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Formation of solidification microstructures in centrifugal cast functionally graded aluminium composites

T.P.D. Rajan and B.C. Pai

Materials and Minerals Division, National Institute for Interdisciplinary Science and Technology (NIIST), CSIR, Trivandrum – 695 019, India

Email: tpdrajan@rediffmail.com, tpdrajan@niist.res.in

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Abstract

A large number of engineering components and structures demand location specific performance under service conditions. A gradual transition in the microstructure or composition can motivate the changes in the functions of the specific locations for meeting the requirements and these tailored materials are termed as functionally graded materials (FGM). Centrifugal casting has emerged as the simplest and cost effective technique for producing large size engineering components of functionally graded metal matrix composites. The present paper describes the formation of different types of gradient solidification microstructures in SiC, B_4C, SiC-graphite hybrid, primary silicon, Mg_2Si and Al_3Ni reinforced functionally graded aluminium composites processed by centrifugal casting and correlate the microstructures with materials and processing parameters. The densities and size of the reinforcements play a major role in the formation of graded microstructures, the high density particles/phases both SiC and Al_3Ni form gradation towards the outer periphery and low density particles like graphite, primary silicon and Mg_2Si form gradation towards inner periphery. The B_4C particle having closer density to Al alloy has given more scattered distribution compare to other systems. However, functionally graded composite containing the SiC and Graphite particles has shown gradation towards inner periphery.

1. Introduction

Functionally Graded Materials exhibit gradual transitions in the microstructure and/or the composition in a specific direction, and hence different functional performance within a part. FGMs 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. The conventional approach of materials selection for component design and fabrication is based on the list of existing engineering materials. In the case of FGM approach of component design, an 'inverse design procedure' is followed, where the choice of basic material ingredients and material processes are combined with three dimensional mechanical analysis to form the graded structures and components for demanding applications. Even though the phenomena of graded structures is prevalent in nature and some of the conventional engineering materials, a formulated concept of making functionally graded materials had been proposed in mid-1980's in Japan. Fabrication of FGM and their components with gradient microstructures and properties are challenging and have technological relevance for the coming years. A wide variety of processing methods such as chemical vapour deposition, physical vapour deposition, sol-gel technique, plasma spraying, molten metal infiltration, self propagating, centrifugal casting, diffusion bonding, laser cladding and controlled mould filling are being developed for the fabrication of functionally graded metal-ceramic composites. Among these Centrifugal casting has emerged as the simplest and cost effective technique for producing large size engineering components of functionally graded metal matrix composites. Functionally graded aluminium composites used for tribological components have attracted more and more interests in recent years and are expected to be used in high speed rotating or reciprocating mass items such as pistons, connecting rods, drive shafts, brake rotors and cylinder liners.

Centrifugal Casting of FGM – A Retrospect

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 first patent on centrifugal casting process was obtained in England by Echardt in 1809 and the first industrial use of the process was in 1848 in Baltimore, USA when centrifugal casting was used to produce cast iron pipes [1]. Until the mid-1980s, the process was used exclusively for the 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 on different types of functionally graded materials (later in 1990s) were initiated. This 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 are 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.

Both horizontal and vertical centrifugal casting methods are used for making FGMs. There are various other variants and methods of using centrifugal casting techniques for making FGM. Centrifugal infiltration process is one of the techniques, where a mold containing a packed ceramic preform located at an end of an elongated runner is rotated and infiltrated with liquid metal. By controlling the metal level above the preform in the runner, the pressure can be varied during the infiltration process. 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 Aluminum Matrix Composite (AMC) wire reinforced cylindrical aluminium component. Processing of FGM by centrifugal casting having a vacuum chamber (vacuum pressure: $P < 03$ Pa) located in the extremity of a rotating arm moving around a vertical axis is described by Velhinho et al [2]. 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.

The variation in the structural features within a part or component is predominant in the case of FGM formed from composite systems 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 enrich at the inner periphery of horizontally spun cylindrical centrifugal castings [3, 4]. The thickness of particle enriched zone decreases with increasing pouring temperature and speed of rotation. Depending on the extent of gradation in microstructure, the properties vary significantly or slightly. Large difference exists between the particle enriched and depleted zones of centrifugally cast FGM and hence it is difficult to generalize their properties. 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 et al producing a functionally graded SiCp 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 [2]. Hence, proper wetting between the particles and the matrix is necessary to reduce particles clustering.

In Al-SiC FGM, a graded distribution of SiC particles are observed near the outer periphery of the casting and higher strength and modulus are observed near the outer periphery. 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. Only few experimental studies are carried out on evaluation of mechanical properties by this approach. Results of tensile tests performed on specimens taken from different positions of the functionally graded Al (A359)/SiC_p composite produced by centrifugal casting have shown that ultimate tensile strength (UTS), yield strength (YS), the hardness and modulus of the FGM are higher near the outer periphery compared to the inner [5]. Further higher hardness values are observed near the outer periphery with higher rpm (1300) than lower one (700) due to the presence higher percentage of SiC particle near outer periphery in the former case. 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 is low for small crack lengths due to the limited dissipation of energy by the thick concentration of SiCp 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 [5]. Al-Graphite FGMs show higher volume fraction of graphite particles near the inner periphery of the casting [3].

Various investigations are carried out on processing FGM using the insitu generated dispersoids such as primary silicon, Al_3Ni, Al_3Ti, Ni_3Al and Al_2Cu. Al_3Ni intermetallic is a hard phase formed in Al-Ni alloys containing less than 42 wt% Ni. Primary Al_3Ni intermetallic phase is observed in Al-Ni alloy containing more than 6 wt% Ni [6]. The density of Al_3Ni intermetallic compound (~4 g/cc) is more than that of aluminium (2.68 g/cc), and hence a composite having graded radial distribution of Al_3Ni near the outer periphery of a hollow cylinder casting can be formed by centrifugal casting. The studies on Al- Al_3Ni formed from Al-20mass%Ni shows the variation in Young's Modulus from 81 to 100 GPa from the inner to the outer surface 6mm tube thick corresponding to the presence of 15.2 and 43.2 vol% Al_3Ni second phase [7]. The evaluation of bending strength at different crack initiation planes having varying volume fractions has shown a maximum average fracture stress of 156 MPa at the location having 24 vol.% Al_3Ni. Al- Al_2Cu FGM containing graded structure of Al_2Cu has been processed using Al-33 mass% Cu eutectic alloy [8]. Al- Al_3Ti FGM has shown Al_3Ti platelets distributed gradually near the outer periphery of a cylindrical casting [9]. AlB_2 particles with higher bulk density than liquid aluminum segregate towards the outer surface leading to a higher wear resistance in Al-AlB_2 FGM [10]. The enhancement in tribological property either inside or outside is one of the major attractions of functionally graded composites.

Few engineering applications have been realized in using FGMs fabricated by centrifugal casting. 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 highly abrasion resistant carbide-rich inner surface. Selectively reinforced casting MMC Power train Components have been developed by Pacific Northwest National Laboratories for the automotive sector using centrifugal casting. Thus, engineering components requiring functionally graded properties can be identified, designed and fabricated through centrifugal casting. Even though few selected systems are investigated and reported in the literature, there is lot of scope for investigating newer possible FGM systems as well as effect of various parameters on the structure and properties. The objective of the present paper is to the fabricate various aluminium alloy based functionally graded composite materials by centrifugal casting and evaluation of different types of solidification microstructures formed during processing and correlation of the microstructures with materials and processing parameters. The microstructural formation in SiC, B_4C, SiC-graphite hybrid, primary silicon,

Mg_2Si and Al_3Ni reinforced functionally graded aluminium composites have been studied.

2. Experimental Methods

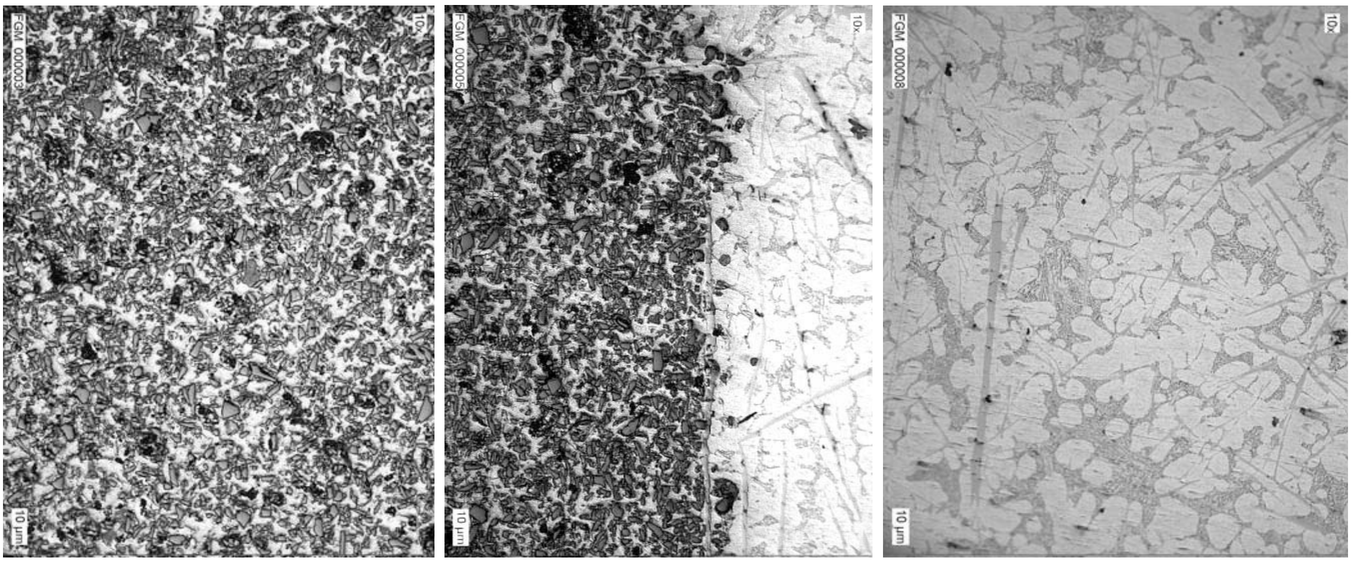
Al alloys are the potential materials for automotive engine components due to their low density, excellent thermal conductivity, easy fabricability and corrosion resistance. Both ex-situ and in-situ reinforced Al FGMs are fabricated by centrifugal casting. The ex-situ reinforced MMC melt are initially synthesised by liquid metal stir casting and then poured into centrifugal casting mould. The various functionally graded aluminium composite systems fabricated are (a) Al-SiC FGM by 356 Al (Al–7Si–0.35Mg) alloy reinforced with green variety SiC particles of 23 μm average particle size; (b) Al- B_4C FGM by 6061 Al (Al-1Mg-0.6Si) alloy reinforced with B_4C of 20 μm average particle size; (c) Al-Si FGM using 390 hypereutectic Al alloy (Al–17Si–4Cu–Mg), where the in situ reinforcement of primary Si particles are formed during solidification; (d) Al-Al_3Ni FGM formed from Al-20%Ni alloy; (e) Al-SiC-Graphite Hybrid FGM using 356 Al alloy reinforced with 23 μm SiC and 60 μm graphite particles; (f) Al-Si-Graphite Hybrid FGM using 390 hypereutectic Al alloy with in-situ primary Si and ex-situ 60 μm graphite particles (g) Al-Si-Mg_2Si hybrid FGM using 390 hypereutectic Al alloy with in-situ primary Si and 5% Mg forming Mg_2Si. The microstructure is observed using Leitz optical microscope along the plane perpendicular to the rotating axis. The Qwin image analyzer is used for determining the percentage of various phases and reinforcement at different locations along the casting. The hardness profiles of the castings are also evaluated in the same manner using Indentec Brinell hardness tester.

3. Results and Discussion

Al-SiC FGM

The microstructure of Aluminium-SiC functionally graded metal matrix composites fabricated by centrifugal casting method in Fig. 1 show the graded distribution of SiC particles in Al(356) alloy matrix at three different locations from the outside periphery of 16 mm thick ring casting. The outer periphery of the casting shows higher concentration of SiC particles than the interior of the casting. The image analysis results depicted in Fig. 2a shows that the outer periphery of the cylindrical casting contains a maximum of 45 vol. % SiC_p followed by a graded and reduced SiC volume percentage of 43, 37, 33 and 30 at 2, 3, 4 and 4.5 mm away from the outer periphery respectively. After 5.5 mm, the volume fraction drops sharply reaching zero at 6.5 mm. By subjecting a homogenous composite melt of Al(356)-15%SiC to a centrifugal force, a maximum volume fraction of 45% has been obtained at the outer periphery leading to selective improvement in specific properties such as hardness and wear resistance. Figure 2b shows higher hardness near the outer periphery of the casting in as cast and aged conditions. The inner periphery of the casting at 15.5 mm from the outer edge has shown the presence of gas porosity and few agglomerated particles. The gas bubbles present in the melt are thrown towards the inner periphery of the casting by the centrifugal force due to their lower density. The agglomerates constituting partially wetted or non-wetted particles or both and gases having lower overall density are also pushed towards the inner periphery. Further, the movement of gas bubbles from the outer periphery towards the inner during the rotation can hinder the particle movement in the opposite direction as well as carry away few particles. The gas and shrinkage porosities thus pushed to the inner periphery can be removed by machining to obtain a sound casting.

The comparison of distribution pattern of centrifugally cast silicon carbide particles reinforced 356 alloy with 2124 and 6061 Al alloys fabricated by the authors shows that there is a sharp transition between the SiC enriched and depleted zones in 356 alloy matrix, whereas a gradual or smooth transition is seen in 2124 matrix alloy. This is obviously due to the presence of varying amount of eutectic liquid, ie. 356 alloy contains more eutectic liquid compared to 2124 alloy, the difference in freezing range (longer freezing range of 2124 alloy - 637-490ºC than 356 alloy - 615-564ºC) and viscosity of the alloy [11]. Hence, the freezing range of the matrix alloy dictates the nature of transition from particle enriched to depleted zone. The vertical centrifugal cast Al (6061)-SiC FGM has shown rich distribution of SiC particle



(a) 3.5 mm (b) 5.5 mm (c) 9mm

Fig. 1 : Microstructures of Al(356)-SiC FGMCC hollow cylinder fabricated by horizontal centrifugal casting. Numbers are the distances from the outer to inner periphery in mm.

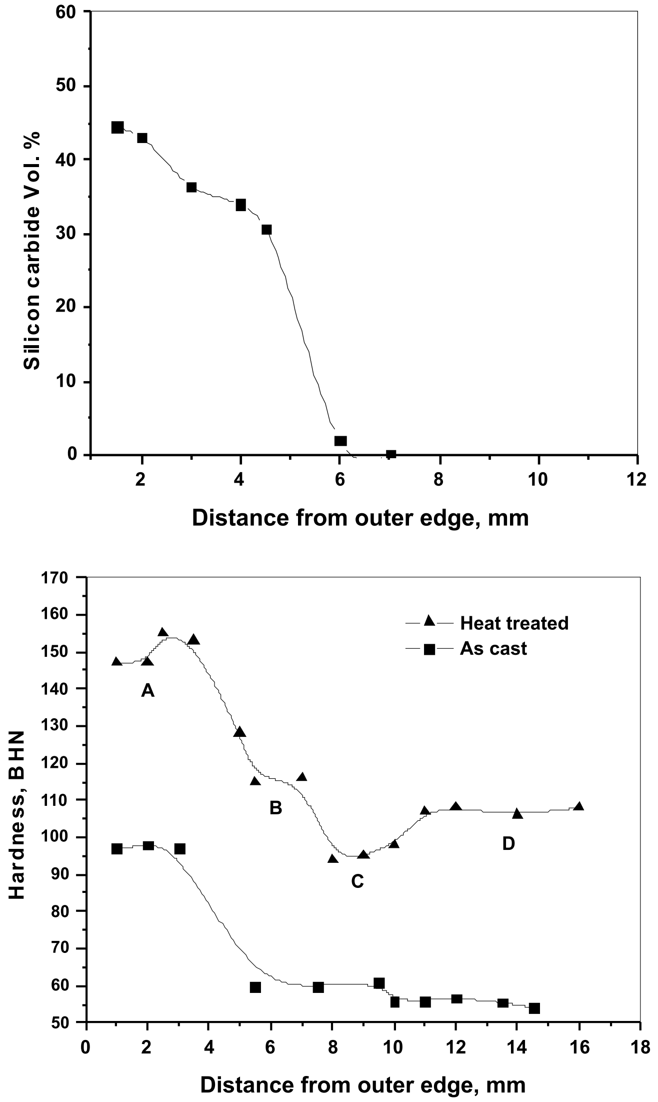


Fig 2 : (a) Graded distribution SiC particle from the outer periphery of the functionally graded Al(356)-SiC centrifugal cast ring and (b) Variation in hardness from outer edge of as-cast and heat treated Al(356)-SiC functionally graded composites

near the outer periphery. The distribution of SiC reduces gradually from a maximum 41% near the outer periphery to 39 vol% at 2.5 mm, 35vol % 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 [12]. When a SiCp 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 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 [13,14].

Al-B_4C

Boron carbide reinforced metal matrix composites (MMC) are uniquely suited as a structural neutron shielding material, where tailorable properties of neutron absorption as well as enhanced mechanical properties such as high strength, stiffness and hardness can be obtained. Figure 3 shows the optical micrographs of 6061 Al- B_4C (20 μm) functionally graded MMC fabricated by horizontal centrifugal casting. Since the density of B_4C is 2.52 g/cc is closer to that of aluminium matrix, the particles are distributed throughout the matrix from outer to the inner periphery of the casting. However, a close observation shows the presence of more particles towards the inner periphery of the casting.

Al-Si FGM

In primary silicon reinforced FGM fabricated using 390 Al alloy by vertical centrifugal casting method (Fig. 4), 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. Compared to that of gravity cast 390 Al alloy the primary silicon particles are refined in centrifugal cast structure. The PCl_5 addition has still reduced the microstructure.

Al- Al_3Ni FGM

Figures 5(a-c) 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 a centrifugally

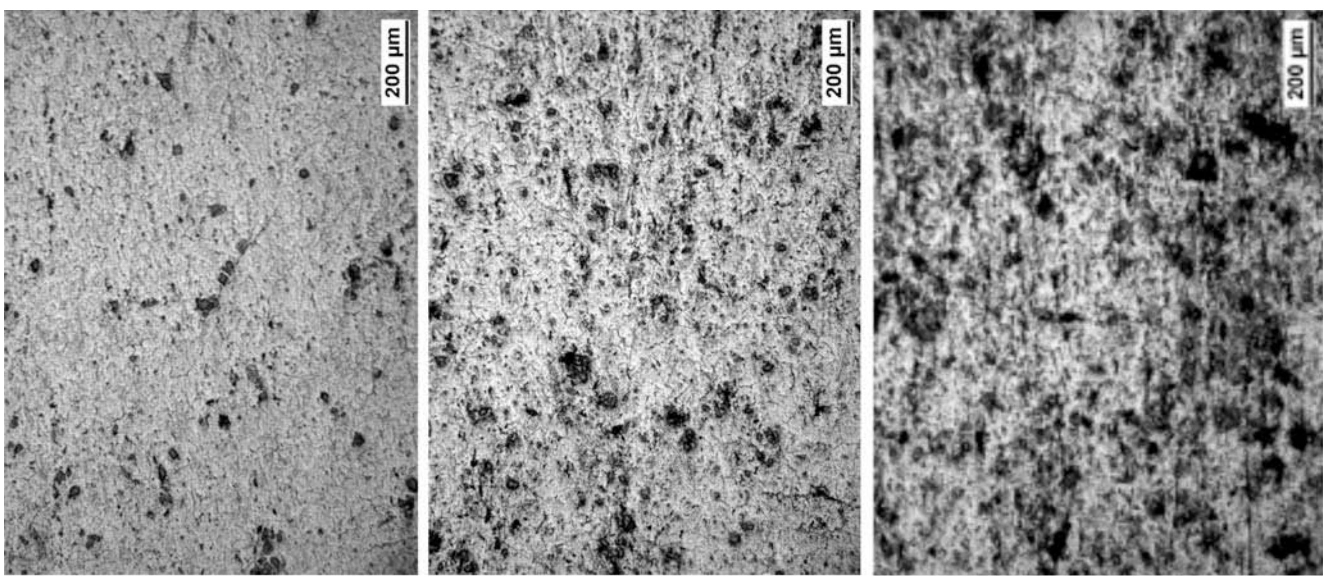
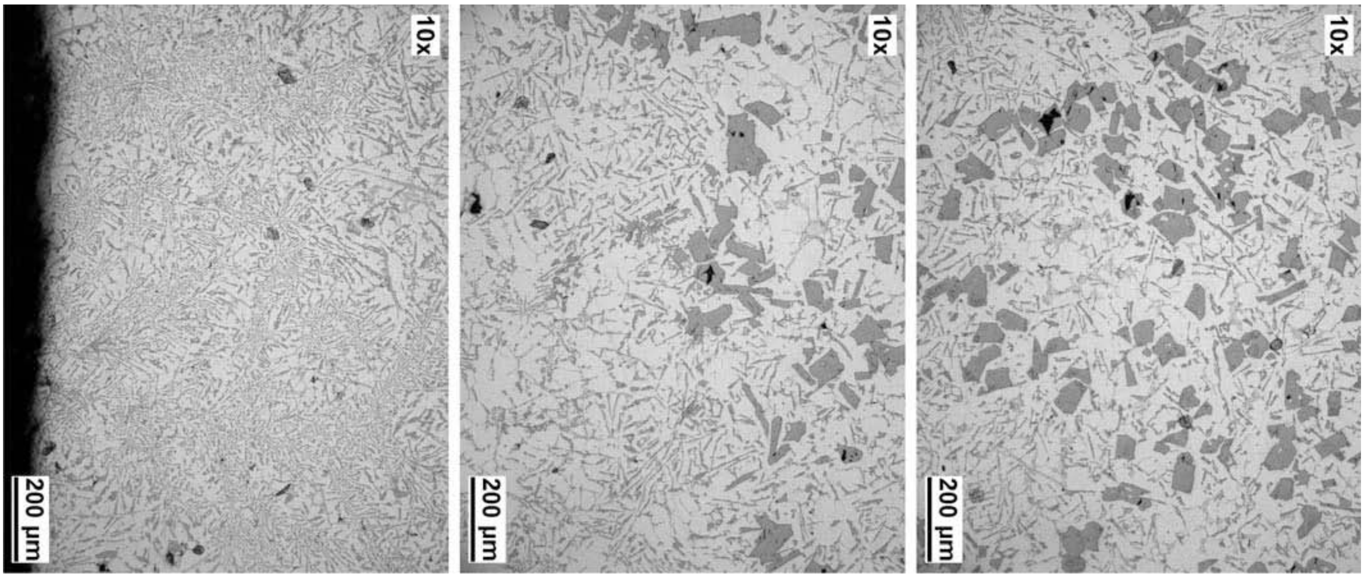


Fig. 3 : Optical micrographs of 6061 Al-B_4C (20 μm) functionally graded MMC fabricated by horizontal centrifugal casting



(a) 0.5 mm (b) 6 mm (c) 10 mm

Fig. 4 : Optical micrographs at different locations from outer to inner periphery of in-situ reinforced functionally graded aluminium matrix composite hollow cylinder fabricated using 390 Al alloy.

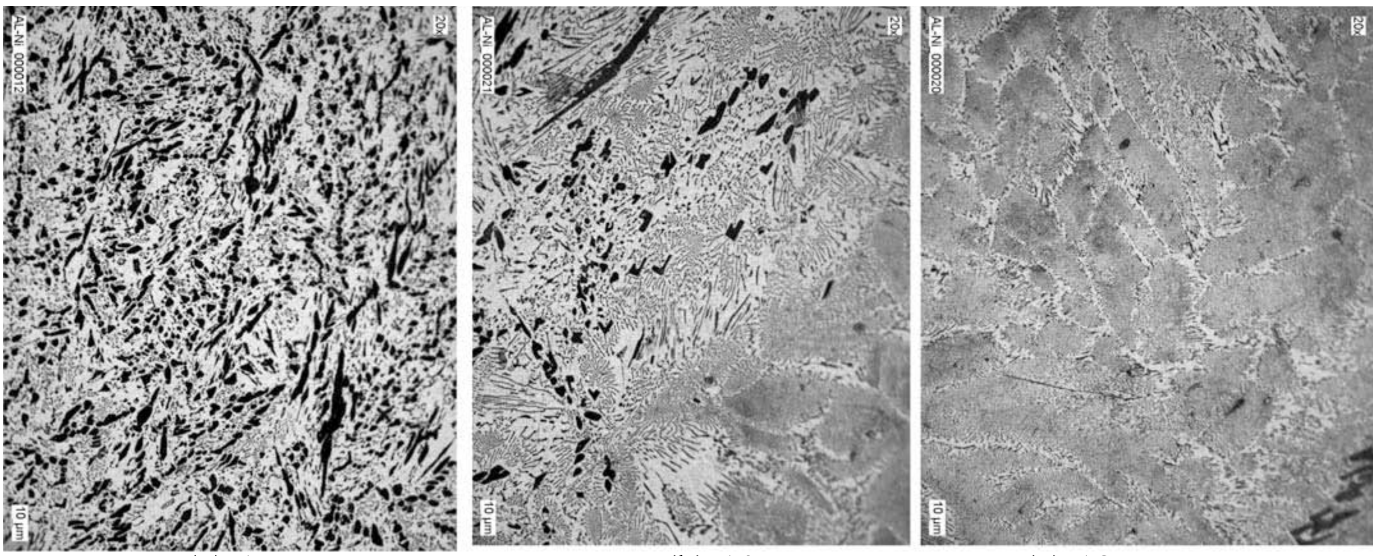
cast hollow cylindrical casting [15]. The region near the outer periphery (Fig. 5(a)) is rich in Al_3Ni primary crystals, whose concentration decreases towards the inner periphery (Figs. 5(b)). The transition from a hypereutectic alloy microstructure to that of a near eutectic or hypoeutectic one takes place at about 10 mm from the outer periphery. The region near the outer periphery (Figs. 5(c)) shows both acicular and equiaxed primary Al_3Ni phases, while the region near the inner periphery shows very fine eutectic phase. The microstructures and hardness profile of Al- Al_3Ni FGM formed from Al-20%Ni shows better graded structure compared to those formed in Al alloys with 10, 30 and 40% Ni [15].

Al-SiC-Graphite Hybrid FGM

The microstructural observation of vertical centrifugal cast 356-10%SiC-5%Graphite hybrid FGM hollow cylinder (Fig. 6) shows that the distribution of a portion of SiC in the outer periphery of the casting and the balance 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 SiCp particles along with graphite particles to the inner periphery of the castings, even though SiC particles possess higher density.

Al-Si-Graphite hybrid FGM

Figure 7 shows the optical micrographs of Al-Si-Graphite Hybrid FGM from outer to inner periphery of the casting. Both the primary silicon particles and the graphite are distributed towards inner periphery of the casting. The graphite particles are observed to be distributed along with the primary silicon particles and there is a possibility of formation of primary silicon along the periphery of graphite particle during solidification. The hard particle reinforcement by primary silicon can improve the strength and abrasive wear resistance and soft particle reinforcement by graphite



(a) 1 mm (b) 10 mm (c) 12 mm

Fig. 5 : Optical micrographs of Al-Al_3Ni FGM formed using Al-20% Ni from outer to inner periphery of the casting.

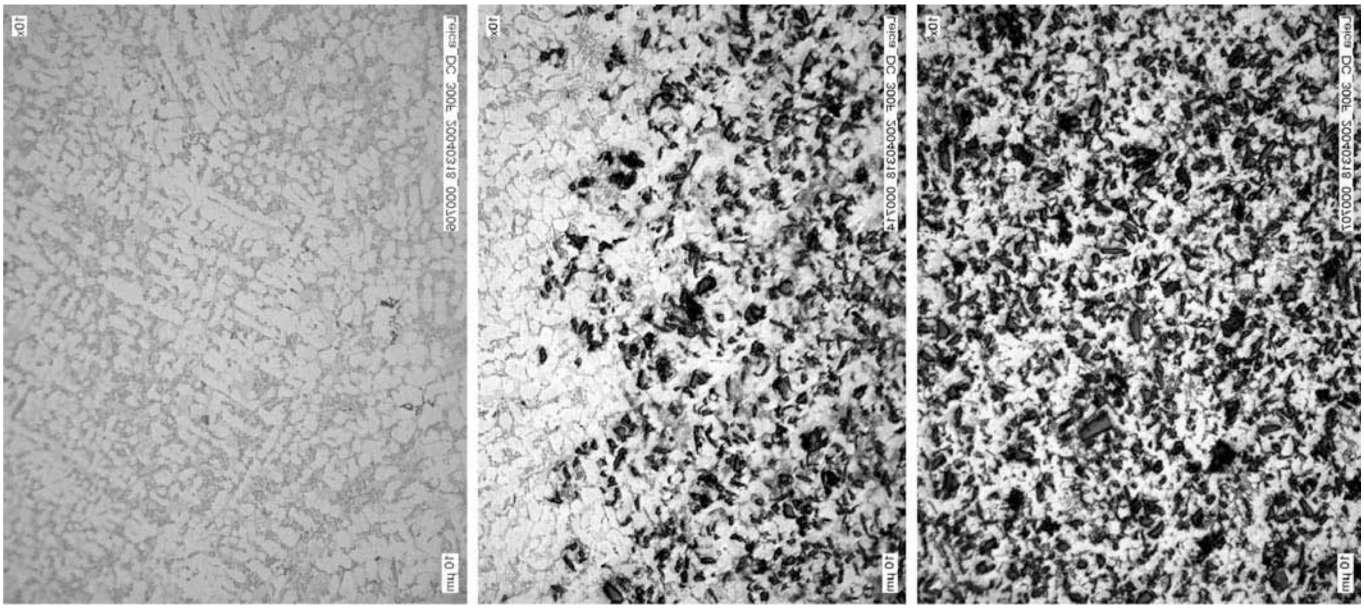
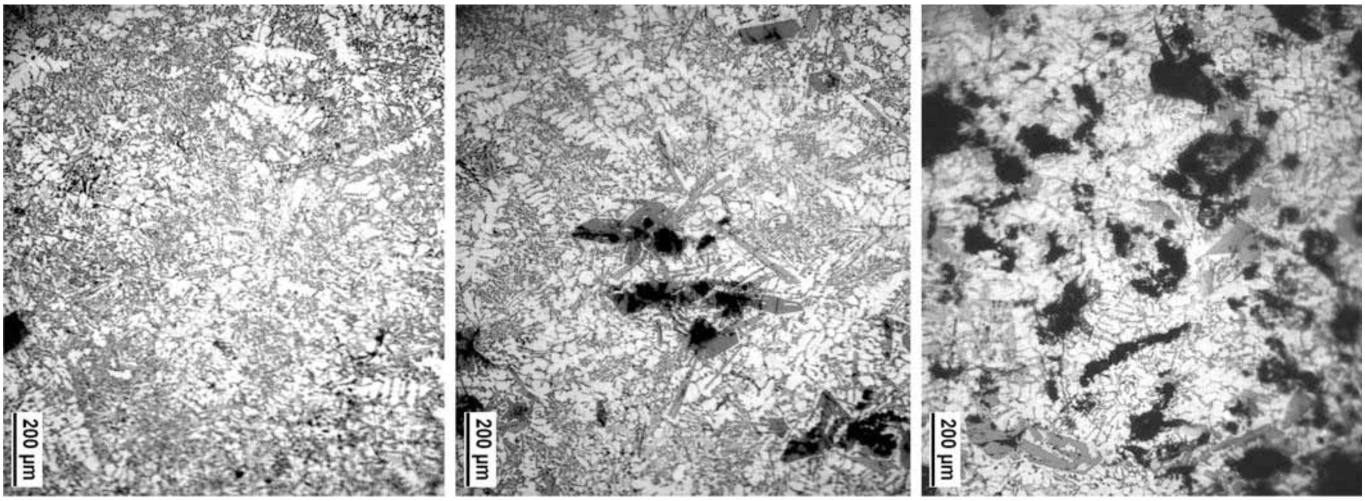
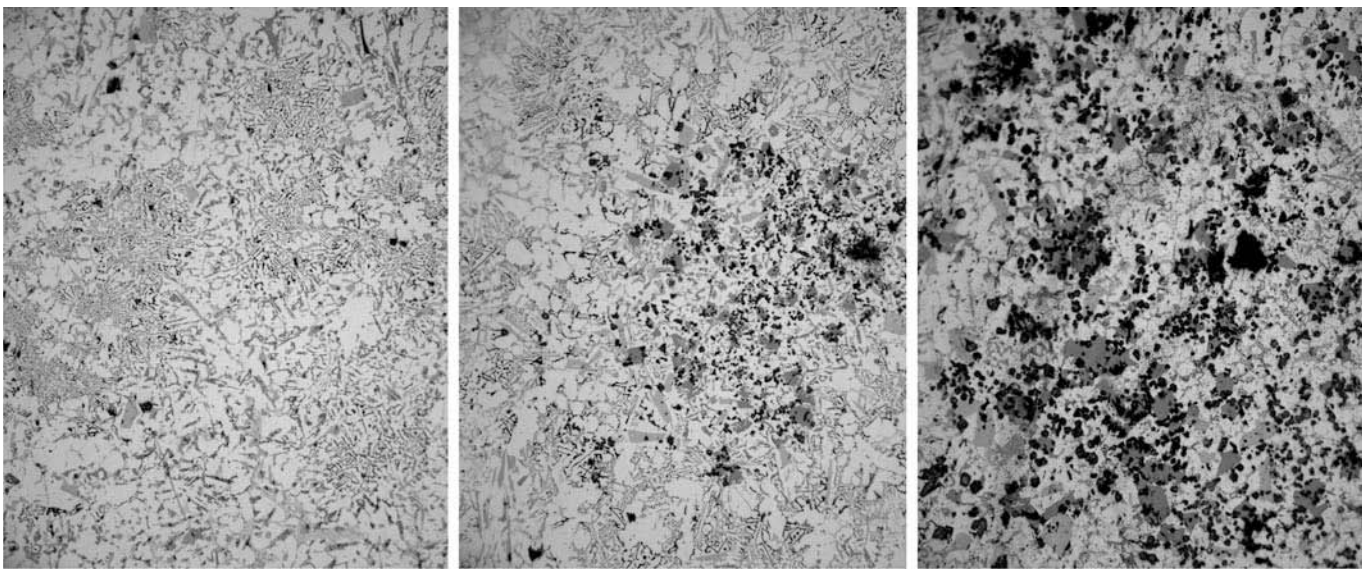


Fig. 6 : Optical micrographs of Al(356)-SiC-Graphite Hybrid FGM from outer to inner periphery of the casting.



(a) 4 mm (b) 6 mm (c) 12 mm

Fig/ 7 : Optical micrographs of Al-Si-Graphite Hybrid FGM from outer to inner periphery of the casting.



(a) 4 mm (b) 8 mm (c) 14 mm

Fig. 8 : Optical micrographs of Al-Si-Mg_2Si hybrid FGM from outer to inner periphery of the casting.

can improve the adhesive wear resistance and act as solid lubricant.

Al-Si-Mg_2Si hybrid FGM

Optical micrographs of Al-Si-Mg_2Si hybrid FGM from outer to inner periphery of the casting is shown in Fig. 8. The presence of high amount of silicon in 390 alloy has lead to the formation of large quantity of primary Mg_2Si phase in the composite with just 5% addition of Mg. The Mg_2Si phase thus formed will act as an in-situ reinforcement and it get segregated towards the inner periphery along with primary silicon particles, since the densities of both the particles are lower than matrix alloy. The size of Mg_2Si insitu reinforcement phase is comparatively smaller to that of the primary silicon and it is observed to be distributed in the edges of primary Si particles as well as individually in the matrix. The in-situ Mg_2Si phase can increase the hardness of the composite in the inner periphery along with the primary silicon particle.

4. Conclusion

Functionally graded composites are formed by centrifugal casting 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. The studies have shown that the high density particles/phases both SiC and Al_3Ni form gradation towards the outer periphery and low density particles like graphite, primary silicon and Mg_2Si form gradation towards inner periphery. The B_4C particle having closer density to Al alloy has given more scattered distribution compare to other systems. However, functionally graded composite containing the SiC and Graphite particles has shown gradation towards inner periphery. Centrifugal casting is proved to be a versatile casting method for producing different types of FGM components based on property requirements.

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