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COMPUTATIONAL MODELING OF CENTRIFUGAL CASTING OF ALUMINA MATRIX COMPOSITE REINFORCED WITH CRYSTALLINE PARTICLES

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Abstract

The centrifugal casting of alumina matrix composite reinforced with crystalline particles (SiC) are studied. The influence of cast process parameters like pouring temperature, temperature, rotating speed and size of casting mould on structure of composite are examined. During centrifugal casting of alloys containing dispersed particles of crystalline, particles move under influence of centrifugal force and segregate. Numerical simulations are performed using the FLUENT two-phase free surface (air and matrix) unsteady flow model (volume of fluid model – VOF) and discrete phase model (DPM).

Key words: centrifugal casting, alumina matrix composite, computational fluid dynamic CFD

1. INTRODUCTION

The centrifugal casting is one of many methods of obtaining alumina matrix composite reinforced with crystalline particles. In our case we take into account composite A356 reinforced by SiC. In the process of casting the solid particles are segregated due to the centrifugal force. This segregation depends on other factors such as: the gradient of density of the liquid matrix and reinforcement, thermal processes connected with solidifying of the cast, processes leading to changes in physical properties of liquid composite. Mathematical description of the casting is difficult because of a nonlinear character of phenomena which take place during the process.

A very important problem is connected with the possible prediction of the behaviour of solid particles in casting, i.e. movement and segregation due to external forces (centrifugal, gravitational or buoyancy forces).

At present there exist a lot of theories trying to describe the behaviour of the composite in the centrifugal casting process. Many current mathematical models of centrifugal casting neglect the influence of gravity (much weaker than centrifugal force). Some models assume a constant velocity of solidification of the composite (Liu et al., 1996), the lack of interaction between solid particles and liquid metal (Kang et al., 1994, Lajoye & Suery, 1988). There is also a model considered by Hartin et al. (1992) which establishes a relation between the movement of particles and viscosity of composite suspension for the direct solidification. Another model proposed by Sobczyk (2001) includes a theoretical description of the temperature and pressure fields appearing due to rotating of liquid suspension and it also includes the description of the motion of reinforcement particles under: centrifugal, gravitational, drag (Stokes's force), hydrostatic buoyancy and Corliolis's forces. A theory developed by Panda el al. (2006) describes

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the impact of solid-liquid interface displacement on the distribution of reinforcement phase. There are not many trials modeling the whole process, i.e. from the moment of filling up the mould to the final solidification of the composite.

The mathematical description of casting process is very complicated for it requires many parameters, such as: pouring temperature, initial temperature of the mould, rotating speed, time of filling up the mould, composition of the composite (percentage of reinforcement particles), kind, diameter and shape of reinforcement particles, size of the mould and others.

This paper can be treated as an introductory description to the project on the modeling process of centrifugal casting of alumina matrix composite reinforced with crystalline particles with the application of modern computer techniques called Computational Fluid Dynamics (CFD). In this case we apply commercial program Fluent 6.1. This program contains the set of ready-made procedures of solving basic problems linked with fluid mechanics and it allows to add external algorithms in the form of user-defined functions (UDFs).

2. NUMERICAL APPROACHES AND IMPLEMENTATIONS

Composites can be considered as a continuous system with dispersed solid phase. In the modeled system there exist two continuous immiscible phases: air and liquid matrix and dispersed particles of reinforcement. To simulate a real system of centrifugal casting of composite (showed in subset (a) and (b) in figure 1) we use two-dimensional model especially dedicated to solving rotating and swirling problems. This axisymmetric swirl model 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

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

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.

To model the air-matrix free surface and volume fraction of particular continuous phases we apply Volume of Fluid approach (VOF). This approach allows to introduce the surface tension between phases and the wall adhesion of fluid on solid surface. The parameters of the process, especially a very high value of rotating speed of the mould, cause that we do not exclude the appearance of turbulent flow of the fluid. Hence, we apply standard k-ε model of turbulence.

As it was mentioned earlier, the reinforcement phase consists of solid particles of crystallite (SiC). In our investigations we assume spherical shape of particles. The motion of particles in fluid can be described in a Lagrangian way by solving a set of ordinary differential equations along the trajectory. In order to calculate the change of particle location and velocity we implement Discrete Phase Model (DPM). The fluid phase in which the reinforcement particles are immersed is treated as a carrier phase in a Eulerian frame. In principle, we neglect particle-particle interaction but we take into consideration the blocked volume which is occupied by particle. Trajectories of individual particles can be treated by balancing the forcers acting on them:

$$F=F_g+F_b+F_c+F_d \quad (2)$$

where: F_d is drag force (discussed below), F_g is gravitational force equals:

$$F_g=g_x\rho_p V_p \quad (3)$$

F_b is buoyancy force equals:

$$F_b=-g_x\rho V_p F_b \quad (4)$$

and F_c is centrifugal force equals:

$$F_c=\rho_p V_p \omega^2 r \quad (5)$$

where ρ_p and V_p are the density and volume of solid particles respectively, ρ is the fluid density, ω is angular velocity. Generally, the centrifugal force is greater then the other. So, for inertia particles we can write a following equation for the force balance (for the x direction in Cartesian coordinates):

$$\frac{du_p}{dt}=F_d(u-u_p)+\frac{g_x(\rho_p-\rho)}{\rho_p}+F_x \quad (6)$$

where u_p is velocity of particle, F_x are other external forces (i.e. centrifugal force), $F_d\,(u-u_p)$ is the drag force per unit particle mass and

$$F_d=\frac{18\mu}{\rho_p d_p^2}\frac{C_D\,\mathrm{Re}}{24} \quad (7)$$

where, u is the fluid phase velocity, u_p is the particle velocity, μ is the molecular viscosity of the fluid, ρ is the fluid density, ρ_p is the density of the particle, and d_p is the particle diameter, g_x gravitational acceleration. Re is the relative Reynolds number, which is defined as

$$\mathrm{Re} \equiv \frac{\rho d_p \left| u_p - u \right|}{\mu} \tag{8}$$

The drag coefficient C_D can be found in number of means either basing on theoretical approaches, e.g. methods by Morsi & Alexander (1972), or experimental investigations. For this dependence Clift et al. (1978) identify several regions which are associated with the flow characteristics around the sphere. For the small Reynolds numbers ($\mathrm{Re} < 0{,}5$) viscous effects are dominating and separation is not observed. In this region, often referred to as the Stokes-regime, the analytic solution for drag coefficient is:

$$C_D = \frac{24}{\mathrm{Re}} \tag{9}$$

For intermediate values of Reynolds number ($0{,}5 < \mathrm{Re} < 1000$) the inertial effects become of significant importance and to count a value of drag coefficient such an expression is very often applied:

$$C_D = \frac{24}{\mathrm{Re}}\left(1 + 0{,}15\,\mathrm{Re}^{0{,}687}\right) \tag{10}$$

Above $\mathrm{Re} \approx 1000$ the drag coefficient remains almost constant up to the critical Reynolds number. This region is referred to as Newton-regime with $C_D \approx 0{,}44$.

In our investigations we assume that particles interact with the continuous phase by a number of laws which describe the transfer of momentum, heat and mass. To take into consideration this transfer we establish the impact on each other. Such two-way coupling means that a extra level of interactions is required in the solution process.

The momentum exchange appears as a momentum sink in the continuous phase momentum balance in any subsequent calculations of the continuous phase flow field. This momentum change is computed as

$$F = \sum \left(\frac{18\mu}{\rho_p d_p^2} \frac{C_D \,\mathrm{Re}}{24} (u_p - u) + F_{\text{other}} \right) \dot{m}_p \Delta t \tag{11}$$

where $\dot{m}_p$ is mass flow rate of the particles, Δt is time step and F_{other} are other interaction forces.

Fluent allows to simulate the heat transfer within each fluid and solid phases and also on the interfaces between them. The heat transfer is depended on the conductivity individual phases and thermal boundary conditions. In order to calculate the exchange in heat we apply standard procedures and boundary conditions proposed by Fluent. The heat transfer from the continuous phase to the discrete phase is computed in Fluent by examining the change in thermal energy of a particle as it passes through each control volume in the Fluent model.

The time solidification process of liquid composite depends on a number of parameters like: pouring temperature, mould temperature (to avoid thermal shock of the mold), conductivity of liquid and solid matrix, conductivity of reinforcement, heat transfer of a matrix-mould interface. In order to simulate solidification we use very easy model which is based on the assumption that as the liquid cools and rapidly becomes more viscous, its velocity will decrease. Hence, the viscosity of matrix can be treated as the function of temperature. We assume linear dependence of viscosity *vs.* temperature in the range between liquidus and solidus temperature. The matrix heat capacity and density we define in the same manner.

3. SIMULATIONAL SYSTEM

The 2D simulation domain of centrifugal casting of composite is shown in figure 1. However, the computational domain has been considered as close as possible to the practical situation. This is the typical axisymmetric problem which can be solved by Fluent. Hence, with respect to symmetry of the real system it is enough to prepare only the half of them. The simulation model consists of several significant parts: external steel cover with funnel for pouring, steel stand on which steel mould is installed. The pressure inlet and mass flow inlet are located at the top and pressure outlet at the bottom, as shown in figure 1. There are two rotating parts, i.e. the mould and the stand.

To our purpose, we discretize domain in Gambit using unstructured triangular mash. In the regions, where necessary, the mash is thickened, i.e. near the rotating walls and inside the mould. In these regions the large velocity gradient occurs. So, it is needed to ensure the stability of the time-step scheme.

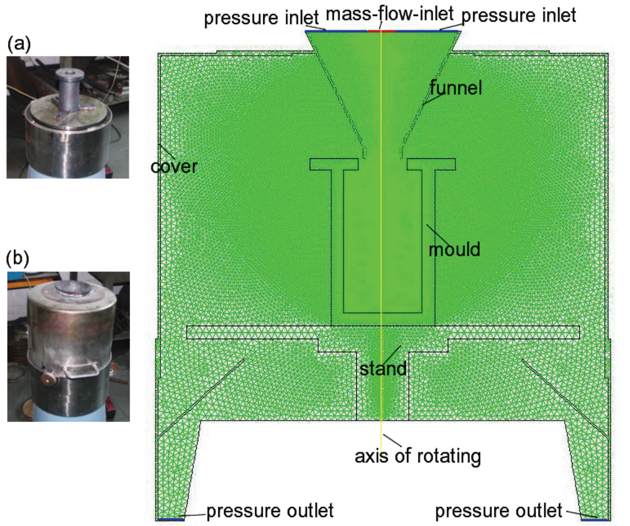

Fig. 1. *The 2D simulation domain of centrifugal casting of composite. Subsets (a) and (b) shows real view of system.*

Table 1. *Theromphysical properties of composite matrix, reinforcement and mould material.*

Parameters	Value
Composite Matrix	
density (liquid and solid) ρ	2380 – 2700 kg/m^3
heat capacity C_p	870 – 1180 J/kg·K
thermal conductivity λ	73 – 151 W/m·K
viscosity μ	1,5 – 2,5×10^{-3}Pa·s
solidus temperature T_{solidus}	580ºC
liquidus temperature T_{liquidus}	620ºC
Reinforcement (SiC)	
density ρ_{p}	3230 kg/m^3
heat capacity $C_{p,\text{p}}$	630 J/kg·K
thermal conductivity λ_{p}	0,32 W/m·K
Mould Material (steel)	
density ρ_{m}	8030 kg/m^3
heat capacity $C_{p,\text{m}}$	502,48 J/kg·K
thermal conductivity λ_{m}	16,27 W/m·K

4. RESULTS AND DISCUSSION

To test our model and to check its usefulness in more advanced studies, we have carried out several simulations. Now, we consider one case in which we assume following values of the simulation parameters: rotating speed of mould 1200 rpm, pouring temperature of liquid composite and temperature of reinforcement particle 720ºC, initial temperature of the mould 420ºC, mass flow rote 0,6kg/s, temperature outside the cover 26ºC, total mass of metal matrix 0,449kg, volume fraction of reinforcement (spherical particles SiC) 2% (0,011kg), diameter of particles 100μm (there is about 7,2×10^6 particles in whole 3D volume – in 2D simulation is needed about 3100 particles), the inside-outside diameters and height of the mould 0,06m, 0,08m and 0,11m, respectively, surface tension air-matrix interface 0,74 N/m, contact angle 120º, time-step 0,0001s. The other parameters are collected in the table 1.

Our calculations can be divided into two significant parts. In the first steady part we solve only energy equations in order to obtain temperature field. This solution can be treated as the initial state for the next simulations. During the second much longer time-dependent part all equations are solved. i.e. flow, swirl velocity, volume fraction, turbulence and energy. Liquid composite matrix is introduced by mass-flow-inlet located at the top of the system. The particles of reinforcement are injected at the same place as a surface. Then mass of composite achieves 0,449kg, introduction of liquid composite and injection of reinforcement is stopped by changing mass-flow-inlet into pressure inlet.

In the beginning, we would like to discuss the behaviour of liquid composite pouring into the system. Figures 2, 3, 4 and 5 show volume fraction of composite with dispersed reinforcement phase for selected time sequences (0,6s, 1s, 2s, 3s). Right subsets present fraction of solidified composite, respectively.

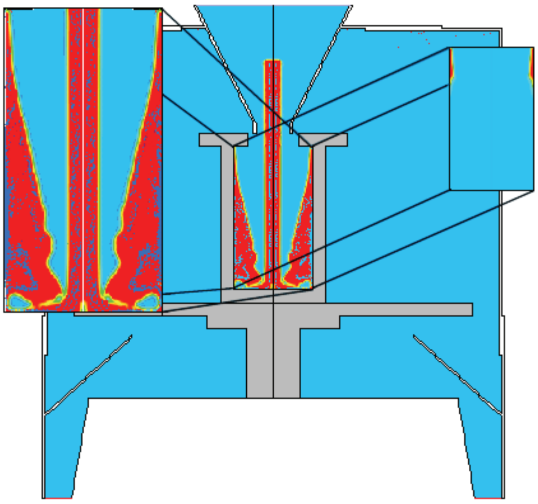

Fig. 2. *Volume fraction of composite (red) with dispersed reinforcement phase (dark blue) and at right subsets fraction solidified composite after 0,6 s.*

First, the composite flows down, at the point of contact with the bottom of the mould and under the influence of centrifugal force caused by the rotating mould, liquid composite is moved to the wall of the mould and next goes up – figure 2 and 3. At the final moment, liquid fluid is distributed on the wall formulating a tube – figure 4 and 5. The thickness of the tube (approximately 0,01m) is different at the top and the bottom. This is an effect of the influence of gravity. There are also well visible effects due to surface tension along air-composite matrix interface and wall adhesion in the form of the meniscus.

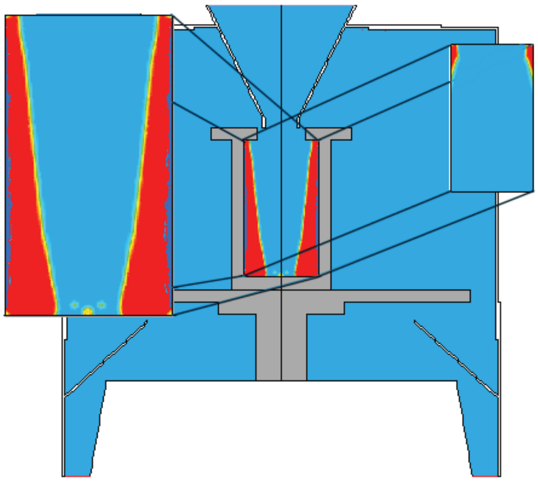

Fig. 3. As above in figure 2 but after 1 s.

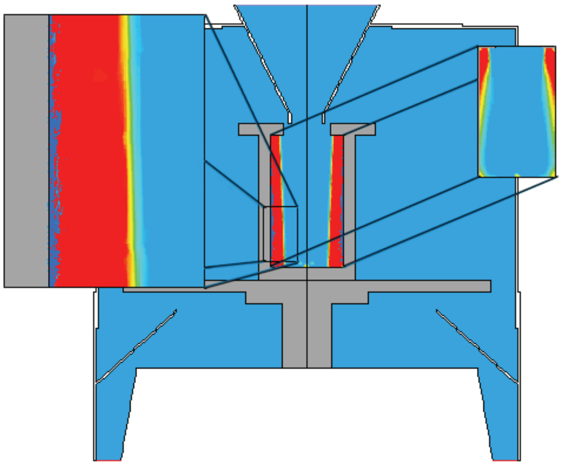

Fig. 4. As above in figure 2 but after 2 s.

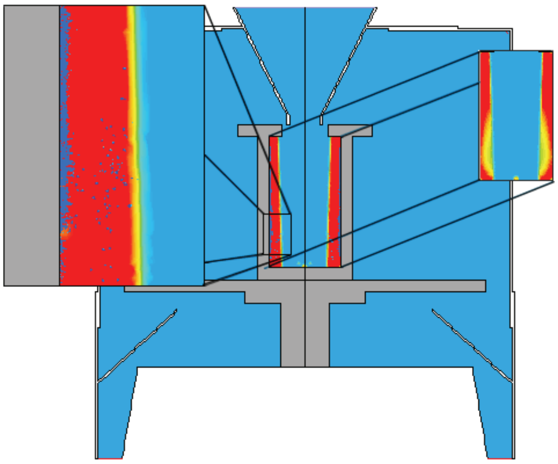

Fig. 5. As above in figure 2 but after 3 s.

To consider the behaviour of reinforcement particles distribute while filling up the mould, we observe that distribution of particles begins practically at the start of pouring. But the most important is the moment of contact of flowing composite with the bottom of the mould and next, the behaviour of fluid. Practically, at this point appears significant process of segregation of reinforcement particles caused by the flow of fluid and the centrifugal force. During this process solid particles are shifted towards the outer part of the cast. Described situations are shown in figures 3 and 4.

The solidification of composite defined through changing of matrix viscosity vs. temperature is shown in right subsets on figures 2, 3, 4 and 5 for a selected time sequence (0,6s, 1s, 2s, 3s). We observe that the real solidification start at the moment then the composite achieves the shape almost of the tube and runs from upper part of the cast to down. During solidification of the composite liquid-solid interface is moving from the outer into the inter part of the cast. We observe the influence of displaced liquid-solid interface on the location of reinforcement particles. This is a result of changes in local viscosity of fluid. Then, the local viscosity increases (because of the decrease of temperature) the particle tends to be in the parts with less viscosity i.e. in the parts which solidify last. This effect is clearly shown at the figure 3 and 4. For considered case, we can assume that after 3,5s solidification is finished, the whole composite phase is solidified. The obtained result in a large degree corresponds to real experiment either with regard to time of process or final distribution of reinforcement particles in casting composite. This shows that CFD programs can be useful tools in investigation of such a problem as presented here.

5. CONCLUSIONS

Considering, in this paper, the example of simulation we indicate that CFD program (Fluent) can be treated as an attractive and useful tool for model centrifugal casting process of alumina matrix composite reinforced by crystalline particles. It can be assumed that the presented model of centrifugal casting and created procedure of simulation can be a basis for more advanced one.

Presented results show that the centrifugal force and thermal phenomena take place a significant role. Centrifugal force determines the final shape of the cast and distribution of reinforcement particles but not entirely. Thermal phenomena decide on hydrostatic and physic properties of the cast. The initial values of casting parameters influence the time of casting and the structure of the composite. So, it is very interesting to continue the investigations basis of presented model and additional parameters and also compare with structure of real cast of composite.

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KOMPUTEROWE MODELOWANIE ODLEWANIA ODŚRODKOWEGO KOMPOZYTÓW ALUMINIOWYCH ZBROJONYCH CZĄSTECZKAMI CERAMICZNYMI

Streszczenie

Odlewanie odśrodkowe jest jedną z metod otrzymywania kompozytów aluminiowych zbrojonych cząsteczkami ceramicznymi. W trakcie procesu następuję segregacja cząsteczek zbrojenia pod wpływem działania siły odśrodkowej. Struktura kompozytu zależy również i od innych czynników: tj. różnicy gęstości pomiędzy materiałem osnowy i zbrojeniem, procesów termicznych związanych z krzepnięciem prowadzącym do zmiany we właściwościach fizycznych ciekłego kompozytu, temperatury zalewania, temperatury formy, składu i właściwości fizycznych kompozytu, prędkości wirowania, rozmiaru cząsteczek zbrojenia i innych. Ze względu na złożoność procesu, w którym wiele zjawisk ma charakter nieliniowy, matematyczny opis procesu jest zagadnieniem trudnym. Rozwój technik komputerowych spowodował, że modelowanie układów ciągłych, a za taki można uznać układ: ciekła osnowa kompozytu i zbrojenie, staje się możliwe, nawet w przypadku złożonego charakteru zagadnienia.

W niniejszej pracy przedstawiono opis projektu, w którym podjęto próbę komputerowego modelowania procesu odlewania odśrodkowego kompozytów aluminiowych zbrojonych cząsteczkami ceramicznymi (SiC) od momentu zalewania formy do zastygnięcia kompozytu. W badanych wykorzystano program Fluent, który należy do grupy narzędzi tzw. numerycznej dynamiki płynów CFD (ang. *computational fluid dynamic*). Program Fluent podobnie jak szereg innych podobnych programów, opiera się na metodzie elementów skończonych oraz metodzie objętości skończonej. Zawiera szereg gotowych procedur, które zastosowano do zamodelowanie odlewania odśrodkowego kompozytów metalowych, tzn. procedury do obliczania rozkładu temperatur oraz prędkości dla dwuwymiarowego układu wirującego (ang. *2D axisymmetric swirl model*), powierzchni swobodnej (ang. *volume of fluid* – VOF), cząsteczek stanowiących fazę rozproszoną (ang. *discrete phase model* – DPM). Ponadto umożliwia dodawanie własnych procedur, definiowanie dodatkowych parametrów i implementowanie ich w programie (*User-Defined-Functions – UDFs*), co było niezbędne w prezentowanym przypadku.

W obliczeniach numerycznych uwzględniono wzajemne oddziaływania pomiędzy ciekłą osnową i zbrojeniem – wymiana ciepła i pędu. Ponadto, przyjęto, że na cząsteczkę zbrojenia oprócz siły odśrodkowej działają i inne siły, tj. grawitacja, wyporu oraz oporu wynikająca z ruch cząsteczki w płynie o określonej lepkości. Zaniedbano natomiast oddziaływania między cząsteczkowe, traktując cząsteczki zbrojenia jako sztywne kule, które blokują zajmowaną przez siebie objętość. Uwzględniono zależność temperaturową takich parametrów ciekłej osnowy jak: gęstość, przewodnictwo cieplne oraz lepkość. Proces zastygania kompozytu zamodelowano poprzez zmianę lepkości ciekłej osnowy wraz ze zmianą temperatury.

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