A MODEL OF MICROSTRUCTURAL SOLIDIFICATION DURING MOULD FILLING FOR SQUEEZE FORMING PROCESSES

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ABSTRACT
This paper deals with a squeeze casting model which is currently being developed. In this paper we focus our interests on mould filling. During mould filling the solidification of the material takes place due to decreasing temperature. We believe that the estimation of microstructural properties during mould filling allows a better prediction of the mechanical properties. An overview of squeeze casting processes is presented by Ghomashi *et al.* [1]. Methods of solving thermal problems including phase transformation are described by Lewis *et al.* [2], microstructure evolution was shown by Thevoz et al. [3], Celentano [4].

NOMENCLATURE
F – pseudoconcentration function,
f_l – liquid fraction,
f_s – solid fraction,
f_e – eutectic fraction,
f_d - dendritic fraction,
f_i^e – eutectic internal fraction,
f_i^d – dendritic internal fraction,
f_g^e – intergranular eutectic fraction,
f_g^d – dendritic grain fraction,
N_e – eutectic grain density,
N_d – dendritic grain density,
R_e – eutectic radius rate,
R_d – dendritic radius rate

THERMAL PROBLEM
Let us consider the thermal problem in the following form

$$\nabla(k\nabla T)+q=\frac{dH}{dT}\frac{\partial T}{\partial t} \tag{1}$$

with the Dirichlet and Neuman boundary conditions

$$S_1(T)=T-T_w=0 \quad S_2(T)=k\left(\frac{\partial T}{\partial n}\right)+h(T-T_w) \tag{2}$$

with enthalpy temperature derivative $dH/dT = \rho c_p$ which depends on the state of the material, where k is the thermal conductivity, ∇T is the temperature gradient, q is the heat source, ρ is the mass density and c_p is the heat capacity, respectively. The equation is solved over the domain Ω and fulfils boundary conditions (on $\partial\Omega$).. The Eqn (1) is discretized using Galerkin method and is integrated explicitly.

FLOW PROBLEM
The flow of material is assumed to be Newtonian and incompressible, Ravindran *et al* [5]. The governing Navier Stokes equations is of the form

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{u}\right)=\nabla\cdot\mu\left[\nabla\mathbf{u}+(\nabla\mathbf{u})^T\right]-\nabla p+\rho\mathbf{g} \tag{3}$$

where $\mathbf{u}$ is the velocity vector, p is pressure, μ is the dynamic viscosity and g is the gravitational acceleration vector. Mass conservation equation $\nabla\cdot\mathbf{u}=0$ gives the incompressibility condition. To track the free surface the volume of fluid method is applied, Hirt *et al* [6]. Free surface tracking is governed by the first order advection equation

$$\frac{\partial F}{\partial t}+(\mathbf{u}\cdot\nabla)F=0 \tag{4}$$

where F is the pseudo-concentration function varying from –1 to 1, $F<0$ indicates the empty region, $F > 0$ indicates the fluid region, $F = 0$ locates the free surface. The Eqn (3) is discretized using Galerkin method while the Eqn (4) with the Taylor-Galerkin one. An implicit time integration algorithm is used to solve the Eqn (3) and when considering the Eqn (4) the explicit integration scheme is used.

MICROSTRUCTURAL SOLIDIFICATION

During the entire process of forming a cast component solidification gradually occurs. A microstructure based solidification model has been employed which results in a better understanding of the process. The model stems from the assumptions given by Thevoz *et al.* [3] and Celentano [4]. The basic assumptions are as follows: the sum of the solid and liquid fractions is equal to one and the solid fraction consists of both dendritic and eutectic fractions, i.e.,

$$f_l + f_s = 1 \qquad f_s = f_d + f_e \tag{5}$$

Further assumptions are utilised because of the existence of interdendritic and intergranular eutectic fractions. The internal fraction consists of both the dendritic and eutectic portions, i.e.,

$$f_s = f_g^d f_i + f_g^e, \qquad f_i = f_i^d + f_i^e \tag{6}$$

The last assumptions lead to the final formulae for the dendritic and eutectic fractions

$$f_d = f_g^d f_i^d \qquad f_e = f_g^d f_i^e + f_g^e \tag{7}$$

and the assumption of the spherical growth

$$f_g^e = \frac{4}{3}\Pi N_d R_d^3 \qquad f_i^e = \frac{4}{3}\Pi N_e R_e^3 \tag{8}$$

where N_d, N_e are the grain densities and R_d, R_e are the grain radii. The grain densities and grains sizes are governed by nucleation and growth evolution laws. The rate of growth of the dendritic and eutectic nuclei is given below. This depends on the undercooling and a Gaussian distribution of the nuclei is assumed.

$$\dot{N}_{(d,e)} = N_{\max(d,e)} \frac{1}{2\Pi} \exp\left(-\frac{\Delta T - \Delta T_{N(d,e)}}{2\Delta T_{\sigma(d,e)}}\right)\left\langle -\dot{T}\right\rangle \tag{9}$$

The rate of the dendritic and eutectic grain radii is established based on experimental dependence. Finally, the internal dendritic fraction depends on the melting temperature and k' is the partition coefficient.

$$\dot{R}_{(d,e)} = f_{R(d,e)} \qquad f_i^d = 1 - \left(\frac{T_m - T}{T_m - T_l}\right)^{\frac{1}{k'-1}} \tag{10}$$

A numerical example is given below.

NUMERICAL EXAMPLE

The numerical example concerns filling of a cavity with aluminium alloy LM25. During the filling process solidification of the material is observed.

The initial temperature of the cast is 650 °C, initial temperature of the mould is 250 °C. The ambient temperature is 20 °C. The thermal boundary conditions are established as fluxes 100 J/sec. The interfacial heat transfer coefficient is 2500 W/m^{2o}C. The material density is 2520 kg/m^3. The wall friction angle is 135. The filling time is 10 sec.

The dependences of heat capacity and conductivity are given in Figures 1 and 2. These are the experimental curves. It can be noted that the phase transformation takes place in the region of 600 °C. The radiuses rates are given in Figures 3 and 4.

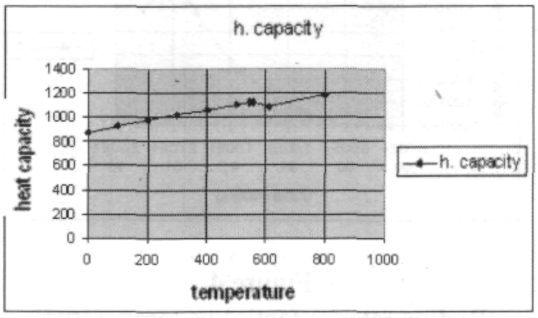

Figure 1
Heat capacity vs temperature

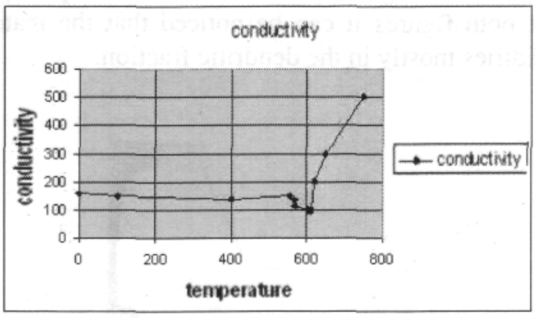

Figure 2
Conductivity vs temperature

The velocities patterns at steps 48 and 87 are given in Figures 5 and 6. Amounts of liquid fraction at the steps 48 and 87 are given in Figures 7 and 8. The two figures show the actual range of filling of the mould. Temperature distributions at steps 48 and 87 are shown in Figures 10 and 11. The cooling starts close to the walls.

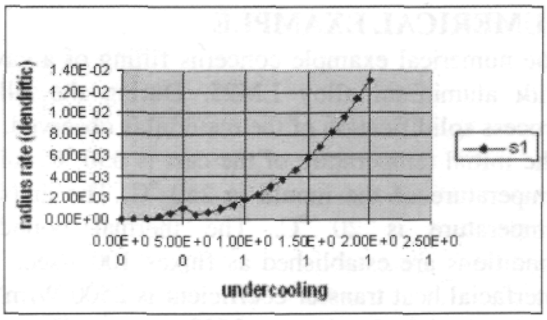

Figure 3
Radius rate (eutectic) vs temperature

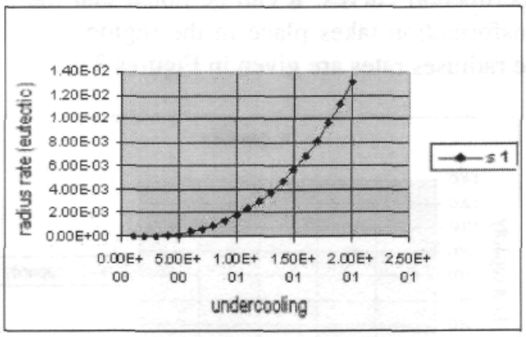

Figure 4
Radius rate (eutectic) vs temperature

Eutectic and dendritic fractions distributions for the step 87 (close to the end of the filling process) are presented in Figures 12 and 13. When comparing the last both figures it can be noticed that the material solidifies mostly in the dendritic fraction.

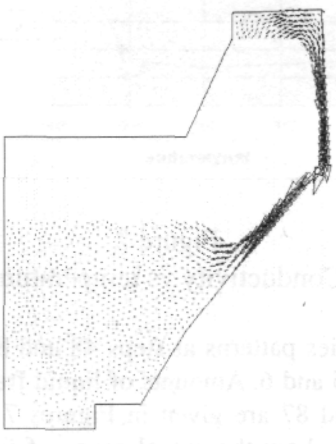

Figure 5
Velocities pattern (step 48)

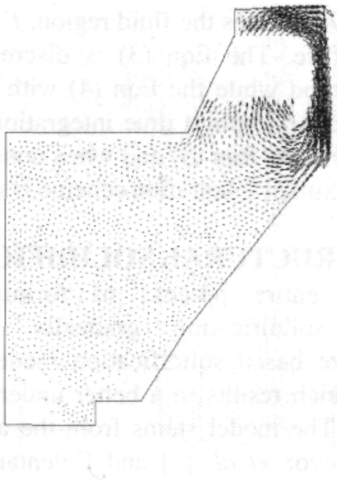

Figure 6
Velocities pattern (step 87)

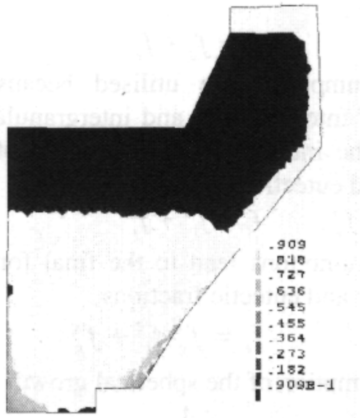

Figure 7
Liquid fraction (step 48)

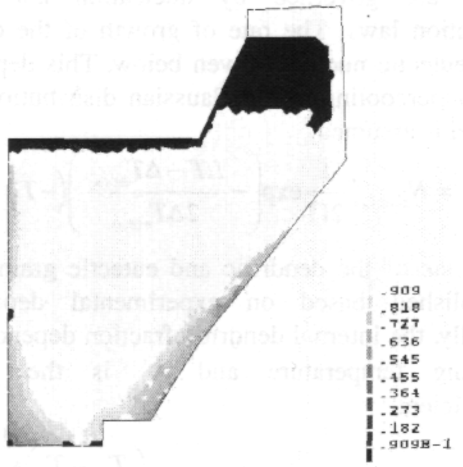

Figure 8
Liquid fraction (step 87)

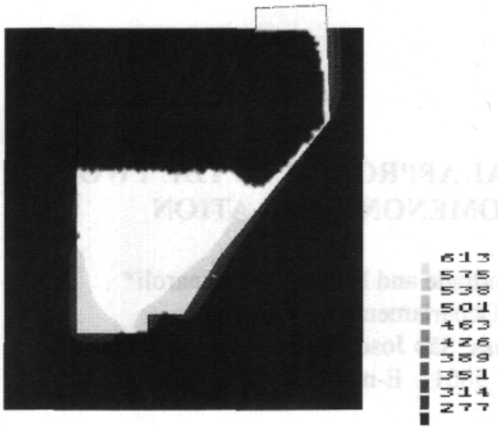

Figure 10
Temperature distribution (step 48)

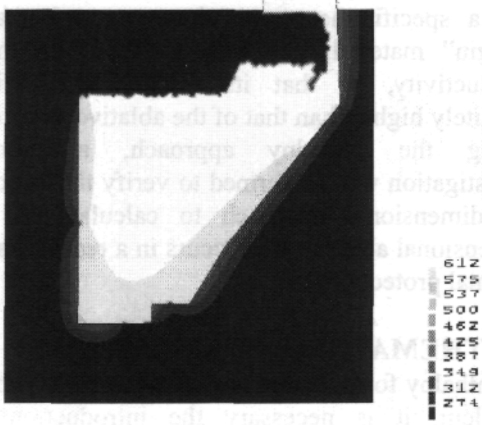

Figure 11
Temperature distribution (step 87)

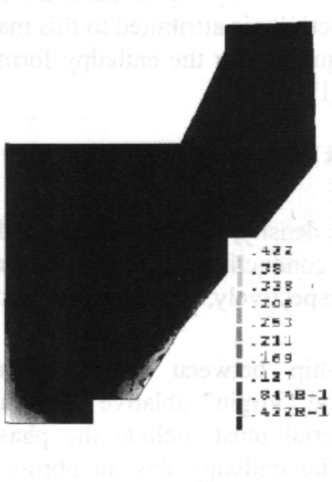

Figure 12
Dendritic fraction distribution (step 87)

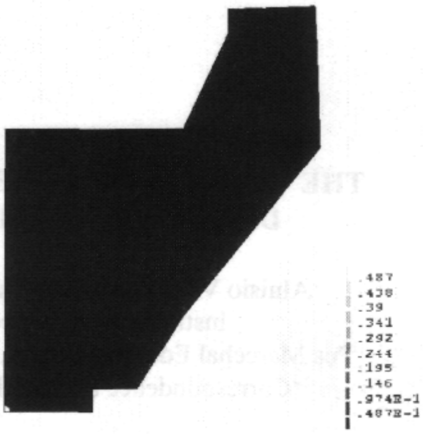

Figure 13
Eutectic fraction distribution (step 87)

FINAL REMARK

In this communication a numerical model of mould filling including a microstructural solidification model and a numerical example are presented.

ACKNOWLEDGMENTS

The Authors would like to thank the Engineering and Physical Sciences Research Council (UK) and GKN Squeezeform for their support.

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