Abstract
The paper presents the results of comparison of hot torsion and hot compression tests of austenitic Cr-Ni steel obtained on modern testing machines. An influence of the method and deformation conditions on flow stress and strain values is shown. A possibility of keeping the defined temperature and strain rate at a constant level is analysed. Occurrence of inhomogeneity of strain in the compressed specimens is presented by calculating the barrelling index and investigating the structure distribution and microhardness.

1. INTRODUCTION
The basis for an analysis of hot metal forming processes is plastometric research which, inter alia, allows to define the dependence of flow stress on deformation conditions, taking into account their variability in time. The research should reproduce to a large extent the real conditions of technological processes as well as facilitate the observation of changes taking place in the material structure during deformation.

The methodology of defining the flow stress is undergoing continuous evolution [1-5]. This is caused by the development of both knowledge of plastic strain conditions and technology, which enables modernisation of test stands. Progress in computer science and electronics makes modern machines for plastometric tests be equipped with more and more perfect computer control systems, data acquisition systems and programmes for analysis and data processing [6].

Among the methods of plastometric research, torsion and compression tests are the ones that are most often used [7,8]. Torsion is carried out mainly on Setaram (France) torsion plastometers. In compression tests deformation dilatometers of Bähr Gerätebau GmbH (Germany) and Gleeble testing machines produced by Dynamic Systems Inc. (USA) are used. The application of different methods and testing machines when plastometric research is not subject to any normalization may cause the obtained results to be diverse. In the paper an attempt is made to estimate the influence of the above mentioned methods and machines on flow stress values, on the example of test results of austenitic chromium and nickel steel. The studies were carried out in research centres of the plants: Vitkovice S.A. (Czech Republic), Krupp-Thyssen Stahl A.G. (Duisburg, Germany), Dynamic Systems Inc. (Poestenkill, USA) and in the Institute for Ferrous Metallurgy – IMŻ (Gliwice, Poland).
2. PROGRAMME AND METHODOLOGY OF RESEARCH

The plastometric tests were carried out on specimens made of 0H18N9 steel of chemical constitution given in table 1.

Table 1.
Chemical constitution of investigated steel [%]:

<table>
<thead>
<tr>
<th>C</th>
<th>Cr</th>
<th>Ni</th>
<th>Mn</th>
<th>Mo</th>
<th>W</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Al</th>
<th>V</th>
<th>Ti,Nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,028</td>
<td>18,40</td>
<td>8,90</td>
<td>0,187</td>
<td>0,27</td>
<td>0,16</td>
<td>0,036</td>
<td>0,012</td>
<td>0,10</td>
<td>0,027</td>
<td>0,01</td>
<td>0,01</td>
</tr>
</tbody>
</table>

Before beginning the tests the specimens were subjected to solution treatment from a temperature of 1200°C and to soaking for 60 minutes, with cooling in water. The way of heating the specimens before deformation and the deformation parameters applied are presented in table 2.

Table 2.
Deformation parameters and the way of heating specimens

<table>
<thead>
<tr>
<th>No.</th>
<th>Deformation temperature $T_0$ [°C]</th>
<th>Strain rate $\varepsilon$ [s$^{-1}$]</th>
<th>Way of heating specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>900</td>
<td>0,04</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>900</td>
<td>2,5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1100</td>
<td>0,04</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1100</td>
<td>2,5</td>
<td></td>
</tr>
</tbody>
</table>

2.1 Torsion tests

Hot torsion was performed on a Setaram torsion plastometer in Vitkovice S.A. plant. Specimens with a radius $R = 3$ mm and length in the measured part $L = 10$ mm (during torsion at strain rate $\varepsilon = 2,5$ s$^{-1}$) and $L = 50$ mm (when $\varepsilon = 0,04$ s$^{-1}$) were used. The values of torque $M$ [Nm], axial force $F$ [N], number of twists $N$ [revolution], torsion speed $\dot{N}$ [rpm] and temperature $T$ [°C] as a function of time $t$ [s] were registered.

Basing on the registered results the values of flow stress $\sigma_p$ [MPa], equivalent strain $\varepsilon$ corresponding to them and real strain rate $\dot{\varepsilon}$ [s$^{-1}$] were determined. The following relations were used:

$$
\varepsilon = \frac{2}{\sqrt{3}} \cdot arcsinh \left( \frac{2\pi RN}{3L} \right),
$$

$$
\dot{\varepsilon} = \frac{\partial \varepsilon}{\partial t},
$$
and

\[ \sigma_p = \sqrt{\frac{\sqrt{3} M}{2 \pi R^2}} \cdot (3 + p + m)^2 + \left( \frac{F}{\pi R^2} \right)^2, \]  

(3)

where:

- \( p \) – parameter depicting stress sensitivity to the strain:

\[ p = \frac{N}{M} \frac{\partial M}{\partial N}, \]  

(4)

- \( m \) – parameter depicting stress sensitivity to the strain rate:

\[ m = \frac{\dot{N}}{M} \frac{\partial M}{\partial \dot{N}}. \]  

(5)

2.2 Compression tests

Hot compression tests were carried out in three research centres: IMŻ, Krupp-Thyssen Stahl A.G. and Dynamic Systems Inc.

In IMŻ the research was carried out on a deformation dilatometer of DIL 805D type of Bähr Gerätebau GmbH. The controlling programme was able to define only deformation rate (speed of punch shift), the maximum value of which was 20 mm/s. In order to approach the assumed strain rate the following shaping speed was applied: 0.3 mm/s, which corresponds to an average strain rate \( \dot{\varepsilon} = 0.04 \text{ s}^{-1} \) and 20 mm/s, which corresponds to \( \dot{\varepsilon} = 2.5 \text{ s}^{-1} \).

Cylindrical specimens of initial dimensions: height \( h_0 = 10 \text{ mm} \) and diameter \( d_0 = 5 \text{ mm} \), were used for the tests.

In Krupp-Thyssen Stahl A.G. the research was performed on a modernised deformation dilatometer of Bähr Gerätebau GmbH allowing to obtain a strain rate of up to 30 s\(^{-1}\). Cylindrical specimens of initial dimensions: \( h_0 = 9 \text{ mm} \) and \( d_0 = 5 \text{ mm} \) were used. In order to decrease friction and ensure a uniform distribution of temperature throughout the specimen volume, molybdenum spacers were placed on the butting faces of the specimen.

In Dynamic Systems Inc. (DSI) hot compression was carried out by means of Gleeble testing machine equipped with a Hydrawedge hot deformation simulator. Cylindrical specimens of initial dimensions: \( h_0 = 15 \text{ mm} \) and \( d_0 = 12 \) were used. For the purpose of ensuring suitable current flow during resistance heating and decreasing friction on the contact surfaces of specimens with anvils spacers made of graphitoidal film with an additive of modifiers were used.

During the compression tests the values of formation force \( F \) [N], temperature \( T \) [°C] and instantaneous specimen height \( h \) [mm] in the function of time \( t \) [s] were registered. The dependence of average unit pressure \( p_m \) [MPa] on strain \( \varepsilon \) was determined on the basis of the formulas:

\[ p_m = \frac{4Fh}{\pi d_0^2 h_0} \]  

(6)

and

\[ \varepsilon = \ln \frac{h_0}{h}. \]  

(7)
In order to define inhomogeneity of strain, barrelling indexes were calculated in compression tests as a relation of bulge volume $V_b$ to total volume $V$ [7]:

$$\Lambda = \frac{V_b}{V} = 1 - \left(\frac{d_s}{d_0}\right)^2 \cdot (1 - \varepsilon_h),$$

where:

- $d_s$ – diameter of a butting face of specimen after deformation [mm],
- $\varepsilon_h$ – relative strain.

3. TEST RESULTS

In order to make a comparative analysis easier, the results of tests carried out on different machines were juxtaposed on common diagrams.

A comparison of temperature changes during deformation of specimens on different machines is shown in fig. 1. Both the results of torsion tests and those of compression tests show an increment of specimens temperature during deformation at a rate of 2.5 s$^{-1}$, the increment being lower at a lower temperature. The biggest increment of specimen temperature was noted on a deformation dilatometer in IMŻ: by $9^\circ$C (at the initial test temperature $T_0 = 1100^\circ$C) and by $36^\circ$C (at $T_0 = 900^\circ$C). Oscillatory courses of the temperatures of twisted specimens probably result from the way of taking measurements (stationary pyrometer registers the temperature from different spots of the revolting specimen).

![Fig. 1. Changes of specimens temperature during torsion and compression tests.](image-url)
A possibility of maintaining constant strain rate on particular machines is presented in fig. 2. The results obtained indicate that constant strain rate is maintained during compression tests on Gleeble machine and on the deformation dilatometer of Krupp-Thyssen Stahl A.G. In the compression tests performed in IMŻ there is only a possibility of maintaining constant deformation rate, which causes an increase of the strain rate. The decrease of strain rate in torsion tests is a result of an out-of-proportion strain increment at a defined constant twist rate [3,4].

![Course of strain rate changes in torsion and compression tests.](image)

In the case of all specimens subjected to compression a bulge of flanks was observed caused by friction on the contact surfaces of the specimens with anvils. Diversity of structure and microhardness in the marked spots on the specimen section presented in fig. 3 acknowledges inhomogeneity of strain in compression tests. The calculated barrelling indexes of specimens (Table 3) show that the application of spacers does not eliminate inhomogeneity of strain in hot compression tests but it has an influence on decreasing inhomogeneity. Regardless of the deformation parameters applied, the barrelling index of specimens compressed on a deformation dilatometer in Krupp-Thyssen Stahl as well as on Gleeble is approximately 20%. The specimens compressed on a deformation dilatometer in IMŻ without any measures eliminating friction are characterized by a barrelling index exceeding 30%.
Fig. 3. Images of structure and microhardness in the marked spots of compressed specimen (deformation dilatometer, IMŻ, $T = 900^\circ$C, $\dot{\varepsilon} = 2,5$ s$^{-1}$, $\varepsilon = 0,7$, magnification 160×)

Table 3.
Values of the barrelling index $\Lambda$ [%] of specimens subjected to hot compression.

<table>
<thead>
<tr>
<th>Deformation parameters</th>
<th>Institute for Ferrous Metallurgy (IMŻ)</th>
<th>Krupp-Thyssen Stahl AG</th>
<th>Dynamic Systems Inc. (DSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>900°C / 0,04 s$^{-1}$</td>
<td>30,4 %</td>
<td>21,0 %</td>
<td>20,1 %</td>
</tr>
<tr>
<td>900°C / 2,50 s$^{-1}$</td>
<td>30,8 %</td>
<td>20,2 %</td>
<td>19,4 %</td>
</tr>
<tr>
<td>1100°C / 0,04 s$^{-1}$</td>
<td>31,0 %</td>
<td>20,5 %</td>
<td>20,2 %</td>
</tr>
<tr>
<td>1100°C / 2,50 s$^{-1}$</td>
<td>32,0 %</td>
<td>22,3 %</td>
<td>19,1 %</td>
</tr>
</tbody>
</table>

The decrease of inhomogeneity of strain on the section of the compressed specimens has a considerable influence on the course of the stress-strain curves, in particular at a lower deformation temperature (Fig. 4). At a temperature of 900°C the values of average unit pressure from compression tests carried out on a deformation dilatometer in IMŻ are much higher than the values of flow stress from torsion tests and the difference is close to 60 MPa. The results of the compression tests in which spacers limiting friction were used show smaller differences in relation to the results from torsion tests.
Fig. 4. Comparison of relation $\sigma_p = f(\varepsilon)$ from torsion tests and $p = f(\varepsilon)$ from compression tests.

4. CONCLUSIONS

- The plastometric research of austenitic chromium and nickel steel has acknowledged a significant influence of the research method and the type of testing machine on the obtained dependence of flow stress on strain, strain rate and temperature.
- The values of average unit pressure obtained in hot compression tests are higher than the values of flow stress determined in torsion tests. This results from the impossibility of eliminating friction on contact surfaces of the compressed specimen with shaping tools. The difference in results is smaller at higher temperatures of testing and with the application of molybdenum or graphitoidal spacers.
- High inhomogeneity of strain in hot compression tests is confirmed both by barrelling measurements and by the diversity of structure and microhardness on the specimen’s cross-section. The barrelling index of specimens does not depend on the deformation parameters applied.
- When carrying out compression and torsion tests at a strain rate of about 2.5 s$^{-1}$, the real specimens temperatures do not correspond with the values defined. This means that the applied systems of specimens heating are not able to correct the thermal effect caused by the work of plastic strain.
- In the compression and torsion tests carried out on a deformation dilatometer in the IMŻ constant strain rate is not maintained. This results, in the case of torsion tests, from the assumed calculation methodology, whereas in compression tests – from maintaining constant deformation rate.

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REFERENCES