ACCOUNTING FOR PHASE TRANSFORMATIONS IN MODELLING STRESSES OCCURRING DURING LAMINAR COOLING AND COILING OF STEEL STRIPS

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Abstract

Residual stresses in hot-rolled sheets complicate the process of laser cutting. The present paper is devoted to predict these stresses occurring during laminar cooling after rolling. The proposed model accounts for the thermal and mechanical processes in the sheet during cooling: i) heat transfer to the environment, ii) heat of phase transformations, iii) thermal stresses, iv) stresses due to dilatometric effect during phase transformations, v) stress relaxation. Stresses due to dilatometric effect caused by phase transformations are investigated in the present paper. A model of phase transitions was developed on the basis of modification of JMAK (Johnson, Mehl, Avrami, Kolmogorov) equation. Coefficients in the model were identified by the inverse analysis of the dilatometric tests. The optimized model was implemented in the finite element model of heat transfer during laminar cooling and in the coil. The advantage of the developed model and computer program is its ability to perform quick calculations for industrial conditions, accounting for the dilatometric effect due to phase transformations. Numerical tests confirmed good predictive capabilities of the model.

Keywords: Laminar cooling, phase transformations, residual stresses

1. INTRODUCTION

The problem of calculations and experimental identification of residual stresses in hot-rolled strips is extremely important. Residual stresses become of practical importance when the laser cutting of strips is applied. Too high level of residual stresses causes bending of the part after cutting and creates difficulties with further processing. The factors influencing the residual stresses include the non-uniform distribution of elastic-plastic deformations, phase transformations occurring during cooling and stress relaxation during rolling and cooling [1]. The goal of this paper was accounting for phase transformations in modelling stresses occurring during laminar cooling and coiling of steel strips.

2. MODELLING OF RESIDUAL STRESSES IN HOT-ROLLED STRIPS

Prediction of stresses occurring in strips during laminar cooling has been of interest of scientists for few decades now. Primary objective of these research was avoidance of waviness of the strip. Several simplified approaches were published three decades ago, see for example [2]. More advanced solutions were published at the beginning of this century. Authors of [3] applied Abaqus software in combination with the JMAK phase transformation model to predict flatness of the strip. This approach was upgraded in [4]. Abaqus was also used in [5] to evaluate the effect of various cooling strategies on residual stresses in strips.

Application of the FE method involves long computing times, which are not acceptable in the industrial practice. Thus, search for less computationally expensive and reasonably accurate models was undertaken. Authors of [6] proposed simple model based on balance of stresses and 2D plasticity for calculation of stresses in aluminium plate. The idea of dividing the strip into several parts was used in [7] by the Authors of the present paper. This model was upgraded in following publications [1,8] by more precise accounting for the dilatometric effect due to phase transformations. The objective of the present paper was to develop the phase transformation model for the selected steels used for manufacturing strips channelled to laser cutting.

3. MODEL

Historically, JMAK type equations [9] were commonly used for simulations of phase transformations. In that approach, all attention is focused on the kinetics and microstructural aspects are essentially ignored. However, since kinetics of transformation is satisfactory for calculation of the dilatometric effect, upgrade of the JMAK model was used in the present paper. The basic JMAK equation is:

$$X = 1 - \exp\left(-kt^n\right) \tag{1}$$

where: X - transformed volume fraction, k, n - coefficients, t - time.

Upgrade of the JMAK equation (1) used in the present work was based on [10] and assumes constant value of the coefficient n. The model for ferritic, pearlitic and bainitic transformations contains 18 coefficients, which are grouped in the vector **a**. Although bainite is not likely to occur in the investigated steels, the bainitic transformation was included in the model for completeness. The coefficient n is represented by a_1, a_{10} and a_{18} for ferritic, pearlitic and bainitic transformations, respectively. Coefficient k was introduced as function of the temperature and the following functions were used for ferritic (k_f) and bainitic (k_b) transformations:

$$k_f = \frac{a_2}{D_\gamma}\exp\left\{-\left[\frac{1}{a_4}\left(T - A_{c3} - \frac{400}{D_\gamma} + a_3\right)\right]^{a_5}\right\} \qquad k_b = a_{17}\exp\left(a_{16} - 0.01 a_{15} T\right) \tag{2}$$

where: D_γ - austenite grain size.

Constant value of the coefficient $k_p = a_{15}$ was assumed for the pearlitic transformation. Incubation time has to be introduced before pearlitic (τ_p) and bainitic (τ_b) transformations and the following equations were used:

$$\tau_P = \frac{a_6}{\left(\mathrm{A}_{c1} - T\right)^{a_8}}\exp\left[\frac{a_7}{R\left(T + 273\right)}\right] \qquad \tau_b = \frac{a_{11}}{\left(a_{20} - T\right)^{a_{13}}}\exp\left[\frac{a_{12}}{R\left(T + 273\right)}\right] \tag{3}$$

where: R - gas constant

The remaining equations in the model describe start temperature for the bainitic transformation:

$$B_s = a_{14} - 425[\mathrm{C}] - 42.5[\mathrm{Mn}] - 31.5[\mathrm{Ni}] \tag{4}$$

where: [C], [Mn], [Ni] - concentrations of carbon, manganese and nickel in steel.

Model composed of equations (1)-(4) was implemented in the code, which simulates laminar cooling of steel strips and was used in calculations of the dilatometric effect.

4. IDENTIFICATION OF MODELS

Three steels with chemical composition in **Table 1** were investigated. The model in Chapter 3 describes transient state, represented by changes of the volume fraction as a response to changes of the temperature. Information about equilibrium state, which is the volume fraction reached when temperature stabilizes, is needed to model phase transformations. This equilibrium is represented by the carbon concentrations at the austenite-ferrite interface $c_{\gamma\alpha}$ and at the austenite-cementite interface $c_{\gamma\beta}$. It determines maximum carbon concentration in the austenite. When this concentration is reached, pearlitic transformation begins. The equilibrium at the austenite-ferrite and at the austenite-cementite interfaces is linearized by the equations:

$$c_{\gamma\alpha} = c_{\gamma\alpha 0} + c_{\gamma\alpha 1}T \qquad c_{\gamma\beta} = c_{\gamma\beta 0} + c_{\gamma\beta 1}T \tag{5}$$

where: $c_{\gamma\alpha 0}$, $c_{\gamma\alpha 1}$, $c_{\gamma\beta 0}$, $c_{\gamma\beta 1}$ - coefficients.

Table 1 Chemical compositions of the investigated steels, wt%

steel	C	Mn	Si	Cr	Mo	Cu	Nb	V	P	S	Al	N
A	0.16	1.5	0.03	0.15	0.05	0.15	0.01	0.02	0.02	0.015	0.038	0.006
B	0.16	0.42	0.03	0.038	-	0.12	-	-	0.009	0.007	0.04	0.0014
C	0.08	0.78	0.03	0.04	-	0.01	-	-	0.09	0.006	0.029	0.0016

All thermodynamic parameters in equations (5) were determined using ThrmoCalc program on the basis of the chemical composition of steels. Coefficients obtained by approximation of data from ThermoCalc for the investigated steels are given in **Table 2**. **Fig. 1a,b,c** shows the part of the C-Fe plot obtained from the ThermoCalc for the chemical compositions given in **Table 1**. In this figure c_0 represents carbon concentration in the steel. **Fig. 1d** shows equilibrium volume fractions of phases as a function of the temperature.

Table 2 Coefficients in equations (5) determined using ThermoCalc

steel	$c_{\gamma\alpha 0}$	$c_{\gamma\alpha 1}$	$c_{\gamma\beta 0}$	$c_{\gamma\beta 1}$
A	5.05909	-0.00609	-1.16237	0.00262383
B	4.23086	-0.00482	-1.14198	0.00259822
C	4.3548	-0.005038	-1.134	0.0025831

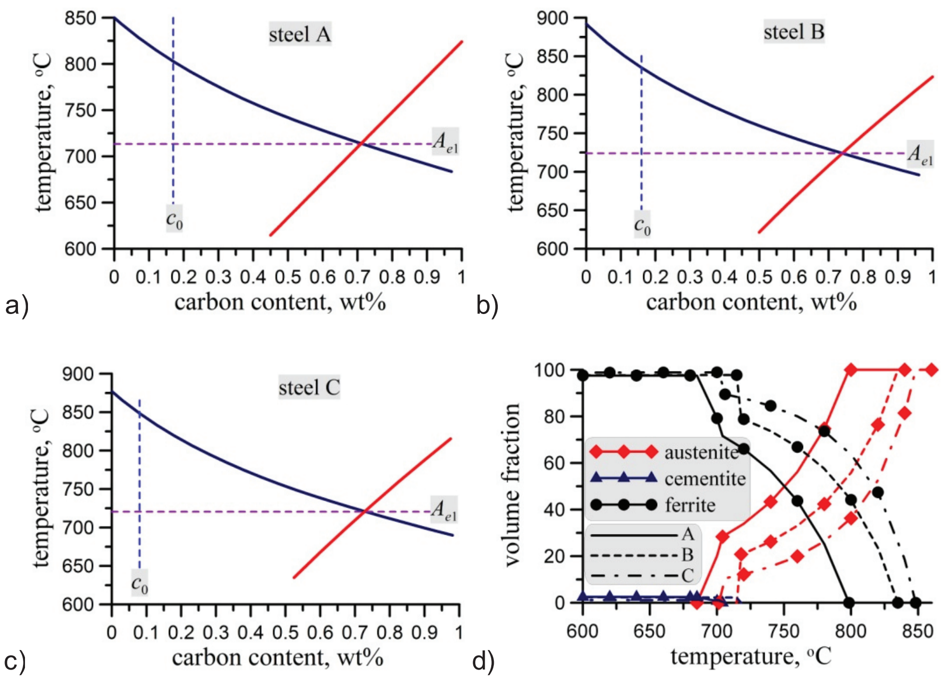


Fig. 1 Part of the phase equilibrium diagram showing equilibrium concentrations at gamma-alpha and gamma-cementite interfaces (a,b,c) and equilibrium volume fractions of phases as a function of the temperature (d)

All these data were used in identification of the coefficients in the phase transformation models. Dilatometric tests with various cooling rates were performed to supply data for identification of the coefficients **a** in the model. Details of the inverse algorithm for identification of the phase transformation models are given in [11]. Coefficients a obtained from the inverse analysis of dilatometric tests for the steel in **Table 1** are given in **Tables 3, 4** and **5**. The model with optimal coefficients was validated by comparison start and end temperatures for transformation calculated by the model and measured in dilatometric tests. Results of this comparison are shown in **Figs. 2a, 3a** and **4a**. Analysis of these results confirmed good predictive capability as far as temperatures of ferritic and bainitic transformations are considered. These transformations are crucial for predictions of the dilatometric effect during laminar cooling.

Table 3 Coefficients in the model obtained from the inverse analysis of dilatometric tests for the steel A

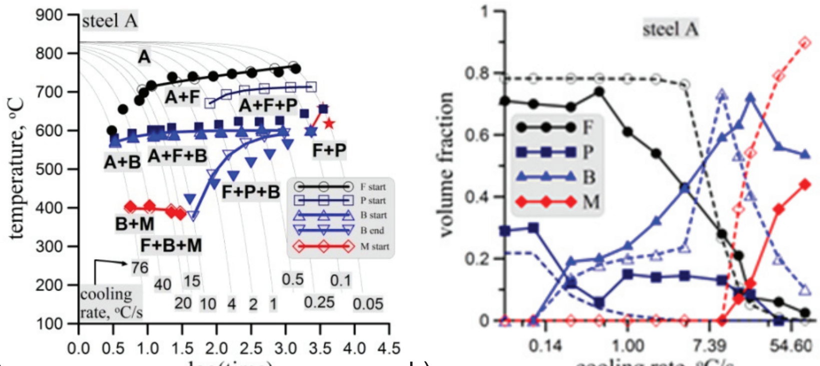
a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
2.599	0.778	103.3	7.53	1.288	2.349	17.75	0.006	1.12
a_{10}	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}	a_{17}	a_{18}
0.502	80.1	56.38	2.626	737	0.262	0.016	1.581	0.604

Table 4 Coefficients in the model obtained from the inverse analysis of dilatometric tests for the steel B

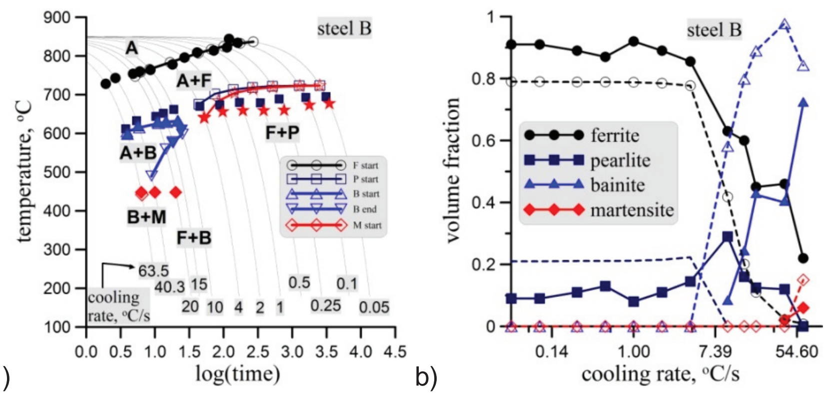
a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
2.353	0.844	98.2	9.339	1.012	3.94	6.0	0.0027	1.783
a_{10}	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}	a_{17}	a_{18}
0.0227	106.3	57.57	2.793	726.1	0.295	0.088	1.908	1.722

Table 5 Coefficients in the model obtained from the inverse analysis of dilatometric tests for the steel C

a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
2.854	1.594	114.6	28.25	2.648	3.706	7.015	0.0029	1.069
a_{10}	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}	a_{17}	a_{18}
0.025	200.4	51.11	3.188	688.5	0.326	0.093	1.689	2.231



a) b)



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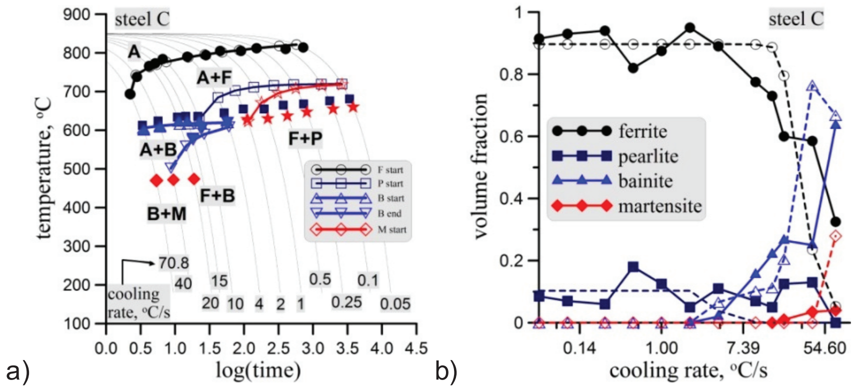

Figs. 2-4 Comparison of start and end temperatures of transformation (a) and volume fractions of phases (b) calculated by the model (open symbols) and measured in dilatometric tests (filled symbols) for three steels

To validate further the model, volume fractions of phases at room temperature after different cooling rates were calculated and compared with the measurements. The results of this analysis are shown in **Figs. 2b**, **3b** and **4b**. Reasonably good agreement between measurements and predictions was obtained.

5. RESULTS

5.1. Numerical tests of phase transformation models

Simulations of laminar cooling were performed to validate the phase transformation model. Nine control points at the cross section were analysed (**Fig. 5**). The results for points p1, p3, p4 and p6 are presented below. Steel B was considered. Strip thickness was 3 mm and width was 1500 mm. Changes of the temperature during laminar cooling are shown in **Fig. 6a** and kinetics of the ferritic transformation is shown in **Fig. 6b**. Intensity of cooling was the same in both sections of the laminar cooling system. Numerical tests confirmed model's capability to predict kinetics of transformations depending on the water flux intensity in subsequent sections of the laminar cooling. It means that the model can be used to optimization of the laminar cooling process.

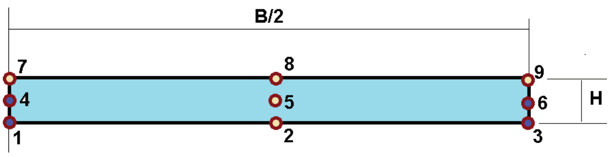

Fig. 5 Location of control points at the cross section of the strip.

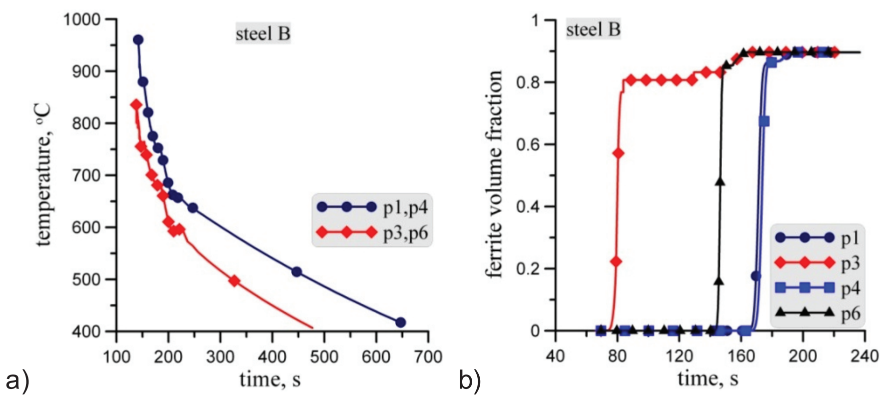

Fig. 6 Changes of the temperature (a) and kinetics of ferritic transformation (b) during laminar cooling

5.2. Calculations of residual stresses

Model of stresses in hot rolled strips during laminar cooling and coiling is described in [1]. This model was connected with the phase transformation model presented in the present paper and simulations of the laminar cooling were performed. Variations of longitudinal stress during cooling are shown in **Fig. 7a**. It is seen that changes of the ferrite volume fraction are correlated with the changes of the stress. Changes of stresses for the time 220-240 s are connected with coiling. Distribution of the longitudinal stress along the width of the strip is shown in **Fig. 7b**, for three locations through the thickness (*y* = 3, 1.5 and 0 mm).

6. CONCLUSIONS

Phase transformation model for three steels was developed and applied to simulation of laminar cooling of hot rolled strips. The model was connected with the program, which predicts residual stresses in strips. Numerical tests were performed and the following conclusions are drawn:

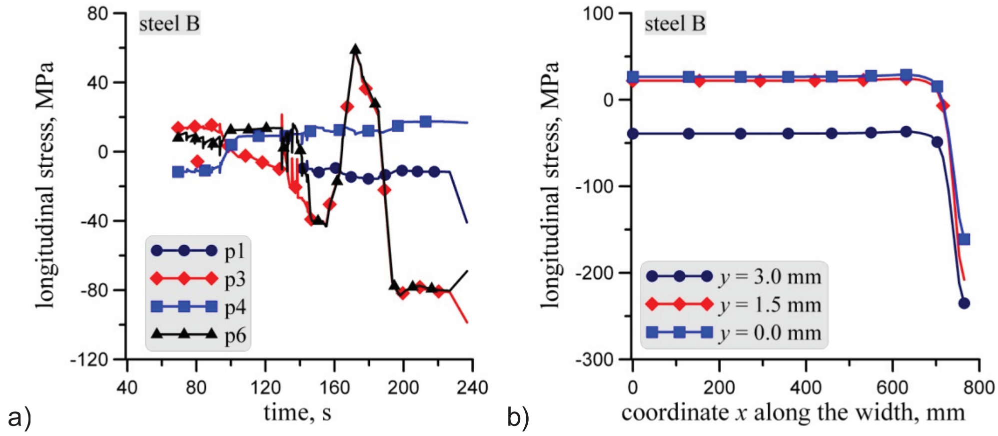

Fig. 7 Changes of longitudinal stress during laminar cooling (a) and final distribution of the longitudinal residual stresses along the width of the strip (b)

- Simple model based on the JMAK equation describes the kinetics of phase transformations with reasonable accuracy, which is satisfactory for the design of parameters of the laminar cooling process.
- Identification of the model was performed by inverse analysis of dilatometric tests and good accuracy of predictions of start and end temperatures, as well as volume fractions of phases, was obtained.
- By connection of the developed model with the program, which calculates residual stresses in strips, accounting for the dilatometric effect became possible.

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REFERENCES

[1] MILENIN A., KUSTRA P., KUZIAK R., PIETRZYK M., Model of residual stresses in hot-rolled sheets with taking into account relaxation process and phase transformation, Procedia Engineering, Vol. 81, 2014, pp. 108 - 113.

[2] YOSHIDA H., Analysis of flatness of hot rolled steel strip after cooling, Transactions ISIJ, Vol. 24, 1984, 212-220.

[3] WANG X., YANG Q., HE A., Calculation of thermal stress affecting strip flatness change during run-out table cooling in hot steel strip rolling, Journal of Materials Processing Technology, Vol. 207, 2008, pp. 130-146.

[4] WANG X., LI F., YANG Q., HE A., FEM analysis for residual stress prediction in hot rolled steel strip during the run-out table cooling, Applied Mathematical Modelling, Vol. 37, 2013, pp. 586-609.

[5] ZHOU Z., THOMSON P.F., LAM Y.C., YUEN D.D.W., Numerical analysis of residual stress in hot-rolled steel strip on the run-out table, Journal of Materials Processing Technology, Vol. 132 , 2003, pp. 184-197.

[6] ZHANG S., WU Y., GONG H., A modeling of residual stress in stretched aluminum alloy plate, Journal of Materials Processing Technology, Vol. 212, 2012, pp. 2463- 2473.

[7] MILENIN A., PIETRZYK M., KUZIAK R., Mathematical model of residual stresses in hot-rolled strips for laser cutting, Proc. Conf. ROLLING 2013, Venice, 2013, CD ROM.

[8] MILENIN A., KUZIAK R., LECH-GREGA M., CHOCHOROWSKI A.,PIETRZYK M., Numerical modeling and industrial testing of residual stresses in hot-rolled sheets, Proc. Conf. AutoMetForm, Freiberg, 2014, 67-71.

[9] AVRAMI M., Kinetics of phase change I. J. Chem. Phys., Vol. 7, 1939, pp. 1103-1112.

[10] DONNAY B., HERMAN J.C., LEROY V., LOTTER U., GROSSTERLINDEN R., PIRCHER H., Microstructure evolution of C-Mn steels in the hot deformation process: the StripCAM model, Proc. 2nd Conf. Modelling of Metal Rolling Processes, eds. BEYNON J.H., INGHAM P., TEICHERT H., WATERSON K., London, 1996, pp. 23-35.

[11] PIETRZYK M., KUZIAK R., Modelling phase transformations in steel, in: Microstructure evolution in metal forming processes, eds, LIN J., BALINT D., PIETRZYK M., Woodhead Publishing: Oxford, 2012, 145-179.