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HEAT TREATMENT OF LARGE CASTINGS FROM STEEL 15Kh3M1FTsL

I. A. Borisov[1]

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The effect of heat treatment on mechanical properties, impact toughness, and cold-shortness threshold of cast steel 15Kh3M1FL is investigated. A heat treatment mode including homogenizing, air hardening, and high-temperature tempering of castings is suggested for commercial use.

INTRODUCTION

In our earlier work [1] we suggested steel 15Kh3M1FL with and without zirconium modifying additive for large-size castings. However, the problems connected with quality melting of this steel and modes of its heat treatment were studied insufficiently fully. In addition, we studied club-shaped specimens with a small cross section, which possessed a higher density and better structure than large castings and thus had a better combination of mechanical properties.

The aim of the present work consisted in determining the main parameters for heat treatment of large castings, i.e., homogenizing, air hardening, and high-temperature tempering in order to ensure properties meeting the performance specification.

METHODS OF STUDY

We melted experimental steels based on the 15Kh3M1FL composition with varied contents of vanadium and aluminum. One tested composition had a microadditive of zirconium. The test steels were melted in an electric arc furnace with a capacity of 0.5 tons. From each heat we obtained castings in the form of a cylindrical preform 300 mm in diameter and 300 mm high with a cone exterior part 250 mm high and a club-like wedge 12 kg in mass (with a size of about 120 × 80 mm).

After cutting the exterior part, templates for studying the macrostructure and the off-center segregation were cut over the vertical axis of the cylindrical parts. Bauman imprints were taken from the templates and the structure was photographed. In addition, we performed a metallographic analysis of the structure and studied the distribution of the nonmetallic inclusions. The composition of the nonmetallic inclusions was determined by a chemical method by electrolytic dissolution of the specimens. The gas content was studied by the method of vacuum melting, and the content of nitrogen was determined by chemical dissolution of chips.

We evaluated the critical points of steel heated to 1000°C at a rate of 200 K/h and cooled to 500°C at a rate v_{cool} = 400 K/h and then at a rate v_{cool} = 200 K/h. Such a cooling mode imitated the process of cooling of large-size castings in air hardening.

The preforms were heat treated in laboratory furnaces with silit heaters and in a special device [2].

The club-like wedges were subjected to preliminary heat treatment including 2-h homogenizing, annealing at 1000°C for 2 h → 690°C for 6 h, and cooling in the furnace.

The templates were used to cut preforms for specimens for studying the effect of the parameters of the final heat treatment, i.e., the homogenizing temperature within 1050 – 1150°C (with a hold $\tau = \text{const} = 10$ h) and the temperature (925 – 1000°C at $\tau = \text{const} = 10$ h) and duration (5 – 25 h at $t_{\text{h}} = \text{const} = 1000$°C) of the hold in hardening, the cooling rate (200, 400, and 600 K/h) from 1000°C (5 h), and the tempering temperature (680 – 740°C at $\tau = \text{const} = 10$ h), on the properties of the steel.

In order to choose the optimum heat treatment parameters we determined the mechanical properties, the impact toughness, and the cold-shortness threshold of specimens cut from the wedges and from cylindrical templates.

The tests for impact toughness were performed at a temperature ranging from + 40 to – 60°C. The cold-shortness temperature was determined from the threshold value of the impact toughness $KCU = 0.3$ MJ/m^2.

The requirements of the performance specification on the mechanical properties of the steels are as follows: $\sigma_{0.2} > 440$ MPa, $\delta > 14\%$, $\psi > 35\%$, $KCU > 0.3$ MJ/m^2, and

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[1] Central Research Institute for Heavy Machine Building (TsNIITMASh), Moscow, Russia.

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TABLE 1. Chemical Composition of Experimental Steels

Tested steel	Content of elements, %											
	C	Si	Mn	Cr	Mo	V	Zr	S	P	Ni	Cu	Al
1	0.12	0.55	0.78	3.0	0.95	0.10	–	0.007	0.012	0.10	0.13	0.04
2	0.13	0.50	0.68	2.9	0.92	0.11	–	0.008	0.011	0.08	0.10	–
3	0.14	0.58	0.65	2.9	0.85	0.08	0.05	0.012	0.012	0.06	0.09	0.03
4	0.15	0.40	0.70	3.1	0.90	–	–	0.009	0.016	0.10	0.09	0.03
5	0.14	0.40	0.68	2.9	0.86	0.08	–	0.010	0.021	0.07	0.10	0.02
6	0.14	0.40	0.70	2.9	0.85	0.08	–	0.011	0.011	0.09	0.09	0.03

the cold-shortness threshold $T_{cs} < 0$°C. The chemical composition of the experimental steels is presented in Table 1. The content of gases and nonmetallic inclusions in the metal of the castings is presented in Table 2.

RESULTS AND DISCUSSION

The results of the study of the microstructure of the tested steels show that the zones of dendrite crystals take up to 75% of the cross section of the casting. The dendrites are primarily thin, long, and extended in the direction of the external part of the ingot. Comparative analysis of the macrostructure of the castings shows that it is virtually independent on the degree of killing by aluminum and on the introduction of vanadium. The macrostructure of castings from the steel modified with zirconium differs somewhat from the macrostructure of other castings, i.e., the metal is etched poorly and the etching discloses finer dendrites. On the whole, the structure of the castings is satisfactory and has a high enough density.

The sulfur imprints show that the castings are virtually devoid of off-center sulfur segregations (whiskers). This is explainable by the low content of sulfur in the metal (within 0.008 – 0.012%) and by the small mass of the casting (350 kg).

The data on the nature and type of nonmetallic inclusions show (Fig. 1) that the metal can be classified as satisfactory with respect to oxides and sulfides (the contamination evaluated in points is 1 – 1.5). However, the nonmetallic inclusions differ in the shape depending on the killing variant. For example, steel *2* (without aluminum) has globular inclusions with a white spot in the center, which is typical for silicates. The metal killed with aluminum chiefly bears fine oxides and accumulations of alumina. Steel *3* with a cerium additive bears coarse zirconium carbonitrides having angular and square shapes. Steel *6* contains a low amount of carbo-

TABLE 2. Content of Gases and Nonmetallic Inclusions in Experimental Steels

Tested steel	Content of gases			$C_{\Sigma}^{\mathrm{n.i}}$, %	Content of nonmetallic inclusions, %				
	O, %	N, %	H, cm^3/100 g metal		SiO	MnO	FeO	CrO	AlO
1	0.0016	0.013	8.40	0.035	–	–	1.6	0.7	97.7
			8.60	0.034			1.5	0.7	97.8
2	0.0013	0.012	8.60	–	–	–	–	–	–
		0.011	10.60						
3	0.0016	0.010	8.10	0.035	6.1	0.2	0.6	0.3	92.8
	0.0013	0.011	8.30	0.030	1.6	0.2	0.6	0.3	97.3
4	0.0005	0.009	4.10	0.012	29.8	0.6	2.3	0.7	66.6
	0.0004	0.010	4.90	0.011	27.0	0.6	1.8	0.7	69.9
5	0.0010	0.014	–	0.018	6.9	0.9	0.9	1.2	90.1
6	0.0008	0.021	3.80	0.018	18.7	0.5	0.5	0.5	79.5
	0.0008	0.025	3.50	0.017	10.1	0.4	0.5	0.5	88.5

Notations: $C_{\Sigma}^{\mathrm{n.i}}$ is the total content of nonmetallic inclusions.

Note. The content (%) of oxygen and nitrogen and the total content of nonmetallic inclusions was determined in terms of the ratio of their mass to the mass of the dissolved metal; the content of each kind of nonmetallic inclusion was determined in terms of the ratio of its mass to the total mass of all inclusions.

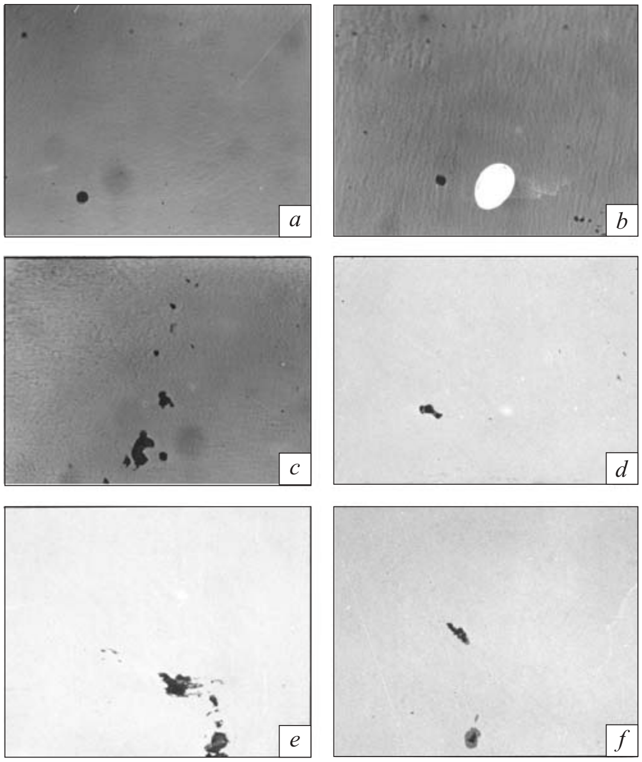

Fig. 1. Nonmetallic inclusions in castings from experimental steels *1* (*a*), *2* (*b*), *3* (*c*), *4* (*d*), *5* (*e*), and *6* (*f*).

nitrides, because the entire nitrogen in it is bound with aluminum in nitrides.

The specimens produced from club-like wedges were subjected to preliminary heat treatment and then used for determining the mechanical properties, the impact toughness from – 40 to + 350°C, and the fraction of the ferrite-pearlite component in the structure. The data presented in Table 3 show that steel *3* alloyed with zirconium has the highest values of the yield strength ($\sigma_{0.2}$ = 420 MPa) and steel *2* not killed with aluminum has the lowest yield strength. It should be noted that despite the high content of carbon (0.15%) steel *4* not bearing vanadium possesses a somewhat lower strength ($\sigma_{0.2}$ = 360 MPa) than steels *5* and *6*. On the whole, the used annealing mode did not provide the strength level required by the specification. At the same time, the ductility characteristics of the experimental steels exceeded considerably the requirements of the specification. For example, the elongation varied within $\delta = 21 - 25\%$ and the contraction $\psi = 72 - 76\%$ (the specified values are $\delta = 14\%$ and $\psi = 35\%$). A high level of properties was obtained in the tests for dynamic impact. The values of the impact toughness exceeded substantially the specified level, i.e., $KCU = 1.3 - 1.7$ MJ/m^2 against the required $KCU = 0.3$ MJ/m^2. The maximum impact toughness at positive temperatures was ex-

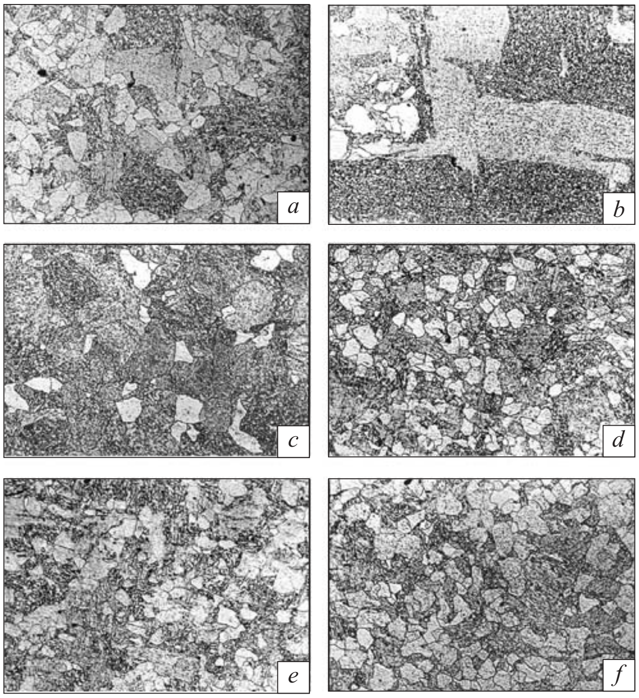

Fig. 2. Structure of experimental steels *1* (*a*), *2* (*b*), *3* (*c*), *4* (*d*), *5* (*e*), and *6* (*f*).

TABLE 3. Mechanical Properties and Fraction of Ferrite-Pearlite Component in the Structure after Preliminary Heat Treatment of Experimental Steels

Test steel	$\sigma_{0.2}$, MPa	$\sigma_{0.2}/\sigma_r$	δ, %	ψ, %	*KCU*, MJ/m^2					F + P, %
					– 40°C	– 20°C	– 10°C	20°C	350°C	
1	340	0.66	25	75	1.1	1.2	1.4	1.6	2.3	50
2	330	0.65	21	76	0.8	1.4	1.7	1.8	2.5	55
3	420	0.74	22	72	0.5	0.6	0.9	1.3	1.6	20
4	360	0.62	25	72	0.8	0.9	1.0	1.4	1.9	45
5	370	0.68	25	72	1.1	1.1	1.2	1.7	2.0	40
6	380	0.70	25	76	1.0	1.1	1.2	1.7	2.4	35

Note. The preliminary heat treatment consisted of 2-h homogenizing at 1050°C, annealing at 1000°C for 2 h → 690°C for 6 h, and cooling in the furnace.

TABLE 4. Critical Points of Experimental Steels in Heating to 1000°C and Subsequent Cooling

Test steel	Ac_1, °C	Ac_3, °C	Ar_1, °C	Ar_2, °C	Ar_3, °C	Ar_4, °C
1	830	900	820	735	510	350
2	820	890	810	740	515	360
3	810	880	770	750	470	330
4	820	900	830	750	520	370
5	835	900	820	750	490	380
6	800	885	800	745	500	360

TABLE 5. Effect of Homogenization Temperature on Mechanical Properties of steels 15Kh3M1FL and 15Kh3M1FTsL after Toughening

Steel	t_{hom},* °C	$\sigma_{0,2}$, MPa	σ_r, MPa	δ, %	ψ, %	*KCU*, MJ/m^2
15Kh3M1FL	1050	480	650	20	61	0.8
		480	655	20	60	1.2
	1100	480	650	19	60	0.8
		470	645	20	60	0.8
	1150	470	645	15	50	0.9
		470	640	20	60	0.7
15Kh3M1FTsL	1050	485	665	22	64	1.0
		480	660	20	66	1.1
	1100	480	655	21	64	0.8
		475	650	19	62	0.7
	1150	470	650	18	52	0.6
		475	655	20	58	1.0

* Homogenization temperature.

hibited by steel *2* not killed with aluminum, and the lowest impact toughness was exhibited by steel *3* modified with zirconium. Steels *1*, *5*, and *6* had a high impact toughness at – 40°C, i.e., $KCU = 1.0 – 1.1$ MJ/m^2. Metallographic studies showed that steels *1*, *4*, *5*, and *6* killed with aluminum possessed virtually similar structures represented by a homogeneous mixture of ferrite and pearlite with very fine grains. The structure of steel *2* (without aluminum) differed from the metal from the heats mentioned above by coarser grains. Tempered bainite dominated in the structure of steel *3* with zirconium (Fig. 2).

In order to determine the modes for the final heat treatment we determined the critical points for the steels. The data of Table 4 show that the critical points of the metal from the experimental heats differ little except for steels *1*, *2*, and *4* with wider ranges or pearlitic transformation of austenite and higher temperatures of bainite decomposition. Analyzing the obtained data we chose steels *3* (15Kh3M1FTsL) and *6* (15Kh3M1FL) as the most promising for further study.

TABLE 6. Effect of Hardening Temperature on Mechanical Properties of Steel 15Kh3M1FL and 15Kh3M1FTsL

Steel	t_h,* °C	$\sigma_{0,2}$, MPa	σ_r, MPa	δ, %	ψ, %	*KCU*, MJ/m^2
15Kh3M1FL	925	340	550	23	65	1.0
		350	560	24	66	1.1
	950	450	630	19	66	0.9
		425	610	20	62	1.0
	975	450	630	19	62	1.2
		400	600	21	66	0.9
	1000	450	620	20	58	1.0
		480	650	18	65	1.1
15Kh3M1FTsL	925	370	560	23	60	1.1
		400	600	20	62	1.1
	950	450	620	23	68	1.0
		455	630	20	65	0.9
	975	470	640	20	60	1.0
		460	630	20	63	0.9
	1000	480	650	18	64	0.9
		480	660	20	63	1.1

* The temperature of heating for hardening.

Note. The properties of the steels are presented after hardening and 10-h tempering at 680°C.

As a rule, the heat treatment of large-size castings involves their homogenizing and toughening (tempering).

The aim of the homogenizing consists in removing the harmful factors appearing in the metal of a casting during hardening, for example, the nonuniformity of the chemical composition over the cross section and the presence of coarse carbides. The homogenization temperature should be rather high (1000 – 1200°C).

The toughening is performed to remove the factors appearing both on the process of hardening of the casting and in homogenization (for example, large grains) and to raise the mechanical properties of the metal. The result depends on the correctness of the choice of the temperature of heating for austenization, of the rate of the cooling during hardening, and of the temperature and duration of the tempering.

Development of the mode of homogenization. We chose the temperature in the 1050 – 1150°C range at the following constant parameters: a hold of 10 h and cooling in the furnace. After homogenization we performed toughening, which consisted of air hardening from 1000°C (10 h) and tempering at 680°C. The results of the study of mechanical properties are presented bin Table 5. We can see that the chosen homogenization temperatures affect the properties of the tested steels inconsiderably. The fact that the properties lower somewhat after homogenization at 1150°C is connected with the growth of austenite grains (data of metallographic analysis). The properties of steels 15Kh3M1FTsL and 15Kh3M1FL do not differ substantially. The obtained re-

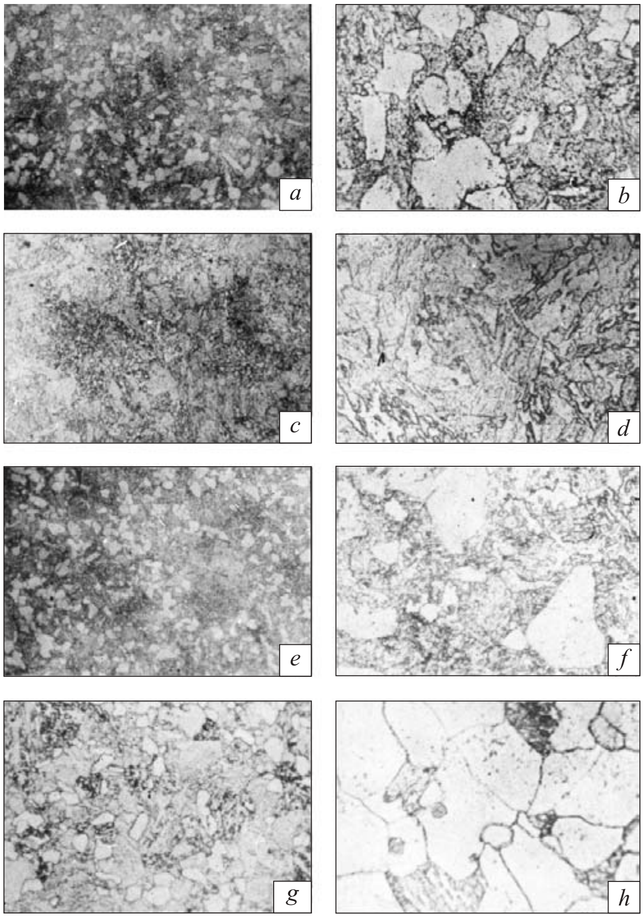

Fig. 3. Structure of steel 15Kh3M1FTsL after hardening from different temperatures: *a*, *b*) 925°C; *c*, *d*) 950°C; *e*, *f*) 975°C; *g*, *h*) 1000°C; *a*, *c*, *e*, *g*) × 100; *b*, *d*, *f*, *h*) × 600.

sults allow us to recommend the temperature range of 1050 – 1100°C for homogenization of large-size castings (with allowance for the scattering of temperature in heat treatment furnaces).

Development of the mode of toughening. In the first stage we studied the effect of the temperature of heating for hardening t_h = 925, 950, 975, and 1000°C and of the cooling rate v_{cool} = 200, 400, and 600 K/h on the properties of the tested steels (Tables 6 and 7). The data of Table 6 show that the strength properties of the preforms heated to t_h = 925 – 950°C are below the level required by the specification, because the chromium and molybdenum carbides do not dissolve fully in austenite. This decreases the hardenability and the strength of the steels. The temperature range of 975 – 1000°C is the most favorable for hardening and ensures the requisite level of properties. Metallographic studies confirm this conclusion.

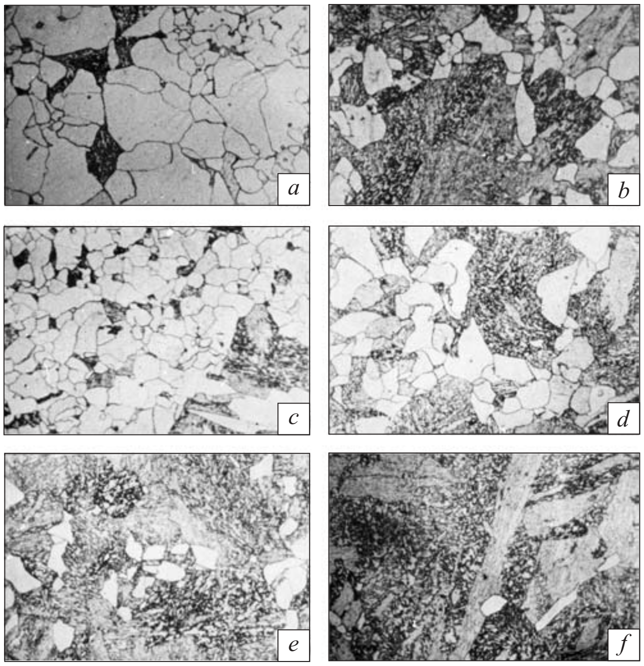

Fig. 4. Structure of steels 15Kh3M1FL and 15Kh3M1FTsL after 5-h hardening from 1000°C with different cooling rates (× 100): *a*, *b*) 200 K/h; *c*, *d*) 400 K/h; *e*, *f*) 600 K/h.

The metal hardened from 975°C has a fine-grained homogeneous structure represented by a ferrite-bainite mixture (Fig. 3). Table 7 shows that the rate of cooling from the temperature of austenization influences substantially the properties of the metal. For example, cases of abrupt decrease in the strength ($\sigma_{0.2}$ = 360 – 380 MPa) and ductility (δ = 10 – 11%, ψ = 24%) were observed in cooling with v_{cool} = 200 K/h. In cooling at v_{cool} = 400 – 600 K/h the properties stabilize and fully meet the requirements of the performance specification. These results are confirmed by the data of metallographic analysis, which reflect the presence of a higher amount of products of diffusion decomposition of austenite at v_{cool} = 200 K/h than at higher cooling rates (Fig. 4). The

TABLE 7. Effect of Cooling Rates in Hardening on Mechanical Properties of Steels 15Kh3M1FL and 15Kh3M1FTsL

Steel	v_{cool}, °C	$\sigma_{0,2}$, MPa	σ_r, MPa	δ, %	ψ, %	*KCU*, MJ/m^2
15Kh3M1FL	200	430	600	10	24	0.9
		360	560	20	64	0.7
	400	500	660	18	60	0.6
		440	610	17	61	0.7
	600	450	620	18	58	1.0
		520	660	19	62	0.9
15Kh3M1FTsL	200	440	620	11	40	0.7
		380	580	21	58	0.8
	400	470	630	21	64	0.7
		460	620	20	66	0.9
	600	470	650	20	64	1.0
		500	670	18	65	0.7

Note. The properties of the steels are presented after 10-h hardening from 1000°C and 10-h tempering at 680°C.

TABLE 8. Effect of Tempering Temperature on Mechanical Properties of Steels 15Kh3M1FL and 15Kh3M1FTsL

Steel	t_{temp}, °C	$\sigma_{0,2}$, MPa	σ_r, MPa	δ, %	ψ, %	*KCU*, MJ/m^2
15Kh3M1FL	680	490	640	18	60	0.7
		510	670	17	58	0.8
	700	500	660	21	66	1.0
		485	640	20	67	1.1
	720	480	635	21	62	1.4
		475	630	22	64	0.9
	740	455	620	22	63	1.4
		445	620	22	60	1.3
15Kh3M1FTsL	680	500	660	19	62	0.7
		500	670	17	59	0.9
	700	460	630	20	64	0.8
		465	630	21	60	1.0
	720	480	650	20	65	1.0
		460	630	19	64	1.5
	740	440	610	23	66	1.5
		445	610	22	65	1.1

Note. The properties of the steels are presented after 10-h hardening from 1000°C and tempering.

steel modified with zirconium has a better combination of properties.

Development of the mode of tempering. We studied the effect of tempering temperatures (680 – 740°C) on mechanical properties. The data presented in Table 8 show that the properties of the experimental steels after tempering in the studied temperature range fully meet the requirements of the specification. The optimum level of mechanical properties is ensured after tempering at 700 – 720°C. In addition, tempering in this temperature range should reduce the residual stresses in the casting, which makes it suitable for commercial production. After tempering at 740°C the yield strength decreases to the specified level. It should also be noted that the temperature of 740°C is close to point Ac_1 for the studied steels, which makes tempering at 740°C undesirable.

The suggested mode of heat treatment of large castings should decrease the content of hydrogen in the metal, provide a uniform structure over the cross section of the casting, and thus ensure a favorable combination of mechanical properties, a low cold-shortness threshold, and minimum residual stresses [3].

In the process of heat treatment special attention should be devoted to the cooling rate in hardening, because it influences considerably the properties of the casting, especially its strength. For this reason, it is expedient to resort to air blow by powerful fans or to water-air cooling for large castings [4].

As for the tested steels, we should mention a certain advantage of the steel with zirconium detectable in the course of our study. However, we cannot give this composition an unambiguous preference.

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