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EFFECT OF THE AGING REGIME ON THE HARDNESS AND AMOUNT OF γ′-PHASE IN HIGH-TEMPERATURE NICKEL ALLOYS KhN56VMTYu AND KhN77TYuR

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It is known that the properties of high-temperature nickel alloys depend considerably on the amount of γ′-phase, which is determined, first of all, by the aging regime. In order to evaluate the properties of these alloys it is expedient to establish the relation between the parameters of the aging regime and the amount of γ′-phase or, which is even more important, between the aging parameters and the mechanical properties. The present paper concerns high-temperature nickel alloys KhN56VMTYu and KhN77TYuR, which are used to establish the relations between the amount of γ′-phase, the hardness, and its increment due to aging and the aging temperature.

We studied[2] specimens 100 × 15 × 10 mm in size (alloy KhN56VMTYu) and 100 × 15 × 12 mm in size (alloy KhN77TYuR) cut from hot-rolled sheets. The chemical composition of the alloys is presented in Table 1. The specimens were quenched in water after a 1-h hold at 1200°C (KhN56VMTYu) and a 1-h hold at 1150°C (KhN77TYuR). The high temperatures of heating for quenching were used to attain fuller homogenization of the alloys. Aging was conducted at 750, 800, 850, and 900°C (both alloys) and at 950°C (alloy KhN56VMTYu) for 0.25, 0.5, 1.0, 5.0, 10, 20, 50, and 100 h. After aging, the specimens were cooled in air. The Brinell hardness of the specimens was measured after quenching and aging. The volume fraction of γ′-phase was determined by quantitative electrolytic separation of the phases [1] with recalculation of the mass fractions to volume fractions [2].

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The hardness HB of quenched and aged specimens was represented as a sum of two components, i.e.,

$$HB = HB_{\text{init}} + \Delta HB, \quad (1)$$

where HB_{init} is the hardness of the alloys in a homogeneous state (after quenching), ΔHB is the increase in the hardness caused by aging.

For an alloy of a specified composition the first term depends predominantly on the grain size (the coarser the grains, the lower the value of HB_{init}) and is determined, first of all, by the temperature of heating for quenching. The second term depends predominantly on the amount of γ′-phase and is determined by the aging regime.

Table 2 presents results of measurement of the total hardness HB of the studied alloys after aging by various regimes. It can be seen that in aging for over 5 h the hardness of the alloys does not depend on the aging time with the exception of alloy KhN56VMTYu in which the hardness virtually does

TABLE 1

Alloy	Content of elements,* %										
	C	Cr	Fe	Mo	W	Al	Ti	Si	Mn	B	Other
KhN56VMTYu	≤ 0.10	19.0 – 22.0	≤ 4.0	4.0 – 6.0	9.0 – 11.0	2.1 – 2.6	1.1 – 1.6	≤ 0.60	≤ 0.50	≤ 0.008	≤ 0.05 Mg
KhN77TYuR	≤ 0.06	19.0 – 22.0	≤ 1.0	–	–	0.6 – 1.0	2.4 – 2.8	≤ 0.60	≤ 0.40	≤ 0.010	≤ 0.010 Ce ≤ 0.070 Cu

* The remainder Ni.

not change after aging at 750° for at least 20 h. As a rule, the aging time of these alloys τ_{ag} exceeds 5 h. In this connection we can assume that the hardness of the alloys studied is a function of the aging temperature.

Figure 1 presents a linear approximation of the relation between the hardness and the aging temperature. The lines are described by equations of the form $y = A + k(x - B)$.

For alloy KhN56VMTYu we have

$$HB \cong 415 - 0.65(t_{ag} - 750) \quad (2)$$

or, after simplification,

$$HB \cong 902.5 - 0.65t_{ag}. \quad (3)$$

For alloy KhN77TYuR we have

$$HB \cong 315 - 0.80(t_{ag} - 750) \quad (4)$$

or, after simplification,

$$HB \cong 915 - 0.80t_{ag}. \quad (5)$$

Taking into account that the initial hardness of the specimens of alloys KhN56VMTYu and KhN77TYuR in a homogeneous state is equal to 190 and 155 *HB* (Table 2), we can determine the temperatures of full dissolution of the γ′-phase in them by Eqs. (3), (5) and (1), namely, $T_{\gamma'} = 1096$ and 950°C, respectively.

It should be noted that Eqs. (2) – (5) are true only for the given alloys with a specified initial hardness of 190 and 155 *HB* (i.e., with a grain size No. 2 – 4). After quenching for a finer grain size the hardness HB_{init} will be somewhat higher. For example, after quenching alloys KhN56VMTYu and KhN77TYuR from 1120 and 970°C in water the structure is characterized by a grain size No. 7 – 6, and the initial hardness is 225 and 195 *HB*, respectively. In this case the first terms in Eqs. (2) – (5) should be increased by the difference between the values of the initial hardness (in the given case by 35 and 40 *HB*, respectively).

It can be seen from Fig. 1 that the loss of strength in alloy KhN77TYuR with increase in the aging temperature occurs more intensely than in alloy KhN56VMTYu (the slope coefficient *K* of the regression line describing the softening is 8.0 and 6.5, respectively). The data of Fig. 1 also show that for the same aging regime the hardness of alloy KhN56VMTYu exceeds that of alloy KhN77TYuR by at least 100 *HB*. The difference is greater, the higher the aging temperature. Taking into account that the first alloy is more alloyed than the second, this feature is quite natural. However, the relations mentioned are indisputable only for a constant grain size in the compared variants, because coarsening of the grains, other conditions being equal, decreases, as a rule, the hardness of the alloys in any state.

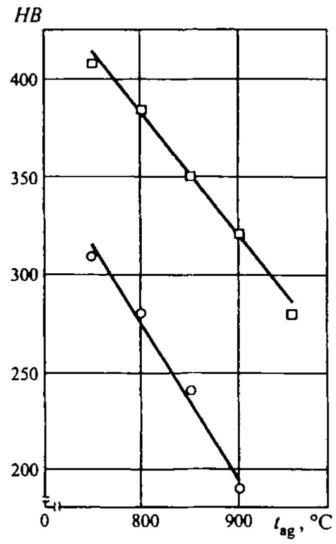

Fig. 1. Dependence of the hardness of hot-rolled sheets of alloys KhN56VMTYu (□) and KhN77TYuR (○) on the temperature of aging conducted after quenching.

Table 3 presents measured volume fractions of γ′-phase in the alloys studied. Just like the hardness, the volume fraction of γ′-phase in aging lasting for over 5 h virtually does not depend on the aging time (except for alloy KhN56VMTYu, in which the fraction of γ′-phase changes little after aging at 750°C for at least 20 h). For this reason in both alloys the vol-

TABLE 2

Alloy	t_{ag}, °C	HB_{init}	Hardness *HB* after quenching and aging for a time, h								HB_{calc}
			0.25	0.5	1.0	5.0	10	20	50	100	
KhN56VMTYu	750	190	290	320	360	380	400	407	410	410	410
	800	190	320	360	375	385	385	385	385	385	385
	850	190	330	340	350	350	350	350	350	350	350
	900	190	330	325	320	320	320	320	320	320	320
	950	190	295	290	290	285	280	280	280	280	280
KhN77TYuR	750	155	200	250	280	305	310	310	310	310	310
	800	155	250	270	280	280	280	280	280	280	280
	850	155	240	250	245	240	240	240	240	240	240
	900	155	210	200	200	195	190	190	190	180	190

Note. Before aging, the specimens of alloy KhN56VMTYu were subjected to quenching in water from 1200°C (1 h), and the specimens of alloy KhN77TYuR were quenched from 1150°C (1 h).

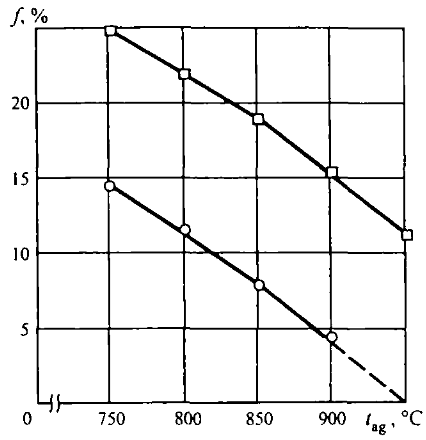

Fig. 2. Dependence of the volume fraction of γ′-phase (f) of hot-rolled sheets of alloys KhN56VMTYu (□) and KhN77TYuR (○) on the temperature of aging conducted after quenching.

ume fraction of γ′-phase (f, %), like the hardness, can be represented as a function of the aging temperature. Figure 2 presents a linear approximation of the available data in the coordinates $t_{ag} - f$. It can be seen that the parameters of interest are related most closely when they are divided into two segments, namely, below 850°C and above 850°C (for alloy KhN56VMTYu) and below 815°C and above 815°C (for alloy KhN77TYuR). The regression equations of these segments in the mentioned temperature ranges for each alloy differ insignificantly with respect to the coefficients that correspond to the slopes of the lines.

For alloy KhN56VMTYu we have

$$f \cong 25 - 0.06\,(t_{ag} - 750) \tag{6}$$

or, after simplification,

$$f \cong 70.0 - 0.06 t_{ag} \tag{7}$$

for $t_{ag} \leq 850$°C and

$$f \cong 19 - 0.077\,(t_{ag} - 850) \tag{8}$$

or, after simplification,

$$f \cong 84.45 - 0.077 t_{ag} \tag{9}$$

for $t_{ag} \geq 850$°C.

For alloy KhM77TYuR we have

$$f \cong 14.3 - 0.060(t_{ag} - 750) \tag{10}$$

or, after simplification,

$$f \cong 59.30 - 0.060 t_{ag} \tag{11}$$

for $t_{ag} \leq 815$°C and

$$f \cong 10.4 - 0.077(t_{ag} - 815) \tag{12}$$

or, after simplification,

$$f \cong 73.155 - 0.077 t_{ag} \tag{13}$$

for $t_{ag} \geq 815$°C.

Figure 2 and Eq. (13) show that the γ′-phase in alloy KhN77TYuR does not form at a temperature exceeding 950°C (which corresponds to the actual state of things [3]). If we extrapolate Eq. (9) to higher temperatures, we will establish that full dissolution of the γ′-phase in alloy KhN56VMTYu occurs at about 1097°C [the 1°C difference from the result calculated using Eq. (3) is caused by rounding of the coefficients].

The laws established allow us to derive regression equations for determining the hardness increment provided by the change in the amount of γ′-phase. This increment of the hardness of an aged alloy (relative to the quenched alloy) depends only on the aging regime (on the aging temperature in a simplified variant).

Figure 3 presents a linear approximation of the points relating ΔHB to f for the alloys studied, plotted using the results presented in Tables 2 and 3. The hardness increment is determined from Eq. (1) using the data of Table 2. The points shown in Fig. 3 for both alloys lie quite close and can be ap-

TABLE 3

Alloy	t_{ag}, °C	Volume fraction of γ′-phase (f, %) after quenching and aging for a time, h								f_{calc}, %
		0.25	0.5	1.0	5.0	10	20	50	100	
KhN56VMTYu	750	11.0	14.0	18.0	19.5	21.5	25.0	25.0	25.0	25.0
	800	17.0	18.0	20.5	22.0	22.0	22.0	22.0	22.0	22.0
	850	18.0	18.2	18.4	19.0	19.0	19.0	19.0	19.0	19.0
	900	14.8	15.1	15.1	15.1	15.15	15.15	15.15	15.2	15.15
	950	10.0	11.1	11.1	11.2	11.25	11.3	11.3	11.3	11.3
KhN77TYuR	750	9.0	11.0	11.5	13.0	14.3	14.3	14.3	14.3	14.3
	800	9.5	10.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
	850	7.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
	900	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2

Note. Before aging, the specimens of alloy KhN56VMTYu were quenched in water from 1200°C (1 h), and the specimens of alloy KhN77TYuR were quenched from 1150°C (1 h).

proximated unambiguously by straight lines passing through the origin. In the coordinates $f-\Delta HB$ these lines are described by the following equations:

$$\Delta HB \cong 8.8f \quad (14)$$

for KhN56VMTYu and

$$\Delta HB \cong 10.84f \quad (15)$$

for KhN77TYuR.

Substituting the values of f expressed in terms of t_{ag} [formulas (7), (9) and (11), (13)] into the dependences obtained we arrive at

$$\Delta HB \cong 616.0 - 0.528t_{ag} \text{ (for } t_{ag} \le 815°\text{C)}; \quad (16)$$

$$\Delta HB \cong 743.2 - 0.678t_{ag} \text{ (for } t_{ag} \ge 815°\text{C)} \quad (17)$$

for KhN56VMTYu and

$$\Delta HB \cong 642.80 - 0.6504t_{ag} \text{ (for } t_{ag} \le 850°\text{C)}; \quad (18)$$

$$\Delta HB \cong 793.00 - 0.8347t_{ag} \text{ (for } t_{ag} \ge 850°\text{C)} \quad (19)$$

for KhN77TYuR.

Using these equations, we can easily calculate the hardness increment due to aging from the aging temperature.

Equations (17) and (19) show that at the temperature of full dissolution of the γ′-phase of the alloys studied (1096 and 950°C) their hardnesses will be close to 190 and 155 *HB* (for the given grain size), which agrees with the actual values (see Table 2).

It follows from Fig. 3 that the growth of the hardness with the volume fraction of γ′-phase in alloy KhN77TYuR occurs more intensely than in alloy KhN56VMTYu. However, the absolute magnitudes of the hardness for alloy KhN56VMTYu are higher than for alloy KhN77TYuR. The first effect can be associated with the fact that the reinforcement of alloy KhN77TYuR by the fields of elastic interphase deformations is greater than in alloy KhN56VMTYu. The higher hardness of alloy KhN56VMTYu is explainable by the higher proportion of γ′-phase at any aging regime and the higher strength of the matrix due to the higher alloying. Close

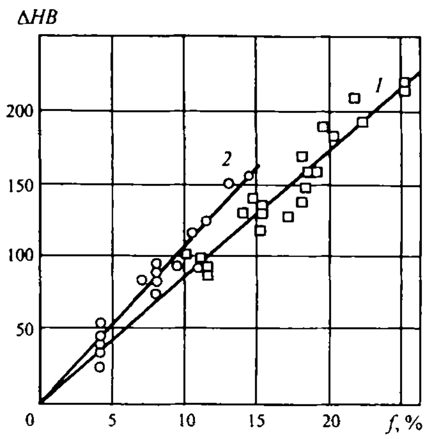

Fig. 3. Dependence of the increase in the hardness of hot-rolled sheets of alloys KhN56VMTYu (*1*) and KhN77TYuR (*2*) on the volume fraction of γ′-phase.

results and conclusions concerning the alloys studied have been obtained in [4].

Thus, the dependences presented allow us to calculate the volume fraction of γ′-phase, the hardness, and its increment due to segregation of the γ′-phase from the aging temperature with an accuracy sufficient for practical purposes. It is possible to take into account the change in the hardness of the alloys caused by grain disintegration.

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