Investigation and Modeling of Recrystallization of Cold Rolled Automotive Steels

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Abstract. Ferrite recrystallization in cold-rolled sheets of automotive steels has been studied using a Gleeble 3800 complex. Mathematical models for quantitative description of the process kinetics and prediction of the recrystallized ferrite grain size have been developed. These models enable performing calculations for any arbitrary heating regimes, including those that are used in industrial production practice, and allow taking into account the effects of a fairly wide range variation of the chemical composition of steels.

1. Introduction
Final microstructure and, consequently, mechanical properties of cold-rolled sheets of automotive steels depend strongly on the recrystallization process. In this regard, in recent years considerable attention has been paid to the experimental studies of the process [1, 2], as well as to the development of adequate mathematical models [3, 4].

In this paper we present some results of experimental investigation of recrystallization kinetics for cold-rolled sheets of 10 steel grades produced at the enterprise ‘Severstal Russian Steel’. This study was carried out with the help of a Gleeble 3800 complex. Quantitative mathematical models for predicting the process kinetics and the recrystallized ferrite grain size as a function of a cold deformation degree, the parameters of initial steel structure and its chemical composition have been developed. The results of modeling calculations are compared with experimental data.

2. Materials and experimental technique
Investigation of the recrystallization kinetics was performed for cold-rolled sheets of 10 steel grades (DX54D, HX220YD, HX260YD, CR210B2, HX260BD, 08Ю, HX300LAD, 08пс, CR420LA, DP600) (08Ю, 08пс are Russian grade marks) with significantly varying contents of carbon, manganese, titanium and niobium (0.004≤C≤0.09; 0.1≤Mn≤0.72; 0.002≤Ti≤0.066; 0.001≤Nb≤0.023 (mass. %)). The degree of deformation during cold rolling varied in the range of 0.5–0.8 (relative deformation).

Reccrystallization kinetics during isothermal annealing at three temperatures in the range of 550–750°C was investigated using the Gleeble 3800 complex for each of the 10 steel grades. The samples were rapidly heated (heating rate is 50°C/s) to the annealing temperature, and held for a definite period (≤ 3000 s). Softening of the studied samples due to recrystallization was estimated by measuring their hardness after cooling to room temperature at a sufficiently high rate (10°C/s). The recrystallized fraction was estimated basing on the hardness data and on metallographic analysis.
3. Mathematical models describing the recrystallization kinetics and a recrystallized ferrite grain size

When constructing the models, the following assumptions based on experimental data were used:

- potential nuclei of the recrystallized grains (‘sustainable’ subgrains) are formed at the original ferrite grain boundaries and have a high angle boundary from the initial stage of structure evolution;
- all subgrains have the same initial size determined by the value of strain hardening during cold rolling;
- subgrains differ in dislocation density and their distribution in dislocation density is taken to be normal;
- recrystallized ferrite grains are formed when growing subgrains reach critical size;
- the form of grains and subgrains is supposed to be spherical;
- the final size of a recrystallized ferrite grain is determined by its original structure (ferrite grain size after hot rolling) and by the degree of deformation during cold rolling.

In accordance with the above assumptions, subgrains nucleated after cold deformation have different dislocation density [4] and their distribution in this density is considered to be normal. At the first stage of modeling a set of subgrain classes characterized by different dislocation density is created. The number of the classes is equal to \( N_{\text{class}} \). Further modeling of the recrystallization kinetics reduces to description of the subgrains growth in all classes with deferent dislocation density, which determines the corresponding different driving pressure.

Upon reaching the critical size by a growing subgrain it is assumed that recrystallized grains are formed in the corresponding class and continue to grow with higher interface mobility than the previous subgrains.

The so-called extended recrystallized metal volume fraction, \( X_{\text{ext}}(t) \), is calculated as follows:

\[
X_{\text{ext}}(t) = \frac{4\pi}{3} \sum_{i} N_{i}^{\text{ext}} \left( \bar{R}_{i}(t) \right)^{3},
\]

where \( N_{i}^{\text{ext}} = N_{i} \) is a number of recrystallized grains in the \( i \)-th class with an average radius equal to \( \bar{R}_{i} \). The actual value of recrystallized volume fraction is calculated as:

\[
X(t) = 1 - \exp \left( -X_{\text{ext}}(t) \right).
\]

3.1. Calculation of the driving pressure of recrystallization

At the stage of the subgrains growth the driving pressure of recrystallization, \( G_{i}(t) \), corresponding to the \( i \)-th class of their distribution in dislocation density, is calculated as:

\[
G_{i}(t) = \frac{1}{2} \bar{\rho}_{i}(t) \mu b^{2},
\]

where \( \mu \) is shear modulus of ferrite; \( b \) is Burgers vector modulus of dislocations.

To determine the initial value of the average dislocation density as a function of strain hardening the following well known formula is used:

\[
\bar{\rho}_{d} = \left( \frac{\Delta \sigma}{\sigma_{0} M_{f} \mu b} \right)^{2},
\]

where \( \Delta \sigma \) is the strain hardening after cold rolling; \( M_{f} \) is the Tailor factor assumed to be 2.7 for ferrite; \( \sigma_{0} \equiv 0.33 \).

A change of the dislocation density due to recovery in the subgrains belonging to the \( i \)-th class is determined on the basis of calculated values of strain hardening, \( \Delta \sigma_{i} \), decreasing with time using the
A equation similar to (4). Calculation of the strain hardening change with time is performed using kinetic equation [5]:

\[
\frac{d\Delta\sigma_i}{dt} = \frac{64\Delta\sigma_i^2 v_i}{9M \rho \alpha_i^2 E} \exp \left[ \frac{U_a}{RT} \right] \sinh \left( \frac{\Delta\sigma_i V_a}{RT} \right).
\]

(5)

where \( U_a \) and \( V_a \) are, respectively, the activation energy and volume of recovery that are assumed to be independent of temperature and chemical composition; \( v_i \) is Debye frequency; \( E \) is Young modulus; \( R \) and \( T \) have their usual meaning.

3.2. Calculation of the subgrains volume density and a recrystallized grain size

As noted above, the model assumes that nucleation of recrystallized subgrains occurs at the boundaries of the original ferrite grains. Accordingly, for the volume density of subgrains, \( N_{sg} \), we can write:

\[
N_{sg} = \frac{\alpha_{sg} S_{gb}(D_{a}^0, \varepsilon)}{S_{sg}^0},
\]

(6)

where \( S_{gb}(D_{a}^0, \varepsilon) \) is an area of deformed ferrite grain boundaries per unit of its volume; \( D_{a}^0 \) is an initial ferrite grain size; \( \varepsilon \) is a degree of deformation; \( S_{sg}^0 \) is an initial area occupied by the sub grain at ferrite grain boundaries.

The dependence of a specific area of deformed ferrite grain boundaries on a degree of deformation is taken into account as follows [6]:

\[
S_{gb}(D_{a}^0, \varepsilon) = 24 \pi D_{a}^0 \left( 0.491e^{\varepsilon} + 0.155e^{-\varepsilon} + 0.143e^{-3\varepsilon} \right).
\]

(7)

This formula takes into account that in the process of rolling deformation initially spherical (equiaxed) ferrite grains change their shape into ellipsoidal.

It was shown that the final size of recrystallized ferrite grains weakly depends on the annealing temperature when it changes in the range of 600°-750°C, i.e. according to the kinetics of the process [4]. Accordingly, this size should be determined by the initial structure of ferrite and the degree of deformation during cold rolling. The analysis of the experimental data obtained in the present study confirms this statement. On this basis, assuming that area \( S_{sg}^0 \) \( \subseteq \overline{G}^{-2}(t = 0) \) for the subgrain volume density under discussion we obtain:

\[
N_{sg} = \alpha_{sg} S_{gb} \left( D_{a}^0, \varepsilon \right) \left( \overline{G}(t = 0) \right)^2,
\]

(8)

where \( \overline{G}(t = 0) \) is the driving pressure of recrystallization at the initial moment, calculated using the average density of dislocations.

An important parameter of the recrystallized structure is the final grain size of ferrite, \( D_{a}^{eff} \). This size may be calculated from the volume density of nuclei as follows:

\[
D_{a}^{eff} = N_{sg} \left( \frac{1}{3} \right).
\]

(9)

3.3. Calculation of the growth rate

In the present model calculations of grain and subgrain growth rates are performed using the following equation:

\[
\nu(t) = M_{GB}^{sg} G(t),
\]

(10)

where \( \nu(t) \) is the growth rate; \( M_{GB}^{sg} \) and \( M_{GB}^{g} \) are effective mobility values for subgrain and grain boundaries, respectively; \( G(t) \) is the driving pressure. The radius of the subgrains in the i-th class under time moment t is:
\[
R'_{sg}(t) = R_{sg}^0 + \int_0^t M'_{gb}G_i(t)\,dt,
\]

where \( R_{sg}^0 \) is the initial sub grain size; \( G_i(t) \) is the driving pressure for sub grain of the \( i \)-th class.

The size of the grain, which is nucleated by time \( \tau \), at time moment \( t \), is:

\[
R'_i(t) = R'_i + \int_\tau^t M'_{gb}\bar{G}(t-\tau)\,dt,
\]

where \( R'_i \) is the initial grain size for the \( i \)-th class that is equal to a corresponding critical sub grain size; \( \bar{G}(t) \) is an average value of driving pressure.

The recrystallized grain boundary mobility is calculated as:

\[
M_{gb}^e(T;Y_{AE}) = M_0^e \exp \left( \frac{S_{gg}(Y_{AE})}{R} \right) \exp \left( -\frac{Q_{gg}(Y_{AE})}{RT} \right),
\]

where \( Q_{gg}(Y_{AE}) \) and \( S_{gg}(Y_{AE}) \) are, respectively, the activation energy and entropy of the diffusion lattice reconstruction, that controls the movement of recrystallized grain boundaries; \( Y_{AE} = \{ y^*_C; y_M; y_S; y_N; y_{Cr}; y_{Mo}; y_{Nb}; y_{Ti}; y_V \} \) is the set of average alloying elements concentrations in a solid solution; \( y^*_C \) is an effective value of carbon concentration in the moving boundary, estimated taking into account cementite particles dissolution upon heating; \( M_0^e \) is a constant parameter.

The entropy of grain growth activation is calculated as,

\[
S_{gg}(Y_{AE}) = \beta_{gg} Y_{AE},
\]

where \( \beta_{gg} \) is an empirical model parameter.

The effective activation energy of the process is assumed to be equal to the activation energy of grain boundary self-diffusion, which is proportional to the volume self-diffusion activation energy (SDAE) \( Q_{sd}(Y_{AE}) \):

\[
Q_{gg}(Y_{AE}) = \alpha_{gg} Q_{sd}(Y_{AE}),
\]

where \( \alpha_{gg} \) is an empirical parameter. SDAE depends on the chemical composition of the solid solution as follows [7]:

\[
Q_{sd}(Y_{AE}) = 311691 - 278242 \left( 1 - \exp \left( -0.394 y^*_C \right) \right) + 88752 y_{Mo}^{0.31} + 22801 y_S - 6490 y_{Cr} + 84864 y_{Mo}^{0.65} - 38575 y_N^{0.3} - 7298 y_V + 132594 y_{Nb}^{0.263} + 82128 y_{Ti}^{0.401} \quad (J/mol).
\]

Subgrain boundaries mobility is calculated using equation:

\[
M_{gb}^e(T;Y_{AE}) = \alpha_{gb}^e M_{gb}^e(T;Y_{AE}),
\]

where \( \alpha_{gb}^e < 1 \) is parameter of the model.

An optimal set of empirical values for model parameters was obtained using an experimental data base for the steels investigated in the present study.

3.4. A brief description of the numerical simulation algorithm

In the numerical model under discussion continuous time evolution of subgrain and grain systems is modeled as a series of changes that occur over short time intervals (steps) \( \delta t^{(k)} \). At each step an increment of subgrain/grain sizes is calculated for all classes. In the process of calculations the subgrains in the \( i \)-th class are transformed into recrystallized grains with the same class index at the time moment when their size reaches critical value \( R'_c \), i.e. under condition: \( R'_{sg} \geq R'_c = 2\gamma / G(t) \), where \( \gamma \) is an effective value of specific energy of the recrystallized grain boundaries.

5. Comparison of simulation results with experimental data

The results of modeling calculations of the recrystallization kinetics for some investigated steels are compared with experimental data in Figures 1, 2.

One can see that the developed model allows one to achieve good agreement with the experiment.
Figure 1. Comparison of the results of recrystallization kinetics calculation with the experimental data for IF-steels: a) HX220YD; b) HX260BD.

Figure 2. Comparison of the results of recrystallization kinetics calculation with the experimental data for investigated steels: a) CR420LA; b) DP600.

The results presented in Figure 3 demonstrate that the complementary model provides good prediction accuracy for a ferrite recrystallized grain size comparable with the error of experimental determination of this parameter.

Figure 3. Calculation results for a recrystallized ferrite grain size in comparison with the experimental data.
Conclusions
Thus, basing on the presented results, the following conclusions can be made:

- mathematical models of recrystallization processes in cold-rolled sheets of investigated steels are developed and described with satisfactory accuracy both the kinetics of the process under isothermal annealing and a recrystallized ferrite grain size;
- the developed recrystallization model predicts with reasonable accuracy the crystallization kinetics in conditions of heating at an arbitrary rate and subsequent isothermal holding, which are employed when annealing cold-rolled sheets in industrial production lines;
- the developed recrystallization model adequately takes into account both the effect of content of carbon and the main substitution alloying elements (Mn, Si, Nb, Ti) on the kinetics of the process, which distinguishes it from the currently available analogs in the published literature.

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