

Forecasting the mean flow stress of carbon and low-alloy steels in hot rolling on a strip mill

Valeriy V Shkatov, Igor P Mazur and Victor V Shkatov

Lipetsk State Technical University, 30 Moskovskaya St., 398055 Lipetsk, Russia

E-mail: mazur_ip@mail.ru

Abstract. The effectiveness of the initial setup of the mill stands depends on the accuracy of the calculation of the mean flow stress of the rolled metal, the value of which is determined not only by the deformation parameters, but also depends on the chemical composition of the steel and the structural transformations of the rolled metal. This article proposes a mathematical model for the prediction of the mean flow stress of carbon and low-alloy steels during hot rolling on a strip mill, which allows to take into account, along with the deformation parameters, the content of chemical elements in the steel and the processes of recrystallization of the metal during deformation and during inter-pass times. The adequacy of the model was checked by comparing the results of the calculation of mean flow stress with the experimental data obtained by rolling of 100 strips 2-12 mm thick of 16 grades of carbon and low-alloy steels on a broadband mill 2000 NLMK. The influence of dynamic, metadynamic and static recrystallization on the mean flow stress of carbon and low-alloy steels in the mill stands is estimated. It is shown that taking into account the processes of recrystallization of the deformed metal can significantly improve the accuracy of the prediction of the mean flow stress.

1. Introduction

Currently, 80-90% of hot-rolled sheet steel is produced on continuous and semi-continuous broadband hot rolling mills, which is explained by higher technical and economic performance of these mills compared to other types [1]. For control and management of technological process of rolling on mills the computer equipment is now widely used.

When changing the thickness, width or chemical composition (steel grade) of the strip, it is necessary to carry out the initial setup of the mill stands, assuming the appointment of optimal deformation and speed parameters of rolling for the new working conditions of the mill. The effectiveness of the initial setup of the mill stands depends on the accuracy of the calculation of the mean flow stress of the rolled metal, the value of which is determined not only by the deformation parameters, but also depends on the chemical composition of the steel (including fluctuations in the content of elements within the steel grade), structural transformations of the rolled metal during deformation and during inter-pass times.

During repeated deformation of the strip steel in the stands of the finishing group of the mill, the following options for the development of recrystallization are possible, leading to the softening or hardening of the metal:

- softening due to dynamic recrystallization during deformation;
- softening due to metadynamic or static recrystallization during inter-pass times;



- hardening due to the summation of strain in adjacent stands in the absence or partial development of recrystallization processes during inter-pass times.

Currently, mathematical models for calculating the mean flow stress during hot rolling on strip mills are known [2-4], taking into account the influence of recrystallization processes. The main drawback of these models is the ability to predict the kinetics of recrystallization only for certain groups of steels with similar chemical composition (for example, C – Mn steels, microalloyed Nb steels), which does not allow to take into account the influence of the branded chemical composition of steels and leads to a decrease in the accuracy of prediction of the mean flow stress.

The aim of the work is to develop a mathematical model for the prediction of mean flow stress of carbon and low-alloy steels during hot rolling on a strip mill, to assess the impact of recrystallization processes (dynamic, metadynamic and static) on mean flow stress of steels.

2. Model for calculating the mean flow stress during hot rolling

During hot rolling of carbon and low alloy steels on strip mills to calculate the mean flow stress in the deformation zone (Fig. 1) the modernized Misaka equation [2, 5] is used:

$$\sigma_s = 9.8 \exp \left(0.126 - 1.75[C] + 0.594[C]^2 + \frac{2851 + 2968[C] - 1120[C]^2}{T + 273} \right) \times (0.768 + 0.137[Mn]) \varepsilon^{0.21} \dot{\varepsilon}^{0.13}, \quad (1)$$

where ε is true strain; $\dot{\varepsilon}$ is strain rate, s^{-1} ; T is temperature, $^{\circ}C$; $[C]$, $[Mn]$ - carbon and manganese content in steel, % (wt.)

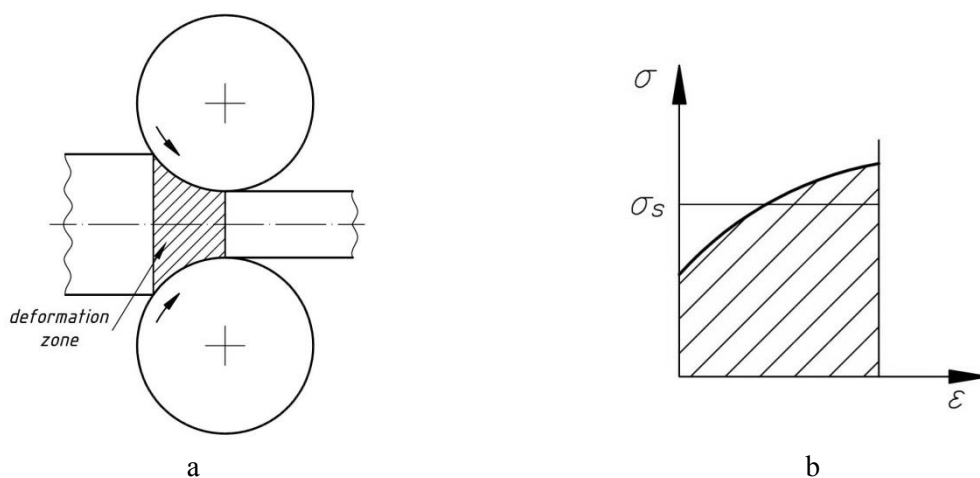


Figure 1. Scheme of deformation (a) and strain hardening (b) of metal during rolling. σ_s is mean flow stress in the deformation zone.

The processes of metal recrystallization, which are developed in the course of multiple deformation in the mill stands, impose a number of restrictive conditions on the use of equation (1). Thus, when the strip is deformed in the cage above a certain critical value of strain ε_c (depending on the steel composition, temperature and strain rate), dynamic recrystallization develops, leading to the softening of the metal during deformation. The value of mean flow stress in this case is determined not by the value of strain in the pass, but by the value of the residual metal hardening, depending on the degree of dynamic recrystallization.

When rolling the strip in the finishing group of the stands of the strip mill, the time between individual compressions varies from a few seconds to fractions of a second. Under these conditions, depending on the chemical composition of the steel and rolling parameters, several options for the

development of recrystallization in the inter-stand spaces leading to the softening or hardening of the metal are possible.

If the strain in the stand is less than critical for the beginning of dynamic recrystallization ($\varepsilon < \varepsilon_c$), then the removal of the hardening in the deformed strip during the movement in the inter-stand interval occurs by static recrystallization of the deformed austenite.

If the strain in the stand is more than critical for the beginning of dynamic recrystallization ($\varepsilon > \varepsilon_c$), then the removal of the hardening in the deformed strip during the movement in the inter-stand interval occurs by metadynamic recrystallization of the deformed austenite, which develops immediately after the end of the deformation (without incubation period).

If during the time between the deformations in the i -th and $(i+1)$ -th stands the recrystallization is not complete or has not begun, then after the deformation in the i -th stand there is a residual hardening, which is added to the deformation in the next stand. The value of the "accumulated" total strain for the calculation of the mean flow stress in the $(i+1)$ -th stand is determined from the expression [6]:

$$\varepsilon_{i+1}^a = \varepsilon_{i+1} + K_a(1 - X_i)\varepsilon_i, \quad (2)$$

where X_i is degree of recrystallization (static or metadynamic) after deformation in the i -th stand;
 K_a is a constant characterizing the degree of recovery development in the deformed metal.

The kinetics of static recrystallization by the Johnson–Mehl–Avrami–Kolmogorov equation was described [7]:

$$X = 1 - \exp \left[-B \left(\frac{\tau}{\tau_{0.5}} \right)^n \right], \quad (3)$$

where X is degree of static recrystallization, fractions;
 $\tau_{0.5}$ is the time for 50% of recrystallization at given deformation parameters and the size of the initial (before deformation) austenite grain, s;
 τ is the current time, s;
 $B = -\ln 0.5$;
 n is the coefficient.

For $\tau_{0.5}$ calculation, the mathematical description of the kinetics of static recrystallization of austenite in carbon and low-alloy steels during hot rolling was used. Along with the deformation parameters, the content of chemical elements in the steel and the grain size of austenite before deformation were taken into account [8]:

$$\tau_{0.5} = 8.591 \cdot 10^{-10} \varepsilon^{-4.09} d_0^{-0.15} \dot{\varepsilon}^{-0.69} d_0^{1.02} \exp \left(\frac{Q_{rec}}{RT} \right), \quad (4)$$

where T is the deformation temperature, K; d_0 is the austenite grain size the before deformation, μm ; R is the universal gas constant, J/(mol·K).

The recrystallization activation energy Q_{rec} depends on the content of chemical elements in steel and is calculated as [8]:

$$Q_{rec} = 166620.38 - 9890.75[C] + 3828.18[Mn] + 9029.92[Si] + 17793.04[Cr]. \quad (5)$$

A common feature of static and dynamic recrystallizations is the movement of high-angle grain boundaries. The driving force for both types of recrystallizations is the excess volume energy accumulated in the process of plastic deformation [9]. Thus, the mechanism of static and dynamic

recrystallizations is the same, the difference is the features of their implementation: after the completion of deformation or during deformation in conditions of continuous growth of the strain. The possibility of predicting the kinetics of dynamic recrystallization based on information about the kinetics of static recrystallization was first shown in works [10, 11].

For calculation the kinetics of metal recrystallization during deformation, the model of dynamic recrystallization of carbon and low-alloy steels was used [12, 13], based on the recalculation of the kinetics of static recrystallization (Eqs. (3)-(5)) to the conditions of continuous growth of the strain degree during deformation. To calculate the structural transformations of dynamically recrystallized metal during the subsequent inter-deformation pause, the model of metadynamic recrystallization was used [14], which was based on the same principles as for the model of dynamic recrystallization.

3. Software implementation and verification of the mathematical model

The model for calculating the mean flow stress of the rolled metal in the finishing stands of the broadband mill was implemented by OBJECT PASCAL language in the DELPHI application development environment. The following information is used as input: the chemical composition of steel, the size of the finished strip, the grain size of austenite at the entrance of the roll to the finishing group of stands, temperature and deformation-speed mode of metal rolling in the finishing group of stands. The output parameters are the degree of recrystallization of the metal in the stands and inter-stand spaces, the mean flow stress σ_s of the rolled metal.

Checking adequacy of the model and assessing the impact of processes of recrystallization on the accuracy of the calculation of mean flow stress was performed on the experimental data that contains information about the deformation-speed parameters of rolling and the experimental values of the mean flow stress of the metal in the finishing stands of continuous broadband mill 2000 NLMK for 100 strips with a thickness of 2-12 mm of the 16 grades of carbon and low alloy steels.

4. Results and discussion

Calculations using the developed model showed that during rolling of carbon and low-alloy steels in the finishing group of stands, dynamic recrystallization can develop during the deformation of the roll in stands 1-3. Residual hardening of the metal after exiting the stand is completely removed by metadynamic recrystallization during the movement of the metal in inter-stand interval. Further deformation in the finishing stands is accompanied by static recrystallization of the deformed metal in the inter-stand intervals, the degree of development of which depends on the steel composition and rolling mode.

The results of the calculation of grain size, recrystallization of austenite and mean flow stress during the rolling of strip of a cross section 3×1500 mm of st3sp steel with a content of 0.15% C, 0.45% of Mn, and 0.20% of Si are presented in table 1, the kinetics of recrystallization of the steel is shown in figure 2.

Table 1. Grain size, recrystallized fraction and mean flow stress forecasting for St3sp grade

Finishing stand #	T (°C)	ε	$\dot{\varepsilon}$	τ_{ip} (s)	d (μm)	ε^a	ε_c	X_{dyn}	X	σ_s^{model} (MPa)	σ_s^{exper} (MPa)
1	924	0.57	9.5	4.7	50.0	0.57	0.44	0.04	1	169	163
2	914	0.54	18.5	3.0	19.9	0.54	0.40	0.06	1	186	181
3	903	0.42	30.8	2.1	17.5	0.42	0.44	–	0.96	195	205
4	874	0.41	51.7	1.4	18.4	0.43	0.55	–	0.90	223	231
5	865	0.39	84.4	1.0	18.3	0.44	0.62	–	0.83	245	250
6	837	0.33	120.8	0.8	18.0	0.41	0.76	–	0.67	272	265
7	828	0.17	105.7	–	17.9	0.29	0.77	–	0.71	255	247

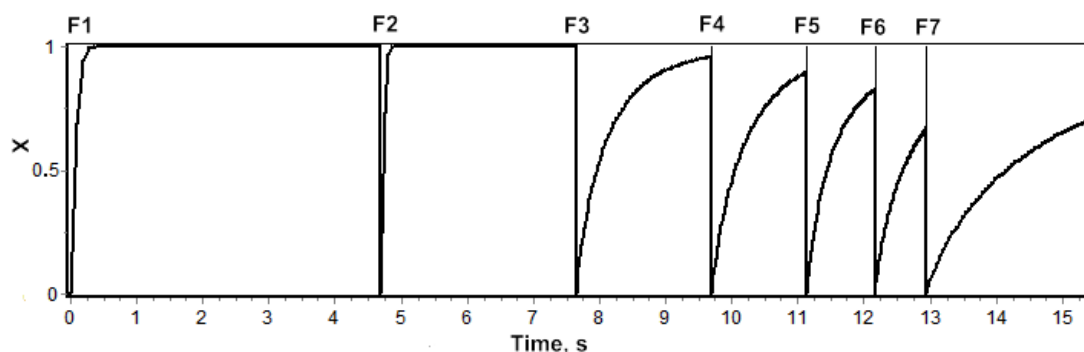


Figure 2. Variation of recrystallized fraction (X) during rolling a strip of st3sp steel in the finishing stands

To assess the effect of recrystallization processes on the prediction accuracy of mean flow stress, the calculation was carried out according to three schemes:

- 1) without taking into account of recrystallization processes of deformed austenite;
- 2) taking into account only the static recrystallization;
- 3) taking into account all types of recrystallization (dynamic, metadynamic and static).

The calculation results of mean flow stress for 100 strips are compared with the experimental data in the table.2. The use of the second scheme allowed to reduce the average relative error of the mean flow stress forecast by 1.5 times compared to the first scheme. Taking into account all types of recrystallization (the third scheme), the average relative error of the mean flow stress forecast decreased by 1.8 times.

Table 2. Results of comparing the calculated and experimental values of mean flow stress

Finishing stand #	Average relative calculation error σ_s , %		
	Scheme 1	Scheme 2	Scheme 3
1	10.49	9.25	5.40
2	5.61	4.84	3.49
3	4.18	4.04	3.71
4	4.60	3.96	3.66
5	4.95	4.66	3.14
6	8.77	4.20	4.15
7	13.53	4.79	4.92
Average by the stand	7.44	5.10	4.07

5. Conclusion

A mathematical model for calculation of mean flow stress of carbon and low-alloy steels during hot rolling on a strip mill is proposed. The influence of dynamic, metadynamic and static recrystallization on the mean flow stress of steel is estimated. It is shown that taking into account the processes of recrystallization of the deformed metal can significantly improve the accuracy of the prediction of the mean flow stress.

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