Numerical simulation of strain hardening and recrystallization in the hot forming processes

M. Pietrzyk

► To cite this version:

M. Pietrzyk. Numerical simulation of strain hardening and recrystallization in the hot forming processes. Journal de Physique IV Proceedings, 1993, 03 (C7), pp.C7-1163-C7-1170. 10.1051/jp4:19937181 . jpa-00251813

HAL Id: jpa-00251813

<https://hal.science/jpa-00251813>

Submitted on 1 Jan 1993

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Numerical simulation of strain hardening and recrystallization in the hot forming processes

M. PIETRZYK

Akademia Gorniczo-Hutnicza, University of Mining and Metallurgy, Mickiewicza 30, 30-059 Krakow, Poland

ABSTRACT

Recent developments for the finite-element modelling of the plastic forming of the metallic materials are described in the paper. The model consists of three parts; mechanical, thermal and microstructural components. First two are described in earlier publication and the focus here is put on the modelling of the microstructural phenomena. Two approaches are described. First uses conventional closed-form equations describing processes of recrystallization and grain growth. Second employs three differential equations giving time derivatives of the dislocation density, recrystallized volume fraction and the grain size.

INTRODUCTION

Fast development of the finite element method in 70-ies and 80-ies led to its wide application to the simulation of metal flow and heat transfer in various metal forming processes. Thermal-mechanical solutions for rolling [1], drawing [2] and upsetting [3] have been developed by the author. Recently, the scientific interest of several researchers focuses on the modelling of the microstructure evolution during hot forming. Several publications dealing with this problem have been published [4-7], but the majority of the authors solves the problem by a connection of the closed form equations describing recrystallization with less or more advanced thermal-mechanical models. However, the information supplied by the finite element modelling of metal flow and heat transfer would allow to use more advanced and accurate description of the microstructural events. The objectives of the present paper have been formulated with the above remarks in mind. A description of the conventional thermal-mechanical-microstructural approach and its abilities is given in the first part of the paper. Then, the advantage is taken from a possibility of an accurate evaluation of temperatures, strain rates and stresses as time functions and simulation of the recrystallization and grain growth in the varying conditions of plastic deformation is performed.

CONVENTIONAL APPROACH

In this approach, more advanced thermal and mechanical components of the model are connected with the conventional description of the microstructural phenomena. Typical flow formulation [8] is coupled with a thermal model based on a finite element solution of the general convective-diffusion equation, yielding the following equations:

$$\frac{\partial}{\partial \mathbf{v}^T} \left\{ \int_V \left(\sigma_p \sqrt{\frac{2}{3} \mathbf{v}^T \mathbf{B}^T \mathbf{E} \mathbf{B} \mathbf{v}} + \lambda \mathbf{B}^T \mathbf{C} \mathbf{v} \right) dV + \int_S \mathbf{N}^T \mathbf{F} \mathbf{v} dS \right\} = 0 \quad (1)$$

$$\left\{ \int_V [(\nabla \mathbf{w})^T k \nabla \mathbf{N} + \rho c_p \mathbf{w}^T \mathbf{v} \nabla \mathbf{N}] dV + \alpha \int_S \mathbf{w}^T \mathbf{w} dS \right\} \mathbf{T} = \int_S (\alpha T_0 + q) \mathbf{N} dS + \int_V Q \mathbf{w} dV \quad (2)$$

where: σ_p - yield strength, $\mathbf{v}$ - vector of velocities, $\mathbf{B}$ - matrix of derivatives of shape functions, λ - Lagrange multiplier, $\mathbf{C} = \{1, 1, 0\}^T$ for the plane strain problems and $\mathbf{C} = \{1, 1, 1, 0\}$ for the axisymmetrical problems, $\mathbf{F}$ - boundary tractions, $\mathbf{T}$ - vector of temperatures, k - conductivity, ρ - density, c_p - specific heat, Q - rate of heat generation due to plastic work, $\mathbf{w}$ - matrix of weighting functions, $\mathbf{N}$ - matrix of shape functions, α - heat transfer coefficient, T_o - ambient temperature or tool temperature, q - rate of heat generation due to friction.

Detailed description of this thermal-mechanical model and boundary conditions is given in [1]. This model is connected first with the conventional equations developed by Sellars [4] and Roberts et al. [9] describing processes of recrystallization and grain growth. In consequence, the thermal-mechanical-microstructural model is developed; this model has been validated experimentally in the laboratory conditions and, finally, has been applied to the simulation of hot rolling [6,10] and forging [11] processes and proved to be very helpful in designing the technological parameters. Microstructural component of the model has been validated experimentally in a number of rolling and forging tests [10,12]. Fig.1 shows the results of one of the published earlier experiments. A reverse hot rolling process in three passes is considered here and measured and calculated distributions of the austenite grain size on the cross section of the steel sample after second and third passes are presented in the figure. The parameters of the experiment include the initial thickness of 11.6 mm, temperature in the furnace 1050°C, reductions 0.18, 0.17 and 0.24 in three passes respectively, time intervals: furnace - 7 s - first pass - 9.3 s - second pass - 9.6 s - third pass - 5 s - quenching. It is seen in Fig.1 that the calculated austenite grain size is within the standard deviation of the measurements. A larger number of results and the microstructures for all the experiments are given in [12].

Fig.1. Measured and calculated grain size on the cross section of the carbon steel samples after reverse hot rolling in 2 and 3 passes.

In order to present model's predictive abilities, a typical results of the simulation of the microstructure evolution in the industrial hot strip rolling are presented below. The hot strip mill in the Sendzimir still works in Krakow consisting of 5 roughing stands and 7 finishing stands has been taken as an example. Since the influence of the initial grain size after heating in the furnace on the microstructure diminishes after few cycles of deformation and recrystallization and the current austenite grains depend on the temperature and strain fields in the last few passes, the results for the finishing mill only will be presented here. The estimated austenite grain size at the entry to the finishing mill is 150 μm .

Current analysis includes an investigation of the controllable parameters (heating temperature, rolling velocity, delay time on the transfer table, amount of water in the descalers and in the laminar cooling,

draft schedules) on the microstructure of the product as well as on the rolling forces, roll torques and temperatures. The basic technological parameters of the investigated process, together with the results of calculations, are given in Table 1. Fig.2 shows how the heating temperature in the furnace and the work of the water descaler before the entry to the finishing train affect the finite austenite grains. An increase of the heating temperature within the range of 50°C has slight influence on the microstructure; an increase of the grain size being observed with the increasing temperature. The work of the descaler has stronger influence. Turning off the descaler results in about 15 percent coarser grains.

Table 1 Pass schedule and process parameters for rolling of 2x830 mm strip [13].

pass	h	r	T_{av}	α	F	M	v	t_n	D_v
	mm		°C	W/m ² K	kN	kNm	m/s	s	μm
0	170	-	1286	-	-	-	-	95	-
1	125	0.26	1258	81300	7240	920	0.99	10	-
2	78	0.38	1245	77900	8680	1140	0.97	18	-
3	52	0.33	1224	76500	7880	780	1.56	15	-
4	38	0.27	1194	75900	5380	320	2.32	15	-
5	30	0.21	1152	75800	4250	200	2.3	45	150
6	15	0.5	1042	79900	9800	640	0.9	5.7	42.3
7	9.5	0.37	1009	77600	7420	280	1.42	3.5	29.1
8	6.2	0.35	978	76200	7410	215	2.18	2.3	23.5
9	4.2	0.32	952	75300	7460	155	3.23	1.5	20.8
10	2.9	0.31	932	74600	6820	115	4.68	1.1	19.1
11	2.4	0.17	912	74200	3600	36	5.65	0.9	23.1
12	2	0.17	892	73800	3770	36	6.78		23.5

h - thickness
 r - reduction
 T_{av} - average temperature
 α - heat transfer coefficient
 F - rolling force
 M - roll torque
 v - rolling velocity
 t_n - time interval
 D_v - average grain size

Fig.2. The influence of the heating temperature and the water descaling on the final austenite grains.

Further analysis included an investigation of the correlation between the rolling schedule and the microstructure. Due to the insufficient power of motors the reductions in last two passes are rather low what results in an increase of the austenite grains in these passes (Table 1). However, after the planned modernization of the mill the power of the motors will be increased and the possibility of an increase of the reductions and a decrease of the rolling temperature will appear. Fig.3 shows how the increase of the reductions in the last two passes influence the microstructure. It is seen that, for constant total reductions, increasing reductions in stands 9 and 10 lead to the decrease of the austenite grains.

Fig.3. Distribution of the austenite grain size across the strip calculated for three different roll pass schedules in the last five stands.

Presented results show the ability of the model to design the optimum rolling technology taking the microstructure and the properties of the product in the consideration. Experimental validation of the model [10,12,14] showed its very good predictive ability for normal hot forming conditions. It was, however, observed during the investigation that the model fails for the critical conditions such as forming in the temperature close to the transformation temperature or applying the deformations close to the critical for the static recrystallization. These observations led to the conclusion that more sophisticated microstructural models should be developed and used in the analyses. A proposition of a new approach is presented in the next section.

DIFFERENTIAL APPROACH

Advantage should be taken from the fact that the finite element models give an accurate account of temperatures, strain rates and strains as functions of time, leading to the simulation of the kinetics of recrystallization and grain growth, depending on the varying conditions of the plastic flow. First step of this approach has been achieved by an introduction of an incremental method, based on the additivity rule, to the calculation of the time of recrystallization under the conditions of high heating/cooling rates [7]. Further work includes taking into consideration variations of the strain rates, strains and temperatures during the deformation. The functions describing time derivatives of the probability of dislocation density $G(\rho_d, t)$, recrystallized fraction x and grain size D :

$$\frac{dG(\rho_d, t)}{dt} = \phi(\Delta\epsilon) - g(\epsilon) - \frac{\nu\gamma}{D} m \tau \rho_d G(\rho_d, t) \quad (3)$$

$$\frac{dx}{dt} = \int_0^{\infty} \frac{\nu\gamma}{D} m \tau G(\rho_d, t) d\rho_d \quad \text{for } \rho_d > \rho_{cr} \quad (4)$$

$$\frac{dD}{dt} = m\sigma_s - D \frac{dx}{dt} \ln N \quad (5)$$

suggested in [15] are implemented into the finite element program and calculations of the microstructure evolution are performed. Main symbols in the equations represent: ρ_d - dislocation density, $\Delta\epsilon$ - strain increment, $\phi(\Delta\epsilon)$, $g(\epsilon)$ - functions representing hardening and softening, respectively,

m - mobility of the grain boundaries, σ_g - grain boundary energy. This approach, showed briefly in [13], enables to simulate the local microstructural phenomena during and after the deformation, without distinguishing the dynamic and static recrystallization.

The main difficulty in the computations is connected with the evaluation of the material constants, such as the mobility of the grain boundaries or the grain boundary energy per unit area. In order to show model's ability, a numerical experiment was performed in [13] and it will be described briefly here. The vacuum melted iron with properties given in [15] was used as a testing material. Uniform deformation at a temperature of 850°C with the constant strain rate of 1/s for 1.55 s, giving a total strain of 1.55. An initial grain size of 100 μm was assumed. Calculations were based on a simultaneous solutions of the equations (3), (4) and (5). Full set of results is given in [13] and some of them are repeated briefly in Fig.4. Situation at the beginning of the deformation and after the strain of 0.4 is shown in Fig.4a. It is seen in this figure how, due to the strain hardening, volume distribution curve of the dislocation density moves toward the right. The strain is, however, too small to achieve the critical density of dislocations which is $6.4 \times 10^{13} \text{ m}^{-2}$. This value is reached for higher strains as it is seen in Fig.4b where the situation for the strain of 0.8 is presented. Recrystallization goes on during the deformation and the kinetics of the transformation is described by the equation (4). Recrystallized material disappears over the volume spectrum of ρ_d and it enters the distribution as a fresh material

Fig.4. Volume distribution of the dislocation density at subsequent stages of the hot deformation of the vacuum melted iron.

with the dislocation density several orders lower, about 10^4 m^{-2} . The grain size is calculated for the recrystallized material from the equation (5), independently for each range of the dislocation density. Further deformation leads to increasing recrystallization and, finally, two recrystallization cycles are seen in Fig.4c and three recrystallization cycles are seen in Fig.4d. When the deformation is finished then the dislocation density decreases due to further recrystallization and softening.

The numerical experiment presented above shows that the suggested approach enables the simulation of local structural phenomena during and after the deformation, without distinguishing static and dynamic recrystallization. Indeed, constant temperature and strain rate were assumed in the computations, but introduction of the varying conditions does not present any difficulty. Next numerical test is performed for a typical hot rolling conditions. The equations (3), (4) and (5) are implemented into the thermal-mechanical finite-element approach and the data obtained from that approach are used in the computations of the microstructure evolution. Fig.5 shows a typical time temperature profiles for hot rolling of flat samples [1]. Two locations on the cross section of the sample are considered; central portion and the area close to the contact zone. Finite element calculations show that the characters of the temperature variations are different for those locations. The centre of the sample is subjected to some deformation heating while the intensive cooling by the strip contact with

the roll prevails in the surface zone. It is also observed that, due to shear strain rates, the surface zone is subjected to larger strains than the central portion of the sample. Figs 6 - 9 show how these typical hot rolling conditions affect the evolution of the microstructure. Situation at the exit from the roll gap is presented in Fig.6. Due to lower strains the curve of the volume distribution of the dislocation density for the centre of the sample moves slower towards the right than that for the surface zone. On the other hand, larger temperatures in the centre cause that the recrystallization begun in that part (dynamic recrystallization) and the recrystallized volume enters the distribution as a fresh material with low dislocation density.

Fig.5. Typical time-temperature profiles for hot rolling.

Fig.6. Volume distribution of the dislocation density at the exit from the roll gap.

Fig.7. Volume distribution of the dislocation density at the centre of the sample in 0.1 s after exit from the roll gap.

Fig.8. Volume distribution of the dislocation density at the surface zone of the sample in 0.5 s and 1 s after exit from the roll gap.

Only insignificant traces of the recrystallization are observed for the surface zone. Fig.7 shows the situation in the centre of the sample 0.1 s after the deformation. Due to further recrystallization the volume of the material with the low dislocation density increases. The recrystallization in the centre of the sample is completed in about 0.15 s after the exit from the roll gap. Different microstructural phenomena are observed in the surface zone (Fig.8). In 0.5 s after the deformation the recrystallized volume fraction is about 12% and it increases to 50% in 1 s after the deformation. The recrystallization time for the surface zone is about 1.5 s. Notice that the recrystallization of the surface layer of the material takes place in the continuously increasing temperature (Fig.5).

Variations of the grain size during the investigated process are shown in Fig.9. The grain size is calculated from the differential equation (3) using current local parameters. It is seen in Fig.9 that due to the dynamic recrystallization in the centre the grain size begins to decrease while the

Fig.9. Grain size variations in two locations during and after hot rolling of vacuum melted iron.

material is still in the roll gap. Right after exit from the pass the recrystallization results in a fast decrease of the grains. In the same time the grains in the surface zone almost do not change. Both recrystallization and grain refinement in the surface layer intensify later, when the grain growth in the centre is observed.

Analysis of all presented results shows that suggested approach gives very good qualitative assessment of the microstructural phenomena in the hot forming of steel. The character of the influence of the temperature, strain rate and strain on the grain size variations is predicted in very good agreement with the experimental data published by a number of authors [4,9,16]. The quantitative accuracy of the model depends on the evaluation of the material constants in the equations (3), (4) and (5). In the present work the data given for the vacuum melted iron [15] are used to present model's ability to

predict the microstructure evolution in the complex, varying conditions of the hot forming. Application of the model to other materials would require introduction of the proper material parameters. Since these parameters are difficult to measure, an experimental validation of the model would be probably required.

CONCLUSIONS

Two approaches to the modelling of the microstructure evolution are presented in the paper. Both use an advanced thermal-mechanical finite-element model to simulate the metal flow and the heat transfer in the deformation zone. Finite element model supplies information regarding the temperature and the strain fields necessary for the simulation of the microstructural phenomena. Two ways of modelling the recrystallization process are used. First is based on the conventional closed form equations developed by Sellars [4] and by Roberts et al [9]. Connection of these equations with the thermal-mechanical model gives very good results for the normal conditions of hot forming. It is shown in the paper that such an approach supplies an interesting information regarding the influence of the controllable parameters of the process on the grain size of the product. Examples of the predictions of the influence of the heating temperature and the hot rolling schedule on the microstructure of the strips are given in the paper.

This approach fails, however, for the critical forming conditions, when the temperatures are close to the transformation temperature or the strains are close to the critical for the static recrystallization. Therefore, a suggestion of a new approach based on the solution of the differential equations describing the dislocation density, the recrystallized volume fraction and the grain size is suggested in the paper. The approach allows to simulate the evolution of the microstructure in an arbitrary complex and varying forming conditions. On the other hand, it requires several material parameters which are difficult to assess.

ACKNOWLEDGEMENTS

The financial assistance received from the Polish Committee for Scientific Research (grant no. 7.0520 91 01) is gratefully acknowledged. Author expresses his thanks to Professor Z. Kedzierski from the University of Mining and Metallurgy in Krakow, Poland, for his advice and suggestions.

REFERENCES

- [1] PIETRZYK M. and LENARD J.G., Thermal-Mechanical Modeling of the Flat Rolling Process, Springer-Verlag, Berlin-Heidelberg-New York, 1991.
- [2] PIETRZYK M., Steel Res., **60** (1989) 459.
- [3] PIETRZYK M., Hutnik, **58** (1991) 63.
- [4] SELLARS C.M., Mat. Sci. Technol., **6** (1990) 1072.
- [5] ZOUHAR G. and HOFGEN H., Proc. 8th PTD Conf., Dearborn, 1988, 23.
- [6] PIETRZYK M., Steel Res., **61** (1990) 603.
- [7] KEDZIERSKI Z. and PIETRZYK M., Metall. Foundry Eng., **18**, (1992) 47.
- [8] KOBAYASHI S., OH S.I. and ALTAN T., Metal Forming and the Finite Element Method, Oxford University Press, New York - Oxford, 1989.
- [9] ROBERTS W., SANDBERG A., SIWECKI T. and WERLEFORS T., Proc. Conf. Techn. & Appl. of HSLA Steels, Philadelphia, 1983, 67.
- [10] PIETRZYK M., KEDZIERSKI Z. and LENARD J.G., Proc. NUMIFORM'92, eds, Chenot J.L., Wood R.D. and Zienkiewicz O.C., Sophia Antipolis, 1992, 749.
- [11] PIETRZYK M., GLOWACKI M. and LENARD J.G., J. Mat. Proc. Techn., (1993) (in press).
- [12] PIETRZYK M., KEDZIERSKI Z., KUSIAK H., MADEJ W. and LENARD J.G., Steel Res., (1993) (in press).
- [13] PIETRZYK M. and LENARD J.G., Proc. Conf. Modelling of Steel Rolling, London, 1993.
- [14] PIETRZYK M., Proc. 11th Conf. Computer Methods in Mechanics, eds, Gilewski W., Chodor L., Kielce-Cedzyna, 1993, 715.
- [15] SANDSTROM R. and LAGNEBORG R., Acta Metall., **23** (1975) 387.
- [16] SAMUEL F.H., YUE S., JONAS J.J. and BARNES K.R., ISIJ Int., **30** (1990) 216.