COUPLED VISCO-PLASTIC THERMO-MECHANICAL MODELS OF STEEL SOLIDIFICATION

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ABSTRACT: Coupled thermo-mechanical models based on highly nonlinear elastic visco-plastic constitutive laws are applied to simulate simultaneous development of temperature and stress that occurs during steel solidification in continuous casting processes. The efficient and robust local visco-plastic integration scheme [Koric 2006] is implemented into both implicit and explicit FE commercial software ABAQUS/Standard and ABAQUS/Explicit via user defined subroutines VUMAT and UMAT. The models are first verified with a semi-analytical solution [Weiner 1963], and later they are applied to simulate 2D and 3D transverse sections of a thin slab caster under realistic operating conditions as they move down the mold. The execution times of the implicit and explicit parallel solvers performing some of these highly computationally demanding analyses are benchmarked on the latest high performance computing platforms.

INTRODUCTION: Continuous casting is the process by which over 90% of steel is produced today. The harsh environment and extreme temperatures make experimenting and taking measurements difficult, and so many numerical models have been developed over the years, mostly using implicit finite element methods. The few seconds the steel spends in the mold are often the most critical, given the large number of possible defects related to initial solidification. The quality of continuously cast products is constantly improving, but there is still a significant amount of modeling work needed to minimize the amount of defects and to maximize the productivity. Numerical modeling of the thermo-mechanical behavior of the shell presents a large number of computational difficulties, such as the integration of the highly nonlinear visco-plastic constitutive laws, treatment of liquid/mushy zone, treatment of latent heat, accounting for the temperature dependence of material properties, contact between the solidified shell and mold surfaces, and coupling between the heat transfer and stress analysis.

A new approach is proposed here to link a cost-effective explicit time integration solution method on the global level with an efficient and robust implicit integration scheme to integrate the highly-nonlinear viscoplastic equations at the local level. The explicit and traditionally-favored implicit FE numerical methods for solidification problems are compared and the advantages that the explicit FE formulation exhibits for this class of difficult, coupled contact problems are demonstrated.

PROCEDURES, RESULTS AND DISCUSSION: Inertial effects are negligible in solidification problems, so using the static mechanical equilibrium as the governing equation is appropriate. However, in this work, the more general statement of conservation of momentum (dynamic equilibrium) is used:

$$\nabla \cdot \boldsymbol{\sigma}(\mathbf{x}) + \mathbf{b} = \rho \ddot{\mathbf{u}} \tag{1}$$

This version of the governing equation allows the use of the mass scaling to cut down on the analysis time. The rate representation of total strain in this elastic-viscoplastic model is given by:

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}_{el} + \dot{\boldsymbol{\varepsilon}}_{ie} + \dot{\boldsymbol{\varepsilon}}_{th} \tag{2}$$

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.

$$\begin{aligned}
&\dot{\bar{\varepsilon}}_{ie}[\sec^{-1}] = f_C \left(\bar{\sigma}[\mathrm{MPa}] - f_1\, \bar{\varepsilon}_{ie} \mid \bar{\varepsilon}_{ie} \mid^{f2-1} \right)^{f3} \exp\left(-\frac{Q}{T[K]} \right) \\
&\text{where:} \\
&Q = 44,465 \\
&f_1 = 130.5 - 5.128 \times 10^{-3}\, T[K] \\
&f_2 = -0.6289 + 1.114 \times 10^{-3}\, T[K] \\
&f_3 = 8.132 - 1.54 \times 10^{-3}\, T[K] \\
&f_C = 46,550 + 71,400\,(\%C) + 12,000\,(\%C)^2
\end{aligned} \tag{3}$$

Q is activation constant, and f_1, f_2, f_3, f_C are empirical temperature, and steel-grade-dependant 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]. The explicit formulation naturally does not require the tangent matrix or other complications needed by implicit methods, which is one of the reasons for increased performance.

A semi-analytical solution of thermal stresses in an unconstrained, elasto-plastic solidifying plate [Weiner 1963] was used to verify both the implicit and explicit computational models. Fig. 1 shows the stress distributions, across the solidifying shell at two different times and compares the semi-analytical solution with the numerical solutions from both the implicit and explicit models. The stress results match very well among all three methods.

The sequentially-coupled work [Koric 2007] to model solidification with a fully-implicit method in a complex geometry environment of a thin-slab funnel continuous mold proved to be a serious computational task. Similar 2D and 3D domains are analyzed here using both the implicit and fully-coupled explicit procedures. Fig. 2 shows the tangential surface stress distribution on the wide face at 5 seconds below meniscus. The funnel pushes the shell to "unbend" it, which alters the stress in the funnel region. Although the bending stresses are most severe at the shell surface, the shell experiences compression through its entire thickness, which is partly due to contact friction, and partly due to squeezing by the narrow face of the mold. The implicit solution grows more compressive in the outer half of the mold. The small differences between the implicit and explicit stress solutions are likely due to the different effects of mesh resolution on the different formulations, as well as the different contact algorithms used.

The performance of the explicit and implicit methods for the 2D funnel mold problems were evaluated for different mesh refinements. Fig. 3 presents a comparison of single-core CPU solution times as mesh refinement increases from 20,000 to 500,000 degrees of freedom (DOF). The CPU times were normalized relative to the CPU time needed for the smallest 20k DOF mesh refinement. The two methods have practically the same efficiency for problem sizes less than about 100,000 DOF. As problem size increases past this threshold, the explicit solver out-performs the implicit solver at an increasing rate. In addition to its large savings in CPU time, the explicit solver required much less memory for all runs: needing on average only 5-10% of the implicit solver memory usage.

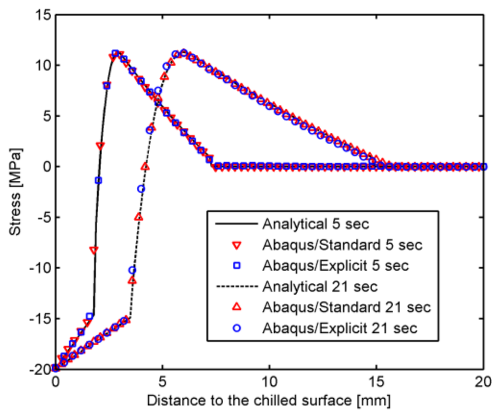

Fig 1. Stress Numerical Validation.

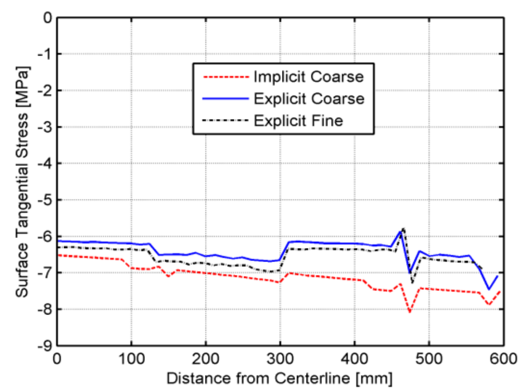

Fig 2. Tangential Surface Distribution

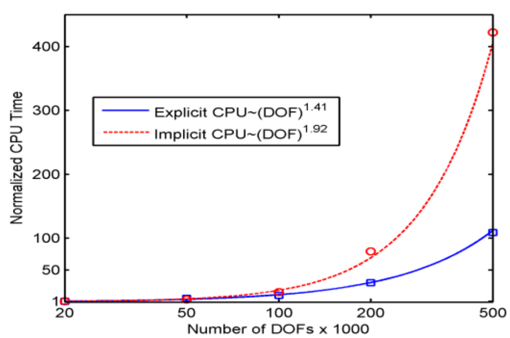

Fig 3. CPU performance

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