# COST 526

## "Automatic Process Optimization in Materials Technology"

(APOMAT)

## Half-Yearly Report (5)

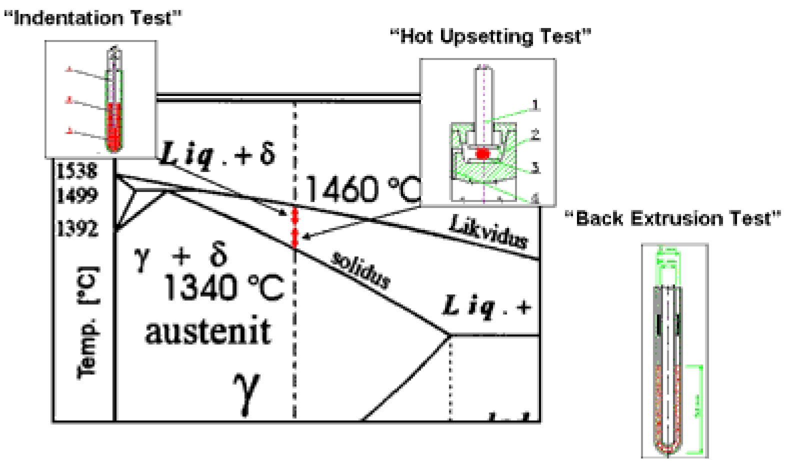
| **1. Reporting Period** | **1 January 2004 – 30 June 2004** |
|---|---|
| Project title | OPTIMIZATION OF FORGING CHARACTERISTICS OF METAL IN MUSHY STATE |
| Project leader<br>Organization | **Jaroslav Horsky**<br>Brno University of Technology, Czech Republic |
| Main collaborators involved | University of Ljubljana, University of Krakow |

| **2. Funding Situation** | |
|---|---|
| Amount of money received specifically for COST | 12 kEuros |
| Other resources partially used for the project | kEuros |

| **3. International Collaboration**<br>(mention group and type of work done in collaboration during the reporting period) |
|---|
| Participation in the Working Group Meeting in Angers + project progress report<br>YES |
| |

| **4. Industry participation**<br>(mention name of companies and work done in collaboration during the whole project) |
|---|
| US Steel Kosice, Vitkovice Ostrava. Measurement of heat boundary conditions. |

| **5. Meetings, visits, exchange of scientists, short-term scientific missions** | **Location, date** |
|---|---|
| | |
| **6. Progress within the reporting period**<br>(Not exceeding 3 pages, including tables and figures) | |
| **Material characteristics of steel forming in mushy state** | |




The forging in semi-solid state is a new technology process which allows production of wires, bars, tubes and boards from ferrous and non-ferrous alloys. Constitutive model and parameters used for the simulation of mushy state steel forming need to be determined or specified.

Experimental program was prepared verifying the influence of the following factors:

- contents of solid and liquid phase,
- loading rate,
- equivalent plastic strain.

The experimental apparatus can perform both the "indentation test" and "hot upsetting test". The indentation of a thin tool into steel in a semi-solid state, can be used at higher temperatures, i.e. also for a larger liquid phase in the specimen. The "hot upsetting test" of a steel cylinder at very high temperatures of the specimen is second method used for study of behaviour semi-solid metal. On the contrary, the temperature, at which the liquid content reaches a value where the tested cylinder cannot keep its original shape and gets destroyed due to the gravity, limits the second test. These two methods enable to study the steel behaviour within the whole temperature range between the liquidus and solidus curves.

As it was mentioned, temperatures higher than some critical value make the hot upsetting test not applicable because the tested cylinder cannot keep its original shape and gets deformed under its own weight. Tests based on extrusion process are better for higher temperatures. To study the material behavior in these temperatures, the U-tube test was performed.

## U-tube test

It is based on axisymmetrical backward extrusion of heated sample in U shaped dies with the outer and inner diameters of 31 mm and 20mm. Shape of simple product manufactured by back extrusion test is shown in figure 1.


**Fig. 1**: Back Extrusion Test: relationship between force and position, temperature 1420 °C (58 % solids), 1440 °C (36 % solids), 1450 °C (10 % solids), velocities of deformation 0.5 cm/min.

The material used for the U-tube test was the tool carbon steel. Such sample was first melted to fill U shaped form. Melted sample had height of 50 mm. The heating was performed in technical Ar gas protection atmosphere. Initial heating temperature was 1500°C with 120 min of heating time. After that, the temperature homogenization period followed during 30 min. The die velocity had constant value of 50 mm/min and temperatures were 1450, 1440 and 1420 °C, which correspond to 10, 36, and 58% volume fraction of solid phase, respectively.

It was observed in the highest temperature test that measured forces very low during almost whole process, (Fig. 2). The force increased slightly at the final stage of the test.

Maximal forces measured in 1420° - 1450°C temperature range were 3500 – 4000N. All the U-tube extrusion results are presented on figure 2.

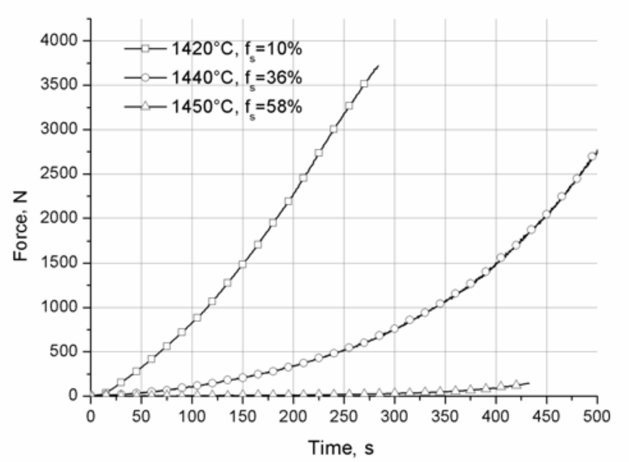



**Fig. 2**: Force vs. time data monitored in the U-tube test.

## Numerical modeling

The numerical models were developed by colleagues from Poland. PhD student, Andrzej Zmudzki and professor, Maciej Pietrzyk, Department of Computer Methods in Metallurgy, Akademia Gorniczo-Hutnicza, Krakow.

Presented test were designed and performed in order to measure data required for the determination of material characteristics. The identification of parameters to be introduced in the constitutive laws was done by the inverse analysis. The main goal of work was evaluation of parameters of material model for the whole range of temperatures between solidus and liquidus lines. Well parameterized equation is needed to reach this goal. The stress strain curve used in simulations was based on modified Spittel's equation with the following form:

$$\sigma = A\exp(m_1 T)\varepsilon^{m_2}\dot{\varepsilon}^{m_3}\exp\left(\frac{m_4}{\varepsilon}\right)(1+\varepsilon)^{m_5 T} \qquad (1)$$

where: $\sigma$ – flow stress [MPa]; $\varepsilon$ – strain [-]; $\dot{\varepsilon}$ – strain rate [$s^{-1}$]; $T$ – temperature [°C].

After the inverse analysis, the following values of parameters were obtained: $A$ = 31800, $m_3$ = 0.05. To cover the whole range of temperatures, other parameters were described as the following functions of temperature:

$$m_1 = -0.0137 + \frac{0.007155}{\left(1 + e^{\left(\frac{T-1440}{8.00418}\right)}\right)} \times \left(1 + 0.115 e^{\left(-e^{-\left(\frac{T-1420.6}{1.38}\right)} - \left(\frac{T-1420.6}{1.38}\right) + 1\right)}\right) 1.42^{(T - T_{crit})}$$

$$m_2 = -0.1323 - \frac{1.62}{\left(1 + e^{\frac{T-T_{crit}}{0.05}}\right)}$$

$$m_4 = -0.05 - \frac{0.34}{\left(1 + e^{\frac{T-T_{crit}}{0.05}}\right)} \qquad m_5 = 0.00002T - 0.0274 \qquad (2)$$

where: $T_{crit} = 1419^{o}C$ – critical temperature.

Presented above functions were evaluated on the basis of results of the inverse analysis. Figure 3 shows plots representing relation of investigated parameters on temperature.

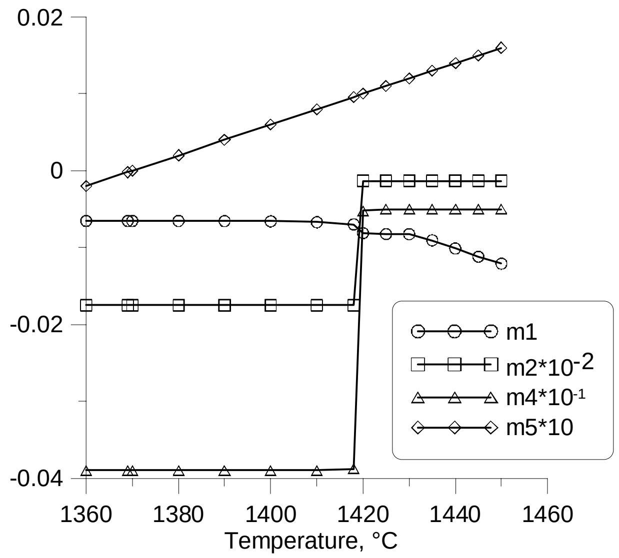



**Fig. 3:** Relation of coefficients in equation (1) on temperature.

It is seen that values of parameters $m_2$ and $m_4$ increases rapidly at the neighborhood of the critical temperature. This situation is reflected in the rapid decrease of the flow stress in this critical temperature, as shown in figure 4a. It is also seen that the softening of the material do not appear above the critical temperature, (Fig. 4b).

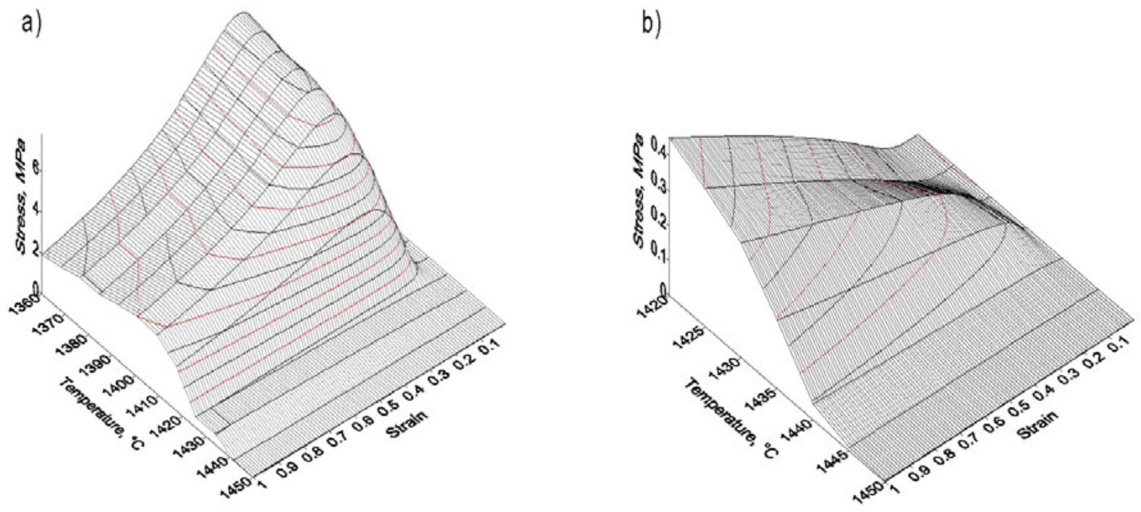



**Fig. 4:** Flow stress surface representation vs strain and temperature.

The stress-strain curves calculated from equation (1) for the temperatures, which were used in the performed tests, are shown in figure 5.

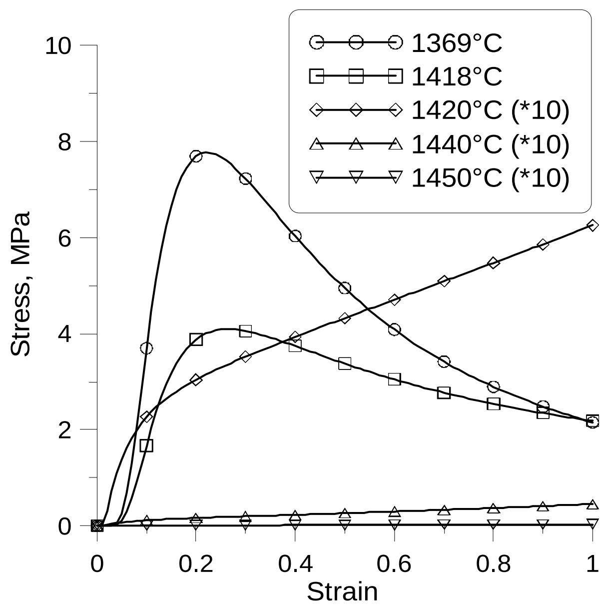



**Fig. 5:** The stress-strain curves calculated from equation (1) for different temperatures.
The values of stresses for higher temperatures are multiplied by 10.

The viscoplastic friction law was used for modelling boundary conditions. The friction stress in this law is:

$$\tau = -\alpha K(T,\bar{\varepsilon})\Delta V^{\,p-1}\Delta V \qquad (3)$$

where: $\alpha$ – friction coefficient, which was assumed to be equal (1) in all analysed cases, *K* – consistency of a material, *p* – sensitivity to the sliding velocity.

## Results

Rheological model described by equation (1) was used in the finite element simulations performed with the Forge 2 code. Three temperatures was selected for the U-tube test modelling: 1420, 1440 and 1450°C, which correspond to 58%, 36% and 10% volume fraction of the solid phase, respectively. Comparison of experimental and simulations results are presented in figure 6.

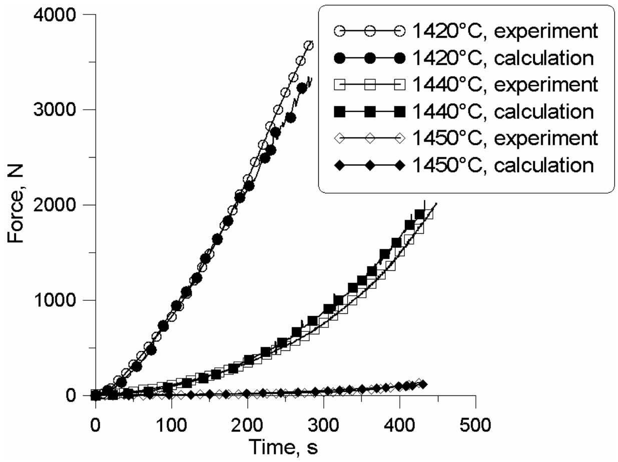



**Fig. 6:** Forces in the U-tube tests measured and predicted by Forge 2 with equation (1) as the rheological model.

Good agreement between experimental data and calculations is observed in both investigated cases.

## 7. List of publications

a) Published

**STEEL GRIPS - Journal of Steel and Related Materials**


Zmudzki, A. – Pietrzyk, –M. Kotrbacek, P. – Horsky, J.: Various Plastometric Tests for Semi Solid Materials and Their Numerical Simulations, 10th International Conference Metal Forming 2004, September 19-22, 2004, Krakow, Poland, ISBN 3-937057-08-0, ISSN 1619-9529.


b) Submitted for publications

c) In preparation