FLOW STRESS AND PLASTICITY OF ALLOYED STEELS

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

**Ključne riječi:** čelik, naprezanje plastičnog tečenja čelika, plasticnost, 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 [2-12].

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]:

\[
\begin{align*}
\sigma &= \frac{3\sqrt{3}M}{2\pi r^3} \\
\tau &= \frac{3M}{2\pi r^3} \\
\sigma &= \tau \sqrt{3} \\
\gamma &= \frac{2\pi n}{L} \\
\gamma' &= \frac{\sigma \gamma}{\pi} = \frac{2\pi f}{L} \\
\varphi &= \frac{2\pi n}{\sqrt{3} L}
\end{align*}
\]

where:

- \(\sigma_t\) - equivalent flow stress, MPa
- \(\tau\) - shear stress, MPa
- \(M\) - torque, torsion moment, Nm
- \(r\) - test radius, mm

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\( \gamma \) - torsion strain (angle deformation)
\( n \) - number of torsions,
\( \gamma^* \) - torsion rate, s\(^{-1}\)
\( f \) - revolving frequency, number of torsions per second, s\(^{-1}\)
\( L \) - test tube length, mm
\( \varphi \) - 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 stress is prevalent.

**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>
<thead>
<tr>
<th>Steel condition</th>
<th>C [%]</th>
<th>Si [%]</th>
<th>Mn [%]</th>
<th>Cr [%]</th>
<th>Ni [%]</th>
<th>Mo [%]</th>
<th>V [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Č 4732</td>
<td>0.45</td>
<td>0.29</td>
<td>0.68</td>
<td>1.02</td>
<td>0.09</td>
<td>0.18</td>
<td>0.01</td>
</tr>
<tr>
<td>Č 4233</td>
<td>0.32</td>
<td>1.05</td>
<td>1.04</td>
<td>1.02</td>
<td>0.10</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Č 8380</td>
<td>0.35</td>
<td>0.30</td>
<td>1.32</td>
<td>0.09</td>
<td>0.06</td>
<td>0.022</td>
<td>0.16</td>
</tr>
<tr>
<td>Č 7400</td>
<td>0.18</td>
<td>0.29</td>
<td>0.55</td>
<td>0.89</td>
<td>0.06</td>
<td>0.53</td>
<td>0.02</td>
</tr>
</tbody>
</table>

The torsion tests were conducted on a torsion plastometer TC-01 Adamel Lhomargy (France) on tubular testing specimens \( \phi \) 6x32 mm, at revolving frequency of the drive shaft \( N = 100 \text{ min}^{-1} \) 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 in 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.

![Flow stress of steel Č 4732 during torsion at temperatures 800 - 1250 °C](image1)

**Slika 1. Naprezanje tečenja čelika Č 4732 pri uvajanju 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.

![Flow stress and deformability indicator for steel Č 4233](image2)

**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 dependence 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 between 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.
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 \( \sigma_f(T) \), for temperature range 800 - 1250 °C, were processed by means of regression analysis to approximate dependence on exponential function [2-9]:

\[
\sigma_f(T) = A \exp(-m \frac{T}{1000})
\]

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>
<thead>
<tr>
<th>Steel grade</th>
<th>Constant ( A )</th>
<th>Exponent ( m )</th>
<th>Correlation coefficient ( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Č 4732</td>
<td>6443.3</td>
<td>-4.0893</td>
<td>0.995</td>
</tr>
<tr>
<td>Č 4233</td>
<td>6898.5</td>
<td>-4.3106</td>
<td>0.992</td>
</tr>
<tr>
<td>Č 8380</td>
<td>7423.9</td>
<td>-4.3704</td>
<td>0.997</td>
</tr>
<tr>
<td>Č 7400</td>
<td>8372.2</td>
<td>-4.4754</td>
<td>0.978</td>
</tr>
</tbody>
</table>

Based on the high values of correlation coefficient \( r \), measurement of the bond between the observed values, where \( r > 0.97 \), excellent functional dependence can be confirmed.

Complete function equations of flow stress of the examined steel grades depending on the temperature \( \sigma_f = \sigma(T) \), 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 $\sigma_r = f(T)$

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Stress flow in dependence on the temperature $\sigma_r = \sigma_f(T)$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Č 4732</td>
<td>$\sigma_r = 107.93 \times [59.698 \exp(-4.0893 T / 100)]$</td>
</tr>
<tr>
<td>Č 4233</td>
<td>$\sigma_r = 92.61 \times [74.485 \exp(-4.3106 T / 100)]$</td>
</tr>
<tr>
<td>Č 8380</td>
<td>$\sigma_r = 93.88 \times [87.829 \exp(-4.3704 T / 100)]$</td>
</tr>
<tr>
<td>Č 7400</td>
<td>$\sigma_r = 95.32 \times [79.075 \exp(-4.4754 T / 100)]$</td>
</tr>
</tbody>
</table>

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 $\sigma_r = \sigma_f(T)$ 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