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INFLUENCE OF CONTENT OF ALLOYING ELEMENTS AND HEAT TREATMENT ON LIFE CHARACTERISTICS OF HIGH-STRENGTH WHEEL STEELS DURING MANUFACTURE OF RAILROAD WHEELS AND THEIR REPAIR SURFACING

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A new concept of creating steels to provide high resistance of the rolling surface of wheels to wear and damage was proposed, requirements for a set of mechanical characteristics of such steels were developed and chemical composition of steel of a new generation for railroad wheels, as well as heat treatment mode during their repair surfacing were substantiated. 15 Ref., 2 Tables, 4 Figures.

Keywords: *high-strength railroad wheels, slid flat, shelled tread, wear, operational reliability*

Growth in the axial load and speed of railway transport requires the creation of high-strength wheel steels, at the same time providing reliability and long life of railroad wheels. Until recently, reducing wear of their rolling surface was one of the most important tasks in solving this problem, which in the world practice was solved by developing low-alloy carbon steels with an increased carbon content (0.6–0.7 %), hardness (>*HB* 300) and tensile strength (>1000 MPa). In particular, in Ukraine, the steel of grade T was proposed to replace the steel of grade 2 [1]. However, the experience in operation of such high-strength wheels showed that on their rolling surface a number of operational damages (slid flats, shelled treads, etc.) grows significantly [2], which results in reducing service life of wheels and the need in expensive reprofiling (machining) of their rim.

Defects on the rolling surface of wheels are caused primarily by initiation and growth of surface and subsurface cracks as a result of a contact fatigue of the metal, as well as crack formation resulted by changes in structure and phase composition under a thermal impact on the metal during braking and cornering. In general, this is the result of the influence of an increased carbon content in such wheel steels on its susceptibility to martensitic transformation [2]. A similar problem of the negative impact of a high carbon content exists during repair surfacing of wheels because of cracking in the heat-affected-zone [3]. Therefore, steels for railroad wheels of a new generation must be high-strength at a low carbon content, have a high crack resistance and an increased thermal stability of the structural-phase composition and mechanical properties. As far as the wheels receive mainly cyclic loads, a preference should be given to the characteristics of cyclic crack resistance of wheel steels. As a result, wheel steels with an increased service life should optimally combine high characteristics of strength and cyclic crack and wear resistance and resistance to contact-fatigue damage formation.

The negative effect of reducing carbon content on the strength of wheel steels should be compensated by their additional alloying. However, the use of chromium, molybdenum and nickel can significantly increase the cost of steel. It is more rational to increase the content of silicon and manganese (promotes a solid-solution strengthening and reduces sensitivity to heat and contact fatigue) [4] and microalloy steel with vanadium and nitrogen (promotes dispersion strengthening due to the formation of nitrides and carbonitrides, which hinder the recrystallization process, providing structural strengthening of steel) [5]. Data on the life characteristics of such complex alloyed steels are almost absent in the literature.

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Table 1 Chemical composition and mechanical characteristics of wheel steels

Variant of steel	C, wt.%	Si, wt.%	Mn, wt.%	[VN]·10^4, wt.%	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %	ΔK_{1th}, MPa·√m	ΔK_{1fc}, MPa·√m
1	0.60	0.34	0.64	–	670	1010	11.5	7.0	100
2	0.63	0.72	0.32	–	1080	1250	10.5	6.6	65
3	0.63	0.18	0.76	8.1	486	843	16.8	6.5	73
4	0.56	0.22	0.87	11.6	547	756	22.2	–	–
5	0.63	0.13	0.65	15.6	520	789	14.6	–	–
6	0.57	0.27	0.85	22.1	877	592	17.0	6.6	87
7	0.61	0.26	0.65	41.9	520	810	18.7	6.6	83
8	0.58	0.97	0.85	–	735	1051	10	6.0	52
9	0.52	0.67	0.81	28.9	806	1025	17.7	6.0/5.0	80/65
10	0.45	1.44	1.36	18.7	869	1060	15	6.3	59

Note. Variants 1 and 2 — steels of grades 2 and T, respectively [1]; variant 8 — steel of grade K [6]; the rest are test steels.

Materials and procedures. Standard high-strength wheel steels of grades 2 and T (Table 1, variants 1 and 2) and new (with solid-solution or nitride strengthening as well as at the simultaneous combination of solid-solution and nitride strengthening) steels for railroad wheels were studied (Table 1, variants 3−10). The investigations were carried out on the specimens cut out from the wheels manufactured according to the technology of PJSC «INTERPIPE NTZ» from steels of grades 2, T and K (variants 1, 2 and 8), as well as from the experimental castings after thermal and thermomechanical treatments (Table 1, variants 3−7, 9, 10), produced according to the technology of PTIMA of the NAS of Ukraine.

The mass fraction of carbon, sulfur and phosphorus was determined according to the standards of GOST 12344–88, GOST 12345−88, GOST 12347−88; nitrogen — by the method of melting specimens in a flow of helium with a purity of 99.99 % in the analyzer TC-30 of the LECO Company; other elements — using the spectral analysis in the installation «Spectromax» according to GOST 18895–97.

Structural stresses of the II kind (τ_{loc}) were determined by the calculation method, using the established indices of the dislocation structure [3]: $\tau_{loc} = Gb\rho t/\pi(1 - v)$ where G is the displacement modulus; b is the Burgers vector; ρ is the density of dislocations, v is the Poisson's ratio, and t is the thickness of the foil.

A short-term strength (yield strength $\sigma_{0.2}$ and tensile strength σ_t) and ductility (relative elongation b) were determined on five-fold cylindrical specimens with a diameter of the working part of 3 or 5 mm at temperatures from 20 to 800 °C.

The characteristics of cyclic crack resistance of steel at a normal tear were determined according to the diagrams of growth rates of fatigue macrocrack — dependences $da/dN - \Delta K_I$ obtained according to the standard procedure (ASTM E647–08) on the compact specimens with a thickness of 8–10 mm at a frequency of 10−15 Hz and the loading cycle asymmetry coefficient $R = 0.1$. As the characteristics of cyclic crack resistance of materials, the fatigue threshold $\Delta K_{th} = \Delta K_{10^{-10}}$ and the cyclic fracture toughness $\Delta K_{fc} = \Delta K_{10^{-5}}$ — ranges of the stress intensity factor at the crack growth rate $da/dN = 10^{-10}$ and 10^{-5} m/cycle, respectively, were selected. In some cases, the values of ΔK_{fc} were set on the range ΔK, when fatigue crack begins to grow spontaneously.

The damage tests were performed on the model specimens of a wheel of 8 mm thickness and 40 mm in diameter in contact with a rail of 220 mm long, 8 mm wide and 16 mm high. The wheels were manufactured of the above-described steels, and the rails were cut out from the head of the natural rail with a hardness of *HRC* 46. The tests were carried out in a specially designed bench [7] under the load on the wheel $P = 1300$ N, which creates stresses in the contact zone of the wheel-rail $p_0 = 750$ MPa, determined by the known Hertz formula.

The rolling surfaces of the wheels were studied under the microscope after $2\cdot10^5$ load cycles (25 km on track) at a magnification of 130 times. The images were analyzed using a specially designed computer program and the average number of defects ‾, mm^{-2} in field of vision of the microscope was determined depending on their size in different parts of the rolling surface and the damage was evaluated by the ratio of the area of shelled treads formed by pitting formation and delamination (F_d) to the total area of the rolling surface of a wheel (F_0). In the conditions of contact fatigue, the damage resistance ($1/D$) and the wear resistance ($1/W$), which are the inverse values respective to the damage $D = F_d/F_0$ and wear $W = (R_0 - R)/R_0$ of the rolling surface of the model wheel were evaluated, where F_d is the area of defects (pitting and shelled treades), F_0 is the area of rolling surface; R is the radius of the wheel after tests; R_0 is its initial value. The averaged values of the characteristics based on the results of the tests of at least three specimens were given.

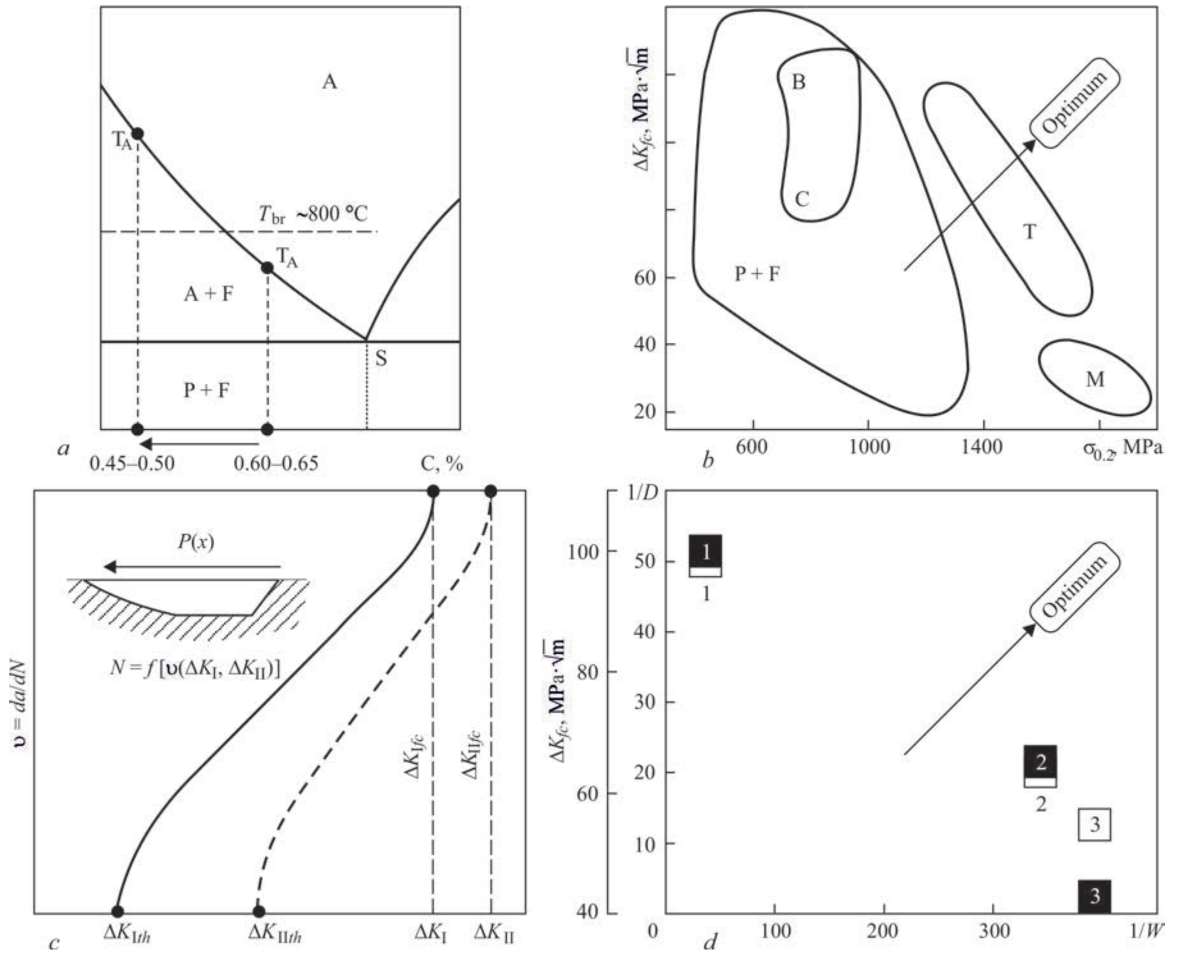


Figure 1 New concept of creating high-strength wheel steels: T_A — austenitization temperature; T_{br} — temperature in the area of wheel-rail contact during braking; A — austenite, F — ferrite, P — pearlite, B — bainite, M — martensite, T — troostite, S — sorbite; 1 — steel of grade 2, 2 — of grade T, 3 — of grade T_m. Light symbols – diagram ($1/D$ – $1/W$); dark – (ΔK_{fc} – $1/W$); description *a–d* see in the text

Results of investigations. *New concept for the development of high-strength wheel steels.* Based on the data of the analysis of operational damages of wheels of type KP-2 and KP-T on all road network of the Ukrzaliznytsia, as well as laboratory investigations of life characteristics of steels of grades 2 and *T*, it was established that mechanical behavior of these steels under the influence of operational factors depends on the carbon content [2]. The obtained results substantiated the need in changing the concept of selection (development) of steels to increase the long life of high-strength railroad wheels, which should be carried out both according to the criterion of wear (which determines the strength and hardness of steels), as well as on the criterion of arising shelled treads of the rolling surface (which determines the crack resistance of steels). An increased (up to 0.7 %) carbon content in the steel of grade T, causing an increase in wear resistance (hardness), facilitates its susceptibility to martensitic transformation, an increase in residual stresses of the II type and, as a result, a decrease in cyclic crack resistance [2]. It was established that a contact-fatigue damage unambiguously depends on the cyclic fracture toughness of steel under the conditions of normal tear (ΔK_{Ifc}) and transverse displacement (ΔK_{IIfc}): it is the largest in the model wheels of the steel, which has the lowest cyclic fracture toughness. At the same time, such an unambiguous dependence is absent when as a determining parameter of crack resistance a fatigue threshold ΔK_{Ith} and ΔK_{IIth} is taken [7, 8].

As a result, a new concept of developing high-strength wheel steels [2] was proposed, which is based on the approaches of structural fracture mechanics (Figure 1). It envisages (Figure 1, *a*) the need in the maximum possible reduction in carbon content to prevent martensitic transformation during braking and crack formation in repair surfacing. It includes the search on the basis of diagrams of structural strength of wheel steels, which provide an optimal combination of characteristics of their strength and crack resistance, taking into account their structure (Figure 1, *b*) and the mechanisms of fracture under the conditions of normal tear and transverse displacement (Figure 1, *c*) to minimize crack formation on the rolling surface of wheels. It regulates the need in providing an opti-

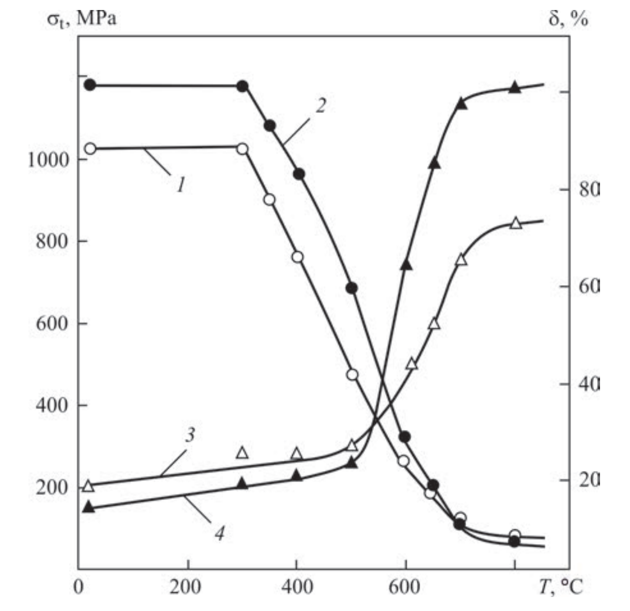


Figure 2 Temperature dependence of strength (1, 2) and ductility characteristics (3, 4) of steels of grades 2 (1, 3) and T (2, 4)

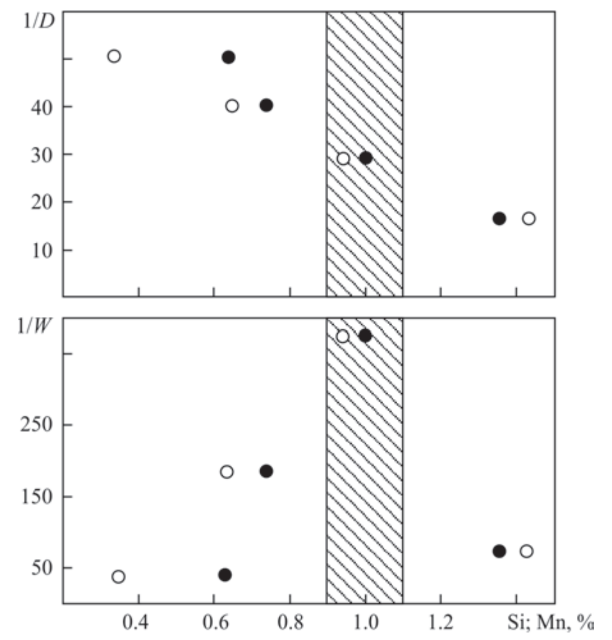


Figure 4 Dependence of resistance to damage and wear on silicon and manganese content, as well as their recommended content (shaded area)

mal combination of their characteristics of wear resistance and a contact-fatigue damage (Figure 1, *d*). Therefore, as the main characteristic of a service life and reliability of wheel steels the diagram was proposed [9], which demonstrates operational reliability (Figure 1, *d*) — dependence between cyclic fracture toughness (ΔK_{fc}), which determines resistance to formation of operational defects on the rolling surface of wheels (1/*D*), and resistance to wear of the flange and rolling surface of wheels (1/*W*). It is obvious that the desired optimum will be located in the upper right corner of this diagram (Figure 1, *d*).

It was also proposed [2] that the second main characteristic of service life and reliability of wheel steels, which determines their susceptibility to formation of slid flats on the rolling surface of wheels, is the dependence of ductility (relative elongation) at temperatures above 500 °C, in particular, at 700 °C, which in this case is informative in contrast to the strength characteristics (Figure 2): the higher the values of δ^{700}, the higher the susceptibility of steel to formation of slid flats [2].

Substantiation of chemical composition of the new high-strength wheel steel. Steel of grade T with a high carbon content (Table 1, variant 2) is introduced for manufacture of high-strength railroad wheels instead of steel of grade 2 (variant 1), it has a high yield and tensile strength, but an elevated high-temperature ductility δ^{700} and a low cyclic toughness of fracture ΔK_{fc}, which causes its high wear resistance at a low damage resistance (Figure 3, *a*) and an increased susceptibility to formation of slid flats (Figure 3, *b*). During microalloying with vanadium and nitrogen, the steels with disper-

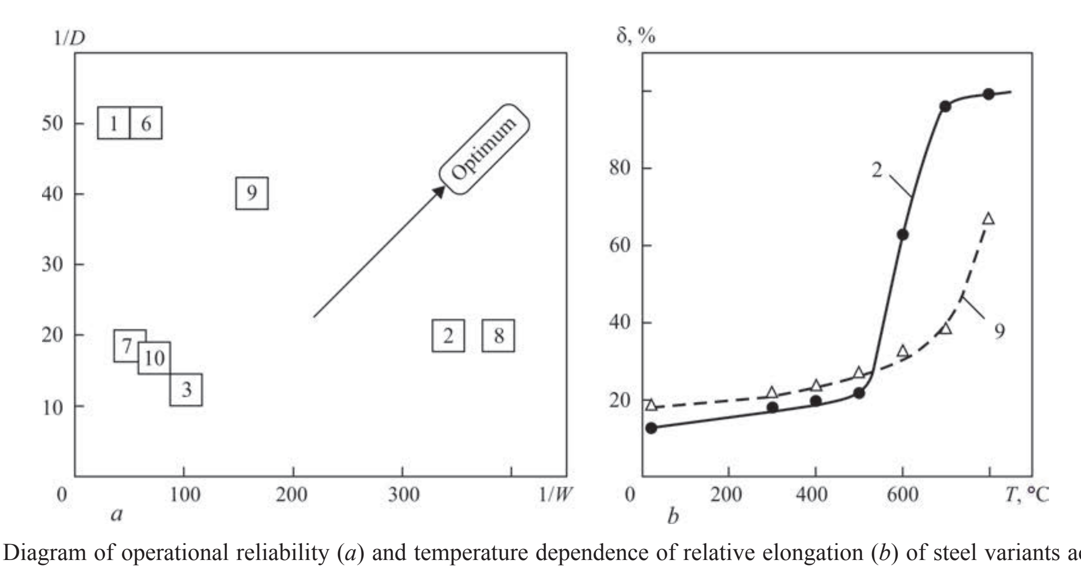


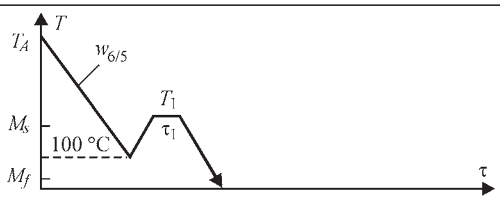
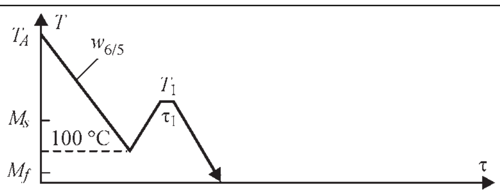
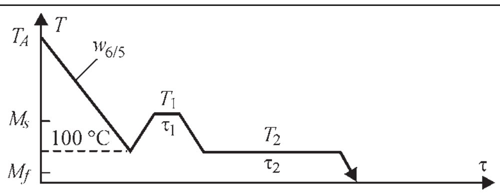
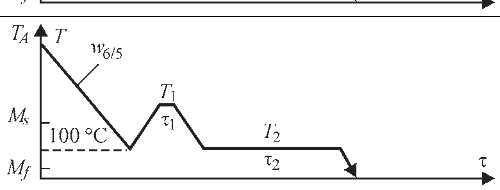
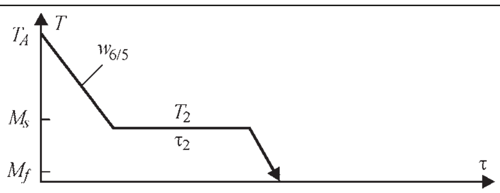
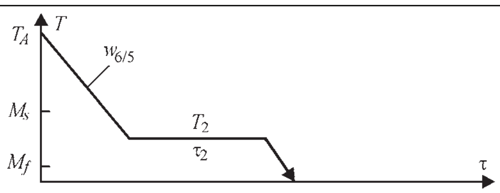
Figure 3. Diagram of operational reliability (*a*) and temperature dependence of relative elongation (*b*) of steel variants according to Table 1

sion strengthening at a lowered carbon content (up to 0.56 %) and silicon (up to 0.13–0.18 %) show increased values of ΔK_{fc} (Table 1, variants 3–7) as compared to standard steel of grade T, but low strength characteristics at a high ductility. Moreover, the optimum of the value [V·N] = 22.1·10^{-4} % was revealed (Table 1, variant 6). This steel has a high resistance to damage, which is at the level set for the steel of grade 2 (Figure 3, *a*), but requires an increased wear resistance [10].

At a solid-solution strengthening when using an increased content of silicon and manganese (Table 1, variant 8), the steel shows a high strength, but the lowest cyclic fracture toughness (ΔK_{fc} = 52 MPa·√m), which is associated with an excessive stress of the structure at a solid-solution strengthening of ferrite at a relatively high (0.58 %) carbon content [4]. Therefore, the steel has a high resistance to wear and a low resistance to damage, similar to that established for the steel of a high-carbon grade T (Figure 3, *a*).

The use of complex strengthening (Table 1, variant 9), namely dispersion and solid-solution one at a low (0.52 %) carbon content, proved to be more effective [11, 12]. Such steel is characterized both by a high yield and also tensile strength, ductility and cyclic fracture toughness. As a result, we obtained the

Table 2 Conditions and parameters of heat treatment of steel 65G

Mode	Scheme and parameters of heat treatment	
1		Temperature of austenitisation T_A = 850 °C; Rate of cooling in the range of 600–500 °C; $w_{6/5}$ = 5 °C/s
2		T_A = 850 °C; $w_{6/5}$ = 5 °C/s; T_1 = 250 °C, τ_1 = 10 min
3		T_A = 850 °C; $w_{6/5}$ = 5 °C/s; T_1 = 300 °C, τ_1 = 1 min
4		T_A = 850 °C; $w_{6/5}$ = 5 °C/s; T_1 = 250 °C, τ_1 = 10 min; T_2 = 100 °C, τ_2 = 2 h
5		T_A = 850 °C; $w_{6/5}$ = 5 °C/s; T_1 = 300 °C, τ_1 = 1 min; T_2 = 100 °C, τ_2 = 2 h
6		T_A = 850 °C; $w_{6/5}$ = 5 °C/s; T_2 = 180 °C, τ_2 = 2 h
7		T_A = 850 °C; $w_{6/5}$ = 5 °C/s; T_2 = 100 °C, τ_2 = 2 h

best combination of damage and wear resistance, as close as possible to the optimum (Figure 3, *a*). At the same time, it has a significantly lower susceptibility to formation of slid flats as compared to standard steel of grade T (Figure 3, *b*). The complex alloying with a further reduction in carbon content (up to 0.45 %) at a sufficiently high content of silicon and manganese (1.36–1.44 %) led to a high strength, low cyclic fracture toughness of steel (Table 1, variant 10), as well as a worse operational reliability as compared to the steel of variant 9 (Figure 3, *a)*.

Let us note, that in all investigated steels the value of fatigue threshold ΔK_{Ith} = 6.0–7.0 MPa·√m (Table 1) is almost constant, i.e. it can be concluded that this parameter is not decisive during optimization of life characteristics of high-strength wheel steels.

Based on the analysis of the obtained results of the influence of chemical composition on life characteristics of steels (Table 1 and Figure 4) and the literature analysis [4], a new high-strength steel (tensile strength of 1050−1100 MPa) of the following chemical composition was recommended (wt.%): 0.45−0.50 C; 0.90−1.10 Si; 0.90−1.10 Mn; 0.14−0.16 V; 0.016–0.018 N at an austenitization temperature of 860−880°C and a tempering temperature of 500−550 °C.

Optimization of heat treatment parameters in repair surfacing. During a long-term operation, the railroad wheels wear out, and on their rolling surface defects of various types appear. Therefore, they are machined and the profile is restored by electric arc surfacing [3]. However, after that, in the heat-affected-zone of the wheel, depending on the carbon content in steel and the cooling rate, a martensitic structure is formed, which is prone to brittle fracture by a facilitated initiation and growth of cracks. This requires the search for effective modes of surfacing and cooling of restored wheels to provide a structural strength of metal in the heat-affected-zone, in particular, increased crack resistance in the high-strength state [13, 14]. To optimize the parameters of the process of cooling wheels after repair surfacing according to the technology developed at the PWI, the influence of different heat treatment conditions (Table 2) on the properties of steel 65G, used as a model wheel steel, was investigated [14].

According to the traditional scheme of Q-n-P treatment [14] (Table 2, modes 2 and 3) as compared to the initial state, an increase in the fatigue threshold ΔK_{th} (by 27 %) and the cyclic fracture toughness ΔK_{fc} (by 27−43 %) was fixed depending on the content of residual austenite. According to the modified scheme (modes 4 and 5), the value ΔK_{th} grows by 38–47 %, and ΔK_{fc} — by 48–66 %. According to the characteristics of cyclic crack resistance, the best result is shown by treatment according to the mode 7 [15], which allows forming a mixed structure in HAZ of upper and lower bainite (~ 66 %) and martensite (~ 34 %) at 2−3 h holding, interrupting the cooling of the steel at 100 °C, i.e. at the temperature between the points of start (M_s) and finish (M_f) of the martensitic transformation. This causes almost 2 times increase in both the fatigue threshold ΔK_{th} as well as the cyclic fracture toughness ΔK_{fc}. Based on the results of electron microscopic investigations, it was established [13] that during this treatment in the metal some changes occured at the substructural level: the density of dislocations ρ decreased approximately by 1.5 times. The comparison of local stresses of the II type τ_{loc} in the structural components of this metal showed that after such an isothermal holding, in the upper bainite the local stresses and strains decreased by 1.4 times; in the lower bainite by 1.5 times; in martensite by 1.3−1.4 times.

Conclusions

1. To improve the resistance of the rolling surface of high-strength (> 1000 MPa) all-rolled railroad wheels to damage and wear, as well as their repairability by surfacing, it is necessary to use steels with a reduced content of carbon (< 0.50−0.55 %), in which the high-strength state is achieved by both solid-solution (alloying with silicon and manganese) as well as dispersion (microalloying with vanadium and nitrogen) strengthening.

2. Based on the developed concept of creating high-strength (> 1000 MPa) wheel steels, a new complex-alloyed steel with a solid-solution (0.90–1.10 % of Si and 0.90−1.10 % of Mn and dispersion ([V·N] = (20−25)·10^{-4} %) strengthening at a lowered (to 0.45−0.50 %) carbon content was proposed, which is superior to the standard steel of grade 2 (0.58−0.62 % C) as to its resistance to wear and damage and repairability by surfacing.

3. Increasing the cyclic crack resistance of the metal in the heat-affected-zone of repair surfacing of high-strength railroad wheels is achieved by the formation of a mixed structure of the upper and lower bainite (~66 %) and martensite (~34 %) at 2−3 h holding at a temperature of 100 °C, interrupting cooling of the steel between the points of beginning (M_s) and finish (M_f) of the martensitic transformation.

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