PLASTICITY OF STEEL TYPES MEANT FOR ROLLING WIRE ROD

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Abstract

The paper presents plasticity tests results for steel types 23MnB4, 30MnB4, C45 and C70 meant for rolling wire rods in modern continuous rolling mill. The assessment of plasticity was conducted in hot torsion test with the use of torsion plastometer in temperature range of wire rod rolling from 850 to 1150°C and strain rates of 0.1; 1 and 10 s^{-1}. The core data for plasticity assessment were the achieved redundancies of yield stress from deformation on the basis of registered torsional moment in function of number of torsions of a sample. On such basis the values which characterize the susceptibility of steel to plastic shaping were determined such as: peak stress, value of deformation corresponding with the maximum stress and deformation till failure. Those values were dependent on temperature and strain rate. The dependency between maximum yield stress with corresponding deformation and the energy of activation with Zener-Hollomon parameter was elaborated together with marking the yield stress function.

Keywords: Hot torsion test, peak stress, strain, plasticity of steel

1. INTRODUCTION

Development of computer programs based on the finite elements method which allows to analyse and design the processes of plastic treatment imposed the need to formulate equations which describe the properties of plastically deformed material and at the same time the plastometric tests which are the basis to elaborate constitutive equations [1]. The achievement of the correct description of plasticity of a given material, particularly the yield stress function, is connected with methodology of experimental marking of yield stresses as well as its mathematical form. The most commonly applied methods for plasticity assessment are compression tests, tension tests, impact tests and model tests of knock-down and rolling. The paper includes the results of plasticity tests for four chosen steel types 23MnB4, 30MnB4, C45 and C70D which are representative for the process of rolling wire rods in continuous rolling system [2-6]. Torsion tests were conducted on torsional plastometer which is part of the equipment of the Institute of Metals Technology at Silesian University of Technology [7]. The assessment of susceptibility to plastic shaping was determined for chosen steel types in temperature range from 850 to 1150 °C and strain rate from 0.1 to 10 s^{-1} on the basis of dependency of yield stress σ_p from strain ε. Prepared dependencies allowed for determination of mutual dependencies between the maximum yield stress and the corresponding with it deformation value depending on Zener-Hollomon parameter. It was also possible to elaborate the function of yield stress in accordance with Hansel-Spittel.

2. METHODOLOGY

The amount of the basic chemical elements included in steel types 23MnB4 and C70 chosen for plasticity tests are presented in **Table 1**. Hot torsion tests for those two chosen steel types were conducted for temperature range for rolling wire rod: 850 °C, 900 °C, 950 °C, 1000 °C, 1050 °C, 1100 °C, 1150 °C and with turn of rotation of: 5 rpm., 50 rpm and 500 rpm, which equal strain rates of 0.1 s^{-1}, 1 s^{-1} and 10 s^{-1}. Samples were heated to a temperature of 1150°C, annealed in this temperature for 30 seconds and next cooled to deformation temperature and twisted till damage. The course of the torsion tests is shown in **Figure 1**.

Table 1 Chemical composition of tested steel types

Grade	Content of chemical elements, [wg. %]								
	C	Mn	Si	P	S	Cr	Ni	Cu	B
23MnB4	0.21	0.97	0.10	0.014	0.009	0.26	0.07	0.17	0.0030
30MnB4	0.31	1.06	0.23	0.013	0.007	0.22	0.07	0.16	0.0030
C45	0.49	0.74	0.22	0.013	0.015	0.08	0.07	0.15	0.0003
C70	0.71	0.57	0.22	0.010	0.011	0.05	0.06	0.13	0.0002

The basis for marking the dependency of flow stress (σ_p) from strain (ε) from hot torsion test was the data from measurements written into an Excel program in columns which included the values of the torsion moment *M* [Nm], axial force *F* [N], temperature *T* [°C], number of sample torsions *N* [rotation] and time *t* [s]. Data processing though filtration, cutting, thinning and smoothening was conducted in Matlab program. Flow stress, true strain and strain rate was calculated with the use of traditional formulas in the torsion theory, flow stress (1):

$$\sigma_p = \sqrt{\left(\frac{\sqrt{3}\cdot M}{2\cdot\pi\cdot R^3}\right)\cdot(3+p+m)+\left(\frac{F}{\pi\cdot R^2}\right)^2}, \tag{1}$$

true strain (2):

$$\varepsilon = \frac{2}{\sqrt{3}}\cdot\frac{\pi\cdot R\cdot N}{L}, \tag{2}$$

strain rate (3):

$$\dot{\varepsilon} = \frac{2}{\sqrt{3}}\cdot\frac{\pi\cdot R\cdot \dot{N}}{L}. \tag{3}$$

In order to describe the influence of process parameters on the properties in mathematical values the Zener-Hollomon Z parameter was calculated in a dependency (4):

$$Z = \dot{\varepsilon}\exp\left(\frac{Q}{R\cdot T}\right), \tag{4}$$

on the basis of activation energy *Q* marked in a constitutive equation (5) [8]:

$$\dot{\varepsilon} = C\exp\left(-\frac{Q}{R\cdot T}\right)\times(\sinh(\alpha\sigma_{pp})^n, \tag{5}$$

where *C*, α, *n* - coefficients.

Activation energy was marked with the use of the program ENERGY 4.0 [9]. Peak flow stress σ_{pp} in parameter Z function was calculated from transformed dependency (5):

$$\sigma_{pp} = \frac{1}{\alpha}\cdot arg\,sinh\left(\sqrt[n]{\frac{Z}{C}}\right). \tag{6}$$

Deformation ε_p corresponding with peak flow stress in function of parameter *Z* was marked in exponential dependency (7) [7]:

$$\varepsilon_p = U\cdot Z^W, \tag{7}$$

where: *U* and *W* are material constants.

In programs used for simulations of plastic processing (i.e. Forge, FormFEM) there are often various forms of Hansel-Spittel function applied. In this paper the following dependency was applied (8):

$$\sigma_p = A\exp(m_1 T)\varepsilon^{m_2}\dot{\varepsilon}^{m_3}\exp\left(\frac{m_4}{\varepsilon}\right), \tag{8}$$

where: ε - equivalent deformation, $\dot{\varepsilon}$- strain rate [s^{-1}], T - temperature [°C], A, m_1, m_2, m_3, m_4 - function coefficient.

Function coefficients (8) were marked on the basis of presented results of plastometric tests. Newton method, implemented in Solver (addition to Excel calculation sheet), was applied. The method uses iteration algorithm of searching the minimum and peak for set objective function. The idea behind marking the coefficients of function (8) was to find such values for which the norm of mean-square error between the values of flow stress marked with the use of such function and the experimental results reaches minimum. Assumed error norm had the form of (9):

$$\phi = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\sigma_{p_{ci}} - \sigma_{p_{mi}}\right)^2} \quad , \tag{9}$$

where: σ_{pci} - value of flow stress calculated on the basis of chosen form of function for i-measurement point, σ_{pmi} - value of flow stress calculated on the basis of torsion tests results for i-measurement point, n - number of measurement points.

3. RESULTS

Overall assessment of plasticity was conducted on the basis of and temperature and speed of deformation. The course of the dependency of yield stress from deformation of tested steel types for various torsion temperature and strain 1 s^{-1} are shown in **Figure 1**.

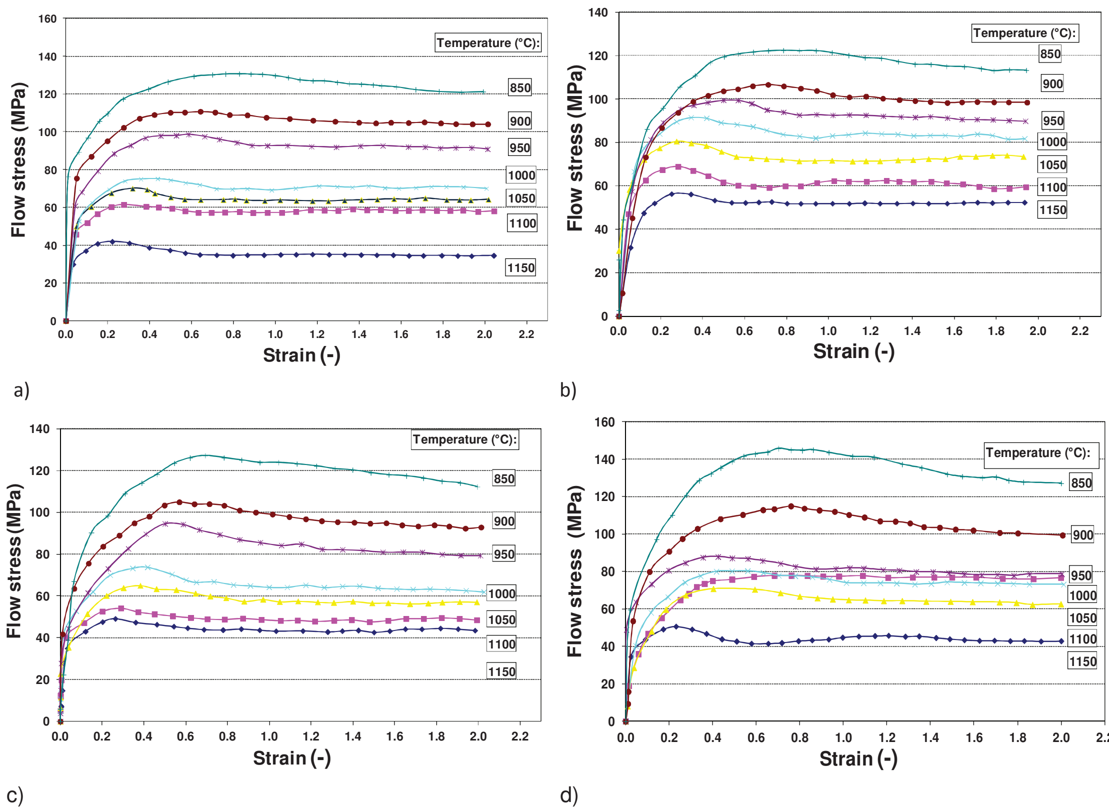
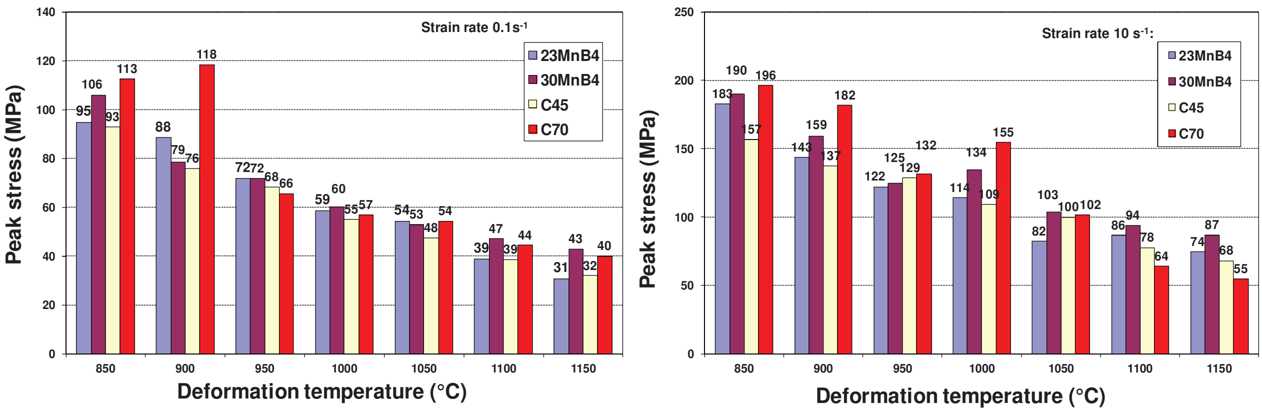


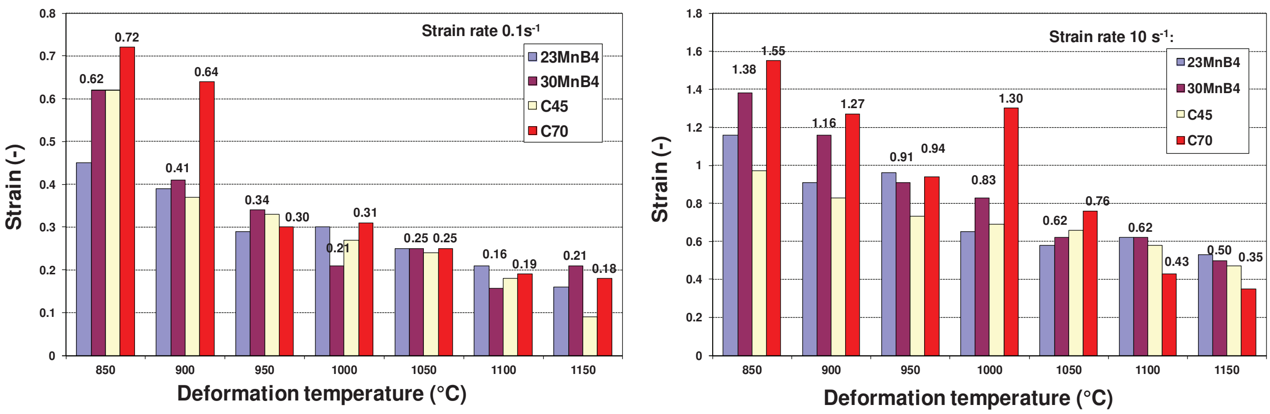
Figure 1 Flow stress (σ_p) in deformation function ε for investigatd steels after hot torsion in temperature from 850 °C to 1150 °C - 23MnB4 (a), 30MnB4 (b), C45 (c) and C70 (d)

For all tested steel types, no matter the achieved deformation parameters range, the flow curves have characteristic course with clearly marked maximum yield stress, next drop of yield stress beyond maximum and range of constant value of yield stress which is typical for ongoing processes of dynamic recrystallization. At the same time the regularities which remain are: the one of the shift of maximum towards smaller deformation values together with temperature increase and the one when the increase of yield values is followed by the increase of deformation speed. The location of the maximum yield stress is strictly dependent on the deformation speed. For smaller strain rate it is in a range from 0.16 to 0.72 and for the biggest from 0.53 to 1.55 and decreases together with the increase of temperature. As mentioned before, the tested steel types are characterized with big deformability which reaches the values of deformation limit ε_g which equals 20 in the lowest deformation temperature and with constant increase of deformability together with the increase of temperature. Comparison of values of peak stress σ_{pp} and strain ε_p depending on temperature and strain rate are shown in **Figure 2** and **Figure 3** presents the dependency of deformation value corresponding with the maximum value of σ_{pp} from deformation parameters.



a) b)

Figure 2 Peak stress σ_{pp} depending on temperature and strain rate: a) 0.1 s^{-1} , b) 10 s^{-1}



a) b)

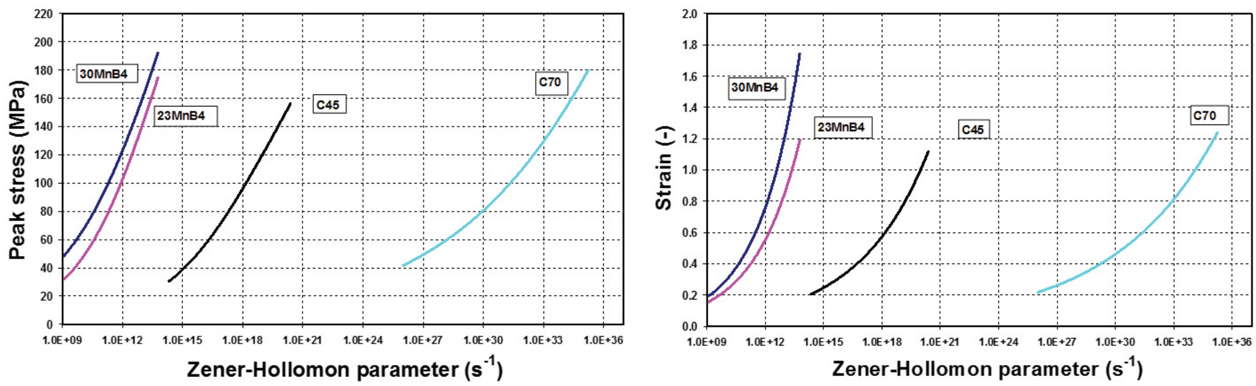
Figure 3 Strain ε_p depending on temperature and strain rate: a) 0.1 s^{-1} , b) 10 s^{-1}

Marked constants from dependencies (4) to (7) are presented in **Table 2** and the course of dependency of peak stress σ_{pp} and strain ε_p from Zener-Hollomon parameter Z are presented in **Figure 4**.

Comparison of the courses of marked functions with flow curves achieved in plastometric tests are presented in **Figure 5**.

Table 2 Material constants of tested steels determined in computer program Energy 4.0

	23MnB4	30MnB4	C45	C70
Q (kJ·mol^{-1})	275.2	264.8	417.1	739.8
n (-)	5.14	6.4	5.97	13.72
□ *(MPa^{-1})*	0.00934	0.00759	0.01438	0.00419
C (s^{-1})	5.85×10^{11}	6.37×10^{11}	2.43×10^{16}	2.28×10^{36}
U (-)	0.0031	0.0027	0.0037	0.0016
W (-)	0.188	0.204	0.122	0.082



a) b)

Figure 4 Dependency of peak stress σ_{pp} (a) and deformation ε_p (b) from Zener-Hollomon parameter *Z*

Values of function coefficients (8) for tested steels in temperature ranges from 850 to 1150 °C, deformation from 0.05 to 2.0 and strain rate from 0.01 to 10 s^{-1} and error value norms (9) are given in **Table 3**.

Table 3 Values of coefficients of assumed flow stress function

Steel grade	*A*	m_1	m_2	m_3	m_4	Φ
23MnB4	2148.8	-0.00332	-0.0247	0.1343	-0.0310	55.40
30MnB4	1418.8	-0.00281	-0.0434	0.1524	-0.0483	137.97
C45	2292.9	-0.00338	-0.0350	0.1286	-0.0265	45.67
C70	3276.6	-0.00367	-0.0109	0.1508	-0.0493-	120.22

3. CONCLUSION

The dependency curves of yield stress from deformation for all tested steel types meant for rolling wire rods within the tested deformation parameters have characteristic course with clearly marked maximum yield stress, next drop of yield stress beyond maximum and range of constant value of yield stress. The regularity which is preserved is: the shift of maximum towards smaller deformation values together with temperature increase and when the yield values increase the strain rate also increases.

The location of maximum yield stress is strongly dependent on the speed of deformation. Tested steel types are characterised with good susceptibility to hot plastic forming, the limit deformation ε_g as a measurement tool for deformability reaches values of above 20 and increases together with temperature increase. The maximum yield stress is varied and to a small extent depends on steel type and to a bigger extent on the temperature and the speed of deformation.

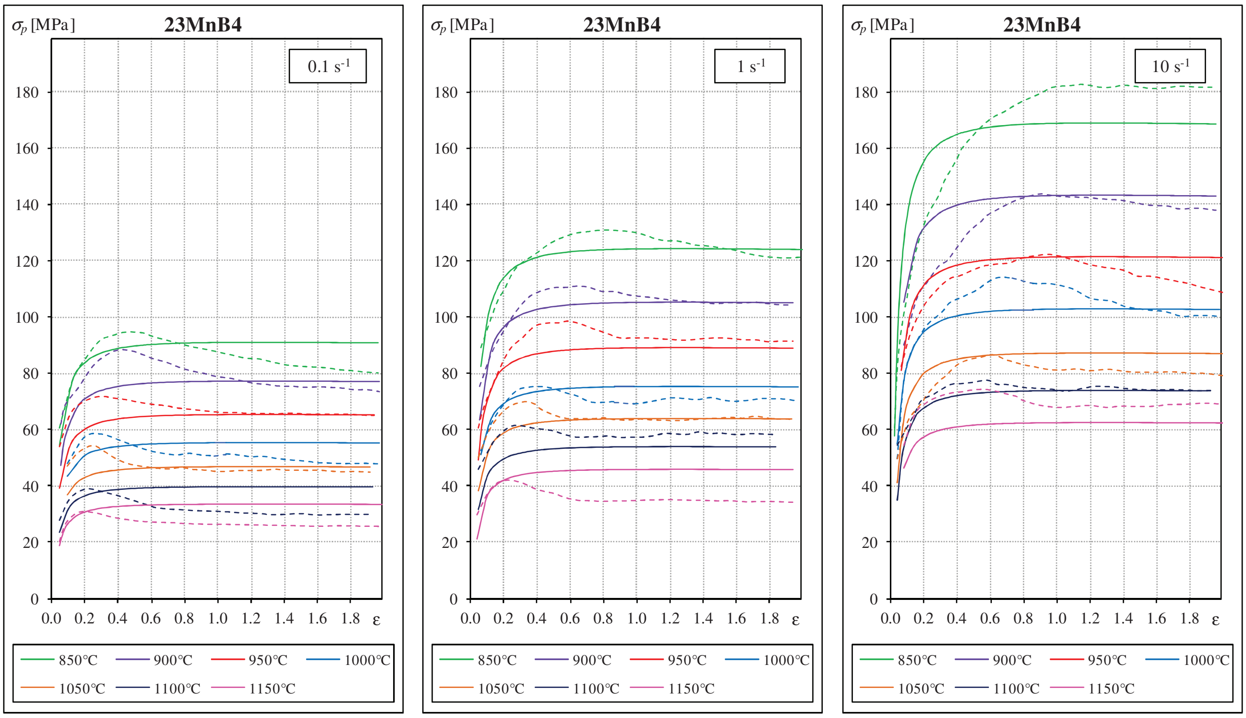


Figure 5 Comparison of the courses of marked functions (full lines) with experimentation curves (broken lines) for steel 23MnB4

Correlations between parameters of the deformation process and mechanical properties defined with the torsion test indicate that the influence of the Zener-Hollomon parameter on the peak flow stress σ_{pp} and corresponding ε_p for both the steels can be presented in the form of a power function such as austenitic steels [10]. Function of flow stress allows to determine, with accuracy to a few percent, what the value of flow stress is depending on the deformation, strain rate and temperature and may be applied in programs for designing and analysis of the processes of hot rolling.

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REFERENCES

[1] McQueen, HJ, Ryan, ND. Constitutive analysis in hot working, Materials Science Eng., 2002, A322., pp. 43-63.

[2] GROSMAN, F., WOŹNIAK, D. The modern wire rod mill. Hutnik - Wiadomości Hutnicze, 2001, no 3, pp. 97-104.

[3] LABER, K. DYJA, H., KOCZURKIEWICZ, B. Analysis of industrial conditions during multi-stage cooling of C70D high-carbon steel wire rod. Materials Testing, 2015 vol 57, Issue 4, pp. 301-305.

[4] KAWALLA, R., GOLDHAHN, G., JUNGNICKEL, W. Laboratory rolling conditions and its effects on rolling parameters on material properties of hot rolled products. In 2nd International Conference on Thermomechanical Processing of Steels. Belgium - Liege, 2004, pp. 17-24.

[5] WOŹNIAK D., GARBARZ A. Technological and constructional foredesign of LPS module for semi-industrial simulation of hot rolling and thermo-mechanical treatment of strip and bars, Prace Instytutu Metalurgii Żelaza, 2012, No. 1, pp.154-160.

[6] KAWULOK, P., KAWULOK, R., SCHINDLER, I., RUSZ, S., KLIBER, J., UNUCKA, P., ČMIEL, K. M. Credibility of various plastometric methods in simulation of hot rolling of the steel round bar. Metalurgija - Metallurgy, 2014, vol. 53, no. 3, pp. 299-302.

[7] HADASIK, E. Researches of metals plasticity, Silesian University of Technology Publisher, Gliwice, 2008.

[8] SCHINDLER, I., BORUTA, J. Utilization Potentialities of theTorsion Plastometer. Silesian University of Technology Publisher, 1998.

[9] KLIBER, I. SCHINDLER, I. KUBINSKI, W., KUZMINSKI, Z.: Determination of plasticity limit using hot torsion test. Steel research international, 1989, 60, pp. 82-91.

[10] KUC, D., NIEWIELSKI, G., CWAJNA, J. Influence of deformation parameters and initial grain size on the microstructure of austenitic steels after hot-working processes. Materials Characterization, 2006, no. 56, pp. 318-324.