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The joint effect of vanadium and nitrogen on the mechanical behavior of railroad wheels steel

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ABSTRACT

Purpose: The aim of the proposed research is to investigate the regularities of the microstructure change, fracture micromechanism and mechanical service characteristics of the high-strength wheel steel with a lowered carbon content under static, impact and cyclic loading depending on the total content of vanadium and nitrogen and also the steel heat treatment modes.

Design/methodology/approach: Alloying with vanadium was carried out in the range of 0.09-0.23% and nitrogen in the range of 0.006-0.018%. All steels were heat treated by normalizing and subsequent tempering at different temperatures in the range of 450-650°C. Steels microstructure was investigated by the optical metallography methods on the microscope EPITIP-2 (Carl Zeiss Jena). Scanning electron microscope Zeiss-EVO40XVP was also used for microstructural and microfractography investigations. Static strength (UTS), relative elongation (TEL), impact toughness tests (KCV) and fatigue crack growth resistance characteristics (fatigue threshold ΔK_{th}, cyclic fatigue fracture toughness ΔK_{fc}) were determined on standard specimens. Rolling contact fatigue testing was carried out on the model specimens.

Findings: The regularities of the change of microstructure, fracture micromechanism and mechanical characteristics of the high-strength wheel steel with a lowered carbon content under static, impact and cyclic loading depending on the total content of vanadium and nitrogen and also the steel heat treatment modes are studied.

Research limitations/implications: The results obtained on laboratory samples should be tested during a real railway wheels investigation.

Practical implications: The steel with the optimal parameter $[V\cdot N]\cdot 10^4 = 22.1\%$ provides high tread surface damaging resistance established on the model wheels.

Originality/value: It was established that after normalization at 950°C and tempering at 550°C the increase of ultimate strength UTS and cyclic fracture toughness ΔK_{fc} by 4% and 19%, respectively; impact toughness at room (KCV^{+20}) and low temperature (KCV^{-40}) in 1.5 and 3.3 times, respectively, when parameter $[V\cdot N]\cdot 10^4$ changes from 7.8 to 22.1% and carbon content from 0.63 to 0.57%.

Keywords: Railway wheel steel, Microalloying, Heat treatment, Microstructure, Mechanical characteristics

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PROPERTIES

1. Introduction

At the end of the XX century, one of the main causes of railway wheels failure became an over-the-norm wear of a tread surface, resulting in a significant rise of costs for maintenance of freight cars. It is impossible to remove wear in the wheel-rail contact region completely, however, it is possible to decrease the wear intensity by improving the profile of the wheel tread surface, optimizing the ratio of the wheel/rail hardness and improving the strength and hardness of the wheel. For solving this problem high-strength wheels were manufactured in the grade T steel (type KP-T) with higher hardness and strength [1,2]. This allowed us to increase the lifetime of the railway wheels of this type, using the criterion of wear resistance, by 30-40% in comparison to type KP-2 wheels made from the grade 2 steels, that was achieved by microalloying with vanadium (~0.1%) at elevated (to 0.65-0.70%) carbon content.

This tendency is typical of the world practice when for improving the strength, hardness, and wear-resistance of the railway wheels the steels with a higher carbon content have been used [3,4]. However, the exploitation experience of "hard" wheels shows that they fail untimely due to the formation of defects on the tread surface (like shelling, spalling, etc.) caused by crack formation under the effect of thermo-force operation factors [1,5]. First of all, this is determined by the tendency of steels with high carbon content to the martensitic transformation that takes place in the region of the wheel/rail contact during braking. According to the proposed concept of the development of new steels for the high-strength railway wheels [1], their operation life should be provided under the condition of the decrease of the carbon content in a wheel steel (to 0.50-0.55%). Deterioration of the steel strength, in this case, should be compensated by other methods. Alloying with chromium, molybdenum, and nickel [6,7] is problematic because increases the steel cost. Use of the wheel steels with precipitation hardening, especially by nitrides and carbonitrides under vanadium and nitrogen microalloying is perspective for solving this problem [8-11]. Besides, such precipitates retard the process of recrystallization, providing the steels structure strengthening. It is shown that microalloying with vanadium and nitrogen increases the stability of austenite and makes it possible to decrease the rate of wheels cooling after austenitization, enabling dispersion of the pearlite, bainite and martensite structures that should positively affect the level of mechanical and functional properties of steels. But, a result of the joints effect of vanadium and nitrogen on serviceability of wheel steels are absent in the literature.

The aim of this paper is to investigate the regularities of the microstructure change, fracture micromechanism and mechanical service characteristics of the high-strength wheel steel with a lowered carbon content under static, impact and cyclic loading depending on the total content of vanadium and nitrogen and also the steel heat treatment modes.

2. Experimental procedures

Steels with a lowered carbon content were investigated (Tab. 1, variants No. 2-5), which were compared with the standard [2] steel (variant No. 1). Alloying with vanadium was carried out in the range of 0.09-0.23% and nitrogen in the range of 0.006-0.018%, while a total content of these elements in steel was characterized by parameter $[V{\cdot}N]{\cdot}10^4$ (Tab. 1).

Mass fraction of carbon, sulfur, phosphorus was determined chemically according to the Standards GOST 12344-88, GOST 12345-88, GOST 12347-88; nitrogen – by the method of specimens melting in a helium flow of purity 99.99% using an analyser TC-30 ("LEKO" company); other elements – by spectral analysis on the installation "Spectromass" according to Standard GOST 18895-97.

All steels were heat treated by normalizing and subsequent tempering at different temperatures in the range of 450-650°C. Austenitization temperature at normalization was chosen for different variants of steels, based on the equilibrium temperature of the nitride-vanadium phase dissolution calculated by the formula [12]:

$$T_{VN}, K = \left(\frac{-9473 + 2436V + 8940N + 932C + 160Mn - 67Si + 419Cr + 1600Al}{\log[V{\cdot}N] - 3.97 + 1.5V + 5.44N + 0.059Si + 0.0128Cr + 0.0598Mn + 0.831Al + 0.48C} \right) \quad (1)$$

and also the investigation results of the temperature influence within the range 850-1000°C on the intensity ofaustenite grain size growth. On this basis, the austenitization temperature during normalizing was 880°C for the steel of variant No. 1; 900°C – No. 2; 930°C – No. 3; 950°C – No. 4 and No. 5.

Table 1.
The chemical composition of steels

No. of steel variant	Mass fraction of elements, %							
	C	Si	Mn	Cr	Al	S	P	$[V{\cdot}N]{\cdot}10^4$
1	0.63	0.18	0.76	0.10	0.053	0.015	0.052	7.8
2	0.55	0.22	0.87	0.28	0.027	0.024	0.042	11.7
3	0.57	0.13	0.65	0.30	0.013	0.025	0.036	15.6
4	0.57	0.27	0.85	0.30	0.041	0.021	0.037	22.1
5	0.59	0.26	0.65	0.31	0.023	0.021	0.042	41.4

Steels microstructure was investigated by the optical metallography methods on the microscope EPITIP-2 (Carl Zeiss Jena). Scanning electron microscope Zeiss-EVO40XVP was also used for microstructural and microfractography investigations.

Static strength (UTS) and relative elongation (TEL) were determined on standard cylindrical specimens with the working part diameter 5 mm at room temperature. Impact toughness tests were performed on standard beam specimens of size 10x10x55 mm with a V-notch at room and low (-40°C) temperatures (KCV^{+20} and KCV^{-40}, respectively).

Fatigue crack growth resistance was determined on compact specimens of basic size 40 mm and thickness 8 mm at a frequency of 10...15 Hz and stress ratio R = 0.05 in the air at a temperature of 20°C. The fatigue crack length was measured optically by a cathetometer KM-6 with a 25-fold magnification. Dependences of fatigue crack growth rate da/dN versus the stress intensity factor range ΔK were constructed by a conventional procedure [13]. The characteristics of fatigue crack growth resistance were the values $\Delta K_{th} = \Delta K_{10}^{-10}$ in low- and $\Delta K_{fc} = \Delta K_{10}^{-5}$ in a high-amplitude region of the diagram – the stress intensity factor ranges at the crack growth rate equal to 10^{-10} and 10^{-5} m/cycle, respectively.

Rolling contact fatigue testing was carried out on the model specimens of a wheel of thickness 8 mm and diameter 40 mm in contact with a rail of length 220 mm, width 8 mm and height 16 mm by means of the proposed earlier method [14]. Wheels were manufactured from the above-described steel after different treatment modes.

3. Results and discussion

The obtained dependences of the change of standard steel mechanical characteristics (variant No. 1) on tempering temperature after normalization show (Fig. 1a) that with the temperature growth the strength has a tendency to decrease which is traditionally accompanied with the plasticity increase. Impact toughness remains practically unchanged, however a tendency to steel embrittlement is demonstrated: the KCV^{-40} values are significantly lower in comparison to KCV^{+20}. Therefore, tempering temperature of 450°C was chosen as optimal for this steel.

High plasticity and impact toughness, slightly reacted on tempering temperature are observed for the steel of variant No. 2 with lowered carbon content and small vanadium and nitrogen total content (Fig. 1b). In this case, the values of KCV^{+20} and KCV^{-40} differ less than for the standard steel. However, as a result of the carbon content decrease, the strength of this steel significantly deteriorates showing some increase in the tempering temperatures range 450-500°C that can be related with precipitation of the secondary phases under α-solid solution decay.

The increase of the vanadium and nitrogen total content in steels No. 3 and No. 4 causes the growth in their strength (Figs. 1c,d) and at the lower carbon content the steel of variant No. 3 approaches the standard steel, while steel No. 4 exceeds it. Plasticity of these steels is commensurable, but the impact toughness of steels No. 3 and No. 4 is signify-cantly higher than in steel No. 1. Here we should note that the value of KCV^{+20} and KCV^{-40} of the steels of variants No. 3 and No. 4 is practically identical (Figs. 1c,d), thus witnessing about their high brittle fracture resistance.

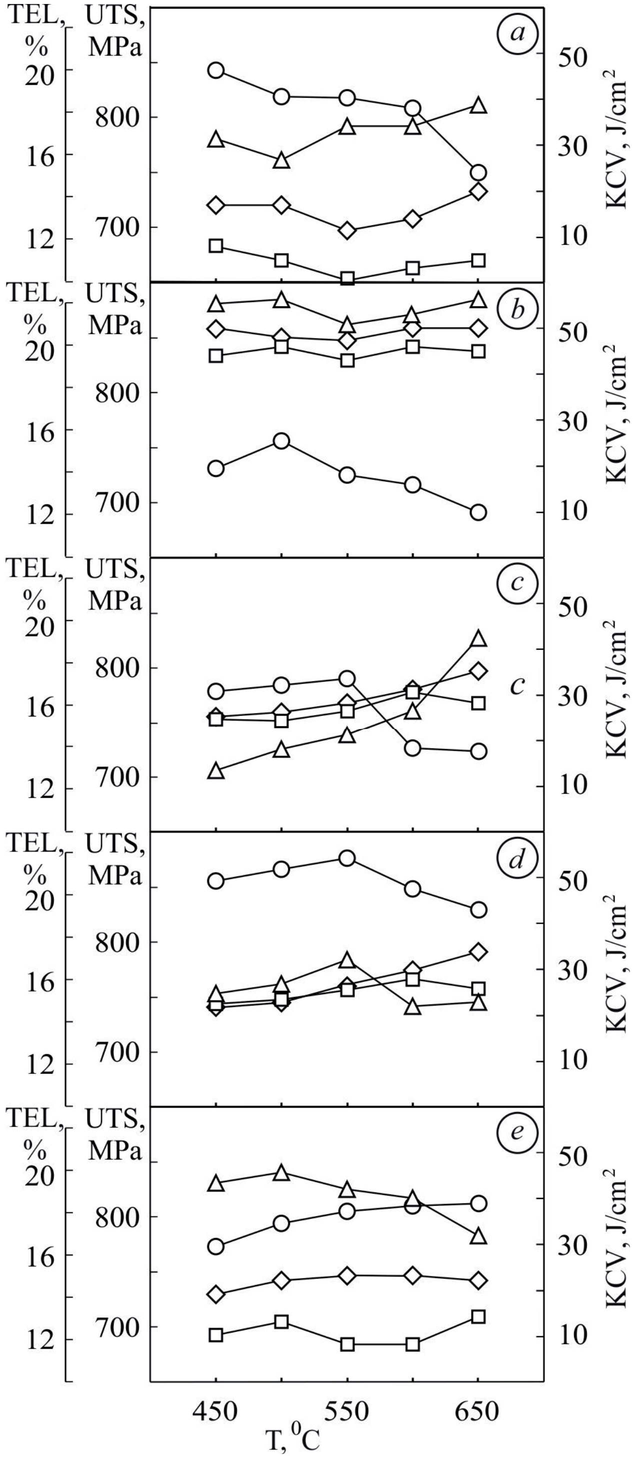

Fig. 1. Dependences of ultimate strength UTS (○), relative elongation TEL (Δ), impact toughness KCV^{+20} (◊) and KCV^{-40} (□) on tempering temperature: a – steel of variant No. 1; b – No. 2; c – No. 3; d – No. 4; e – No. 5 (according to Tab. 1)

It is also seen that the increase in their strength is observed when the tempering temperature increases up to 550°C. It is evidently caused by the intensification of precipitation hardening at 550°C, and consequently this temperature is optimal.

Further increase in the total content of vanadium and nitrogen in the steel of variant No. 5 causes the decrease in the strength and impact toughness (Fig. 1e) in comparison to the steel of variant No. 4. The values of impact toughness KCV^{-40} again become lower in comparison to with KCV^{+20}. The strength of the steel of variant No. 5 increases monotonically along with the tempering temperature increase. However, the tempering temperature of 600°C was chosen as the optimal one in future investigations taking into account the variation tendencies of other characteristics.

Thus, under microalloying with vanadium and nitrogen to reach the improved mechanical characteristics, the austenitization and tempering temperatures should be increased to 950°C and 550°C, respectively, in comparison to the standard steel, when at the optimal content of $[V{\cdot}N]{\cdot}10^4$ = 22.1% and a carbon content of 0.57% the higher strength and resistance to brittle fracture are obtained.

Analysis of microstructure of the steels of variants No. 1, No. 4 and No. 5 after optimal modes of austenitization and tempering shows (Fig. 2) that in all cases it is pearlitic-ferritic, where ferrite is located as a net around the pearlitic colonies. It is seen (Fig. 2a comparing to Figs. 2b,c) that joint effect of vanadium and nitrogen causes (besides precipitation hardening) the significant fragmentation of structural elements due to a retarded coagulation during heating and the increase of pearlitic component. Such alloying has also an influence on the pearlite morphology (Fig. 2d comparing to Figs. 2e,f): the distance between cementite plates and their length decrease. In this case, higher fraction of the pearlitic phase in steel of variant No. 5 (Fig. 2f), in comparison to the optimal variant No. 4 (Fig. 2e), are the result of the higher content of non-solved VN-phase in the solid solution, that promotes the premature disintegration of the γ-solid solution. The observed microstructural peculiarities fully agree with the obtained steels mechanical properties (Fig. 1).

Serviceability of a steel taking into account the defects formation resistance on the tread surface of railway wheels is determined by its fatigue crack growth resistance [1, 14]. It is established (Table 2) that variation of the chemical composition and heat treatment modes does not affect the fatigue threshold ΔK_{th} of investigated steels, what is typical for the given class of materials, but their fatigue fracture toughness ΔK_{fc} is sensitive: at $[V{\cdot}N]{\cdot}10^4 = 22.1\%$ (variant No. 4) it is by 19% higher than for the standard steel (variant No. 1); at $[V{\cdot}N]{\cdot}10^4 = 41.4\%$ (variant No. 5) it is by 4% lower than for variant No. 4.

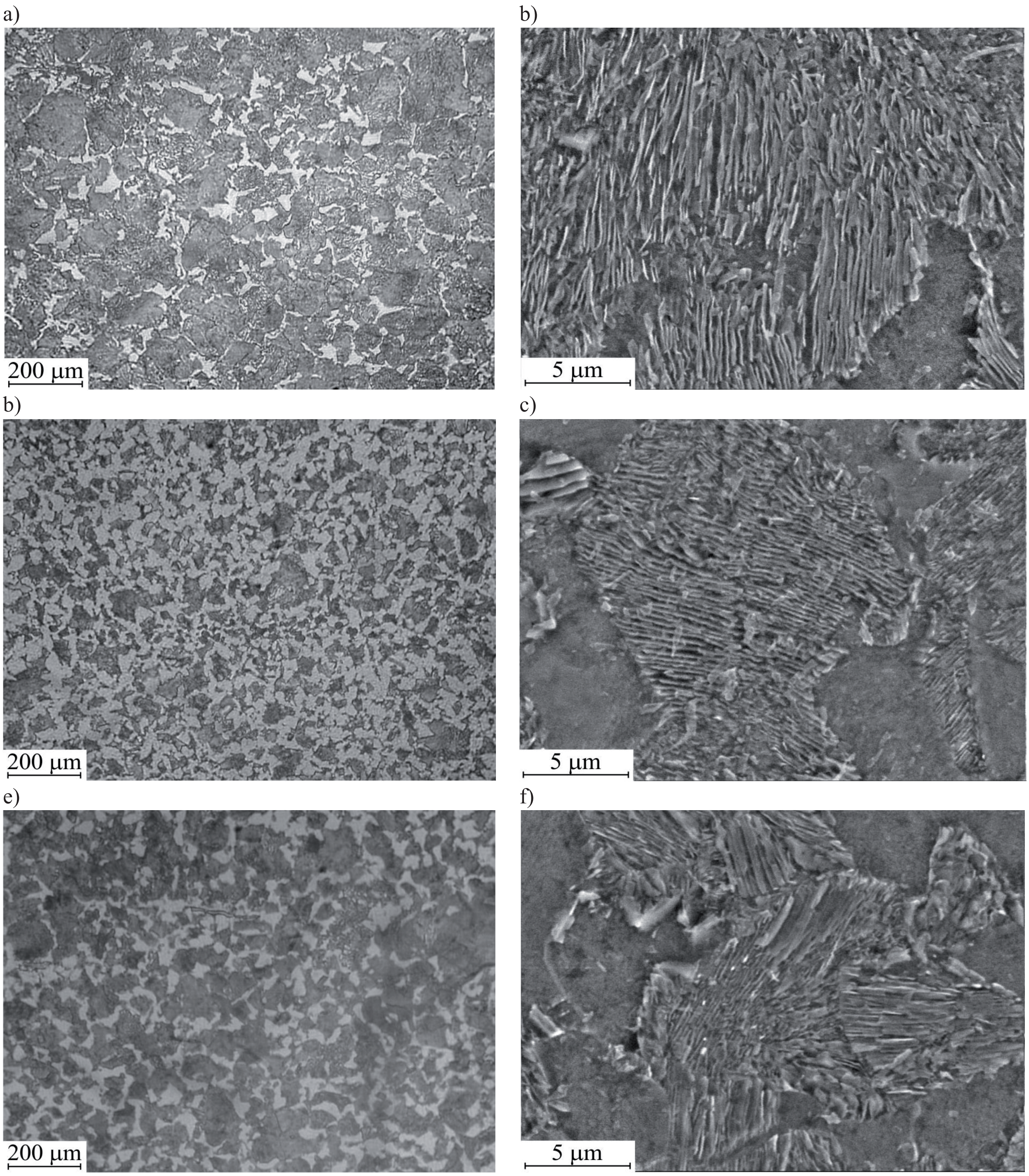

Fig. 2. Optical (a,c,e), and SEM (b,d,f) micrographs showing microstructure of the steels of variant No. 1 (a,b), No. 4 (c,d) and No. 5 (e,f) at optimal austenitization and tempering temperatures

Table 2.
Characteristics of crack growth resistance and damaging of steels*)

No. of steel variant**)	ΔK_{th}	ΔK_{fc}	$[UTS \cdot \Delta K_{th} \cdot \Delta K_{fc}] \cdot 10^{-4}$	P, %
	MPa·$\sqrt{m}$			
1	6.5	73	40.0	8.2
4	6.6	87	50.4	2.0
5	6.6	83	44.4	5.4

*) After optimal austenitization and tempering modes;
**) According to Table 1.

This is related with the micromechanism of their fatigue fracture (Fig. 3).

In standard steel a fatigue crack in the high-amplitude region propagates predominately by a transgranular cleavage (Fig. 3a), thus witnessing about high internal local stresses in the steel with an increased carbon content. Complex microalloying with vanadium and nitrogen, at the decreased carbon content, promotes the formation of local microplasticity, thus causing the formation of deformed combs in the fracture surfaces which surround the cleavage facets. These combs of a dimple (soft) character are more intensive in the fracture surfaces of the steel of variant No. 4 (Fig. 3b) in comparison to variant No. 5 (Fig. 3c), that causes high cyclic fracture toughness of this steel (Tab. 2).

It is worth characterizing the operation reliability of wheel steels by the complex parameter of materials structural strength $[UTS \cdot \Delta K_{th} \cdot \Delta K_{fc}]$, that combines the characteristics of their strength and fatigue crack growth resistance [1,15]. It is seen from Table 2 that by these two parameters the steel of variant No. 4 prevail variants No. 1 and No. 5 in 1.26 and by 1.14 times, respectively. On the other hand, investigation of the contact fatigue damaging of the tread surface of model wheels demonstrates (Fig. 4) that the least amount of defects is fixed for wheels made from the steel of variant No. 4. Besides, parameter $P=F/F_0$, where F is the defects area on the tread surface, F_0 is the tread surface area, correlates well with the complex parameter of structural strength (Tab. 2).

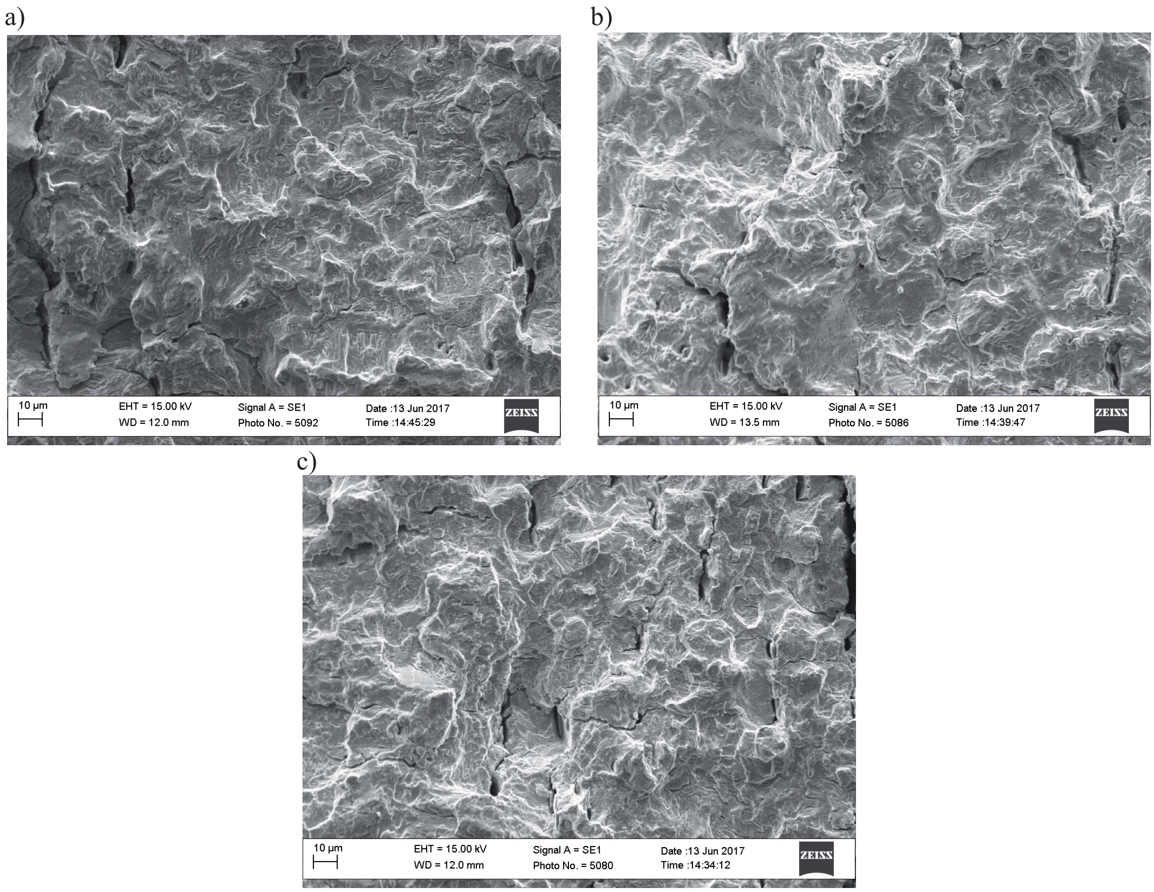

Fig. 3. SEM microfractographs of steel specimens: a – variant No. 1; b – No. 4; c – No. 5 at the fatigue crack propagation rate $da/dN \approx 10^{-6}$ m/cycle

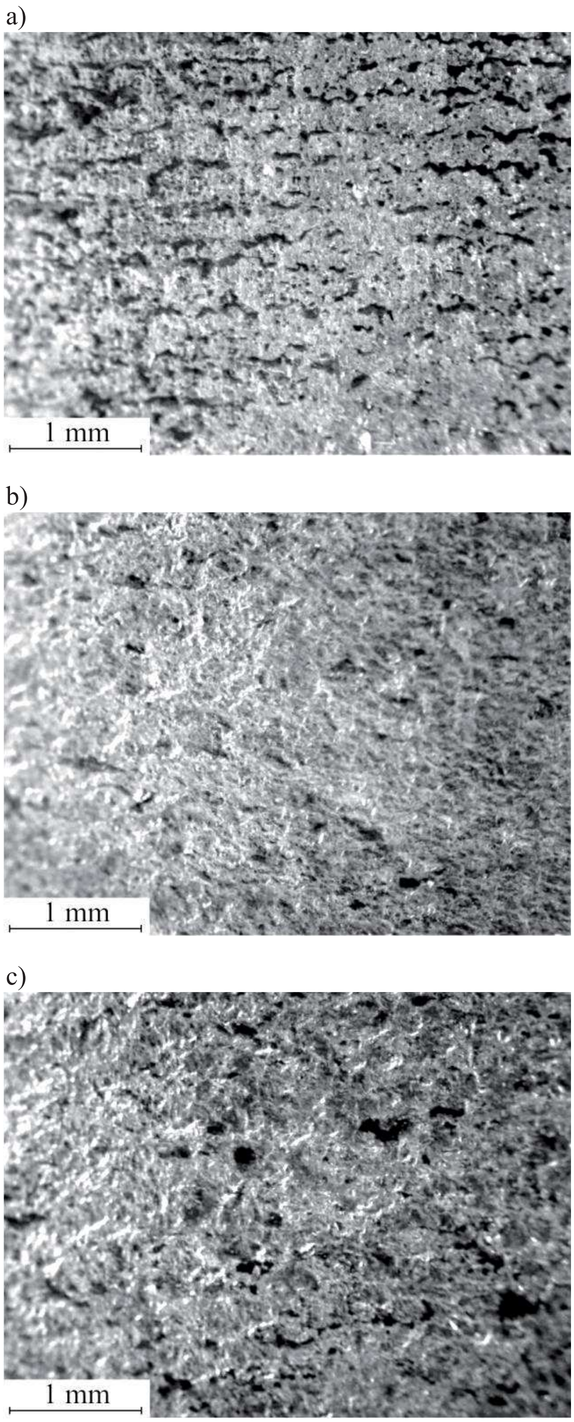

Fig. 4. The tread surface of model wheels: a – variant No. 1; b – No. 4; c – No. 5

Thus, this steel, that has the least parameter P and the greatest cyclic fracture toughness ΔK_{fc}, possesses the best operating characteristics.

4. Conclusions

1. To reduce crack formation on the tread surface of the high-strength railway wheels it is necessary to decrease the carbon content in the wheel steel, compensating the loss of its strength in this case by precipitation hardening and structure strengthening using common microalloying of steel with vanadium and nitrogen.
2. Optimal microstructure and mechanical properties of such wheel steel are obtained at the content of $[V \cdot N] \cdot 10^4 = 22.1\%$ and temperature of austenitization 950°C and tempering temperature 550°C.
3. It is proved that the damaging resistance of wheel tread surface correlates with the cyclic fatigue fracture toughness ΔK_{fc} of wheel steel and also with a new parameter of the structural strength of materials $[UTS \cdot \Delta K_{th} \cdot \Delta K_{fc}]$.

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