STAINLESS STEELS

EFFECT OF ALLOYING ON THE MARTENSITIC TRANSFORMATION IN STAINLESS STEELS

A. P. Gulyaev, A. P. Shlyamnev, and N. A. Sorokina

One of the principal methods of increasing the strength of steel is to obtain a martensitic structure. The effect of alloying elements on the martensitic transformation in Fe-Ni steels has been investigated several times [1, 2, etc.]. However, the data on Fe-Cr and Fe-Cr-Ni stainless steels are inadequate.

We investigated the effect of cobalt, nickel, and molybdenum on the kinetics of the martensitic transformation in stainless steels containing 9 and 13% Cr.

Five series of maraging steels (< 0.02% C) were tested (Table 1).

The steels were melted in a 35-kg vacuum arc furnace and cast in two 17-kg ingots. The ingots were forged and rolled to bars 15 mm in diameter, from which samples were prepared. The kinetics of the martensitic transformation was investigated by means of the Akulov torque magnetometer by the method reported in [1].

Figure 1 shows the martensite curves for the experimental steels. The addition of cobalt to Fe-Ni steels raises $M_s$ and $M_f$ considerably* [1, 2], while cobalt lowers $M_s$ and $M_f$ somewhat (an average of 5-7°C for each 1% Co; see Figs. 1a and 2a) in steels with 13% Cr (series 1 in Table 1). Figure 2a shows that the reduction of $M_s$ and $M_f$ is linear: $M_s$ (°C) = 440 - (5-7) % Co. $M_f$ can be determined fairly accurately by the equation: $M_f$ (°C) = $M_s$ (°C) - (133-135).

Despite the fact that cobalt lowers $M_s$ in chromium steels, the amount of retained austenite was 10-15% (see Table 1) and remained practically unchanged at any of the cobalt concentrations investigated, which may be due to the fact that chromium (13%) has a stronger effect than cobalt as an austenite-forming element. Chromium lowers the stacking fault energy [3], and consequently the martensitic transformation occurs at a higher rate [4]. It is not excluded that the effect of cobalt in lowering $M_s$ and $M_f$ may increase at higher chromium concentrations.

We also investigated the Fe-9Cr and Fe-9Cr-14Co systems (series 2 and 3 in Table 1) alloyed with 4-12% Ni, and the Fe-13Cr-14Co system with 2-8% Ni (series 4).

The martensite curves and the positions of $M_s$ and $M_f$ for the first two series are shown in Fig. 1b and c, and Fig. 2b and c. It can be seen that the addition of 1% Ni to the Fe-9Cr steel lowers $M_s$ and $M_f$ by an average of 30°C; the variation is linear: $M_s$ (°C) = $a$ - $b$ · % Ni.

* $M_s$ was taken as the temperature at which 5% α phase was formed; $M_f$ was taken as the temperature corresponding to 95% α phase (of the total quantity which can be formed in the given steel).

Table 1

<table>
<thead>
<tr>
<th>Series No.</th>
<th>Alloying elements, %</th>
<th>Retained austenite at 20°C, %</th>
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<tr>
<td></td>
<td>Cr</td>
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Fig. 1. Martensite curves for steels of series 1 (a), 2 (b), 3 (c), and 5 (d).

Fig. 2. Effect of alloying elements on $A_S$, $M_S$, and $M_f$ of alloys from series 1 (a), 2 (b), 3 (c), and 5 (d).

However, the addition of 14% Co leads to a greater reduction of $M_S$ and $M_f$ (1% Ni lowers $M_S$ and $M_f$ by 40 and 50°, respectively), and the variation is close to quadratic: $y = ax^2 + b$.

Mathematical treatment of the results [5] showed that the lowering of $M_S$ in Fe-9Cr-14Co alloys with increasing nickel concentrations is in satisfactory agreement with the equation: $M_S$ (°C) = $-3.571 \cdot (\% \text{ Ni})^2 + 510$.

Thus, the combined effect of cobalt and nickel on lowering of $M_S$ and $M_f$ is much larger than each of them separately, and the lowering of the $\gamma \rightarrow \alpha$ transformation range is accompanied by a slight increase in the amount of retained austenite except for the Fe-9Cr-14Co steel with 11% Ni. After completion of the $\gamma \rightarrow \alpha$ transformation, about 30% austenite was retained in this steel (see Table 1).

As would be expected, raising the nickel concentration from 4 to 8% in Fe-13Cr-14Co steel leads to a greater reduction of $M_S$ and $M_f$. With around 6% Ni the martensitic transformation is completed at negative temperatures; with 8% the transformation is suppressed down to $-196^\circ$.

In connection with the fact that molybdenum in steels with a martensitic structure increases the toughness at low temperatures [6] and also induces precipitation hardening [7], it was expedient to study the effect of molybdenum on the kinetics of the martensitic transformation in Fe-9Cr-14Co-6Ni steels (series 5) and Fe-13Cr-14Co-6Ni steels. On cooling, the Fe-9Cr-14Co-6Ni steels undergo the martensitic transformation at temperatures from 350 to $-50^\circ$. The steel with 9.5% Mo is an exception, with no martensitic transformation down to the temperature of liquid nitrogen. The data shown in Figs. 1d and 2d indicate a sharp reduction of $M_S$ and $M_f$ with increasing amounts of molybdenum (close to $y = ax^2 + b$), the transformation occurring at a lower rate with increasing temperatures. All the Fe-13Cr-14Co-6Ni steels with molybdenum (2-10%) remained austenitic down to $-196^\circ$.

When the steels of series 1 are heated above 750°, and the others above 600-650°, the reverse $\alpha \rightarrow \gamma$ transformation occurs. In steels of series 3 with over 6% Ni and in series 5 the reverse $\alpha \rightarrow \gamma$ transformation can evidently occur partly by means of ordering. Tests of series 5 steels showed that when previously quenched samples are heated to temperatures near the completion of the reverse $\alpha \rightarrow \gamma$ transformation the subsequent $\gamma \rightarrow \alpha$ transformation, beginning at the same temperature, is greatly suppressed; in this case the amount of $\alpha$ phase does not exceed 20-25% of the initial value. This phenomenon may be an indirect confirmation of the fact that the reverse $\alpha \rightarrow \gamma$ transformation occurs in these steels by ordering with formation of "phase strain hardened" austenite after cooling [8]. It was reported in [7, 9] that molybdenum prevents the development of diffusion processes in these steels during heating, and thus promotes the $\alpha \rightarrow \gamma$ transformation by the martensitic mechanism.