VISCO-PLASTIC MULTI-PHYSICS MODELING OF STEEL SOLIDIFICATION

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ABSTRACT: Thermo-mechanical steel solidification models, based on highly nonlinear elastic visco-plastic constitutive laws in solid and featuring efficient and robust local implicit integration scheme, are coupled with cfd turbulent calculations in the liquid pool via enhanced latent heat method. The new multi-physics model of metal solidification is applied to calculate temperature, stress, and deformation of solidifying shell in a commercial caster with real geometry.

INTRODUCTION: Many manufacturing and fabrication processes such as foundry shape casting, continuous casting and welding have common solidification phenomena. One of the most important and complex of these is continuous casting, which produces 90% of steel today. Even though the process is constantly improving, there is still a significant need to minimize defects and to maximize quality and efficiency. The difficulty of plant experiments under harsh operating conditions makes computational modeling an important tool in the design and optimization of these processes. Increased computing power and better numerical methods have enabled researchers to develop better models of many different aspects of these processes. Coupling together the different models of heat transfer, solidification distortion, stress generation and turbulent fluid flow to make accurate predictions of the entire real processes remains a challenge.

PROCEDURES, RESULTS AND DISCUSSION: Inertial effects are negligible in solidification problems, so using the static mechanical equilibrium as the governing equation is appropriate.

$$\nabla \cdot \boldsymbol{\sigma}(\mathbf{x}) + \mathbf{b} = 0 \quad (1)$$

The rate decomposition of total strain in this elastic-viscoplastic model is given by:

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}_{el} + \dot{\boldsymbol{\varepsilon}}_{ie} + \dot{\boldsymbol{\varepsilon}}_{th} \quad (2)$$

where $\dot{\boldsymbol{\varepsilon}}_{el}, \dot{\boldsymbol{\varepsilon}}_{ie}, \dot{\boldsymbol{\varepsilon}}_{th}$ are the elastic, inelastic, and thermal strain rate tensors respectively.

Viscoplastic strain includes both strain-rate independent plasticity and time dependant creep. Creep is significant at the high temperatures of the solidification processes and is indistinguishable from plastic strain [Kozlowski 1992] proposed a unified formulation with the following functional form to define inelastic strain.

$$\dot{\bar{\varepsilon}}_{ie}[\sec^{-1}] = f_C \left(\bar{\sigma}[MPa] - f_1 \bar{\varepsilon}_{ie} \,|\, \bar{\varepsilon}_{ie} \,|^{f2-1}\right)^{f3} \exp\left(-\frac{Q}{T[K]}\right)$$

where :

$$Q = 44,465 \qquad (3)$$

$$f_1 = 130.5 - 5.128 \times 10^{-3}\, T\,[K]$$

$$f_2 = -0.6289 + 1.114 \times 10^{-3}\, T\,[K]$$

$$f_3 = 8.132 - 1.54 \times 10^{-3}\, T\,[K]$$

$$f_C = 46,550 + 71,400\,(\%C) + 12,000\,(\%C)^2$$

Q is activation constant, and f_1, f_2, f_3, f_C are empirical temperature, and steel-grade-dependent constants. The system of ordinary differential equations defined at each material point by the viscoplastic model equations is converted into two "integrated" scalar equations by the backward-Euler method and then solved using a special bounded Newton-Raphson method [Koric 2006, Koric 2009].

3D fluid flow of the molten steel in the liquid pool is modeled with the Navier-Stokes equations with addition of two turbulence equations for the turbulent kinetic energy K, and its dissipation $\in$. The fluid flow governing equations are solved using the finite-volume method with the SIMPLE method and first-order upwinding to give the pressure, velocity, and temperature fields at each cell in the computational domain, and the heat flux at the domain boundary surfaces. The shape of the domain is specified by extracting the position of the solidification front (liquidus temperature) from the solidifying shell model, and the symmetry planes of the mold. The effect of shell growth is incorporated as mass and momentum sinks.

Results from the fluid flow model of the liquid domain affect the solidifying shell model by the heat flux crossing the boundary, which represents the solidification front, or liquidus temperature. This "superheat flux" q_{super} can be incorporated into a fixed-grid simulation of heat transfer phenomena in the mushy and solid regions by enhancing the latent heat [Koric 2010] This enables accurate uncoupling of complex heat-transfer phenomena into separate simulations of the fluid flow region and the mushy-solid region. The additional latent heat ΔH_f to account for superheat flux delivered from the liquid pool can be calculated from:

$$\Delta H_f = \frac{q_{super}(\boldsymbol{x},t)}{\rho_{solid}\left|v_{interface}\right|} \qquad (4)$$

The entire multiphysics model was applied to solve for fluid-flow, temperature, stress, and deformation in a complex-shaped beam blank caster under realistic continuous casting conditions. First, the thermo-mechanical model of the solidifying shell is run assuming a uniform superheat distribution driven by the temperature difference between T_{init} and T_{liq}, and artificially increasing thermal conductivity in the liquid region by 7-fold. The heat fluxes leaving the shell surface provide the boundary conditions for the thermo-mechanical model of the mold, which in turns supplies the next run of the shell model with mold temperature and thermal distortion boundary conditions. The position of the solidification front in the shell model defines an approximate shape of the liquid pool for the fluid flow model, which is used to calculate the superheat flux distribution. Finally, an improved thermo-mechanical model of solidifying shell is re-run which includes the effects of the superheat distribution and mold distortion, and completes the first iteration of the multiphysics model. Because the shell profile from the improved thermo-mechanical model has little effect on superheat results in the liquid pool, a single multiphysics iteration is sufficient to produce an accurate shell growth prediction.

The shell thickness at 90% liquid predicted by initial thermo-mechanical only and the full-multiphysics models is compared with measurements around the perimeter of a breakout shell obtained from a commercial caster in Figure 1, while the maximum and minimum principal shell stress contours at 457 mm below the meniscus are given in Fig. 2.
The initial thermo-mechanical model assuming a uniform superheat distribution can only roughly match the shell thickness variations. Shell thickness variations at the corners and shoulder due to air gap formations were captured owing to the interfacial heat transfer model.
However, the middle portion of the wide face is 4 mm thicker in the measurement. This is evidently caused by the uneven superheat distribution due to the flow pattern in the liquid pool, as this location is farthest away from the pouring funnels and has the least amount of superheat. In contrast, the shoulder region receives the highest amount of superheat, so the measured shell thickness there is more than 2 mm thinner than the initial thermo-mechanical model prediction. The improved multiphysics model that includes the fluid flow effects matches the shell thickness measurement around the entire perimeter much more accurately. It is already in use to study and quantify problems such as crack formation in in continuous-cast steel.

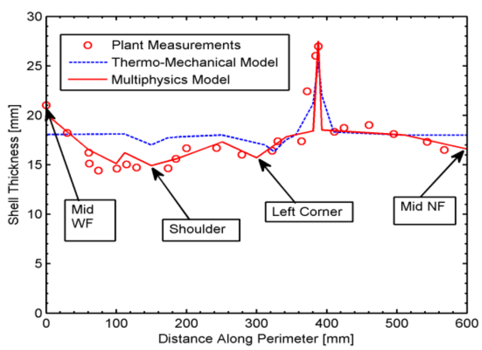

Fig 1. Shell Thickness Comparison

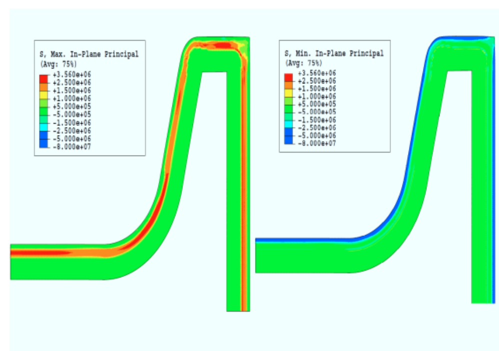

Fig 2.Principal Stresses 457 mm below Meniscus

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