COST 526

“Automatic Process Optimization in Materials Technology”
(APOMAT)

Half-Yearly Report

1. Reporting Period	**1.1.2003 – 30.6.2003**
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 Tomasz Kondek Pweł Matuszyk Jerzy Gawąd Andrzej Zmudzki

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 Brussels + project progress report ❐ **YES**

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

Lack of the reliable material model required for the accurate FEM simulation of deformation processes of semi-solid materials and plastometric tests, which are not adequate in case of deformation of these materials, makes researches reasonable enough. The new test for evaluation of material properties of metal alloys deformed in semi-solid state, supplies information regarding both rheological and friction models of metal alloys in semi-solid state and the measured data can be directly used in the inverse analysis of the deformation process. The test is based on combination of forward and backward extrusion process, as shown on figure 1.

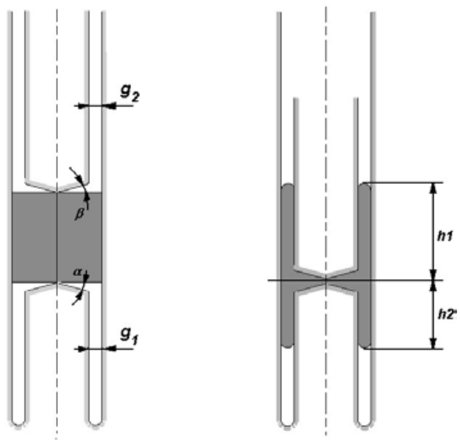

Fig. 1. *Proposed die set*.

MATERIAL MODEL

Parallel to preparations of researches on forming of materials in semi-solid state, the work on reliable material model has been conducted. The material behaviour during the deformation depends strongly on stress state and structure of solid phase, which can vary from globular to dendritic (i.e. steels). During the deformation of materials in semi-solid state with dendritic structure, three stages of the deformation can be seen. The first is the hardening period, which involves densification of solid powder and flow of liquid. The second is softening period, when surface cracks and breakage of solid particles occur. The third one is hardening period, which involves plastic deformation of solid particles. Searching for an accurate model of this process has been performed in the project. The model proposed by Yoon et. al., which supplies information about flow stress for both globular and dendritic structure of solid phase, was selected. Constitutive equations of this model are listed below:

$$\bar{\varepsilon} < \bar{\varepsilon}_{cr} \qquad \bar{\sigma}_f = K\left(\frac{\bar{\varepsilon}}{\bar{\varepsilon}_{cr}}\right)^n \exp(b)\dot{\bar{\varepsilon}}^m \tag{1}$$

$$\bar{\varepsilon} \geq \bar{\varepsilon}_{cr} \qquad \bar{\sigma}_f = K\exp\left(b\frac{\bar{\varepsilon}-\bar{\varepsilon}_{st}}{\bar{\varepsilon}_{cr}-\bar{\varepsilon}_{st}}\right)\dot{\bar{\varepsilon}}^m \tag{2}$$

The consistency parameter K is calculated as follows:

$$f_s > f_{cr} \qquad K = K_0\exp\left[C_2\left(f_s - f_{cr}\right)\right] \tag{3}$$

$$f_s \leq f_{cr} \qquad K = K_0\frac{1-\left[\beta(1-f_s)\right]^{2/3}}{1-\left[\beta(1-f_{cr})\right]^{2/3}} \tag{4}$$

where: $\bar{\varepsilon}_{cr}$ – critical strain, f_{cr} – critical solid fraction $\bar{\varepsilon}_{st}$ – steady state strain, b = $C_2(1-S_0)$, where

S_0 – initial breakage ratio. The breakage ratio in solid particles is defined as linear function of strain:

$$S = C_1\left(1 - S_0\right)\frac{\bar{\varepsilon} - \bar{\varepsilon}_{st}}{\bar{\varepsilon}_{cr} - \bar{\varepsilon}_{st}} \tag{5}$$

In equations (2) – (5) C_1 = 2.2 β = 1.5, C_2 = 4.2 (coefficients evaluated during parameter studies). For globular structure the ratio S_0 = 1, and for dendritic S_0 = 0. The comparison of calculated and measured data from simple hot upsetting tests is shown in fig. 2.

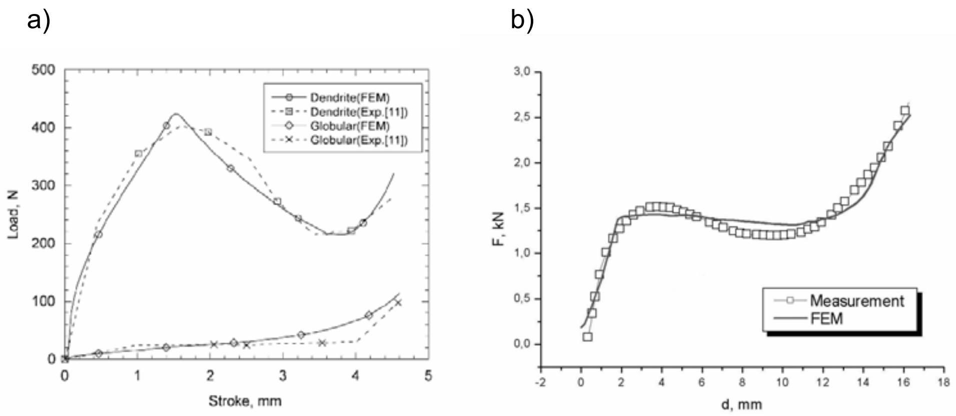

Fig. 2. *Comparison of experimental load-displacement curves and FEM results (a) for Sn-15%Pb alloy (performed by Yoon et. al); (b) for tool carbon steel (after the Inverse analysis)*.

The data from hot upsetting test for cylindrical samples, performed in The Technical University of Brno (Czech Rep.), has been used to verify the proposed model. The Inverse analysis of test results has been carried out to evaluate the model parameters. Examined material was a tool carbon steel containing: 1.03%C, 0.22%Mn, 0.05%Ni, 0.19%Si, 0.09%Cu, 0.01%P, 0.03%S, 0.04%V.

The Simplex algorithm was applied to solve the minimization problem, and FEM code was used to solve the direct problem in the inverse analysis. As shown in fig. 2b, achieved results show correct model behaviour, for both different types of alloys and their structures. Evaluated set of parameters for tool carbon steel is presented in table 1.

Table 1. *Evaluated model parameters.*

$\bar{\varepsilon}_{cr}$	0.12173	f_{cr}	0.88341
$\bar{\varepsilon}_{st}$	4.29562	K	0.27171
C_1	3.26332	β	0.06805
C_2	0.36704	m	0.001
n	0.39525	S	8.77E-05
a	0.01213		

In spite of correct description of load-displacement curve, accounting for the softening phenomenon in the second stage of deformation, the hot upsetting test is not efficient enough for semi-solid materials. All examined samples broke at the end of deformation. In such case, determination of the friction conditions, which is the objective of plastometric tests, cannot be achieved. The friction coefficient evaluation is based on the shape of the sample after deformation. Thus, research in the project focus on proposed new plastometric test based on combined extrusion.

EXTRUSION AND RING COMPRESSION TESTS

After the sensitivity analysis performed during last reporting period, the optimal shape of the dies was proposed with parameters of dies: α = 0°, β = 3.75°, g_1 = 27.7 mm, g_2 = 3 mm, as shown in fig.1. This die set was manufactured and assembled on Gleeble 3800 simulator in The Institute for Ferrous Metallurgy in Gliwice (Poland). The copper samples were extruded in room temperatures. Beyond this, the ring compression tests were performed in the same conditions and friction coefficient evaluated from extrusion test was validated.

The extrusion test was made with various dimensions of input samples: diameter 17.9 – 18.5 mm, height: 5 – 7 mm. Two different diameters of working part of lower die were used: 9.5 and 11 mm, with gaps: g_2 = 4.2 mm and 3.5 mm respectively. The strain rate was $\dot{\varepsilon}$ =1s^{-1}. View of samples after extrusion is shown in fig.3.

Fig. 3. *Extruded Cu samples*.

The ring compression tests were performed for various dimensions of samples: outer diameter 12 – 18 mm, inner diameter: 6 – 9 mm, height: 4 – 6 mm. Two different strain rates were used $\dot{\varepsilon}$ =0.1s^{-1} and 1s^{-1}. View of samples after compression is shown in fig.4. The inverse analysis has been performed to evaluate the friction coefficient.

Fig. 3. *Rings after the compression*.

FRICTION MODEL IDENTIFICATION

To identify friction conditions, the inverse analysis was performed for both ring compression test and extrusion test. Finite element codes Comp_axi (for ring compression) and Forge 2 (for extrusion) were used to solve the direct problem in the inverse analysis. The objective function for extrusion test is given as follows:

$$\Phi = \sum_{i=1}^{Ns} \sqrt{\frac{1}{Ns}\left(\frac{d_i^c - d_i^m}{d_i^m}\right)^2} \qquad (7)$$

where: d^c – calculated sample dimensions, d^m – measured sample dimensions.

The objective function for ring compression test is given as follows:

$$\Phi = \sum_{i=1}^{Ns} \sqrt{\frac{1}{Ns}\left(\frac{x_i^c - x_i^m}{x_i^m}\right)^2} \qquad (8)$$

where: d^c – calculated shape coordinates, d^m – measured shape coordinates.
The Simplex optimization method is used for minimization of the cost functions.

3D EXTRUSION TEST

During the thixoforming processes, which are mainly not axisymmetrical, the chemical composition segregation phenomenon appears. During axisymmetrical processes the segregation is not so likely. In this case the three-dimensional (non axisymmetrical) version of combined extrusion process is needful. Schematic view of the dies is shown in fig. 4. Both rams' angles and gaps should be parameterized to generate different shapes during optimization. The automatic surface mesh generator was developed to perform optimization of dies shape in 3D processes, which show maximal sensitivity to rheology of the material and to friction conditions.

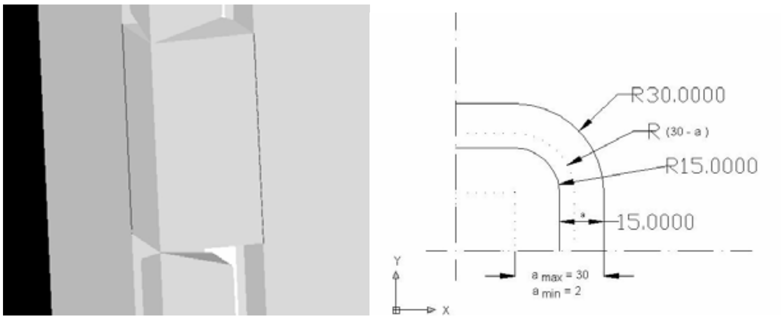

Fig. 4. *Schematic view of dies for the 3D test*.

Rams' angles may vary form 0° to 30° and gaps from 30 to 2 mm. Figure 5 shows generated dies. First die has angle of 5° and wider gap of 20 mm. The second – angle: 0° and narrow gap: 15 mm.

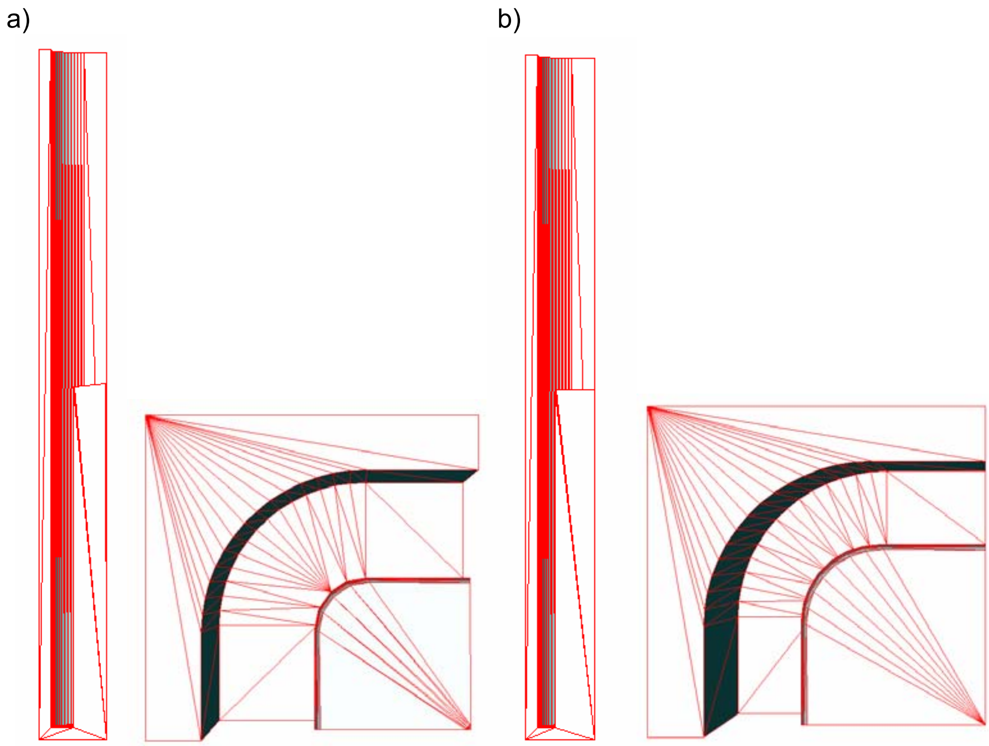

Fig. 5. *Generated dies: (a) wide gap, rams angle = 5°, (b) narrow gap, angle = 0°(flat)*.

The analysis of sensitivity of material flow to friction conditions and to material's rheology is based on the ratio H:

$$H = \frac{h_2}{h_1} \tag{9}$$

The objective function of sensitivity of ratio H and extrusion load F to the rheological parameter is defined as:

$$\Phi = \sqrt{\left(\frac{\partial H(\mathbf{a})}{\partial \mu}\right)^2 + \left(\frac{\partial H(\mathbf{a})}{\partial K}\right)^2 + \left(\frac{\partial F(\mathbf{a})}{\partial K}\right)^2} \qquad \mathbf{a} = \{\alpha, \beta, g_1, g_2\}^T \tag{10}$$

Finite difference approximation of the derivative in this equation is used:

$$\frac{\partial H(\mathbf{a})}{\partial \mu} = \frac{H_{\mu 1} - H_{\mu 2}}{\mu_1 - \mu_2}; \qquad \frac{\partial H(\mathbf{a})}{\partial K} = \frac{H_{K1} - H_{K2}}{K_1 - K_2}; \qquad \frac{\partial F(\mathbf{a})}{\partial K} = \frac{F_{K1} - F_{K2}}{K_1 - K_2} \tag{11}$$

where: $H_{\mu 1}$, $H_{\mu 2}$ – values of the ratio H calculated for the friction coefficients μ_1 and μ_2, respectively; H_{K1}, H_{K2}, F_{K1}, F_{K2} – values of the ration H and extrusion load F calculated for the rheological parameter K_1 and K_2, respectively.

Example simulation based on developed generator has been made. Results are shown in fig. 6.
The 3D test is the objective of the further analysis.

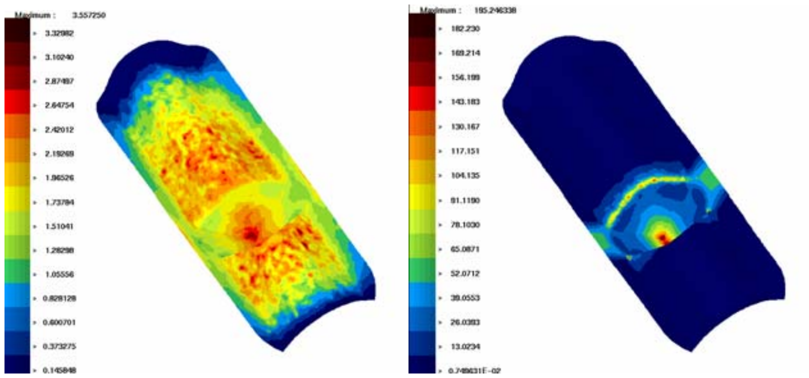

Fig. 6. *Calculated strain and stress distribution in the 3D.*

CONCLUSIONS

•The search for reliable material model has been performed and inverse analysis was used to evaluate parameters of the selected model.

•Yoon's model, with the coefficients determined using inverse analysis, gives good results for simple hot upsetting of tool steels in semi solid state. This model can be applied to simulations of thixoforming processes.

•The extrusion and ring compression of copper in room temperature has been performed.

•Inverse analysis for ring compression is used to evaluate friction coefficient in direct and indirect (combined) extrusion

•Comparison between experimental and FEM results for copper is to be performed.

•The sensitivity analysis for 3D die set is to be done during future work.

7. List of publications

a) Published

b) Submitted for publications

Propozycja eksperymentu do wyznaczania parametrów reologicznych stopów metali odkształcanych w fazie pół-ciekłej. Conf. KomPlasTech 2004, Zakopane, Poland.
A. Żmudzki, J. Gawąd, M. Papaj, R. Kuziak, J. Kusiak, M. Pietrzyk

Proposition of experiment for evaluation of material properties of metal alloys deformed in semi-solid state. Conf. ESAFORM 2004, Trondheim, Norway.
A. Żmudzki, J. Gawąd, M. Papaj, R. Kuziak, J. Kusiak, M. Pietrzyk.

Validation of the direct-indirect extrusion test, designed for evaluation of flow properties of metal alloys deformed in semi-solid state. Conf. METALFORMING 2004, Krakow, Poland.
A. Żmudzki, J. Gawąd, 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, J. Gawąd, M. Papaj, R. Kuziak, J. Kusiak, M. Pietrzyk