UDK 669.14.018.298:620.175:539.38
Izvirni znanstveni članek

ISSN 1318-0010
KZLTET 33(1-2)5(1999)

INVESTIGATION OF STEEL FLOW STRESS AND PLASTICITY AT HIGH TEMPERATURES

RAZISKAVE MEJE TEČENJA IN PLASTIČNOSTI JEKEL PRI POVIŠANIH TEMPERATURAH

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Prejem rokopisa - received: 1998-11-10; sprejem za objavo - accepted for publications: 1999-02-09

The steel flow stress and plasticity by elevated temperatures are investigated. The results of hot torsion tests in the temperature range from 1073 K to 1473 K (800°C - 1200°C) on different steels are presented and discussed.

Key words: steel, flow stress, deformation, plasticity, high temperatures, hot torsion test

V delu so predstavljeni rezultati raziskav meje tečenja in plastičnosti, legiranih konstrukcijskih jekel, po metodi torzije pri povišanih temperaturah od 1073K do 1473K (800°C - 1200°C).

Ključne besede: jeklo, meja tečenja, plastičnost, visoka temperatura, metoda vroče torzije

1 INTRODUCTION

Several million t. of steel are hot worked into rolled, forged and other products by means of various tehnological procedures of plastic processing in which great amounts of energy are need to master the deformation resistance of the steel.

Knowing the metal flow stress it is possible to predict the magnitude of the force required for deformation, the machine and tool straining, the energy consumption and to analyse the suitability of the selected technology and the effect of the material plasticity[1-9]. The objective of this investigation was to learn the most about the limit plastic flow strain and the technological plasticity of differend steels.

Torsion tests were performed at high temperature and on the base of exsperimental results equations for the analytical calculation of flow stress were determined by means of the regression mathematical analysis.

2 STEEL FLOW STRESS BY TORSION TEST - THEORETICAL ANALYSIS

To determine the value of steel flow stress laboratory methods of stretching, compression, and torsion are applied. Each of these methods has advantages and disadvantages. Usually, the experiment is selected with the strain scheme most resembling to the actual industrial procedure. It is also desirable to combine more methods in the testing. When the torsion test is used at high-temperature torsion $T > 0{,}5\ T_{melting}$ stress flow and deformation are calculated by using the derived expressions under the Mises' condition[1-9]:

$$\sigma_T = 3M\sqrt{3} / 2\pi r^3$$

$$\tau = 3M / 2\pi r^3$$

$$\sigma = \tau\sqrt{3}$$

$$\gamma = 2r\pi n / L$$

$$\gamma^* = \partial\gamma/\partial t = 2r\pi f/L$$

$$\varphi = 2r\pi n/(L\sqrt{3})$$

with:

σ_T - equivatent flow stress, MPa
τ - shear stress, Mpa
M - torque, torsion moment, Nm
r - test radius, mm
γ - torsion strain (angle deformation)
n - number of torsions
γ^* - torsion rate, s^{-1}
f - revolving frequency, number of torsions per second, s^{-1}
L - test tube length, mm
φ - equivalent strain, equivalent deformation

The torsion test, as compared to other experiments, provides a sufficiently realistic information on the flow stress, and the temperature range of maximal plasticity of steel. It is specially suited for the simulation of plant operations where tangential stresses prevail.

3 EXPERIMENTAL RESULTS AND COMMENTS

The flow stress and plasticity were determined on various special steel grades alloyed with and/or chromium, molybdenum, nickel, vanadium, tungstene, as steels for special applications, for surface hardening and nitriding: 38H2MJUAT (GOST), 35NCD16 (AFNOR), Č 4737 (HRN), 28X3CHMB (GOST), and a stainless corrosion resistant steel Č 4570 (HRN).

The chemical composition of the investigated steels is presented in **Table 1**.

The torsion tests were performed on the TC-01 Adamel Lhomargy torsion plastometer on tubular testing

Table 1: Chemical compositions in wg %

Steel	C %	Si %	Mn%	Cr %	Ni %	W %	Mo %	V %	Al %
38H2MJUAT	0.37	0.42	0.42	1.49	0.28	-	0.20	0.01	1.05
35 NCD 16	0.38	0.28	0.45	1.83	3.55	-	0.37	0.017	
Č 4737	0.26	0.30	0.51	3.12	0.03	-	0.46	0.02	
28X3CHMB	0.28	0.97	0.79	2.97	1.19	0.88	0.40	0.14	
Č 4570	0.16	0.74	0.72	14.9	2.80	-	0.022	0.01	

specimens 6x32 mm, at the revolving frequency of the drive shaft N = 100 min^{-1} which is equivalent to the deformation rate 1 s^{-1}. The testing was performed in temperature range between 800 and 1200°C by steps of 50°C.

The torsional moment and the equivalent strain for the steel 35NCD16 are presented in **Figure 1**.

The maximal moment M_{max}, which is the indicator of the steel flow stress, continuously decreases from 8.5 Nm at 800°C to 1.5 Nm at 1200°C.

In **Figure 2** the flow stress and the number of torsions up to the fracture, which are the indicators of steel plasticity are shown. The flow stress continuously decreases from 165 MPa at 800°C to 45 Mpa at 1200°C, while the number of revolutions up to fracture (n) increases constantly from 10 at 800°C to 98 revolutions before the fracture at 1200°C. The known fact of flow stress decrease and plasticity increase with the increase in temperature is confirmed.

In **Figure 3** the results of testing of the steel 35NCD16 are shown a number of revolutions to fracture and the flow stress in dependence of temperature are shown. While the flow stress decreases continually with the increasing temperature the maximal number of revolutions is achieved at 1250°C and it is even slightly lower at 1250°C than at 1150°C. That suggests that by a

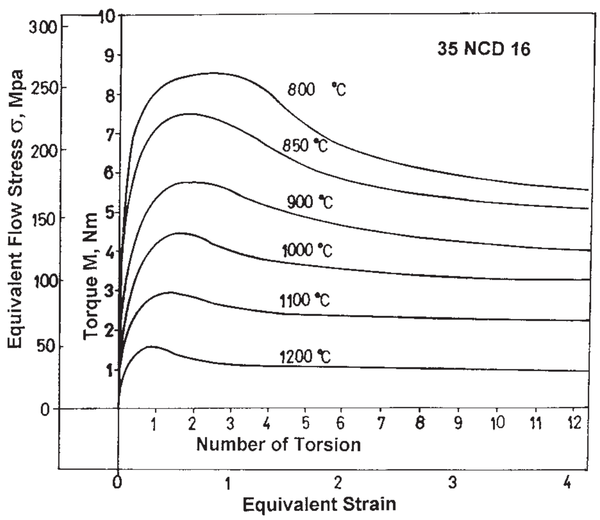

Figure 1: Torsional moment and equivalent stress of steel 35NCD16 by tests in temperatures range from 800 to 1200°C

Slika 1: Torzijski moment in ekvivalentna napetost za jeklo 35NCD16 v razponu temperature 800 do 1200 °C

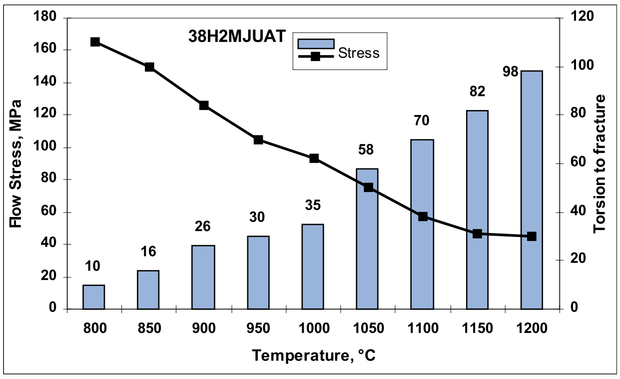

Figure 2: Flow stress and plasticity for the steel 38H2MJUAT in dependence of the testing temperature

Slika 2: Meja tečenja in preoblikovalnost za jeklo 38H2MJUAT v odvisnosti od temperature preizkušanja

stil higher temperature the impairing of the steel workability could be expected.

The results of testing of the steel Č 4737 are shown in **Figure 4**. The number of revorutions before the fracture n decreses, when the temperature is increased from 800°C to 900°C. By further temperature increase the number of revolutions is increased to a peak at 1150°C. Above this temperature is fastly decreased to only 15 revolutions at 1250°C.

Flow stress by the steel Č 4737 increases from the temperature of 800 to 850°C, because of the increasing share of austenite, the phase with the higher flow stress in the microstructure on expense of the share of softer

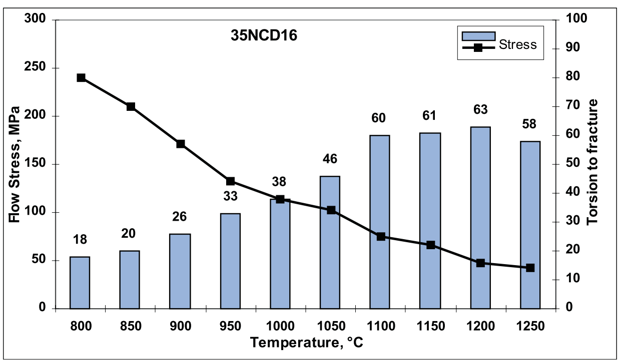

Figure 3: Flow stress and plasticity for the steel 35NCD16 in dependence of the testing temperature

Slika 3: Meja tečenja in preoblikovalnost jekla 35NCD16 v odvisnosti od temperature preizkušanja

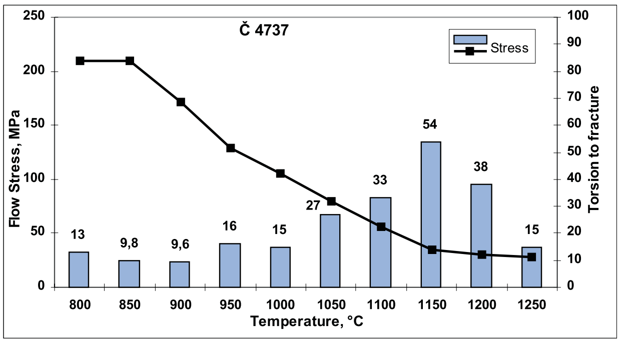

Figure 4: Flow stress and plasticity for the steel Č 4737 in dependence of the testing temperature
Slika 4: Meja tečenja in preoblikovalnost jekla Č 4737 v odvisnosti od temperature

ferrite. By further increase of temperature flow stress the acquires the usual dependence and the plasticity.

The changes of microstructure above 1150°C and their effect on worcability were not yet experimentally investigated. It is supposed that the impaired worcability could result from carbide precipitation and eutectic melting or from effects of dynamic recrystallization of austenite producing a very heterogeneus austenite grain size.

The flow stress continously decreases with the increasing testing temperature, and no effect was was found which would match the decrease of steel workability above 1150°C. It is therefore evident that the workability, represented as number of revolutions to fracture, is more sensitive to microstructural processes, also those induced by the deformation, than flow stress.

The flow stress and the number of revolutions before the fracture in dependence of the temperature are presented in **Figure 5** for the steel 28X3CHMB. The number of revolutions before the fracture shows a similar temperature dependence as in **Figure 3**. The overall level of plasticity is lower and the peak plasticity reached at the lower temperature of 1150°C. Considering the similar content of carbon and chromium as in steel

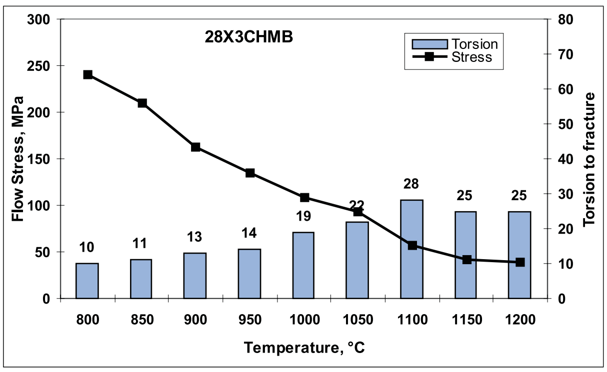

Figure 5: Flow stress and plasticity for the steel 28X3CHMB in dependence of the testing temperature
Slika 5: Meja tečenja in preoblikovalnost jekla 28X3CHMB v odvisnosti od temperature

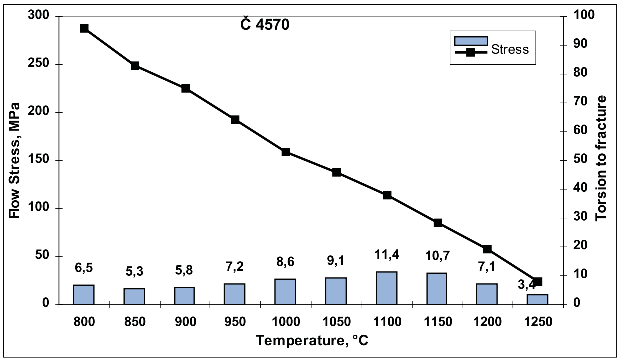

Figure 6: Flow stress and plasticity for the steel Č 4570 in dependence of the testing temperature
Slika 6: Meja tečenja in preoblikovalnost jekla Č 4570 v odvisnosti od temperature

Č4737 also a similar effect of temperature on plasticity as in **Figure 4** would be expected. The difference could be explained assuming either that tungstene and molybdenium bind a part of carbon to a stable carbide phase and impairing the formation of a carbide eutectic wich in chromium or that both mentioned elements and nickel have a favourable effect on dinamical softening processes producing a heterogeneus austenite grain size. No particularity is found on the effect of temperature on flow stress.

In terms of number of revolutions to fracture the workability of the steel Č 4570 is very poor in comparison to other investigated steels. The peak workability is achieved at 1150°C, and by further temperature increase it drops rapidly. Considering the chemical compositions it is assumed that the lower workability is due to the high content of chromium in solution, especially the presence of chromium carbide precipitates in low temperature range and that the drop of workability above 1100°C is due to the formation of an intergranular carbide eutectic. It is expected therefore that the workability drop would be even greater by higher content of carbon in the steel.

The flow stress decreases virtually proportionally to the increase of testing temperature and, as by previous tested steels shows no indication connected to the drop of workability above 1150°C.

4 ANALYSIS OF THE DEPENDENCE FLOW STRESS - TESTING TEMPERATURE

In modern research it is necessary, whenever it is possible, to provide a functional description of the experimental data based on their mathematical analysis.

The steel flow stress dependence on temperature $\sigma_T = f(T)$ for the temperature range 800 - 1200°C, was processed by means of regression analysis to according to the linear and exponential function:

$$\sigma_T(T) = -n\,(T - T_o) + a \qquad (1)$$

$$\sigma_T(T) = A\,\exp(-m\,(T - T_o)/1000) \qquad (2)$$

where: T[K], T_o = 273K and T-T_o [K] = t [C] can be applied.

It was found that for four investigated steels the temperature dependence $\sigma_T=f(T)$ can be aproximated to the exponential function 2. In **Table 2** the values of the constant A, exponent m are calculated, and the correlation coefficient r are given. The very high correlation coefficient confirms the correctness of the use of the exponential equation 2 for the analytical representation of the relationship flow stress versus testing temperature.

Table 2: Constant A, exponent m, and correlation coefficient r

Nr.	Steel	constant A	exponent m	correlation coefficient r
1.	38H2MJUAT	2823.9	-3.4321	0.994
2.	35NCD16	6554.6	-4.0236	0.989
3.	Č 4737	19418.9	-5.3013	0.979
4.	28X3CHMB	12790.7	-4.8101	0.978

By the steel Č 4570 it was found that the relationship flow stress testing temperature is aproximated to the best with the linear function 1. The calculated values of the slope coefficient n, the constant a, and the correlation coefficient r, are shown in **Table 3**.

Table 3: Slope coefficient n, constant a, and correlation coefficient r

Steel	Slope n	Constant a	correlation coefficient r
Č 4570	-0.5835613	755.23567	0.997

Also by this steel the correlation coefficent is very high and confirms the correctness of the linear aproximation.

In **Table 4** the equations for the dependence flow stress versus testing the temperature in form $\sigma_T = \sigma_o [f(T)]$, which applies for the temperature range 800 - 1200°C, are shown. In the presented form the equations can be used for the modelling of hot working processes based the evolution of flow stress during the processing.

Table 4: Dependence flow stress on temperature $\sigma_T= \sigma_o [f(T)]$, MPa

Nr.	Steel	$\sigma_T= \sigma_o [f(T)]$, MPa
1.	38H2MJUAT	σ_T = 91.26 [30.943 exp (-3.4321 (T-T_o)/1000)]
2.	35NCD16	σ_T = 117.25 [55.902 exp (-4.0236 (T-T_o)/1000)]
3.	Č 4737	σ_T = 96.80 [200.597 exp (-5.3013 (T-T_o)/1000)]
4.	28X3CHMB	σ_T = 104.21 [122.744 exp (-4.8101 (T-T_o)/1000)]
5.	Č 4570	σ_T = 171.67 [-0.0033993 (T-T_o) + 4.3993457]

T - temperature, K, T_0 = 273 K

5 CONCLUSIONS

The following conclusions are proposed on the base of this investigations as well as the quoted references.

- The flow stress and the hot workability of several steels with different chemical composition were established by torsion tests.
- It was confirmed that with increasing temperature the flow stress decreases and the worcability increases. The worcability is above 1150°C affected by microstructural and deformation processes to a different extent. In presence of above appr. 3% chromium the worcability start to decrease above a temperature, which depends on the chemical composition of the steel.
- The impairing effect of chromium is diminished or even removed by addition of tungstene and/or molybdenium to the steels, which of bind carbon into stable carbides.
- No effect of elements established by testing the temperature dependence of worcability was found on the temperature dependence of flow stress. It seems, therefore, that flow stress is sensitive to a much lower extent than the worcability to the temperature and deformation induced processes in the austenite microstructure.
- Functional equations of flow stress depending on the temperature $\sigma_T = \sigma_o [f(T)]$ have been established for the temperature ramge 800°C - 1200°C, which can be applied in mathematical models for the analytical calculation of stress of plastic steel flow.

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