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DETERMINATION OF THE CAUSES OF ROLLING SURFACE DAMAGE DURING OPERATION OF THE RAILWAY WHEELS

Purpose. Substantiation of the mechanism of damage formation on the rolling surface of railway wheels by different strength levels to determine optimal structural state of the carbon steel.

Methodology. The material for study was steel from rim fragments of the railway wheels with a carbon concentration of 0.61 and 0.69 % and other chemical elements within the range of the grade composition. Samples for mechanical tests were subjected to thermal hardening to obtain different structural states. The microstructure was examined under light and electron microscopes, using quantitative metallography techniques. Metal wear was determined under dry friction conditions, with different degrees of slippage, on a machine of the SMC-2 type. Hardness was estimated by the Rockwell method, and micro hardness of structural components – on a PMT-3 micro hardness tester.

Findings. Based on the analysis of the wheel-rail interaction, it was determined that resulting inhomogeneity at distribution of plastic deformation and heating temperature in the plane of the contact surface are due to the development of slippage processes. Heating the metal to temperatures higher than onset of phase transformations and subsequent accelerated cooling determine the mechanism of structural transformations. The difference between adjacent sections of the rolling surface with different structural states and corresponding level of strength determines conditions for the formation of a fracture center of the railway wheel during operation.

Originality. Heating the metal to temperatures above onset of phase transformations from the wheel sliding along rail and subsequent forced cooling is the cause of formation of gradient of the structures from pearlite to martensitic-bainite. The cyclic nature of the change in the structural state of the metal from simultaneous influence elevated temperatures, high plastic deformations and phase transformations corresponds to the development of low-cycle fatigue processes. Plastic deformation of the rolling surface area with martensitic or bainite structures is accompanied by softening, and with pearlite structures – by a hardening process.

Practical value. The obtained results of the development of phase transformations in carbon steel on rolling surface will be useful in determining optimal structural state of the railway wheels of different strength levels.

Keywords: *railway wheel, rolling surface, temperature, local slide, hardness*

Introduction. According to the analysis of cases of damage to the rolling surface of railway wheels during operation, it is very difficult to single out the most significant factor of influence. Against background of contributions from seasonal changes in ambient temperature [1], settings of the brake system and supporting elements of the wheel set bogie [2, 3], which are taken into account by the standards for the operation of rolling stock [4, 5], the state metal at rolling contact plane is of exceptionally high importance [6, 7].

According to the mechanical scheme of the wheel-rail interaction, the inevitable presence of a shear component of plastic deformation at contact plane during rolling and especially during braking of rolling stock is one of the reasons for heating to certain temperatures [8, 9].

The limited plane of mechanical contact between the wheel and rail, when braking the rolling stock, can lead to heating of the rim layers near the rolling surface, to temperatures of onset of phase transformations in carbon steel [10, 11].

According to a detailed analysis, the causes of damage to the wheel rolling surface should be divided into qualitatively different sources. First of all, dependence of diffusion mass transfer processes should be noted, which determine the heating rate of the wheel metal, on contact phenomena. Based on this, increase in distance from the cooling surface is accompanied by corresponding changes in phase composition of the carbon steel.

Considering that degree of heating of the wheel rim metal from arising frictional stresses on the wheel-rail contact surface is limited by the development of diffusion mass transfer processes [11, 12], it is quite expected that an increase in distance will contribute to decrease in the heating temperature.

After the braking stage is stopped, heated rim layers are subjected to forced cooling.

With a certain analysis of the structure state of heated wheel metal, only rim layers that are subjected to heating to temperatures higher than Ac_1, with subsequent accelerated cooling at rates higher than the critical value, are capable of transformation by a shear or intermediate mechanism. However, with cooling at a rate not sufficient to transform austenite areas into martensite or bainite, their transformation occurs by a diffusion mechanism [8, 11]. At the same time, accelerated cooling contributes to the formation of more dispersed pearlite-type structures, compared to the derived structural state of steel at manufacture of the railway wheels.

In proportion to the dispersion of pearlite structures, there is an increase in hardness in limited areas, compared to the bulk metal of the wheel rim at derived state. The above phenomenon is one of the sources formed of gradient of residual internal stresses. In comparison with the structure formation by diffusion mechanism, formation of martensitic or bainite cells is accompanied by the emergence of a significantly higher level of residual internal stresses. This is due to the fact that in addition to occurrence of residual stresses from gradient of the temperature during cooling, stresses are also added from the change in type of crystal lattice during phase transformation.

The fact is that during transformation austenite phase into martensite, the surface-centered cubic crystal lattice is replaced by a volume-centered one. In this case, the source occurrence of residual stresses is the difference in density of filling space unit cell of the crystal lattice with iron atoms and occurrence of strengthening from super saturation with carbon atoms of the solid solution. As a result, the total effect of the development processes of phase and structural transformations can exaggerate the strength limit, which leads to the formation of a fracture of metal of the wheel during operation.

Thus, at first glance, a number of mutually unrelated influence factors, determined by the operating conditions of the railway wheel, in fact determine the nature of the development processes structural transformations of the carbon steel. At same time, the features of the development phase transformations at the stages of heating and cooling of the rim are accompanied by a corresponding change in the complex of properties [12, 13]. Violations of uniformity of the distribution internal stresses at rim over the rolling surface are one of the reasons for decrease in resistance of the metal to the formation of fracture centers [14].

State of the problem. During operation of a railway wheel, depending on the conditions of heat removal from the rolling surface, the system of residual internal stresses in the rim will necessarily change. Given the simultaneous influence of high heating temperatures and plastic deformations in the plane of the contact surface [15, 16], determining optimal structural state by carbon steel of the railway wheel is a rather complex solution [17, 18].

Comparative analysis of the operation of the railway wheels with a strength up to 1 GPa (type *P*) indicates an increase in wear resistance by approximately 30–40 % of the wheels with a strength higher than 1 GPa (type *T*) [10, 14].

At same time, the number of emerging sliders and chipped on the rolling surface in *T* wheels increased. According to the technology of manufacturing railway wheels, a high-strength state is achieved, in addition to thermal hardening, by an additional increase in the carbon content, compared to the basic composition.

According to [6, 10], with a hardness of the *T*-type wheel steel of 3.25–3.4 GPa, the level of crack resistance, especially at low operating temperatures, was lower compared to the *P*-type wheels.

Analysis of the operation of the railway wheels of different strength levels shows that on the rolling surface of the *T*-type wheels, the number of areas with signs of sliding is greater compared to wheels with a strength of up to 1 GPa [19, 20].

Purpose. To substantiate the mechanism of damage formation on the rolling surface of railway wheels of different strength levels to determine the optimal structural state of carbon steel.

Research methodology. The material for study was steel from the rim fragments of railway wheels with a carbon concentration of 0.61 and 0.69 % and the amount of other chemical elements within the range of the base steel grade composition. From the rim fragments of wheel type *P* (with a strength of up to 1 GPa and a carbon content of 0.61 %) and *T* (with a strength higher than 1 GPa, with a carbon content of 0.69 %) samples were made to determine hardness, rolling wear, and microstructure studies. To obtain different structural states in steels, the samples were subjected to heat treatment.

In a chamber-type furnace, the samples were heated to temperatures higher than Ac_3, kept for a period sufficient to complete phase transformations in steels, and cooled at a rate higher than the critical value, while preventing oxidation. The microstructure was studied using light and electron microscopes, using quantitative metallography techniques [21].

The wear characteristics of the metal were determined by testing on a machine of the SMC-2 type, under dry friction conditions, with different degrees of slippage. The hardness of the steels was determined by the Rockwell method, and micro hardness of the structural components was determined on a PMT-3 microhardness tester.

Results and discussion. According to the studies of rim fragments, it is very difficult to determine difference in formed metal gouges on the rolling surface railway wheels of the different strength levels (Fig. 1). Although, with a more careful analysis, it is possible to determine details that separate wheels by the derived structural state of the steel and corresponding set of properties.

Let us consider the mechanism of influence of plastic deformation on condition of metal rolling surface of the wheel.

Generalization of a large number of research results on the causes of damage to the rolling surface of railway wheels [22, 23] indicates the need to separate factors by the nature of influence on the internal structure of the carbon steel. When the wheel is rolling, there is an intensive development of plastic deformation, with a high degree of non-uniform distribution in micro volumes of metal near the rolling surface. At same time, to determine the nature of structural changes, we will assume the absence of influence of the thermal component of the load.

a

b

Fig. 1. Appearance of gouges on the rolling surface of railway wheels of type T (a) and P (b)

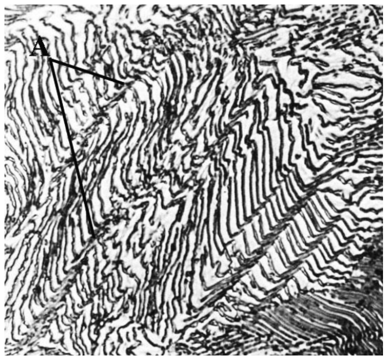
Under such conditions, the process of forming a gouge, as one of the common types of damage to the wheel rolling surface, will consist of two stages. First, under the action of normal stresses, cracks nucleate on the rolling surface, and then extraction of a metal fragment from the rim will be due to the action of tangential stresses [14].

The initial stages of plastic deformation are characterized by a very high degree of its inhomogeneous distribution, including in microvolumes of steel (Fig. 2, *a*).

Against the background of significant metal area without signs of plastic deformation, the places of its concentration are determined by significant changes in shape of phase components. So, the curvature of carbide phase plates of the pearlite colony indicates that the limit of accumulation of defects of the crystal structure have been practically reached in such places [10, 24].

As a result, the concentrated bend of the carbide phase plates turns into a cut (Fig. 2, *a*, designation *A*), which with a certain probability is capable of transforming into a micro crack cell.

Thus, even with small plastic deformations, in carbon steels, at the level of microstructural components, cells appear that can serve as the nucleus of metal fracture. But, considering the frequency of occurrence of gouges on the rolling surface, this alone is not enough. On the other hand, the analysis of rolling surface of a railway wheel after removal from service indicates the existence a large number of lines from concentrated plastic deformation (Fig. 2, *b*, designation *B*). The places of their intersection can also later turn into embryo of metal failure.



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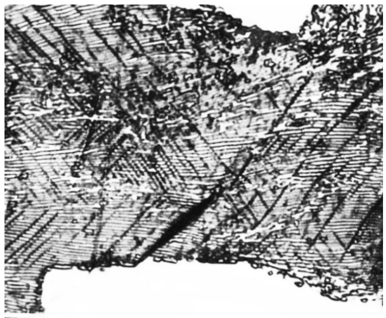

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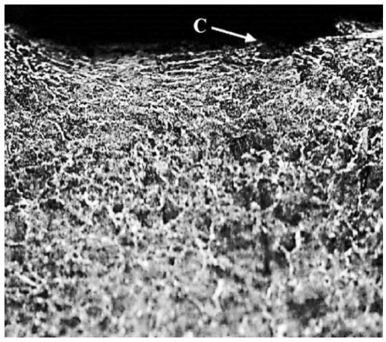

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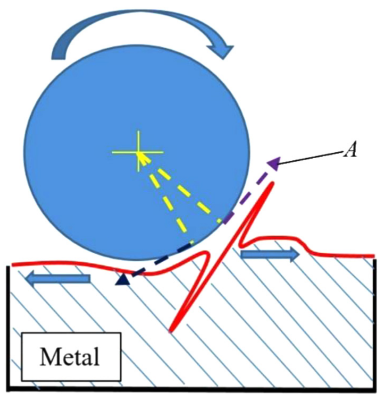


d

Fig. 2. The structure of the pearlite colony after deformation of steel (a), lines from plastic deformation on rolling surface of the wheel (b), view of the rolling surface profile (c), schematic representation of intrusions and extrusions (d):

A — the direction of plastic flow of metal from the arising tangential stresses in the plane of the contact surface. Magnification: a — 1,300; b — 200; c — 100

Upon detailed examination profile of the wheel rolling surface, the deformation lines (Fig. 2, *b*) actually represent alternating micro-volumes of extruded (extrusion) and absent (intrusion) metal (Fig. 2, *c*, designation *C*). If imagine that extruded volume of metal during the next rolling cycle will be destroyed and removed from the contact surface, then the behavior of intrusion is qualitatively different.

During the next loading cycle, the intrusion may temporarily close after its occurrence, but the metal integrity will not be restored. This is due to insufficient rate of diffusion mass transfer and the specific relief of the intrusion surfaces (Fig. 2, *d*, designation *D*).

Moreover, during the subsequent rolling load cycle, the energy consumption for opening already formed intrusion will be significantly lower since the energy for its origin has already been spent. Excess energy during continued metal loading can contribute to further growth of intrusion into the rim depth, but this scheme of fracture embryo formation also has its limitations. First of all, these are very small sizes and their relatively uniform location on the rolling surface.

Indeed, if they consider only consequences of mechanical nature interaction of the wheel and rail at the contact surface, then conditions for the transformation intrusions into a stably growing micro crack, in general, will be determined by the ratio metal wear rate and growth rate of intrusion. Under conditions when the metal wear rate of contact surface exceeds growth rate of intrusion from cyclically varying loads, the damage formation process will be absent.

On the other hand, in order for an intrusion at metal of the wheel rim to turn into a stably growing micro crack, a number of conditions must be met. First, prerequisites must be created for the violation uniform arrangement extrusions and intrusions of the metal on the rolling surface. The fulfillment of this condition is possible only due to the violation uniformity of the load on the wheel metal.

Considering that main factors of the load are the magnitude of normal stress in the wheel-rail contact plane and magnitude of the shear deformation, their simultaneous increase will only contribute to the acceleration of growth of intrusions into the metal. On the other hand, for a relatively short period of time of the wheel rolling, the value of the normal pressure can most likely be accepted as a constant characteristic. Then, often unpredictable changes occurrence of the shear component at tangential stress diagram will be a factor contributing to occurrence unevenness in distribution of intrusions, as the main factor in the formation of damage to the rolling wheel's surface of different strength levels.

Compared with mechanical factors of influence, the structural state and ability of the metal to resist formation and growth fracture embryos acquire a certain value.

Based on this, the development of deformation strengthening processes and the corresponding structural changes in the metal must certainly lead to the blunting of the intrusion mouth, which, in turn, will stop its transformation into an embryo destruction of the carbon steel. At the same time, the given schemes of the metal damage occurrence at level of microstructural components of the metal to a greater extent correspond to the conditions of uniform wear of the wheel on the rolling surface.

The processes of structural changes in the metal acquire a significant influence on formation of a fracture site on rolling surface of the wheel under conditions of deviation from the regulatory limitations of operation of the railway wheel. One of the examples of the given deviations is excessive wheel sliding on the rails during emergency braking of the rolling stock, non-simultaneous operation of the brake system of the wagons, etc.

Unbalancing of the rolling stock brake system leads to the fact that in a very short time after operation of the brake system at the first car, areas of sliding appear. On the contact surface of the wheel with a rail, areas are formed not only with a violation of the geometric dimensions of the rolling circle, but also with excessive overheating of the metal to temperatures onset of phase transformations.

Depending on the sequential or simultaneous action of significant plastic deformations and heating temperatures, significant gradients of internal stresses arise, which is a prerequisite for occurrence of surface damage to the wheel. In this state of affairs, studies on the influence of heating temperature on structural transformations in the wheel metal, which precede formation of the sliding area, acquire a certain significance.

Compared with the influence of plastic deformation on the structure and properties of the wheel steel on the rolling surface, intensity of heating acquires a certain significance. The main source of heating of the rolling surface is a level of emerging frictional stresses. As a result of the wheel-rail coupling, not only a heating of the metal to a certain temperature is achieved, but also the emergence of a temperature gradient both along a plane of the contact patch and a thickness of the wheel rim.

The typical structure of carbon steel of the wheel (Fig. 3, *a*), after formation of a slip zone from braking of the rolling stock, at absence of accelerated cooling, is accompanied by qualitative changes (Fig. 3, *b*).

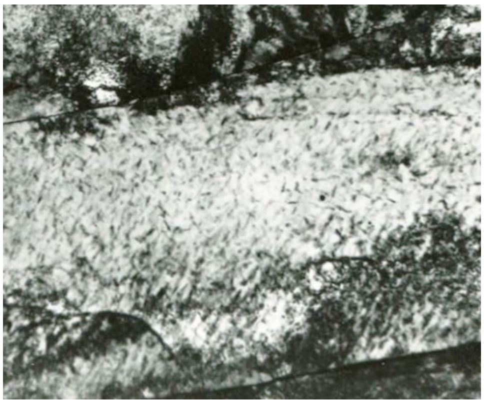
In order to increase hardness of metal of the railway wheel, in addition to thermal hardening, it was once proposed to increase the carbon concentration in steel to 0.69 %. It was believed that increasing carbon concentration would contribute to decrease in the volume fraction of structurally free ferrite and increase degree of super saturation of solid solution for carbon during thermal hardening of the wheel elements. However, in comparison with wheels (with a strength of up to 1 GPa), an increase in the number of sliders at wheels with 0.69 % *C* was obtained [14].

To determine the mechanism of influence of carbon content in the steel on the number of emerging sliders during operation of wheels, it is necessary to use the iron-carbon phase equilibrium diagram [25]. When heating steel, the temperature of pearlite transformation into austenite is 727 °C (Ac_1). For the manufacture of railway wheels, steels with a carbon content within the range of the grade composition of 0.55–0.65 % *C* are used, but the use of steel with 0.69 % *C* led to significant embrittlement of railway wheels.

According to the analysis of the phase diagram, the higher carbon content, the lower temperature (Ac_3) of complete transformation ferrite-pearlite mixture into austenite. The resulting effect can be identified as a decrease in metal's resistance to the onset of hot plastic deformation.

a

b



c

Fig. 3. Structure of heat-hardened steel with 0.6 % C (*a*) [14], *in the slider section without cooling* (*b*) *and after accelerated cooling* (*c*). *Magnification: a – 800; b – 2,000; c – 18,000*

Indeed, considering that during local wheel sliding, a thin layer of metal in the contact zone with the rail is able to heat up to temperatures of the ultra-high plasticity, increasing the carbon concentration of steel should only contribute to bringing the moment of slippage closer.

The above generalization is confirmed by the assessment of recrystallization temperature in carbon steel, which can be considered as a boundary of the beginning development processes of softening of cold-deformed metal on the rolling surface. Thus, the temperature interval of the development recrystallization by most metals and alloys is subject to the dependence

$$T_R \sim K \cdot T_S,$$

where T_R is the recrystallization temperature; K is the coefficient, for recrystallization it is equal to 0.4–0.6; T_S is the solidus temperature according to the phase diagram.

With increasing carbon concentration in steel, T_S decreases. Additional confirmation is the results of the study into kinetics of changes in strength characteristics of thermally hardened steels upon heating. It was determined that the rate of decrease in strength steel of the railway wheel *T*, starting from temperatures of 500–525 °C, exceeds the similar characteristics of steel of the wheel *P* [14].

Thus, one of the reasons for the increase in the number of damages to the rolling surface of the wheels by type *T* in comparison with type *P* may be increased plasticity of the steel after the same heating, higher than 500–525 °C. The decrease in resistance of the metal to appearance of the first signs of the plastic flow facilitates conditions of the emerging moment of sliding wheel on the rails.

If we take into account the fact that area of the wheel-rail contact patch will increase in proportion to the increase in plasticity, the specific pressure on the rail will decrease and, as a result, the friction stress will decrease.

Under the same operating conditions of the wheels, probability of sliding will have an inversely proportional dependence on the level of arising friction stresses. As a result, the increased number of formed slippage areas will contribute to the increase in inhomogeneity of the hardness distribution on the rolling surface, which will reduce resistance of metal to the genesis of fracture centers under cyclic loading [14, 21].

A similar effect on the level of hardness of surface was observed from to changes in the temperature and corresponding structural transformations in medium carbon steel under pulsating contact loads [15, 17].

The degree of sliding was found to depend on the ratio at normal and tangential components of the applied stress. The hardness along a slip spot, near the boundaries, was higher, and in the middle of a spot it was lower. Micro hardness measurements along the slip area on the rolling surface of the railway wheel also revealed a softening of the metal, which is proportional to the increase in the heating temperature. At the boundaries of a slider, where part of the strengthening from cold deformation was preserved, a slight heating does not lead to a significant softening of the metal [12, 14]. Even at absence of accelerated cooling of the metal, there is no significant change in hardness at the boundaries of the slider.

As one moves from the boundary along the slider, a consistent increase in the heating temperature will contribute to the acceleration of softening processes, with the maximum effect in the middle of the slip spot. Moreover, in proportion to the increase in the intensity of metal heating, the temperature gradient will also increase, which is confirmed by the distribution of micro hardness along the slip area.

At heating temperatures lower than Ac_1, the absence of phase transformations, regardless of the cooling rate, leads to the emergence of residual tensile stresses. Another thing is when the temperature exceeds Ac_1 value.

According to the Fe-C phase equilibrium diagram, exceeding Ac_1 value by temperature is accompanied by the transformation of pearlite colonies into austenite grains. As a result, in a thin layer near the rolling surface, the structure of carbon steel will consist of approximately 16–20 % ferrite, and the rest is austenite. With further cooling, the speed of cooling will determine the mechanism of transformation of the austenite cells. At low cooling rates, austenite will transform into pearlite colonies of the different dispersion.

Cooling at a rate close to the critical value will lead to the formation of bainite structures, and at higher critical values – to martensitic ones.

Thus, formation of slip zones, with different heating temperatures and cooling rates, transforms the uniformly hardened rolling surface after cold deformation into a striped one, with structures ranging from pearlite type (Fig. 2, *a*) to a mixture of structures bainite and martensitic (Fig. 3, *c*). When operating a railway wheel with the given structural heterogeneity of metal on the rolling surface, the difference in the ability of components of the phases to strain hardening should lead to a change in hardness in a wide range of values. The hardness distribution along the slider confirms the above position [13, 14].

The influence of rolling deformation on the hardness of the phases formed at different mechanisms. To determine the nature of the influence of plastic deformation on the metal after formation of a slider, the process was simulated under normal rolling deformation conditions. Initially, samples of the carbon steel with 0.61 % *C* after quenching on the martensite were investigated. Samples with a hardness of 65 HRC were loaded under conditions of the normal rolling deformation on the SMC-2 machine. The influence of deformation was assessed by the change in hardness of the sample surface.

When rolling deformation without slip, with a normal pressure 0.2 GPa on the sample and an angular spindle rotation speed of 300 min^{-1}, after 1,200 revolutions, the surface hardness decreased to 60.5 HRC, which was 7 % of the initial state. Additional slip of 10 % contributed to further softening of the metal. The decrease in hardness to 60 HRC was achieved with two times less spindle revolutions. An increase in the value of the slipping does not lead to a change in the nature of softening. Qualitatively different behavior during deformation of the rolling was observed for steel with a pearlite structure (Fig. 2, *a*). Under constant loading conditions, after 50 spindle revolutions, the hardness increased by 10 %. The use of sliding at 10 and 20 % led to a corresponding increase in hardness by 14–15 % from the initial state.

Thus, after formation of a slider on the rolling surface, the boundaries separating metal areas with a qualitatively different structural state and the corresponding nature of behavior at strain hardening, due to the increase in the gradient by hardness at operation of the railway wheel, are capable of transforming into centers of the fracture.

The above scheme is confirmed by the successive stages of transformation structure of the metal on the rolling surface during operation of wheels. Almost all cases of formation of the gouges on the rolling surface are preceded formation of light-colored areas, commonly called "white spots" [6, 12].

Such areas are due to the development of phase transformations in metal of the wheel, which lead to the formation of martensitic or bainite structures. To the influence of phase transformations, one should add contribution from the change in geometric dimensions of the metal under influence of heating temperatures.

In general, if we assume that hardness of the rolling surface after a certain service life is on average 35 HRC, then after formation of the slider, it can increase to 55–60 HRC.

Further, with an increase in the total plastic deformation during operation of the wheels, hardness will decrease. Thus, a sequential change in the structural state of the metal from the total action of elevated temperatures, high plastic deformations and phase transformations is similar in influence to the development of low-cycle fatigue. The accumulated nature of damage at the microscopic level, after a certain service life of the railway wheel, causes formation of a metal fracture embryo capable of further growth.

Conclusions.

1. Based on the analysis of the wheel-rail interaction, it was determined that the ratio between effects of hardening and softening of the metal is the main cause of damage to the rolling surface.

2. The degree of non-uniformity of distribution of the plastic deformation and the heating temperature are the main factors of occurrence of local slipping areas on the rolling surface of a railway wheel.

3. In proportion to the increase in the intensity of the wheel slipping along the rail, the metal heating temperature increases along the plane of the contact surface. At heating temperatures of carbon steel above the beginning of the phase transformations, the mechanism of structural transformations is determined by the conditions of the subsequent cooling.

4. The formation of a qualitatively sundry structural state of carbon steel on the rolling surface determines the nature of influence of plastic deformation on the strength properties. Areas of the rolling surface with martensitic or bainite structures soften after plastic deformation, and those with pearlite structures strengthen.

5. An increase in the difference in the complex of properties of the carbon steel between areas of the rolling surface with a qualitatively different structural state, due to an increase in the hardness gradient during wheel operation, will be able to transform into fracture centers.

References.

1. Bondarenko, I., Lukoševičius, V., Keršys, R., & Neduzha, L. (2024). Investigation of dynamic processes of rolling stock–track interaction: experimental realization. *Sustainability*, *15*, 5356. https://doi.org/10.3390/su15065356

2. Zirek, A., & Onat, A. (2020). A novel anti-slip control approach for railway vehicles with traction based on adhesion estimation with swarm intelligence. *Railway Engineering Science*, *28*, 346-364. https://doi.org/10.1007/s40534-020-00223-w

3. Shretha, S., Spiryagin, M., & Wu, Q. (2019). Friction condition characterization for rail vehicle advanced breaking system. *Mechanical systems and signal processing*, *134*, 106324. https://doi.org/10.1016/J.ymssp.2019.106324

4. Hu, Y., Zhou, L., Ding, H.H., Tan, G.X., Lewis, R., Liu, Q.Y., Guo, J., & Wang, W.J. (2020). Investigation on wear and rolling contact fatigue of wheel-rail materials under various wheel/rail hardness ratio and creepage conditions. *Tribology International*, *143*, 106091. https://doi.org/10.1016/j.triboint.2019.106091

5. Liu, P., Quan, Y., Wan, J., & Yu, L. (2021). Experimental investigation on the wear and damage behaviors of machined wheel-rail materials under dry sliding conditions. *Materials (Basel)*, *14*(3), 540. https://doi.org/10.3390/ma14030540

6. Vakulenko, I., Plitchenko, S., Bolotova, D., & Asgarov, Kh. (2023). Influence hot plastic deformation on the structure and properties of carbon steel of the railway wheel. *Scientific Journal of Silesian University of Technology, Series Transport*, *121*, 257-266. https://doi.org/10.20858/sjsutst.2023.121.16

7. Liu, M., Fan, Y., Gui, X., Hu, J., Wang, X., & Gao, G. (2022). Relationship between microstructure and properties of 1,380 MPa grade bainitic rail steel treated by online bainite-based quenching and partitioning concept. *Metals*, *12*, 330. https://doi.org/10.3390/met12020330

8. Malvezzi, M., Pugi, L., Papini, S., Rindi, A., & Toni, P. (2013). Identification of a wheel–rail adhesion coefficient from experimental data during braking tests. *Proceedings Institution Mechanical Engineers, Part F: Journal Rail Rapid Transit*, *227*, 128-139. https://doi.org/10.1177/0954409712458490

9. Molyneux-Berry, P., Davis, C., & Bevan, A. (2014). The influence of wheel/rail contact conditions on the microstructure and hardness of railway wheels. *The Scientific World Journal*, Article ID 209752. https://doi.org/10.1155/2014/209752

10. Vakulenko, I. O., Vakulenko, L. I., Bolotova, D. M., Kurt, B., Asgarov, H., & Colova, O. (2022). Influence structure on the plasticity of carbon steel of the railway wheel rim in operation. *Scientific Journal of Silesian University of Technology, Series Transport, 115*, 183-192. https://doi.org/10.20858/sjsutst.2022.115.13

11. Pereira, H. B., Alves, L. H. D., Rezende, A. B., Mei, P. R., & Goldenstein, H. (2022). Influence of the microstructure on the rolling contact fatigue of rail steel: Spheroidized pearlite and fully pearlitic microstructure analysis. *Wear*, 498-499. https://doi.org/10.1016/j.wear.2022.204299

12. Seo, J.-W., Hur, H.-M., & Kwon, S.-J. (2022). Effect of mechanical properties of rail and wheel on wear and rolling contact fatigue. *Metals*, *12*, 630. https://doi.org/10.3390/met12040630

13. Langueh, A., Brunel, J-F., Charkaluk, E., Dufrenoy, P., Tritsch, J-B., & Demilly, F. (2013). Effects of sliding on rolling contact fatigue of railway wheels. *Fatigue and Fracture of Engineering Materials and Structures, 36*, 515-525. https://doi.org/10.1111/ffe.12020

14. Vakulenko, I., Bolotova, D., Perkov, O., & Lisniak, A. (2016). Influence of hot reduction parameters on the steel austenite structure of a railway wheel. *Scientific Journal of Silesian University of Technology, Series Transport, 93*, 141-148. https://doi.org/10.20858/sjsutst.2016.93.15

15. Gao, G., Liu, R., Fan, Y., Qian, G., Gui, X., Misra, R. D. K., & Bai, B. (2022). Mechanism of subsurface microstructural fatigue crack initiation during high and very-high cycle fatigue of advanced bainitic steels. *Journal of Materials Science and Technology, 108*, 142-157. https://doi.org/10.1016/j.jmst.2021.08.060

16. Gao, M. X., Song, H., Yang, J., & Fu, L. J. (2019). Study on residual stress and strain during rail rolling contact of straight U75V rail. *Metalurgija, 58*(3-4), 203-206.

17. Qiu, J., Zhang, M., Tan, Z., Gao, G., & Bai, B. (2019). Research on the microstructures and mechanical properties of bainite/martensite rail treated by the controlled-cooling process. *Materials (Basel), 12*(19), 3061. https://doi.org/10.3390/ma12193061

18. Chepil, R., Vira, V., Kulyk, V., Kharchenko, Y., & Duriagina, Z. (2018). The peculiarities of fatigue process zone formation of structural materials, *Diagnostyka, 19*(4), 27-32. https://doi.org/10.29354/diag/94754

19. Liu, M., Wang, J., Zhang, Q., Hu, H., & Xu, G. (2021). Optimized properties of a quenching and partitioning steel by quenching at fine martensite start temperature. *Metals and Materials International, 27*, 2473-2480. https://doi.org/10.1007/s12540-020-00726-5

20. Soares, H., Zucarelli, T., Vieira, M., Freitas, M., & Reis, L. (2016). Experimental characterization of the mechanical properties of railway wheels manufactured using class B material. *Procedia Structural Integrity, 1*, 265-272. https://doi.org/10.1016/j.prostr.2016.02.036

21. Voor, G. V. (2015). Introduction to Quantitative Metallography. Solutions for Materials Preparation, Testing and Analysis. *Buehler, a division of Illinois Tool Works, 1*(5), 1-4.

22. Makino, T., Kato, T., & Hirakawa, K. (2012). The effect of slip ratio on the rolling contact fatigue property of railway wheel steel. *International Journal of Fatigue, 36*(1), 68-79. https://doi.org/10.1016/j.ijfatigue.2011.08.014

23. Cvetovski, K., Ahlstrom, J., & Persson, C. (2012). Subsurface crack networks and RCF surface cracks in pearlitic railway wheels. *9th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM '12),* (pp. 27-30). August 2012, Chengdu, China. Retrieved from https://research.chalmers.se/en/publication/236496

24. Sandström, J. (2012). Subsurface rolling contact fatigue damage of railway wheels – a probabilistic analysis. *International Journal of Fatigue, 37*, 146-152. https://doi.org/10.1016/j.ijfatigue.2011.11.002

25. LUMITOS AG (2020). *Eisen-Kohlenstoff-Diagramm*. Retrieved from https://www.chemie.de/lexikon/Eisen-Kohlenstoff-Diagramm.html#Darstellung_der_Phasen_im_Eisen-Kohlenstoff-Diagramm

Визначення причин ушкодження поверхні кочення при експлуатації залізничних коліс

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Мета. Обґрунтування механізму утворення ушкоджень поверхні кочення залізничних коліс різного рівня міцності для визначення оптимального структурного стану вуглецевої сталі.

Методика. Матеріалом для дослідження були сталі фрагментів ободу залізничних коліс із концентрацією вуглецю 0,61 і 0,69 % та інших хімічних елементів у межах марочного складу. Зразки для механічних випробувань піддавали термічному зміцненню для отримання різного структурного стану. Мікроструктуру досліджували під світловим і електронним мікроскопами, з використанням методик кількісної металографії. Знос металу визначали за умов сухого тертя, з різним ступенем проковзування, на машині типу СМЦ-2. Твердість оцінювали за методикою Роквелла, а мікротвердість структурних складових на мікротвердомірі типу ПМТ-3.

Результати. На основі аналізу взаємодії колеса з рейкою визначено, що виникаюча неоднорідність розподілу пластичної деформації й температури розігріву у площині контактної поверхні обумовлені розвитком процесів проковзування. Розігрів металу до температур, вищих початку фазових перетворень, і наступне прискорене охолодження визначають механізм структурних перетворень. Різниця між сусідніми ділянками поверхні кочення з різним структурним станом і відповідним рівнем міцності визначає умови формування осередку руйнування залізничного колеса при експлуатації.

Наукова новизна. Розігрів металу до температур, вищих початку фазових перетворень від проковзування колеса по рейці, та наступне примусове охолодження є причиною утворення градієнту структур від перлітних до мартенсито-бейнітних. Циклічний характер зміни структурного стану металу від одночасного впливу підвищених температур, високих пластичних деформацій і фазових перетворень відповідає розвитку процесів малоциклової втоми. Пластична деформація ділянки поверхні кочення з мартенситною або бейнітною структурою супроводжується пом'якшенням, а з перлітною – процесом зміцнення.

Практична значимість. Отримані результати розвитку фазових перетворень у вуглецевій сталі при навантаженні коченням стануть у нагоді при визначенні оптимального структурного стану залізничних коліс різного рівня міцності.

Ключові слова: *залізничне колесо, поверхня кочення, температура, деформація зсуву, твердість*

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