Rational chemical composition and heat treatment models of rails made from E76HF steel using the heat of rolling heating

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Abstract. On the pilot plant the experiments in the differentiated heat treatment by air using the heat of rolling heating of rails produced from steel E76HF with three chemical compositions comprising various contents of chromium, manganese and silicon were carried out. The effect of heat treatment parameters on the structure and properties of rails was examined. According to the results of experiments the rational chemical composition was determined, as well as the heat treatment modes recommended for a mass production of differentially thermo-strengthened rails of DT350 category.

1. Introduction

Thermal hardening is one of the effective ways to enhance the performance properties of metal, so at the moment most of the rails produced in the world are subjected to a hardening heat treatment [1-5]. Until recently, the process of production of rail products by the domestic enterprises included a separate heating of the rails before their volumetric oil hardening [5-7]. Compared with the rails hardening using heat of the rolling heating this technique is more expensive. However, as it is known, the rail steel possesses high flake sensitivity [8], and for prevention of flakes formation at the time of technology development for volumetric hardening, rails after rolling were subjected to slow cooling.

After introduction in the production of the steel vacuumization the main reason of flakes formation – high hydrogen content has been eliminated. This allowed without losses in quality of rails the heat treatment technology from the rolling heat to be applied, which was implemented by several foreign rails producers. In 2005 at JSC "NKMK" was put into operation the vacuum vessel, and in 2007 it was decided to conduct a staged reconstruction of rail production, with the introduction of a differentiated line of hardening by air from the rolling heat. In order to identify promising chemical compositions of the rail steel and the modes of heat treatment of rails by air from the rolling heat, a series of experiments was conducted in heat treatment of rail samples on the pilot unit using a separate and rolling heating.

The description of a unit, methods and results of the experiments are presented in [9]. The experimental results of the treated rail samples produced from steel of grade E76F are presented in [10]. In our earlier studies [10] we found that during hardening rails, produced from steel E76F, by rolling heating the necessary level of strength properties and hardness is achieved by hardening at a


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sufficiently high rate – not less than 4°C/sec (about 4000 mm H_2O), and the plastic properties are at a quite low level and do not meet the standard requirements. To improve the complex of properties and determine the optimal in terms of resource saving heat treatment parameters we conducted experiments of heat treatment of rail samples from carbon steel alloyed with manganese, silicon, chromium and vanadium.

2. Material and research methods

The study object of this paper are thermally hardened by compressed air on the pilot unit sample of length ~ 400 mm, selected from hot-rolled rails of type R65, steel E76HF according to the State Standards (GOST) R 51685. The rolling of the rails was carried according to the current technology. From the bottom end of the feed on the hot cutting saws 2-3 samples were selected. Reaching the temperature of the hardening start one sample was cooled in the pilot unit, the rest all the time remained in the bucket with hot rail crop for prevention of a significant temperature drop.

Samples, selected on the hot cutting saws at a temperature of 900-940°C, were subjected to subcooling to temperatures 750-900°C and hardening with the rate up to 8°C/s at different modes.

The temperature during the experiments was recorded by manually infrared pyrometer of type Raynger MX.

After experiments from the upper part of the head of each probe in accordance with requirements of GOST 51685 samples were cut to determine by Brinell method the hardness on the rolling surface and along the head cross-section, to test for tension and the impact bending, microsections for microstructure control. The hardness test was conducted by the method of Brinell on the hardness tester of TSh-2M type by the ball with diameter of 10 mm under load of 3000 kgf according to GOST 9012-59. Tension properties were determined on the tension testing machine EU-40 with the force of 10 tonnes on the cylindrical samples of 6 mm in diameter and the initial effective length of the working part 30 mm, prepared in accordance with the requirements of GOST 51685 and GOST 1497.

Impact bending test was performed on the impact pendulum-type testing machine MK-15 in accordance with GOST 9454 on the standard samples of sized 10x10x55 mm with U-shape cut of radius 1 mm and depth 2 mm at temperatures of +20°C and -60°C. The metal microstructure was revealed by electrolytic polishing of the microsection surface in 5% acetic solution of perchloric acid and etching in 4% alcoholic solution of nitric acid.

3. Development of a chemical composition for research

The development of advanced chemistry compositions was performed on the basis of rails with the category T1 (NE), micro-alloyed with vanadium in the amount of 0.07-0.08%. Traditionally manganese and silicon are introduced into the rail steel that enhance the strength properties of the steel.

However, studies showed [10] that air hardening due to its low cooling capacity, containing ~ 0.30% of silicon and up to 0.90% of manganese, failed to achieve a balanced set of properties meeting the regulatory documents requirements. Therefore, to provide the desired standard properties an additional alloying with austenite-stabilizing elements was needed.

One of the most common and widely available elements enhancing depth of hardening and hardening capacity of steel, is chrome. In order to achieve the desired set of properties under moderate conditions of heat treatment the minimal chromium content was limited at the level of 0.35-0.40%. It should be noted that chromium has a significant influence on the weldability of steel, which is especially important due to the annual increase in the length of the welded rail joints on the network of JSC “Russian Railways”, so during development of the chemical composition the upper limit of the chromium content was limited at level 0.50-0.55%.

Based on the above considerations variants for experimental steels No.1 and No.2 were proposed which are similar in chemical composition of the rails of T1 (NE) category of the current production and differed in chromium content, the quantity of which amounted to 0.42% and 0.55% respectively.

On the basis of previous experiments [9] on air hardening from a separate heating, it was found that the optimum ratio of strength and plastic properties is achieved in the steels rails with high silicon content, with a moderate content of manganese and chromium. On this basis we developed an experimental variant of chemical composition No.3 differing from No.1 and 2 in the lower content of manganese (0.78%), higher silicon content (0.55%) and moderate amounts of chromium (0.46%).

For experiments on heat treatment on the basis of the offered recommendations three experimental melts were performed O74, O77, O76. The smelting of the experimental material was carried out in the electric arc furnaces of 100 tonnes. Casting of the vacuum degassed metal took place in CCM in the form of billets with section 300x330 mm. Heating of continuous cast steel billet in the WB furnace and rolling were carried out according to the current rails production technology of R65 type. The content of chemical elements in the metal of experimental melts defined by the chemical and spectral method is presented in Table 1.

Table 1. Contents of chemical elements in the experimental metal.

Variant No.	Mass concentration of chemical elements, %									
	C	Mn	Si	Cr	P	S	Al	V	Ni	Cu
O74	0.76	0.87	0.32	0.55	0.015	0.006	0.002	0.07	0.08	0.13
O77	0.77	0.91	0.31	0.42	0.015	0.008	0.003	0.08	0.07	0.12
O76	0.79	0.78	0.55	0.46	0.014	0.015	0.002	0.07	0.08	0.14
GOST requirements R 51685-2013 for steel E76HF	0.74-0.82	0.75-1.15	0.20-0.80	0.20-0.60	not less 0.025	not less 0.025	not less 0.005	0.03-0.15	not less 0.20	not less 0.20

3.1. Heat treatment of rail steel – melt O74

The heat treatment of rails square. O74 chromium content of 0.55% was carried out by temperature 705 - 850° C at the rate of 2.4 - 2.8 0C / s during 105 - 125 s. Modes of heat treatment and mechanical test results are presented in Table 2.

Table 2. Heat treatment parameters using heat of rolling heating and mechanical properties of rails R65 from steel grade E76HF – melt O74.

No.	Heat treatment parameters			Mechanical properties				KCU, at temperature		Hardness over the head cross-section, HB				
	T, °C	Cooling rate °C/sec	Time, sec	σ_{yield}	σ_{ten}	δ_5	ψ	+20 °C	-60 °C	HB_{rail} tread top	HB_{10}	HB_{22}	HB gage corner 1	HB gage corner 2
				N/mm^2		%		J/cm^2						
1.1	750	2.8	125	960	1370	10.5	36	23	8.5	406	406	398	415	415
1.2	780	2.8	125	1040	1400	9.4	35	20	9.7	415	415	395	415	415
1.3	815	2.8	125	1000	1410	14	30	16	4.9	420	415	406	415	415
1.4	845	2.8	125	1020	1410	11	27	14	6	429	406	393	415	415
1.5	700	2.4	105	760	1230	10	18.5	12	3.6	380	380	388	359	361
1.6	780	2.4	120	970	1380	11.5	27	8.4	6	411	390	385	395	393
1.7	850	2.4	120	950	1380	15	31	22	6	415	415	404	409	409
GOST requirements R 51685-2013 for rails of category DT350				not less 800	1240	9.0	25.0	15.0	-	363-401	not less 341	341	341	

The presented in Table 2 data show that all test samples except sample No. 1.5, showed high values of ultimate strength and yield stress and plastic properties of satisfactory values. Sample No. 1.5 was

treated by heat from 700 °C. During tensile test the metal showed the values of mechanical properties which do not meet the standard requirements for heat hardened rails.

With the increase in the cooling rate the strength properties and hardness improve over the head cross-section. Among the samples No. 1.1-1.4, hardened at 2.8 °C/sec, there is a tendency to increase the strength properties and reduce specific elongation and impact viscosity with the temperature of the start of heat treatment.

The impact viscosity of the rails hardened at lower rate (2.4 °C/sec) showed lower values not satisfying the standard requirements. The experimental rails are characterized by high values of hardness over the head cross-section, and except for the rail, strengthened at the temperature from 700°C, exceed the set by the standard maximal allowable hardness values on the surface of the head rolling.

Impact tests at temperatures below freezing showed a low level of impact viscosity of all experimental metal not exceeding 10 J/cm2.

The metal microstructure of experimental rails is a thin-plate and sorbitic pearlite. From the rolling surface of the head in the head centre and from the fillets to a depth of 11 mm in samples No. 1.1-1.4, hardened at 2.8 °C/sec, we observed the intermediate transformation products, unacceptable according to the requirements of normative and technical documentation on rail products. As the temperature of the beginning of heat treatment lowers the tendency appears to increase the magnitude of the layer with the presence of a bainite structure.

With a decrease in the cooling rate to 2.4°C/sec the layer depth with the areas of bainitic structures is reduced to 0.3-0.5 mm. Metal sample No. 1.5 does not contain bainite; pearlite has a rough, lamellar structure.

3.2. Heat treatment of rail steel – melt O77

The rails heat treatment of type R65 melt O77 with chromium content of 0.42% was carried out at the rate 2, 2.4, 2.8 °C/sec, from the temperatures 750-860°C during 120-125 sec. The heat treatment parameters and results of mechanical tests parameters are given in Table 3.

From the data presented in Table 3 it can be seen that the metal of this group is characterized by high values of hardness on the rolling surface and over the head cross-section, very high strength properties and relatively low level of plastic properties, mainly the relative contraction. Fully complies with the standard for rails DT350 category only metal sample No. 2.4, heat-treated for 125 sec with a cooling rate 2.8°C/sec from 810°C.

The temperature of the beginning of hardening at a given cooling rate or decrease in the cooling rate ceteris paribus leads to a decrease in the values relative of relative contraction.

Table 3. Parameters of heat treatment and mechanical properties of rails R65 from steel grades E76HF – melt O77.

No.	Heat treatment parameters			Mechanical properties				KCU, at temperature		Hardness, HB				
	T, °C	Cooling rate, °C/sec	Time, sec	σ_{yield}	$\sigma_{tensile}$	δ_5	ψ	+20 °C	-60 °C	HB_{rail} tread top	HB_{10}	HB_{22}	HB gage corner 1	HB gage corner 2
				N/mm^2		%		J/cm^2						
2.1	780	2.8	125	980	1380	13	30	21	10	420	404	390	404	401
2.2	780	2.8	125	940	1360	13	25	8.4	8.4	423	409	395	401	401
2.3	802	2.8	125	980	1380	9.3	26	19	9.7	415	415	401	415	415
2.4	810	2.8	125	940	1370	9	26	15	6	398	409	393	415	415
2.5	830	2.8	125	1010	1400	11.5	22.5	16	8.4	415	409	395	415	415
2.6	860	2.8	125	990	1400	11.5	21.5	22	9.7	404	404	398	415	415
2.7	760	2.4	120	880	1350	9.9	21.5	17	6	423	404	398	404	401
2.8	800	2.4	120	930	1230	8.9	23.5	19	12	409	409	401	401	401
2.9	870	2.4	120	950	1360	9.2	24	19	6	409	409	409	409	404

2.10	750	2	120	900	1350	12.5	23	11	12	401	390	390	383	383
2.11	790	2	120	900	1350	12.5	23.5	17	8.4	409	395	383	395	395
2.12	845	2	120	920	1340	11.5	24	18	6.1	404	404	393	409	409
GOST requirements R 51685-2013 for rails of category DT350				not less					-	363-401	not less			
				800	1240	9.0	25.0	15.0			341			

In the microstructure of samples No. 2.1, 2.2 and 2.7 with the temperature of the beginning of heat treatment 780-760°C, from the rolling surface, in the centre and from the fillets side, to a depth of 3 mm and 1.5 mm respectively, we observed areas of bainite.

3.3. Heat treatment of rail steel – melt O77

In view of the fact that melt O76 was made in accordance with the recommendations [9] obtained earlier, based on the positive results in experiments on differential hardening of rail samples by furnace heating, then the metal of this melt was used for the largest number of experiments, at different modes about 50 samples of rails R65 were hardened. The heat treatment was carried out rails at a cooling rate from 2 to 3.3°C/sec for 60-160 seconds. Below we summarize the results of the tests.

Hardening at 2°C/sec

Table 4 contains the data on heat treatment of rails melt O76 at a cooling rate by air 2°C/sec.

From the data presented in Table 4 it can be seen that with the temperature increase of the beginning of hardening and cooling duration the mechanical properties are improved. At lower temperatures of the beginning of hardening, a relatively low level of plasticity properties are observed.

The highest properties are obtained by hardening 800°C/sec.

Hardening at 2.4°C/sec

The test results of metal hardened at a rate 2.4°C/sec are given in Table 5, from which it follows that for all samples relatively high properties were obtained. With the temperature increase of the beginning of hardening the yield strength rises at a comparable level of ultimate tensile strength and plastic properties. The best level of impact viscosity we obtained in the samples hardened from the temperature ~750°C.

Hardening at 2.8°C/sec

Test results of the metal hardened at a rate 2.8°C/sec are shown in Table 6.

From the data presented it can be seen that at hardening rate of 2.8°C/sec for 60 sec the requirements of mechanical properties of GOST R51685-2013 are meet, but at a depth of 22 mm a low hardness was found. With the increase of the cooling duration the level of strength properties and hardness increases as well. For all samples except for sample No. 1.13, hardened from the temperature of 700°C, a satisfactory level of impact strength at a test temperature of + 20°C was observed.

Table 4. Parameters of heat treatment and mechanical properties of rails from melt O76 at a cooling rate by air 2°C/sec.

No.	Heat treatment parameters			Mechanical properties				KCU, at temperature		Hardness, HB				
	T, °C	Cooling rate, °C/sec	Time, sec	σ_{yield}	$\sigma_{tensile}$	δ_5	ψ	+20°C	-60°C	HB_{rail} tread top	HB_{10}	HB_{22}	HB gage corner 1	HB gage corner 2
				N/mm^2		%		J/cm^2						
2.1	780	2.8	125	980	1380	13	30	21	10	420	404	390	404	401
2.2	780	2.8	125	940	1360	13	25	8.4	8.4	423	409	395	401	401
2.3	802	2.8	125	980	1380	9.3	26	19	9.7	415	415	401	415	415
2.4	810	2.8	125	940	1370	9	26	15	6	398	409	393	415	415
2.5	830	2.8	125	1010	1400	11.5	22.5	16	8.4	415	409	395	415	415
2.6	860	2.8	125	990	1400	11.5	21.5	22	9,7	404	404	398	415	415
2.7	760	2.4	120	880	1350	9.9	21.5	17	6	423	404	398	404	401
2.8	800	2.4	120	930	1230	8.9	23.5	19	12	409	409	401	401	401

2.9	870	2.4	120	950	1360	9.2	24	19	6	409	409	409	409	404
2.10	750	2	120	900	1350	12.5	23	11	12	401	390	390	383	383
2.11	790	2	120	900	1350	12.5	23.5	17	8.4	409	395	383	395	395
2.12	845	2	120	920	1340	11.5	24	18	6.1	404	404	393	409	409
GOST requirements R 51685-2013 for rails of category DT350				not less					-	363-401	not less			
				800	1240	9.0	25.0	15.0			341			

Table 5. Parameters of heat treatment and mechanical properties of rails from melt O76 at cooling rate by air 2.4°C/sec.

No.	Temp at the beginning, °C	Time, sec	Mechanical properties				KCU at temperature		Hardness, HB				
			σ_T	σ_B	δ	ψ	+20 °C	-60 °C					
			N/mm^2		%		J/cm^2		HB_{rail} tread top	HB_{10}	HB_{22}	HB_{gage} corner 1	HB gage corner 2
1.7	735	105	935	1360	10	29	12	8.4	415	401	383	395	393
1.8	745	135	940	1375	10.5	32	20.5	7.3	409	401	383	395	401
1.9	750	125	960	1360	11	34	20	6.1	415	401	378	406	398
1.10	810	125	960	1375	10	32	16	6.2	415	409	390	406	415
1.11	830	135	975	1375	10	34	16.5	7.4	415	415	388	415	388
1.12	850	125	970	1370	9.8	30	6.1	7.2	415	401	375	401	398
GOST requirements R 51685-2013 for rails of category DT350			not less						363-401	not less			
			800	1240	9.0	25.0	15.0	-		341			

Hardening at 3.3°C/sec

Data from test samples hardened at a rate 3.3°C/sec are shown in Table 7.

The presented data show that during hardening at a rate of 3.3°C/sec sufficiently high properties throughout the temperature range of the hardening start – from 700 to 880°C were obtained. The increase in the heat treatment duration leads to a significant increase of strength properties and hardness; with the reduction in cooling duration the impact viscosity increases.

Metal microstructure of all rails melt O76 is a thin-plate pearlite with scattered ferrite formations on the grain boundaries. Bainite is not detected in the microstructure of the rails. Some increase in the volume fraction of the structure-free ferrite with the decrease of the temperature of the hardening start.

Table 6. Parameters of heat treatment and mechanical properties of rails from melt O76 at a cooling rate by air 2.8°C/sec.

No.	Temp at the beginning, °C	Time, sec	Mechanical properties				KCU at temperature		Hardness, HB				
			σ_{yield}	$\sigma_{tensile}$	δ	ψ	+20°C	-60°C					
			N/mm^2		%		J/cm^2		HB_{rail} tread top	HB_{10}	HB_{22}	HB_{gage} corner 1	HB gage corner 2
1.13	700	125	925	1350	12.5	29	10.1	7.7	415	412	393	401	401
1.14	760	110	975	1380	10.5	33	17	6.6	415	404	388	415	406
1.15	775	105	940	1370	10	31	21	6.1	409	406	388	409	409
1.16	810	60	850	1260	11.5	25	23.5	8	378	363	333	375	370
1.17	840	70	850	1255	11.5	26.2	23.5	7.9	378	356	337	368	370
1.18	840	125	995	1395	9.8	28	18	7.3	438	420	401	423	417
1.19	865	115	955	1390	10.2	30	21	8.6	412	401	383	409	401
GOST requirements R 51685-2013 for rails of category DT350			not less					-	363-401	not less			
			800	1240	9,0	25	15			341			

Table 7. Parameters of heat treatment and mechanical properties of rails from melt O76 at a cooling rate by 3.3°C/sec.

No.	Temp at the beginning, °C	Time, sec	Mechanical properties				KCU at temperature		Hardness, HB				
			σ_{yield}	$\sigma_{tensile}$	δ	ψ	+20°C	-60°C	HB_{rail} tread top	HB_{10}	HB_{22}	HB_{gage} corner 1	HB gage corner 2
			N/mm^2		%		J/cm^2						
1.19	700	125	950	1355	10	27	16,5	7,5	426	404	395	406	406
1.20	770	125	960	1365	10	31	15	9,2	426	409	393	409	406
1.21	787	90	895	1290	13,1	25,2	20	8	388	383	370	385	383
1.22	800	110	945	1370	11,3	29,5	15,5	7,2	415	409	388	409	409
1.23	840	105	890	1290	13,5	28	25,5	10	388	383	368	388	385
1.24	850	100	970	1380	9,8	28	15	8	406	404	375	393	398
1.25	880	125	985	1385	10,5	32	16	8	426	409	390	409	409
GOST requirements R 51685-2013 for rails of category DT350			not less					-	363-401	not less			
			800	1240	9,0	25	15			341			

4. Conclusions

The performed studies revealed that:

- The most consistent results for the microstructure, without occurrence of needle structures in the largest temperature range (from 700 to 880°C) and cooling rates (from 2 to 3.3°C/sec) are provided by heat treatment of metal melt O76.
- Hardening of rails from steel of grade E76HF at a temperature below 730-750°C might result on poor plasticity properties.

Thus, the most promising for the commercial production is the rail steel close in its chemical composition to the metal of melt O76 with chromium content in the range of 0.38-0.43%; silicon 0.54-0.60%; manganese 0.80-0.90%; vanadium 0.03-0.04%. This chemical compound has high processability, since it can be processed in the wide temperature range of the beginning of hardening – from 700 to 880°C, and at various cooling rates – from 3.3 to 2°C/sec.

For the industrial implementation it is recommended:

- To provide a high performance it is recommended to perform heat treatment at temperatures above 800°C;
- To improve the efficiency it is recommended to perform heat treatment at a cooling rate of 2-2.4°C/sec;
- Optimal cooling duration 90-110 sec.

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