# FORMABILITY OF STEELS FOR ROLLING OF WIRE ROD

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**Abstract**

The paper presents results of steel 23MnB4 and C70 plasticity tests meant for rolling wire rods on modern continuous rolling mill. Plasticity assessment was conducted in hot torsion test performed on swing plastometer in temperature range of rolling wire rode from 850 to 1150°C and deformation speed of 0.1; 1 and 10 $s^{-1}$. The basis for plastic

ity assessment was the dependency between flow stress and deformation achieved on the basis of registered torsion moment in function of the number of sample torsions. On such basis the characteristic values were determined: peak flow stress, deformation value which corresponds with peak stress and deformation to failure. Those values are dependent on deformation parameters and certain dependencies between peak flow stress and corresponding deformation with activation energy of the deformation process and Zener-Hollomon parameter were elaborated.

**Keywords:** Hot torsion, flow stress, plasticity of steel, wire rod

## 1. INTRODUCTION

Development of computer technology which enables the analysis of plastic treatment processes urged the need to formulate equations which describe the values of the plastically deformed material and at the same time plastometric tests which are the basis to prepare constitutive equations. Achievement of the correct description of the plasticity of given material, particularly in flow stress function, is connected with mathematical form of function as well as methodology of experimental determination of flow stresses. Most often used methods of technological assessment of plasticity are: tension tests, compression tests, torsion tests, impact value tests and model boosting up and rolling tests. Applied plastometric test methods bring the conditions of tests performance close enough to real conditions of the processes of plastic treatment. This paper presents results of plasticity tests for two chosen types of steel 23MnB4 and C70 which are representative for the rolling process of wire rod in continuous rolling mill [1]. Torsion tests were conducted on torsion plastometer which is owned by the Institute of Metals Technology at Silesian University of Technology [2]. Assessment of susceptibility to plastic deformation was determined for chosen steel types in temperature range from 850 to 1150°C and deformation speed from 0.1 to 10 $s^{-1}$ on the basis of dependency of flow stress $\sigma_p$ from deformation $\varepsilon$.

## 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 turns/min., 50 turns/minute and 500 turns/min., 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 **Fig. 1**.

**Table1** Chemical composition of tested steels: 23MnB4 and C70

| Grade | Content of chemical elements, [mass %] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 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 |
| C70 | 0.71 | 0.57 | 0.22 | 0.010 | 0.011 | 0.05 | 0.06 | 0.13 | 0.0002 |

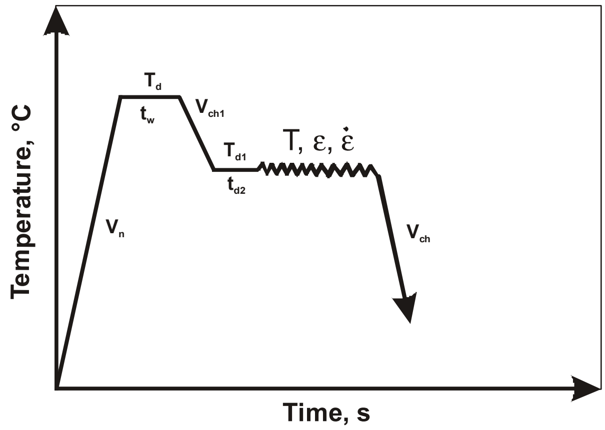



**Fig. 1** Diagram of the conducted hot torsion tests

The basis for marking the dependency of flow stress ($\sigma_p$) from strain ($\varepsilon$) 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) [3]:

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

where: C, $\alpha$, n - coefficients.

Activation energy was marked with the use of the program ENERGY 4.0 [3]. Peak flow stress $\sigma_{pp}$ 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 $\varepsilon_p$ corresponding with peak flow stress in function of parameter Z was marked in exponential dependency (7) [4]:

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

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):

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

where: ε - equivalent deformation, $\dot{\varepsilon}$ - strain rate [$s^{-1}$], T - temperature [°C], A, m1, m2, m3, m4 - function coefficient.

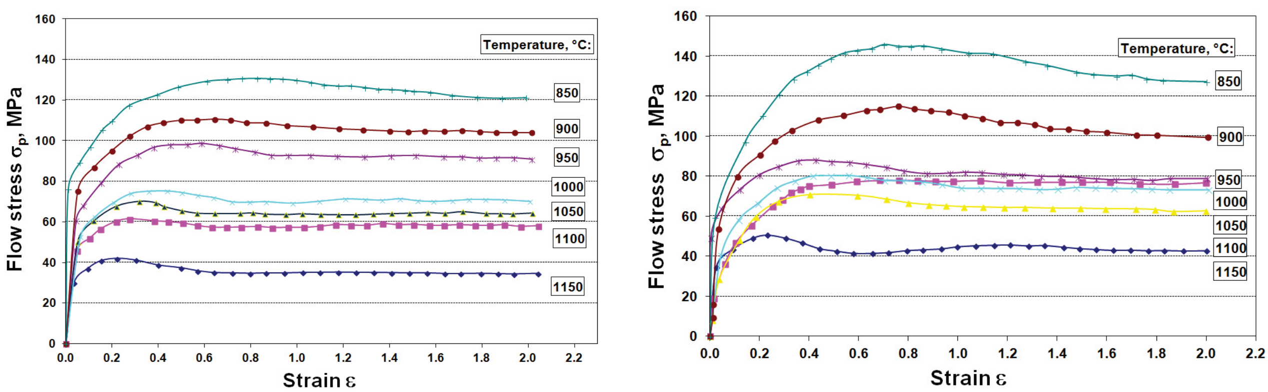
Function coefficients (8) were marked on the basis of presented results of plastometric tests. Newton method, implemented in Solver (addition to Excel calculation sheet), was applied. The method uses iteration algorithm of searching the minimum and peak for set objective function. The idea behind marking 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):

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

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

## 3. RESULTS

General assessment of plasticity was conducted on the basis of dependencies and temperature and strain rate. The course of dependency of flow stress from deformation for steel 23MnB4 and C70Dfor different torsion temperatures and strain rate of 1 $s^{-1}$ are shown in **Fig. 2 a, b**.




a) b)

**Fig. 2** Flow stress ($\sigma_p$) in deformation function ε for investigatd steels after hot torsion in temperature from 850°C to 1150°C - 23MnB4 (a), C70 (b)

Tested steels are characterised with big deformability which reaches the value of deformation limit of $\varepsilon_g$ above 20, which is why the presented range of deformation was limited to the value equal 2.0. For both steel types, independently from the performed range of deformation parameters, the flow curves have characteristic course with distinctively marked peak of flow stress ($\sigma_{pp}$), next drop flow stress below peak and the range of constant value of flow stress which is typical for the appearance of the process of dynamic recrystallization. For both steel types, independently from the performed range of deformation parameters, the flow curves have characteristic course with distinctively marked peak of flow stress ($\sigma_{pp}$), next drop flow stress below peak and the range of constant value of flow stress which is typical for the appearance of the process of dynamic recrystallization.

At the same time the regularity is maintained of the shift of peak towards smaller deformation values together with increase in temperature as well as increase of stress value with the increase of deformation speed. The location of the peak point of flow stress strictly depends on the deformation speed. For the smallest strain rate it can be found in the range from 0.16 - 0.72, and for the biggest strain rate from 0.53 to 1.55 and declines with the temperature increase. As it was mentioned before the tested steels are characterised with big deformability which reaches limit value of deformation $\varepsilon_g$ equal 20 in the lowest deformation temperature and with constant increase of deformability with temperature increase. Comparison of the values of peak flow stress $\sigma_{pp}$ depending on temperature and strain rate in shown in **Fig. 4**.

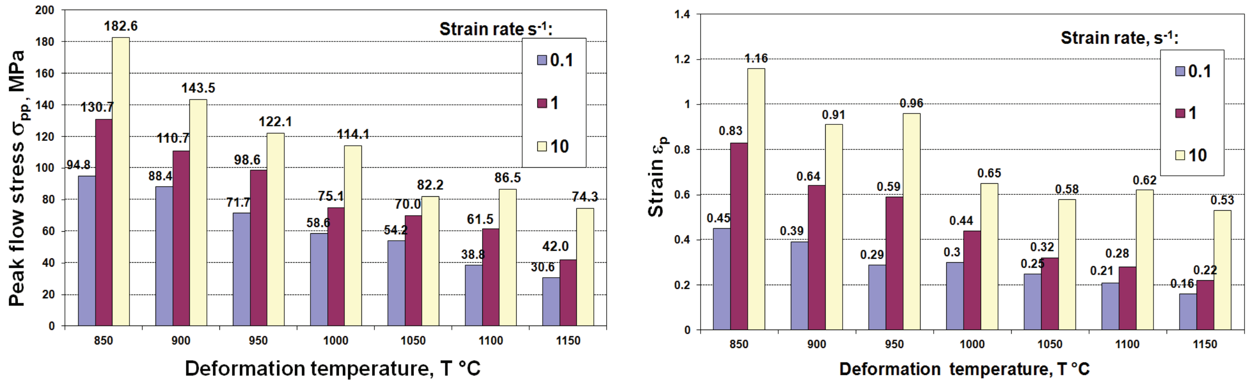



**Fig. 3** Peak flow stress ($\sigma_{pp}$) (a) and deformation ($\varepsilon_p$) depending on temperature T and strain rate for steel 23MnB4

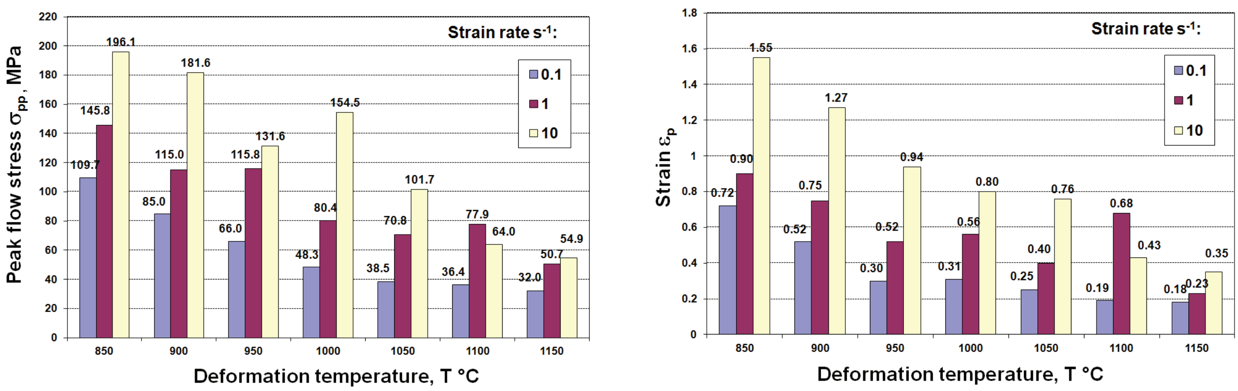
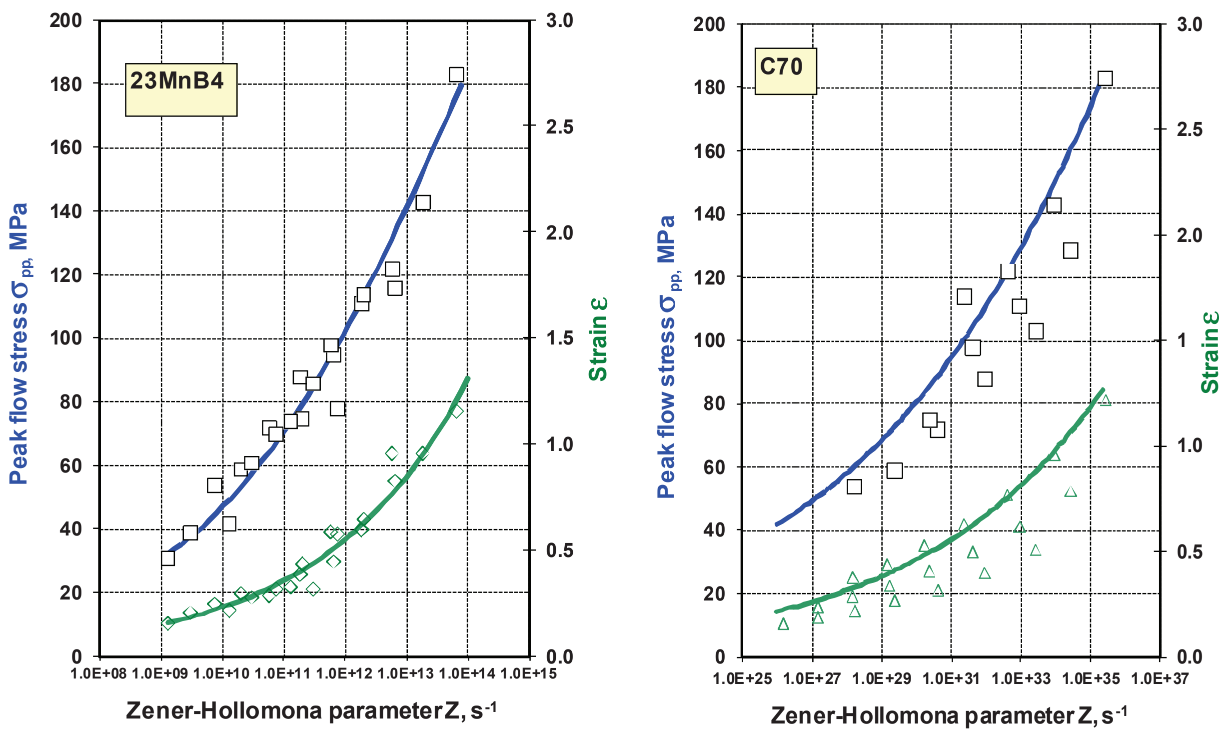



**Fig. 4** Peak flow stress ($\sigma_{pp}$) (a) and deformation ($\varepsilon_p$) depending on temperature T and strain rate for steel C70

Marked constants for dependencies from (4) to (7) are presented in **Table 2**, and the course of the dependency of peak flow stress ($\sigma_{pp}$) and deformation ($\varepsilon_p$) and Zener - Hollomon parameter Z was given for investigated steels in **Fig. 5**.

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

| | 23MnB4 | C70 |
|---|---|---|
| Q [kJ·mol$^{-1}$] | 275.2 | 739.8 |
| n [-] | 5.14 | 13.72 |
| α [MPa$^{-1}$] | 0.00934 | 0.00419 |
| C [s$^{-1}$] | $5.85\times10^{11}$ | $2.28\times10^{36}$ |
| U [-] | 0.0031 | 0.0016 |
| W [-] | 0.188 | 0.082 |




a) b)

**Fig. 5** Dependency peak flow stress ($\sigma_{pp}$) (a) and deformation ($\varepsilon_p$) from Zener-Hollomon parameter Z for investigated steel a- 23MnB4, b- C70

Values of function coefficients (8) for tested steels in temperature ranges from 850 to 1150°C, deformation from 0.05 to 2.0 and deformation speed 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* |
| **C70** | 3276.6 | -0.00367 | -0.0109 | 0.1508 | -0.0493- | *137.97* |

Comparison of the courses of marked functions with flow curves achieved in plastometric tests are presented in **Fig. 6**.

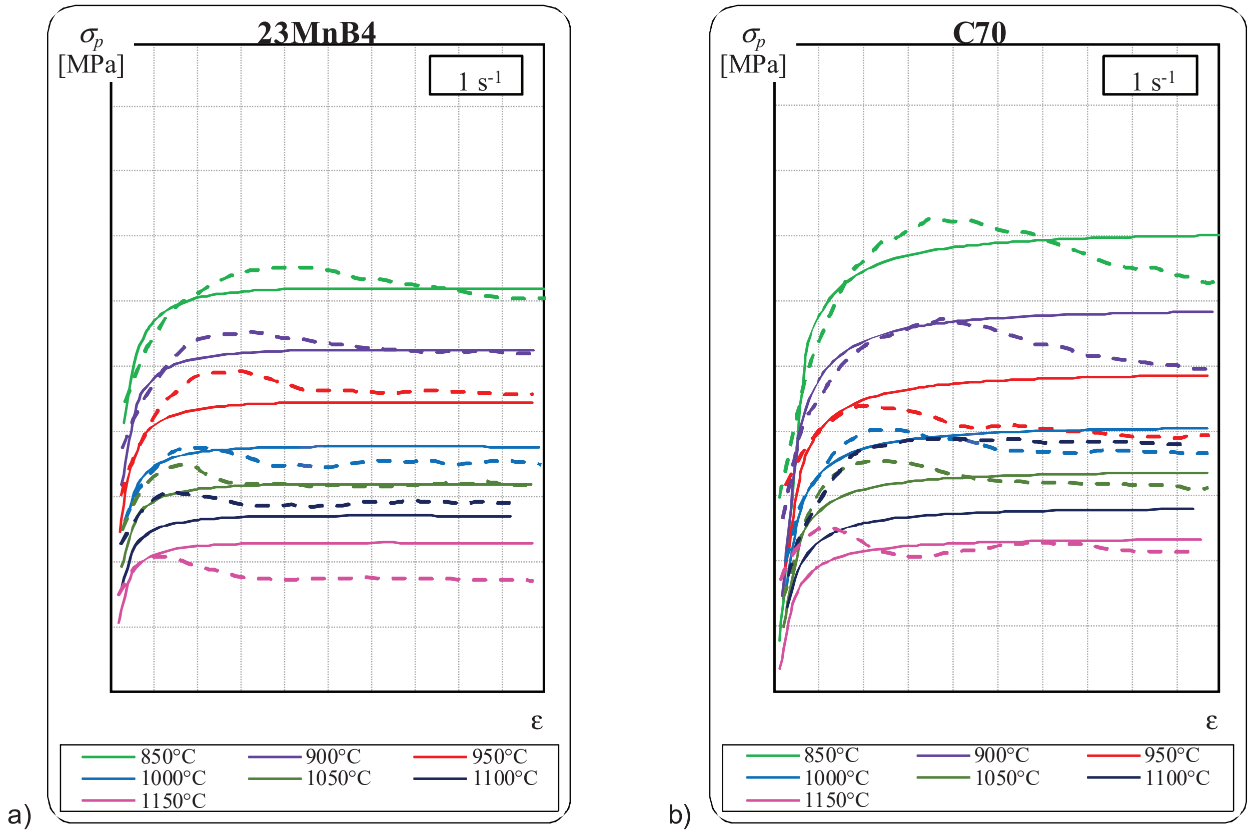



**Fig. 6** Comparison of the courses of marked functions (full lines) with experimentation curves (broken lines) for steel 23MnB4 (a) and C70D (b)

## 4. CONCLUSION

Curves showing dependency of flow stress from deformation of steel types 23MnB4 and C70 in the range of tested deformation parameters have characteristic course with clearly marked peak of flow stress, next drop of flow stress below peak and the range of constant value of flow stress. The regularity is maintained of the shift of peak towards smaller deformation values together with temperature increase and the increase of stress value with the growth of deformation speed. The location of flow stress peak is strictly dependent from the rate of deformation.

Tested steels are characterised with big deformability which reaches the value of limit deformation $\varepsilon_g$ above the value of 20 and in the lowest temperature of deformation there is a constant increase of deformability together with temperature increase. Peak flow stress is differentiated to a small degree depending on steel type and is more dependent on temperature and the strain rate. 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 $\sigma_{pp}$ and corresponding $\varepsilon_p$ for both the steels can be presented in the form of a power function such as austenitic steels [5, 6].

Flow stress function in the form of Hansel-Spittel dependency allows to determine with the accuracy up to a few percent the value of the flow stress depending on deformation, the rate of deformation and the temperature and it can be applied in programs for analysis of rolling processes of tested steel types.

## ACKNOWLEDGEMENTS

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