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# AN INVESTIGATION OF THE HOT DEFORMABILITY OF LOW-ALLOYED STEELS USING TORSION TESTS

# RAZISKAVA VROČE PREOBLIKOVALNOSTI MALOLEGIRANIH JEKEL S PREIZKUSI TORZIJE

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The hot-torsion deformability was investigated for several heat-treatment steels in the temperature range 800–1250 °C. The number of revolutions to fracture and the flow stress were determined. For every steel a function of the form $\sigma_{\mathrm{fl}} = \sigma_0 A \exp(-m/T)$ was deduced.

Key words: heat treatment steels, hot deformability, flow stress, dependence flow stress on temperature

Določeni sta deformabilnost in meja tečenja za jekla za toplotno obdelavo v območju temperature 800–1250 °C. Na podlagi eksperimentalnih rezultatov je bil za vsako jeklo razvit analitični izraz v obliki $\sigma_{\mathrm{pl}} = \sigma_0 A$ eksp $(-m/T)$ za odvisnost med mejo tečenja in temperaturo.

Ključne besede: jekla za toplotno obdelavo, meja tečenja, deformabilnost, odvisnost meja tečenja – temperatura

## 1 INTRODUCTION

By knowing the flow stress it is possible to predict the force required to deform steel and the straining of machines and tools, it is also possible to deduce the consumption of energy and to analyze the technology in terms of the maximum hot-working temperature [1-14].

In this paper the results of an investigation of the hot workability in terms of the number of revolutions to fracture and the resistance to deformation – termed, the deformability and flow stress – for six different heat-treatment steels in the temperature range 800–1250 °C are presented. The deformability, defined as the number of revolutions to fracture, at every checked temperature and the flow stress, deduced from the steel's resistance to deformation, were determined. Using regression analysis the numerical relations for the dependence of the flow stress on the temperature were deduced.

## 2 EXPERIMENTAL WORK

Laboratory methods of stretching, compression, and torsion were applied to determine the hot workability of steels as well as their deformability and flow stress. Each of these methods has its advantages and disadvantages; however, usually the method and strain scheme that reproduce most accurately the actual hot-working process are used. For high-temperature torsion tests the stress, the flow stress and the extent of deformation are calculated using the expressions derived by applying the von Misses' conditions [2-9]:

$$\begin{aligned}
&\sigma_T = 3M\sqrt{3}/2\pi r^3\\
&\tau = 3M/2\pi r^3\\
&\sigma = \tau\sqrt{3}\\
&\gamma = 2r\pi n/L\\
&\gamma^* = \partial\gamma/\partial t = 2r\pi f/L\\
&\varphi = 2r\pi n/(L\sqrt{3}) \qquad (1)
\end{aligned}$$

where:

$\sigma_T$ – equivalent flow stress, MPa
$\tau$ – shear stress, MPa
$M$ – torque, maximum torsion moment, Nm
$r$ – test radius, mm
$\gamma$ – torsion strain (angle of deformation)
$n$ – number of revolutions,
$\gamma^*$ – torsion rate, $\mathrm{s}^{-1}$
$f$ – revolving frequency, number of revolutions per second, $\mathrm{r\ s}^{-1}$
$L$ – test tube length, mm
$\varphi$ – equivalent strain (deformation)

When compared to other testing methods, the hot-torsion test provides a sufficiently reliable information on the deformation resistance and deformability. It is particularly suited for simulating the hot working of metals and alloys with processes with prevailing tangential stresses.

## 3 DEFORMABILITY, EXPERIMENTAL RESULTS AND COMMENTS

The investigation was carried out on several heat-treatment steels of the type and chemical composition given in **table 1**.

**Table 1:** Chemical compositions of the investigated steels
**Tabela 1:** Kemijska sestava jekel

| | Steel | C /% | Si /% | Mn /% | Cr /% | Ni /% | Mo /% | V /% | Al/% |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 41CrAlMo7 | 0.37 | 0.42 | 0.42 | 1.49 | 0.28 | 0.20 | 0.01 | 1.05 |
| 2 | 35NCD16 | 0.38 | 0.28 | 0.45 | 1.83 | 3.55 | 0.37 | 0.017 | |
| 3 | 32CrMo12 | 0.26 | 0.30 | 0.51 | 3.12 | 0.03 | 0.46 | 0.02 | |
| 4 | 43CrMo4 | 0.45 | 0.29 | 0.68 | 1.02 | 0.09 | 0.18 | 0.01 | |
| 5 | 13CrMo44 | 0.18 | 0.29 | 0.55 | 0.89 | 0.06 | 0.53 | 0.02 | |
| 6 | N80 | 0.35 | 0.30 | 1.32 | 0.09 | 0.06 | 0.022 | 0.16 | |

**Table 2:** Number of revolutions to fracture and flow stress
**Tabela 2:** Število vrtljajev do zloma in meja tečenja

| *T* /°C | Number of revolutions to fracture | | | | | |
|---|---|---|---|---|---|---|
| | 41CrAlMo7 | 35NCD16 | 32CrMo12 | 43CrMo4 | 13CrMo44 | N80 |
| 800 | 10 | 18 | 13 | 14 | 11 | 9.2 |
| 850 | 16 | 20 | 9.8 | 16 | 10 | 9 |
| 900 | 26 | 26 | 9.6 | 22 | 14 | 12 |
| 950 | 30 | 33 | 16 | 36 | 18 | 17 |
| 1000 | 35 | 38 | 15 | 41 | 23 | 22 |
| 1050 | 58 | 46 | 27 | 74 | 26 | 23 |
| 1100 | 70 | 60 | 33 | 83 | 30 | 30 |
| 1150 | 82 | 61 | 54 | 77 | 39 | 38 |
| 1200 | 98 | 63 | 38 | 69 | 48 | 44 |
| 1250 | | 58 | 15 | 65 | 54 | 39 |

| *T* /°C | Flow stress /MPa | | | | | |
|---|---|---|---|---|---|---|
| | 41CrAlMo7 | 35NCD16 | 32CrMo12 | 43CrMo4 | 13CrMo44 | N80 |
| 800 | 201 | 240 | 213 | 257 | 201 | 208 |
| 850 | 156 | 210 | 207 | 190 | 192 | 180 |
| 900 | 126 | 171 | 171 | 177 | 152 | 144 |
| 950 | 105 | 132 | 129 | 122 | 130 | 98 |
| 1000 | 93 | 114 | 105 | 116 | 94 | 79 |
| 1050 | 75 | 102 | 79.5 | 86 | 78 | 67 |
| 1100 | 57 | 75 | 55.8 | 80 | 67 | 55 |
| 1150 | 46.5 | 66 | 34.5 | 73 | 57 | 42 |
| 1200 | 45 | 48 | 30 | 61 | 47 | 35 |
| 1250 | | 42 | 28.5 | 39 | 39 | 31 |

The torsion tests were performed with a TC-01 Adamel Lhomargy plastometer on tubular test specimens with dimensions $\phi = 6$ mm × 32 mm at the revolving frequency of the drive shaft of $N = 100$ r min$^{-1}$, which is equivalent to a deformation rate of 1 s$^{-1}$. The test temperature was in the range 800–1250 °C, with tests in steps of 50 °C.

The obtained results are shown in **figures 1 to 6** as a dependence on the number of revolutions to fracture, termed as the deformability and the equivalent flow stress calculated from the resistance to deformation according to the equations 1.

For all steels the flow stress decreases continuously from the lowest test temperature to the highest test temperature. The number of revolutions increases from the lowest to the highest temperatures continuously only for two steels, steels 1 and 5 (**figures 1 and 5**), while for all others the stress and the maximum number of revolutions, and accordingly also the higher deformability, was achieved at a critical temperature that is different for each of the steels. The maximum deformability is different for the different steels, it ranges between 98 revolutions to fracture for steel 1 at 1200 °C and 44 revolutions to fracture for steel 6 at 1200 °C. The strong dependence on the chemical composition and the microstructure is evidenced by the fact that the second largest deformability of 83 revolutions to fracture is observed for steel 3 at 1100 °C.

For the steel 2 (**Figure 2**) the number of revolutions $n$/r to fracture increases gradually up to 1100 °C and remains virtually constant with a further increase of the test temperature up to 1250 °C. For the steel 3, the deformability changes little up to 1000 °C (**figure 3**), it then increases quickly up to a temperature of 1150 °C, and drops very quickly with a further temperature increase to 1250 °C. The deformability at 1250 °C is

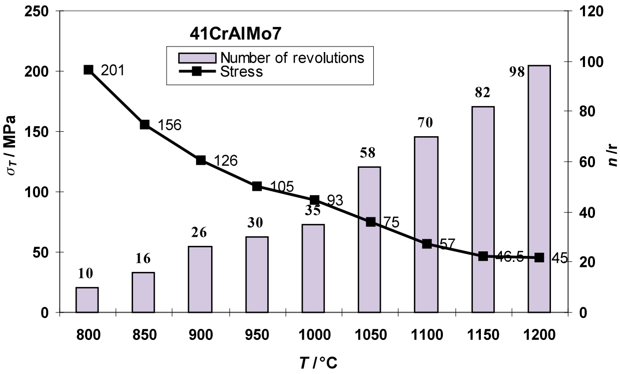


**Figure 1:** Flow stress $\sigma_T$ and number of revolutions $n$ to fracture for the steel 1 (41CrAlMo7)

**Slika 1:** Meja tečenja $\sigma_T$ in število vrtljajev $n$ do zloma za jeklo 1 (41CrAlMo7)

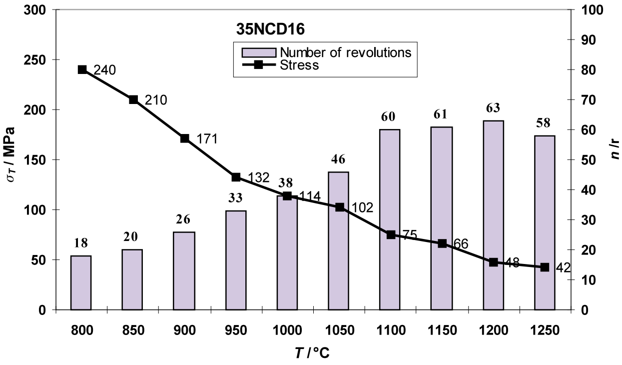


**Figure 2:** Flow stress $\sigma_T$ and number of revolutions $n$ to fracture for steel 2 (35NCD16)

**Slika 2:** Meja tečenja $\sigma_T$ in število vrtljajev $n$ do zloma za jeklo 2 (35NCD16)

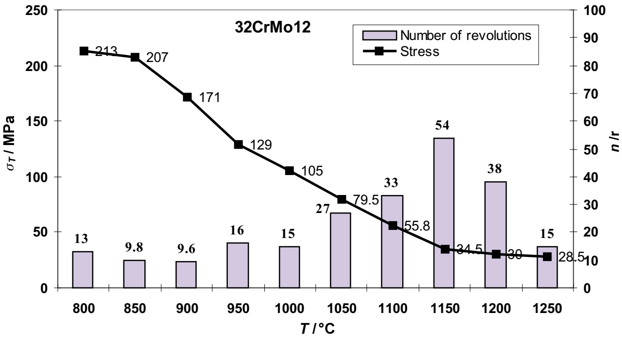


**Figure 3:** Flow stress $\sigma_T$ and number of revolutions $n$ to fracture for steel 3 (32CrMo12)

**Slika 3:** Meja tečenja $\sigma_T$ in število vrtljajev $n$ do zloma za jeklo 3 (32CrMo12)

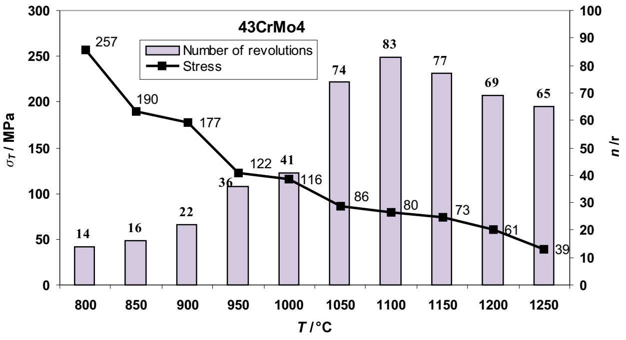


**Figure 4:** Flow stress $\sigma_T$ and number of revolutions $n$ to fracture for steel 4 (43CrMo4)

**Slika 4:** Meja tečenja $\sigma_T$ in število vrtljajev $n$ do zloma za jeklo 4 (43CrMo4)

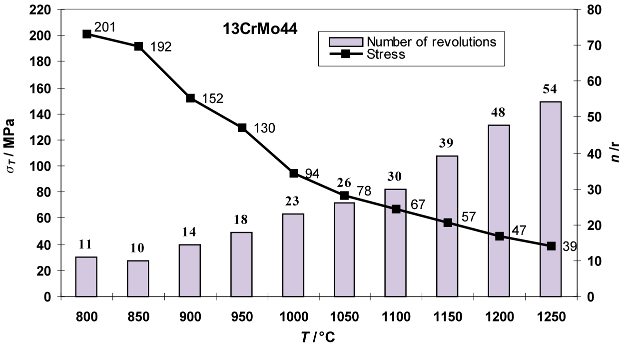


**Figure 5:** Flow stress $\sigma_T$ and number of revolutions $n$ to fracture for steel 5 (13CrMo44)

**Slika 5:** Meja tečenja $\sigma_T$ in število vrtljajev $n$ do zloma za jeklo 5 (13CrMo44)

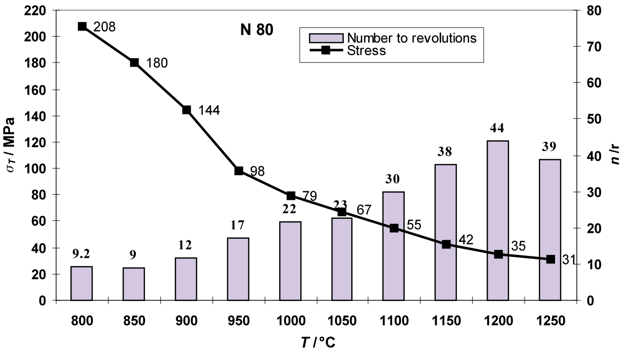


**Figure 6:** Flow stress $\sigma_T$ and number of revolutions $n$ to fracture for steel 6 (N80)

**Slika 6:** Meja tečenja $\sigma_T$ in število vrtljajev $n$ do zloma za jeklo 6 (N80)

approximately equal to that at 800 °C, although the flow stress is a few times lower.

The number of revolutions to fracture increases for steel 4 gradually up to 1100 °C (**figure 4**) and then it drops gradually and slowly with a further increase of the temperature. The effect of the temperature on the deformability is similar for the steel 6 (**figure 6**), only the maximum number of revolutions to fracture is achieved at the higher temperature of 1200 °C.

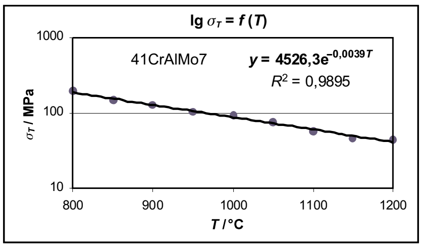
The number of revolutions to fracture, which is a measure of the steel's deformability, depends on the steel's chemical composition and on the steel's microstructure at the test temperature. By increasing the temperature above 900 °C, coarsening of the austenite grains occurs and some carbide precipitates are dissolved in the austenite. The solution temperature depends on the carbide type. It is below 950 °C for cementite (iron carbide $Fe_3C$), while the solution temperature is much higher for steels containing chromium. In these steels, carbides of the type $M_{23}C_6$ can form by solidification[15]. At every temperature the specimen is isothermally maintained at the test temperature for 10 min. It is evident, therefore, that the initial grain size is greater at a higher temperature and, since the number of revolutions to fracture increases at least to a critical level for all tested steels, it is clear that the initial austenite grain size does not affect the steel's deformability. Also, the microstructure which is produced at a higher temperature as a result of dynamic softening processes does not impair the deformability. It seems, therefore, justified to attribute the decrease in the number of revolutions above a critical temperature for some steels to the formation of a new phase. The new phase is, as it will be shown later, virtually without effect on the flow stress, indicating that its share in the microstructure is very small. It is assumed, thus, that it appears at the grain boundaries while the specimen is maintained at the test temperature and before the deformation begins. The presence of a liquid eutectic phase on the grains' surface would diminish their cohesive force and lead to fracture at a lower number of revolutions. The comparison of the critical temperature level indicates that the two active elements are carbon and chromium. The critical temperature is lower when the sum (% C + % Cr) is higher. Already, a small difference in the steel chemistry leads to the formation of the liquid phase and the comparison of the composition of steels 1 and 4 indicates that the role of carbon is stronger than that of chromium. On the other hand, the comparison of steels 1 and 6 shows that the effect of manganese is similar to that of chromium.

## 4 FLOW STRESS

The flow stress decreases monotonously when increasing the test temperature up to the maximum tested level, and it is independent of the effect of temperature on the deformability. This confirms that the share of the new phase, which impairs the deformability, was too small to visibly affect the flow stress.

Whenever possible, it is useful to deduce a functional description of the observed process based on a mathematical analysis of the experimental results. These results for flow stress were processed by regression analysis to approximate the empirical dependence of flow stress on test temperature to the exponential function [2-9]:

$$\sigma_T(T) = \sigma_0 A_1 \exp(-mT/1000) \qquad (2)$$



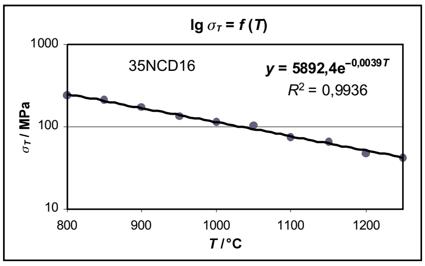


**Figure 7:** The dependence of flow stress $\sigma_T$ on test temperature $\sigma_T = f(T)$ for two steels processed with regression analysis to approximate the exponential function

**Slika 7:** Meja tečenja $\sigma_T$ v odvisnosti od temperature torzije $\sigma_T = f(T)$ za dve jekli obdelana z regresijsko analizo zaradi približka eksponentni odvisnosti

For the steels 1 and 2 the obtained relationships for flow stress and test temperature are shown in **figure 7**.

In **table 3** both constants *A* and *m* and the correlation coefficient r derived from test results are given for all the tested steels, and in **table 4** the numerical equations derived for all the tested steels are shown. The comparison of the effect of temperature on the flow stress is easier on the basis of the values given in **table 2**.

**Table 3:** Values of the constant *A*, exponent *m*, and correlation coefficient *r*

**Tabela 3:** Vrednosti za konstanto *A*, eksponent *m* in koeficient korelacije *r*

| Steel | constant *A* | exponent *m* | correlation coefficient *r* |
|---|---|---|---|
| 41CrAlMo7 | 4526.3 | -3.90 | 0.99 |
| 35NCD16 | 5892.4 | -3.92 | 0.99 |
| 32CrMo12 | 15848 | -5.13 | 0.97 |
| 43CrMo4 | 6443.3 | -4.09 | 0.99 |
| 13CrMo44 | 8372.2 | -4.47 | 0.98 |
| N80 | 7423.9 | -4.37 | 0.99 |

**Table 4:** Numerical relation for the dependence of flow stress on temperature $\sigma_T = f(T)$

**Tabela 4:** Analitična odvisnost meja tečenja – temperatura deformacije $\sigma_T = f(T)$

| Steel | The dependence of flow stress on the temperature $T$ /°C<br>$\sigma_T(T) = \sigma_0 A_1 \exp(-mT/1000)$ /MPa |
|---|---|
| 41CrAlMo7 | $\sigma_T = 91.6 \cdot 49.48 \exp(-3.90\ T/1000)$ |
| 35NCD16 | $\sigma_T = 116.4 \cdot 50.62 \exp(-3.92\ T/1000)$ |
| 32CrMo12 | $\sigma_T = 96.8 \cdot 163.7 \exp(-4.09\ T/1000)$ |
| 43CrMo4 | $\sigma_T = 107.9 \cdot 59.69 \exp(-4.09\ T/1000)$ |
| 13CrMo44 | $\sigma_T = 95.3 \cdot 79.07 \exp(-4.47\ T/1000)$ |
| N80 | $\sigma_T = 93.8 \cdot 87.82 \exp(-4.37\ T/1000)$ |

The deduced numerical relations can be used for calculation of the flow stress of steel and for mathematical models relating the effect of steel composition and its hot workability.

## 5 CONCLUSIONS

Based on the processing of information found in the quoted references and the results of this investigation the following conclusions were formulated:

- It is confirmed that by increasing the temperature the steel's resistance to deformation rsp. the low stress is continuously decreased up to the maximum test temperature of 1250°C, while the number of revolutions to fracture, which is a measure of the deformability of the steel, is increased up to the maximum test temperature for only two of the six tested steels. For the other steels the number of revolutions to fracture increased up to a critical temperature and decreased by further increasing of temperature;
- The chemical composition has a limited effect on the flow stress, while it affects strongly the number revolutions to fracture and confirms that the steel's hot workability is related strongly to the chemical composition;
- The increased austenite grain size does not affect the flow stress and the number of revolutions to fracture. This indicates that the dynamic softening processes are not affected by the austenite grain size;
- The critical temperature of the maximum number of revolutions to fracture depends on the carbon and chromium contents in the steel. By increasing the content of both elements, the number of revolutions is decreased. Manganese has a similar effect as chromium;
- Considering the findings in this investigation it is assumed that the deformability is decreased above a critical temperature because of the formation in the steel of a new phase, which weakens the cohesive force between the austenite grains. Based on the fact, that the critical temperature is lowered by a higher content of carbon and chrome, it is assumed that this phase is a liquid eutectic carbide phase – austenite. This phase is already formed during the isothermal holding of the specimens before the deformation. Based on the fact that the new phase has no effect on the flow stress, it is assumed that it is formed in a very small quantity, that it does not affect the dynamic softening phenomena, it does, however, lower the steel's deformability and hot workability.
- A numerical equation relating the flow stress to the test temperature was deduced from the experimental findings for all the tested steels by regression analysis.

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