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APPLICATION OF THE MICROSTRUCTURE DEVELOPMENT MODEL TO THE MULTISCALE FEM SIMULATION OF METAL FORMING PROCESSES

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Abstract

Models of recrystallization and grain growth mechanisms in hot forming processes are rarely implemented in the commercial finite element codes. However, most of the commercial packages give ability to implement additional modules for specific phenomena calculation. The algorithm for recrystallization in hot forming processes and its application in commercial finite element code FORGE2 are presented in this paper. Most of commonly used models calculate the microstructure evolution only after the deformation. The influence of microstructure restoration during deformation is represented by flow stress equations containing softening terms. In this study the model describing dynamic recrystallization phenomena during metal forming processes and its direct influence on the flow stress, is taken into consideration. The analysis is based on the calculation of the recrystallized fraction and the kinetics of austenite grain size evolution in micro scale, and its relation to the material flow in the macro scale. Results of the FEM calculations combined with the proposed microstructural model of hot compression and rolling processes is presented for C-Mn steels and compared with the experimental observations.

Key words: dynamic recrystallization, multiscale analysis, hot forming

1. INTRODUCTION

The essential condition for proper design of production technology and properties of final products, is the ability to predict the microstructure development during the forming operations. Hot forming processes are pointed out by Jonas (1988), as particularly important, when the recrystallization process impacts structural changes in the material. The microstructure development is highly dependant on temperature, strain and strain rate fields. Since the control of stress, strain, strain rate and temperature fields can be performed by FEM software, it is possible to calculate the microstructural evolution of materials. Kuziak et al. (1997) combined FEM calculations with microstructural models, for hot working of different steels and with the phase transformation models, for cooling process after hot working.

Commonly used commercial FEM codes give the ability to properly predict usually highly inhomogeneous fields of strain, strain rate and temperature. The microstructural models are still developed, or the microstructure changes are not followed during the deformation, therefore the FEM software is often not equipped with such solutions or implemented models are very simplified. However most of current software give ability to extend their computational capabilities by implementation of external models. Two goals of current work are specified:

- development of an algorithm for recrystallization in hot forming processes and its application in commercial finite element FORGE2 code,
- analysis of results of calculations using the model describing the dynamic recrystallization and grain size reduction during metal forming

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processes and their direct influence on the flow stress.

2. MODEL ASSUMPTIONS

Modeling of microstructure evolution during forming is based on multiscale approach recently developed by Pietrzyk et al. (2005). In each integration point of finite element, models of phenomena proceeding in microscale are calculated (kinetics of recrystallization, grain size evolution), depending on local conditions in the material (temperature, strain and strain rate). Quantities, calculated in the micro scale, are send to the FEM model in macro scale to calculate new fields of strain and stress with respect to microstructural behavior.

The algorithm for static, dynamic and metadynamic recrystallization used in simulations is presented in figure 1. Presented solution gives capability to follow values of volume recrystallized fractions and grain sizes during the entire process (during and after deformation).

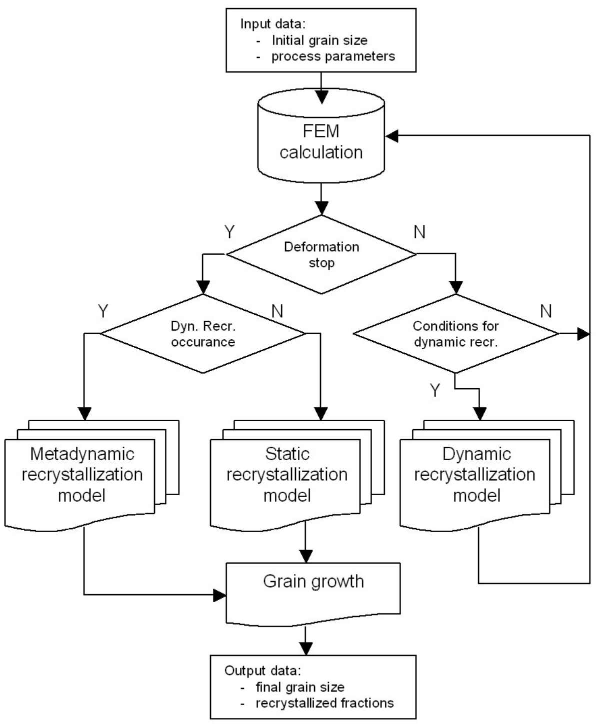

***Fig. 1.** Block diagram of algorithm for microstructure evolution modeling.*

The microstructure development model is based on classical equations proposed by Sellars (1990), which describe recrystallization kinetics and austenite grain growth in C-Mn steels. During the deformation process, after each step of FEM calculations the calculated strain is compared with the critical strain ε_c for dynamic recrystallization appearance, which is the function of process conditions and local grain size in the material:

$$\varepsilon_c = 4.9 \times 10^{-4} Z^{0.15} D^{0.5} \tag{1}$$

where: Z – Zener-Hollomon parameter, D – grain size.

Figure 2 shows schematic illustration of strain evolution during deformation. When the strain exceeds the critical value, the dynamic recrystallization is initiated (point no. 1 in figure 2a).

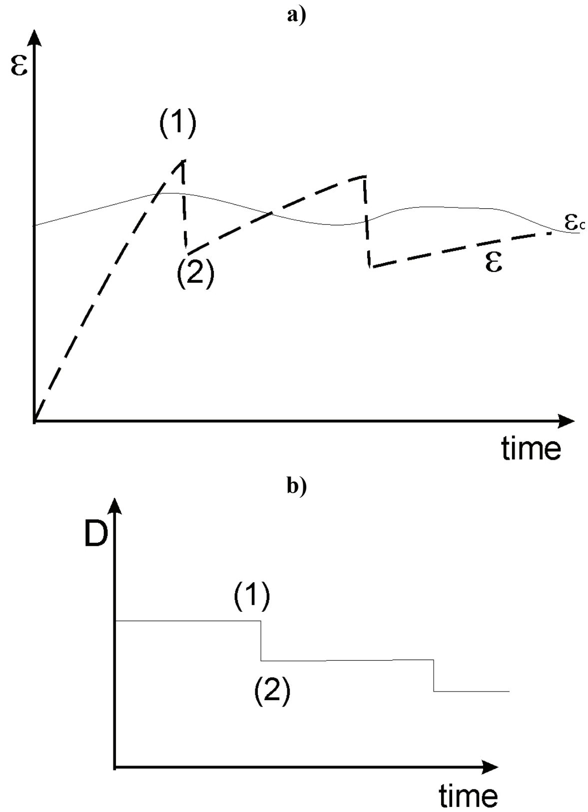

***Fig. 2.** Evolution of strain (a) and dynamically recrystallized grain size (b) during deformation process.*

In each integration point of the finite elements mesh, the change of grain size caused by initiation of recrystallization is taken into account during every time step of calculation (point no. 1 in figure 2b). The grain size during dynamic recrystallization is calculated from equation:

$$D_{DYN} = 16000 Z^{-0.233} \tag{2}$$

The change of grain size is associated with the calculation of dynamically recrystallized volume fraction:

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

where: A – material constant, ε – strain, ε_c – critical strain.

Additionally, in the next time step, local decrease of strain and consequently decrease of the flow stress is taken into account (point no. 2 in figure 2a and 2b). Reduction in strain is calculated using the equation:

$$\varepsilon = \left(1 - X_{DYN}\right)\varepsilon \tag{4}$$

where: X_{DYN} – dynamically recrystallized volume fraction.

Afterwards, during the process, increase of strain takes place again, up to the moment of exceeding the critical strain. At the end of the deformation process, the structure of the material is nonuniform. At the zones where dynamic recrystallization was not initiated, the grain size is equal to its initial value, while at the zones where dynamic recrystallization was initiated the grains are smaller then initial value according to the equation (2). Further on, the dynamically recrystallized volume fraction of the material recrystallizes metadynamically and the rest of the material is assumed to recrystallize statically. The kinetics of static recrystallization is described by equation:

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

where: t – interpas time, $t_{0.5}$ - time for 50% recrystallization.

The statically recrystallized grain size is calculated from:

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

where: D_0 – initial/previous grain size.

The metadynamic recrystallization takes place in the material after the deformation when the dynamic recrystallization occurred. After the end of the recrystallization process, the austenite grain growth process is calculated according to the equation:

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

where: t – cooling time, T – temperature.

3. NUMERICAL SIMULATIONS

The procedure of uniaxial compression of cylindrical samples with Ø55x80 dimensions, was chosen to validate the proposed model. Process parameters are as follows: die stroke – 30mm, die velocity – 50mm/s, sample temperature – 1150°C. The friction coefficient is $\mu = 0.25$.

Since the static and metadynamic recrystallization appear after the deformation process (they are also well explored by Sellars (1990), Hodgson (1993) and Nowak et al. (2000)) and are a consequences of phenomena taking place during the deformation, the microstructural changes during deformation are essential for proper process conditions design and in consequence properties of the final product. Therefore, results of dynamic recrystallization and grain size evolution during the deformation are analyzed. Distributions of strain and strain rate in the material during uniaxial compression are shown in figure 3.

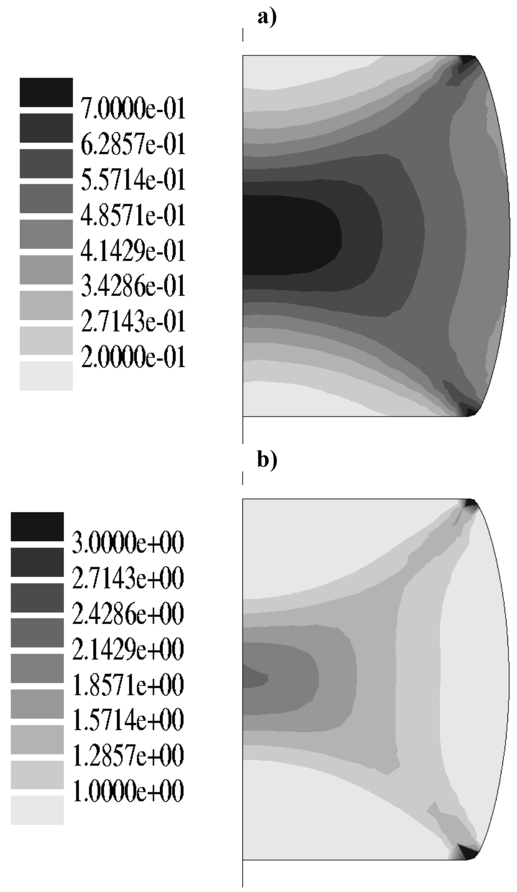

Fig. 3. *Strain (a) and strain rate (b) distribution in deformed sample.*

Strain and strain rate fields are highly nonuniform. Therefore, large differentiation of structural changes is observed. When strain exceeds critical strain value, areas with dynamically recrystallized grains appear in the sample. Restoration of microstructure reduces strain values according to equation (4) below the critical strain value, and causes that dynamic recrystallization is stopped. Consequently, the dynamic recrystallization front takes a wave form, which is clearly visible in figure 4, showing areas dynamically recrystallized in the sample cross-section during subsequent steps of compression.

Similar effect can be observed for dynamically recrystallized volume fraction (figure 5).

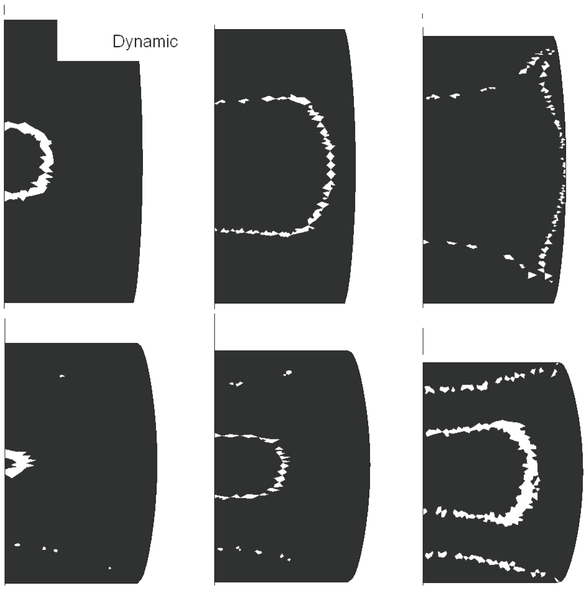

Fig. 4. Dynamic recrystallization areas in sample cross-section during subsequent steps of compression.

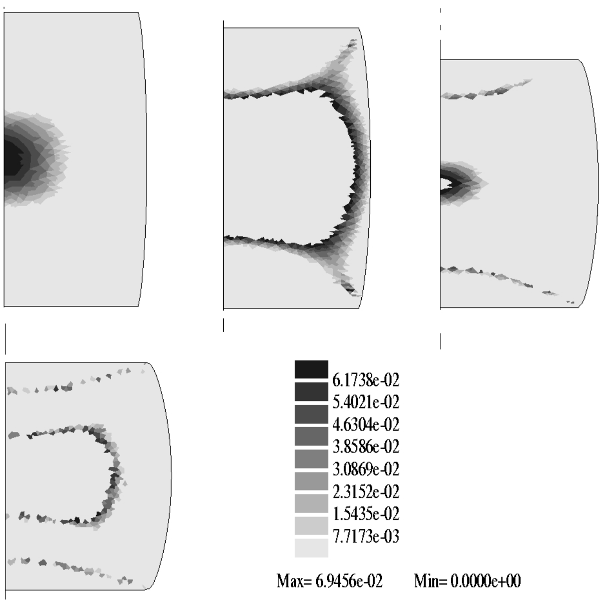

Fig. 5. Distribution of recrystallized fraction during subsequent steps of compression.

In specific time step, after exceeding the critical strain value for dynamic recrystallization, the dynamic microstructure rebuilding (reduction of grain sizes in dynamic recrystallization areas) takes place. In consequence, the strain is reduced using value of dynamically recrystallized volume fraction. In that case the recrystallized volume fraction is also locally reduced, becoming an initial microstructure for the next time step of calculation. In remaining volume of material, the increase of strain is still observed. Hence, in the following time steps the dynamic recrystallization can be reinitiated. In particular cases the phenomena of passing waves can be observed (figure 5). Figure 6 shows evolution of the average austenite grain size during subsequent steps of deformation process.

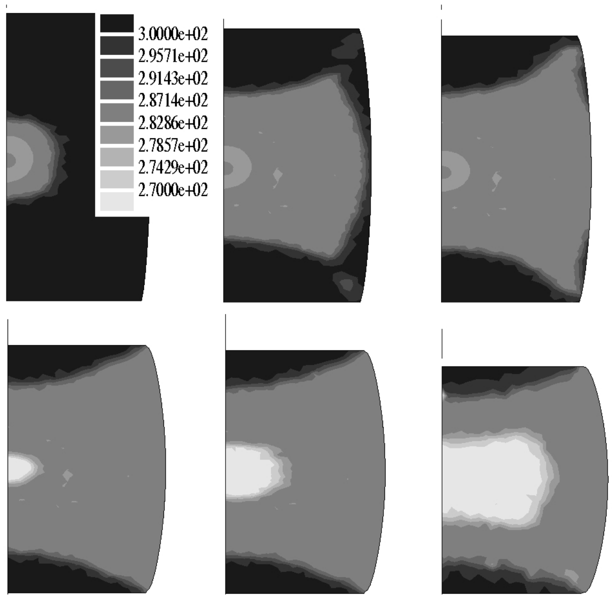

Fig. 6. The average austenite grain size during subsequent steps of compression.

The experimental data for C-Mn steels microstructure evolution during forming was presented by Liu and Lin (2003). The observed grain size during forming in temperature 1100°C, with strain rate 0.5 s^{-1}, remains in good agreement with data calculated using presented model, as seen in figure 7.

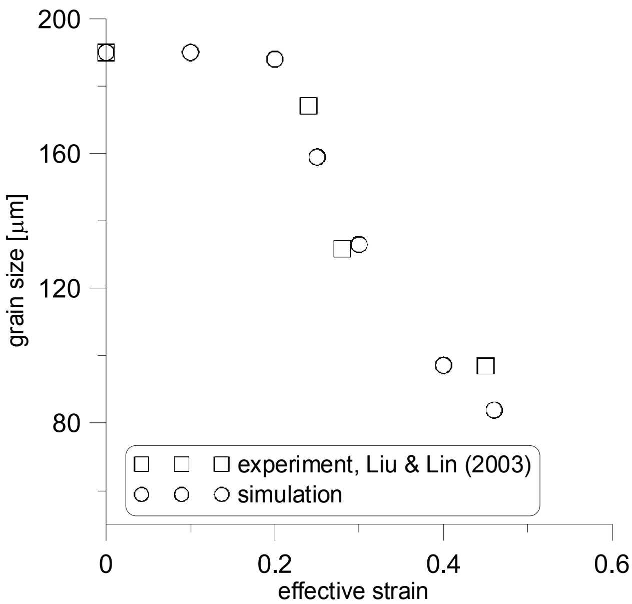

Fig. 7. Comparison between experimental and calculated austenite grain size.

The ability to follow microstructural changes in the material during deformation process allows to 'on-line' control of the industrial processes where proper microstructure of material is one of desired quality factors, e.g. the hot rolling process. The 10mm thick slab hot rolling with 25% reduction was chosen for numerical analysis. Remaining parameters were following: slab temperature – 1100°C, strip velocity – 187mm/s. The friction coefficient is $\mu = 0.25$.

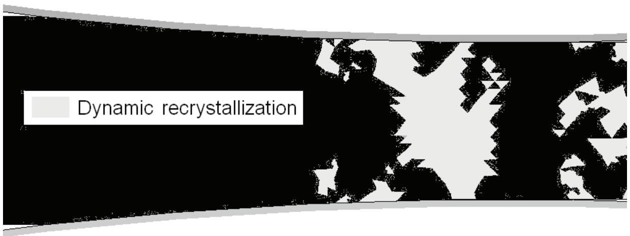

Fig. 8. *Dynamic recrystallization zones during rolling process.*

Results of simulation of rolling process are shown in figures 8 and 9. As it is shown in figure 8, in the deformation zone, the start-up of dynamical microstructure rebuilding process takes place. Due to inhomogeneities visible in figure 8, the final microstructure is also inhomogeneous (figure 9).

Fig. 9. *The average austenite grain size during rolling process.*

4. CONCLUSIONS

The way of tracking changes of microstructural parameters during the deformation, was presented. Dynamically recrystallized volume fraction influences the reduction of strains and in consequence reduces the real flow stress. In commonly used models the grain size is assumed to be constant with uniform distribution during the deformation and the evolution of microstructure is calculated after the deformation. In the presented approach the grain size changes during the deformation, which leads to its nonuniform distribution after the deformation.

The reliable numerical models describing microstructure evolution in the material under deformation allow to design proper technological processes for required structural and mechanical properties of the final products. However, the proposed approach still requires further wider experimental validation and proper calibration.

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ZASTOSOWANIE MODELU ROZWOJU MIKROSTRUKTURY W WIELOSKALOWEJ SYMULACJI MES PROCESÓW PRZERÓBKI PLASTYCZNEJ METALI.

Streszczenie

Modele mechanizmów rekrystalizacji i rozrostu ziarna podczas odkształcenia metali na gorąco są dość rzadko implementowane w oprogramowaniu opartym o Metodę Elementów Skończonych (MES). Jednakże większość z komercyjnego oprogramowania oferuje możliwość dołączania dodatkowych modułów obliczeniowych do modelowania specyficznych zjawisk zachodzących w odkształcanym materiale. W artykule przedstawiono algorytm modelowania zjawiska rekrystalizacji w materiale odkształcanym na gorąco, oraz jego implementację w komercyjnym programie FORGE2 opartym o MES. W większości z powszechnie używanych modeli ewolucja mikrostruktury obliczana jest na podstawie końcowego stanu materiału, po odkształceniu. Natomiast wpływ odbudowy mikrostruktury podczas odkształcenia reprezentowany jest poprzez równania naprężenia uplastyczniającego zawierające człon opisujący mięknięcie materiału. W niniejszym opracowaniu pod uwagę wzięto model opisujący zjawisko rekrystalizacji dynamicznej podczas odkształcenia metalu i jego bezpośredni wpływ na wartość naprężenia uplastyczniającego. Analiza zjawiska oparta jest o obliczenia w skali mikro ułamka objętości zrekrystalizowanej oraz kinetyki zmian wielkości ziarna austenitu, oraz wpływ tych zjawisk na płynięcie metalu w skali makro. Przedstawione zostały wyniki obliczeń MES połączonych z modelem mikrostrukturalnym, procesu spęczania oraz walcowania na gorąco stali węglowo-manganowych, oraz porównanie modelu z danymi eksperymentalnymi.

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