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COMPUTER MODELLING OF MICROSTRUCTURE DEVELOPMENT DURING MULTISTAGE DEFORMATION

1. INTRODUCTION

The possibility of prediction of the microstructure development during hot forming processes is crucial in reliable design and performance of production process, which final results offer expected mechanical properties. Such development of microstructure is controlled mainly by the parameters of material flow i.e. strain, strain velocity and temperature.

Currently, most of the commercial computer applications dedicated to simulation of metal forming processes e.g. Forge2, Adina, DynaForm is based on the FEM [1]. This method offers the possibility of obtaining detailed information about distribution of strain, stress, strain velocity and temperature in formed material. Beyond applications mentioned above, used in simulations of spatial 3D processes, other group of software can be distinguished. Its members are applied in plane and axisymmetric 2D analysis. Simulations in 3D space are in most cases time consuming, therefore 2D numerical solutions are applied instead, because of their higher efficiency. However, in many commercial applications there is no possibility to include description of material microstructure and its influence on the numerical model by implementation of such phenomena like recrystallization, grain growth or dislocation propagation. This lack of microstructure model is important constrain of mentioned software and possesses high impact on the quality of obtained results. Therefore, the main objective of this paper is focused on the implementation of the microstructure development model in Forge2 software, based on semi-empirical equations. The diagram of the performed calculations in each element of the mesh is presented in Figure1. Such solution requires modification of application's source codes, which are implemented in Fortran programming language. The application of thermomechanical FEM model joint with the set of equations, which describes the microstructure development allowed to predict the distribution of microstructure parameters in whole material sample. The results of these calculations are presented in the following sections of this paper.

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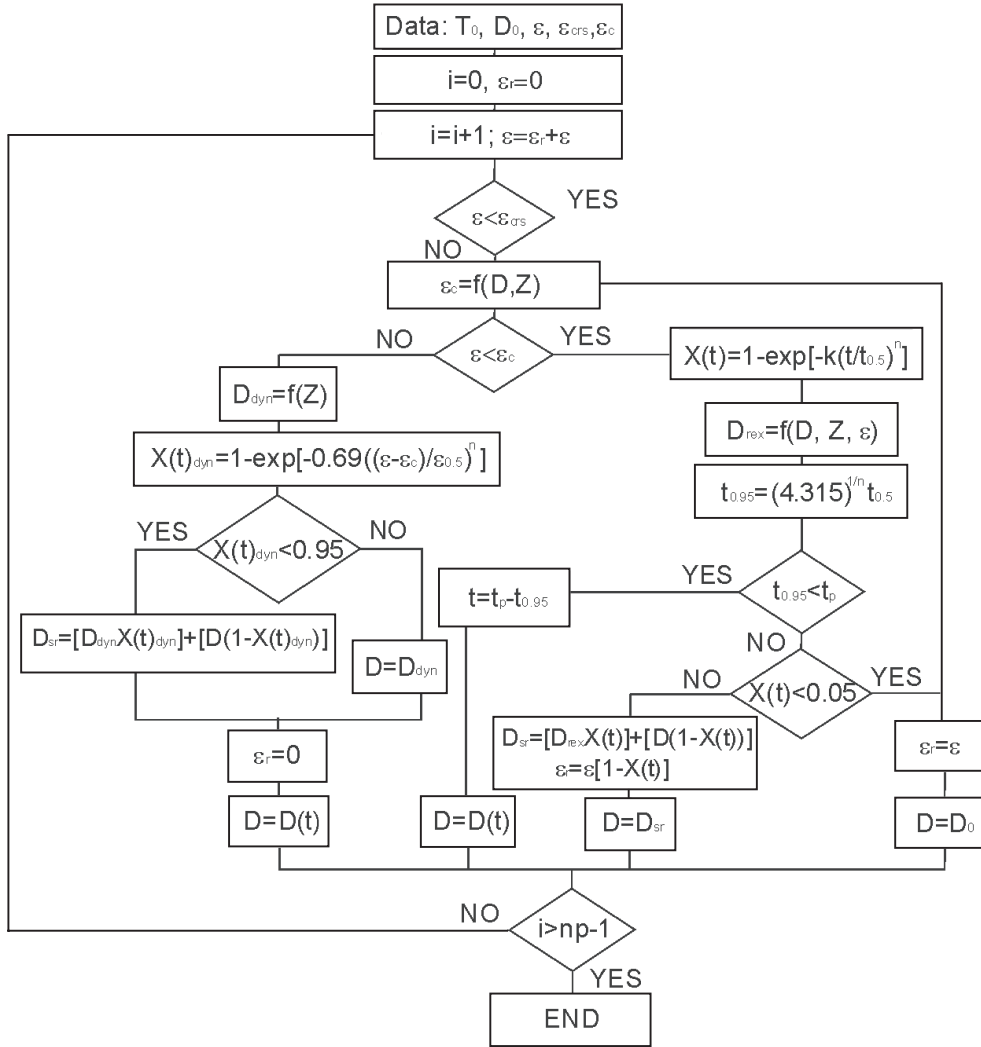
Data: T_0, D_0, ε, ε_{crs}, ε_c

$i=0$, $\varepsilon_r=0$

$i=i+1$; $\varepsilon=\varepsilon_r+\varepsilon$

$\varepsilon<\varepsilon_{crs}$ YES / NO

$\varepsilon_c=f(D,Z)$

$\varepsilon<\varepsilon_c$ NO / YES

YES branch: $X(t)=1-exp[-k(t/t_{0.5})^n]$

$D_{rex}=f(D, Z, \varepsilon)$

$t_{0.95}=(4.315)^{1/n} t_{0.5}$

$t_{0.95}<t_p$ YES / NO

YES: $t=t_p-t_{0.95}$

NO: $X(t)<0.05$ NO / YES

$D_{sr}=[D_{rex}X(t)]+[D(1-X(t))]$
$\varepsilon=\varepsilon[1-X(t)]$

$\varepsilon_r=\varepsilon$

NO branch: $D_{dyn}=f(Z)$

$X(t)_{dyn}=1-exp[-0.69((\varepsilon-\varepsilon_c)/\varepsilon_{0.5})^n]$

$X(t)_{dyn}<0.95$ YES / NO

YES: $D_{sr}=[D_{dyn}X(t)_{dyn}]+[D(1-X(t)_{dyn})]$

NO: $D=D_{dyn}$

$\varepsilon_r=0$

$D=D(t)$ $D=D(t)$ $D=D_{sr}$ $D=D_0$

$i>np-1$ NO / YES

END

Fig. 1. Block diagram calculations describing the microstructural parameters in integration point

2. MATHEMATICAL MODELS

During the calculations the Forge2 software has been used, equipped with FEM based on viscoplastic model of material flow.

The Norton-Hoff equation has been used to describe the material properties

$$\sigma_{ij} = \frac{2K}{\left(3\dot{\varepsilon}_i\right)^{1-m_v}}\dot{\varepsilon}_{ij} \qquad (1)$$

The friction conditions were based on the joint laws of Coulomb and Treska

$$\tau = \min\left(\tau_{Coulomb};\ \tau_{Treska}\right) = \min\left(\mu\, p\, \frac{\mathbf{v_s}}{|\mathbf{v_s}|};\ m\, \frac{\sigma_p}{\sqrt{3}}\, \frac{\mathbf{v_s}}{|\mathbf{v_s}|}\right) \tag{2}$$

The details of mathematical model were described in [2].

The introduction of equations, which describe the development of microstructure is possible by application of novel or modification of existing procedures. In Forge2 software it is possible to apply self-designed novel equations, which are responsible for calculation of values in Gauss integration points by using *userparam.f* file or in mesh nodes through *cparutil.f* file. The model of microstructure development uses conventional equations elaborated by Sellars *et al.* [3], which describe kinetics of recrystallization and grain growth of austenite. Thus, in case of occurrence of dynamic recrystallization, the kinetics of this phenomenon can be described by the following equation

$$X_{DYN} = 1 - \exp\left[A\left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_c^{1.05}}\right)^{1.32}\right] \tag{3}$$

The volume of dynamically recrystallized grains can be calculated from the following equation

$$D_{DYN} = 16000 Z^{-0.233} \tag{4}$$

In the opposite case, when dynamic recrystallization has not been initialized, then after the end of forming process the static recrystallization is started. The kinetics of static recrystallization is described as follows

$$X_{STAT} = 1 - \exp\left[-0.69\left(\frac{t}{t_{0.5}}\right)^{1.7}\right] \tag{5}$$

The volume of statically recrystallized grains can be calculated from the following equation

$$D_{REX} = 25\left(14.925\ln\left(\frac{10^{-9} Z}{8.5}\right)\right)^{-0.67}\frac{D_0}{\varepsilon} \tag{6}$$

The process of austenite grain growth is started right after the end of static recrystallization due to the following equation

$$D(t)^2 = D_{REX}^2 + 10^{6.6 - \frac{6200}{T}}\, t \tag{7}$$

3. SIMULATION CONDITIONS AND OBTAINED RESULTS

The numerical analysis of microstructure development has been performed for extrusion process of tubes made of carbon-manganese steel. The input forging is characterized by very sophisticated shape, thus, it requires performance of multi stage forging process. The examples of such technological processes described in details with good practice guides can be found in literature [4]. One of such processes namely 4-stage deformation was proposed by Chalupczak and Thomas in [5]. The step-by-step scheme of this approach is presented in Figure 2 (Fig. 2a – stage 1, unbounded compression, Fig. 2b – stage 2, concurrent extrusion, Fig. 2c – stage 3, collar die forging in closed impression, Fig. 2d – stage 4, backward tube extrusion).
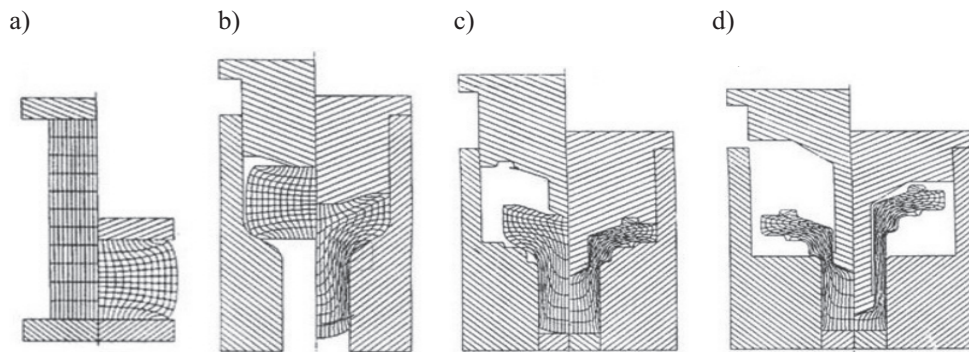
a)   b)   c)   d)

Fig. 2. *Scheme of the sleeve forging process [5]: a) upsetting; b)forward extrusion; c) piercing and forging of the flange; d) backward extrusion*

The most important part of the process described above is stage III (collar die forging). During this treatment zones of difficult material flow occur, what should be considered in the preceding stage. The parameters configured in that moment, e.g. forming perform shape, possess large influence on the features of final product, its advantages and possible drawbacks like overlaps. Thus, the parameters of each stage of the simulated process were established on the basis of similar computer simulations to avoid these drawbacks and obtain assuming proper technological parameters.

Fig. 3. *Grain size distribution after first stage*

To perform simulation of described process the following parameters have been assumed: forging temperature 950°C, tools temperature 250°C, environment temperature 20°C, lubrication with graphite water solution, rheological model originated from [6] and initial grain size 300 μm. Selected results obtained from the calculations of 1st, 2nd, 3rd and 4th stage are presented in the Figures from 3
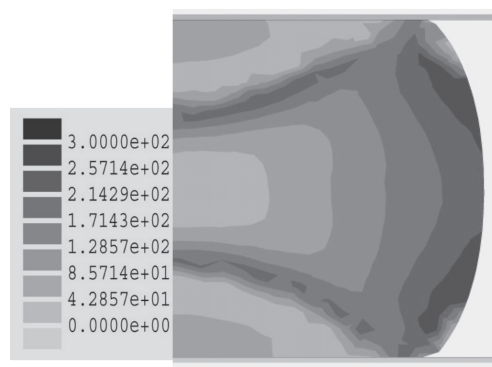
to 7 respectively. The image of the result of 4th stage of simulations presents only the changes in the deformation zone. This difference is caused directly by the character of the treatment in 4th stage, when major part of the material flows in unbounded conditions.
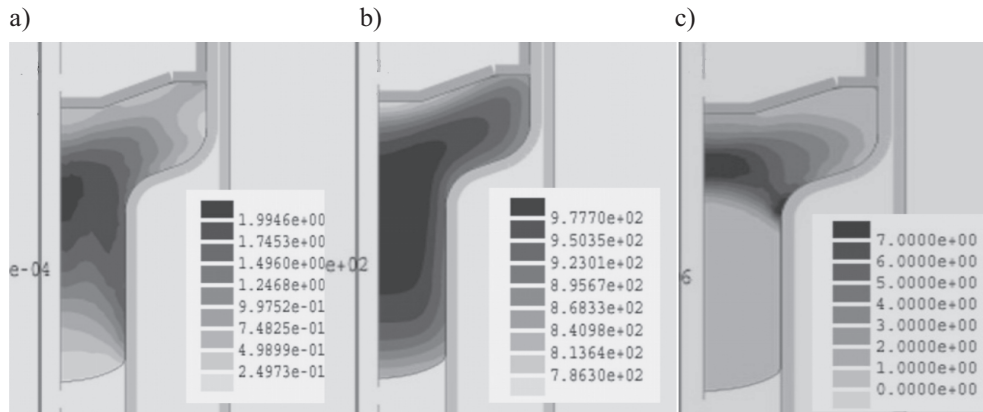
a)   b)   c)

Fig. 4. *Distribution of: a) deformation; b) temperature; c) strain rate after second stage*

Figure 3 shows distribution of grain size after stage 1. It can be clearly seen that presented distribution is characteristic for a compression process. However, the largest changes in microstructure take place during the 2nd and 3rd stages. The distributions of local values of strain, temperature and strain velocity for 2nd treatment are presented in Figure 4. On the basis of these results the volume of recrystallize grain has been calculated and type of recrystallization has been determined (Fig. 5).
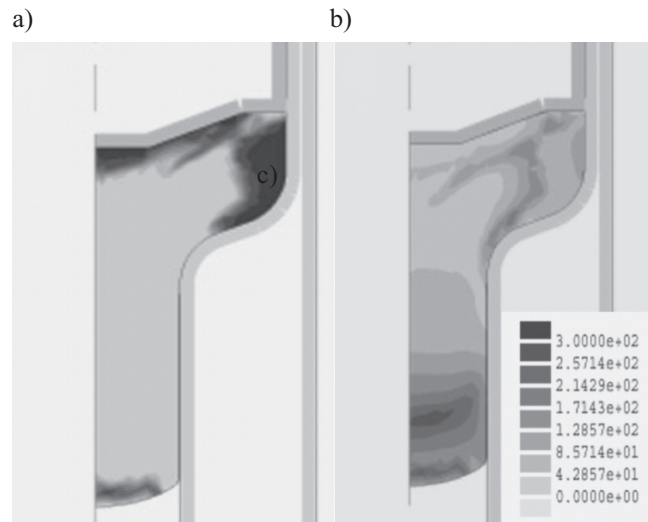
a)   b)

Fig. 5. *Distribution of: a) type of recrystalization; b) grain size after second stage*

Lighten areas in Figures 5a and 6b are related to dynamic recrystallization and darken ones present static recrystallization. From the attached images it can be seen that almost whole part of microstructure have been changed by occurred dynamic processes (the fraction of recrystallized volume equals 90–100%).
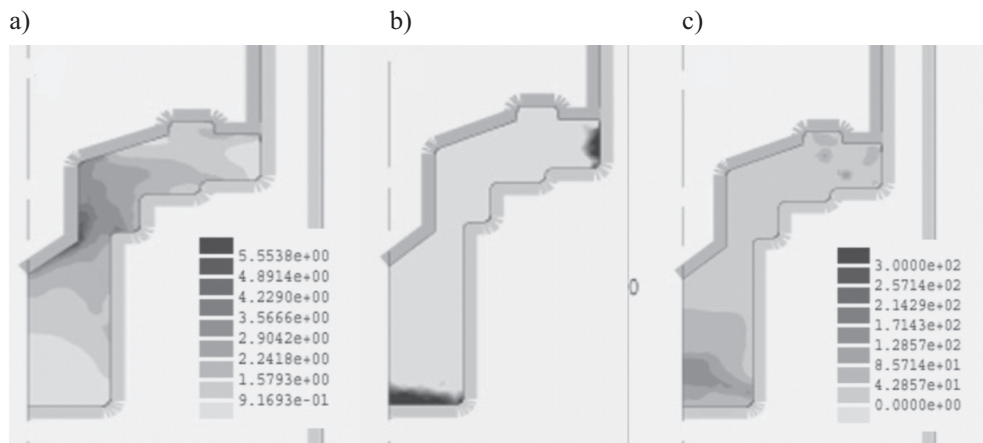
a)   b)   c)

Fig. 6. *Distribution of : a) deformation; b) temperature; c) grain size after third stage*
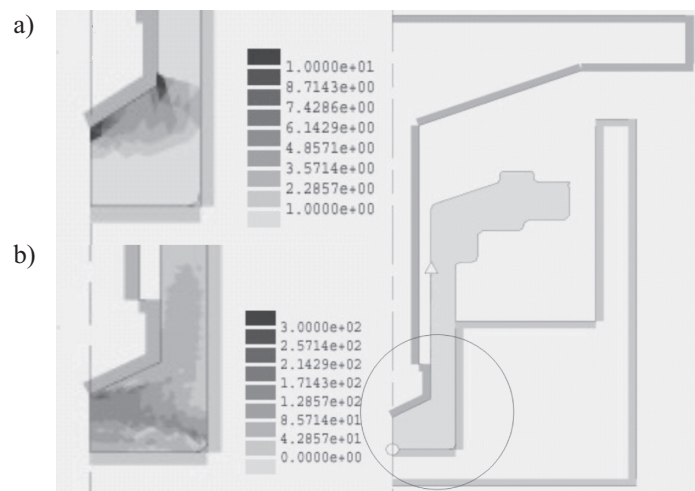

Fig. 7. *Distribution of: a) strain rate; b)grain size after fourth stage*

Due to the phenomenon of dynamic recrystallization, which occurred during the simulated forming process, the final grain size in whole material was 3 up to 4 times smaller than in original form (final average grain size equals 40–50 μm). The dynamic recrystallization has occurred in 4th treatment in deformation zone as well (Fig. 7), while the rest of microstructure stayed unchanged from previous stage.

4. SUMMARY

The paper presents the proposition of inclusion of microstructure development model for carbon-manganese steel in Forge2 software. However, analogous procedure can be applied in case of other materials. The proposed approach consists of two methods connected to each other namely semi-empirical equations of microstructure development and termo-mechanical FEM model. The main advantage of such methodology is the possibility of prediction of the microstructure parameters distributions inside processed material. In consequence, the tool, based on the thermomechanical-microstructural approach, supporting design of material hot forming processes has been created.

Similarly like in case of the presented model, other equations, which describe the mechanical properties of final product, can be included into the codes of Forge2 software by using *userparam.f* file. Such improvement allows to enhance the quality of obtained results by the possibility of prediction of mechanical properties of final product.

The distributions of process parameters obtained from presented computer simulation as well as microstructure changes (grain size, fraction of recrystallized volume, type of recrystallization) are coherent to the expectations. However, the equations establishing microstructure behaviour are described by many parameters, which influence the final result. Thus, in most cases the equations cannot be generalized onto the different classes of steel. To obtain good quantity results the parameters, based on metallographic investigation for proper material, have to be used.

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