NUMERICAL SIMULATION OF CENTRIFUGAL CASTING FOR FUNCTIONALLY GRADED METAL-MATRIX COMPOSITES

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ABSTRACT

Functionally graded materials (FGM's), particularly in the form of Al-SiC metal matrix composites (MMC's) are advanced materials, having high abrasion resistance, high toughness and thermal resistance at the surface. Centrifugal casting is one of the method for processing this type of MMC, but accurate control of the reinforcement particles distribution has not yet been completely obtained. In this work, mushy state solidification characteristics in centrifugal casting are numerically simulated using computational fluid dynamics (CFD) techniques to study the distribution of reinforcement particles. Effect of process parameters on the distribution of reinforcement particles are examined by varying rotational speed and volume fraction of reinforcement. Further, investigation on the characteristics of cooling curves during solidification process is also carried out. Volume of fluid (VOF) method is used to simulate the multi-phase fluid flow during the mushy state of solidification. Solidification patterns and cooling curves generated clearly show a strong influence of process parameters on the distribution of reinforcement particles and solidification rate.

Key words: *Centrifugal casting, CFD, Functionally graded materials, Mathematical modeling, Solidification pattern.*

1. INTRODUCTION

Functionally Graded Material (FGM), belongs to a class of advanced materials with varying properties along the change in direction. FGM is a two phase heterogeneous composite characterized by a compositional gradient from one component to the other. In FGMs the one property of matrix phase component is mated with other property of reinforcement phase component. FGMs offer great promise in applications where the operating conditions are hazardous. For example, wear resistance linings, cutting tool insert coating, protective coating on turbine blades, rocket heat shields, heat exchangers, thermoelectric generators, internal combustion engine components, plasma facings, and manufacturing of tubes, etc. Several fabrication methods are employed to produce FGMs. Functionally graded materials can be classified into two types, thin and bulk FGM. Thin FGM are relatively thin surface coating, while the bulk FGM require thick layer of coatings. Thin surface coatings FGM are produced by Deposition technique, Plasma Spraying, Self-propagating High temperature Synthesis etc. Bulk FGM is produced using powder metallurgy, centrifugal casting etc [1]. Owing to the importance of FGM, there are lots of research work are carried out regarding the material processing and properties of the FGM. Among various fabrication methods centrifugal castings acquire high mechanical strength and fine grained structure, Inclusions and impurities are lighter and high production rate [2]. Centrifugal casting is widely used for casting thin-wall cylinders. It uses the centripetal force to distribute the molten metal inside the mold. In centrifugal casting, there is a fixed mold which is rotating along the corresponding axis. The melts centrifugally move towards the mold wall because of the centripetal force. The melt will solidify after cooling. A schematic of the process can be seen in figure 1.

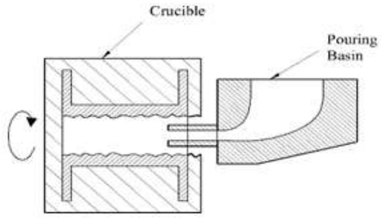


Figure 1 Working principle of centrifugal casting

Due to its high temperature and invisible mold condition in centrifugal casting, makes it difficult to know the mechanism of molten material inside the mold. It is important to know the mechanism of the molten metal inside mold, since it will help the manufacturer to know more accuracy of the flow of the molten material so that it can work for improving the productivity and quality of the products. The fluid flow is an important factor in centrifugal casting process. With the understanding of the fluid flow in centrifugal casting, it possible to reduce the number of defects thus to improve the product quality. A lot research work has been carried out in this field, which includes both experimental and numerical study [3]. From previous research study, it has been found the rotational speed and particle size determines the quality of the centrifugal cast component. A high rotational speed will result in high centripetal force which can create very high swirl in the liquid pool [4]. When rotational speed is low, there are chances for defects in casting. Kestur Sadashivaiah [5] has carried out both numerical simulation and cold model experiment based on horizontal centrifugal casting and studied the effect of various variables on flow patterns. Numerical simulation is a good and cheap method for studying and investigating the different controllable parameters which will influence the quality of final product. J.W. GAO [6] has carried out a numerical simulation of solidification in centrifugal casting process of functionally graded materials. He found that the angular velocity, solidification rate and the geometrical nature of the particle flow are responsible for creation of the particle concentration gradient in solidified products. J Bohacek [7] has studied the solidification process of work rolls which are made by the centrifugal casting process. A 2D numerical simulation was carried out to investigate the average flow dynamics. Zagorski et. al. [8] carried out computer simulation of gravity casting of the metal matrix composites reinforced with ceramics using ANSYS FLUENT. ANSYS FLUENT is computer software which is used for modeling the fluid flow, heat transfer and chemical reactions in complex geometries. It is equally suited for incompressible and compressible fluid-flow simulations [9]. Their numerical model describes the process considering solidification and its influence on the distribution of reinforcement particles. Recently, George et. al. [8] modeled mushy state of solidification process of Al-SiC MMC’s by treating Al- SiC as a single phase material. However, in stir casting, the centrifugal force acting on the fluids will tend to separate the fluids. Accurate modeling of these phenomena requires a multi-phase model approach. Among various multiphase modelling the VOF model can be used to model two or more immiscible fluids [10,11].Vinay Chandran [12] has studied the horizontal centrifugal casting process of manufacture aluminium-silicon carbide FGM by ANSYS fluent. Solidification model is available in the Fluent CFD code which can be used for simulate the melting, solidification, casting, and crystal growth. This model is controlled by enthalpy of formation and it does not track the phase change during simulation.

In this paper, numerical simulation of mushy state characteristics and cooling curve analysis of centrifugal casting process have been done using CFD solver FLUENT by varying relevant process parameters such as rotational speed and volume fraction of reinforcement. Contour plots of mushy state solidification pattern and cooling curve characteristics obtained from simulation study are examined to find the effect of process parameters. The results show a strong influence of process parameters on particle distribution and, the observations are in good agreement with the experimental data. Further, this work demonstrates the capability of CFD in the field of manufacturing and paves path for immense future research.

2. MODELING AND SIMULATION

Centrifugal casting process is considered as a case of mixing of fluids. centrifugal casting process involves fundamental in the fields of multiphase fluid flow, heat transfer, turbulent flow and solidification.

Theory

Fluid flow can be mathematically represented by a set of conservation equations. The conservative equations involved in centrifugal casting process are conservation of mass, momentum and energy (1-3) together with two sink terms are considered to model solidification process in centrifugal casting (4,5).

To be able to numerically solve these equations, finite difference, finite element, spectral element method etc are used. The result of the discretization process is a finite set of coupled algebraic equations that need to be solved simultaneously in each cell by an iterative procedure. Iteration of the solution will be completed only after each variable has been solved. Generally, segregated solution approach is used, in which a guessed pressure field is used in the solution of the momentum equation to get new velocities. Then new velocities are substituted in the continuity equation and energy equation to find corrections needed for the velocities. Based on velocity corrections, a pressure correction is computed which, then added to the original guessed pressure to get updated pressure, and the entire process is repeated until convergence criteria are met [13].

Simulation

In the present work, flow field developed due to centrifugal action is simulated. Simulation consists of three stages. The first stage is a preprocessing stage which consists of geometric modeling and meshing. The second and third stages are solution phase and post processing, respectively. For each simulation trail, process parameters varied are rotational speed (ω = 100rad/sec, 150rad/sec and 200rad/sec) and volume fraction of reinforcement (VF = 10%, 20%, and 30%).

Geometric Modeling and Meshing

A schematic representation of centrifugal casting setup is depicted in Fig.2A two dimensional model of the crucible is considered. Geometric modeling and meshing is carried out using ANSYS ICEM CFD. The crucible diameter is chosen as 60 mm, and the wall thickness as 10 mm. The inside space of the crucible is filled by molten aluminium and silicon carbide particles is the domain for analysis. For the discretization of the domain, an unstructured mesh with triangular elements is used. After conducting mesh sensitivity study, a mesh having 1790 triangular elements has been chosen for the present study. This mesh (Fig.3) is imported to the FLUENT software.

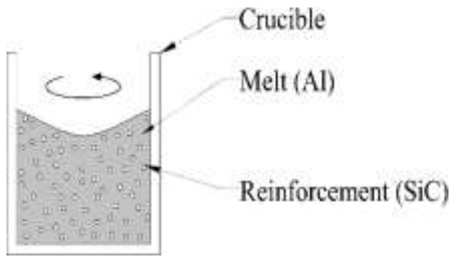


Figure 2 Centrifugal casting setup

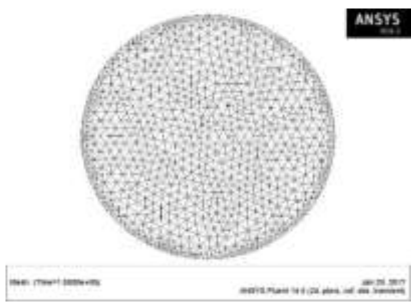


Figure 3 A typical two dimensional mesh

Assumptions

The assumptions used to create the simulation model are stated below.

- Size of the Silicon carbide particles are assumed to be small so that it flows like a fluid [10].
- Reinforcement particles are initially assumed to be uniformly placed inside the crucible.
- crucible is made of cast steel to act as a solid wall.
- Fluids are treated as Newtonian fluids.
- Initial temperature of the system is assumed to be 930^{0}C.

Boundary Conditions

Thermal boundary conditions are incorporated via system coupling. No slip occurs inside the crucible. The contact resistance is taken as 0.001m^2-K/W for crucible wall. The properties of the materials selected for simulation study are shown in TABLE1. The properties in any given cell are either purely representative of one of the phases, or representation of a mixture of the phases, depending upon the volume fraction values.

Table 1 Material Properties

Properties	**Aluminium**	**Silicon carbide**	**Cast steel**
Density(kg/m^3)	2720	3210	7200
Specific Heat(J/kg-K)	963	750	500
Thermal Conductivity(W/m-K)	170	120	23.2
Viscosity(kg/m-s)	1.4×10^{-3}	1×10^{-3}	N/A
Molecular weight(kg/kgmol)	26.891	40.11	N/A
Standard state enthalpy(J/kgmol)	3.29×10^{8}	7.19×10^{8}	N/A
Reference Temperature(K)	900	900	N/A
Pure solvent Melting heat(J/kg)	4×10^{5}	3.6×10^{5}	N/A
Solidus temperature(K)	865	1700	N/A
Liquidus temperature(K)	925	2500	N/A

Solution Method

The finite difference method is used for discretization of governing equations explained in the previous section. In this, the derivatives are replaced with finite differences evaluated at the cell centers using a truncated Taylor series expansion. Among different schemes available for this, a second order upwind differencing scheme is used because it will reduce the numerical error in the final solution. The multiphase VOF model, enthalpy model, and solidification & melting model are enabled in the FLUENT. The phases are selected in such a way that primary phase is aluminum and secondary phase is silicon carbide. To account for turbulence flow, a wall function in the near wall region is selected. Calculations are carried out in a rotational frame of reference, rotating at a constant angular velocity. The solution is carried out in FLUENT using a two-dimensional, pressure-based, segregated and unsteady flow solver. The solution techniques include pressure velocity coupling scheme using SIMPLE, momentum and turbulent kinetic energy discretization using second order upwind scheme, and volume fraction discretization using Geo-reconstruct. All solution variables are initialized before the iteration. The solution process involves iterations wherein the entire set of governing equations is solved repeatedly until the solution converges. Finally, the results of mushy state solidification pattern and cooling curve characteristics are plotted using post processor.

3. RESULTS AND DISCUSSION

In this section, results obtained from simulation study are presented and discussed in detail. Mainly mushy state solidification pattern for various combinations of process parameters are shown. These solidification patterns for all the cases are generated at the same computational time of 1 sec. Further, cooling curve characteristics for various cases are also summarized.

Effect of Stirrer Speed

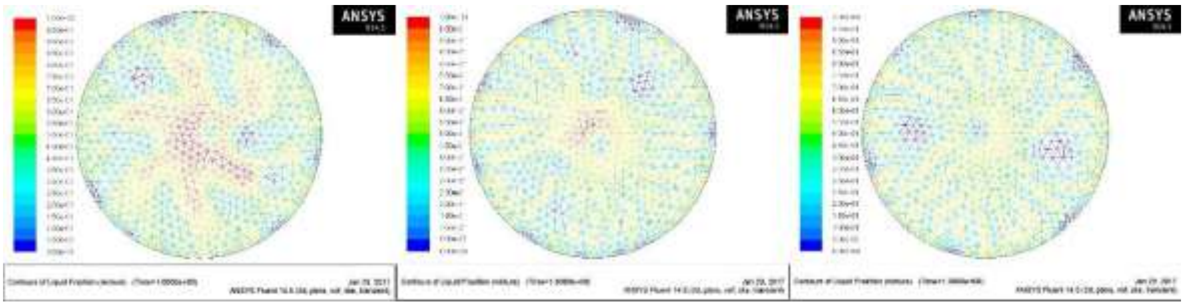
Mushy state solidification patterns corresponding to different rotational speeds, ω =100, 150, and 200rad/sec are shown in Fig.4 - 6, respectively. In these figures, liquid fraction scale is shown on the left side of the solidification pattern. Red color in solidification patterns indicates the liquid phase (β=1.0), blue color indicates solid phase (β=0.0) and colors in between show liquid fraction ranging from zero to one. When initial red color (liquid phase) changes to uniform green color shows that the molten matrix has reached semisolid state (mushy state). The continuous monitoring of solidification pattern of all simulation trials from the initial iteration, it was observed that there is directional solidification. Directional solidification indicates that solidification is beginning from boundary of the crucible and then it is propagating inwards to the center of the crucible. From Fig.3 - 5 it is clear that when rotational speed increases from 100rad/sec to 200rad/sec the time taken to reach mushy state (green color) is not the same. The presence of uniform green color in figures show that it has reached the mushy state is but in figures corresponding to 10% volume fraction there is red color concentrated at the center, which is an indication of molten aluminium, which in turn indicates that corresponding to this condition mushy state is not reached. It can also be seen from that red color is unevenly distributed which shows the degree of non uniformity in solidification process. From the simulation study it is inferred that rotational speed has significant effect on solidification rate. When rotational speed increases, turbulence and shear rate will increase which in turn accelerates the solidification rate because of stirring speed promotes binding between matrix and reinforcement. It also promotes formation of vortex which is responsible for dispersion of particulates in liquid metal. At the same time when it increases beyond certain limit solidification and distribution of reinforcement are affected adversely due over swirl produced inside the crucible.

Effect of Volume Fraction

Mushy state solidification patterns corresponding to different volume fraction, VF =10%, 20%, and 30% are shown in Fig.4 - 6, respectively. In Figure corresponding to 30% volume fraction blue color is joined together and it is seen like a tree structure, which is a measure of reinforcement clustering. From Fig.3 - 5, it is evident that when volume fraction is increased from 10% to 30% there is a tendency for segregation or clustering of reinforcement particle. These simulation results clearly show a strong influence of volume fraction on clustering tendency and solidification rate. When volume fraction reaches 30% the reinforcement particles forms spike like structure which starts from circumference of the casting and it extends upto center of the crucible. But for volume fraction 20% the reinforcement particles are seen surrounded by the outer periphery of the casting which provided good functional quality to the composites. For 10% SiC also like in 30% SiC spike like structure is obtained which extends towards the center, which is not surrounded at the outer so the directional properties cannot be achieved.

Both parameters are having interaction effects that are variation of both parameters simultaneously affect the final microstructure of the FGM. Corresponding to 150rad/sec and 20% reinforcement combination gives better results compared with other combinations of rotational speed and volume fraction. It is also inferred from the simulation study that Numerical Simulation of Centrifugal Casting for Functionally Graded Metal-Matrix Composites

centrifugal casting does not provide good casing compared with other process for the production



of FGM.

Figure 4 Solidification pattern for rotational speed 100rad/sec and volume fractions (a) 10% (b) 20% (c) 30%.

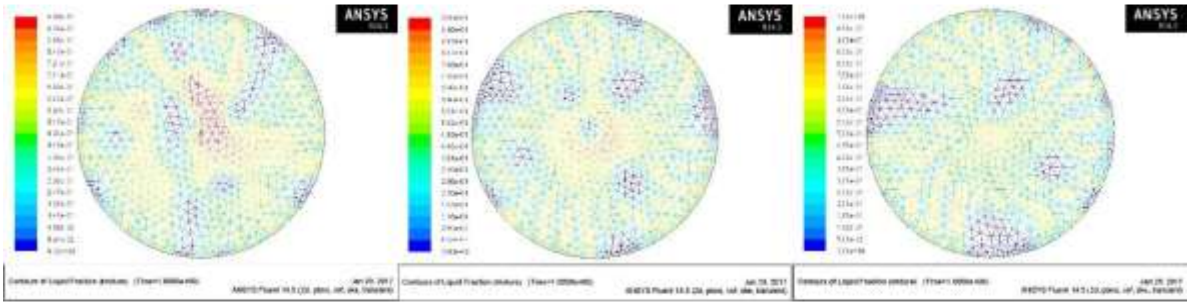
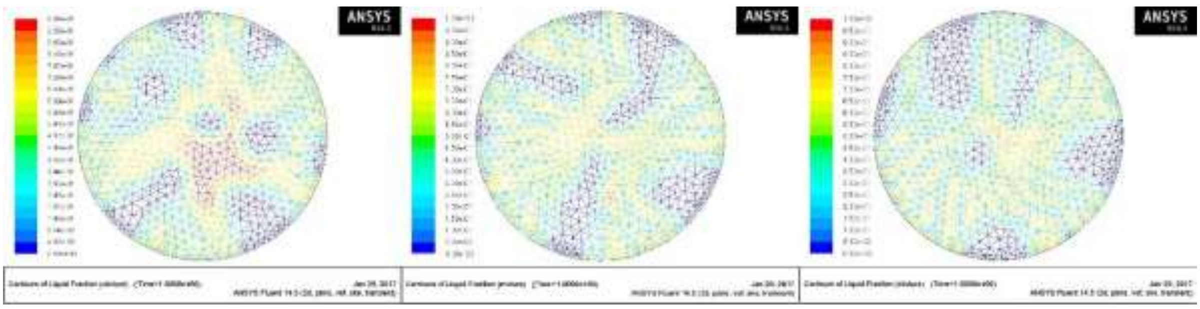


Figure 5 Solidification pattern for rotational speed 150rad/sec and volume fractions (a) 10% (b)

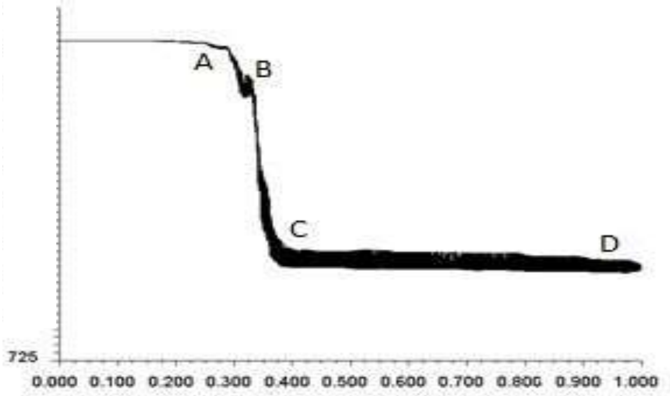


20% (c) 30%.

Figure 6 Solidification pattern for rotational speed 200rad/sec and volume fractions (a) 10% (b) 20% (c) 30%.

To study the effect of process parameters on cooling curve characteristic a typical cooling curve, corresponding 20% volume fraction of SiC, and rotational speed of 150rad/sec is shown in Fig.7. Cooling curve's vertical axis show minimum temperature inside the crucible in degree Kelvin and horizontal axis show the computational flow time in seconds. In all simulation curves obtained there is an initial dip in the curve (point 'A' in Fig.7), which represents nucleation temperature of primary phase. Then it rises to a point 'B' called liquid us arrest temperature. The difference between these two points shows the degree of liquid us under cooling. After liquid us arrest temperature the curve falls to eutectic nucleation temperature followed by eutectic growth temperature (from point 'C' to point 'D'). The information that can be gathered from the study is the extent of under cooling, which provides energy for creation new solid- liquid interface. Larger the extent of under cooling greater will be the number of nucleous formed. Also the area under cooling curve provides information about latent heat released during solidification process.

The various characteristics obtained during numerical simulation of cooling curve analysis are tabulated in TABLE 2. From TABLE 2 it is clear that when rotational speed increases by keeping volume fraction constant solidification and eutectic solidification time are seen delayed. The difference between solidification and eutectic solidification start time is low for 150rpm and 20%reinforcementlevel. So, this cooling curve analysis validates the previous solidification result obtained. The comparison of cooling curves of the composite for different process parameter combinations provides interesting information that may be useful to control composite's behavior during thermal treatment and final microstructure.



Flow time(s)

Figure 7 A typical cooling curve for Al-SiC MMC

Table 2 Cooling Curve Characteristics of Various process parameter combination

Rotational Speed(rad/sec)	Solidification Start time(s)			Eutectic Solidification Start time(s)		
	Volume fraction of reinforcement (%)					
	10%	20%	30%	10%	20%	30%
100	0.100	0.100	0.100	0.200	0.250	0.450
150	0.200	0.250	0.250	0.350	0.350	0.400
200	0.300	0.300	0.350	0.475	0.500	0.550

4. CONCLUSION

The experimental methods to study mushy solidification pattern and cooling curve analysis of centrifugal casting process are difficult and the research towards the same is still being carried out. The present work aims towards developing a simulation method which considers relevant process parameters like rotational speed and volume fraction of reinforcement. Contour plots of mushy state solidification pattern obtained for different simulation cases clearly show the influence of process parameters on solidification rate and distribution of reinforcement particles. Moreover, simulation of cooling curves clearly shows the dependence of process parameters on solidification time. Rotational speed promotes faster solidification rate. But beyond certain speed limit there is a chance for clustering of reinforcement particles. Clustering of reinforcement particles is promoted by increase in volume fraction. Overall the present study establishes the capability of CFD to predict solidification patterns in centrifugal casting process.

REFERENCES

[1] B. Kieback A, A. Neubrand B C, H. Riedel C, Processing techniques for functionally graded materials, Materials Science and Engineering A362, 2003, 81–105.

[2] G. Chirita, D. Soares and F. S. Silva, Advantages of the centrifugal casting technique for the production of structural components with Al–Si alloys‖, Materials and Design, vol.29, 2008, 20–27.

[3] Ebisu Y, Computer simulation on Macrostructure in Centrifugal Castings, AFS Transactions, 1977, 643-655.

[4] Madhusudhan , Narendranath S, and G C Mohan Kumar, Properties of Centrifugal Casting at Different Rotational Speeds of the Die, International Journal of Emerging Technology and Advanced Engineering, Volume 3, Issue 1, 2013, 727-731.

[5] Kestur Sadashivaiah Keerthiprasad, Mysore Seetharam Murali, Pudukottah Gopaliengar Mukunda and Sekhar Majumdar "Numerical Simulation and Cold Modeling experiments on Centrifugal Casting" Metallurgical and Materials Transactions B, Volume 42, Issue 1, 2011, 144-155.

[6] Gao J. W and Wang C. Y, Modeling the Solidification of Functionally Graded Materials by Centrifugal Casting, Material Science and Engineering, A292, 2000, 207-215.

[7] Jan bohacek, Abdellah kharicha, Andreas ludwig and Menghuai W U, Simulation of Horizontal Centrifugal Casting: Mold Filling and Solidification, ISIJ International, Vol. 54 2014, No. 2, 266–274.

[8] R Zagorski and S Golak, Modeling of Solidification of MMC Composites during Gravity Casting Process, Metallurgia 52, 2013, 2, 165- 168.

[9] J George, S Janardhanan andM T Sijo, A Numerical Study on Stir Casting Process in a Metal Matrix Composite Using CFD Approach, Advanced Materials Research, Vol. 1119, 2015, 533-541.

[10] C W Hirt and B D Nichols, Volume of fluid VOF for the dynamics of free boundaries, Journal of Computing Physics, 39, 1981, 201-225.

[11] K Johansson, Numerical Simulation of Fuel Filling with Volume of Fluid Master's Thesis, Chalmers University of Technology Gothenburg, Sweden, 2011.

[12] Vinay Chandran R, Deviprasad Varma P R and Abdul Samad P A, CFD Simulation of Centrifugal Casting of Al-SiC FGM for the Application of Brake Rotor Disc, International Journal of Engineering Trends and Technology, Volume 28, Number 6, 2015, 304-306.

[13] E M Marshall and A Bakker, Computational Fluid Mixing, in Handbook of Industrial Mixing: Science and Practice (eds E L Paul, V A A Obeng and S. M. Kresta), John Wiley & Sons, Inc., Hoboken, NJ, USA, 2003.

[14] Mr. Amol D. Sable, Dr. S. D. Deshmukh, Preparation of Metal-Matrix Composites By Stircasting Method. *International Journal of Mechanical Engineering and Technology*, 3(3), 2012, pp. 404-411.

[15] Jyothi P.N, A. Shailesh Rao, M.C. Jagath and K. Channakeshavalu. Understanding the Melt Flow Behaviour of Za Alloys Processed Through Centrifugal Casting. *International Journal of Mechanical Engineering and Technology*, 4(1), 2013, pp. 163-172.