Simulation analysis of stirring parameters in stir casting of AA7068/VC/B₄C Hybrid metal matrix composite using ANSYS

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Abstract. Aluminium-based metal matrix composites (AMMCs) are the most commonly used MMC in the automotive and aerospace applications, because of its special properties. The better way to produce MMCs is stir casting method. In the solid-liquid mixing vessel, a remarkable effect on the particle distribution is its flow behaviour of the fluid. Therefore to lead the experimental research, simulation analysis is a powerful tool. The complexity of obtaining a uniform mixture is an important obligation in the method of stir casting. The advantage of obtaining equal dispensation inside the matrix is a serious issue that affects the features and nature of the integrated materials. The dispensation of the reinforcing particles inside the matrix is dependent on numerous parameters at the time of casting. Crucible particle distribution that is stirred during stir casting was simulated in this work using ANSYS and validation was done based on the value of suspension quality. The effects of some important stirring process parameters such as impeller blade angle and stirrer speed of the molten matrix were examined to get the better particle distribution. AA7068 was used as the matrix and vanadium carbide (VC) and boron carbide (B₄C) were used as the reinforcements.

1. Introduction
In most cases, material selection is a difficult decision-making task. Sometimes materials with less weight are not physically strong, and soft materials are not strong and bad in resistance to fatigue. For engineering applications, it is not quite practical to obtain a unique material with all essential features. Besides, features of materials are very much influenced in the working condition and the type of application of load. Therefore, nowadays joining of various materials as a mixture or compound is a requirement. And so on can utilize the various beneficial features given by the various materials.

Metal matrix composite is a composite material formed by mixing two constituent parts. One is a metal part (matrix) which is usually a lighter material that provides support to the second part. The second part is of different metal or maybe another material (reinforcements) used to change the physical properties of the composite. Aluminium-based MMCs are the most commonly used MMC in the automotive and aerospace applications [1]. Aluminium-based MMCs, formed by mixing two constituent parts. One of the constituents is an aluminium/aluminium alloy (i.e., Al-Si, Al-Cu, Al-Si-Mg alloys), which is usually a lighter material that provides support to the second part and is termed as matrix phase. The second part is sunk in this matrix called reinforcements. This is of different material or maybe other materials. SiC, Al₂O₃, C, B, B₄C, AlN, BN, etc. are used as reinforcements to change the physical properties of the composite [2]. Homogeneously distribute the reinforcement phases during the manufacturing of composite is very difficult to obtain a defect-free microstructure [3]. Of the various production processes available for metal matrix composites, stir casting is generally accepted.
as a particularly promising route for commercial implementation. Its advantages are its simplicity, flexibility, and applicability to large-scale production [4].

In a stir casting process, the reinforcing phases are distributed into the molten matrix by mechanical stirring. The resulting molten alloy can be utilised for other castings. An important concern related to stir casting is the separation of strengthening particulates that occur due to the appearing or settling of the strengthening particulates at the time of processes like melting and casting. The last dispensation of solid particles depends on the features of materials and operation parameters. They are wet state of molten particles, the strength of the mixture, the relative density, and the solidification rate. The distribution of particles in the molten matrix depends on the geometry of the mechanical stirrer, the stirring parameters, and the position of the mechanical stirrer at melting, the melting temperature, and the characteristics of the added particles [5] [6].

It is very difficult to measure liquid flow behaviour in the liquid-metal process. Due to that, numerous analysis were carried out to study the blending properties within stir casting by the aid of CFD tools. Temperature related fluid analysis for metal matrix composite casting was done to inspect the dispersion of SiC particles in stir casting [7]. With the use of CFD simulation, the capacity of blending was noticed [8]. This affects the pattern of flow in the blending container. By the aid of CFD techniques, test the dispersion of solid particulates within the liquid in the inner part of the stirred tank [9][10]. Both the two phases, matrix phase and solid phase were modelled by multi-phase modelling approach. First liquid and second granular phases were resolved in every unit of the domain. To reach the flow parameters for good homogeneity of particles, flow models can be investigated by the help of CFD simulation.

There is no much studies related to AA7068. In this research, Crucible particle distribution that is stirred during stir casting was simulated using ANSYS. The effects of some important stirring process parameters such as impeller blade angle and stirrer speed of the molten matrix were examined to get the better particle distribution. AA7068 was used as the matrix and VC and $B_4C$ were used as the reinforcements. The grades, doped with $B_4C$ and VC as growth inhibitor exhibits more hardness than other comparable doped alloys [11].

2. Methodology

The mixing system, CFD simulation, modelled system and meshing details are discussed in this section.

2.1 Mixing system

The models have been set as a three-phase fluid flow model. The primary phase fixed as liquid aluminium and the secondary and tertiary phases as $B_4C$ and VC respectively each with the volume fraction of 10%. The particle size of 30$\mu$m was used. The viscosity characteristics of liquid aluminium have been recorded by many researchers as Newtonian with a viscosity rate similar to water, of 1mPaS. The densities of liquid aluminium alloy 7068, boron carbide and vanadium carbide were 2850, 2520 and 5770 kg/m$^3$ respectively.

Physical Dimensions: Internal diameter of the flat-bottomed cylindrical crucible was set at 105 mm and was filled to a level of 65 mm in all tests. The impeller of four flat blades made up of steel with diameter 80 mm, width 10 mm and 2 mm thick blades set at $35^0, 40^0, 45^0$, and $50^0$ angles to the right, was prepared to move vigorously up. From the base of the crucible, the height of the stirrer was 20 mm. The stirrer speeds were set at 200, 300 and 500 rpm.

2.2 CFD simulation

Computational fluid dynamics solvers employ Finite Volume Method, in that the area under discussion is split into a finite number of cells called control volumes. Field of flow is got by resolving equation of conservation of flow i.e., mass, momentum, energy and species etc. Continuity and momentum equations for the first liquid phase and second and third granular phases are resolved for all units in that area.
For getting the solution for governing equations for flow of fluids Eulerian k-ε dispersed turbulence model is implemented. This is a multi-phase model. Where the interphase momentum interchange in the middle of two scattered phases has been developed by Syamlal–Obrien-symmetric drag force model. At the same time, Gidaspow drag force model has used for continuous and scattered phases. Changes regarding the transfer of mass caused by cavitation, virtual mass force, lift force, evaporation, condensation, boiling etc. are not evaluated. For resolving the governing equations regarding the flow of fluid ANSYS software is used. In that CFD code of Fluent 16.0 module, which is based on finite volume code is utilised.

2.2.1. Governing Equations. The governing equations for both fluid phase and particulate phase of continuity and momentum are resolved in every unit of the area [7]. The governing equations for the liquid phase and granular phases are the followings

The continuity equation is:
\[
\frac{\partial}{\partial t} (\alpha_l \rho_l) + \nabla \cdot (\alpha_l \rho_l v_l) = 0 \tag{1}
\]

The momentum equation is:
\[
\frac{\partial}{\partial t} (\alpha_l \rho_l v_l) + \nabla \cdot (\alpha_l \rho_l v_l v_l) = -\alpha_l \nabla p + \nabla \cdot (\alpha_l \mu_l \nabla v_l) + F_l + K_{sl}(v_s - v_l) \tag{3}
\]

Where \( \alpha \) - the volume fraction, \( v \) - velocity and \( p \) - pressure. \( l \) and \( s \) stand for the liquid phase and solid phase respectively, and \( \tau_{ls} \) is the stress-strain tensor of phases, that is given by:
\[
\tau_{ls} = \alpha_l \mu_l \left[ (\nabla v_{ls} + \nabla v_{ls}^T) - \frac{2}{3} \nabla \cdot v_{ls} \right] \tag{5}
\]

The volume fraction of the liquid phase and particulate phase is governed by the equation:
\[
\alpha_l + \alpha_s = 1 \tag{6}
\]

Coefficient of momentum exchange is determined using Gidaspow model by with WEN and YU model and Ergun equation (Tamayol 2008).
\[
K_{sl} = K_{sl} = \frac{3}{4} \frac{\alpha_l \alpha_s \mu_l}{d_s} - 2.65 \tag{7}
\]

\[
C_d = \frac{24}{R_{e_s}} \left[ 1 + 0.15 (\alpha_l R_{e_s})^{0.687} \right] \tag{8}
\]

\[
R_{e_s} = \frac{P_{d_s} |v_s - v_l|}{\mu_l} \tag{9}
\]

Where \( C_d \) - drag coefficient, \( d_s \) - diameter of the particulate phase.

2.2.2. Turbulence Modelling Equations. The flow of fluid in the blending container is move in a twisting or spiralling pattern. So flow model RNG k-ε turbulence that makes good solutions is used for resolving the turbulence equations. The issue of twisting or spiralling of turbulence to increase the precision of flow manner is contained in the model [7]. The controlling equations for turbulent kinetic energy (k) and its energy dissipation rate (\( \varepsilon \)) are shown below.

\[
\frac{\partial}{\partial t} (k) + \frac{\partial}{\partial x_i} (k u_i) = \frac{\partial}{\partial x_i} \left[ \alpha_k \mu_k \frac{\partial k}{\partial x_i} \right] - \rho \mu_k \frac{\partial u_i}{\partial x_i} - \rho \varepsilon \tag{10}
\]

\[
\frac{\partial}{\partial t} (\varepsilon) + \frac{\partial}{\partial x_i} (\varepsilon u_i) = \frac{\partial}{\partial x_i} \left[ \alpha_k \mu_k \frac{\partial \varepsilon}{\partial x_i} \right] - C_{1e} \frac{\varepsilon}{k} \rho \mu_k \frac{\partial u_i}{\partial x_i} - C_{2e} \frac{\varepsilon^2}{k} - R_e \tag{11}
\]

The effective viscosity (\( \mu_\varepsilon \)) by considering the effect of swirl is:
\[
\mu_\varepsilon = \rho C_\mu \frac{k^2}{\varepsilon} f(\alpha_s, \Omega_\varepsilon) \tag{12}
\]

\[
R_e = \frac{C_\rho \rho^{\eta^3}(1-\eta \eta_0) \varepsilon^2}{k} \tag{13}
\]

The closure coefficients are: \( \alpha_k = 1.393, \alpha_s = 1.393, C_\mu = 0.0845, \alpha_\varepsilon = 0.07, \eta_0 = 4.38, \beta = 0.012 \).

\( \eta = \hat{S} k/\varepsilon \), where, \( \hat{S} \) - the modulus of the mean rate-of-strain tensor that is \( \hat{S} = (2s_{ij} s_{ij})^{1/2} \). where \( s_{ij} \) is the rate-of-strain tensor.
\[ S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]

(14)

\( \Omega \)- characteristic swirl number, \( C_{1 \varepsilon} = 1.42 \) and \( C_{2 \varepsilon} = 1.68 \) are constants of the model.

2.3 Modelled system

Figure 2.1. System with different impeller blade angles a) 35° b) 40° c) 45° d) 50°

3. Results and discussion

3.1 Model validation

The blending operation of different types of systems (solid and liquid or solid, solid and liquid) inside the stirring tank is determined by the existing suspension quality [10]. In 1980 Bohnet and Niesmak put forward about suspension quality that was divided as homogeneous suspension, just suspension and incomplete suspension based on the rate of standard deviation \( S \) of solid phase’s concentration. \( S \) is denoted as

\[ S = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( \frac{\alpha_{sl}}{\alpha_{s,avg}} - 1 \right)^2} \]

(15)

Here \( n \) - number of testing positions to take the measurements of solid phase’s local holdup, \( \alpha_{sl} \)-local volumetric concentration and \( \alpha_{s,avg} \)-mean volumetric concentration.

If \( S \) less than 0.2 that is a homogeneous suspension. If \( S \) is in between 0.2 and 0.8 then it is just suspension and if the value of \( S \) is greater than 0.8 it is the incomplete suspension. In this, the value of standard deviation \( S \) of \( B_4 \)C and VC in secondary and tertiary phases on different working context is calculated in the basis of \( \alpha_s \) collected in all computational units.

Conducted the mesh grid independent study. Richardson’s extrapolation method was used. CFD simulation was done with a grid refinement factor greater than 1.3. Tetrahedral cells were used and a monotonic convergence of the flow parameters were obtained. Standard deviation were got by
extrapolating the values set on from the simulation models. The grid convergence values were less than 5%. From this CFD simulation is grid independent.

3.2 Evaluation of suspension quality

![Figure 3.1. Standard deviation value of phase two](image)

![Figure 3.2. Standard deviation value of phase three](image)

The standard deviation rates obtained for both phase two and phase three shown in Fig. 3.1 and 3.2 are very much lower than 0.2 demonstrating homogeneous suspension. Value of standard deviation nearer to zero gives good particulate mixing of the systems. The Speed value of the impeller become greater, the value of the solid phase’s standard deviations become smaller. In a similar working context VC have greater standard deviation (suspension quality) compared to $B_4C$. 
3.3 Distribution of $B_4C$ and VC particulates

In the blending container contours of volume fraction after blending is given in Fig. 3.3 and 3.4. The velocity distribution contour of $B_4C$ and VC particulates are shown in Fig.3.5 and 3.6. The $B_4C$ and VC particles with 10 volume percentage the entire area were put a patch prior to the initiation of the steady-state simulation. The velocity contour and volume fraction contour of $B_4C$ and VC particles with different impeller blade angle and stirrer speed were evaluated. If the speed became greater, then the value of mixing became greater too. For best uniform particles suspension, the volume fraction of the $B_4C$ and VC particles should be 0.1 all over the inner side of the fluid domain. From different contours obtained for volume fraction and velocity, it is clear that blending is very slow close to the centre of the tank when we examine the portion close to walls.
4. Conclusions
The quality of aluminium-based MMC’s produced through stir casting process extremely depends upon the selection of processing parameters. The flow patterns obtained from the numerical simulation assist the engineers in the proper selection of these parameters. Value of standard deviation nearer to zero gives good particulate mixing of the systems. The Speed value of the impeller become greater, the value of the solid phase’s standard deviations become smaller. In a similar working context VC have greater standard deviation (suspension quality) compared to \( B_4 \)C. Low blade angle and high rotating speed of the stirrer is found to be beneficial in attaining MMC with uniform distribution of particles. A perfect stirrer speed is needed to avoid the gas entrapment which is occurred due to the extra turbulence nearer to the liquid level. The shearing action transmitted from the revolving blades avoid the particle agglomeration and confirm homogeneous suspension of particles in the melt. Hence, an increase in stirrer speed enhances axial flow (i.e. particle penetration depth) and lower blade angle accelerates the dispersion rate of reinforcements. An MMC developed by stir casting with processing parameters of 35° stirrer blade angle and stirring speed of 500 rpm is found to produce a uniform distribution of reinforcement particles in the base aluminium alloy matrix.

Only two stirring parameters were simulated in this study. Therefore uniform particle distribution still requires the study of numerous stirring parameters. Also, experimental studies may be carried out to determine the casting quality.

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