

Conference Paper

Study of the Strain Resistance During the Tests of the Wheel Steel

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Abstract

Increasing attention to the issues of obtaining materials with ultrafine grain structure by plastic deformation methods increases the relevance of studies of the strain resistance σ_s of metals and alloys during hot deformation. To obtain the required metal structure it is necessary to conduct studies on plastometer of different values of thermomechanical process parameters. In the article, a study of strain resistance σ_s of low carbon steel on the plastometer at Czestochowa University of technology was conducted. The adjustment of the strain resistance values with the application of mathematical models was carried out to determine during hot deformation of wheel steel the influence of the temperature θ , rate $\dot{\epsilon}_u$ and degree ϵ_u of deformation on the strain resistance σ_s .

Keywords: strain resistance; temperature, rate and degree of strain; plastometer test; carbon low-alloyed steel; regression analysis; beta coefficient, strain resistance model.

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1. Introduction

The search for new technical solutions directly linked with the study of the physics and mechanics of the metal forming processes, rheology behavior of the material and the formation of the metal structure. The most important characteristic of the material is the strain resistance σ_s . The σ_s value must be known to assess the heterogeneity of strength and mechanical properties in the volume of the metal, to calculate the power parameters of the process, which determine the stable flow of the metal deformation process. Many works are devoted to the development of adequate mathematical models for strain resistance calculations [1-10]. Most of the studies based on the plastometer tests, which allow to consider the influence of degree ϵ_u , rate $\dot{\epsilon}_u$ and temperature θ of deformation on σ_s .

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2. Determination of the Influence of Thermomechanical Parameters of the Tensile Process on the Strain Resistance

The staff of the Metal Forming Department of Ural Federal University (Ekaterinburg, Russia) together with the scientists of Czestochowa Technological University (Czestochowa, Poland) conducted studies of the dependence of the thermomechanical parameters of the tensile process on the strain resistance of low-carbon steel. For this purpose, the samples were tested on the torsion plastometer «STD 812» of Czestochowa Technological University. Chemical composition of the steel is presented in the Table 1.

The determinants varied in the following range: deformation temperature $\theta = 800^{\circ}\text{C} \div 1200^{\circ}\text{C}$; strain degree $\epsilon_u = 0 \div 6,5$; strain rate ξ_u was $0,1 \text{ s}^{-1}$; $1,0 \text{ s}^{-1}$ and $10,0 \text{ a}^{-1}$. The tests were carried out at constant temperature and strain rate in a vacuum chamber.

TABLE 1: Chemical composition of the sample material during testing on the plastometer, %.

C	Mn	Si	P	S	Cr	Ni	Cu	Al	Mo
0,21	0,97	0,10	0,014	0,009	0,26	0,07	0,17	0,024	0,014
N	Pb	Al	As	Cb	V	Ti	B	Zn	Sn
0,0119	0,001	0,020	0,007	0,002	0,004	0,047	0,0030	0,018	0,012

Equations (1) and (2) were used to calculate the degree and speed of torsional deformation and to determine the strain resistance equation (3) was used [2-4]:

$$\epsilon_u = \frac{2 \cdot \pi \cdot r \cdot N}{\sqrt{3} \cdot L} (\tau); \quad (1)$$

$$\dot{\epsilon}_u = \frac{2 \cdot \pi \cdot r \cdot \dot{N}}{\sqrt{3} \cdot 60 \cdot L}; \quad \dot{\epsilon}_u = \frac{2 \cdot \pi \cdot r \cdot \dot{N}}{\sqrt{3} \cdot 60 \cdot L}; \quad (2)$$

$$\sigma_s = \frac{\sqrt{3} \cdot 3 \cdot M}{2 \cdot \pi \cdot r^3}, \quad (3)$$

where: r – sample radius, L – sample length, N – number of sample rotations, \dot{N} – rotation speed, M – torque.

Figure 1 shows deformation hardening curves of steel depending on the strain degree and strain rate at temperature 1200°C .

Similar dependences are observed for other thermomechanical parameters of the process. It is found that at the beginning of the test there is an intensive increase in the strain resistance, and when strain degree ϵ_u reaches a certain value, the metal is practically not strengthened, and with further deformation, the strain resistance decreases, i.e., the material is softening.

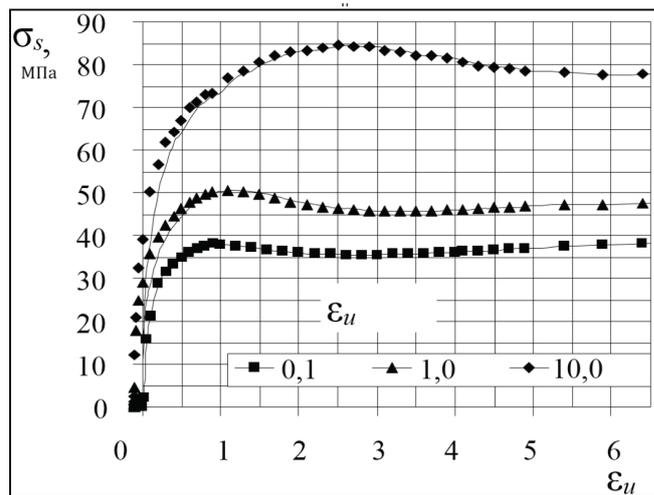


Figure 1: Change of strain resistance depending on the degree and rate of deformation at temperature 1200°C.

3. Processing of the plastometer tests results for determination of strain resistance

For determination of strain resistance σ_s the equation proposed in the work [11] is widely used:

$$\sigma_s = A \epsilon_u^n \xi_u^k \exp(-p\theta), \tag{4}$$

where $\epsilon_u, \xi_u, \theta$ – degree, rate and temperature of deformation; n, k and p – empirical coefficients. The linearized equation has the following form:

$$\ln \sigma_s = \ln A + n \ln \epsilon_u + k \ln \xi_u - p\theta, \tag{5}$$

The parameters of the model (5) are convenient to represent in normalized form:

$$X_1 = \frac{\ln \epsilon_u - \ln \epsilon'_u}{J_{\ln \epsilon_u}}; X_2 = \frac{\ln \xi_u - \ln \xi'_u}{J_{\ln \xi_u}}; X_3 = \frac{\theta - \theta'}{J_\theta},$$

where $\epsilon'_u, \xi'_u, \theta'$ – values of the model parameters in the center point of the experiment, which have typical values for the technological process of the railway wheel manufacturing; $J_{\ln \epsilon_u}, J_{\ln \xi_u}, J_\theta$ – variability intervals of the parameters of the model.

The regression equation takes the following form:

$$y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{23} X_2 X_3 + b_{123} X_1 X_2 X_3 + b_{11} X'_1 + b_{22} X'_2 + b_{33} X'_3$$

Parameters that affect σ_s were set, during the experiment design basic level (BL), variability intervals (ΔX), as well as upper and lower factor levels (-1/+1) were determined (Table 2).

TABLE 2: Factors affecting yield stress.

Factors	-1	BL	+1	ΔX
X_1 –straindegree ϵ_u , %	0,25	0,45	0,65	0,2
X_2 - strain rate ξ_u , s ⁻¹	5	10	15	5
X_3 – test temperature, θ , °C	900	1000	1100	100

A second-order central composition plan was used, which as a "core" has a matrix of linear orthogonal total factorial experiment 2^3 , to which tests in the center point of the experiment and tests in the so-called "star points" with coordinates $(\pm\alpha, 0, 0)$, $(0, \pm\alpha, 0)$, $(0, 0, \pm\alpha)$ were added.

The orthogonality of the central compositional plan is provided by the appropriate selection of the star shoulder α (for three factors $\alpha = 1,215$) and special transformation of quadratic variables x_i^2 by equation $X'_i = x_i^2 - d$, where d – correction factor, depending on the number of factors, f or three factors $d = 0,73$. The significance of regression coefficients was tested by Student criterion. Experiment matrix to establish dependence $\sigma_s = f(\epsilon_u, \xi_u, \theta)$ is shown in Table 3. The right extreme column of the matrix shows the experimental values of $\ln \sigma_s$, obtained during plastometric testing by upsetting steel samples with chemical composition, %: 0,55C; 1,0 Mn; 0,5 Si; 0,2 V; 0,25 Cr; 0,25 Ni; 0,25 Cn; S, P < 0.04. [14].

Due to the orthogonality of the planning matrix, its coefficients are calculated using the following formulas:

$$b_i = \frac{\sum_{j=1}^n x_{ij} y_i}{\sum_{j=1}^n x_{ij}^2}; \quad b_{ii} = \frac{\sum_{j=1}^n x_{ij} y_i}{\sum_{j=1}^n x_{ij}^2}; \quad b_{ij} = \frac{\sum_{j=1}^n (x_{ij} x_{iu}) y_j}{\sum_{j=1}^n (x_{ij} x_{iu})^2}.$$

By the calculations results were determined: $b_0 = 2,960$; $b_1 = 0,075$; $b_2 = 0,118$; $b_3 = 0,316$;

$$b_{1u} = 0,02; b_{2u} = -0,012; b_{3u} = 0,033; b_{12} = 0; b_{13} = 0; b_{23} = 0; b_{123} = 0.$$

The significance of the coefficients is checked by the Student criterion

$$t_i = \frac{b_i}{S_{bi}},$$

for that the reproducibility dispersion is determining by five parallel experiments in the central point of the plan

$$S_{eocn}^2 = \frac{\sum_{i=1}^6 (y_{0i} - \bar{y}_0)^2}{6 - 1} = \frac{1}{6 - 1} \left[\sum_{i=1}^5 y_{0i}^2 - \frac{1}{6} \left(\sum_{i=1}^5 y_{0i} \right)^2 \right] = 0,008.$$

The dispersion of the regression equation coefficients is determined by the following formulas:

$$S_{bi}^2 = \frac{S_{eocn}^2}{\sum_{j=1}^n x_{ij}^2}; \quad S_{bii}^2 = \frac{S_{eocn}^2}{\sum_{j=1}^n x_{ij}^2}; \quad S_{biu}^2 = \frac{S_{eocn}^2}{\sum_{j=1}^n (x_{ij} x_{iu})^2}.$$

TABLE 3: Second order orthogonal plan for three factors.

		Factors (coded value)			Factors (nominal value)			Response variable \hat{y}	$\ln \sigma_s$
		X_1	X_2	X_3	\tilde{x}_1	\tilde{x}_2	\tilde{x}_3		
Plan core	1	-1	-1	-1	0,25	5	900	3,084	3,085
	2	+1	-1	-1	0,65	5	900	3,232	3,232
	3	-1	+1	-1	0,25	15	900	3,320	3,321
	4	+1	+1	-1	0,65	15	900	3,468	3,467
	5	-1	-1	+1	0,25	5	1100	2,453	2,454
	6	+1	-1	+1	0,65	5	1100	2,601	2,595
	7	-1	+1	+1	0,25	15	1100	2,689	2,706
	8	+1	+1	+1	0,65	15	1100	2,837	2,853
Star points	9	-1.215	0	0	0,21	10	1000	2,871	2,889
	10	+1.215	0	0	0,69	10	1000	3,051	3,058
	11	0	-1.215	0	0,45	1,59	1000	2,817	2,818
	12	0	+1.215	0	0,45	18,41	1000	3,104	3,105
	13	0	0	-1.215	0,45	10	831,8	3,344	3,344
	14	0	0	+1.215	0,45	10	1168,2	2,577	2,580
Plan center point	15	0	0	0	0,45	10	1000	2,851	2,851
	16	0	0	0	0,45	10	1000	2,851	2,848
	17	0	0	0	0,45	10	1000	2,852	2,856
	18	0	0	0	0,45	10	1000	2,851	2,859
	19	0	0	0	0,45	10	1000	2,851	2,854
	20	0	0	0	0,45	10	1000	2,851	2,845

By the calculations results were determined:

$$S_{b_0} = 0,02; S_{b_1} = S_{b_2} = S_{b_3} = 0,027; S_{b_{1u}} = S_{b_{2u}} = S_{b_{3u}} = 0,033.$$

The Student t-test for each of the coefficients was: $t_{b_0} = 148,036$; $t_{b_1} = 2,76$; $t_{b_2} = 4,38$; $t_{b_3} = 11,68$; $t_{b_{1u}} = 0,549$; $t_{b_{2u}} = 0,36$; $t_{b_{3u}} = 1$. Because the critical value $t_{0,05;6-1} = 2,571$ (Student t-test), then all coefficients except $b_0, b_1; b_{2u}b_3$, can be considered not significant. Therefore, finally the regression equation can be written as:

$$\hat{y} = 2,96 + 0,075X_1 + 0,0118X_2 + 0,0316X_3.$$

The response values \hat{y} obtained by this equation for the experiment plan points are shown in Table 3. Comparing the obtained \hat{y} values with the experimental y_i the adequacy dispersion was found, given that the number of significant coefficients in the regression equation is four:

$$S_{04}^2 = \frac{\sum_{i=1}^{20} (y_i - \hat{y}_i)^2}{20 - 4} = 0,005.$$

The adequacy of the equation is checked by Fisher criterion:

$$F = \frac{S_{04}^2}{S_{eocn}^2} = 0,625.$$

The equation is adequate, since composed F-ratio is less than the theoretical $F < F_{0,05;m_1;m_2} = 4,74$, where $m_1 = n - l = 20 - 10 = 10$ – number of freedom degrees of adequacy dispersion, $m_2 = n_0 - 1 = 6 - 1 = 5$ – number of freedom degrees of reproducibility dispersion. Considering the normalization of the model parameters (4-5), obtained the following equation

$$\ln \sigma_s = 4,78 + 0,191 \ln \epsilon_u + 0,176 \ln \xi_u - 0,00286 \cdot \theta,$$

then the mathematical model

$$\sigma_s = 119 \epsilon_u^{0,191} \xi_u^{0,176} \exp(-0,00286 \cdot \theta)$$

can be considered adequate and recommended for technological and strength calculations.

4. Summary

Studies of the dependence on the strain resistance of low-carbon steel in dependence of the thermomechanical parameters of the tensile process were conducted. It is found that at the beginning of the test there is an intensive increase in the strain resistance, and when strain degree reaches a certain value, the metal is practically not strengthened, and with further deformation, the strain resistance decreases, i.e., the material is softening. The correction algorithm of the strain resistance value of mathematical model is presented. A mathematical model of the relation between the strain resistance and the thermomechanical parameters of the tensile process was obtained. The adequacy of the model and the possibility of its use to study the influence on the strain resistance of thermomechanical parameters independently of each other were proved based on the application of statistical analysis methods.

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