MATHEMATICAL MODEL FOR EVALUATING LANKFORD COEFFICIENT IN AUTOMOTIVE SHEET STEELS

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Abstract

In this paper we present a mathematical model for evaluating the Lankford coefficient (LC) in automotive sheet steels as a function of the ferrite grain size after hot rolling, the degree of cold rolling reduction, the chemical composition, and the volume fractions of perlite and bainite in the final structure. Empirical parameters values of the model were determined using the experimental data base on average LC in 138 strips of 13 steel grades, produced at PJSC Severstal, with a significant range of chemical composition variation. Complementary, databases on calculated steel microstructure parameters after hot rolling, and after heat treatment of cold-rolled strips on a continuous annealing line were used when creating the model. There is a satisfactory agreement between the results of LC calculations made by the developed model and the experimental data. The mean absolute value of relative error in the calculations for considered steels is 7.1 %.

Keywords: Mathematical modelling, Lankford coefficient, automotive steels, cold rolling, annealing

1. INTRODUCTION

Deep drawing ability is an important technological characteristic of the automotive sheet steels determining the quality of the body parts obtained by stamping. This ability is directly proportional to the Lankford coefficient (LC) [1]. LC value is defined as a ratio of true deformation in width to corresponding deformation in thickness when a flat specimen is stretched (usually at 20 %). The average LC value is calculated as: $r_m = 0.25 (r_0 + 2r_{45} + r_{90})$, where r_0, r_{45}, r_{90} are LC values determined on samples cut along the rolling direction and at the angles of 45 and 90° to it. A practical importance of LC caused a large number of studies of complex LC dependence on steel chemical composition and technological parameters of sheet production [2-4]. LC depends on the ratio of texture components {111} / {100} and increases with increasing fraction of the {111} component (fraction of the recrystallized grains with {111}-planes lying in rolling plane). LC decreases with increasing free C content in steel structure before cold rolling. In IF-steels this content is reduced by additional micro-alloying with Ti and Nb. An increase in Mn, as well as in P and S contents, leads to decrease of LC. The data from various sources on the effect of ferrite grain size before cold rolling differ. Increase of grain size and of cold rolling reduction lead to an increase of LC.

In this paper we describe mathematical model for evaluating LC in automotive sheet steels produced at PJSC "Severstal". The set of empirical model parameters values was determined using the experimental data base for an average LC value for different steel grades.

2. INVESTIGATED STEELS AND DATABASES USED FOR MODEL CALIBRATION

In developing the model experimental database on LC mean value was used for 138 strips of 13 steel grades with average chemical composition presented in **Table 1**. Hot rolling of steels was carried out at the mill 2000 of PJSC "Severstal". After subsequent cold rolling strips were heat treated on continuous annealing line. LC

measurements in final sheet with thickness varied from 0.6 to 2.0 mm for three directions (r_0, r_{45}, r_{90}) were carried out using a standard industrial procedure. Complementary, databases on calculated steel microstructure parameters after hot rolling and after cold-rolled strips annealing were used when creating the model. Calculations for the hot rolled and cold-rolled and annealed structures were performed using the integral computer models STAN 2000 [5] and CRP-1, respectively.

Table 1 Average chemical compositions of the steels (wt. %)

Steel	Number of strips	C	Mn	Nb	Ti	P
DX56D	6	0.004	0.11	-	0.069	0.010
01YuT	4	0.005	0.11	-	0.068	0.006
CR3	4	0.004	0.11	-	0.072	0.006
HX220YD	9	0.006	0.62	-	0.067	0.037
HX260YD	13	0.005	0.71	-	0.068	0.058
HX180BD	22	0.004	0.24	0.017	0.018	0.019
HX220BD	9	0.004	0.57	0.016	0.017	0.029
HX260LAD	2	0.08	0.33	0.023	0.015	0.010
HX300LAD	25	0.07	0.35	0.027	0.016	0.010
HX340LAD	22	0.07	0.43	0.040	0.015	0.010
HX420LAD	20	0.08	0.88	0.069	0.017	0.013
DP600	1	0.09	1.65	-	-	0.014
DP780	1	0.14	1.84	0.026	-	0.015

3. CORRELATION DEPENDENCES OF LC ON VARIOUS PHYSICAL PARAMETERS

After hot rolling most of the steels considered (DX65D, 01YuT, CR3, HX220YD, HX260YD, HX180BD and HX220BD, 67 strips) have polygonal ferrite (PF) structure. The structure of HX260LAD, HX300LAD and HX340LAD (49 strips) is a mixture of polygonal ferrite and a small amount of perlite (PF+ P). Predominantly ferritic structures of DP600 and DP780 (2 strips) contain small amounts of perlite and bainite (PF+P/B). The structure of HX420LAD (20 strips) is predominantly bainitic with a small amount of polygonal ferrite (B + PF).

Figure 1a shows a correlation dependence of LC on the effective grain size calculated as: $d_G^{eff} = \left(d_G^{PF} V_{PF} + d_G^{B} V_B\right) / \left(V_{PF} + V_B\right)$, d_G^{PF} - polygonal ferrite grain size, d_G^{B} - bainite block size, V_{PF}, V_B - volume fractions of ferrite and bainite after hot rolling, respectively. It can be seen from **Figure 1a** that for ferrite and ferrite-perlite structures there is a distinct tendency to an increase of LC with increasing effective grain size (for these structures: $d_G^{eff} = d_G^{PF}$). At the same time for bainite structures of HX420LAD steel this trend is not traced. **Figure 1b** confirms a known correlation between LC and degree of a cold rolling reduction. **Figure 1c** shows LC dependence on the parameter w_C^{Σ} calculated using the STAN 2000 program [5] (in which a physically justified quantitative model of the austenite decomposition is implemented): $w_C^{\Sigma} \equiv w_{C_{eq}}^{PF}\left(\tilde{T}_{PF}\right)$ - equilibrium C content in ferrite at the end of the austenite-to-ferrite transformation during cooling after hot rolling; $\tilde{T}_{PF}$ - average transformation temperature. It can be seen that there is a tendency of LC reduction with the increase of w_C^{Σ} that is particularly pronounced for the ferrite-pearlite structures.

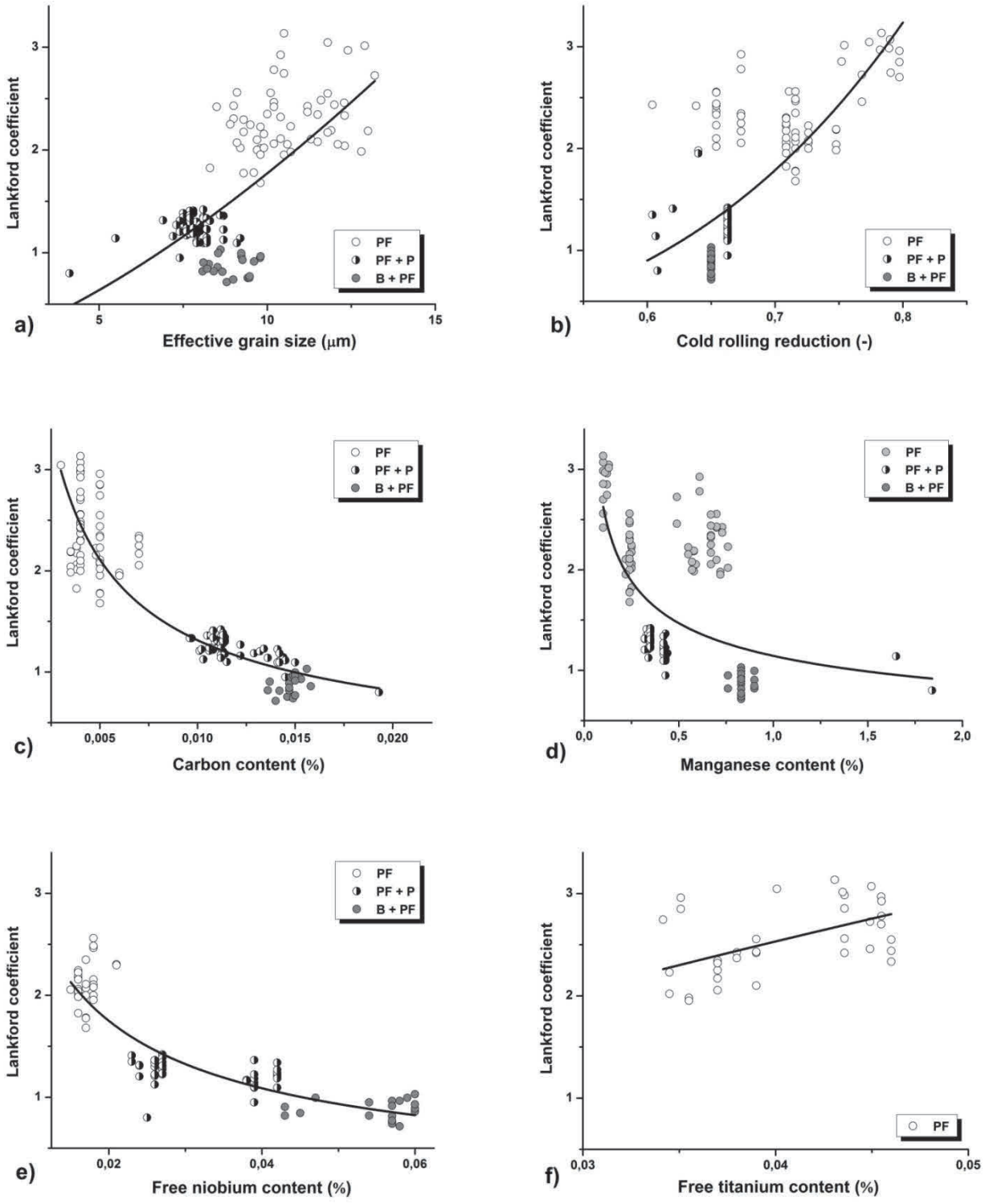

Figure 1 Correlation dependencies of the Lankford coefficient on different physical parameters of the model (trend lines are constructed using power functions): a) effective grain size, d_G^{eff} ; b) cold rolling reduction, ε; c) C content, w_C^{Σ} ; d) Mn content, w_{Mn} ; e) free Nb content, w_{Nb}^{free} ; f) free Ti content, w_{Ti}^{free}

Figures 1d,e,f show LC dependences on contents of Mn, free Ti (w_{Ti}^{free}) and Nb (w_{Nb}^{free}) retained in the austenite solid solution after hot rolling. Calculations of these contents are performed with STAN 2000 program according to the following equations:

$$w_{\mathrm{Ti}}^{free} = w_{\mathrm{Ti}} - 3.4\, w_{\mathrm{N}} - 1.5\, w_{\mathrm{S}} - w_{\mathrm{Ti}}^{\mathrm{TiC}} \quad (1)$$

$$w_{\mathrm{Nb}}^{free} = w_{\mathrm{Nb}} - w_{\mathrm{Nb}}^{\mathrm{Nb(C,N)}} \quad (2)$$

where $w_{\mathrm{Ti}}, w_{\mathrm{Nb}}, w_{\mathrm{N}}, w_{\mathrm{S}}$ - total contents of Ti, Nb, N, S in steel (wt. %); $w_{\mathrm{Ti}}^{\mathrm{TiC}}, w_{\mathrm{Nb}}^{\mathrm{Nb(C,N)}}$ - mass fractions of Ti and Nb bound in TiC and Nb(C,N) particles formed in deformed austenite during hot rolling. For calculation of w_{Ti}^{free}, it is taken into account that a part of Ti is removed from the solid solution at high temperatures (prior to start of hot rolling) due to formation of the TiN and TiS particles. There is a tendency to LC decrease with increasing free Nb content (**Figure 1e**). An increase in free Ti content leads to an opposite effect (**Figure 1f**). A clear dependence of LC on P content was not revealed, however this content is included in the set of physical parameters of the model.

4. DESCRIPTION OF THE MODEL, MODELING RESULTS AND DISCUSSION

In the proposed model the following expression is used to calculate average LC value:

$$r_m = r_m^0 + \Delta r_m^{GS} + \Delta r_m^{\varepsilon} + \Delta r_m^{\mathrm{C}} + \Delta r_m^{\mathrm{Mn}} + \Delta r_m^{\mathrm{P}} + \Delta r_m^{PE} + \Delta r_m^{B} \quad (3)$$

where different terms responds to the contributions of: r_m^0 - constant base contribution, Δr_m^{GS} - grain size, Δr_m^{ε} - cold rolling reduction, Δr_m^{C} - C content, $\Delta r_m^{\mathrm{Mn}}, \Delta r_m^{\mathrm{P}}$ - Mn and P contents, $\Delta r_m^{PE}, \Delta r_m^{B}$ - perlite and bainite in the final structure. The contribution of P was taken into account according to the data from literature indicating a decrease in LC when P content is increased. Perlite and bainite contributions are taken into account because their presence in final sheet structure leads to decrease in ductility affecting also LC.

The following equations are used to calculate the listed contributions:

$$\Delta r_m^{GS} = \alpha_{GS} \left(d_G^{eff} \right)^{\beta_{GS}} \left(V_{PF} + V_B \right) \quad (4)$$

V_{PF}, V_B - volume fractions of ferrite and bainite in the structure after hot rolling,

α_{GS}, β_{GS} - empirical model parameters (EMP)

$$\Delta r_m^{\varepsilon} = \alpha_{\varepsilon}\, \varepsilon^{\beta\varepsilon} \quad (5)$$

$\alpha_{\varepsilon}, \beta_{\varepsilon}$ - EMP

$$\Delta r_m^{\mathrm{Mn}} = \alpha_{\mathrm{Mn}}\, w_{\mathrm{Mn}} \quad (6)$$

w_{Mn} - Mn content, $\alpha_{\mathrm{Mn}}, \beta_{\mathrm{Mn}}$ - EMP

$$\Delta r_m^{\mathrm{P}} = \alpha_{\mathrm{P}}\, w_{\mathrm{P}} \quad (7)$$

w_{P} - P content, α_{P} - EMP

$$\Delta r_m^{PE} = \alpha_{PE}\left(V_{PE}^U + V_{PE}^D\right) \quad (8)$$

$V_{PE}^U + V_{PE}^D$ - pearlite volume fraction in the final structure, α_{PE} - EMP

$$\Delta r_m^B = \alpha_B\left(V_B^U + V_B^D\right) \quad (9)$$

$V_B^U + V_B^D$ - bainite volume fraction in the final structure, α_B - EMP.

To describe the contribution of C the following approach is used:

$$\Delta r_m^{\mathrm{C}} = \alpha_{\mathrm{C}}\left(w_{\mathrm{C}}^{eff}\right)^{\beta_C}\left(V_{PF}^U + V_{PF}^D\right) \quad (10)$$

$$\begin{cases} w_{\mathrm{C}}^{eff} = w_{\mathrm{C}}^*, \ if \ \ w_{\mathrm{C}}^* > 0 \\ w_{\mathrm{C}}^{eff} = 0, \quad if \ \ w_{\mathrm{C}}^* \le 0 \end{cases} \quad (11)$$

$$w_{\mathrm{C}}^* = w_{\mathrm{C}}^{\Sigma} - \left[\alpha_{\mathrm{C}}^{\mathrm{Ti}} w_{\mathrm{Ti}}^{free} + \alpha_{\mathrm{C}}^{\mathrm{Nb}} w_{\mathrm{Nb}}^{free} + \alpha_{\mathrm{C}}^{\mathrm{Mn}} w_{\mathrm{Mn}}\right] \quad (12)$$

$\alpha_{\mathrm{C}}, \beta_{\mathrm{C}}, \alpha_{\mathrm{C}}^{\mathrm{Ti}}, \alpha_{\mathrm{C}}^{\mathrm{Nb}}, \alpha_{\mathrm{C}}^{\mathrm{Mn}}$ - EMP, $V_{PF}^U, V_{PE}^U, V_B^U$ - volume fractions of corresponding constituents in the final structure that have not undergone austenitic transformation during annealing, $V_{PF}^D, V_{PE}^D, V_B^D$ - volume fractions of the constituents in the final structure formed as a result of austenite decomposition after annealing. The sum in square brackets of (12) is used for an empirical evaluation of the total amount of C in polygonal ferrite grains that is in a bound state with the atoms of carbide-forming elements (Ti, Nb, Mn) in the corresponding clusters or fine precipitates formed in cooling a hot-rolled strip before coiling or during its subsequent slow cooling. In accordance with this w_{C}^* is equal to the amount of C, part of which remains n the solid solution in the thermodynamically equilibrium quantity, while the other, the "super-equilibrium" part, is released at the ferrite grain boundaries as tertiary cementite. Equilibrium C content in the solid solution under conditions of its interaction with the carbide-forming elements is a variable quantity depending on the contents of these elements. Taking into account the low C equilibrium quantity a simplified approach is used in the model (see equations (11), (12)) allowing its equality to zero. The obtained optimal values of EPM (other than zero) are presented **in Table 2.**

Table 2 Values of the empirical model parameters (dimensions are obvious from the equations (4)-(11)

EMP	r_m^0	α_{GS}	β_{GS}	α_ε	β_ε	α_{C}	β_{C}	$\alpha_{\mathrm{C}}^{\mathrm{Ti}}$	$\alpha_{\mathrm{C}}^{\mathrm{Nb}}$	α_{P}	α_{PE}	α_B
Value	2.52	3.6	0.8	0.5	0.8	-39	0.7	0.13	0.03	-9	-1	-1.98

Figure 2 shows that results of calculations using the developed model are in good agreement with the experimental data. Average absolute value of the relative error in calculations for the entire set of steel strips under consideration is 7.1% that is comparable to the error in LC measuring.

The values of α_{Mn} and $\alpha_{\mathrm{C}}^{\mathrm{Mn}}$ parameters turned out to be zero. A zero value indicates a practical lack of a direct influence of Mn in the solid solution on LC. The same $\alpha_{\mathrm{C}}^{\mathrm{Mn}}$ parameter value shows that, in comparison with Ti and Nb, the contribution of formation of Mn clusters with C atoms is negligible. This is consistent with results of calculations of the binding energies in ferrite for Ti-C, Nb-C, Mn-C pairs that are, respectively, 0.2, 0.3 and 0.07 eV [6]. Observed tendency toward a decrease in LC with increasing Mn content (**Figure 1d**) is

due to its other contributions in equation (3). Such contributions are Δr_m^{GS} and Δr_m^{C}. Indeed, an increase in Mn content leads, all other conditions being equal, to decrease in the temperature interval of austenite-to-ferrite transformation and, accordingly, to decrease in the ferrite grain size, and also to increase in w_C^{Σ} value.

Values of the parameters α_C^{Ti} and α_C^{Nb} determining the C amount bound in ferrite upon alloying with 1 wt. % of Ti and Nb are equal to 0.13 and 0.03, respectively (**Table 3**). When passing to atomic percents, this ratio is ≈ 2.2. Thus, the model "testifies" to significantly higher efficiency of Ti compared to Nb in binding free C. In case of Nb there is a dependence of Δr_m^{GS} and Δr_m^{C} on its content, which has the same nature as for Mn, *i.e.* free Nb leads to decrease in the ferrite grain size and to significant growth of w_C^{Σ}. For Nb these effects are stronger and make up a major cause of decrease in LC with increasing of Nb content in the steel (**Figure 1e**).

In addition, we highlight the following result that seems to be important. In the literature, when discussing the C effect on LC, this effect is attributed only to free C content in steel structure before cold rolling that has no sufficient basis. A correlation dependence of LC on w_C^{Σ} parameter (first introduced in the present study) shows a decrease in LC with increase of w_C^{Σ} that is particularly pronounced for steels with ferrite-perlite structure. This effect occurs when w_C^{Σ} values vary in the range from 0.01 to 0.02 wt. %, which is much higher than free C content in the ferrite solid solution at cold rolling temperature. This means that LC depends not only on the content of C in solution, but also on its amount released at grain boundaries of ferrite as tertiary cementite. This conclusion is new and shows that additional free C appearing in the solution when ternary cementite particles are dissolved during heating of cold-rolled sheet significantly affects the recrystallization and resulting texture. The physical mechanism of this effect is of interest, and deserves further investigation and analysis.

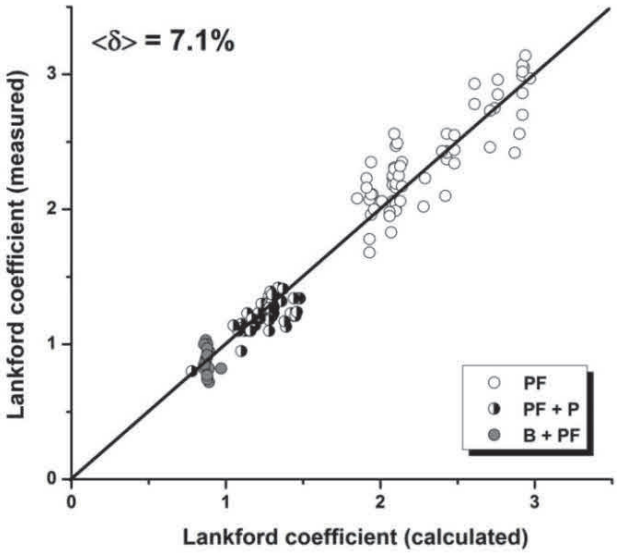

Figure 2 Comparison of the calculated and measured values of the Lankford coefficient

<δ> is an average absolute value of relative error of calculations for the whole set of steel strips.

5. CONCLUSION

The mathematical model has been developed for evaluating LC as a function of the ferrite grain size after hot rolling, the degree of cold rolling reduction, the chemical composition of steel, and the volume fractions of perlite and bainite in the final structure. The results of LC calculations using the model created are in good

agreement with the experimental data. Average absolute value of the relative error of the calculations for the entire set of steel strips considered is 7.1 % that is comparable to the error in LC measurements.

Physical mechanisms determining the observed dependences of LC on Mn and Nb contents are presented.

To describe LC dependence on C content, its calculated amount in ferrite at the end of the austenite-to-ferrite transformation during cooling after hot rolling is first used. The conclusion is drawn that LC is determined not only by the free C content in solid solution before cold rolling, but also by its amount releasing at ferrite grain boundaries as tertiary cementite.

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