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REGULAR CHANGES IN THE STRENGTH OF MARAGING STEELS UPON COMPLEX ALLOYING WITH COBALT, NICKEL, AND MOLYBDENUM

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INTRODUCTION

High-strength maraging steels are produced with various combinations of the base alloying elements, i.e., nickel, cobalt, and molybdenum [1 – 3]. The aim of the present work was to determine the optimum proportion of these elements that would provide a specified level of strength at a high resistance to brittle fracture.

METHODS OF STUDY

We studied experimental compositions of steels of the type 03N18K9M5 with 10 – 18% Ni, 2 – 6% Mo, and 3 – 21% Co with a total amount of 27 – 33%. The latter condition predetermined a reduced amount of cobalt with the corresponding increase in the content of nickel and molybdenum. The steels were molten in vacuum induction furnaces. The specimens for standard mechanical tests were heat treated by the following regime: quenching from 980°C for 30 min in water + aging at 480°C for 3 h + cooling in air. Cylindrical specimens 5 mm in diameter were tested for tensile strength with determination of the strength (σ_r, $\sigma_{0.2}$) and ductile (δ_5, ψ) characteristics; we also tested specimens with a circular notch with a radius of 0.1 mm and evaluated their σ_r^n. Then we determined the impact toughness *KCU* and *KCT* of the specimens.

The general rules of the complex influence of the alloying elements were determined by the method of mathematical design. The experiment was planned using a matrix obtained by cutting a three-dimensional simplex by planes that corresponded to the extreme values of the alloying range (Fig. 1). This provided a determinant of the information matrix (M) $\xi = 0.8 \times 10^{-5}$ at a variance of the values of the studied function $d_{max} = 18.5$, $d_{mean} = 8.5$, and $d_{min} = 4.8$ [4]. The results obtained were used to plot graphs on which we drew the same-level lines of the studied characteristics. The hatched areas on the graphs corresponded to constant values of the characteristics within a standard error determined by a computer program, and the domains between the curves corresponded to intermediate values.

RESULTS OF THE STUDY

As applied to the ultimate rupture strength σ_r (MPa) and yield strength $\sigma_{0.2}$ (MPa), we obtained the following regression equations:

$$\sigma_r = 1334 + 129.7\text{Mo} + 110.7\Sigma + 27.3\text{Mo}\Sigma; \quad (1)$$

$$\sigma_{0.2} = 1208 + 118.4\text{Mo} + 106.5\Sigma + 3.64\text{Mo} + 40.6\Sigma^2, \quad (2)$$

where Mo = (% Mo – 4)/2; Σ = (% Σ – 30)/3; % Σ = % Ni + % Mo + % Co.

Comparing the diagrams with different total contents of alloying elements (the difference was provided by changing the initial cobalt content), we established that with every 3% increase in the cobalt content the values of $\sigma_{0.2}$ and σ_r increased by 100 MPa. An increase in the nickel content (at a respective decrease in the cobalt one) did not change the strength characteristics (Fig. 2). However, with an increase in the concentration of molybdenum the alloys hardened, despite the simultaneous decline of the amount of cobalt. In this case, the strength characteristics increased by 25 – 30 MPa when the molybdenum content increased by 1% at a total content of the alloying elements of Σ = 27 – 30% and by 50 MPa at a total content of Σ = 33%.

The dependences of the ductility characteristics δ_5 (%) and ψ (%) on the content of the alloying elements are describable by the regression equations

$$\delta_5 = 15.6 - 0.41\text{Ni} - 0.74\text{Mo} - 1.12\Sigma + 0.48\text{Mo} \cdot \text{Ni}; \quad (3)$$

$$\psi = 64.7 - 2.57\text{Mo} - 1.93\Sigma + 3.84\text{Mo}^2 - 2.48\Sigma^2, \quad (4)$$

where Ni is (% Ni – 14)/4.

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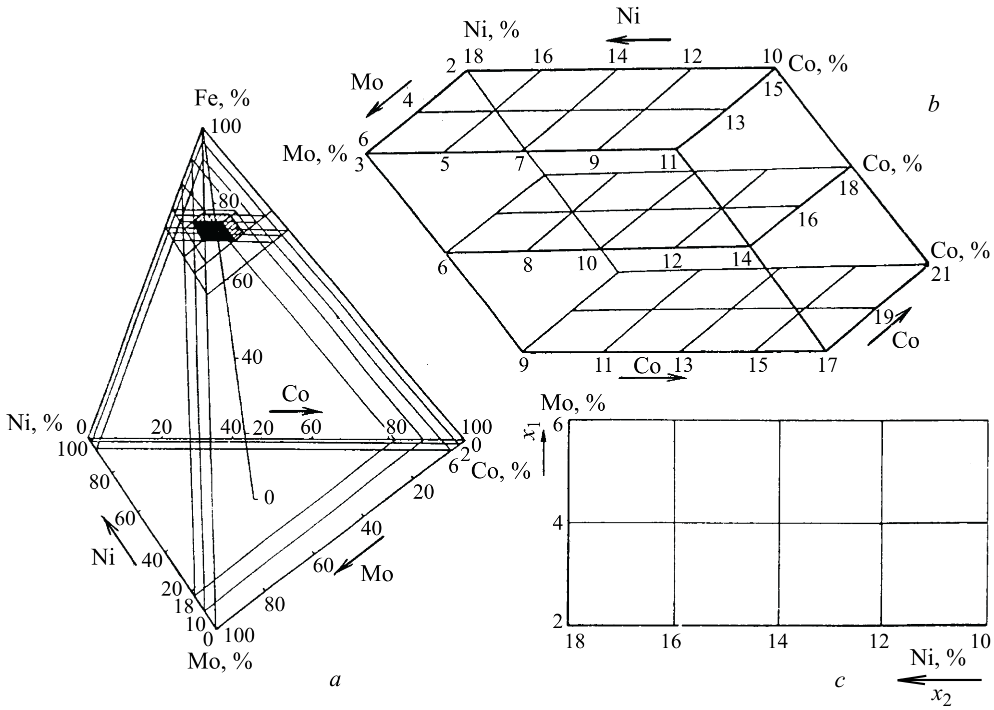

Fig. 1. Three-dimensional simplex with boundaries of the specified compositions (*a*), the investigated domain (*b*), and the plan of the experiment (*c*) for steels in the Ni – Co – Mo alloying system.

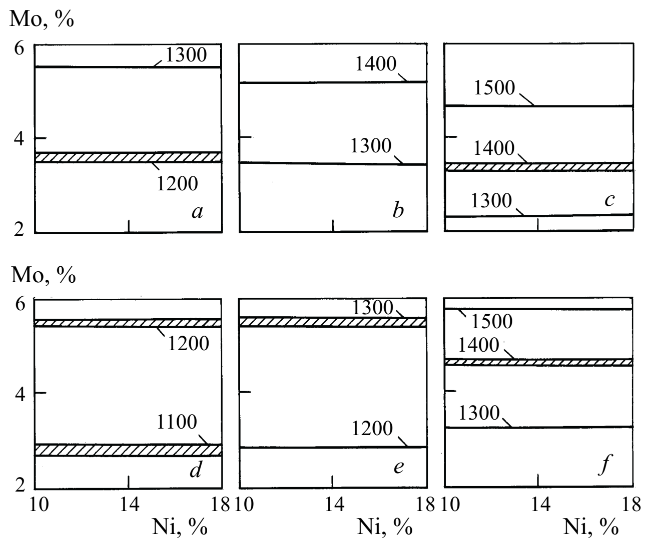

Fig. 2. Curves of the same levels of ultimate rupture strength σ_r ($a - c$) and yield strength $\sigma_{0.2}$ ($d - f$) of steels complexly alloyed with nickel, molybdenum, and cobalt in a total amount of 27% (*a*, *d*), 30% (*b*, *e*), and 33% (*c*, *f*) (the numbers at the curves present the values of σ_r and $\sigma_{0.2}$ in MPa).

It can be seen that δ and ψ change in opposite directions. Specifically, every 3% increase in the cobalt concentration decreases the elongation by 1%. As the nickel content increases from 10 to 18% with the respective decrease in the cobalt content, the elongation increases by 1 – 1.5% (Fig. 3*a* – *c*). The elevation of the molybdenum content by 4% compensated by the respective decrease in the cobalt content decreases the elongation by 0.5% at 10% Ni and by 1.5 – 2% at 18% Ni. It should be noted that the level of the elongation remains quite high ($\delta_5 \geq 14\%$), and its range does not exceed 4%. The relative reduction of area changes within a still narrower range (Fig. 3*d* – *f*) from 72 to 66% with the enhancement of the strength. These data show that maraging steels have a quite high level of ductility in a wide range of strength characteristics.

We obtained original dependences for the ultimate rupture strength σ_r^n (MPa) of notched specimens, which are describable by the following regression equations (for an adequate second-order model):

$$\sigma_r^n = 2150 - 250\text{Ni} + 175\text{Mo} + 50\Sigma - 90\text{NiMo} - 118\text{Ni}\Sigma + 59\text{Mo}\Sigma - 195\text{Ni}^2 - 149\Sigma^2.$$

As the total content of alloying elements increases, the strength of notched specimens increases, and so does the strength of intact specimens. The values of σ_r^n exceed those of σ_r, which indicates the ductile nature of the fracture (Fig. 4). It should be noted that the sensitivity of high-nickel and high-cobalt steels to the notch differs. For most high-cobalt steels (with 10% Ni), σ_r^n exceeds σ_r only somewhat; their proportion is 1.1 – 1.3. In steels with 18% Ni (with the corresponding decrease in the cobalt content), the proportion of σ_r^n / σ_r increases to 1.7.

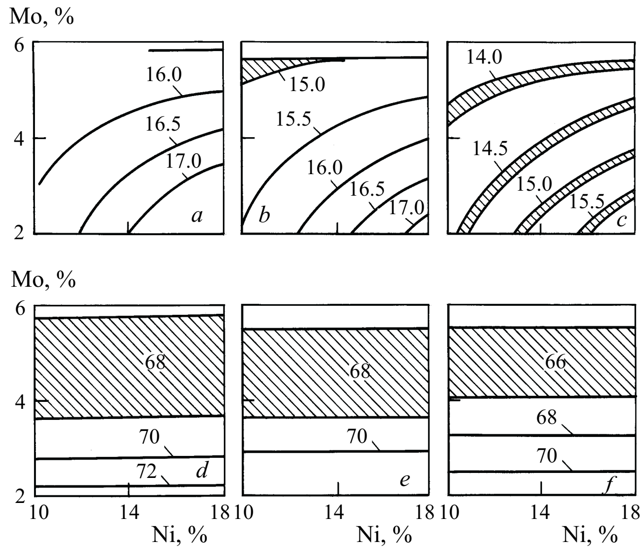

Fig. 3. Curves of the same levels of elongation δ_5 ($a - c$) and relative reduction of area ψ ($d - f$) in steels complexly alloyed with nickel, molybdenum, and cobalt in a total amount of 27% (a, d), 30% (b, e), and 33% (c, f) (the numbers at the curves present the values of δ_5 and ψ in %).

The impact toughness increases when their composition shifts towards high-nickel combinations, and its maximum values are attained when molybdenum is contained in the alloy in an amount below 3% (Fig. 5).

It should be noted that the general level of the impact toughness is highly and poorly sensitive to the changes in the ultimate rupture strength. This is confirmed by the similarity of the obtained dependences of the impact toughness on the total content of elements, when the latter changes within 27 – 33%. The results of the evaluation of *KCU* and *KCT* (MJ/m^2) can be described by regression equations in accordance with an adequate model of the second order, i.e.,

$$KCU = 1.68 - 0.46Ni + 0.37Mo \cdot Ni - 0.29Ni^2 + 0.32\,Mo^2 - 0.26\Sigma^2; \quad (6)$$

$$KCT = 0.82 - 0.7Ni + 0.46Mo \cdot Ni + 0.43Ni^2. \quad (7)$$

DISCUSSION OF RESULTS

The elevation of the strength of steels in the considered Ni – Co – Mo alloying system is caused by segregation of intermetallic compounds $(Fe, Ni)_2Mo$ and Ni_3Mo (at < 5% Mo), Ni_3Mo (at ≥ 5% Mo), and Fe_7Mo (at ≥ 10% Mo) [1]. Cobalt does not directly enter the composition of the hardening phase, but it increases the volume fraction of segregations, whereas when its content exceeds about 15% it introduces additional hardening due to the formation of a superlattice [1, 5]. In addition, cobalt in steels of this alloying system elevates the martensite point, thus decreasing the content of the soft phase, i.e., retained austenite [6].

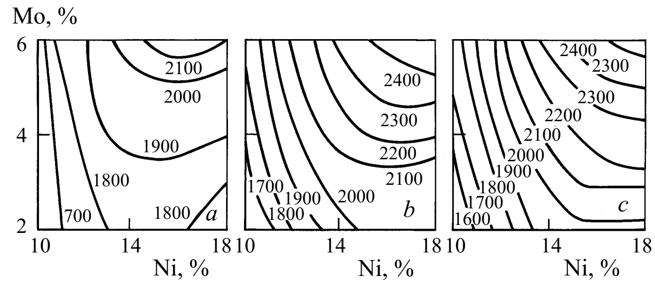

Fig. 4. Curves of the same level of ultimate rupture strength σ_r^n for notched specimens complexly alloyed with nickel, molybdenum, and cobalt in a total amount of 27% (a), 30% (b), and 33% (c) (the numbers at the curves present the values of σ_r^n in MPa).

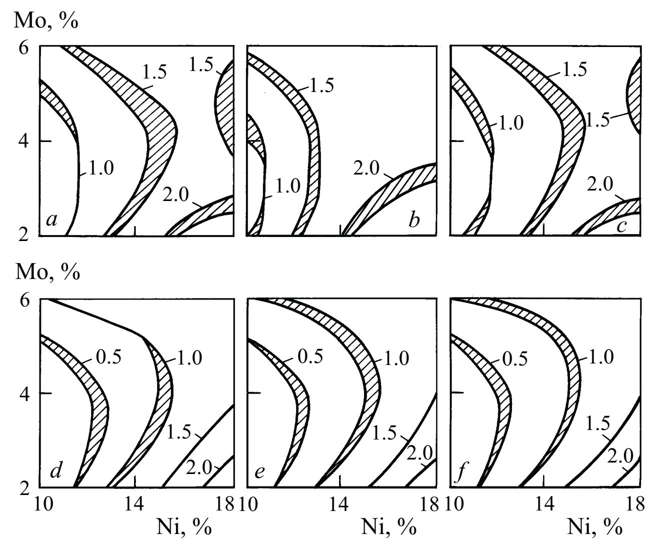

Fig. 5. Curves of similar levels of impact toughness *KCU* ($a - c$) and *KCT* ($d - f$) of steels complexly alloyed with nickel, molybdenum, and cobalt in a total amount of 27% (a), 30% (b), and 33% (c) (the numbers at the curves present the values of *KCU* and *KCT* in MJ/m^2).

The results obtained show that the strength of the steel for the most part increases with the concentration of molybdenum, and this effect intensifies with increase in the cobalt content and, consequently, in the total content of all the elements. Judging by the variation of the level of strength, in the latter case the steel hardens by about 33 MPa with the introduction of every 1% cobalt. In this case, when the cobalt addition is compensated by a corresponding decrease in the amount of nickel (at a constant total content of the alloying elements), the level of strength remains virtually constant. This reflects the equivalence of the hardening produced by the elements in question in the chosen range of concentrations. Proceeding from the obtained data, we can calculate the hardening effect due to molybdenum alloying, i.e., 83 MPa per every 1% Mo.

The strength level produced by this alloying in maraging steel (σ_r = 1200 – 1500 MPa) is quite moderate to provide a high ductility and impact toughness, and, correspondingly, a low sensitivity to brittle fracture. However, there is an obvious tendency to worsening of these characteristics and elevation of the sensitivity to notching under an equivalent replacement of nickel by cobalt. In this connection, the almost classical alloying of maraging steel with 15 – 18% Ni, 6% Mo, and up to 12% Co provides the maximum strength in notched specimens. Such recommendations are important for choosing the matrix for maraging steel whose strength is elevated by additional alloying with aluminum and titanium.

CONCLUSIONS

1. Complex alloying of maraging steel with nickel, cobalt, and molybdenum in a total amount of 27 – 33% provides $\sigma_r = 1200 - 1500$ MPa. The highest reinforcement is provided by molybdenum (about 83 MPa per every 1% Mo); the efficiency of the strengthening by nickel and cobalt is about the same (about 33 MPa per 1% introduced element).

2. An equivalent replacement of nickel by cobalt at the same strength level of maraging steel worsens its ductility and impact toughness and increases its sensitivity to notching.

3. Alloying of maraging steel with 15 – 18% Ni, 6% Mo, and 12% Co provides the maximum strength in notched specimens.

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