



COST 526

**“Automatic Process Optimization in Materials Technology”  
(APOMAT)**

**Half-Yearly Report**

<b>1. Reporting Period</b>	<b>1.7.2002 – 31.12.2002</b>
Project title	OPTIMIZATION OF FORGING CHARACTERISTICS OF METAL IN MUSHY STATE
Project leader	Jaroslav Horský
Organization	Brno University of Technology, Czech Republic
Main collaborators involved	University of Ljubljana, University of Krakow

**2. Funding Situation**

Amount of money received specifically for COST

11.5 kEuros

Other resources partially used for the project

kEuros

**3. International Collaboration**

(mention group and type of work done in collaboration during the reporting period)

Participation in the Working Group Meeting in Budapest + project progress report

YES

**4. Industry participation**

(mention name of companies and work done in collaboration during the whole project)

Nová Huť Ostrava. Measurement of heat boundary conditions and implementation into concast simulator.

**5. Meetings, visits, exchange of  
scientists, short-term scientific  
missions**

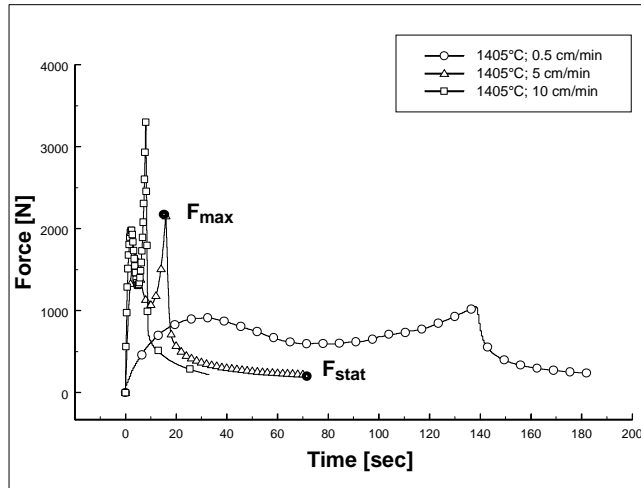
**Location, date**

## 6. Progress within the reporting period

(Not exceeding 3 pages, including tables and figures)

### Identification of material parameters

The problem of selection of a material model for semi-solid forming and identification of appropriate material characteristics is a subject of a growing number of papers. They can be generally divided into several groups, according to the predominant area of interest and applicability.



**Figure 1.** Resisting force as a function of time (temperature 1405 °C, tool velocity 0.5; 5 and 10 cm/min).

The most important factor that controls the flow behavior is the relative fraction of solid and liquid, which is in turn controlled by temperature. At low solid fraction, above 0.05, the material behaves as non-Newtonian, history dependent fluid, (Turng *et al.*, 1991), (Flemings 91), (Joly *et al.*, 1976).

At higher solid fraction, approximately above 0.7, the material can behave as a nonlinear viscoplastic solid. The flow resistance increases dramatically as the solid fraction reaches critical values representing the development of interconnected network. Here, again, different approaches can be found, based first on internal variable constitutive models. Such models employ two sets of equations, one set that represents the flow behavior, the other represents the evolution of structure, (Kang *et al.*, 1998), (Yoon *et al.*, 2001), (Zavaliangos *et al.*, 1995). The value of such models is substantial in their effort to understand and include actual physical processes governing the flow of material and provide a more accurate representation of the flow behavior for simulation. Although internal variable models offer substantial promise, much remains to be done to produce a complete, user-friendly tool, integrated into a well established FE-based simulation software.

Practical industrial demands can be sometimes met by relatively simple models, where the semi-solid material is considered from the global point of view as a single phase material, (Flemings 91), (Laxmanan *et al.*, 1980). Although the scope of validity of such phenomenological models is limited, their simplicity is the advantage that must be taken into account when calibrating or using such models.

As the compression experiments described above covered the area of relatively high fraction of solid, viscoplastic material model according to Perzyna was used, (Perzyna 68). Here, the flow curve of material is described by

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$$\sigma = \left[ 1 + \left( \frac{\dot{\epsilon}}{\gamma} \right)^m \right] \sigma_0(\epsilon) \quad [1]$$

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where:

$\sigma$  = material yield stress,

$\dot{\epsilon}$  = equivalent plastic strain rate,  
 $m$  = strain rate hardening parameter,  
 $\gamma$  = material viscosity parameter,  
 $\sigma_0(\epsilon)$  = static yield stress of material, which is a function of some hardening parameters in general.

We suppose that the static yield stress – for given temperature and solid fraction–depends on the cumulated plastic strain only. Such conclusion is based on the experiments results, where the relaxed static stress drops to the same value shortly after the ram stops, irrespective of its previous velocity – see the static force  $F_{stat}$  on Fig. 1. The following procedure was then used to evaluate the parameters of the model:

Set of compression experiments was realized, covering certain range of velocity. In our case, three experiments with solid fraction 0.7 and ram velocity 0.5, 5 and 10 cm/min were realized, resulting in measured force-displacement curves according to Fig. 2.

For two selected velocities,  $v_1$  and  $v_2$ , maximal and relaxed forces  $F_{max1}$ ,  $F_{max2}$ ,  $F_{stat1}$ ,  $F_{stat2}$  were used to obtain mean values of maximal and static stress

$$\sigma_{max1} = \frac{F_{max1}}{S}, \quad \sigma_{max2} = \frac{F_{max2}}{S}, \quad \sigma_{stat1} = \frac{F_{stat1}}{S}, \quad \sigma_{stat2} = \frac{F_{stat2}}{S}. \quad [2]$$

Appropriate strain rate at the end of compression

$$\dot{\epsilon}_1 = \frac{v_1}{h}, \quad \dot{\epsilon}_2 = \frac{v_2}{h}. \quad [3]$$

In the above equations,  $h$  is height of the specimen at the end of compression and  $S$  ideal cross section without bulging, obtained from  $S \cdot h = S_0 \cdot H_0$

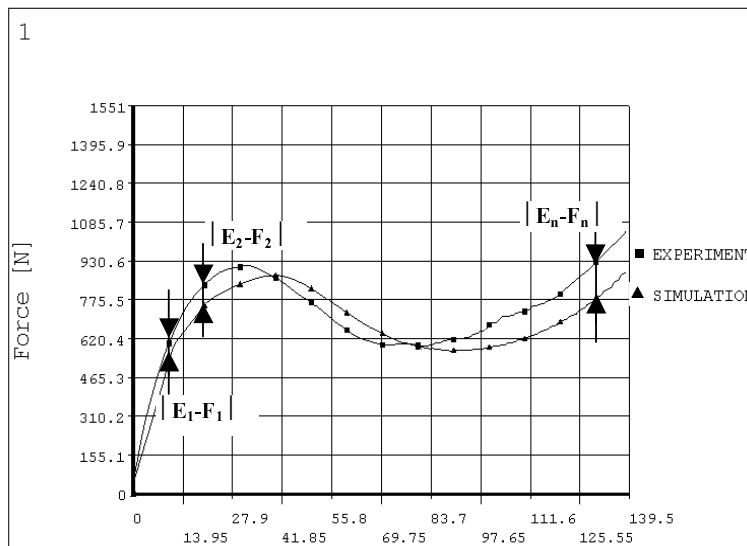
Strain rate hardening parameters  $m$ ,  $\gamma$  can be then evaluated from the Perzyna's relation at the end of compression under velocity  $v_1$ , resp.  $v_2$ .

$$\frac{\sigma_{max1}}{\sigma_{stat1}} = 1 + \left( \frac{\dot{\epsilon}_1}{\gamma} \right)^m, \quad \frac{\sigma_{max2}}{\sigma_{stat2}} = 1 + \left( \frac{\dot{\epsilon}_2}{\gamma} \right)^m. \quad [4]$$

The first estimate of parameters  $m$ ,  $\gamma$  is then complemented by evaluation of the static yield stress curve  $\sigma_0(\epsilon)$ , which is based on the minimization of differences among the results of experiments and their numerical simulation. If we denote  $E$  the compression force obtained from experiment and  $F$  the force from simulation (see Fig. 2), the problem can be formulated as minimization of an objective function

$$s = \sum_{i=1}^{k \cdot n} [E_i - F_i]^2 \quad [5]$$

where  $n$  is number of check points on the force – displacement curve and  $k$  is number of realized and simulated experiments (for different ram velocities).



**Figure 2.** *Minimization of results difference.*

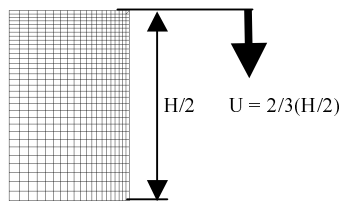
The simulations were realized as an axisymmetrical problem by ANSYS (Fig. 3), using for minimization the algorithm, based on the sequential unconstrained minimization technique. Design variables of the process were selected points on the yield stress curve  $\sigma_0(\epsilon)$ , which is approximated as a continuous, piecewise linear curve.

Another parameter to be obtained is the friction between ram and specimen. This can be either estimated from the difference of measured and computed bulging in repeated computations, or it can be added as another design variable with bulging difference being a new objective function. As this rigorous method rather complicates the computational procedure with little gain, the engineering assessment is preferred at this moment.

After obtaining the static yield stress curve  $\sigma_0(\epsilon)$ , rate hardening parameters estimated by eq. [4] from mean values of stress and strain can be now corrected by the same minimization procedure described above by eq. [5]. The only difference now is that the design variables are the values  $m, \gamma$ , instead of the curve  $\sigma_0(\epsilon)$ , which is now held fixed.

Using the described procedure, the following parameters of the material model [1] were identified:

- static yield curve  $\sigma_0(\epsilon)$
- strain rate hardening parameter  $m = 0.35$
- viscosity parameter  $\gamma = 3.3 \times 10^{-4}$



**Figure 3.** *FE mesh.*

## 7. List of publications

### a) Published

### b) Submitted for publications

Horský, J.- Kotrbáček, P. - Petruška, J. - Řídký, R.: Experimental Study of Semi-solid steel deformation, International Journal of Forming Processes.

### c) In preparation

