COST 526 – Project CZ2
Final Report
Optimization of Forging Characteristics of Metal in Mushy State

Jaroslav Horsky

Brno University of Technology

Technicka 2896/2, Brno, Czech Republic

1. Introduction

Processing metals in semi-solid or mushy state has emerged as a vital commercial process to produce metal and metal-matrix composite components. Among other benefits, it reduces the force requirement in forging processes because of the lower flow stresses involved, or increases die life in die casting operations due to the lower temperature associated. 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. This technology also enables production and manufacturing of composite materials that can't be forged any other way. Most of the work in the past has been focused on the determination of material characteristics of relatively low-melting temperature materials, including aluminium, magnesium, tin, lead and their composites. Because of the high-melting temperatures and other related measurement difficulties, there is a relatively small amount of experimental data available on steels. As a result, an indentation and a hot upsetting testing apparatus have been developed to study the deformation behaviour of the mushy state steels, (Kotrbacek *et al.*, 1997). In the indentation test, the forming conditions of the semi-infinte space indentation and back extrusion are simulated, (Horsky *et al.*, 1998). The steel specimen was evaluated at a wide range of solid or liquid contents at various forming speeds.

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

The most important factor that controls the flow behaviour 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 a 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 behaviour, the other that represents the evolution of structure, (Kang *et al.*, 1998), (Yoon *et al.*, 2001), (Zavaliangos *et al.*, 1995).

2. Goal of the project

The goal of project is to determine material characteristics of material forming in mushy state and consequently, their application in mathematical models describing the process concerned.

Present work focuses on various plastometric tests, like hot upsetting and 'U-tube' tests (due to experiments and their numerical verification) or 'needle' and 'double cup' extrusion tests. Schematic illustrations of these tests are presented in Figure 1. The tests are designed for evaluation of material properties of metal alloys deformed in semi-solid state. Analyzed tests supply information regarding both rheological and friction parameters for alloys in semi-solid state and the measured data can be directly used in the inverse analysis of the deformation process.

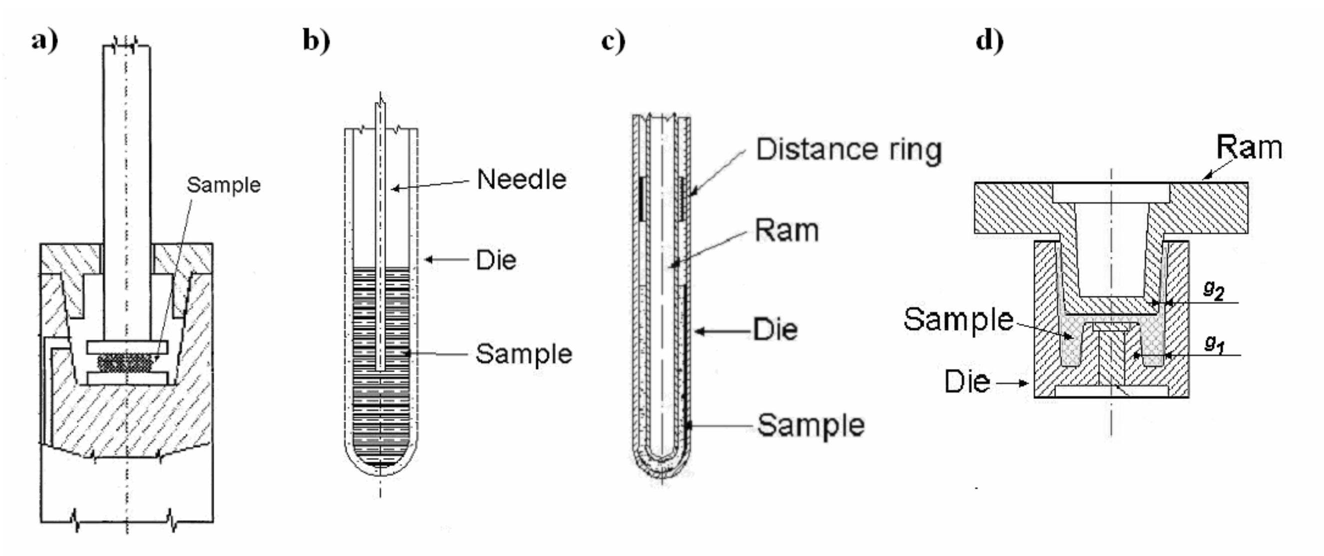

Fig. 1: Schematic illustrations of: a) Hot upsetting test, b) 'Needle' test; c) 'U-tube' test; d) 'Double cup' extrusion test.

3. Simulator, calibration, quality function and optimization algorithms, including assessment with respect to alternatives

A non linear viscoplastic model developed by Perzyna (Perzyna 68) was used. Here, the flow curve of material is described by

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

where:

σ = material yield stress,

$\dot{\varepsilon}$ = equivalent plastic strain rate,

m = strain rate hardening parameter,

γ = material viscosity parameter,

$\sigma_o(\varepsilon)$ = static yield stress of material, which is a function of some hardening parameters in general.

We suppose that the static yield stress for any given temperature and solid fraction depends on the cumulated plastic strain only. Such conclusion is based on the experimental results, where the relaxed static stress drops to the same value shortly after the ram stops, irrespective of its previous velocity. The procedure of evaluation of the constitutive parameters is then based on the computational simulation of the compression test and minimisation of the deviation between the measured and computed values of the compression force.

The computational simulations were realized by ANSYS as a viscoplastic problem, using the updated Lagrangian approach to cope with large strain and displacements. The evaluation of constitutive parameters was based on minimisation of the objective function

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

where n is the number of check points on the force – displacement curve, k is the number of realized and simulated experiments for different ram velocities and E_i , F_i are the compression forces obtained from experiment and from computation, respectively. The minimisation technique used was the subproblem approximation method, which can be described as an advanced zero-order method in that it requires only the values of the dependent variables, and not their derivatives. Key role in this method plays the quadratic approximation of the objective function. Each optimization loop generates a new data point, and the objective function approximation is updated. It is this approximation that is minimized instead of the actual objective function.

Design variables of the minimisation were the constitutive parameters m, γ and a table of discrete values of $\sigma_0(\varepsilon)$, from which the static yield stress can be reconstructed as a continuous, piecewise linear curve. To increase efficiency and stability of the minimisation procedure, it is good to start with realistic values of design variables.

4. Main scientific outcome

Relatively new technology - metal processing of material in mushy state was investigated during this project. Experimental equipment and methodology of research was developed. New constitutive equations for description of behaviour of mushy state material were formulated. Influence of different parameters on forging process was investigated. Optimized parameters were fond.

5. Main technical outcome

Results of this investigation can be used in applications like continuous casting, hot rolling and special technology of metal forming. Based on knowledge describing material behaviour in above mentioned processes, numerical models for designing and controlling purposes could be created.

6. Collaboration within COST 526

University of Ljubljana, Prof. Sarler. Using of mushy state characteristic in continuous casting simulations.

University of Krakow, Prof. Pietrzyk. Collaboration in computational software, optimization strategy, simulation of forging process.

7. Cooperation with industry

Nova Hut (Mittal Steel), Ostrava
Steelworks Trinec
Vitkovice Ostrava

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