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DETERMINATION OF CHARACTERISTICS OF PLASTICITY OF SELECTED MEDIUM AND HIGH CARBON STEEL GRADES IN HOT TORSION TEST

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This study presents results of the examinations aimed at determination of rheological properties of selected grades of medium and high-carbon steel grades (C45 and C72D). The examinations were carried out for the hot torsion test using STD 812 torsion plastometer. The results of experimental studies were approximated with the function used for determination of yield stress depending on strain, strain rate and temperature. The study allowed for development of mathematical models of rheological properties of steel grades studied in the analysed scope of parameters of strain and temperature.

Key words: plasticity, medium and high-carbon steel, hot torsion test, strengthening curves, temperature

INTRODUCTION

The basic parameter that characterizes plastic forming properties of material is yield stress, which, under conditions of uniaxial state of stress, is a function of strain (ε), strain rate ($\dot{\varepsilon}$), temperature (T) and strain history [1].

Determination of the relationships between yield stress and parameters of metal forming is particularly important for conditions of hot forming since the processes that result from the mechanism of plastic deformation, processes of material strengthening and heat-activated processes depending on the duration of the phenomenon occur simultaneously in the structure of the material, leading to its weakening [2].

There are a number of research methods discussed in the literature used for determination of the values of yield stress as a function of parameters of strain and temperature. Such methods include tensile strength testing, compression strength testing and torsion testing. According to numerous authors, the most convenient method to determine flow curve for high temperatures is torsion test [1].

This test has been widely used in plastometer studies due to the invariable state of stress that is most similar to pure shear and no friction [1]. The torsion test allows for determination of yield stress in an indirect manner, using the hypothesis of material effort. Another benefit of this method is opportunity to achieve substantially greater strain than in other tests [1, 3]. The test allows for creation of more reliable conditions for achievement of constant strain rate and offers the best way to model multi-level strain [1].

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TEST PURPOSE, SCOPE OF THE STUDY AND METHODOLOGY

The aim of the study was to determine rheological properties of C45 and C72D steel grades with chemical composition in Table 1.

Table 1 **Chemical composition of investigated steel grades / wt.%**

	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Al
C45	0,49	0,74	0,22	0,01	0,02	0,08	0,07	0,01	0,15	0,02
C72D	0,71	0,57	0,22	0,01	0,01	0,05	0,06	0,01	0,13	0,03

The tests were carried out using torsion plastometer STD 812 (Figure 1). The study used specimens with measurement basis length: l = 4 mm and diameter: d = 10 mm.

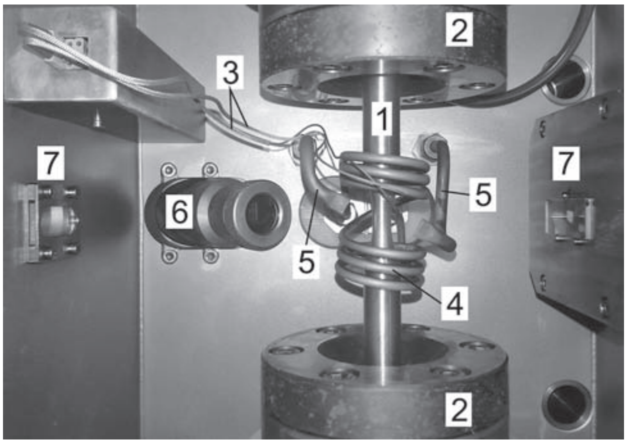


Figure 1 Specimen during examination in the chamber of STD 812 torsion plastometer: 1 - specimen, 2 - holders, 3 - thermocouples, 4 - induction solenoid, 5 - cooling system, 6 - pyrometer, 7 - sensors for measurement of specimen diameter

Plastometer tests were carried out for the following scopes of parameters: temperature: 800 ºC - 1 200 ºC, strain rates: 0,1 s^{-1}; 1,0 s^{-1} and 10,0 s^{-1} and true strain from 0 to 6,5.

Calculation of true strain during torsion used the equation (1), whereas true strain rate was determined based on the equation (2). Yield stress was determined based on the equation (3) [1]:

$$\varepsilon = \frac{2\cdot\pi\cdot r\cdot N}{\sqrt{3}\cdot L} \qquad (1)$$

$$\dot{\varepsilon} = \frac{2\cdot\pi\cdot r\cdot \dot{N}}{\sqrt{3}\cdot 60\cdot L} \qquad (2)$$

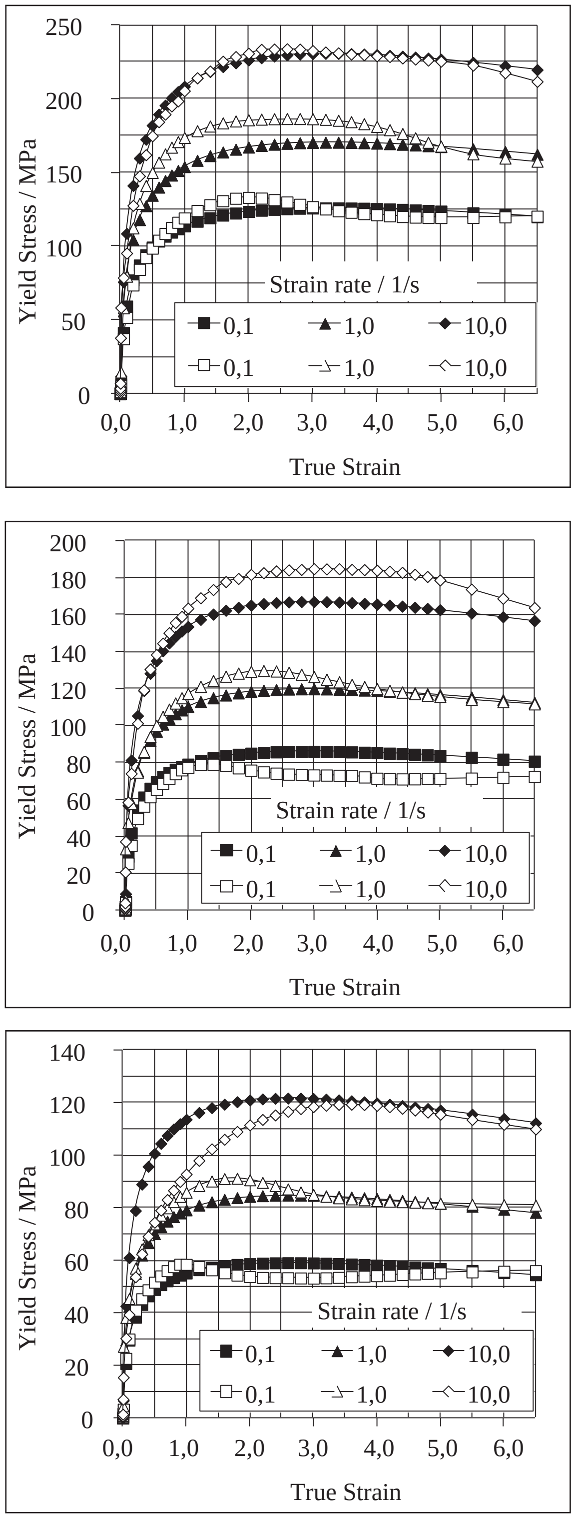
$$\sigma_p = \frac{\sqrt{3}\cdot 3M}{2\pi r^3} \qquad (3)$$

where: r – specimen radius, L – specimen length, N – number of torsions (revolutions), $\dot{N}$ – rotational velocity, M – torque.

In order to utilize the results of the study and obtain the mathematical relationship between the value of yield stress and parameters of strain and temperature, the results of the studies were approximated with functional correlations described by the equation (4) [6]. The coefficients of the equation are presented in Table 2.

$$\sigma_p = A\cdot e^{m_1\cdot T}\cdot T^{m_8}\cdot \varepsilon^{m_2}\cdot e^{\frac{m_4}{\varepsilon}}\cdot (1+\varepsilon)^{m_5\cdot T}\cdot e^{m_6\cdot\varepsilon}\cdot \dot{\varepsilon}^{m_3}\cdot \dot{\varepsilon}^{m_7\cdot T} \qquad (4)$$

where: σ_p – yield stress, T – temperature, ε – true strain, $\dot{\varepsilon}$ – strain rate, A, $m_1 \div m_8$ – coefficients of the function.



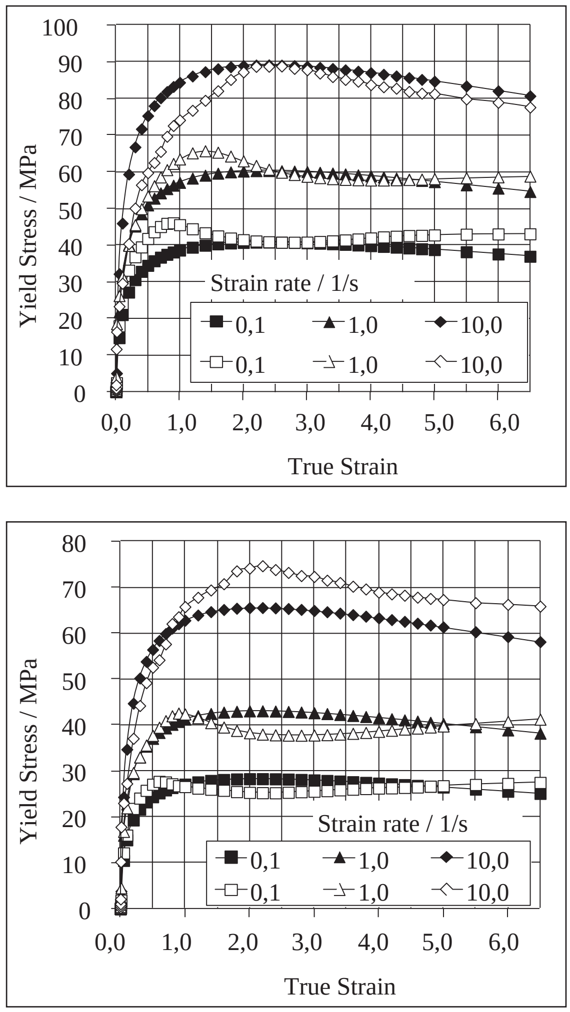
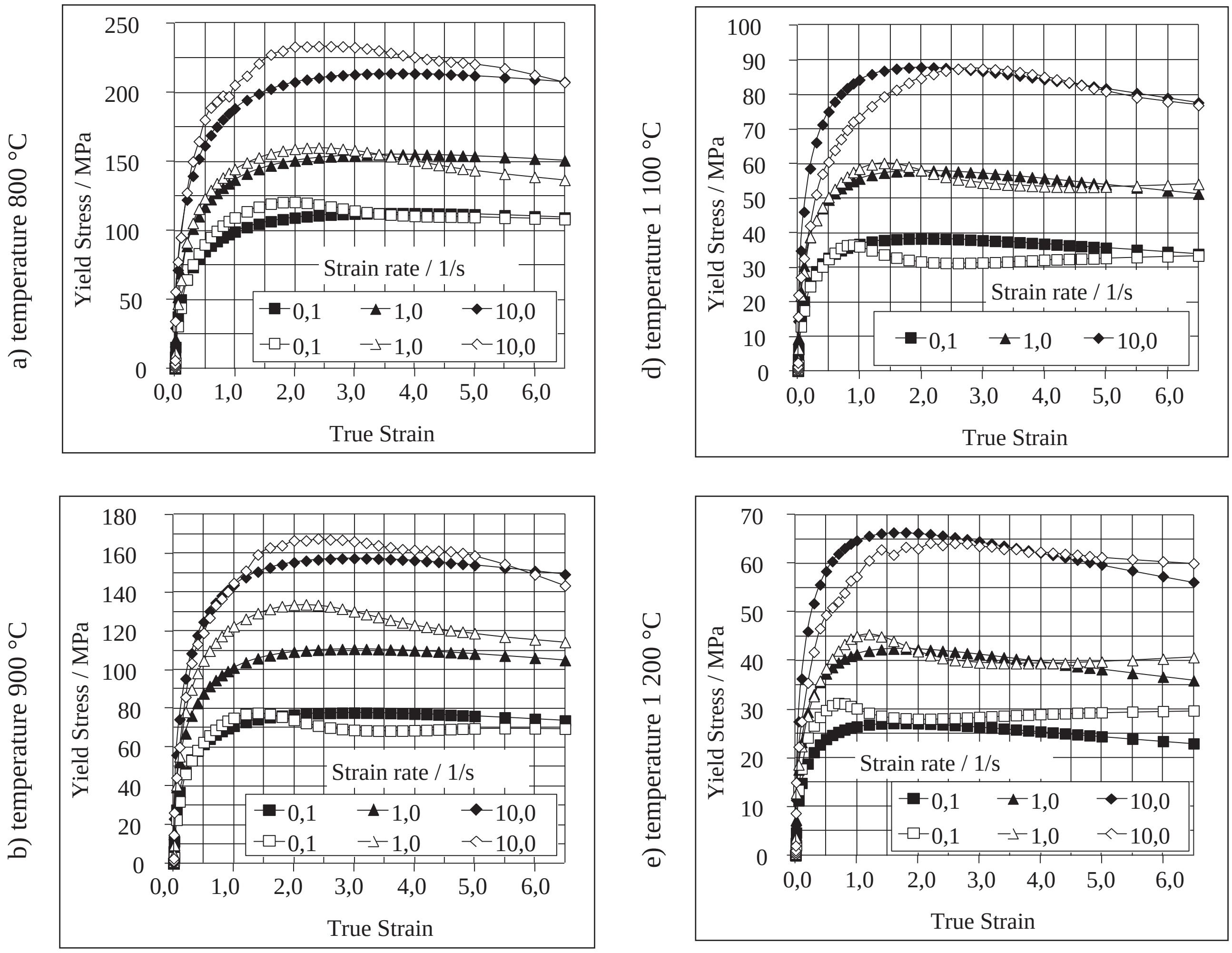


Figure 2 Flow curves for C45 steel, empty symbols: data from plastometer testing, filled symbols: results after approximation according to the equation (4), coefficients - see Table 2



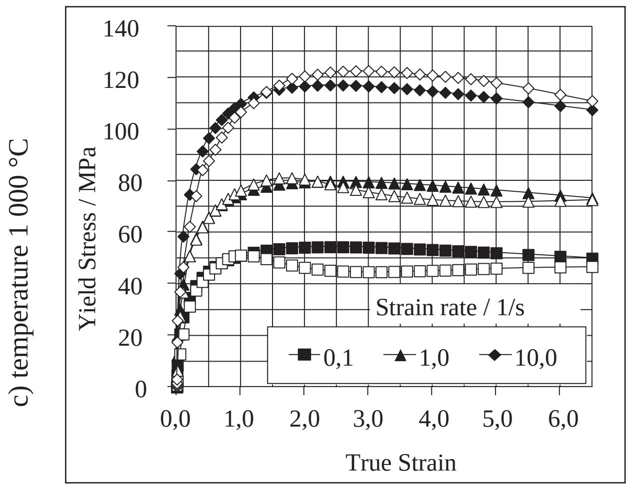


Figure 3 Flow curves for C72D steel, empty symbols: data from plastometer testing, filled symbols: results after approximation according to the equation (4), coefficients - see Table 2

INVESTIGATION RESULTS

Actual and approximated profiles of changes in yield stress for C45 steel are presented in Figure 2.

At strain temperature of 800 ºC and strain rate of 0,1 s^{-1}, yield stress for C45 steel, after reaching the maximum level (at true strain of around 2) decreases insignificantly and then remains steady. During deformation of the steel analysed at the strain rate of 1,0 s^{-1} and 10 s^{-1}, yield stress, after reaching the maximum value (at true strain of around 2,5) starts to decrease its value.

Based on the analysis of actual strengthening curves for C45 steel at temperatures of 900 ºC and 1 000 ºC it was found that, for the strain rate of 0,1 s^{-1}, yield stress after reaching the maximum value (at true strain of around 1) reduces minimally and then an insignificant increase is observed. For the strain rate of 1,0 s^{-1} and 10 s^{-1}, yield stress for the steel grade analysed, after reaching the maximum value, decreases constantly.

In the case of deformation of C45 steel at temperatures of 1100 ºC it was found that, for the strain rate of 0,1

s^{-1} and 1,0 s^{-1}, yield stress after reaching the maximum level reduces insignificantly and then an insignificant increase is observed. During deformation of the steel grade analysed at temperature 1 100 ºC and strain rate of 10 s^{-1}, yield stress after reaching the maximum value at true strain of around 2 shows a continuous decline.

In the case of deformation of C45 steel at temperatures of 1 200 ºC it was found that, for the strain rate of 0,1 s^{-1} and 1,0 s^{-1}, yield stress after reaching the maximum level reduces insignificantly and then the value is insignificantly increased. During deformation of the steel studied at strain rate of 10 s^{-1}, yield stress after reaching the maximum value at true strain of around 2 shows a continuous decline.

Actual and approximated profiles of changes in yield stress for C72D steel are presented in Figure 3.

At strain temperature of 800 ºC and 900 ºC and strain rate of 0,1 s^{-1} yield stress of C72D steel, after reaching the maximum value (at true strain of around 1,5) reduces insignificantly and then remains steady. For the strain rate of 1 and 10 s^{-1}, after reaching the maximum value (at true strain of around 2), a constant decline in the value of yield stress was observed for the material studied.

Based on the analysis of actual strengthening curves for C72D steel at temperatures of 1 000 ºC and 1 100 ºC it was found that, for the strain rate of 0,1 s^{-1} and 1,0 s^{-1}, yield stress after reaching the maximum level reduces minimally and then an insignificant increase is observed. A continuous decline in the value of yield stress is observed after exceeding true strain of 2,7 during deformation of the steel grade analysed in the study at temperatures of 1 000 ºC and 1 100 ºC at strain rate of 10 s^{-1}.

In the case of deformation of C72D steel at temperatures of 1 200 ºC it was found that, for the strain rate of 0,1 s^{-1} and 1,0 s^{-1}, yield stress after reaching the maximum level reduces insignificantly and then an insignificant increase in this value is observed. Deformation of the steel grade analysed in the study at the temperature of 1 200 ºC and strain rate of 10 s^{-1} causes that, after exceeding the true strain of 2,5, yield stress decreases continuously.

Analysis of actual and approximated material strengthening curves of the steel grades studied (Figures 2 and 3) reveals high concordance between the true values of yield stress of the materials analysed and values obtained as a results of approximation.

Based on approximation of the results obtained from plastometer testing, the values of coefficient of the equation (4) for the steel were determined, see Table 2.

Table 2 **Values of parameters A and m1÷m9 used for determination of values of yield stress in steel grades analysed in the study**

Steel	Values of parameters obtained through approximation of the equation (4)				
C45	*A*	m_1	m_2	m_3	m_4
	1 4087,50	- 0,003	0,2814	0,0297	- 0,0177
	m_5	m_6	m_7	m_8	
	- 0,0003	- 0,0415	0,0001	- 0,311	
C72D	*A*	m_1	m_2	m_3	m_4
	4 766,93	- 0,0025	0,389314	0,0301	- 0,0035
	m_5	m_6	m_7	m_8	
	- 0,0005	- 0,0283	0,000137	- 0,1926	

SUMMARY

The investigations aimed at determination of rheological properties of C45 and C72D steel grades and analysis of the results obtained lead to the following conclusions:

- results of plastometer examinations of steel obtained in torsion tests show the significant effect of strain, temperature and strain rate on the value of yield stress in steel grades studied,
- the increase in the strain rate caused simultaneous increase in the value of yield stress, whereas the increase in temperature of the materials studied results in a decline of yield stress,
- comparison of actual and approximated strengthening curves for the steel grades analysed in specific temperature ranges, strain and strain rate shows the substantial concordance between true values of yield stress and values obtained as a result of approximation,
- the results of plastometer testing allow for implementation of rheological properties of the steel grades studied to databases of the most of computer pieces of software used for numerical modelling of metal forming processes,
- taking actual rheological properties of steel grades analysed during numerical modelling is likely to improve accuracy of computation with respect to actual technological processes.

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Note: The professional translator for the English language is Czeslaw Grochowina, Studio Tekst, Poland