COST 526
“Automatic Process Optimization in Materials Technology”
(APOMAT)

Half-Yearly Report

To be sent to **V.Tesch@access.rwth-aachen.de** until **August 27, 2004**

1. Reporting Period	**1.1.2004 – 30.6.2004**
Project title	Optimization of Tool Shape in the Tests Aiming at Identification of Models Describing Rheological and Mechanical Properties of Metallic Alloys
Project leader Organization	Maciej Pietrzyk
Main collaborators involved	Jan Kusiak Danuta Szeliga Andrzej Zmudzki Bartłomiej Wierzba Tomasz Kondek Paweł Matuszyk Jerzy Gawąd

2. Funding Situation

Amount of money received specifically for COST	67,8 kEuros
Other resources partially used for the project	0 kEuros

3. International Collaboration
(mention group and type of work done in collaboration during the reporting period)

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

π **YES**

π ~~NO~~

4. Industry participation
(mention name of companies and work done in collaboration during the whole project)

No

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)

Parts of work done in reporting period:

Optimization of Tool Shape in the tests aiming at identification of models describing rheological and mechanical properties of metallic alloys

The work performed during reporting period was divided into three parts. First part contained development of the user friendly Inverse analysis software for interpretation of results of tension and compression tests. Second part contained complex sensitivity analysis of performed compression and extrusion experiments to take into consideration whether the extrusion processes is competitive to standard ring compression test in the evaluation of material properties and boundary conditions. The last part of the work comprised still needful researches for proper material model for semi solids. The Cellular Automata approach for diffusion phenomenon mdelling and it’s transition from micro to macro scale for semi-solid material behaviour modelling was proposed.

INVERSE ANALYSIS SOFTWARE

To perform Inverse analysis of any deformation process, it should be described by the set of equations:

$$\mathbf{d} = F(\mathbf{x},\mathbf{p}), \qquad F : R^l \to R^r \tag{1}$$

where $\mathbf{d} = \{d_1,...,d_r\}$ - vector of measured output process parameters, $\mathbf{x} = \{x_1,...,x_k\}$- vector of model parameters (unknown), $\mathbf{p} = \{p_1,..., p_l\}$ - vector of process variables (process conditions), *r* – number of measured parameters, *k* – number of unknown parameters in the model, *l* – number of process variables.

The objective of the inverse analysis is an evaluation of optimum values of vector **x** components, What leads to minimization, with respect to the vector **x**, of the distance between vectors containing calculated and experimental values described by following goal function:

$$\Phi(\mathbf{x}) = \sum_{i=1}^{n} \beta_i [\mathbf{d}_i^c(\mathbf{x}, \mathbf{p}_i) - \mathbf{d}_i^m]^2 \tag{2}$$

where: $\mathbf{d} = \{d_1^m,...,d_r^m\}$ - vector of measured data, $\mathbf{d} = \{d_1^c,...,d_n^c\}$ - vector of calculated data, β_i – weight factors (*i* = 1 .. *n*), *n* - number of sampling points. Measured data $\mathbf{d}^m$ is obtained from experiment and values $\mathbf{d}^c$ are calculated using numerical or analytical model of the direct problem.

The inverse analysis is rather complicated and not esay to perform with standard (commercial) optimization and FEM codes. Therefore complex and user frendly inverse software (Opty_Axi) dedicated for tension and compression tests analysis was elaborated. It contains three parts of analysis: 1. Measured data processing; 2. Definition of the analysed process (geometry, conditions, etc.); 3. Preliminary and full inverse analysis. Examples of Opty_Axi interface system are presented in figure 1 (left – process conditions definition; right – flow stress equation and optimization parameters set-up). Opty_Axi software has modular architecture, and specific modules can be extended, e.g. new optimization procedures can be introduced or different FEM codes for direct problem solving.

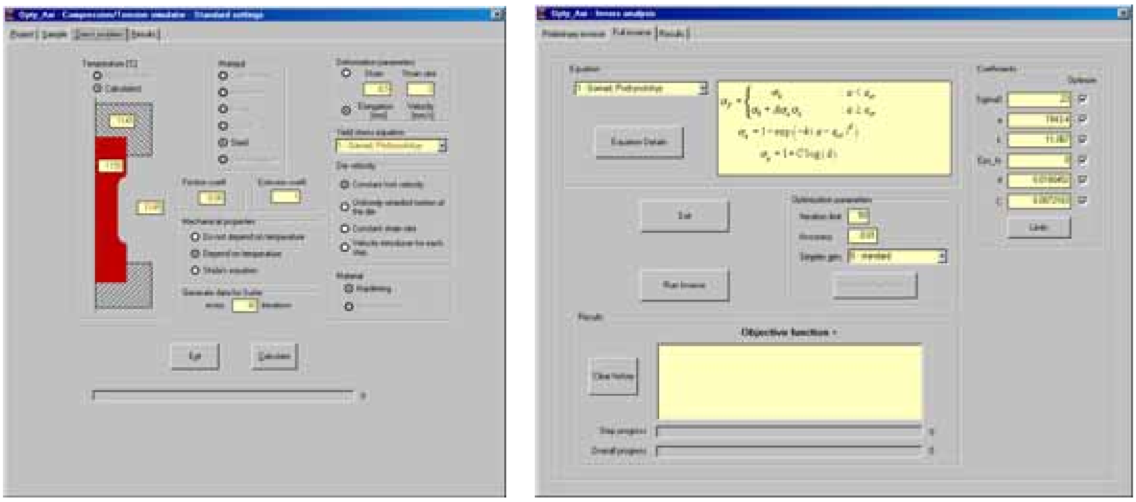

Fig.1. Process parameters and flow stress computations windows (Opty_Axi)

SENSITIVITY ANALYSIS OF RING COMPRESSION AND EXTRUSION PROCESSES

Design of plastometric test dedicated to specific materials, e.g. semi-solids, despite optimization tasks, has to be based on the analysis of sensitivity of the parameters, which are measured in the test, with respect to the parameters, which are to be identified. The comparison of the sensitivity of the measured parameters of the ring compression test and forward-backward extrusion test process on the rheological and friction parameters was the prime objective of this part of the work.

The primary analysis included evaluation of correlation between the independent and dependent variables in the ring compression test. The selected results of this analysis obtained for the ring ϕ18×ϕ9×6 mm are presented in Figure 2. The independent variables, which were considered, are: friction coefficient μ, hardening coefficient a and hardening exponent m in the strain hardening curve. The dependant variables are load F and inner and outer radius of the ring after compression: R_{in-top}, $R_{out-top}$, - inner and outer radius at the contact surface, respectively, $R_{in-centre}$, $R_{out-centre}$ - inner and outer radius at the centre of the sample, respectively. It is seen that the load is correlated to the coefficient a, slightly less correlated to the friction coefficient μ and almost no correlation is observed between the load and the hardening coefficient m. Dimensions of the ring after compression are correlated to the friction coefficient μ and no correlation is observed between the ring dimensions and the parameters of the strain hardening curve.

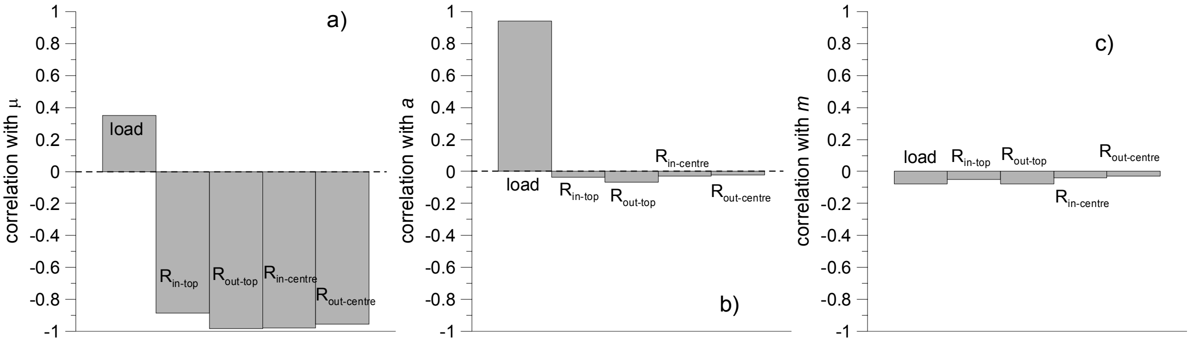

Fig.2. Correlation between measured parameters in ring compression and: a) friction coefficient, b) hardening coefficient a, c) hardening exponent m.

A large number of the finite element simulations is needed for the evaluation of correlations. Since simulation of the forward-backward extrusion process requires very long computing times, it was not possible to perform such an analysis for this process. Therefore, the second task of the sensitivity analysis included determination of the following coefficients:

$$S_{ring-1} = \frac{1}{R_{in\_0}} \frac{\partial R_{in\_top}}{\partial \mu} \qquad S_{ring-2} = \frac{1}{R_{out\_0}} \frac{\partial R_{out\_top}}{\partial \mu}$$

$$S_{ring-3} = \frac{1}{R_{in\_0}} \frac{\partial R_{in\_centre}}{\partial \mu} \qquad S_{ring-4} = \frac{1}{R_{out\_0}} \frac{\partial R_{out\_centre}}{\partial \mu} \tag{3}$$

$$S_{extr-1} = \frac{1}{h_{10}} \frac{\partial h_1}{\partial \mu} \qquad S_{extr-2} = \frac{1}{h_{20}} \frac{\partial h_2}{\partial \mu}$$

where: h_1, h_2 – height of the filling of the gap in the upper and lower die in extrusion, respectively, R_{in}, R_{out}, - initial inner and outer radius, respectively. Index "0" refers to the average value of the considered parameter.

The objective of this analysis was evaluation how sensitive are the parameters, which are measured in the ring compression and in the extrusion, on the friction coefficient. Definition of coefficients in equation (3) as dimensionless parameters allowed direct comparison of sensitivities for the two tests. The results are presented in Figure 3. The sensitivity of the height h_1 and h_2 was calculated separately for the two different lower ram diameters: 9.5 mm corresponds to index D1 and 11 mm corresponds to the index D2.

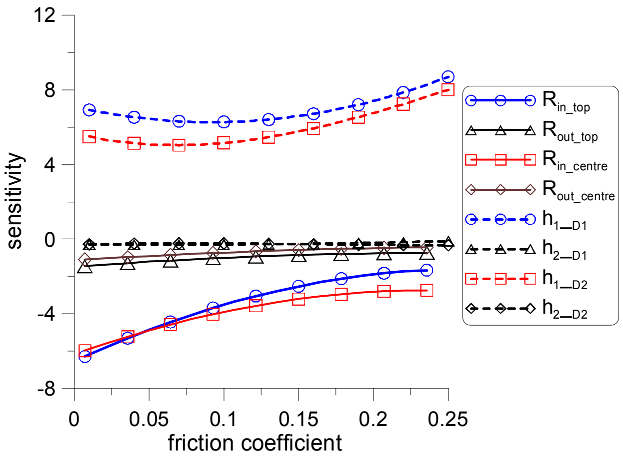

Fig.3. Sensitivity of dimensions of samples after the test on the friction coefficient calculated according to equations (3) as a function of the friction coefficient.

It is seen that the sensitivity of dimensions of rings to friction coefficient is slightly smaller than that observed for forward-backward extrusion. It is also seen that the inner radius of the ring is more sensitive to the changes of the friction coefficient than outer radius. It is confirmed by the plots in Figure 4 (left), which were obtained for the ring ϕ12×ϕ6×4 mm. The shape of the ring calculated for various friction coefficients is compared with the experimental data in this figure. Changes of the friction coefficient cause larger changes of the inner radius comparing to the outer radius. Similarly, it is seen in Figure 3, that the height of the thicker wall of the extruded cup (h_2) is less sensitive to the friction coefficient then the height of the thinner wall (h_1).

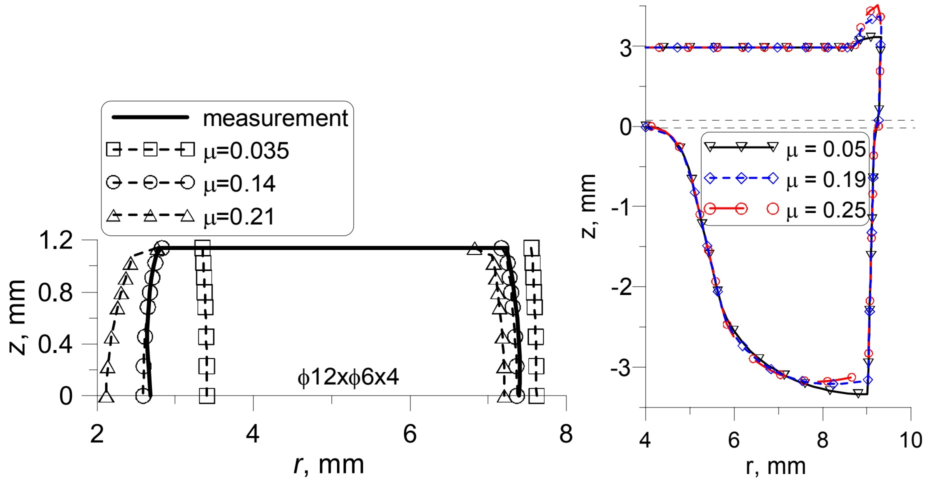

Fig.4. Shape of the ring (left) and extruded cup (right) obtained from measurements and calculated for various friction coefficients.

It is confirmed by the results shown in Figure 4 (right), where the shape of the cross section of the extruded cup calculated for various friction coefficients is presented. The best agreement with the experiment was observed for the friction coefficient of 0.19. Notice that a central part of the cross section (between dotted lines) is removed to make the plot clearer. Figure 3 also shows that relation of the sensitivity of sample dimensions on the value of the friction coefficient is opposite for the two investigated tests. Sensitivity of the dimensions of the extrudate increases with the increasing friction coefficient while the opposite tendency is observed for the ring dimensions.
Figure 5 shows sensitivity of loads to friction coefficient for ring compression and extrusion tests. The sensitivity for both considered tests is defined as:

$$S_{load\_\mu} = \frac{1}{F_0}\frac{\partial F}{\partial \mu} \qquad S_{load\_a} = \frac{1}{F_0}\frac{\partial F}{\partial a} \qquad S_{load\_m} = \frac{1}{F_0}\frac{\partial F}{\partial m} \tag{4}$$

where: F_0 – average load during the test.

It is seen that both investigated tests show similar sensitivity of loads to parameters of the strain hardening function. Sensitivity of loads to friction coefficient differs slightly for the two tests, it increases rapidly for large friction coefficients in the extrusion and an opposite tendency is observed in the ring compression. In general, the sensitivity of load to the rheological parameters is lower than that to friction and its dependence on friction, as well as on rheological parameters itself, is weak.

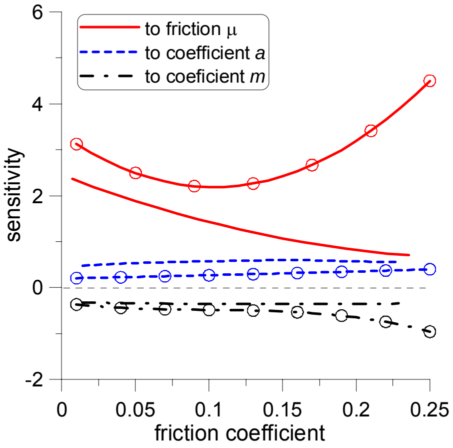

Figure 5. Sensitivity of loads to changes of the friction coefficient μ, hardening coefficient a and hardening factor m calculated according to equations (4). Lines with symbols represent extrusion and lines without symbols represent ring compression.

CAFE COMPUTATIONS APPROACH

As it was shown in previous reports and researches definition of proper material model for semi-solid materials FEM calculation is a very difficult task. Commonly used models and flow stress equations are not efficient enough or are efficient for small range of process parameters (e.g. temperature). Hence the new Idea of using Cellular Automata for such materials was proposed. At the initial stage of research the diffusion CA modelling and an Idea of micro to macro scale transition (micro – diffusion of atoms of one metal inside atomic lattice matrix of other; macro – solid particle movement inside the liquid phase) was proposed (figure 6). The CA approach is based on equation of motion (local momentum conservation equation):

$$\rho \left.\frac{Du}{Dt}\right|_u = -\nabla p + Div\sigma + f + \rho \left.\frac{Dv_d}{Dt}\right|_u \tag{5}$$

The diffusion of atoms and, for the future, solid particle movement is strongly dependent on stress and deformation state of the material. Following forces can act on the mass:
1.The force of stress, exerted across the surface
2.The viscosity force, acting on the surface
3.An external force, acting on the mass in volume
4.Diffusion force, acting on the mass.

The equation of motion has the form of the Navier-Stokes equation, except for the additional diffusional term f_d:

$$f_d = \rho \frac{D v_d}{Dt}\bigg|_u \tag{6}$$

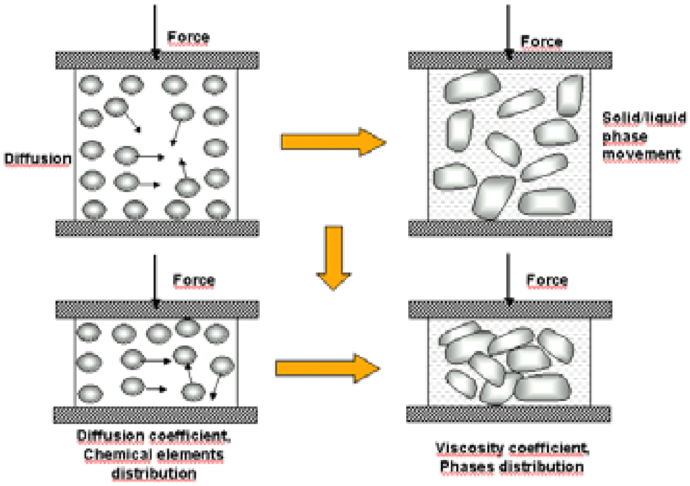

Fig.6. Idea of transition from diffusion to semi solid material behaviour under force acting on the material

The CAFE approach is a combination of Cellular Automata and Finite Elements computations. The Cellular Automata is introduced to every element of FE mesh (as seen on figure 7). After each iteration of FEM computations the stress and deformation tensor is transmitted into CA and the diffusion coefficient is calculated. In consequence, the chemical composition distribution during deformation process can be obtained.

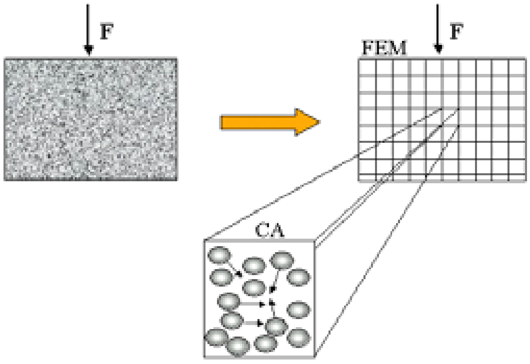

Fig.7. Idea of the CAFE approach

In the macro scale the distribution of solid and liquid phases during deformation and their influence on material flow can be obtained. The phase composition is not dependant only on temperature. During semi-solid material deformation densification of solid particle and liquid phase outflow is observed. Such solution (CA application) can provide information on semi-solid material behaviour close to one observed in real processes.

SUMMARY

Three parts of work were performed during desribed reporting period:

- User friendly Inverse analysis software for results interpretation of tension and compression tests was developed.
- Complex sensitivity analysis of performed compression and extrusion expermentswas made. The conclusion from this part is that the extrusion process is competitive in material properties and boundary conditions evaluation to standard ring compression test.
- The Cellular Automata approach for diffusion phenomenon mdelling and it's transition from micro to macro scale for semi-solid material behaviour modelling was proposed.

7. List of publications

a) Published

Identification of friction model in extrusion, Conf. Konstrukcja I Technologia Wytłoczek I Wyprasek, Poznań 2004, Obróbka Plastyczna Metali, nb.3, 2004, pp.69-78, A. Żmudzki, R. Kuziak, M. Papaj, M. Pietrzyk.

Validation of the forward-backward extrusion test, designed for evaluation of friction coefficient and flow properties of metal alloys deformed in semi-solid state. Conf. METALFORMING 2004, Krakow, Poland, Steel Grips, nb.3, 2004, pp.541-545, A. Żmudzki, M. Papaj, R. Kuziak, J. Kusiak, M. Pietrzyk.

Various Plastometric Tests for Semi Solid Materials and Their Numerical Simulations, Conf. METALFORMING 2004, Krakow, Poland, Steel Grips, nb.3a, 2004, pp.735-739, A. Żmudzki, M. Pietrzyk, P. Kotrbacek, J. Horsky.

b) Submitted for publications

Identification of Material model for aluminium using hot double-cup extrusion test, Conf. ESAFORM 2005, Cluj-Napoca, Romania, A. Żmudzki, M. Papaj, R. Kuziak, J. Kusiak, M. Pietrzyk.

c) In preparation

Design of the test for identification of parameters in friction and rheological models for very soft materials. Archives of Metallurgy
A. Żmudzki, R. Kuziak, M. Pietrzyk