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Research paper

Graded Distribution of Solute Particles in Centrifugal Casting

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Abstract

The paper analyzed the processing factors responsible for gradation of second phase, rejected solute particles in centrifugal casting that would lead to the production of functionally graded materials (FGMs). The experiment conducted under laboratory simulated conditions involved the solidification of molten wax as the matrix and wood and sand particles as reinforced materials, in a rotating mould. The use of the prototype to establish the influence of the processing factors could be accomplished at a considerably low cost and was decisive in fixing the effect of these factors like the rotational speed of the mould and mould dimension in the real life metal casting paving a way for tailoring the FGMs keeping an eye to its specific end use.

Keywords: *Centrifugal Casting; Gradation; Prototype Material; Segregation Pattern; Solidification Structure.*

1. Introduction

The solidification structure and segregation in centrifugal casting play an important role on mechanical properties of the casting. A fine equiaxed grain structure provides a homogeneous and isotropic mechanical property [1]. As we know that centrifugal casting is known to have a 'banding' [2-4] microstructure due to segregation of alloys which gives a graded distribution of second phase alloys/ reinforcement particles from the outer to inner wall of the casting. The graded distribution of materials (FGMs) are now a days gaining popularity in different industries like automobile, aerospace, roles and grinding wheels etc. FGMs shows a unique advantages of the smooth transition of thermal stresses across the thickness and minimized stress concentration at the interfaces of dissimilar materials [5]. Due to its unique properties, it is used in turbine components and rocket nozzles where steep temperature gradient is addressed. There are many ways of production of FGMs such as solidification processing, CVD, spray atomization, powder metallurgy etc. [6,7]. From all above processes, centrifugal casting and gravity casting is the cheapest and economical way to produce FGMs [8-13] with the advantages of bulk production of large parts. Also, the casting structure produced by using centrifugal casting method have a continuous gradual distribution of reinforcement particles from one zone to another which helps to avoid any distinct interface and the stress produced by the interface [14], resulting a stress free continuous casting structure. Segregation of particles in the centrifugal casting product decides the macrostructure and functional gradation of mechanical properties. Sedimentation and flow induced migration of particles in the melt introduce concentration profile of particles which provides for smooth transition in electrical and thermal stresses across the thickness and minimize the stress concentration at the interface of dissimilar materials. Another important characteristic of centrifugal casting is structural refinement of the product which gives an improved mechanical properties. Segregation pattern of reinforcement particle or rejected solute particle is an important characteristic of centrifugal casting. Mostly, the denser particle in the melt segregate towards the outer region of the casting and the less dense particle collected towards the center of rotation due to the rotational speed of the mould. Apart from that, the opposite can also be happen. When the freezing pattern is perfectly maintained, the rejected heavy solute particles can be pushed towards the inner portion of the casting increasing the mechanical properties of that zone. Also, it is possible to get a solute rich region at the centre position of the casting by maintaining a proper combination of process parameters. When the mould rotates, one solidification front starts from the mould wall towards the centre of the casting due to conduction of heat through the mould wall where another solidification front starts from the inner portion of the casting towards the outer wall of the casting at the same time due to forced convection and radiation in the melt. In these cases, where the two solidification front meets, creates a layer with rejected heavy solute particles. In this way, a particular segregation pattern of solute/reinforcement particle can be tailored by manipulating the process variables such as mould dimensions, rotational speed of the mould, cooling rate of mould, pouring temperature of the mould, mould preheat temperature etc keeping in mind the end use of casting which cannot be easily achieved by using other methods of producing FGMs. Several experimenters used centrifugal casting method for production of FGMs mainly using Al as matrix and SiCp as reinforcement particles[15-28] which is extensively used in automobile and aerospace industries.

To study the segregation pattern and solidification pattern in centrifugal casting, involving the use of actual industrial material requires considerable investment in both plant and tooling. For economic reasons and convenience, model materials have been introduced in laboratory experiments to simulate the behavior of prototype metallic alloys. Generally used prototype materials are plasticine, waxes, leads, aluminium etc.[29]. The physical modeling method is an alternative method over numerical and analytical method. It has been employed in many simulation processes before [29-33]. Though, the numerical and analytical method have many advantages, it requires accurate knowledge of the material properties and other processes parameter values as inaccurate data leads to highly erroneous result. Also using FEM codes requires

highly trained technical personnel who know about the process. Thus, for economical point of view physical modeling can be proved to be beneficial over all the methods because it consider all the factors simultaneously which affects during the process. Using other methods cannot give accurate result as certain values need to be assumed.
In this study, the segregation and solidification pattern of centrifugal casting of wax is studied and analyzed confirming the movement of reinforcement particle in liquid melt. Wax is taken because of its low melting point and its tendency to crystallize, so that solidification pattern and segregation pattern can be easily visualized. Here, wax is used as the simulating medium where as sand and wood dust is used as the reinforcement particles.

2. Experimental Setup

A vertical centrifugal casting setup is fabricated in the central workshop, which is presented in Fig.1. A mild steel pipe of 62 mm diameter and its thickness of 3 mm is cut into two halves along the longitudinal axis. Two halves are aligned properly to prepare a split mould with a concentric form and two halves become symmetrical. The two halves of mould is then clamped together in order to make a cylindrical section. The clamped mould is then attached to the base plate followed by the pulley. Another pulley is fixed on the top of DC motor and both pulleys are connected using V belt. A ball bearing arrangement is made in order to reduce the vibration of mould during the rotation of the mould. A frame is made by angles and plates to support the mould and motor. Mould is seated on the frame by nut and bolts. In the similar way motor has been fixed on the frame by nuts and bolts. Motor is connected to the variac to control the voltage and so that the speed of the motor can be regulated. By variation of motor speed, the speed of the pulley varies accordingly. So, mould speed also varies with the variation of the speed of pulley. Speed of the mould and the motor is observed using stroboscope.
Wax is melted in the oven at 130°C. After fully melting of wax, the molten wax is then mixed with reinforcement particles such as wood dust and sand by proper stirring before pouring. The mixture is then poured into the rotating mould which is rotated at 250 rpm. Prior to pouring, the mould is lined with basic ramming mass and pre-heated properly. A varied solute concentration of wood dust and sand particles are taken to analyze the segregation and solidification pattern in the casting. Wood dust and sand particles were taken because of its large difference in densities so that segregation pattern can be easily obtained. Wood dust is then colored red in order to distinguish the two different layers. In oven dry condition, the density of wood dust is 358 kg/m3. But when it is immersed in hot liquid it absorbed the liquid and the density increased to 892 kg/m3 which is called its green strength density. Green strength density is calculated by dividing the total mass of wet wood dust particles with the volume of particles. For that, we have immersed the wood dust particle in the hot liquid wax and strained it when it is properly absorbed the liquid and settled down in the bottom of the container. The wet wood dust is then properly packed in a small container and weighted in order to find the mass of the wet wood dust. The container volume is considered as the total volume of the wet wood dust particles.
Mass of the wet wood dust = Total mass-mass of the container
Physical properties of the matrix and reinforcement particles are shown in Table-1. Dimension of the casting and mould is given in Table-2. After solidification, the product is removed from the mould and cut into slices in order to examine the properties and distribution of the particles in the casting. The experimental setup performing the casting operation is presented in Fig.2.

Table-1: Physical properties of the matrix and reinforcement

Physical properties	Paraffin wax	Sand	Wood dust
ρ , kg/m^3	737 (135°C)	1600	358 oven dry 892 green strength density*
D , mm	----	0.8	0.2

** Green density of wood = mass of the wet wood particles/ volume of particles*

Table-2: Dimension of casting and mould

Length (mm)		Thickness(mm)	
Casting	**Mould**	**Casting**	**Mould**
200	250	29	3

3. Results and Discussions

Fig 3 (a) shows the solidification structure of the wax at 250 rpm (with 0.05 vol % of wood dust and 0.02 vol% of sand). From the figure dendrite growth from the outer layer of the casting can be clearly figured out. Up to 5mm distance from the outer wall, a crystal clear structure is shown with less dendrite arms generated at some places. This is due to the small amount of solute particle present in the matrix. Fig 3(c) (0.10 vol% of wood dust and 0.02 vol% of sand) shows two distinct layers of solidification. At the centre of the casting, an equiaxed zone is noticed and a columnar zone is figured out close to the mould wall.
The trend in fig 3(a) shows that when a liquid with less solute content is poured into the rotating mould, chill crystals formed at the mould wall could not grow out due to less or no solute content. Therefore, it is difficult for the crystals to be detached and transported by convention and turbulences, resulting less bulk nuclei in the melt. Therefore, dendritic growth from the surface, grow unaffectedly towards the centre of the casting. A crystal clear structure at immediate mould wall is figured out because of the high centrifugal force at the mould wall. High centrifugal force at the mould wall breaks the growing crystals and helps to reduce the grain size in case of metals. Here as the wax is used, the fine grain size is visualized as a crystal clear structure in the casting.
As the concentration of the solute particles increases, solidifications starts at different positions apart from the chill crystals generated at the mould walls. Due to increase in solidification sites, more equiaxed grain structure is noticed at the centre of the mould. This could be understood by nucleation and growth mechanism. As the concentration increases, chill wall crystals detached more easily which result increase in bulk nucleation density in the melt. With increase in concentration of solute particles, columnar zone is replaced by the equiaxed zone due to dendrite remelting and breaking. Because, as the concentration of solute particles increases, dendrite arms becomes more sharper having solute pockets in it which is more like to be detached with centrifugal force and latent heat of remelting. So grain structure can be manipulated or fine equiaxed grains can also be produced keeping in mind the end use of the casting. If the product requires an equiaxed grain structure throughout the casting, it can be easily attained by increasing the solidification rate which can be achieved by manipulating the process parameter of casting. The increase in inclusion or solute composition also helps to creates more solidification sites for the nucleation of crystals. By increasing the solidification rate and centrifugal force with increase in solute composition one can achieve a fine grain structure throughout the casting. Solidification rate can be increased by increasing mould rotational speed, increasing mould cooling rate, lowering the melt pouring temperature etc.
Also mould dimension plays an important role in deciding the grain structure of the casting. Smaller mould diameter helps to achieve a fine grain structure throughout the section if a proper solidification rate is employed. When solidification rate is high and a high centrifugal force is exerted in the liquid metal, there

will be no sufficient time for the crystal to grow to make columnar structure. On the other hand, the high centrifugal force exerted in the liquid metal will break the dendrite arms growing out of the crystals which will result a fine grain structure casting product.

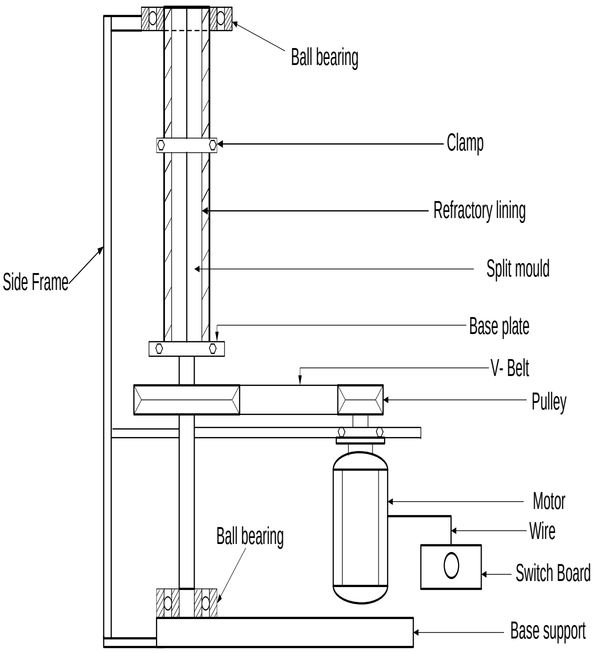
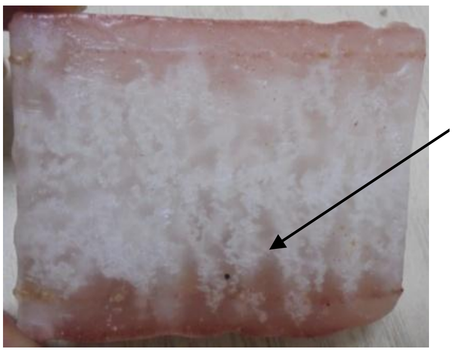
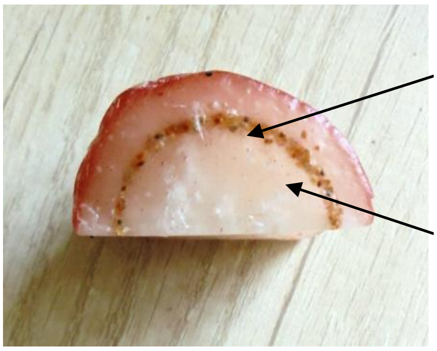


Fig.1: Schematic diagram of experimental setup

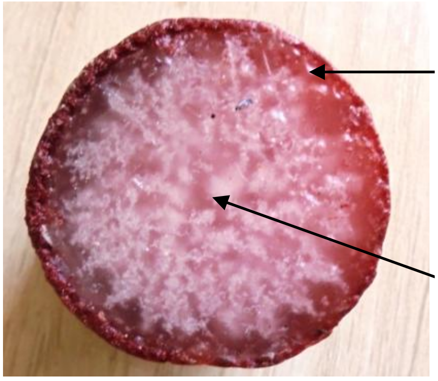
Fig.2: Rotation of mould at 250 rpm



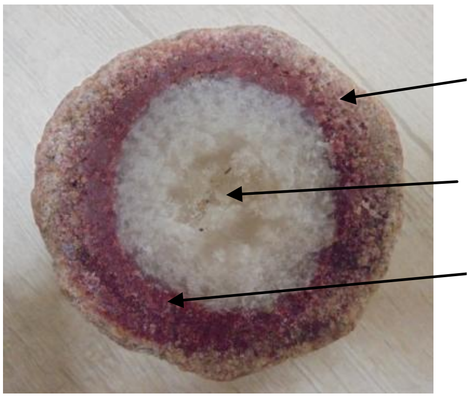
(a)



(b)



(c)



(d)

Fig.3: Centrifugal casting of prototype model at 250 rpm (a,b) 0.5 vol% wood and 0.02 vol% of sand, (c) 0.10 vol% of wood and 0.02 vol % of sand, (d) 0.16 vol% of wood and 0.19 vol% of sand

All crystals formed in the melt in centrifugal casting are subjected to the centrifugal force. The motion of the crystals is affected by the centrifugal force as well as turbulence flow within the liquid. Turbulent flow mainly affects the volume of each crystal where as centrifugal force affect the surface area of the crystals. So accordingly, for larger crystals having lower area to volume ratio, centrifugal force, pushes them towards the outer wall of the casting. In this way smaller crystals are collected at the centre of the casting creating an equiaxed structure.

We know that segregation of particles depends upon many factors like density of particles, viscosity of the melt, particle size etc. It also depends upon various process parameters like rotational speed of the mould, pouring temperature of the melt, density difference between melt and reinforcement particles and volume fraction of the reinforcement particles. From Fig 3(a) and Fig 3(b), it is shown that sand particles, despite of having higher density than wood dust, are segregated in the middle of the casting where as wood dust particles are segregated at the outer wall of the casting. This is because the concentration/ vol% of sand particles in the melts. It is very difficult to form the sand thickness region at 0.02 vol% of sand particle as it is of very less concentration. Due to centrifugal force effect on sand particles, it travelled the whole distance but after striking the mould wall, it moves back to inside the melt as there is less concentration of sand particles in the melt. The less number of sand particles cannot be able to provide enough restricting force to prevent the motion of the sand particles, those are returning into the melt by striking the mould wall. So the sand region is formed at the middle of the casting. With increase in concentration of wood dust particles from 0.5 vol% to 0.10 vol%, shown in Fig 3(c), a small thickness layer of wood dust particles is shown in the outer casting surface where some sand particles also shown embedded in it. This is because sand particles having higher density reached the mould wall first and due to its less concentration it came back to the liquid after striking the wall and this process continues till the wood dust reached the peripheral region. After that sand particles could not able to come back to the liquid as higher concentration of wood dust particles prevent it from striking back into the melt. Also this much period of time is enough for the solidification to start from the mould wall. Thus, sand and wood dust particles could not able to come back into the liquid and segregated at the outer wall of the casting.

To get a distinct thickness region of sand and wood dust particles like FGMs, 0.19 vol% of sand and 0.164 vol% of wood dust were taken. In Fig 3(d), a distinct wood and sand layer is observed. It is interesting to note that, despite of having very low density compared to sand particles, wood particles able to reach close to sand segregated region. Here viscosity, temperature gradient and size of mould played an important role for this type of trend.

It is observed that, there is a very less temperature drop resulting in no change in viscosity in the liquid which helps the particles to reach the mould periphery easily without any barrier. Another factor is also employed for the segregation is the mould size, as it is very small compared to the rotational speed used, wood particles able to cover the distance before the solidification begins. Due to the above reason, wood particles, despite of having very less density compared to the sand particles able to reach close to the sand thickness zone easily before the solidification front moves towards the inner portion of the casting. It can also be said that, the tendency of absorbing the hot molten liquid by the wood particles, increases the density which helps the wood particles to move towards the mould wall. Unlike other two cases (Fig 3(a) and 3(c)), on the other hand, a clear sand segregated zone is noticed because of the increase in concentration of the sand particles which prevents the former sand particles to strike backwards and a distinct segregated zone is formed.

From the above physical modeling, it is noticed that only density difference does not play important role in segregation. Instead, combine effect of mould size, rotational velocity of mould, solute% plays important role in segregation. By playing with the mould size, rotational velocity of mould, solute %, we can tailor the segregated region according to end use of the product.

This is an optimized and stepping down approach prior to the metal using as the matrix. By using prototype model we can minimize the cost of the production. After finding a suitable process parameter combination using prototype model, the actual casting can be made using metal as the matrix and could get the desired product with required mechanical properties.

4. Conclusions

From the observation, below conclusions can be made

(i) Increase in concentration of reinforcement particles, a distinct segregation zone can be achieved.

(ii) With increase in solute concentration, a combination of primary columnar zone at the mould wall and secondary equiaxed zone at the centre is noticed. A less solute concentration results in a fully developed columnar zone, from the mould wall to the centre of the casting.

From the above physical modeling it can be said that by manipulating different process parameters, one can achieve a desired particle distribution. Mould dimensions, speed of rotation and the resultant temperature gradient play important roles in deciding the particle distribution in the centrifugal casting making the casting suitable for specific end uses.

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