M. GOLJA, M. BURŠÁK

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FLOW STRESS AND PLASTICITY OF ALLOYED STEELS

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This paper deals the results of investigation the flow stress of several various steel alloys and deformability by torsion test in hot condition in the temperature range 800 °C - 1250 °C on alloyed structural steels for special application.

Key words: *steel, flow stress of steel, plasticity, deformability, torsion test*

Naprezanje tečenja i plastičnost legiranih čelika. U radu su predstavljeni rezultati istraživanja naprezanja plastičnog tečenja čelika i deformabilnost, metodom uvijanja u toplom u temperaturnom području 800 °C - 1250 °C legiranih konstrukcijskih čelika za posebne namjene.

Ključne riječi: *čelik, naprezanje plastičnog tečenja čelika, plastičnost, deformabilnost, metoda uvijanja*

INTRODUCTION

Over 500 million tones of crude steel production in the world is formed into rolled, forged and other products by means of various technological processes of metal forming where huge amounts of energy need to be employed to master the resistant forces and material stress [1-9].

By knowing the metal and alloy flow stress it is possible to predict the force magnitude required for deformation, machine and tool straining, and energy consumption and to analyze the issues of the selected technology and material plasticity [2-12].

The research objective is to learn as much about the strain of material flow and its technological deformability. The paper presents the results of investigation of flow stress and limit deformability of alloyed construction steels. Torsion test was applied at higher temperatures. Based on the experimental results of measuring, expressions for analytical calculation of flow stress were determined by means of regression mathematical analysis.

THEORETICAL EXAMINATION OF STEEL FLOW STRESS BY TORSION TEST

To determine the value of steel flow stress, laboratory methods of stretching, compression, and torsion were applied. Each of these methods has its advantages and disadvantages and we usually choose the experiment, the strain scheme of which is most resembling to the actual procedure. During examination it is desirable to combine and use the results of the more selective method. When using the torsion test, at high-temperature torsion, stress flow and deformation are calculated by using the derived expressions under the Misses´ condition [2-9]:

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

$$\tau = \frac{3M}{2\pi r^3}$$

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

$$\gamma = \frac{2r\pi n}{L}$$

$$\gamma^* = \frac{\partial\gamma}{\partial t} = \frac{2r\pi f}{L}$$

$$\varphi = \frac{2r\pi n}{\sqrt{3}L}$$

where:

σ_T - equivalent flow stress, MPa
τ - shear stress, MPa
M - torque, torsion moment, Nm
r - test radius, mm

M. Golja, Faculty of Metallurgy, University of Zagreb, Sisak, Croatia, M. Buršák, Faculty of Metallurgy, Technical University of Košice, Košice, Slovakia

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 sufficiently realistic information on the flow stress, temperature range of maximal deformability of steel, and it is equivalent to the conditions of simulation of plant operations where tangential stresss prevail.

EXPERIMENTAL PART OF INVESTIGATION FLOW STRESS OF STEEL AND DEFORMABILITY BY METHOD OF TORSION AT HIGHER TEMPERATURES WITH COMMENTS

Within the experimental part, flow stress and deformability were examined on various special steel, alloyed with and/or chrome, manganese, molybdenum, nickel, vanadium, steel for special applications and improving, HRN Č 4732, Č 4233, Č 8380, Č 7400.

Results of chemical composition examination of the stated steel grades were defined on an ARL 31000 emission quantum-meter and presented in the following table:

Table 1. **Chemical compositions**
Tablica 1. **Kemijski sastav**

Steel condition	C [%]	Si [%]	Mn [%]	Cr [%]	Ni [%]	Mo [%]	V [%]
Č 4732	0.45	0.29	0.68	1.02	0.09	0.18	0.01
Č 4233	0.32	1.05	1.04	1.02	0.10	0.02	0.01
Č 8380	0.35	0.30	1.32	0.09	0.06	0.022	0.16
Č 7400	0.18	0.29	0.55	0.89	0.06	0.53	0.02

The torsion tests were conducted on a torsion plastometer TC-01 Adamel Lhomargy (France) on tubular testing specimens ϕ 6x32 mm, at revolving frequency of the drive shaft N = 100 min^{-1} which is equivalent to the deformation rate 1 s^{-1}. The selected test temperature was ranging between 800 and 1250 °C at a 50 °C step.

The results of torsion tests for the steel grade Č 4732, equivalent flow stress during torsion and number torsion to fracture at temperatures 800 - 1250 °C are presented at Figure 1.

Figure 1. shows that the maximal flow stress continuously decreases from 257 MPa at 800 °C to 39 MPa at 1250 °C.

The number of torsions up to the fracture n, as an indicator of steel deformability increases constantly from 14 torsions at 800 °C to 83 torsions before the fracture at 1100 °C.

The decrease of deformability at higher temperatures is affected by a few factors, such as the size of the austenitic grain, diluted elements, and their influence on the degree of dynamic recrystallization of austenite after which the size of the austenitic grain may be heterogenic.

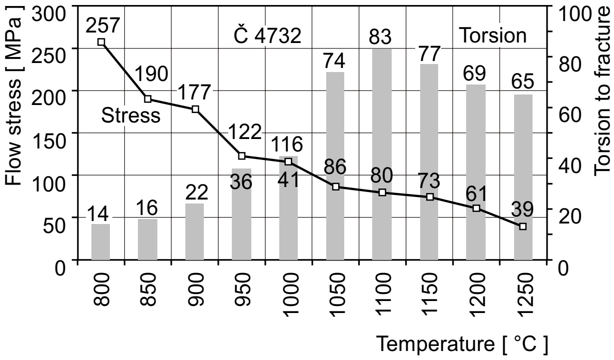

Figure 1. **Flow stress of steel Č 4732 during torsion at temperatures 800 - 1250 °C**
Slika 1. **Naprezanje tečenja čelika Č 4732 pri uvijanju na temperaturama 800 - 1250 °C**

The results of torsion tests for the steel grade Č 4233 and number of torsions up to the fracture as indicators of deformability are shown in Figure 2.

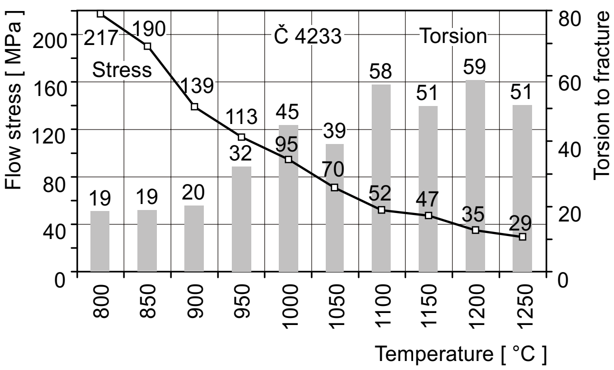

Figure 2. **Flow stress and deformability indicator for steel Č 4233**
Slika 2. **Naprezanje tečenja i deformabilnost za čelik Č 4233**

Figure 2. shows that the steel flow stress continuously decreases from 217 MPa at 800 °C to 29 MPa at 1250 °C.

The number of torsions up to the fracture n, as an indicator of steel deformability increases from 19 torsions at 800 °C to 59 torsions before the fracture at 1200 °C. Above 1000 °C the inclination of the n curve is different.

In the comments of the results the usual dependance can be stated according to which flow stress decreases and plasticity increases with the increase in temperature.

For steel Č 8380, group test results of flow stress and the number of torsions up to the fracture as a deformability indicator at temperatures betwen 800 and 1250 °C are presented in Figure 3.

It is evident from Figure 3. that the maximal flow stress continuously decreases with the increase in temperature.

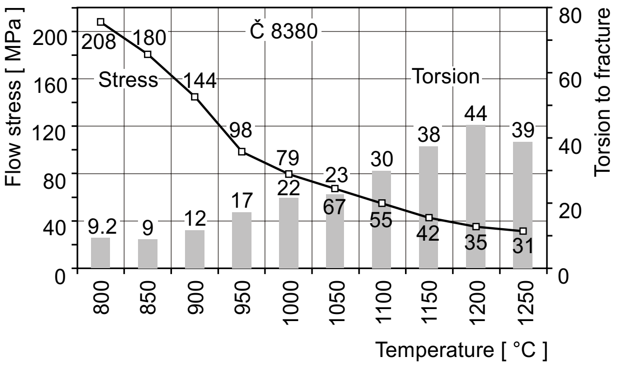

Figure 3. **Flow stress and deformability for steel grade Č 8380**
Slika 3. **Naprezanje tečenja i deformabilnost za čelik Č 8380**

The number of torsions up to the fracture, as indicator of steel deformability shows the increase from 9 torsions at 850 °C up to 44 torsions before the fracture at 1200 °C.

With the temperature increasing, flow stress decreases and the deformability increases.

For steel grade Č 7400, the results of testing the flow stress and number of torsions up to the fracture as an indicator of deformability at 800 - 1250 °C are shown in Figure 4.

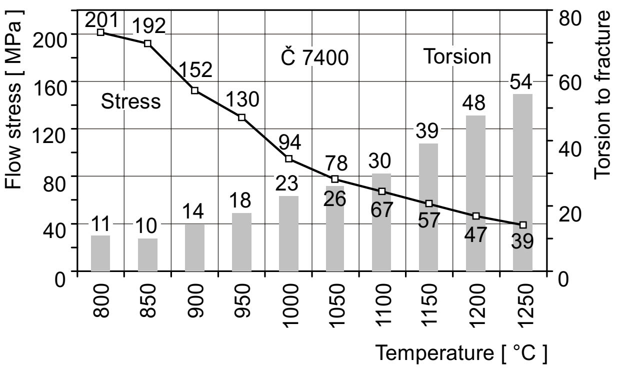

Figure 4. **Flow stress and deformability for steel grade Č 7400**
Slika 4. **Naprezanje tečenja i deformabilnost za čelik Č 7400**

Number of torsions before the fracture *n*, as steel deformability indicator, shows a decrease from 11 torsion at 800 °C to less than 10 torsions before the fracture at temperatures of 850 °C, as well as an uneven increase with a peak of 54 torsions at 1250 °C. Flow stress does decrease with the increase in temperature from 800 to 850 °C, which can be explained with the fact that below 850°C a two-phased structure prevails, where one of the phases, i.e. the ferite, has a lower flow stress. With the increase in temperature homogeneity, flow stress acquires the usual dependence, and these changes affect the plasticity, as well.

In the temperature range 800 - 850 °C, if the number of torsions before the fracture is below 10, it is generally considered very low steel plasticity. The decreased deformability stress can also be explained with two-phased state of the structure at these temperatures.

This steel shows a more expressed decrease in deformability at higher temperatures regarding the chemical composition.

Based on the comparative analysis the influence of individual alloying elements on plasticity is obvious. Chrome effects the decrease in plasticity above the particular temperature and its influence grows stronger with the increase of the carbon content. Carbon can have an affect on the plasticity only if the content of chrom is high enough. Molybdenum has a favorable affect on the plasticity and it increases the plasticity.

MATHEMATICAL ANALYSIS OF EXPERIMENTAL RESULTS OF STEEL FLOW STRESS MEASURING

In modern time research, whenever it is possible, it is necessary to provide a functional description of the observed process based on the mathematical analysis of experimental measuring results.

The measured values of steel flow stress, most depending on the temperature $\sigma_T = f(T)$, for temperature range 800 - 1250 °C, were processed by means of regression analysis to approximate dependence on exponential function [2-9]:

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

Table 2. provides the results of the mathematical analysis of flow stress for the examined steel grades, depending on the temperature, processed by regression analysis to approximate exponential function, where values of the constant *A* and exponent *m* for every steel grade are calculated, with correlation coefficient *r*.

Table 2. **Values of the constant *A*, exponent *m*, and correlation coefficient *r***
Tablica 2. **Vrijednosti za konstantu *A*, eksponent *m* i koeficijent *r***

Steel grade	Constant *A*	Exponent *m*	Correlation coefficient *r*
Č 4732	6443.3	- 4.0893	0.995
Č 4233	6898.5	- 4.3106	0.992
Č 8380	7423.9	- 4.3704	0.997
Č 7400	8372.2	- 4.4754	0.978

Based on the high values of correlation coefficient *r*, measurement of the bond between the observed values, where $r > 0.97$, excellent functional dependance can be confirmed.

Complete function equations of flow stress of the examined steel grades depending on the temperature $\sigma_T = \sigma_o f(T)$, which apply for the temperature range 800 - 1250 °C, are shown in Table 3.

Table 3. **Function dependence flow stress of steel on the temperature $\sigma_T = f(T)$**

Tablica 3. **Funkcijska ovisnost naprezanja tečenja čelika o temperaturi $\sigma_T = f(T)$**

Steel grade	Stress flow in dependence on the temperature $\sigma_T = \sigma_0 f(T)$ [MPa]
Č 4732	σ_T = 107.93 [59.698 exp (- 4.0893 T /1000)]
Č 4233	σ_T = 92.61 [74.485 exp (- 4.3106 T /1000)]
Č 8380	σ_T = 93.88 [87.829 exp (- 4.3704 T /1000)]
Č 7400	σ_T = 95.32 [79.075 exp (- 4.4754 T /1000)]

The established functional dependence can be used in practice for analytical calculation of flow stress of steel and applied in future mathematical models.

CONCLUSION

Based on the processing of information provided in the technical and scientific literature, as well as own research, the following conclusions can be drawn:

The flow stress of alloyed structural steels and their deformability were established by torsion tests.

The dependence has been confirmed according to which the increase in temperature causes the flow stress to fall and deformability to grow.

However, the deformability at elevated temperatures is affected by the thermal and dynamic processes of strengthening and softening, by which plasticity is increased only up to a particular temperature level, and when the optimal processing temperature is exceeded the unusual dependence prevails according to which deformability decreases as temperature grows.

Functional equations of flow stress depending on the temperature $\sigma_T = \sigma_0 f(T)$ have been established for the temperature range 800 - 1250 °C, which can be applied in mathematical models for analytical calculation of flow stress of different steel alloys.

REFERENCES

[1] I. Mamuzić, V. M. Drujan: Teorija, materijali, tehnologija čeličnih cijevi, Hrvatsko metalurško društvo, Zagreb 1996., s. 103, 175-292

[2] M. Golja, L. Medvedeva, A. Skorobogatko: Plastic Flow of an Inhomogeneous Bar Compressed by Rigid Indentors, ACTA METALLURGICA SLOVACA (ISSN-1335-1532), 2 (1996) 21-25

[3] R. Kopp, J. M. Heusen: Improvement of Accuracy in Determining Flow Stress in Hot Upsetting Tests, Max Plank Institut, Steel Research 64 (1993) 8/9, 377-384

[4] G. Zouhar, R. Kost, R. Blasner, M. Budach: Computersimulation der Gefugeentwicklung fur Erzeugnisse aus Dunbrammengies und Walzanlagen, Stahl und Eisen 115 (1995) 1, 65-67

[5] W. Heller, H. P. Haugardy , R. Kawalla: Stahl und Eisen 116 (1996) 4, 115-122

[6] I. Schindler, J. Boruta: Deformační odpory oceli pri vysokoredukčnim tvareni za tepla, Hutnicke listy 50 (1995) 7/8, 47-50

[7] T. Kvackaj, I. Pokorny: Mathematical model of stress-strain curves, Metalurgija 34 (1995) 4, 145-149

[8] I. Mamuzić, I. Binkevich: Application of finite element method to the analysis of coils of thin cold-rolled strip, Metalurgija 34 (1995) 4, 151-153

[9] I. Mamuzić, L. Medvedeva, A. Skorobogatko: Fem investigation of the parameters of the local plastic deformations of an inhomogeneous bar; Metalurgija 35 (1996) 1, 27-29

[10] R. Turk, M. Knap, R. Rodić: Experimental - numerical and microstructural control of hot strip rolling. *Acta Metall. Sin.* 13 (2000) 1, 369-378

[11] M. Knap, R. Turk: Expert system for determination of the optimal control program for the workability testing of materials on the gleeble 1500 machine, Metalurgija 40 (2001) 3, 165-168

[12] R. Turk, I. Peruš, M. Knap: Modeling and the reliability of calculated flow curves, Metalurgija 41 (2002) 1, 23-28