*Metal Science and Heat Treatment* *Vol. 43, Nos. 3 – 4, 2001*

# HEAT TREATMENT

UDC 669.15-194.55:621.785.7

# EFFECT OF TEMPERING ON THE STRUCTURE AND PROPERTIES OF HIGH-PURITY MARTENSITIC STEEL

**É. Yu. Kolpishon[1] and A. M. Korchagin[1]**

Translated from Metallovedenie i Termicheskaya Obrabotka Metallov, No. 4, pp. 12 – 14, April, 2001.

## INTRODUCTION

High-chromium Ni – Mo – V steels of the martensitic class are used for the production of gas turbine disks. In the process of operation of a gas turbine at a temperature of up to 550°C the disks work under the conditions of thermal and low-cycle fatigue, thermal embrittlement, and high tensile stresses. The material of the disks has to meet strict requirements with respect to the strength properties given that the ductility and the impact toughness are preserved at a high level. These properties are provided by increasing the purity of the metal and optimizing the technology of their heat treatment, tempering in particular.

The aim of the present work was to study the effect of tempering regimes in a temperature range of 550 – 600°C with holds of 0.5 – 270 h on the structure and properties of a super-pure high-chromium steel of the martensitic class. We analyzed the effect of the carbide types and of their size on the fracture behavior of the steel.

## METHOD OF STUDY

The Izhorskie Zavody Company has developed and tested a super-pure steel 10Kh12N3M2FA-A instead of TsDM steel of conventional purity (Table 1) for the production of gas turbine disks with a power exceeding 100 MW.

This steel has a low content of Si, Mn, S, P, Al, nonmetallic inclusions, and admixtures of nonferrous metals, which substantially influences its structure and properties. We studied the conditions of tempering on the structure and properties of steel 10Kh12N3M2FA-A smelted in the plant.

The specimens and commercial preforms were quenched in the laboratory from 1050°C in water and tempered at 510 – 600°C for 0.5 – 270 h. The Holomon parameter

$$\mathrm{Hp} = T(20 + \log \tau) \times 10^{-3}$$

was changed from 17 to 18.1 (here $T$ is the tempering temperature, K, and $\tau$ is the tempering time, h).

After the heat treatment the specimens were tested for tensile strength and impact bending.

The microstructure of steel 10Kh12N3M2FA-A was studied under a light microscope at a magnification of × 1600. The carbide phases were analyzed under an electron microscope[2] at a magnification of up to × 50,000. The microscopic sections were etched with “Turbochrom” reagent (200 ml $H_2O$, 2 ml HCl, 5 g $FeCl_3$).

The content and composition of the carbide phase were determined by the method of chemical analysis of precipitates obtained by electrolytic dissolution.

The x-ray diffraction analysis[3] of the carbides was performed in a DRON-2.0 diffractometer in copper $K_\alpha$ radiation.

**TABLE 1**

| Steel | Contents of elements, % | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Cr | Ni | Mo | V | Al | N | Nb | Si | Mn | P | S |
| TsDM | 0.08 – 0.12 | 11.0 – 12.5 | 2.5 – 2.9 | 1.45 – 1.75 | 0.2 – 0.35 | ≤ 0.05 | ≤ 0.05 | 0.1 | ≤ 0.3 | ≤ 0.6 | ≤ 0.02 | ≤ 0.015 |
| 10Kh12N3M2FA-A | 0.08 – 0.15 | 11.5 – 12.25 | 2.5 – 3.0 | 1.5 – 2.0 | 0.25 – 0.4 | ≤ 0.02 | ≤ 0.06 | — | ≤ 0.05 | ≤ 0.04 | ≤ 0.005 | ≤ 0.004 |

---

[1] Izhorskie Zavody Joint-Stock Company, St. Petersburg, Russia.

[2] The electron microscopy was conducted by A. E. Korneev (GTsN TsNIITMASh).

[3] The x-ray diffraction analysis was conducted by P. M. Mazurov (Izhorskie Zavody JSC).

0026-0673/01/0304-0141$25.00 © 2001 Plenum Publishing Corporation

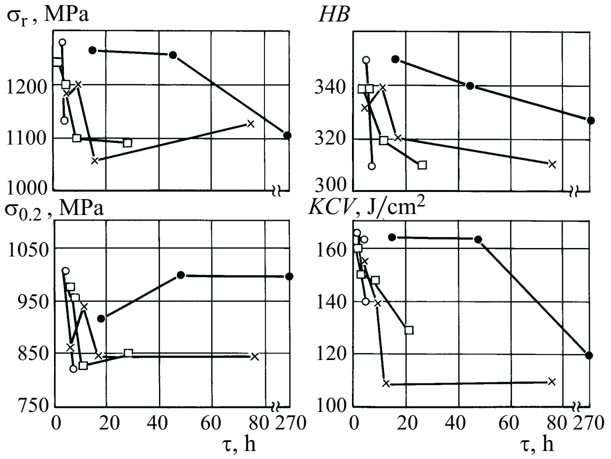

**Fig. 1.** Dependence of the mechanical properties and hardness of steel 10Kh12N3M2FA-A on the tempering time at various temperatures: ○) 600°C; □) 570°C; ×) 550°C; ●) 530°C.

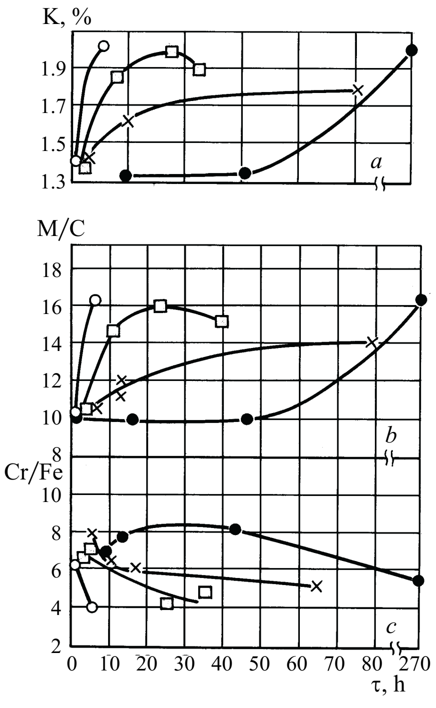

**Fig. 2.** Dependence of the content of carbides (*a*) and the ratios M/C (*b*) and Cr/Fe (*c*) in the carbide phase of steel 10Kh12N3M2FA-A on the tempering time at various temperatures: ○) 600°C; □) 570°C; ×) 550°C; ●) 530°C.

The mechanical properties were compared with the results of the chemical and x-ray diffraction analyses of the carbides and the data of the electron microscopy.

## RESULTS AND THEIR DISCUSSION

The results of the tests of the specimens are presented in Fig. 1. The hardness (strength) values at $t_{\text{temp}} = 530 - 600°\text{C}$ at a hold of up to 10 h correspond to Hp = 17.4. The strength increases after tempering at 530°C for 75 h (Hp = 18.0).

At $t_{\text{temp}} = 530°\text{C}$ the impact toughness and the hardness decrease while Hp grows from 17.4 to 18.0. After tempering at 550, 570, and 600°C with a hold of up to 20 h (Hp = 17.0 – 17.4) they decrease abruptly. The maximum hardness is observed for nitrides $VN_{0.35}$ and carbides $M_3C$ (we also detected traces of particles of $M_{23}C_6$ 0.1 μm in size). The decrease in the hardness is connected with the growth in the size of the carbide particles to 1 μm and with the appearance of the $M_{23}C_6$ carbide in the carbide phase. The content of the carbides increases due to the increase in the fraction of iron and the growth in the M/C ratio, which is typical for the reaction $M_2C \rightarrow M_3C \rightarrow M_{23}C_6$ (Fig. 2).

Using the known Eshelby formula $\sigma_y = \sigma_m + \Delta\sigma$ (where $\sigma_y$ is the yield strength, $\sigma_m$ is the heat resistance of the matrix, and $\Delta\sigma$ is the structure-dependent component) we made an attempt to determine the influence of the size of the carbides and the intercarbide distance on the yield strength. The critical stress of crack nucleation $\sigma_{cr}$ (N/mm$^2$) of a carbide was evaluated by the expression [1]

$$\sigma_{cr} = \sqrt{\frac{2E\gamma_{ef}}{\pi(1-\nu^2)d}} = 0.96\sqrt{\frac{1}{d}},$$

where $d$ is the diameter of the carbide particle, $E$ is the Young's modulus, $\gamma_{ef}$ is the effective surface energy, and $\nu$ is the Poisson coefficient.

The yield strength is well describable by the known equation [2]

$$\sigma_y = \sigma_m + \Delta\sigma_g + \Delta\sigma_c,$$

where $\sigma_m$ is the shear resistance of the matrix, $\Delta\sigma_g = K d_g^{-1/2}$ ($d_g$ is the grain size), and $\Delta\sigma_c$ is the increment of the yield strength connected with the presence of the carbonitride phase.

As a rule, the carbide diameter is close to the intercarbide distance. In the coagulation of the carbides their contribution ($\Delta\sigma_c$) to the yield strength decreases and the value of the critical stress of crack nucleation decreases too, i.e.,

$$\Delta\sigma_c = 0.85\frac{GP}{2\pi D}\ln\frac{d}{4b},$$

where $G$ is the shear modulus, $b$ is the modulus of the Burgers vector, $d$ is the carbide diameter, and $D$ is the distance between the carbides.

It is known that brittle fracture occurs when the stress of crack nucleation $\sigma_{cr}$ is less than the yield strength $\sigma_y$. It is interesting to evaluate the effect of the size of the carbides on these characteristics. The results of computation by the formulas presented above are given in Table 2. It can be seen that change in the size of the carbides in the observed range can either increase or decrease $\sigma_y$ by about 100 MPa,

**TABLE 2**

| $d$, μm | $\sigma_{cr}$, MPa | $\sigma_c$, MPa, at a distance $D$, μm, between the carbides | | | | |
|---|---|---|---|---|---|---|
| | | 0.1 | 0.3 | 0.5 | 1 | 2 |
| 0.1 | 960 | 124 | 48 | 29 | 15 | 7.5 |
| 0.3 | 550 | 155 | 60 | 36 | 18 | 9.0 |
| 0.5 | 480 | 169 | 65 | 39 | 19.5 | 10 |
| 1 | 300 | 188 | 72 | 44 | 22 | 11 |
| 2 | 210 | 207 | 80 | 48 | 24 | 12 |

whereas the critical stress of crack nucleation can change by a factor of 2 – 5.

Figure 3 presents the results of the computation of $\sigma_{cr}$ for carbides of various sizes and the yield strength as a function of the test temperature. The slope of the curve describing $\sigma_{cr}$ was determined by testing the specimens at + 20 and + 350°C.

At $d = 0.1$ μm $\sigma_{cr} > \sigma_y$ in the entire range of service temperatures; at $d = 1$ μm $\sigma_{cr} < \sigma_y$, i.e., brittle fracture is inevitable. At $d = 0.3$ μm the test temperature obviously affects the fracture behavior, i.e., we may obtain $\sigma_{cr} \lesseqgtr \sigma_y$.

With allowance for the results of the computations we can explain the degradation of the properties in long-term holds at 482°C (3000 h and more) by the coarsening of the carbide phase to about 2 μm.

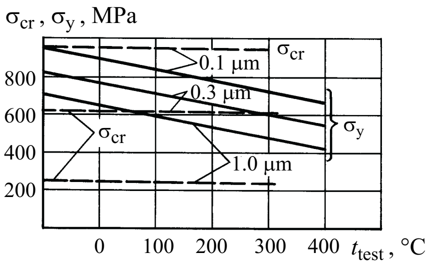

**Fig. 3.** Effect of the test temperature and the size of the carbides on the critical stress of crack nucleation ($\sigma_{cr}$) and the yield strength ($\sigma_y$) of steel 10Kh12N3M2FA-A. The numbers at the curves denote the sizes of the carbides.

## CONCLUSIONS

1. The change in the mechanical properties of super pure high-chromium steel 10Kh12N3M2FA-A of the martensitic class directly depends on the growth of the carbides in its structure.
2. The optimum combination of properties in steel 10Kh12N3M2FA-A is provided by tempering at 530°C for 50 h.

## REFERENCES

1. J. F. Nott, *Fundamentals of Fracture Mechanics* [Russian translation], Metallurgiya, Moscow (1978).
2. *HNS-90. Preprints for the 2nd International Conference Stahleisen*, Düsseldorf (1990), pp. 167 – 170.