Archives of Materials Science and Engineering
Volume 28
Issue 7
July 2007
Pages 441-444
International Scientific Journal
published monthly as the organ of
the Committee of Materials Science
of the Polish Academy of Sciences

Pouring mould during centrifugal casting process

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Received 25.04.2007; published in revised form 01.07.2007

ABSTRACT

Purpose: The paper presents the model and the example simulations of the centrifugal casting of metal matrix composite reinforced with SiC, especially the distribution of the velocity of liquid composite for the initial stage of pouring the mould (up to 1s).

Design/methodology/approach: Numerical simulations have been performed using the CFD program FLUENT 6.1.To simulate pouring the mould, axisymmetric swirl model has been applied. To model the air-matrix free surface (and also volume fraction of particular continuous phases) and dispersed phase, Volume of Fluid approach (VOF) and Discrete Phase Model (DPM) have been used, respectively. The turbulent flow of the fluid has been simulated by the standard k-ε model of turbulence.

Findings: The results show that the behaviour of composite in pouring process depends strongly on the existence of reinforcement and process parameters and the initial stage of the casting can probably have an influence on the segregation and various final distribution of reinforcement particles.

Research limitations/implications: The implemented simulational scheme can be used to study the behaviour of liquid composite during casting and the final simulational structure of composite should be verified experimentally.

Practical implications: The simulation by CFD program (Fluent) can be treated as an attractive and useful tool for modelling centrifugal casting process of metal matrix composite reinforced by ceramic particles. The created model and procedures can be come the basis for more advanced researches.

Originality/value: The development of CFD program and the computer technology allow to study even complicated problems. Hence, we have implemented the CFD program to simulate the centrifugal casing of composite.

Keywords: Casting; Centrifugal casting process; Metal matrix composite; CFD simulations

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Nowadays we observe the great interest in both experimental and theoretical investigations of a new type material like metal matrix composite reinforced with ceramic particles. The special physical properties of metal matrix composites cause that this materials have application in many domain of industry, e.g. motor industry.

There are a lot of methods of obtaining metal matrix composite. One of them is centrifugal casting. The characteristic feature of composites produced in centrifugal casting is heterogeneous structure, i.e. during the process, due to gradient of densities of liquid matrix and reinforcement, the segregation of particles is occurred. It is this segregation of particles which has significant influence on properties of the composite.

There are many experimental researches that concern a lot of problems connected with obtaining the metal matrix composite

[1-7]. As was mentioned earlier we focus on the centrifugal casting. The experimental data indicates that there are many parameters which have an influence on the centrifugal casting, such as: pouring temperature, initial temperature of the mould, rotating speed and size of the mould, time of pouring the mould, composition of the composite, type, diameter and shape of particles and others.

The mathematical description of centrifugal casting is very difficult because of a lot of parameters mentioned above and appearing processes e.g. thermal, hydrodynamic, solidification, segregation of particles. These processes affect each other. Moreover, the existence of solid particles has additional influence on the behaviour of the composite during the process and complicate the mathematical description. At present there exist theories which, more or less precisely, describe the behaviour of the composite in the centrifugal casting process [8-13]. The description presented by them is often incomplete and refers only to some chosen elements of the process.

In this paper we present computational simulations of centrifugal casting of aluminum matrix composite reinforced with SiC particles at the initial stage of the pouring process, i.e. up to 1s. These simulations have been carried out based on procedures and scheme included in the program Fluent 6.1 [14].

2. Theory

2.1. Theoretical model

In the considered system there exist two continuous phases: air and liquid matrix with dispersed particles of reinforcement. The axisymmetric swirl model (included in program Fluent) is applied to simulate the real system. This approach allows to study the flow in 2D and includes the prediction of the circumferential (or swirl) velocity. The tangential momentum equation for 2D swirling flows may be written as

$$\frac{\partial}{\partial t}(\rho w)+\frac{1}{r}\frac{\partial}{\partial x}(r\rho u w)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho \upsilon w)= \frac{1}{r}\frac{\partial}{\partial x}\left[r\mu\frac{\partial w}{\partial x}\right]+\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^3\mu\frac{\partial}{\partial r}\left(\frac{w}{r}\right)\right]-\rho\frac{\upsilon w}{r} \tag{1}$$

where x is the axial coordinate, r is the radial coordinate, u is the axial velocity, υ is the radial velocity, w is the swirl velocity, ρ is the density of fluid, and μ is the viscosity of the fluid. The idea of model is shown in Figure 1.

To model the air-matrix free surface and volume fraction of particular continuous phases we have applied Volume of Fluid approach (VOF). To simulation of turbulent flow we have introduced standard k-ε model of turbulence. In order to calculate the change of particle location and velocity we have implemented Discrete Phase Model (DPM). The theories: VOF, k-ε model and DPM are also included in program Fluent [14]. In the model particles interact with the continuous phase by a set of laws which describe the transfer of momentum, heat and mass [14].

The trajectories of individual particles can be treated by balancing the forcers acting on them: $F = F_g + F_b + F_c + F_d$, where: F_d is the drag force equals:

$$F_d = \frac{18\mu}{\rho_p d_p^2}\frac{C_D \, Re}{24} \tag{2}$$

where: u_p is the particle velocity, ρ_p is the density of the particle, and d_p is the particle diameter, Re is the relative Reynolds number and C_D is the drag coefficient which is calculated by Morsi & Alexander methods [15]. F_g is gravitational force equals: $F_g = g_x \rho_p V_p$, where: g_x is gravitational acceleration, V_d is volume of particles. F_b is buoyancy force equals: $F_b = g_x \rho V_p$. F_c is centrifugal force equals: $F_c = \rho_p V_p \omega^2 r$, where ω is angular velocity.

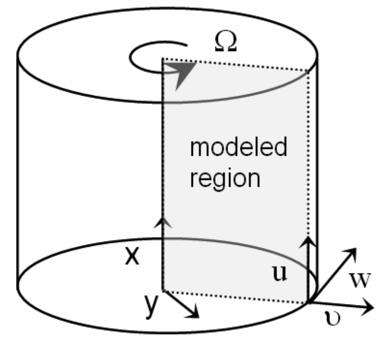

Fig. 1. The axisymmetric swirl model with modeled area and directories of component velocity.

Generally, the centrifugal force is greater than the others and has a crucial influence on the behaviour of the liquid composite and the distribution of the velocity.

The existence of big amount of the dispersed phase causes that its particles may interact with one another. We have assumed the possibility of collisions of particles. In this purpose we have used standard procedure included in program Fluent. Moreover, the interactions between particles cause the decrease of velocity value of the liquid matrix. This effect influences the viscosity of the liquid matrix and can be expressed as [11]:

$$\mu_{pop} = \mu\left(1 + 2.5V_f + 7.6V_f^2\right) \tag{3}$$

where: V_f is the volume fraction of particles.

In order to simulate solidification we have used very simply model which is based on the assumption that as the liquid cools and rapidly becomes more viscous, its velocity will decrease. Hence, we have assumed linear dependence of viscosity vs. temperature in the range between liquidus and solidus temperature. The matrix heat capacity and density we have defined in the same manner.

To calculate the exchange the heat, we have applied standard procedures and boundary conditions proposed by Fluent, i.e. on the outside wall of the mould we have assumed constant value of temperature (constant temperature in the thermostat), on the inside wall of the mould we establish the condition of equality of temperature.

2.2. Simulational domain

With respect to symmetry of the real system of centrifugal casting, we have prepared the model in which only the half of it is taken into account. The simulation model consists of several significant parts: external and internal walls of the steel mould, funnel for pouring the liquid composite and the pressure-inlet and mass-flow-inlet which are located at the top. We assume that liquid matrix of composite is introduced to the mould by mass-flow-inlet with fixed value of mass flow rate. The spherical particles of reinforcement are injected into the liquid matrix as a surface at the mass-flow-inlet with fixed total flow rate scaled by face are (area of mass-flow-inlet) to ensure the even distribution of reinforcement particles.

3. Result and discussions

In order to calculate the distribution of the velocities and volume fraction of the composite we have carried out several simulations for aluminium matrix composite reinforced with SiC and for aluminium matrix without reinforcement. Now, we consider the cases in which we have assumed the following values of the simulation parameters: rotating speed of mould 1200 rpm, pouring temperature of liquid composite 725ºC, initial temperature of the mould 240ºC, mass flow rote of matrix composite 0,8kg/s, temperature on the outside wall of the mould 240ºC, total mass of metal matrix about 0,7kg, volume fraction of reinforcement (spherical particles SiC) 5% (0,035kg), diameter of particles 40μm, the inside-outside diameters and height of the mould 0,06m, 0,08m and 0,12m, respectively. The parameters of the matrix composite (composite A356) equal: density 2380 – 2700 kg/m^3 (liquid and solid), heat capacity 870 – 1180 J/kg·K, thermal conductivity 73 – 151 W/m·K, viscosity 1,5 – $2{,}5\times10^{-3}$Pa·s, solidus temperature 580ºC, liquidus temperature 620ºC [11]. The values of density, heat capacity, thermal conductivity and viscosity for matrix of composite refer to liquidus and solidus temperature, respectively. The parameters of SiC equal: density 3230 kg/m^3, heat capacity 630 J/kg·K, thermal conductivity 0,32 W/m·K [11]. The parameters of steel mould equal: density 8030 kg/m^3, heat capacity 502,48 J/kg·K, thermal conductivity 16,27 W/m·K (database of Fluent [14]).

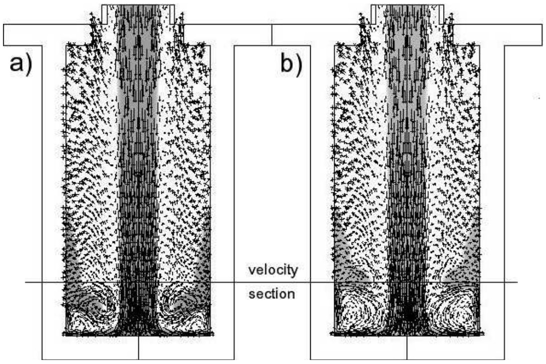

Fig. 2. The magnitude velocity distribution for matrix composite without SiC (part a) and for composite with SiC (part b) after 0,21s, grey colour refers to volume fraction of matrix composite

All simulations we have started from the initial state in which there is only one phase (air) and the field of temperature and velocity are known. The initial state has been prepared during time-independent steady simulations in which only flow, swirl velocity, turbulence and energy equations have been solved.

In the main time-dependent simulations the second phase (liquid matrix) have been introduced into the mould by mass-flow-inlet. and the volume fraction equation has additionally been solved.

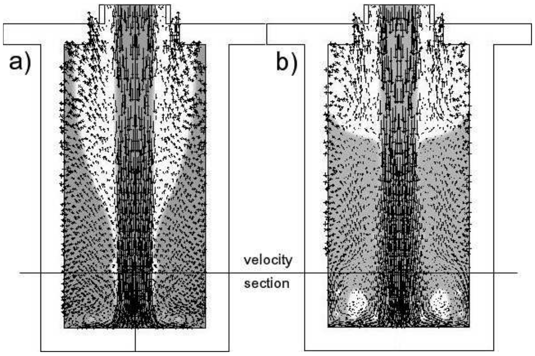

Fig. 3. Like in Figure 2 but after 0,7s

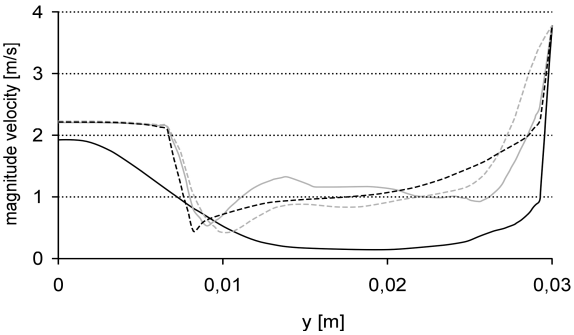

Fig. 4. The magnitude velocity for matrix composite without SiC (dotted line) and composite (continuous line) after 0,21s (grey line) and after 0,7s (black line)

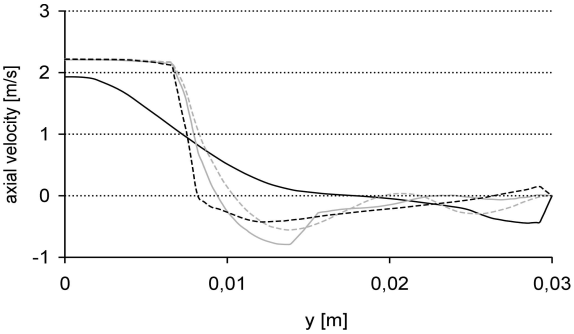

Fig. 5 The axial velocity – description like in Fig. 4

The particles of SiC have been injected at the same place as a surface. Then mass of composite has achieved about 0,7 kg, the mass-flow-inlet has been changed into pressure-inlet – the introduction of composite has been finished.

First, the liquid composite, introduced by mass-flow-inlet, under influence of gravity, moves down. At the moment when liquid composite achieves the bottom of the mould, under the influence of centrifugal force caused by the rotating mould, the composite is moved to the wall of the mould and next goes up. At the Figure 2 and 3 we present the velocity distribution for the matrix composite without reinforcement (part a) and for the composite (part b) after 0,21s and 0,7s, respectively.

The Figures show that the significant differences occur in the behaviour of the matrix composite without SiC and the composite.

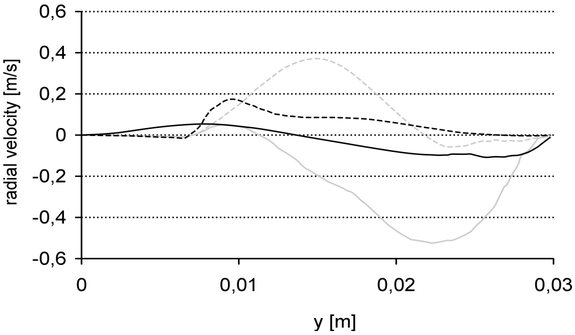

Fig. 6 The radial velocity – description like in Fig. 4

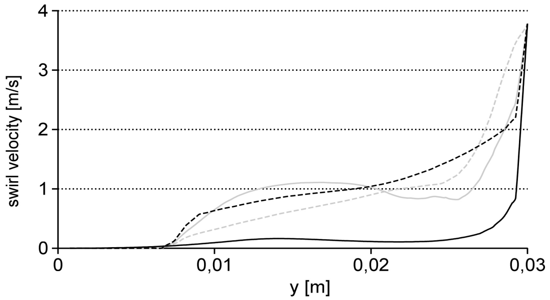

Fig. 7 The swirl velocity – description like in Fig. 4

The liquid composite matrix due to less viscosity goes up faster and spreads over the wall of the mould. The composite behaves differently. This difference seems to be caused by the existence of the reinforcement particles which increase the liquid matrix viscosity and make the flow difficult.

At the Figures 4, 5, 6 and 7 we present the distribution of magnitude, axial, radial and swirl velocity for the matrix composite without SiC and for the composite after 0,21s and 0,7s in the place shown at Figures 2 and 3. We see that the most significant differences occur in distribution of swirl and radial velocity, i.e. the value of swirl component velocity for the composite is less compared with the matrix composite without SiC, however the value of radial component velocity is greater. This effect, at the considered range of time process, is getting more visible as long as the time of pouring process is carried out.

4. Conclusions

The considered examples of simulation indicate that CFD program (Fluent) can be treated as an attractive and useful tool for modelling centrifugal casting process of metal matrix composite reinforced by ceramic particles. The created model and procedures can be come the basis for more advanced researches.

The simulations show that the behaviour of composite in pouring process depends strongly on the existence of reinforcement and process parameters. We can also affirm that observed behaviour of composite during the initial stage of the casting can probably have an influence on the segregation and various final distribution of the particles. It is obviously recommended to verify the simulational results experimentally. However, there are experiments which confirm simulational results connected with final distribution of particles [7].

Acknowledgements

The present work is supported by the Ministry of Science and Higher Education grant 3 T08B 044 28.

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