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Mechanical behavior of wheel steels with solid solution and precipitation hardening

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ABSTRACT

Purpose: The aim of the proposed research is to investigate operational properties of a wheel steel treated with simultaneous solid solution and precipitation hardening at various carbon content, in comparison with the standard wheel grade T steel.

Design/methodology/approach: The mechanical behaviour of wheel steels with increased content of silicon, manganese, vanadium, and nitrogen at various carbon content has been investigated and compared to that of the standard high-strength wheel grade T steel. The steels were undergo thermal treatment due to austenitic heating up to a temperature of 950°C with cooling down in water to 550°C followed by intense blowing of blanks in the air. After that, a tempering was performed at a temperature in the range of 450-650°C. Static strength (UTS), relative elongation (TEL), impact toughness tests (KCV) were determined on standard specimens. The characteristics of Mode I fatigue crack growth resistance of steel were determined on the basis of fatigue macrocrack growth rate diagrams $da/dN–\Delta K_I$, obtained by the standard method on compact specimens with the thickness of 10 mm at a frequency of 10-15 Hz and the stress ratio $R = 0.1$ and $R = 0.5$ of the loading cycle. The characteristics of Mode II fatigue crack growth resistance were determined on the basis of $da/dN–\Delta K_{II}$ diagrams, obtained earlier method on edge notched specimens with the thickness 3.2 mm at a frequency of 10-15 Hz and $R = –1$ taking account of the crack face friction. Rolling contact fatigue testing was carried out on the model specimens.

Findings: The regularities of the change of mechanical characteristics of the high-strength wheel steel with simultaneous solid solution and precipitation hardening at lowered carbon content under static, impact and cyclic loading are studied.

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

Practical implications: The investigated steel with simultaneous solid solution and precipitation hardening provides high wear resistance of the tread surface and damage resistance determined on the model wheels.

Originality/value: A steel with solid solution hardening due to increased content of silicon (up to 0.7%) and manganese (up to 0.8%) and also with precipitation hardening (at optimal content of vanadium and nitrogen [V·N]·10^4 = 28.9%) at lowered carbon content (0.52) possesses high strength and fatigue fracture toughness in cases of Mode I and Mode II loading, causing better combination of wear and damage resistances of the tread surface of the model wheels, as compared to corresponding parameters for grade T steel.

Keywords: Railway wheel steel, Alloying, Resistance to flat formation, Wear and damaging

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MATERIALS

1. Introduction

Until recently, one of the most important tasks was to reduce the wear of the tread surface of railway wheels, which in the world practice was solved by the development of low-alloy steels [1-4] with increased carbon content (0.6-0.7%), hardness (> 300 HB) and the ultimate strength (>1000 MPa). However, the operating experience has shown [5, 6] that on the tread surface of such high-strength wheels, the number of operational damages (flat, shelling, spalling, etc.) significantly increases, which results in a shorter lifetime of the wheels.

In general, this is the result of the effect of high carbon content on the propensity of such wheel steels to cracking. Consequently, steels for the new generation of railway wheels must have high strength at low carbon content, high crack growth resistance under static (K_{IC}), dynamic (K_{ID}, KCV) and cyclic (ΔK_{th}, ΔK_{fc}) loads, possess high thermal stability of mechanical properties [5,6]. Since wheels generally undergo cyclic loads, it is preferable to provide the characteristics of fatigue crack growth resistance, determined for the cases of Mode I and Mode II loading [6].

The negative effect of reducing carbon content on the strength of wheel steels should be offset by additional alloying, such as higher content of silicon and manganese, which contribute to solid solution hardening [7-10], as well as nitride precipitation hardening [11-14].

The aim of the proposed research is to evaluate operational properties of a wheel steel with simultaneous solid solution and precipitation hardening at various carbon content, in comparison with the standard wheel grade T steel.

2. Experimental procedures

The mechanical behavior of wheel steels with increased content of silicon, manganese, vanadium, and nitrogen at various carbon content (Table 1) has been investigated and compared to that of the standard high-strength wheel grade T steel [1].

Weight 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.

The steels were undergo thermal treatment due to austenitic heating up to a temperature of 950ºC with cooling down in water to 550ºC followed by intense blowing of blanks in the air. After that, a tempering was performed at a temperature in the range of 450-650ºC. Holding time at austenitic temperature was 1 hour. Holding time for blanks at tempering temperature was 1 hour, followed by cooling down in the air.

Table 1.
The chemical composition of steels

No. of steel	Weight fraction of elements, %						
	C	Si	Mn	Cr	Al	S	P	[V·N]·10^4
1	0.64	0.70	1.30	0.42	0.014	0.021	0.021	25.5
2	0.52	0.67	0.81	0.37	0.014	0.030	0.025	28.9

Static strength (UTS) and relative elongation (TEL) were determined on standard cylindrical specimens with a diameter of the working part of 3 mm and a length-to- diameter ratio of 5:1 in the temperature range 20-800ºC. Impact toughness tests were performed on standard beam specimens of size 10x10x55 mm with a V-notch at room and low (-40ºC) temperatures (KCV^{+20} and KCV^{-40}, respectively).

The characteristics of Mode I fatigue crack growth resistance of steel were determined on the basis of fatigue macrocrack growth rate diagrams $da/dN–\Delta K_I$, obtained by standard method [15] on compact specimens with the thickness of 10 mm at a frequency of 10-15 Hz and the stress ratio $R = 0.1$ or $R = 0.5$ of the loading cycle in the air at a temperature of 20 °C. The characteristics of Mode II fatigue crack growth resistance were determined on the basis of $da/dN–\Delta K_{II}$ diagrams, obtained by authors method [16] on edge notched specimens with the thickness 3.2 mm at a frequency of 10-15 Hz and $R = –1$ taking account of the crack faces friction [17]. In this case, the range $\Delta K=K_{max}-K_{min}$ was taken to be 2 K_{max}.

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 [15]. 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 [18]. Rails were cut out from a head the full-scale rail of hardness 46 HRC.

Operational reliability of steels in case of contact fatigue was evaluated using a complex diagram which characterizes resistance to damage of wheel steels (*1/D*) and their wear resistance (*1/W*) [19]. These characteristics are inverse values of the damage $D = F_d/F_0$ and rolling surface wear $W = (R_0 – R)/ R_0$ of a model wheel respectively, where F_d is the area of defects (pittings and spalling). This area was measured using an optical microscope with a special computer image processing software; F_0 is a tread surface area; R is a wheel radius measured after tests; R_0 is an initial wheel radius. Tests were performed at a contact stress of 750 MPa for $2 \cdot 10^5$ loading cycles (corresponding the total distance of 25 km).

Each value represents averaged data of three samples. The standard deviation for the parameter D is 0.5%, and for W is 0.6%.

3. Results and discussion

The ultimate tensile strength of the steel No. 1 is decreased gradually with increasing a tempering temperature while the plasticity is increased reaching the maximum value at a temperature of 600 ºC (Fig. 1a). It was therefore assumed that an optimal combination of strength and plasticity is achieved at the tempering temperature 600ºC. Optimum combination of strength and plasticity for the steel No. 2 is achieved at a tempering temperature of 550ºC (Fig. 1b). Therefore, these steels were further investigated after tempering at 600ºC and 550ºC, respectively.

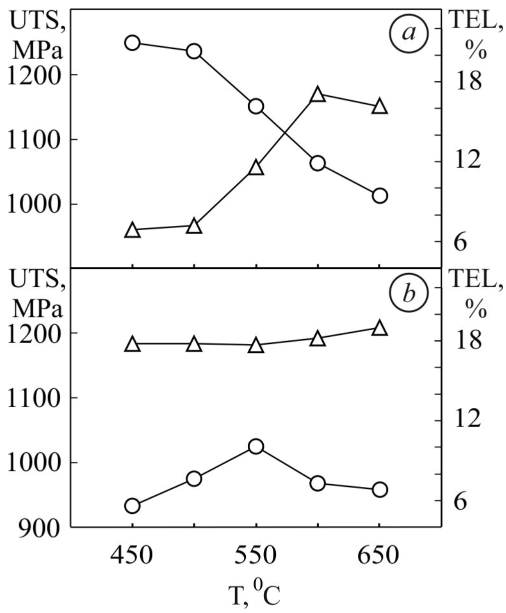


Fig.1. Dependences of ultimate strength UTS (○), relative elongation TEL(Δ) on tempering temperature: a – steel No. 1; b – No. 2 (according to Table 1)

In particular, when assessing the impact toughness, it was found that in cases of testing at room temperature and at a low temperature the steel No. 2 has an advantage over the steel No. 1 by 23 and 17% respectively (Table 2).

Table 2.
Impact toughness of investigation steels

No. of steel*)	Optimal tempering temperature, ºC	Impact toughness, J	
		KCV^{+20}	KCV^{-40}
1	600	2.6	1.2
2	550	3.2	1.4

*) According to Table 1.

It was established that the standard grade T steel has an advantage over the steels No. 1 and No. 2 for the ultimate tensile strength by 10-16% at temperatures up to 400ºC, but with a further increase in the test temperature its strength is lowered by 5-30% comparing to these steels (Fig. 2a, curve 3 against curves 1 and 2, respectively). At a test temperature of 800ºC, practically the same strength values were obtained for all the steels.

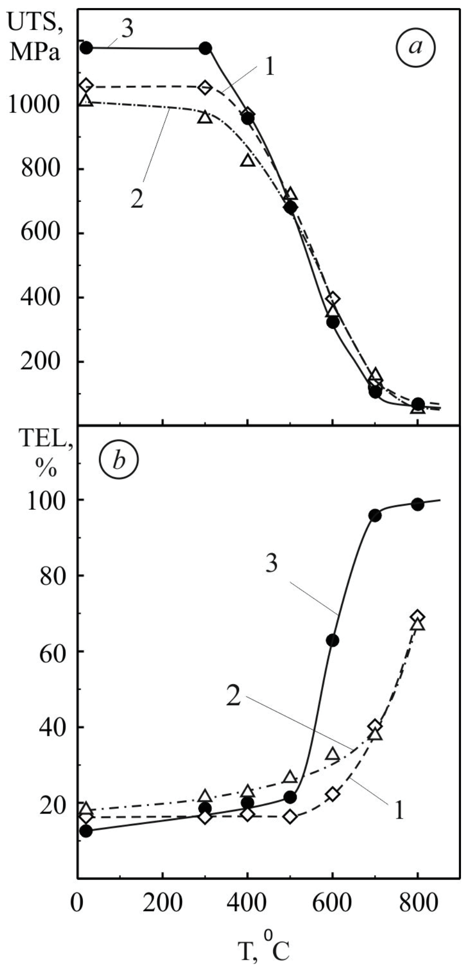


Fig. 2. Temperature dependences of mechanical characteristics of investigated steels No. 1 (curves 1), No. 2 (curves 2) and also standard grade T steel (curves 3) [6]: a – ultimate strength, b – relative elongation TEL

An important feature of a wheel steel is the nature of the change in the parameters of plasticity at temperatures above 500ºC, since high-temperature plasticity (relative elongation TEL) indicates the tendency of the steel to flat formation on the tread surface of the wheel during braking: it grows with increasing TEL values [6]. It was established that in the temperature range up to 500ºC no discernible plasticization of all investigated steels occurs (Fig. 2b). At temperatures of 500-700ºC, a slight plasticization of the steels No. 1 and No. 2 is observed, which increases significantly in the range of 700-800ºC (curves 1 and 2, respectively). Significant plasticization of the grade T steel is already observed above 500ºC (curve 3), and at 700ºC its plasticity is 2.4 times higher than of steels No. 1 and No. 2. Therefore, according to the propensity to flat formation on the tread surface of the wheels (plasticization of steel at high temperatures), the steels No. 1 and No. 2 have substantial advantage over the standard grade T steel.

In the conditions of Mode I loading for steels after solid solution and precipitation hardening, the fatigue fracture toughness $\Delta K_{I\,fc}$ at R=0.1 increases by 23-31% (from 65 to 85 and 80 MPa$\cdot\sqrt{\text{m}}$ for the steels No. 1 and No. 2, respectively) as compared to the standard grade T steel (Fig. 3a). The steel No. 2 has the highest fatigue fracture toughness at R=0.5 simulating the effect of residual stresses ($\Delta K_{I\,fc} = 65$ MPa$\cdot\sqrt{\text{m}}$), which is higher by 11% than for the steel No. 1 ($\Delta K_{I\,fc} = 58$ MPa$\cdot\sqrt{\text{m}}$). In this case, the fatigue fracture toughness of the standard grade T steel is more than 2 times lower ($\Delta K_{I\,fc} = 24$ MPa$\cdot\sqrt{\text{m}}$). Note that for high-strength wheel steels, the threshold stress intensity factor range $\Delta K_{I\,th}$ varies slightly (Figs. 3a, b)

For Mode II loading (Fig. 3c) it was found that the threshold stress intensity factor range$\Delta K_{II\,th}$ for the steel No. 2 is more than 1.3 times lower than for the steel No. 1 (23 vs. 31 MPa$\cdot\sqrt{\text{m}}$), but according to the fatigue fracture toughness $\Delta K_{II\,fc}$, which determines the damage of the tread surface of the wheels [18], the steel No. 2 predominates the steel No. 1 in more than 1.3 times (122 vs. 92 MPa$\cdot\sqrt{\text{m}}$).

It was determined after contact fatigue tests that values the damage of the tread surface was 5.0% for the model wheels made of the steel No. 1 and the standard grade T steel (Fig. 4a, c), and for those made of the steel No. 2 was 2.5% (Fig. 4b).

The serviceability of wheel steels under operating conditions is to be assessed on a comprehensive basis using characteristics of wear resistance (*1/W*) and their damage resistance (*1/D*), based on the operational reliability diagram [19]. It was revealed (Fig. 5) that the steel with nitride strengthening of the optimal chemical composition [13] has the highest resistance to damage (position *5*), but it has a low resistance to wear. The standard grade T steel (position 3) has a high resistance to wear, but it has a low resistance to damage. It is obvious that the desired optimum is located in the upper right corner of this diagram (Fig. 5). It is seen that the steel No. 2 with solid solution and precipitation hardening (position 2) is approaching this optimum.

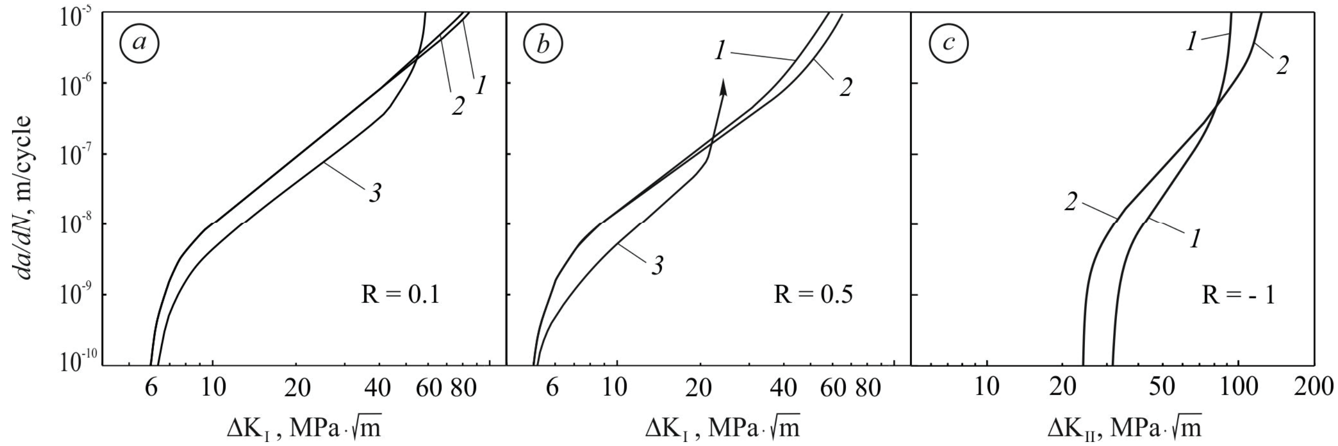
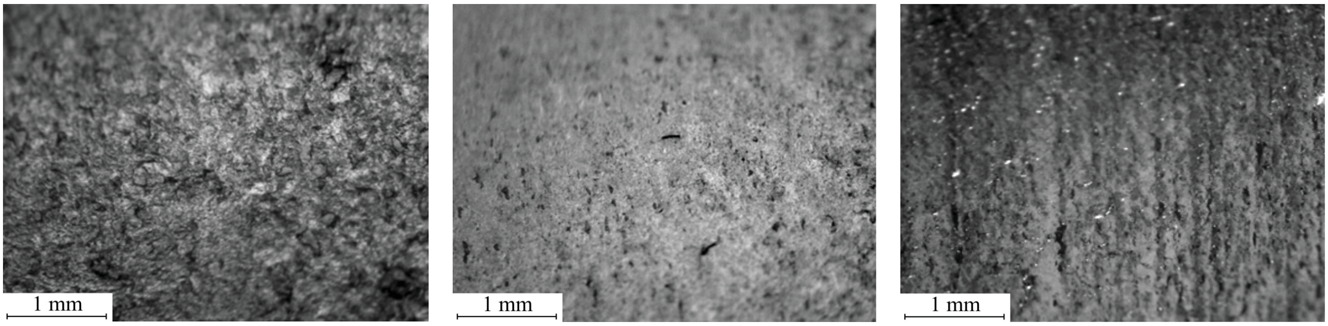


Fig. 3. Fatigue macrocrack growth rate diagrams of steels No. 1 (curves 1), No. 2 (curves 2) and also standard grade T steel (curves 3) [20] under (a, b) Mode I and (c) Mode II loading.



(a) (b) (c)

Fig. 4. The tread surface of model wheels made of: a – steel No. 1; b – No. 2; c – standard steel of grade T [6]

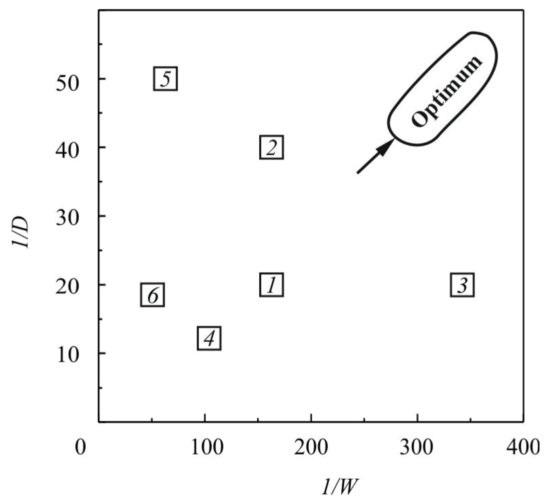


Fig. 5. Operational reliability diagram of wheel steels: 1 – No. 1; 2 –No. 2; 3 – standard grade T steel [6]; (4-6) – steels with precipitation hardening [13]

4. Conclusions

1. By using solid solution hardening due to increased content of silicon (up to 0.7%) and manganese (up to 0.8%) and also precipitation hardening (at optimal content of vanadium and nitrogen $[V{\cdot}N]{\cdot}10^4 = 28.9\%$) at lowered carbon content (0.52), a wheel steel was formed which has lesser tendency to flat formation on the tread surface of the wheels, as compared to the standard grade T steel.
2. Such steel possesses high strength and fatigue fracture toughness in cases of Mode I and Mode II loading, causing better combination of wear and damage resistances of the tread surface of the model wheels, as compared to corresponding parameters for grade T steel.

References

[1] All-rolled wheels. Specifications: DSTU GOST 10791-2016, M.: Standardinform, 2016 (in Russian).

[2] AAR Manual of Standards and Recommended Practices Wheels and Axles. Wheels, Carbon Steel. Specification M-107/M-208-2016, 2016.

[3] JIS E 5402-1:2015. Japanese Standards Association. Railway rolling stock. Solid wheel. Part 1: Quality requirements, 2015.

[4] TB/T 2708-1996. China Railway and Train Standards. Technical specifications for rolled solid wheels of railway rapid passenger car, 1996.

[5] M. Diener, A. Ghidini, Materials for heavy haul solid wheels: new experiences, Proceedings of the Institution of Mechanical Engineering, Part F: Journal of Rail and Rapid Transit 224 (2010) 421-428, DOI: https://doi.org/10.1243/09544097JRRT356.

[6] O.P. Ostash, V.H. Anofriev, I.M. Andreiko, L.A. Muradyan, V.V. Kulyk, On the concept of selection of steels for high-strength railroad wheels, Materials Science 48/6 (2013) 697-703, DOI: https://doi.org/10.1007/s11003-013-9557-7.

[7] D. Zeng, L. Lu, Y. Gong, Y. Zhang, J. Zhang, Influence of solid solution strengthening on spalling behavior of railway wheel steel, Wear 372-373 (2017) 158-168, DOI: https://doi.org/10.1016/j.wear.2016.12.025.

[8] K. Cvetkovski, J. Ahlström, B. Karlsson, Monotonic and cyclic deformation of a high silicon pearlitic wheel steel, Wear 271 (2011) 382-387, DOI: https://doi.org/10.1016/j.wear.2010.10.047.

[9] D. Zeng, L. Lu, Y. Gong, N. Zhanga, Y. Gong, Optimization of strength and toughness of railway wheel steel by alloy design, Materials and Design 92 (2016) 998-1006, DOI: https://doi.org/10.1016/j.matdes.2015.12.096.

[10] X. Ren, J. Qi, J. Gao, L. Wen, B. Jiang, G. Chen, H. Zhao, Effects of heating rate on microstructure and fracture toughness of railway wheel steel, Metallurgical and Materials Transactions A 47/2 (2016) 739-747, DOI: https://doi.org/10.1007/s11661-015-3264-y.

[11] F. Zhao, M. Wu, B. Jiang, C. Zhang, J. Xie, Y. Liu, Effect of nitrogen contents on the microstructure and mechanical properties of V-Ti microalloyed steels for the forging of crankshafts, Materials Science and Engineering A 731 (2018) 360-368, DOI: https://doi.org/10.1016/j.msea.2018.06.070.

[12] Yu.Z. Babaskin, S.Ya. Shipitsyn, Microalloying of structural steel with nitride-forming elements, Steel in Translation 39/12 (2009) 1119-1121, DOI: https://doi.org/10.3103/S0967091209120201.

[13] V.V. Kulyk, S.Ya. Shipitsyn, O.P. Ostash, Z.A. Duriagina, V.V. Vira, The joint effect of vanadium and nitrogen on the mechanical behavior of railroad wheels steel, Journal of Achievements in Materials and Manufacturing Engineering 89/2 (2018) 56-63, DOI: 10.5604/01.3001.0012.7109.

[14] B.S. Ivanov, G.A. Filippov, K.Yu. Demin, K.A. Moskovoi, A.E. Semin, Modifying wheel steel with nitrogen, Steel in Translation 37/9 (2007) 769-772, DOI: https://doi.org/10.3103/S0967091207090112.

[15] Standard test method for measurement of fatigue crack growth rates, ASTM E647-08, V03.01, ASTM, 2008, DOI: 10.1520/E0647-15E01.

[16] Ya.L. Ivanyts'kyi, T.M. Lenkovs'kyi, V.M. Boiko, S.T. Shtayura, Methods for the construction of the kinetic diagrams of fatigue fracture for steels under the conditions of transverse shear with regard for the friction of crack lips, Materials Science 49/6 (2014) 749-754, DOI: https://doi.org/10.1007/s11003-014-9670-2.

[17] Y.L. Ivanytskyj, T.M. Lenkovskiy, Y.V. Molkov, V.V. Kulyk, Z.A. Duriagina, Influence of 65G steel microstructure on crack faces friction factor under mode II fatigue fracture, Archives of Materials Science and Engineering 82/2 (2016) 49-56, DOI: 10.5604/01.3001.0009.7103.

[18] O.P. Ostash, V.V. Kulyk, T.M. Lenkovskiy, Z.A. Duriagina, V.V. Vira, T.L. Tepla, Relationships between the fatigue crack growth resistance characteristics of a steel and the tread surface damage of railway wheel, Archives of Materials Science and Engineering 90/2 (2018) 49-55, DOI: 10.5604/01.3001.0012.0662.

[19] O.P. Ostash, I.M. Andreiko, V.V. Kulyk, Method for evaluating of serviceability wheel steels, Patent of Ukraine No. 106836, 9 (2014) 4 (in Ukrainian).

[20] O.P. Ostash, I.M. Andreiko, V.V. Kulyk, O.I. Babachenko, V.V. Vira, Influence of the mode of thermal treatment and load ratio on the cyclic crack-growth resistance of wheel steels, Materials Science 45/2 (2009) 211-219, DOI: https://doi.org/10.1007/s11003-009-9177-4.