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## MODELLING OF METAL FORMING PROCESSES AND MULTI-PHYSIC COUPLING.

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**Key words:** Forming Process, Thermal Coupling, Induction Heating, Micro-Structure.

**Summary.** *The main important physical phenomena which can be coupled with the mechanical computation of metal forming processes are analyzed. We present briefly the case of strong thermal coupling when localization occurs, solid and liquid interactions, electro magnetic and thermal coupling, and multi scale coupling for predicting metallurgic microstructure evolution.*

### 1 INTRODUCTION

Since about thirty years ago, numerical modeling of metal forming processes was starting to be developed in laboratories, refs. [1] to [4], mostly with the finite element method. On the other hand, several physical phenomenons' still remain very approximately known, either during the forming process itself, or during the heating or cooling process, and in heat treatment operations. It is an industrial demand to predict with the same software the material evolution during the whole process.

### 2 MECHANICAL APPROACH OF METAL FORMING PROCESSES [5]

#### 2.1 Constitutive modeling

Additive decomposition of the strain rate tensor into elastic and plastic parts is written:

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^e + \dot{\boldsymbol{\varepsilon}}^p \quad (1)$$

The Perzyna formalism is often retained for the plastic component of the strain rate tensor:

$$\dot{\boldsymbol{\varepsilon}}^p = \frac{1}{K} \left\langle \frac{\sigma_{eq} - R}{K} \right\rangle^{\frac{1}{m} - 1} \boldsymbol{\sigma}' \quad (2)$$

where  $\boldsymbol{\sigma}'$  is the deviatoric stress tensor,  $\sigma_{eq}$  the equivalent stress,  $R$  the yield stress,  $K$  the consistency and  $m$  the strain rate sensitivity index.

At the interface between part and tool the friction shear stress can be modelled by :

$$\boldsymbol{\tau} = -\alpha_f(\sigma_n) \mathbf{K} |\Delta \mathbf{v}|^{q-1} \Delta \mathbf{v} \quad (3)$$

$\alpha_f$  is a function of the normal stress  $\sigma_n$ , and  $\Delta \mathbf{v}$  is the tangential velocity.

For a quasi incompressible flow, it is desirable to utilize a mixed formulation:

$$\int_{\Omega} \boldsymbol{\sigma}' : \dot{\boldsymbol{\varepsilon}}^* dV - \int_{\partial\Omega_c} \dot{\boldsymbol{z}} \cdot \mathbf{v}^* dS - \int_{\Omega} \dot{p} \operatorname{div}(\mathbf{v}^*) dV = 0 \quad (4)$$

$$-\int_{\Omega} (\operatorname{div}(\mathbf{v}) + \dot{p} / \kappa) p^* dV = 0 \quad (5)$$

## 2.2 Finite element approximation

The discretization scheme must be compatible with numerical and computational constraints:

- Remeshing and adaptive remeshing ;
- Unilateral contact analysis,
- Iterative solving of non linear and linear systems;
- Domain decomposition and parallel computing;
- Easy transfer of physical internal parameters, for multi physic coupling.

## 3 THERMAL AND FLUID-SOLID COUPLING

### 3.1 Classical thermal and mechanical coupling

The classical heat equation for deformable bodies is written simply:

$$\rho c \frac{dT}{dt} = \operatorname{div}(k \operatorname{grad}(T)) + f_w \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}} \quad (6)$$

$f_w$  is a fraction viscoplastic heat dissipation; and the constitutive law depends on T, e. g.:

$$\mathbf{K} = \mathbf{K}_0 (\varepsilon_0 + \bar{\varepsilon})^n \exp(\beta/T), \quad m = m_0 + m_1 T \quad (7)$$

### 3.2 Localization

When the thermal and mechanical coupling is strong enough, such as in processes where localization in narrow shear bands can occur (e. g. in high speed machining), coupling at each time step is compulsory and a fixed point algorithm may not converge. In this case it is desirable to treat simultaneously the mechanical and thermal equations. We have a non linear problem with unknown nodal temperature  $\mathbf{T}^{t+\Delta t}$ , velocity  $\mathbf{V}^{t+\Delta t}$ , and pressure  $\mathbf{P}^{t+\Delta t}$ , which can be solved by a global Newton-Raphson method.

### 3.3 Fluid solid coupling during heating or heat treatment

Fluid - solid coupling is an important issue in several industrial processes. During heating in a furnace, we must take into account the flow of the surrounding gas and heat exchange between the gas and the preforms, in order to determine precisely the temperature field inside

the work-pieces which will be formed. The problem is even more complicated when one wants to predict the quenching process with water which will be vaporized at the contact of a hot work piece. An analogous situation arises in casting of large work pieces during the cooling process, when a solid fraction interacts with a moving fluid. An efficient frame for this coupling is to use an ALE formulation for the liquid phase.

#### 4 ELECTRO MAGNETIC COUPLING

Many industrial heating devices use direct or induced currents to generate heat inside a work piece. Simulation of the process is based on a coupling between electromagnetic, thermal and mechanical phenomena. The general Maxwell equations can be simplified in the axisymmetrical case : they are written in term of the electric field  $\mathbf{E} = (0, E_\theta(r, z), 0)$ . The heat equation includes the local heat rate, generated by the eddy currents, and integrated over one period  $\mathcal{T}$  :

$$\bar{Q}_{em} = \left( \int_0^{\mathcal{T}} \sigma |\mathbf{E}|^2 dt \right) / \mathcal{T} \quad (8)$$

The case of a workpiece in ferromagnetic EN3 mild steel heated at 930 °C is presented in fig. 1. The work piece is heated by an inductor of the same length. Process parameters are: frequency: 500Hz, current density: 8.108 Amps/m<sup>2</sup>, electromagnetic time step:  $\mathcal{T}/64=3.125 \cdot 10^{-5}$ s, and thermal time step: 0.5s.

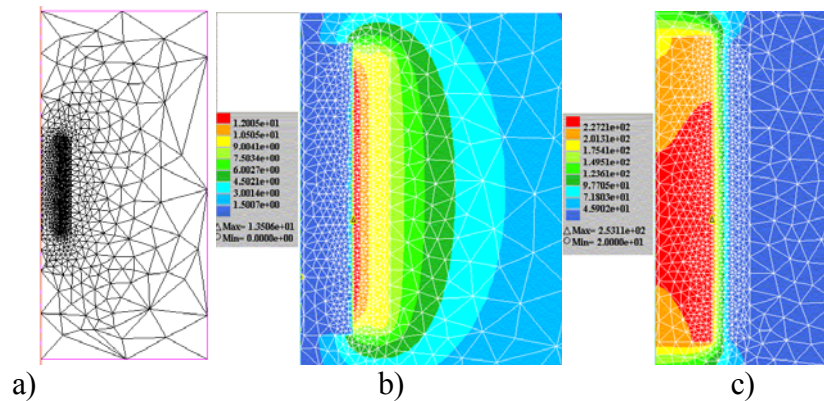


Figure 1 : a) Finite element mesh; b) Electric field; c) Temperature field

#### 5 COUPLING WITH MICROSTRUCTURE EVOLUTION

The Macroscopic approach is typically used with the Avrami formula to describe the recrystallization fraction X:

$$X = 1 - \exp \left( -\ln \left( \frac{t}{t_{0.5}} \right)^k \right) \quad (9)$$

$t_{0.5}$  is the half recrystallization time, and k the Avrami exponent. This strategy has been used with the 3D Finite Element code Forge3® for forging simulations, as shown in fig. 2.

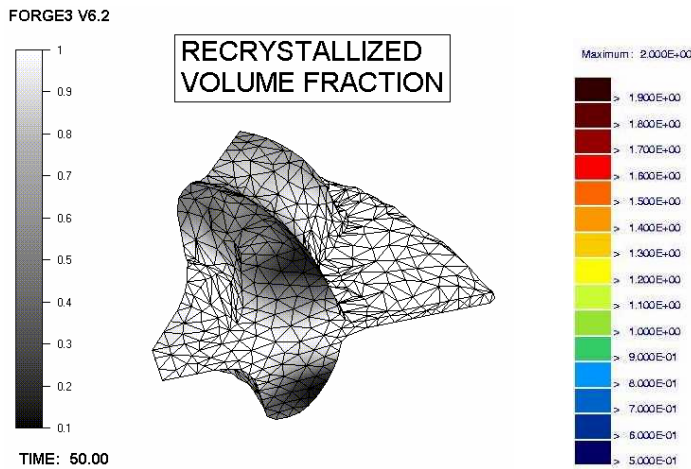


Figure 2. Recrystallized volume fraction maps of a forged 316l part

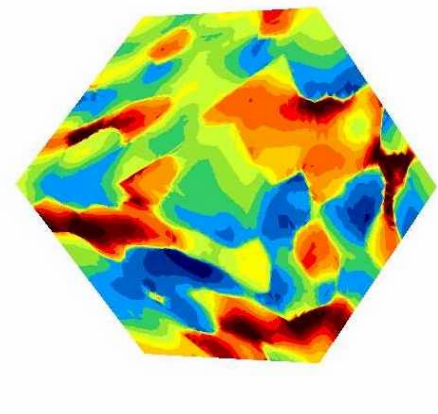


Figure 3. Strain field calculated for the two-phase material volume

The multi-scale coupling consists for example in meshing a heterogeneous microstructure, for studying the relationships between the microstructure and its evolution, and the associated constitutive law. A calculation of strain distribution for a two-phase ensemble is presented in Figure 3 (for more details see ref. [7]).

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