various fabrication routes for FGM such as chemical vapour deposition, physical vapour deposition, sol-gel technique, plasma spraying, molten metal infiltration, self-propagating high temperature synthesis, spray forming, centrifugal casting, etc., the ones based on solidification route are preferred because of their economics and capability to make large-size products. Among the major solidification processing methods, viz. centrifugal casting, settling, infiltration, spray casting and laser melt processing, the former has emerged as the simplest and cost-effective technique for producing large-scale and size engineering components. The gradient in composition or microstructure is formed mainly due to the density difference between the molten metal and phases or particles present in the system.

Centrifugal casting is the process, where molten metal is poured into a rotating or spinning mould to solidify it to a desired shape by the high compressive pressure exerted by the centrifugal force. The evolution of centrifugal casting is given in Table-1. The first patent on a centrifugal casting process was obtained in England by Echardt in 1809. The first industrial use of the process was in 1848 in Baltimore, when centrifugal casting was used to produce cast iron pipes[1]. Until the mid-1980s, the process was used exclusively for production of large symmetrical components such as pipes, bushings, rolls for steel mills, bearings, cylinders, shafting, gears and other shapes. Since then research and development on centrifugal casting of metal matrix composites and later in 1990s on different types of functionally graded materials was initiated.

PRINCIPLE OF CENTRIFUGAL CASTING

Centrifugal casting process is based on the principle of centrifugal force. The molten metal is introduced into a rotating mould and the metal is retained by centrifugal force around the circumference till it solidifies. The exterior surface of the casting takes the form of the inside contour of the mould. The centrifugal force acting upon a rotating body is proportional to the radius of rotation and the square of the velocity.

$$F_c = mr\,\omega^2 = mv^2 \qquad \text{...... (1)}$$

Where F_c = centrifugal force (N), m = mass (kg), r = radius (m), ω =angular velocity (rad/ sec) and v = peripheral speed (m/s).

The gravitational force on the mass would be given by

$$F_g = mg \qquad \text{...... (2)}$$

where g = acceleration due to gravity (m/s^2)

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Table-1: Evolution of Centrifugal Casting Process

Year	Milestones
1809	First patent on centrifugal casting process obtained in England by A.G. Echardt.
1848	First industrial use of the process in Baltimore to produce cast iron pipes.
1920s	Large-scale manufacturing of cast iron pipes and development of mathematical theory for centrifugal casting.
1980s	Fabrication of metal matrix composites by centrifugal casting.
1990s	Processing of functionally graded materials by centrifugal casting.

Hence, the factor (G) by which the normal force of gravity is multiplied during rotation is given by,

$$G = \frac{F_C}{F_g} = \frac{r\omega^2}{g} \quad \ldots\ldots (3)$$

$$= \frac{r}{g}\left(\frac{\pi}{30}\right)^2 N^2 = \frac{0.01rN^2}{g}$$

Where, N = revolutions per minute (rpm).

On the other hand, $N = \left(\frac{Gg}{0.011r}\right)^{1/2} = 29.9\left(\frac{G}{r}\right)^{1/2}$

$$= 42.3\left(\frac{G}{D}\right)^{1/2} \quad \ldots. (4)$$

Where, D = rotational diameter (m)

The G values suggested for metal die mould and sand lined centrifugal castings are 50-100 and 25-50 respectively[2]. Higher G values leads to excessive stresses and hot tears in the outside surface of casting.

Classification of Centrifugal Casting

The centrifugal casting process can be classified based on its axis of mould rotation (horizontal, vertical and inclined axis centrifugal casting) or depending on the nature of casting (True centrifugal, Semi-centrifugal and Centrifuge centrifugal casting).

In *horizontal centrifugal casting* (Fig. 1(a)), the axis of mould rotation is in the horizontal axis. This method is mainly used of making long tubes of simple shape with casting length to diameter ratio above four.

In *vertical centrifugal casting* (Fig. 1(b)), the axis of mould rotation is in the vertical axis and it is possible to use a variety of moulds including that for solid shapes. This process is applicable for small components, where the diameter exceeds its length, i.e. when the ratio of casting length to diameter is less than one. Shorter components, such as rings and flanges are frequently cast vertically.

In *inclined centrifugal casting*, axis of mould rotation is at an angle to the horizontal axis. Moore Sand Span process is an example for this kind of castings. This process is suitable when the ratio of casting Length to Diameter falls between one and four.

True Centrifugal Casting method always has a true cylindrical bore or inside diameter regardless of shape or configuration. It is used to produce cylindrical or tubular castings by spinning the mould about its own axis. The process can be either vertical or horizontal, and the need for a centre core is completely eliminated. Castings produced in metal moulds by this method have true directional cooling or solidification from the outside of the casting toward the axis of rotation. This directional solidification results in the production of high-quality defect-free castings.

Semi-centrifugal casting produces castings configurations determined entirely by the shape of the mould on all sides, by spinning the mould about its own axis. A vertical spinning axis is normally used for this method. Cores may be necessary if the casting is to have hollow sections. Directional solidification is obtained by proper gating, as in static casting. Castings that are difficult to produce statically can often be economically produced by this method, because centrifugal force feeds the molten metal under pressure many times higher than that in static casting. Typical castings of this type include gear blanks, pulley sheaves, wheels, impellers, and electric motor rotors.

In *centrifuge centrifugal casting* method, the casting cavities are arranged about the centre axis of rotation like the spokes of a wheel, thus permitting the production of multiple castings. Centrifugal force provides the necessary pressure on the molten metal in the same manner as in semi-centrifugal casting. This casting method is typically used to produce valve bodies and bonnets, plugs, yokes, brackets, and a wide variety of various industrtal castings.

Advantages and Disadvantages

The major advantages and disadvantages of the centrifugal casting process are given below[3] :

Advantages

- Most economical method for producing a superior quality tubular or cylindrical casting with regard to casting yield.
- Formation of hollow interiors in cylinders without cores in true centrifugal casting.
- Highest technical and economical effect in casting the components such as pipes, sleeves, rings, gears and turbine discs with blades.
- Fine-grained structures at the outer surface of the casting free of gas porosity and shrinkage cavities.
- Dense casting as the metal solidifies under pressure.
- Cleaner casting because the impurities and foreign materials are pushed to the inner surface, which can be removed by machining.
- Possibility of production of functionally gradient materials and bimetallic tubes.
- Production of number of small components in single pouring.

Disadvantages

- Increased segregation tendency of alloys during solidification under the forces of rotation, limits its applicability to few alloy systems.
- Increase in finishing allowances to remove segregates and non-metallic inclusions at the internal surfaces of casting.

FUNCTIONALLY GRADED MATERIALS

Functionally Graded Materials (FGM) are the emerging new class of advanced materials, which exhibit gradual transitions in the microstructure and/or the composition in a specific direction, and hence different functional performance within a part. FGM are in their early stages of evolution and are expected to have a strong impact on the design and development of new components and structures with better performance. FGM are mostly composites having continuous variation in composition along a certain direction[4]. Figure 2 shows the schematic illustration of an FGM with continuously graded microstructure. The presence of gradual transitions in material composition in FGM can reduce or eliminate the deleterious stress concentrations and result in a wide gradation of physical and / or chemical properties within the material.

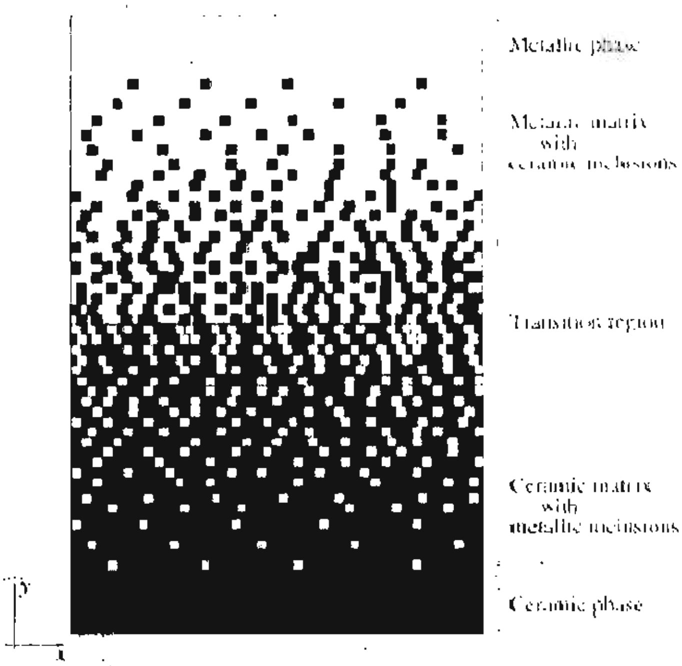


Fig. 2 : Schematic illustration of an FGM with continuously graded microstructure.

The FGM concept originated in Japan in 1984 during the space plane project in the form of a proposed thermal barrier material capable of withstanding a surface temperature of 2000 K and a temperature gradient of 1000 K across a cross section <10 mm. However, the gradient materials are not new; since they exist in the nature (the Earth itself is graded). The man has extensively utilised either natural or processed materials containing microstructural gradients. For example, both heat and mass diffusion techniques have been used over centuries to create functional, microstructural and /or compositional gradients in steel. The new aspect of FGM is the realisation that gradients can be designed at the microstructural level to tailor materials, most notably composites, for the specific functional and performance requirements of an intended application.

Centrifugal Casting of FGM

Centrifugal casting is one of the economic methods for making functionally graded materials. The process uses the radial forces generated from centrifugal casting to segregate a second discrete phase from the matrix of composite materials. When particle-containing slurry is subjected to centrifugal force, two distinct zones of particle enriched and depleted are formed. The extent of particle segregation and relative locations of enriched and depleted particles zones within the casting is mainly dictated by the melt temperature, metal viscosity, cooling rate, the densities of the particle and liquid, particle size and magnitude of centrifugal acceleration. Depending on the density of particles, the lighter particles segregate towards the axis of rotation, while the denser particles move away from the axis of rotation.

Figure 3 depicts the schematic setup of centrifugal casting having a vacuum chamber (vacuum pressure: P < 0.3 Pa) located in the extremity of a rotating arm moving around a vertical axis for producing FGM[5]. During rotation of the mould, the molten metal is forced to the cavity under centrifugal force and the particles in the melt moves towards the extreme end.

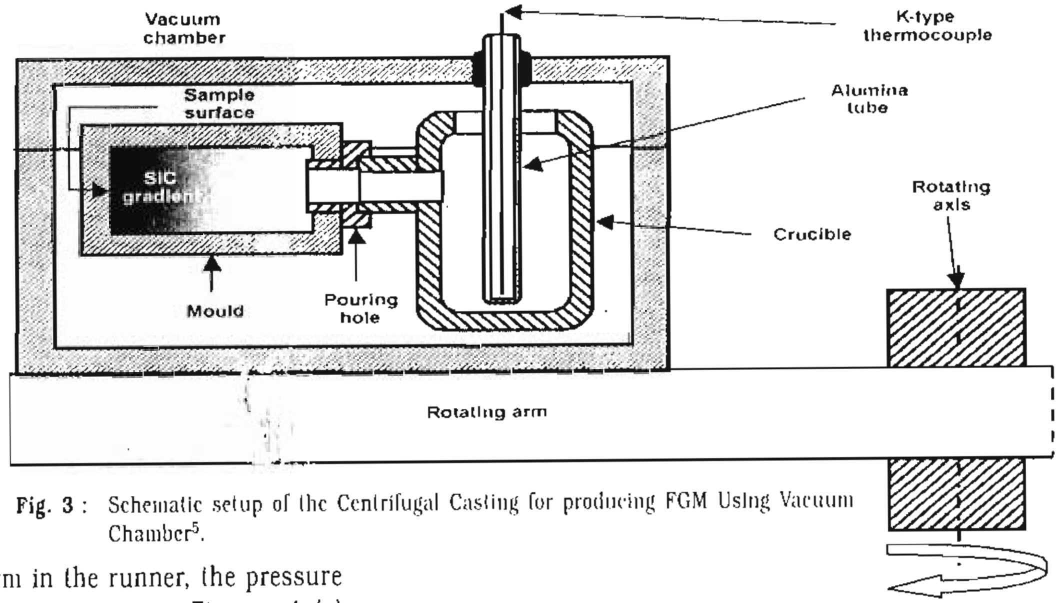


Fig. 3 : Schematic setup of the Centrifugal Casting for producing FGM Using Vacuum Chamber[5].

In *centrifugal infiltration process*, a mould containing packed ceramic preform located at an end of an elongated runner was rotated. By controlling the metal level above the preform in the runner, the pressure can be varied during infiltration process. Figures 4 (a) and (b) show schematic drawings of low-pressure centrifugal infiltration process and high-pressure centrifugal infiltration process respectively.

In another process, continuous aluminium matrix composite wires have been used as cylindrical preform material and liquid aluminium metal is poured and infiltrated under centrifugal force. This process produces Aluminium Matrix Composite (AMC) wire reinforced cylindrical aluminum component. Figure 5 shows (a) functionally graded aluminium tube reinforced with AMC wire, (b) Cross section through the aluminium tube and (c) The structure of the interface between the AMC wire embedded in aluminium matrix[6].

Structural Characteristics

The main characteristic of centrifugal cast microstructure is the variation in the structural features depending upon the location within a part or component. This variation is predominant in composites than in alloys. In the case of aluminium matrix composites, the particle enriched zone of the heavier particles such as SiC, alumina and zircon are at the outer periphery and the lighter particles such as graphite, mica and microbaloons of carbon are at the inner periphery of horizontally spun cylindrical centrifugal castings. The thickness of particle-enriched zone decreases with increasing pouring temperature and speed of rotation. Figure 6 shows the cross-section of centrifugal cast of Al-Graphite and Al-Zircon composites[7,8]. Table-2 lists the observations made on centrifugal casting of different metal matrix composites systems[9-16].

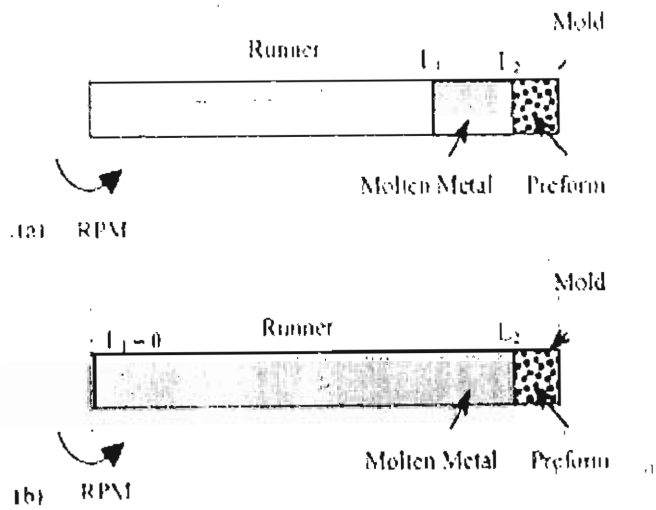
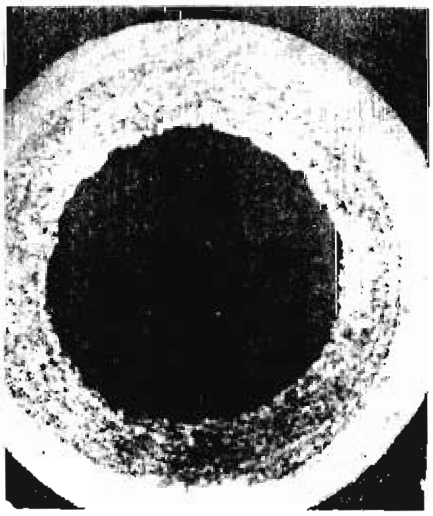


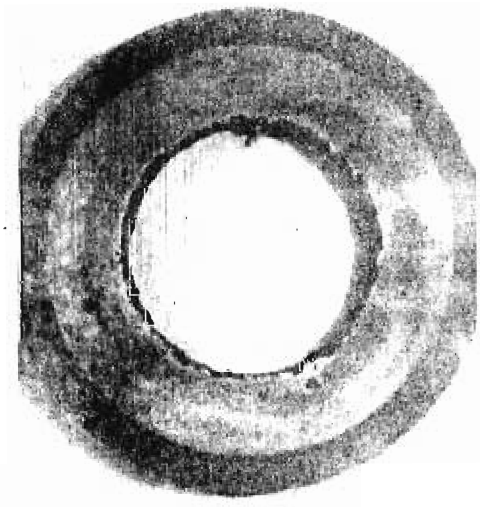
Fig. 4 : Schematic Drawings of (a) Low-Pressure Centrifugal Infiltration Process and (b) High-Pressure Centrifugal Infiltration Process.

Table-2 : Observations made on Centrifugal Casting of Different Aluminium Metal Matrix Composites

System		*Observations*
Al-SiC	▪ ▪ ▪	Graded distribution of SiC particles near the outer periphery of the casting. Higher strength and modulus near outer periphery. A smooth and gradual distribution of particles is observed when mixture of particle sizes is used.[9,10,11]
Al-Graphite	▪	Higher volume fraction of graphite partieles near the inner periphery of the casting.[7]
Al-Si	▪	Primary Si particles are observed near the inner periphery of the hollow casting.
Al-Al_3Ni	▪ ▪ ▪	Primary Al_3Ni phases near the inner periphery of the casting. Al-20%Ni forms the best graded distribution compared to Al-10/30/40 %Ni.[12] Young's Modulus vary from 81 to 100 GPa across the 6mm tube wall thickness from the inner to outer surface, reflecting 15.2 and 43.2 vol% Al_3Ni second phase.[13]
Al-Al_2Cu	▪	Graded structure of Al_2Cu is observed in Al-33 mass% Cu eutectic system.[14]
Al-Al_3Ti	▪	Al_3Ti platelets are distributed gradually near the outer periphery of cylindrical casting [Yoshimi, 1999 and 2001a].
Al-AlB_2	▪	AlB_2 particles with higher bulk density than liquid aluminium segregate towards the outer surface regions leading to higher wear resistance.[15]
Al-SiC-Graphite	▪	Graded distribution of SiC and graphite particles near the inner periphery of the casting. Few percentage of SiC is also observed near outer periphery.
Al-(Al_3Ti+ Al_3Ni)	▪	Hybrid Al-(Al_3Ti+ Al_3Ni) show superior wear resistance than pure Al. The wear resistance at outer region of ring is higher compared to inner region.[16]



(a)



(b)

Fig. 6 : Centrifugal Casting of Al-Graphite and Al Zircon composites[7,8].

Figure 7 shows the optical microstructures of the vertical centrifugal cast Al (6061)-SiC FGM. The experimentally measured volume fractions with respect to the distance of Al (6061)-SiC functionally graded metal matrix composites (FGMMC) are depicted in Fig. 8. The distribution of SiC particle is rich near the outer periphery as observed from the microstructure. The distribution of SiC reduces gradually from a maximum 41% near the outer periphery to 39 vol% at 2.5 mm, 35 vol% at 3.5 mm, 24 vol% at 4.5 mm and 15 vol% at 5mm. At 6 mm, there is no SiC particles and it is purely the Al(6061) matrix alloy[10]. When a mixture of varying particle sizes (14, 23 and 42 µm average particle sizes (APS)) of equal proportion is used for making Al(356)-SiC FGM, a smooth

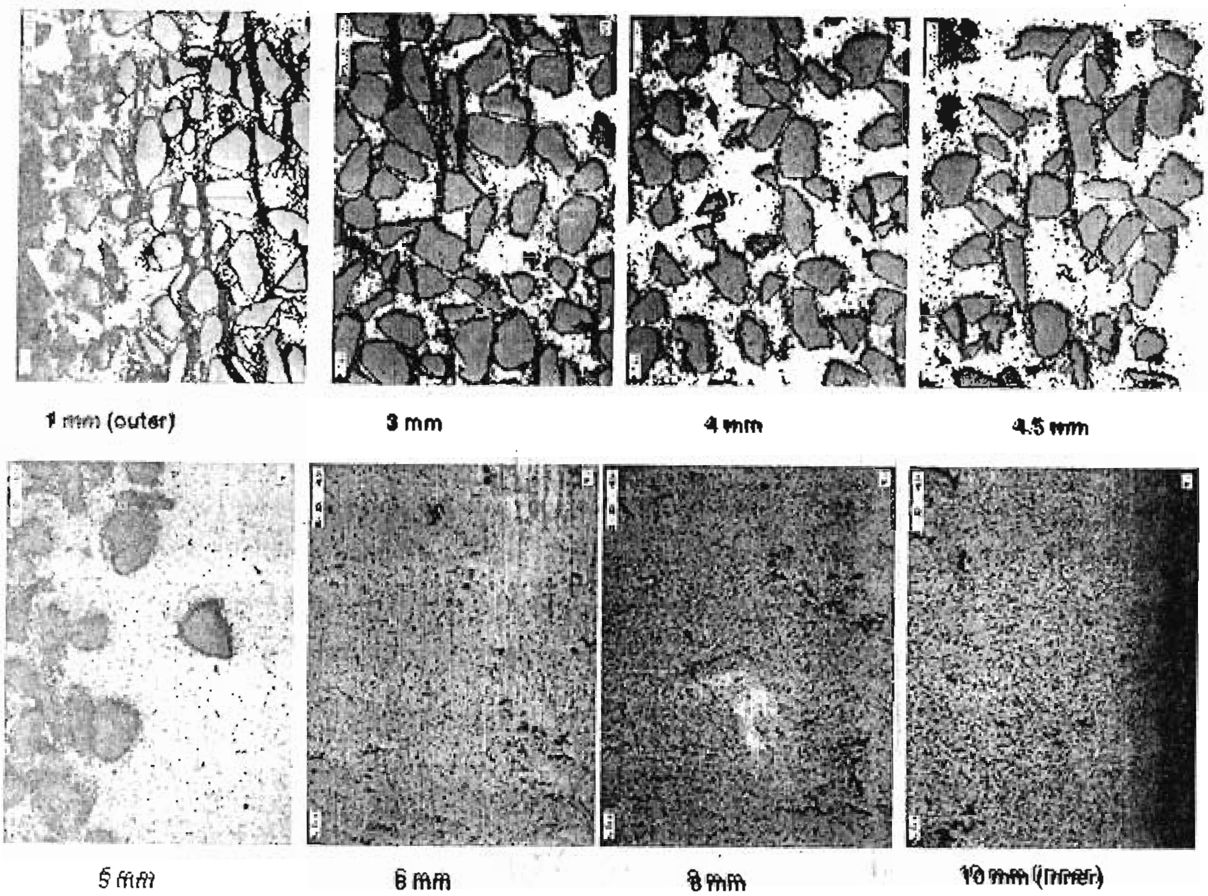


Fig. 7 : Optical Photomicrographs of Al (6061)-SiC FGM[10].

and gradual distribution of particles is observed, whereas in Al(356)-SiC FGM made by single size particles (23 µm APS) a sharp gradation is observed[11].

In Al-20% silicon, FGM fabricated by vertical centrifugal casting method (Fig. 9), the primary silicon particles formed are segregated as a graded layer in the inner periphery of casting leading to better hardness and improved wear resistance. The size and volume of primary Si decreases towards the outer periphery reaching 0% at about 25% of the length from the inner periphery.

Figures 10(a-d) show the typical microstructures of Al-Al_3Ni functionally graded MMC formed from Al-20%Ni alloy from the outer to the inner periphery of the centrifugally cast hollow cylindrical casting[12]. The region near the outer periphery (Fig. 10(a-b)) is rich in Al_3Ni primary crystals, whose concentration decreases towards the inner periphery (Fig. 10(c- d)). The transition from a hypereutectic alloy microstructure to that of a near-eutectic or hypoeutectic one takes place at about 10 mm from the outer periphery. The region near the outer periphery (Fig. 10(a-b)) shows both acicular and equiaxed primary Al_3Ni phases, while the region near the inner periphery shows very fine eutectic phase.

The microstructural observation of vertical centrifugal cast LM25-10%SiC-5%Graphite FGM hollow cylinder (Fig. 11) shows that the distribution of a part of SiC in the outer periphery of the casting and the other part in the inner periphery along with the graphite particles leading to a hybrid functionally graded composite. The hindered settling phenomenon is responsible for the segregation of hybrid particles to the inner periphery of the castings.

Hypereutectic Al-Mg_2Si alloy tubes with graded distribution of the primary Mg_2Si particles were produced by centrifugal casting[17]. Influence of rotation speed of the centrifugal mould and cooling rate during casting was investigated. Lower rotation speed resulted in better gradient distribution of Mg_2Si primary particles accompanied with higher volume fraction of the casting defects. With an increase in rotation speed, an apparent change of the particle distribution profile in the outer periphery can be observed. Meanwhile, the influence of rotation speed on the particle distribution in the inner periphery is rather small. The extremely high cooling rate achieved by using a copper mould with water cooling leads to a very fine microstructure in the outer periphery when compared with the same area in the other tubes obtained by using graphite mould. Hence, both the microstructure and the macro-segregation in the centrifugal tubes are tailorable.

During centrifugal casting, the segregation of particles due to particle movement is slowed down as a result of decreasing melt temperatures and crowding of particles occurring in progressively narrow zones during solidification. Velhinho etal producing a functionally graded SiC_p-reinforced aluminium-matrix composites by centrifugal casting have observed that SiC particles are partially clustered with some pores due to imperfect wetting of ceramic particles by the molten aluminium alloy[5]. Hence, proper wetting between the particles and the matrix is necessary to reduce particles clustering. Figure 12 shows the distributions of SiC along the thickness of the Functionally gradient Al (A359)/SiC_p composites fabricated at 1300 rpm and 700 rpm.[18].

The ability to produce and tailor a gradient in the reinforcement distribution hinges first on an understanding of the migration of the particles in the melt before solidification. Lajoye and Suery[19] modelled this process in the context of centrifugal casting considering the trajectory of a solid particle in the liquid, from the moment it enters the segregative force field till the moment it is trapped in place by the moving solidification front.

Properties of Centrifugally Cast FGM

The presence of graded microstructures in functionally graded material leads to variation in the physical, mechanical and tribological properties within a part or component. Depending on the extent of gradation in microstructure, the properties vary significantly or slightly. In the case of centrifugally cast FGM, the difference in properties will be much greater compared to the matrix and hence it is difficult to generalise their properties.

Unlike other castings, sampling is also a difficult job. One of the approaches in sampling is selecting specimens from different locations representing the diverse composition or concentration of phases or particles within a component. Few experimental studies are reportedly carried out on evaluation of mechanical properties by this approach. Results of tensile tests performed in specimens taken from different positions of the functionally graded Al A359/SiC_p composite produced by centrifugal casting is shown in Fig. 13 (a, b and c)[18]. The ultimate tensile strength (UTS), yield strength (YS) and modulus of the FGM are higher near the outer periphery compared to the inner. A centrifugally cast Al(356)-SiC FGM disc of 300 mm diameter and 24 mm thickness processed by the authors has shown higher strength and modulus near the outer periphery due to higher concentration of SiC particles when compared to the region near inner periphery.

In centrifugally cast material, hardness will be usually non-uniform due to the segregation of phases due to various factors. For e.g., the microstructure of a vertically cast nodular cast iron shows increase in ferrite from external surface to internal surface due to the decrease in cooling rate and hence a reduction of hardness in the same direction[20]. Hardness increases with the increase in Si content in aluminium alloys. Therefore in hypereutectic alloys, segregation of Si content at the inner portion increases hardness. In functionally graded Al A359/SiC_p composite, the hardness is higher near the outer periphery compared to inner region. Higher hardness values are observed near the outer periphery with higher rpm (1300) than lower (700) one (Fig. 13d) due to the presence higher percentage of SiC particle near outer periphery (Fig. 12). In centrifugally cast Al(356)-SiC FGM also, higher hardness is obtained near the outer periphery of the casting[9].

The gradient distribution of particles in FGM allows the matrix to absorb the energy by plastic deformation leading to improvement in fracture toughness. The fracture toughness of Al 359-20 Vol% SiC_p FGM composite low is for small crack lengths due to the limited dissipation of energy by the thick concentration of SiC_p at the edge. On the contrary, for longer crack lengths and decreased SiC content, the material surrounding the crack tip is able to plastically deform more. Therefore, there is more absorption of the energy imposed by the external loads leading to increased fracture toughness of the composite[18]. In centrifugally cast hypereutectic Al-Si system, the gradation of silicon in the inner side enhances the fatigue resistance[21].

The enhancement of tribological property is one of the major attractions of functionally graded composites. Higher wear resistance is observed in outer surface regions of Al-AlB_2 FGM processed by centrifugal casting due to higher AlB_2 particles concentration.[15]

Engineering Components and their Applications

Fabrication of functionally graded components by centrifugal casting method has wide scope for different engineering applications. Figure 14 shows few functionally graded aluminium matrix composite prototype components fabricated by centrifugal casting for engineering application at National Institute for Interdisciplinary Science and Technology, Trivandrum. Al-SiC FGM fishing boat cable pulleys are reported to be fabricated successfully by centrifugal casting method. Centrifugal casting has been applied to develop clutch drums composed of hard TiC particles embedded in aluminium-bronze matrix for naval applications. The lighter TiC particles, initially suspended in the heavier molten bronze, migrate to the centre during centrifugal casting, producing a carbide-rich inner surface that is highly abrasion resistant. Selectively reinforced casting MMC Powertrain Components have been developed by Pacific Northwest National Laboratories for the automotive sector using centrifugal casting. Engineering components requiring functionally graded properties can be identified, designed and fabricated through the centrifugal casting techniques.

CONCLUSION

Centrifugal casting is emerging as one of the versatile casting methods for producing different types of FGM components. Functionally graded composites can be formed by centrifugal casting technique through segregation of particles due to centrifugal force, either at the inner or the outer periphery of the casting, depending on the relative densities of the particles and the melt. Both the microstructure and the macro-segregation of phases and reinforcing particles in the centrifugal cast components are tailorable. Ample scope exists for further development of new functionally graded materials systems and engineering components through centrifugal casting.

Acknowledgments

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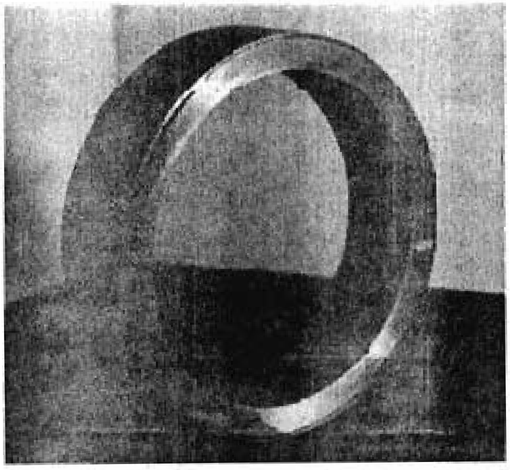

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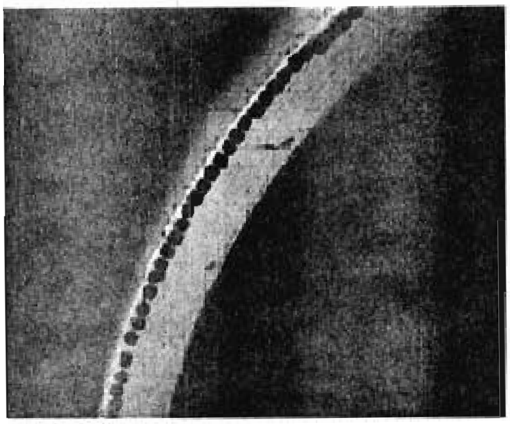

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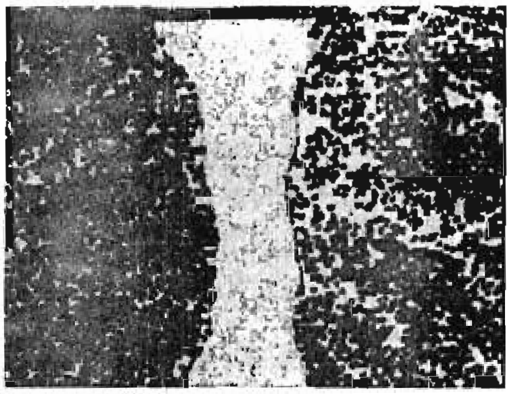
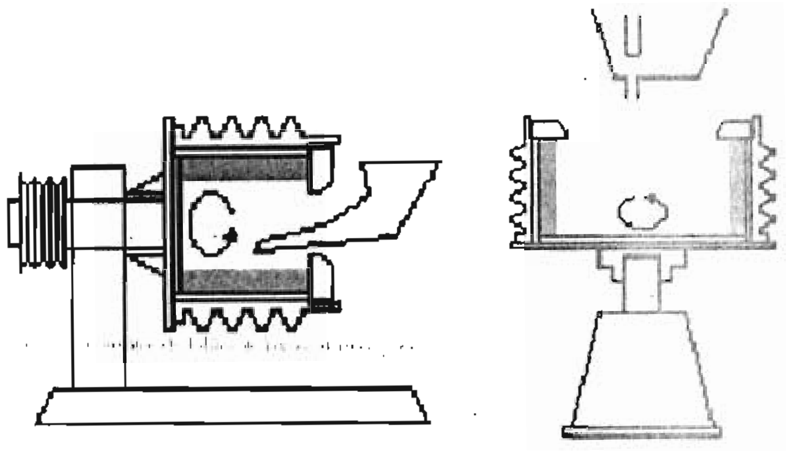


(c)

Fig. 5 : (a) Functionally Graded Aluminium Tube reinforced with Aluminium Matrix Composite (AMC) wire. (b) Cross-section through the Aluminium Tube and (c) The structure of the interface between the AMC wire embedded in Aluminium Matrix.[6]



(a) (b)

Fig. 1 : Schematic sketch of (a) Horizontal and (b) Vertical Centrifugal Casting.

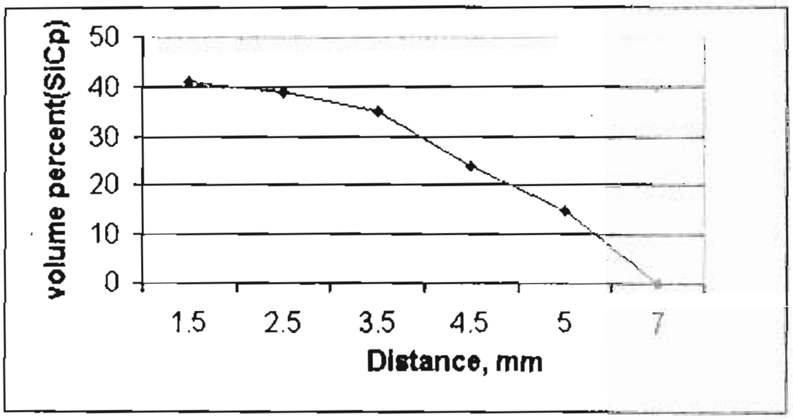


Fig. 8 : SiC Particle distribution in Al (6061)-SiC FGM[10].