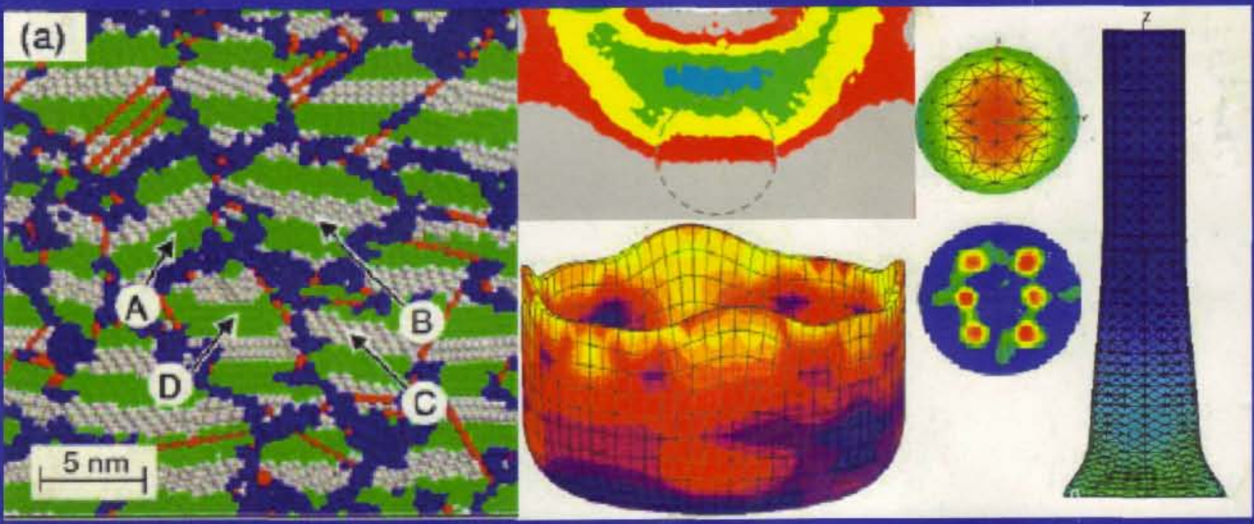
Dislocations, Plasticity, Damage and Metal Forming: Material Response and Multiscale Modeling



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STRESS ANALYSIS OF SQUEEZE FORMING PROCESSES

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ABSTRACT- During the squeeze forming process stresses in the mould and cast are developed due to temperature and applied pressure. A knowledge of the level of stresses in the cast serves to evaluate the quality of products and a knowledge of the stresses in the mould helps to evaluate the durability of the mould. During squeeze forming processes the pressure may be applied directly to the cast or through the punch. In the last case large plastic strains are developed. The problem is thermomechanical, coupled. The problem is solved using a staggered approach. A microstructural solidification model has also been included.

INTRODUCTION: The paper deals with a squeeze casting model which is currently being developed. The application of microstructural solidification models should allow us to predict better the residual stresses distribution. The interest of the readers is directed towards the influence of second order effects like initial stresses, voids, etc. An overview of squeeze casting processes is presented by Ghomashi *et al.* [2000]. A description of thermomechanical problems is shown by Sluzalec [2000], Vaz *et al.* [1996]. Methods of solving thermal problems including phase transformation are described by Lewis *et al.* [1996], microstructure evolution was shown by Celentano [1994].

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

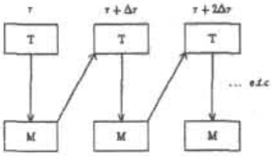
$$\nabla(k\nabla T)+q+\chi\boldsymbol{\sigma}:\boldsymbol{\varepsilon}_p=\frac{dH}{dT}\frac{\partial T}{\partial t},\quad S_1(T)=T-T_w=0,\quad S_2(T)=k\left(\frac{\partial T}{\partial n}\right)+h(T-T_w)\quad (1)$$

with enthalpy rate $dH/dT=\rho c_p$ 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 heat capacity, respectively. The equation is solved over the domain Ω and fulfils Dirichlet and Neumann boundary conditions (on $\partial\Omega$), respectively. The additional term $\chi\boldsymbol{\sigma}:\boldsymbol{\varepsilon}_p$ represents plastic work converted into heat (χ is the Taylor-Quinney coefficient, $\boldsymbol{\sigma}$ is the stress tensor and $\boldsymbol{\varepsilon}_p$ is the plastic strains tensor).

MECHANICAL PROBLEM: Mechanical problem, $\sigma_{ij,j}+X_i=0$, is also defined over domain Ω. It fulfils stress and displacement boundary conditions, $p_i=\sigma_{ji}n_j$, $u_j=0$, on $\partial\Omega$ where n_j are the normals to the boundary and u_j are the prescribed displacements.

The elastoplastic constitutive law $\sigma_{ij} = D_{ijkl}^{e-p}\varepsilon_{ij}$ is employed. The large displacements problem is described in the Updated Lagrangian configuration.

COUPLING STRATEGY: The general staggered scheme for two field problem (thermal and mechanical) is presented in Fig. 1 (left). The solution is obtained by sequential execution of thermal and mechanical modules.



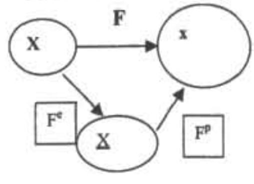


Fig 1. Coupling strategy (left), gradient decomposition (right).

The temperature field is passed to the mechanical module affecting the loading, constitutive parameters and the contact conditions. The plastic work and the air-gap which is based on the contact conditions are transferred from the mechanical to the thermal module.

STRESS INTEGRATION ALGORITHM: When considering the finite strains effect, the gradient $\mathbf{F} = \partial(\mathbf{X}+\mathbf{u})/\partial\mathbf{X}$ is decomposed into its elastic and plastic parts, $\mathbf{F} = \mathbf{F}^e\mathbf{F}^p$, Fig 1 (right). To integrate the constitutive relations the deformation increment $\Delta\mathbf{D}$ is rotated to the unrotated configuration by means of rotation matrix obtained from polar decomposition $\mathbf{F} = \mathbf{VR} = \mathbf{RU}$, $\Delta\mathbf{d} = \mathbf{R}_{n+1}^T\Delta\mathbf{D}\mathbf{R}_{n+1}$, then the radial return is performed and stresses are transformed to the Cauchy stresses at $n+1$, $\boldsymbol{\sigma}_{n+1} = \mathbf{R}_{n+1}\boldsymbol{\sigma}_{n+1}^u\mathbf{R}_{n+1}^T$.

CONSTITUTIVE RELATIONS: The additivity of small elastic, viscoplastic and thermal strains $\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^e + \dot{\varepsilon}_{ij}^{vp} + \varepsilon_{ij}^T$ and the Hooke's law $\dot{\sigma}_{ij} = D_{ijkl}\dot{\varepsilon}_{ij}^e$ lead to linearized, incremental stress-strain relation, $\Delta\mathbf{S} = \mathbf{D}(\Delta\boldsymbol{\varepsilon} - \Delta\boldsymbol{\varepsilon}^{vp} - \Delta\boldsymbol{\varepsilon}^{\mathrm{T}})$, the viscoplastic strains increment is calculated from the viscoplastic strain rate evaluation as follows

$$\varepsilon^{vp} = \gamma < \varphi(F) > \frac{\partial Q}{\partial S}, \quad \langle \varphi(F) \rangle = \begin{cases} 0 & F \le 0 \\ \varphi(F) & F > 0 \end{cases} \tag{2}$$

where F and Q are the yield and plastic potential functions, γ is the fluidity parameter. Asscociated flow rule is used, $F=Q$. Accounting for a generalized trapezoidal integration rule, $\Delta\boldsymbol{\varepsilon}^{vp} = \Delta t\left[(1-\theta)\dot{\boldsymbol{\varepsilon}}^{vp,n} + \theta\dot{\boldsymbol{\varepsilon}}^{vp,n+1}\right]$, applying Taylor expansion one gets the viscoplastic strain rate at time $n+1$

$$\dot{\boldsymbol{\varepsilon}}^{vp,n+1} = \dot{\boldsymbol{\varepsilon}}^{vp,n} + \left(\frac{\partial\dot{\boldsymbol{\varepsilon}}^{vp}}{\partial\mathbf{S}}\right)^n \Delta\mathbf{S}^n, \quad \Delta\boldsymbol{\varepsilon}^{vp} = \dot{\boldsymbol{\varepsilon}}^{vp,n}\Delta t + \mathbf{C}^n, \quad \mathbf{C}^n = \theta\Delta t\left(\frac{\partial\dot{\boldsymbol{\varepsilon}}^{vp}}{\partial\mathbf{S}}\right)^n \tag{3}$$

The viscoplastic strain increment is of the form: $\Delta\mathbf{S} = \breve{\mathbf{D}}\left(\Delta\varepsilon - \dot{\boldsymbol{\varepsilon}}^{vp}\Delta t - \boldsymbol{\alpha}\Delta T\right)$ where $\breve{\mathbf{D}}$ is the the matrix of the form: $\breve{\mathbf{D}} = (\mathbf{I}+\mathbf{DC})^{-1}\mathbf{D}$, α is the vector of thermal expansion coefficients and ΔT is the increment of temperature.

CONTACT TREATMENT: The interfacial heat transfer coefficient is used for establishing the interface thermal properties of the layer between the mould and the cast part. It depends on the air conductivity (k_{air}), thermal properties of the interfacing materials and the magnitude of the gap (g). The formula is adopted: $h=k_{air}/(g+k_{air}/h_o)$. The value of h_o, an initial heat transfer coefficient should be taken from experiment. When considering the mechanical contact the penalty approach is applied.

SOLIDIFICATION MODEL: During the entire process of forming a part the solidification process takes place. The basic assumptions: the sum of the solid and liquid fractions is equal one $f_l + f_s = 1$, the solid fraction consists of dendritic and eutectic fractions, $f_s = f_d + f_e$. Further assumptions are connected with the existence of interdendritic and intergranular eutectic fractions. The internal fraction consists of its dendritic and eutectic portions, $f_s = f_g^d f_i + f_g^e$ and $f_i = f_i^d + f_i^e$. Final formulae for the dendritic and eutectic fractions (spherical growth): $f_d = f_g^d f_i^d$, $f_e = f_g^e f_i^e + f_g^e$, $f_g^e = 4\Pi N_d R_d^3/3$ and $f_i^e = 4\Pi N_e R_e^3/3$, where N_d, N_e, are the grain densities and R_d, R_e are the grain radii. The rate of growth of the dendritic and eutectic nuclei depends on the undercooling, $\Delta T_{(d,e)} = T_{(d,e)} - T$ and Gaussian distribution of the nuclei is assumed.

$$\dot{N}_{(d,e)} = N_{\max(d,e)}\frac{1}{2\Pi}\exp\left(-\frac{\Delta T - \Delta T_{N(d,e)}}{2\Delta T_{\sigma(d,e)}}\right)\left\langle -\dot{T}\right\rangle , \quad f_i^d = 1-\left(\frac{T_m - T}{T_m - T_l}\right)^{\frac{1}{k'-1}} \tag{4}$$

The rate of the dendritic and eutectic grain radii is established based on experimental dependence, $\dot{R}_{(d,e)} = f_{R(d,e)}$. Finally, the internal dendritic fraction f_i^d depends on the melting temperature and k' is the partition coefficient.

FINAL REMARK: A mathematical framework of the developed squeezed casting model is presented, the numerical examples will be given in the full paper.

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