HEAT-RESISTANT STEELS AND ALLOYS

EFFECT OF DEFORMATION FOLLOWED BY TEMPERING ON
THE MECHANICAL PROPERTIES OF STEEL 15Kh1MF

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Currently there is only limited and contradictory information about the effect of plastic deformation and post-deformation tempering on the heat-resistance properties of thermally stable Cr--Mo--V-steels used in the manufacture of power-generating-equipment elements [1-4]. We have studied the effect of cold plastic deformation followed by high-temperature tempering on the mechanical properties of steel 15Kh1MF with short-term and prolonged tests over a wide temperature range. This study was carried out on pipeline metal in two structural states: I) ferrite with carbides precipitated from it and a small amount (5-10%) of granular bainite; II) granular bainite.

Blanks were deformed using uniaxial extension by 10 ± 1%. According to current technology, cold-deformed pipe is submitted to tempering at 700-750°C for 1 h. Two tempering schedules were selected whose temperature and duration are determined by the lower and upper boundaries of the recommended treatment: at 710°C for 1 h and at 750°C for 5 h. In addition, some of the blanks after deformation were subjected to soaking for 5 h at 780°C. This treatment was carried out with the aim of determining the effect of a little overheating above the Ac³ point (770°C) on the mechanical properties of specimens.

Cold plastic deformation to 10%, causing a marked increase in dislocation density and the width of interference lines β(111)α and β(211)α', leads to a marked increase in strength and reduction in plastic properties for the steel in both of the test structural states (see Table 1). Simultaneously there is a sharp reduction in impact strength, and this is most severe for steel with a ferrite-carbide structure. It should be noted that this change in mechanical properties with plastic deformation is more significant with a lower original material strength.

Post-deformation tempering at 710°C leads to a reduction in strength and to an increase in ductile characteristics to values close to those for the original undeformed material. However, the yield point is quite high, particularly for a ferrite-carbide structure. This may be caused by partial retention of cold work during tempering, and this is indicated by the results of electron microscope and x-ray analysis.

Heating of deformed steel with a bainitic structure above Ac³ (in the intercritical range) leads to formation of austenite along grain boundaries (10-15%), which during subsequent cooling undergoes bainite-martensite transformation. Steel with this structure has an increased ultimate strength and a somewhat lower impact strength.

The temperature dependence of mechanical properties with short-term tests for original and deformed metal is similar to that described in [5], and it indicates that over the whole test temperature range, in deformed metal strength properties are retained at a higher level, and ductility properties at a lower level, compared with the undeformed state. The properties of tempered metal have intermediate values (Fig. 1).

Stress-rupture tests on steel 15Kh1MF in various original and deformed states were carried out with uniaxial tension, with a constant load in the temperature range 560-630°C, and at stresses from 60 to 240 MPa. Results of the tests are given in Figs. 2, 3. In all test cases metal stress-rupture strength was placed along regression lines whose position was determined in a computer by the least-squares method. The correctness of the rectilinear relationships is confirmed by the high values of the correlation coefficient, i.e., more than 0.95% [sic].

### TABLE 1

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Width of lines $\beta$ $10^{-6}$ rad</th>
<th>Dislocation density, m$^{-3}$</th>
<th>$\sigma_0$</th>
<th>$\sigma_{0,2}$</th>
<th>$\delta$</th>
<th>$\psi$</th>
<th>$\sigma_n$, MPa</th>
<th>$a_n$, MJ/m$^2$</th>
<th>HRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(110)$_\beta$</td>
<td>(211)$_\alpha$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original (without deformation)</td>
<td>2,5/3,6</td>
<td>6,4/14,1</td>
<td>4,1 $10^{14}$/---</td>
<td>520/660</td>
<td>270/500</td>
<td>29/24</td>
<td>76/74</td>
<td>0,24/0,15</td>
<td>03/93</td>
</tr>
<tr>
<td>Deformation by 10%</td>
<td>5,6/6,1</td>
<td>10,8/27,9</td>
<td>4,0 $10^{14}$/---</td>
<td>600/680</td>
<td>578/650</td>
<td>19/17,5</td>
<td>69/72</td>
<td>0,28/0,17</td>
<td>99/97</td>
</tr>
<tr>
<td>The same, 15%</td>
<td>3,2/4,4</td>
<td>10,1/19,4</td>
<td>1,9 $10^{14}$/---</td>
<td>550/650</td>
<td>380/550</td>
<td>20/22</td>
<td>75/</td>
<td>0,19/0,25</td>
<td>94/91</td>
</tr>
<tr>
<td>Deformation by 10% + tempering at 710 $^\circ$C for 1 h</td>
<td>---/4,6</td>
<td>---/14,1</td>
<td>---/---</td>
<td>---/---</td>
<td>---/---</td>
<td>---/---</td>
<td>---/---</td>
<td>---/---</td>
<td>---/---</td>
</tr>
<tr>
<td>Deformation by 10% + tempering at 750 $^\circ$C for 1 h</td>
<td>---/735</td>
<td>---/510</td>
<td>---/24</td>
<td>---/73</td>
<td>14/22</td>
<td>---/---</td>
<td>---/---</td>
<td>---/---</td>
<td>---/---</td>
</tr>
<tr>
<td>Deformation by 10% + heating at 780 $^\circ$C for 5 h</td>
<td>---/735</td>
<td>---/510</td>
<td>---/24</td>
<td>---/61</td>
<td>14/22</td>
<td>---/---</td>
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</table>

**Note.** The numerator gives data for specimens with a ferrite-carbide structure, and the denominator gives data for a bainite structure.

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**Fig. 1.** Mechanical properties of steel 15Kh1MIF with a bainitic structure in the original (solid lines) and deformed (broken lines) states.

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We now consider the effect of the degree of deformation on the heat-resistance properties of steel 15Kh1MIF in different structural states.

**Metal with a Ferrite–Carbide Structure.** Deformation with $\varepsilon = 10\%$ leads to an increase in stress-rupture strength of the metal (see Fig. 2). An increase in the degree of deformation to 15% has practically no effect on this property. It should be noted that the stability of original deformed metal, estimated by the tangent of the slope angle for stress-rupture straight lines, is similar in value. After tempering at 710$^\circ$C for 1 h the stress-rupture strength for deformed metal is reduced a little, but it does not reach values typical for the original state.

The long-term ductility of this metal in all test cases decreased with an increase in test base (Fig. 2). With short test bases prior deformation has no marked effect on ductility, and with long test bases the long-term ductility of deformed metal decreases more rapidly than for undeformed material. This reduction is more marked as the test base increases and the degree of prior deformation increases. Post-deformation tempering leads to an increase in long-term ductility to values close to that in the original state.*

**Metal with a Bainitic Structure.** Under the test conditions studied, stress-rupture strength and stability of deformed metal are mainly lower than for the original material (Fig. 3). Judging from the path of the straight lines, an increase in stress-rupture strength after cold plastic deformation may only be expected in short-term tests based on a few tens of hours or less, i.e., at high stresses. At low stresses the stress-rupture

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*Similar relationships were obtained for long-term relative reduction of area at failure.