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MODELING OF SOLIDIFICATION OF MMC COMPOSITES DURING GRAVITY CASTING PROCESS

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The paper deals with computer simulation of gravity casting of the metal matrix composites reinforced with ceramics (MMC) into sand mold. The subject of our interest is aluminum matrix composite (AlMMC) reinforced with ceramic particles i.e. silicon carbide SiC and glass carbon Cg. The created model describes the process taking into account solidification and its influence on the distribution of reinforcement particles. The computer calculation has been carried out in 2D system with the use of Navier-Stokes equations using ANSYS FLUENT 13. The Volume of Fluid approach (VOF) and enthalpy method have been used to model the air-fluid free surface (and also volume fraction of particular continuous phases) and the solidification of the cast, respectively.

Key words: casting solidification, aluminum matrix composites, simulation, computational fluid dynamic (CFD)

INTRODUCTION

Currently, we have been observing a vast interest in the research of casting processes for various types of materials, including metal matrix composites reinforced with ceramic particles. As the example we can give aluminum matrix composites which may be reinforced with heterophase mixture of ceramic particles e.g. silicon carbide SiC and glass carbon Cg. One of the methods that is used to study the behavior of composite during casting process is the experimental gravity casting of liquid composite into the sand mold [1,2]. Therefore, the studies described in the paper refer to the course of the solidification process and the final structure of the composite through applying the computer simulations. The simulations have been carried out by using the program ANSYS Fluent 13,0 which belongs to Computational Fluid Dynamics group (CFD) [3-5]. This program contains several calculating methods based on tested and widely used theories, and techniques which are connected with the modeling of mass and thermal transfers, multiphase systems and solidification. Moreover, Fluent enables the user to implement their own programs written in UDF's code.

The investigation of the casting process of the composite requires taking into account some factors which affect the course of the solidification and final arrangement of reinforcement [4,5]. In the case of the gravity casting the elements such as the fields of the external forces e.g. the gravity force and the difference between the density of the composite matrix and the reinforcement particles may cause the segregation of reinforcement. During the casting in the electromagnetic field the electromagnetic buoyancy also affects the reinforcement segregation [6]. The next factor comprises the dislocation of solidification front as well as the change of physical properties of the solidifying cast (transfer from liquid stage into solid one) [7,8]. The final effect of particle segregation is better noticeable for longer solidification processes. The solidification speed depends on the intensity of the heat flow and its exchange at the interfaces i.e. thermal boundary conditions between the liquid cast phase and the mold wall as well as thermal conditions of the mold material [5].

THEORIES

Fluent includes a lot of methods and ready procedures for modeling fluid flow, heat transfer and discrete phase in complex geometries. It provides a complete mesh flexibility, including the ability to solve flow problems using unstructured meshes.

We have assumed that the simulation system contains two continuous phases: air and liquid matrix with dispersed particles of reinforcement. Therefore, we have applied the Volume of Fluid approach (VOF) to simulate the immiscible continuous phases [9]. This approach assigns the interface between immiscible phases by calculating of continuity equation for volume fraction of one component. The VOF allows modeling the wall adhesion of fluid on the solid surface and also introducing the surface tension between phases by using the continuum surface force scheme (CSF) [10].

The computer simulation of the cast solidification requires additional source terms responsible for the modification of energy and mass transfer equations, especially in the phase transition point. Therefore, we have implemented the enthalpy method [3,11], which

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assumes that the same system of differential equations and boundary conditions are counted in the entire computational domain and introduces the characteristic parameter called liquid fraction *β*. This parameter characterizes the state of material in the specified point of the domain:

$$\beta = \begin{cases} 0 & \text{for} \quad T < T_S \\ \dfrac{T - T_S}{T_L - T_S} & \text{for} \quad T_S < T < T_L \\ 1 & \text{for} \quad T > T_L \end{cases} \tag{1}$$

where T_L and T_S are liquidus and solidus temperature, respectively. The value of liquid fraction parameter changes from 0 for solid phase to 1 for liquid phase. In the phase transition range ($T_S < T < T_L$) the liquid fraction assumes fractional value.

To model the location and velocity of the discrete phase (reinforcement particles) we have used Discrete Phase Model (DPM). In the model the particles interact with the continuous phase by a set of laws, which describe the transfer of momentum, heat and mass [3-5]. The trajectories of individual particles can be treated by balancing the forces acting on them:

$$F = F_d + F_g + F_b \tag{2}$$

where: F_d is the drag force equals:

$$F_d = \frac{18\mu}{\rho_p d_p^2} \cdot \frac{C_D \mathrm{Re}}{24} \tag{3}$$

where: 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 [12]. F_g is gravitational force equals:

$$F_g = g_x \rho_p V_p \tag{4}$$

where: g_x is gravitational acceleration, V_p is volume of particles. F_b is buoyancy force equals:

$$F_b = -g_x \rho V_p \tag{5}$$

where ρ is the density of the fluid.

We have also considered the collision between the particles of the discrete phase. DPM includes the collision but does not assume occupation of the space by particles. The developed model introduces a UDF's procedure containing the algorithm that describes the above problem. The collisions are detected by checking the distance between the parcels, which are the groups of the particles of dispersed phase. Therefore, it is important to designate the diameter of the parcels.

PHYSICAL PROPERTIES

We have assumed that the viscosity of composite matrix depends on the temperature. This relation has been used as a supplement for the computation model describing the interactions between reinforcement particles and the effects of solidification front displacement. We have also included the impact of reinforcement particles on the matrix viscosity [4,5]:

$$\mu_{pop} = \mu\,(1 + 2{,}5\,V_f + 7{,}6\,V_f^2) \tag{6}$$

where: V_f is volume fraction of particles.

To simulate the turbulent flow the standard k-ε model of turbulence has been introduced [3,13].

SIMULATION MODEL

We have developed the simulation model which consists of several parts: the steel mount on which sand mold is installed and the steel pouring vessel – Figure 1. We have located the pressure-inlet at the top and the sides of the system. The vessel area has been changed into interior region during the simulation. The simulation domain has been discretized in the program Gambit by using an unstructured rectangular mash.

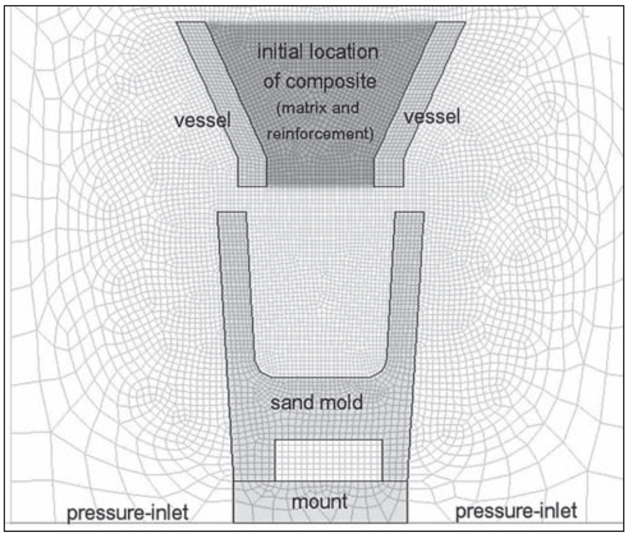

Figure 1 Simulation model

We have assumed the following values of the simulation parameters: pouring temperature of liquid composite 725 ºC, initial temperature of the system 25 ºC, volume fraction of reinforcement (spherical particles): SiC 10 % and Cg 10 %, diameters of particles: SiC

Table 1 **Physical properties of alloy AK12 and composite AK12/SiC/Cg [3-5]**

Material parameters	AK12	AK12/SiC/Cg
density ρ	2 680 kg/m³	
heat capacity c_p	981 J/kg·K	
thermal conductivity λ	134 W/m·K	
viscosity μ (liquid - solid)	1,5×10-3	
solidus temperature T_S	– 10,0 Pa·s	551 ºC
liquidus temperature T_L	559 ºC	558 ºC
latent heat L	572 ºC	324 kJ/K
tension air-alloy interface γ	395 kJ/K	
contact angle	0,98 N/m²	
	120 °	

Table 2 **Physical properties of sand mold, SiC and Cg [3-5]**

Material Parameters	Sand mold	SiC	Cg
density ρ	2 700 kg/m³	3 230 kg/m³	1 800 kg/m³
heat capacity c_p	674 J/kg·K	1 010 J/kg·K	710 J/kg·K
thermal conductivity λ	0,83 W/m·K	84 W/m·K	150 W/m·K

50 μm and Cg 100 μm. As the composite matrix we have used the aluminum alloy AlSi12CuNiMg, modified with a 2 % magnesium and 0,03 % strontium addition – AK12. The other parameters of SiC and Cg, as well as the composite matrix AK12, composite AK12/SiC/Cg and sand mold are included in Tables 1 and 2.

RESULT AND DISCUSSION

The simulation has started from the initial state with two phases: air and liquid composite in the selected location and the determined temperature distribution. This distribution has been prepared during time-independent steady simulations for which only energy equation has been solved. In the main time-dependent simulations the flow, turbulence and volume fraction equations have been solved additionally for time-step which equals 0,0001. In the selected location the two types of particles (SiC and Cg) have been injected by surface-injected method.

The Figure 2 presents the course of the solidification of the composite by showing the increase of the solid fraction for the selected time sequences. The solid fraction is defined as (1 – β). We observe that the time and the course of solidification are closely connected with the assumed physical parameters of the simulation and materials particularly the low value of the thermal conductivity of the sand mold. The solidification process of the cast is closely related to a decrease of temperature in each part of the system. The proper solidification begins after about 62 s. The simulation shows that the solidification of the composite finishes after 317 s. A detailed analysis of simulation data shows that at the initial stage of the process, the solidification takes places near the walls of the mold and at the interface. Then the crystallization front assumes two directions: from the bottom wall to the top and from the interface down. It finishes below the center of the cast.

Because of the slow solidification of the cast, we have observed a clear segregation of the reinforcement particles. It is confirmed by the Figure 3 showing the DPM Concentration and final the arrangement of SiC and Cg particles. The impact of the forces from equation (2), especially gravitational and buoyancy forces, causes the appropriate behavior of the particles. The SiC particles (larger density vs. matrix density) move down in contrast to Cg particles (lower density vs. matrix density) which shift towards the upper part of the cast. The reinforcement particles form distinct layers.

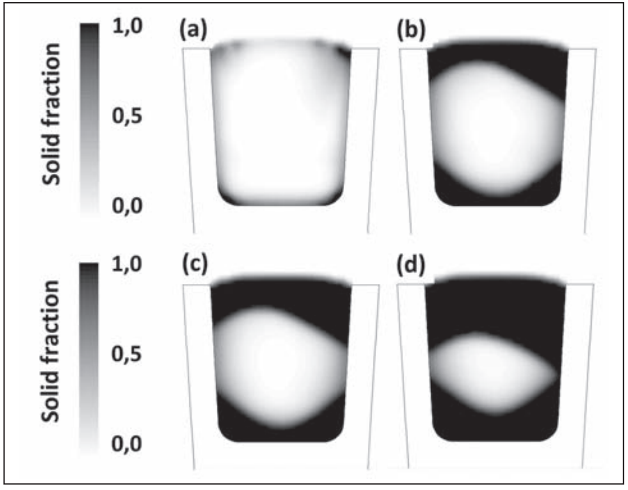

Figure 2 Solid fraction for the composite AK12/SiC/Cg after time (a) 80 s, (b) 160 s, (c) 180 s and (d) 240 s.

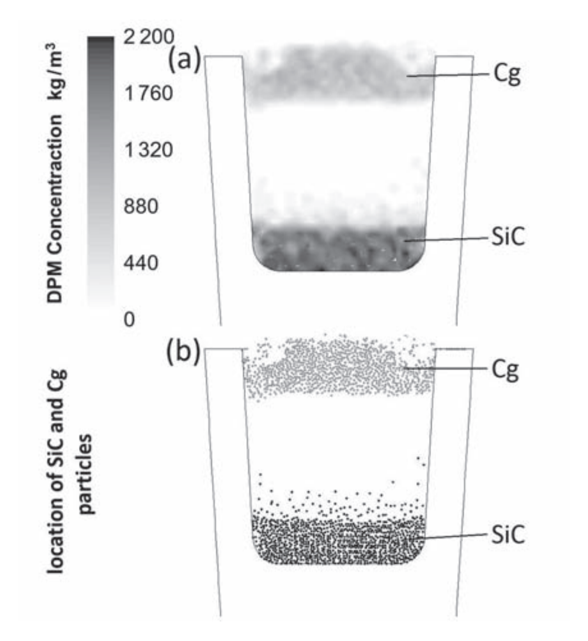

Figure 3 DPM Concentration (a) and location of SiC and Cg particles (b) at final stage for composite AK12/SiC/Cg.

CONCLUSIONS

The results of the computer simulation curried out by ANSYS Fluent indicate that the procedures and techniques included into this program can be useful to study the course of the solidification process for even more complex materials such as aluminum matrix composite reinforced with heterophase mixture of ceramic particles. In addition, Fluent also allows predicting the final arrangement of the reinforcement particles. However, while performing the simulations there appears a problem related to the selection of the appropriate simulation parameters one of which is to define the time-step. Due to the long time of the calculations, it is important to assume the optimum time-step, so as to shorten the calculation time and ensure a good convergence. Another problem is to develop a suitable calculation domain and perform its right discretization.

The analysis of the simulation results shows that the course of the composite solidification is closely related to the assumed thermal boundary conditions and physical parameters of the materials. Slow cooling of the cast causes that the clear segregation of the reinforcement particles occurs in this process. The movement of the particles is the result of balancing of the forces in which the density of particles and fluid are taken into account.

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Note: A. Żółkiewska is responsible for English language, Katowice, Poland