THE ANNALS OF “DUNAREA DE JOS” UNIVERSITY OF GALATI.
FASCICLE IX. METALLURGY AND MATERIALS SCIENCE
N^0. 2 – 2011, ISSN 1453 – 083X

can be encountered during mechanical processing of materials.

The general form of constitutive equation is:

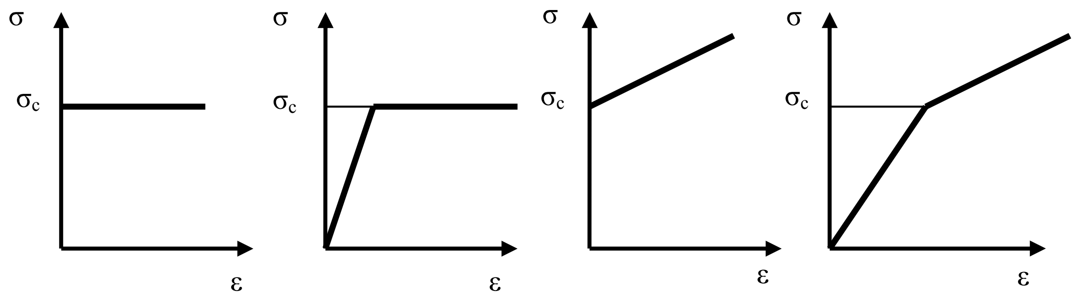
$$\overline{\sigma} = f(\varepsilon, \dot{\varepsilon}, T, \sigma^*) \tag{1}$$

where: σ, true stress; ε, true plastic strain; $\dot{\varepsilon}$, strain rate; T, temperature; σ^*, parameter dependent of the history of deformation.

Considerable efforts have been carried out over decades to develop quantitative constitutive relations which describe the flow strength of materials as a function of process variables, i.e., strain, strain rate and temperature, for the correct modeling of processes.

Empirical and semi-empirical relations obtained from experimental data are widely used in deformation models because they are easier to develop.

Idealized stress–strain curves that are frequently used in applications are illustrated in Fig. 1.



a. rigid - perfectly plastic b. elastic-perfectly plastic c. rigid-work hardening d. elastic-work hardening

Fig. 1.

Most non-uniform distributions of stress and plastic deformation have been analyzed by an approximate two- or three-dimensional combined stress generalization of one of these idealized uniaxial curves. An approach to achieve a satisfying formulation for time dependent behavior is to generalize plasticity to cases within the strain-rate-sensitive range. One such generalization has been provided by the theory of visco-plasticity.

The most widely used constitutive equations for the analysis, the simulation and the design processes of metal forming at ambient temperature and at relatively low rates of deformation, are [3]:

Hollomon equation:

$$\sigma = C\varepsilon^n \tag{2}$$

Ludwik equation:

$$\sigma = \sigma_0 + C\varepsilon^n \tag{3}$$

Swift equation:

$$\sigma = C(\varepsilon + \varepsilon_0)^n \tag{4}$$

Voce equation:

$$\sigma = \sigma_s - (\sigma_s - \sigma_0)\exp(-n\varepsilon) \tag{5}$$

None of the above equations is entirely satisfactory for all materials and deformation conditions. These simple equations can be used for a satisfactory description of the stress-strain behaviour of particular materials such as steels, copper and aluminium alloys.

There is also a group of equations that also take into account the strain rate, apart from the strain. Some of them are: Backofen equation:

$$\sigma = C\varepsilon^n \dot{\varepsilon}^m \tag{6}$$

Hart equation:

$$\sigma = \sigma^* \exp[-(\frac{\dot{\varepsilon}^*}{\dot{\varepsilon}})^{\lambda}] + \sigma_0(\dot{\varepsilon})^{1/M} \tag{7}$$

Wagoner equation:

$$\sigma = C(\varepsilon + \varepsilon_0)^n (\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})^m \tag{8}$$

Equations that take into account the strain, the strain rate but also the temperature have the following forms:

$$\sigma = C\varepsilon^n \exp(n_1\varepsilon)\dot{\varepsilon}^m \exp(a_1 T) \tag{9}$$

$$\sigma = C\varepsilon^n \exp(n_1\varepsilon)\dot{\varepsilon}^{(m+bT)} \exp(a_1 T) \tag{10}$$

In the case of hot working processes for large strain, the effect of strain on flow stress can be neglected. There is a particular relationship among flow stress, strain rate, and deformation temperature. The combined effects of temperature and strain rate on the deformation behaviors can be expressed by the Zener–Hollomon parameter [5, 8,9,14,15].

$$\sigma = f(\dot{\varepsilon} \exp\frac{Q}{RT}) = f(Z) \qquad (11)$$

$$Z = \dot{\varepsilon} \exp\frac{Q}{RT}$$

In the above relations the parameters have the following signification: σ_0, the yield point; σ, the flow stress; σ_s, n, n_1, the coefficients of strain hardening; m, strain rate sensitivity; ε_0, pre-strain; C, M, λ, a, a1, b, b1, experimentally determined parameters or functions; Q, activation energy for deformation (kJ/mol), R is the universal gas constant (8.314 J/(mol K)); Z, Zener-Hollomon parameter.

2. Example of simulation of advanced forming processes

The main objective of the forging process designer is to produce a workpiece of a given shape and dimensions without any defect. In general complex shapes of the workpiece require several forging phases to be manufactured. The selection of the number and configuration of the intermediate stages, dies geometries and forging conditions for every phase are the basic tasks involved in the process design. Other aspects, playing a major role at the moment of designing a suitable forging sequence, are the forces required to form the piece, the material flow during deformation, the die wear, etc. Regarding these aspects, the designer can obtain useful information from a FEM simulation. The visualization of the deformation process at each stage help to design or improve the required performances in order to ensure that the dies are totally filled with forged material as well as that no flow defects appear. Also the geometrical parameters of the performances can be optimized on the basis of improving the flow pattern or reducing the amount of die wearing.

The numerical models can advance the critical areas where the material flow or the strain and stress are likely to produce a damaged piece or an unacceptable tool wearing. Figure 2 presents the type of information which can be extracted from numerical simulation [1, 2, 4].

When professional softwares such as ABACUS, MARC, DEFORM, AUTOFORGE, FORGE, as well as a new-generation of large-capacity computers, were developed, it became possible to analyse various manufacturing processes with descriptions of the real behaviour of materials.

Forge (a commercial software developed at CEMEF, Ecole des Mines de Paris) was developed for the analysis of plastic deformation processes.

The program is based on the finite element method for cold and hot metal forming. It enables the thermo-mechanical simulation of the plastic deformation processes of metals in an axisymmetric, homogeneous and isotropic state of deformation and obeys the von Mises criterion. In this work was used the version 2009 of Forge software.

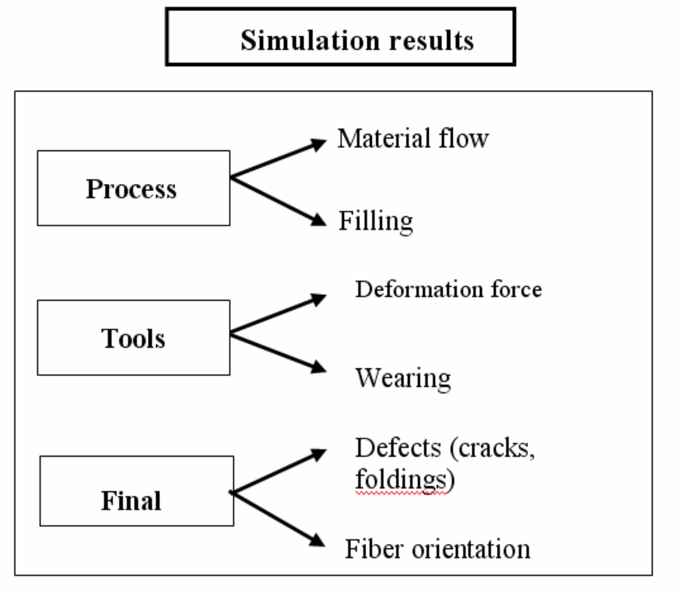


Fig. 2.

The calculations of the metal flow, stress field, strain, strain rate and temperature are conducted on the assumption of the viscoplastic model of the deformed body.

The tensorial form of the Norton-Hoff law used in **FORGE2009®** is written as:

$$s = 2A(T, \bar{\varepsilon}, ...)(\sqrt{3} * \dot{\bar{\varepsilon}})^{m-1} \dot{\varepsilon} \tag{12}$$

$$A(T, \bar{\varepsilon}) = A_0 * (\bar{\varepsilon} + \bar{\varepsilon}_0)^n * e^{\frac{\beta}{T}} \tag{13}$$

Where ***s*** is the deviatoric stress tensor, A is the consistency of material, $\bar{\varepsilon}$ the equivalent strain, m the strain rate sensitivity, $\dot{\varepsilon}$ the equivalent strain rate, β material constant, n the strain hardening index and $\bar{\varepsilon}_0$ is a small constant.

The flow formulation introduced by Hensel and Spittel is written as:

$$\sigma = A * e^{m_1 T} * T^{m9} * \varepsilon^{m2} * e^{m4/\varepsilon} * (1+\varepsilon)^{m5T} * e^{m7\varepsilon} * \dot{\varepsilon}^{m3} * \dot{\varepsilon}^{m8T} \tag{14}$$

Where $m_{1...9}$ are sensitivity parameters.

In the following an application of **Forge** in order to simulate an advanced plastic deformation process is presented [5]. Dieless drawing is an incremental process of plastic deformation, which permits the deformation of usual industrial materials (wires, tubes, bars) by controlling the heat temperature/local cooling without dies. The concept of dieless drawing is: to cause necking, the semiproduct is locally heated, and to stop further deformation, the necked part is cooled. The principle of dieless drawing is presented in Figure 3.

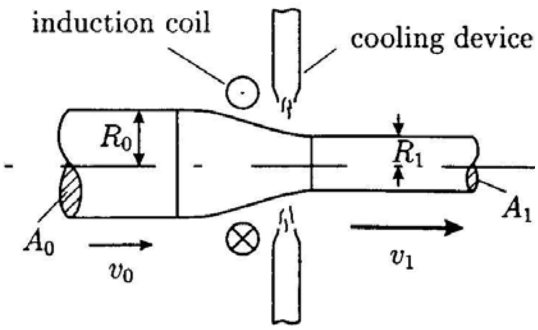


Fig. 3. *Principle of dieless drawing.*

Finite element simulation with thermo-mechanical analysis was carried out using the **FORGE2009®** software. Figure 4 shows the axisymmetric model used and Figure 5 shows the part discretisation. A 3D axisymmetrical model of the wire was constructed and meshed with tetraedrical elements. The model was both thermally and mechanically loaded to simulate dieless drawing conditions. A mesh of the wire was generated using three-node axisymmetric element.

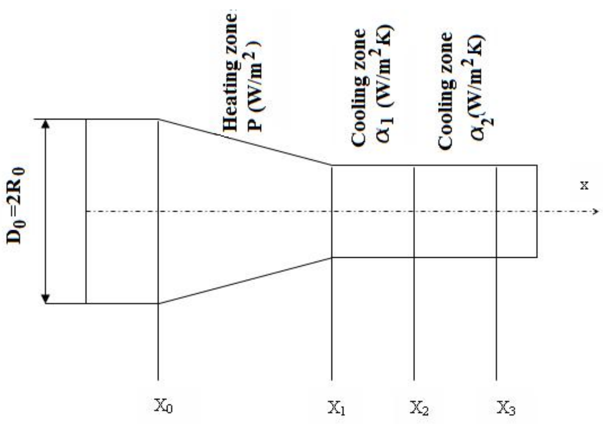


Fig. 4. *Simulation model.*

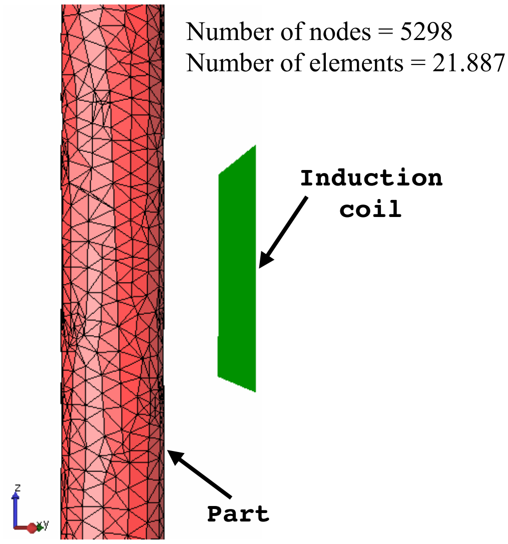


Fig. 5. *Part discretisation*

Table 1

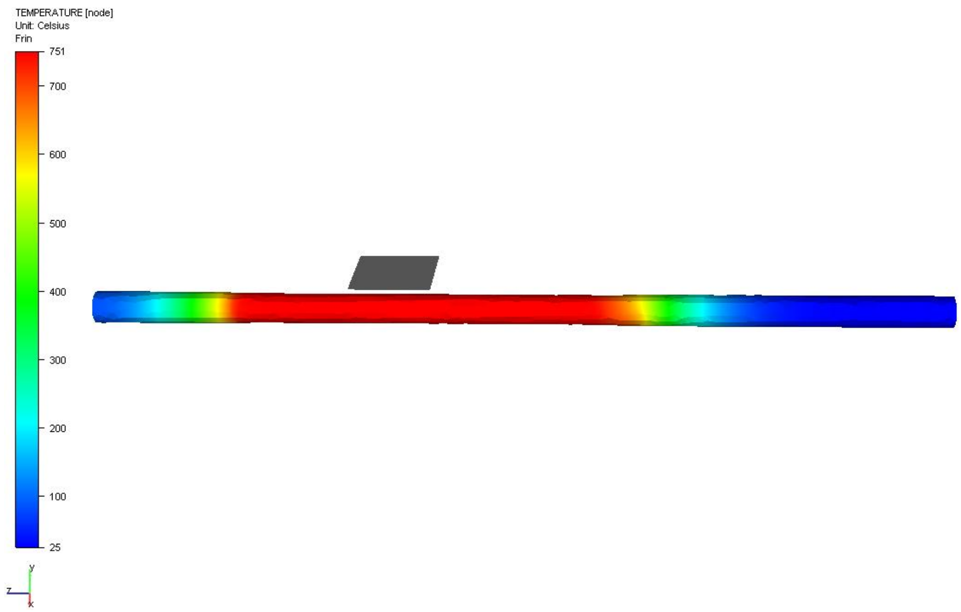
Wire diameter, D_0, mm	4
Length of wire, L,mm	400
Heating width, H, mm	40
Cooling width 1, C_1, mm	5
Cooling width 2, C_2, mm	20
Drawing velocity, V_0, mm/s	1,76
Drawing velocity, V_1, mm/s	2,8
Heat transfer coefficient, α_1, W/m^{2}K	10000
Heat transfer coefficient, α_2, W/m^{2}K	30

Table 2

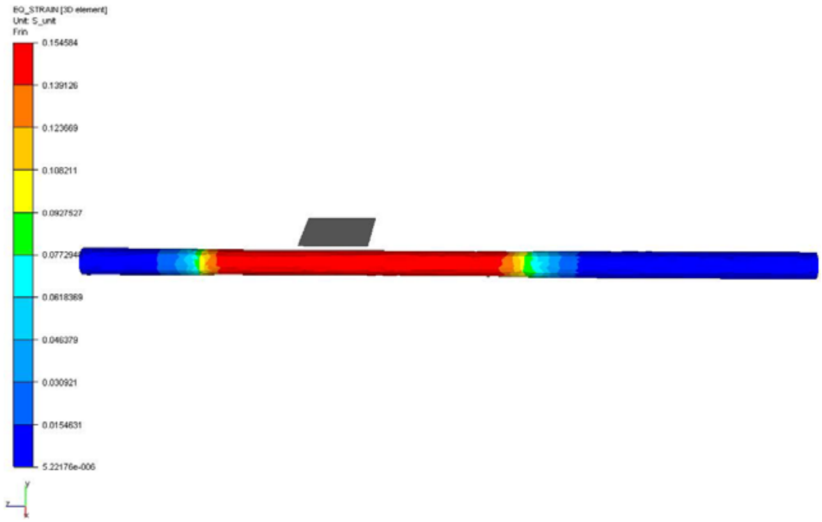
Thermal conductivity, W/mK	46
Specific heat, J/kg K	500
Mass density, kg/m^3	7850

Dimensional and process parameters used in finite element simulation are presented in Table 1. The material used for dieless drawing simulation is steel C45, with the thermal coefficients presented in Table 2.

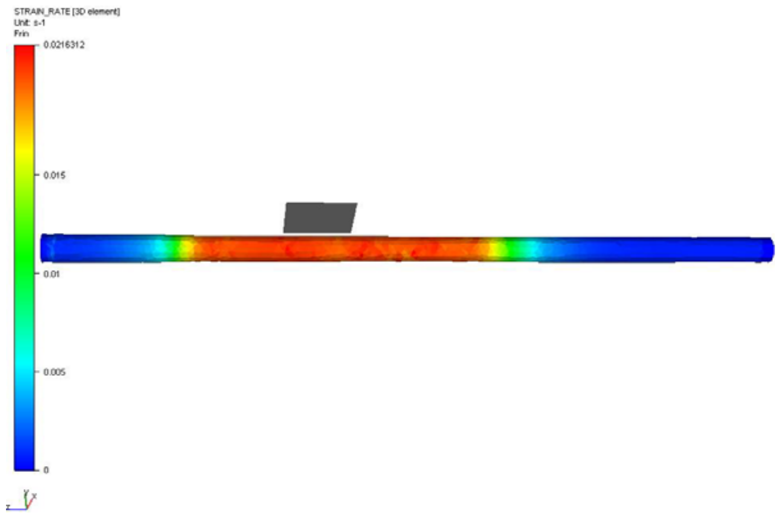
The following pictures represent the distribution of the main deformation parameters: temperature, equivalent strain, strain rate and von Mises stress.



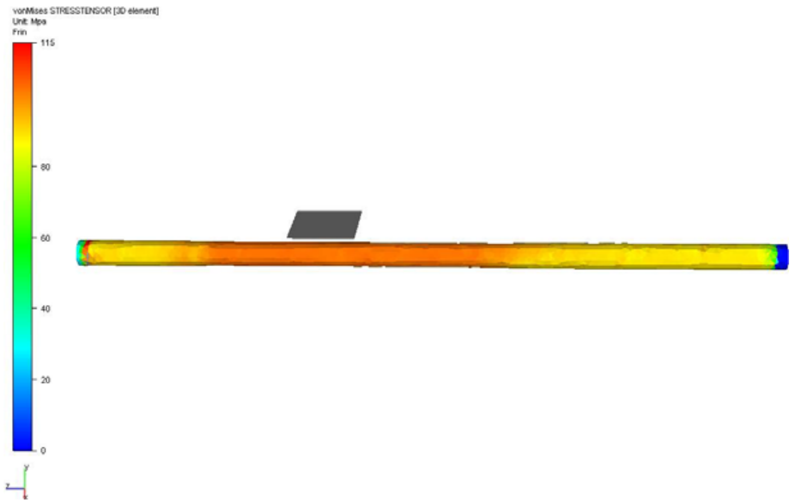
Temperature distribution



Equivalent strain distribution



Strain rate distribution



Von Mises stress distribution

Fig. 6. *Dieless drawing parameters distribution.*

The mathematical model presented can be used to describe the occurrence of deformation during the process. For modeling purposes, velocities V_0 and V_1 were assigned to the incoming and outgoing material nodes, respectively. The simulation calculation consisted principally of a thermomechanical analysis of the plastic deformation of the wire. The temperature distribution of a wire in the dieless drawing process is determined by the heat quantity supplied by the heating coil, the thermal conductivity of the tubes, heat transfer induced by cooling coil and radiation to the air. The researchers concluded that successful dieless drawing was achievable if the drawing velocities and temperature profiles permitted the occurrence of transformation plasticity. In this class of plasticity, deformation occurs during a phase change where a threshold stress is necessary to initiate deformation.

From the images presented in figure 6 it can be observed that the evolution of deformation parameters (temperature, strain, strain rate, von Mises stress) in the deformation zone are in accordance to theoretical principles of plastic deformation. The mathematical model presented can be used to describe the occurrence of deformation during the dieless drawing process.

4. Conclusions

After a brief survey of the mathematical basic formulations suitable for material constitutive equations, some theoretical and numerical issues were discussed. To demonstrate the interest of numerical modeling and simulation for design of the forming processes, an example was presented.

The aspects regarding the FEM analysis are concentrated on the **FORGE2009®** software. It appears that the main deformation parameters of the processes can be predicted with existing models or with reasonable updates of these computer codes. The aim of future research is to verify the validity of FEM model by experiment for the dieless drawing process.

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