CURRENT DEVELOPMENTS ON THE COUPLED THERMOMECHANICAL MODELING OF METAL CASTING PROCESSES

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ABSTRACT In this paper current developments on the computational simulation of coupled thermomechanical metal casting processes are presented. A thermodynamically consistent material model allowing a continuous transition between the initial fluid-like and the final solid-like phase is modeled by considering a J2 thermoviscoplastic model. A thermomechanical contact model, taking into account the insulated effects of the air-gap due to thermal shrinkage of the part during solidification and cooling, is introduced. Within a FE setting, using low-order interpolation elements, a multiscale stabilization technique is introduced to avoid volumetric locking and pressure instabilities arising in incompressible or quasi-incompressible problems. Computational simulation of industrial casting processes show the good performance of the model.

INTRODUCTION: Up to now, mostly purely thermal models have been considered to study the evolution of the solidification and cooling phenomena. This is mainly due to the fact that a (purely) thermal analysis is easier and less costly, and therefore more convenient for large scale industrial simulations. However, an accurate modeling of stresses and deformations during the solidification and cooling phases of the part is essential to capture the accurate thermal pattern in metal die casting processes. In fact, the thermal deformation of both part and mold modify the original interfacial heat transfer among all the casting tools involved in the process. The relationship between heat transfer coefficients and air-gap has been closely observed. On the other hand, it must be observed that the mechanical interaction between part and mold induced by the thermal deformations and contact pressure leads to a modification of the final shape and residual stresses of the casting system. An accurate study of the thermal stresses induced during the casting process can prevent mold fissures and an excessive amount of accumulated residual stresses in the part, results that cannot be captured with a purely thermal simulation.

PROCEDURES, RESULTS AND DISCUSSION: As a result of the stabilized formulation proposed by the authors in [Agelet de saracibar et al. 2006, Chiumenti et al. 2004], the weak form of the linear momentum balance equation takes the form:
where $\tau_e$ is a stabilization parameter and $\Pi$ is the smooth projection of the pressure gradient onto the finite element space, computed at each time-step as:

$$
\langle \eta, \Pi \rangle - \langle \eta, \nabla p \rangle = 0
$$

The mechanical model for the cast part and the mold material is consistently derived from a thermo-elasto-viscoplastic free-energy potential [Agelet de Saracibar et al. 1999, 2001]. Constitutive equations for the deviatoric part of the stress tensor $\mathbf{s}$ together with the kinematic and isotropic hardening stress-like variables $\mathbf{q}$ and $q$, respectively, are described by the following equations:

$$
\mathbf{s} = 2G \text{dev}(\mathbf{e} - \mathbf{e}^\eta), \quad \mathbf{q} = -f_s(\Theta)\frac{2}{3}K_\varepsilon \mathbf{\dot{e}}, \quad q = -f_s(\Theta)[(\sigma_\varepsilon - \sigma_0)(1 - \exp(\delta \varepsilon)) + H \mathbf{\dot{e}}]$$

where $G = G(\Theta)$ is the (temperature dependent) shear modulus, $K_\varepsilon$ and $H$ are the coefficients of the linear kinematic and isotropic hardening laws and finally, $\sigma_\varepsilon = \sigma_\varepsilon(\Theta)$ and $\sigma_0 = \sigma_0(\Theta)$ are the (temperature dependent) saturation and initial flow stress parameters. We consider associative plasticity using a temperature dependent J2 yield surface $\Phi(\mathbf{s}, \mathbf{q}, q, \Theta)$ defined as:

$$
\Phi(\mathbf{s}, \mathbf{q}, q, \Theta) = \|\mathbf{s} - \mathbf{q}\| - R(q, \Theta)
$$

where $R(q, \Theta)$ is the (temperature dependent) yield-surface radio defined as:

$$
R(q, \Theta) = f_s(\Theta)\sqrt{\frac{2}{3}}[\sigma_0(\Theta) - q]
$$

For a liquid state the radius of the yield surface vanishes and a Norton-Hoff law can be derived in terms of a temperature-dependent viscosity parameter $\eta = \eta(\Theta)$ such that,

$$
\mathbf{s} = \eta \mathbf{\dot{e}}^\eta
$$

The weak form of the energy balance equation (neglecting the mechanical dissipation and elastoplastic heating terms) takes the following expression [1-5]:

$$
\big\langle C_\varepsilon \dot{\Theta} + \dot{L}_\varepsilon, \delta \Theta \big\rangle + \big\langle k \nabla \Theta, \nabla \delta \Theta \big\rangle = \big\langle R(\Theta), \delta \Theta \big\rangle_{\partial \Omega} - \big\langle q_{\text{cond}} + q_{\text{conv}} + q_{\text{rad}}, \delta \Theta \big\rangle_{\partial \Omega}
$$

where $\overline{q}$ is the prescribed normal heat flux on the boundary and $q_{\text{cond}}, q_{\text{conv}}, q_{\text{rad}}$ are the conduction, convection and radiation heat fluxes, respectively, at the contact interface.
steel mold behaviour has been modeled by a simpler thermoelastic model. The initial temperature is 650ºC for the casting and 250ºC for the mold. Cooling system has been kept at 20ºC. The heat transfer coefficient takes into account the air-gap resistance due to the casting shrinkage. Fig. 1 shows (from left to right) the temperature, von Mises deviatoric stress and equivalent plastic strain distributions. Temperature evolution at different times, as well as thermal shrinkage during the solidification, are shown in Fig. 2.

Fig. 1. From left to right, temperature, von Mises deviatoric stress and equivalent plastic strain distributions

Fig. 2. Temperature evolution at different times on a section. Thermal shrinkage during the solidification process can be also shown.

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REFERENCES: