STRUCTURAL STEELS

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EFFECT OF CARBON, CHROMIUM, AND NICKEL ON THE $\alpha \Rightarrow \gamma$ TRANSFORMATION AND PROPERTIES OF Cr – Ni – Mo – V STEELS

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The aim of the present investigation is to determine some regular features of alloying Cr – Ni – Mo – V steels for critical parts with allowance for the structure, hardenability, level of properties, and semibrittleness temperature. For this purpose the concentration of carbon in Cr – Ni – Mo – V steels was varied from 0.03 to 0.47%, chromium from 0 to 4%, and nickel from 0 to 5% at a constant concentration of the other elements (~0.5% Mo, 0.6% Mn, 0.25% Si, ~0.1% V, 0.015% S, 0.012% P), and the cooling rate from the austenitization temperature was varied from 25 to 1000°C/h.

The experiments were conducted on the basis of the second-order designs 3$^3$ and 3$^4$ (see Table I) [1, 2].

Twenty-seven test heats of Cr – Ni – Mo – V steels were studied. The metal was cast into 50-kg ingots forged in the temperature range of 900 – 1200°C to prepare forgings with a square cross section 20 x 20 mm in size and a length of 200 mm. The forgings were annealed at 850 – 950°C and tempered at 600 – 660°C for 12 h. The critical points of the steels were investigated by heating and cooling the specimens in a dilatometer of a Formastor system. The specimens were heated to the temperature of austenitization at a rate of 20°C/h and cooled at the rates presented in the Table 1. In order to determine the mechanical properties and the semibrittleness temperature the preforms were heat-treated on a special installation in accordance with the following regime:

<table>
<thead>
<tr>
<th>Factors of variation</th>
<th>$C$, %, $X_1$</th>
<th>Cr, %, $X_2$</th>
<th>Ni, %, $X_3$</th>
<th>$\log v$, %, $X_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper level (+ 1)</td>
<td>0.47</td>
<td>4.0</td>
<td>5.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Intermediate level (0)</td>
<td>0.25</td>
<td>2.0</td>
<td>2.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Lower level (- 1)</td>
<td>0.03</td>
<td>0.0</td>
<td>0.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Range of variation (1)</td>
<td>0.22</td>
<td>2.0</td>
<td>2.3</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Note. Three cooling rates $v$ were used in the experiments. For forgings with a diameter of 0.3, 1.0, and 2.0 m the rates were 1000°C/h (the lower level $\log v = 0.3$), 100°C/h (the zero level $\log v = 0.5$), and 25°C/h (the upper level $\log v = 0.7$), respectively.

The experimental results were processed using software for correlation and regression analyses (WANI-2200T).

Effect of alloying on the critical points $Ac_1$ and $Ac_3$ of heated Cr – Ni – Mo – V steels. On the basis of a statistical analysis and with allowance for the significance of the coefficients we obtained the following equations for calculating the critical points ($Ac_1$ and $Ac_3$) of heated steels as a function of the concentration of carbon [C], chromium [Cr], and nickel [Ni]:

$$\begin{align*}
\end{align*}$$

where $[C] = \frac{C - 0.25}{0.22}$; $[Cr] = \frac{Cr - 2}{2}$; $[Ni] = \frac{Ni - 2.5}{2.5}$.

Analysis of Eq. (1), which relates the temperature $Ac_1$ of steel to the concentrations of C, Cr, and Ni, shows that chromium hardly affects this critical point (it is not contained in the formula). A change in the carbon concentration from 0.03% to 0.25% decreases $Ac_1$ by about 50°C. As the carbon concentration is increased from 0.25% to 0.47%, the rate of the fall of $Ac_1$ decreases. As the nickel concentration is changed from 0 to 5%, the value of $Ac_1$ decreases gradually, on the average at a rate of 20°C for each 1% Ni. A certain joint effect of carbon and nickel on $Ac_1$ has been established.
Analysis of Eq. (2), which relates the temperature $A_c_1$ to the concentrations of C, Cr, and Ni, shows that this dependence is more complicated than that for $A_c_1$.

As the carbon concentration is increased from 0.03% to 0.25%, the temperature $A_c_1$ decreases by 160°C. With an increase in the nickel concentration from 0 to 5% $A_c_1$ decreases gradually (on the average by 10°C for each 1% Ni). We established that up to a 2% concentration chromium increases $A_c_1$, whereas at a chromium concentration exceeding 2% $A_c_1$ decreases (by 45°C for each 1% Cr).

It is of interesting to solve Eqs. (1) and (2) simultaneously under the condition that $A_c_1 = A_c_3$ and the concentrations of chromium and nickel are equal to zero. The system has two solutions, namely, the concentration of carbon can be 0 or 0.54%, which does not contradict concepts of metallurgy, for a base containing 0.5% Mo, 0.6% Mn, 0.1% V, and 0.25% Si.

Investigation of the effect of alloying on the critical points of Cr – Ni – Mo – V steels in cooling. On the basis of a statistical analysis and with allowance for the significance of the coefficients we obtained the following equations for calculating the critical points of steels in cooling as a function of the concentrations of carbon, chromium, and nickel and the cooling rate.

The temperature of the beginning of the pearlitic transformation is determined as

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$$

where $1/\log v = \frac{0.5}{0.2}$; $[C] = \frac{C - 0.25}{0.22}$; $[Cr] = \frac{Cr - 2}{2}$; $[Ni] = \frac{Ni - 2.5}{2.5}$.

An analysis of Eq. (3), which relates the temperature of the beginning of the pearlitic transformation in steel to the concentration of carbon, chromium, and nickel and the cooling rate from the austenitization temperature, has shown the following regular features. As the carbon concentration is increased from 0.03 to 0.25%, $Ar_{p_1}$ falls substantially (by about 100°C). As the concentration of nickel is increased from 0 to 2.5%, the temperature of the beginning of bainite transformation (by about 220°C) as its concentration is increased from 0.03 to 0.25%. With an increase in the concentration of chromium from 0 to 2% the temperature of the beginning of bainite decomposition decreases, and with its further increase to 4% it increases by about 110°C.

As the concentration of nickel is increased from 0 to 2.5%, the temperature of the beginning of bainite transformation gradually falls by 210°C, and when the nickel concentration is increased from 2.5 to 5%, the corresponding temperature falls by 140°C.

The cooling rate from the austenitization temperature also affects substantially the temperature of bainite decomposition. For example, as the cooling rate is increased from 25 to 100°C/h, $Ar_{p_1}$ decreases by 160°C, and as it is increased from 100 to 1000°C/h, $Ar_{p_1}$ decreases by about 100°C.

An analysis of Eqs. (3) and (4) shows that the effect of the alloying elements and the cooling rate from the austenitization temperature on the critical temperatures of decomposition of supercooled austenite is rather complex. The concentration dependences of the critical temperatures have minima, namely, $Ar_{p_1}$ has a minimum at 0.38% C and 2.0% Cr, and $Ar_{p_1}$ has a minimum at 0.37% C and 2.1% Cr. The presence of the minima indicates indirectly that chromium carbides do not dissolve completely at the accepted austenitization temperatures.

It should be noted that the suggested equations should be used quite carefully despite their statistical significance (the coefficients of multiple correlation are at least 0.75).

Based on the results obtained in our investigation of the effect of the carbon, chromium, and nickel concentrations and the cooling rates (1000, 100, and 25°C/h) on the level of the mechanical properties of the steels studied we constructed mathematical models.

Computations of the regression equations have shown that all the models are statistically significant (the coefficients of multiple correlation lie within 0.76 – 0.99).

As an example, we present in Fig. 1 dependences of the yield strength ($\sigma_{0.2}$) and the semibrittleness temperature ($T_g$) on the concentrations of carbon, chromium, and nickel in Cr – Ni – Mo – V steels and the cooling rates (1000, 100, and 25°C/h).

An analysis of the data presented in the figure shows that in the case of rapid cooling from the austenitization temperature (v$_{cool}$ = 1000°C/h) a constant level of the yield strength can be obtained by increasing the concentration of carbon and