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RESEARCH OF THE STRUCTURE CHANGES CLOSE TO THE TREAD SURFACE OF THE RAILWAY WHEELS DURING OPERATION

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Summary

The structural and chemical changes near the tread surface of the railway wheels with the different tread profiles during operation were investigated. The influence of the structural changes in steel on forming of the micro-destructions and tread wearing was determined. The advantages of the complex-curvilinear tread surface were shown.

Introduction

The quality of the railway steel determines in many respects the safety of the train operation. The railway wheel has complicated shape. It serves as a support of the vehicle, a guide member for the movement and as a brake drum. Each of its elements (rim, web, hub) has its own function and undergoes stresses inherent to them. The multiple complex of the vertical and lateral loadings acts on the wheel. The loadings depend on pulling, guiding and lateral forces, and the essential part of which is composed by inertial forces from the unsprung parts. During the operation the wheel is in the complex stressed state determined by the chain of the contact, dynamic and cyclic stresses. The dynamic stresses are originated by the pressing of the wheel while rolling motion on rail, loads during impacts on the rail joints etc. The contact stresses are governed by the wheel-rail contact and brake shoes when tangential stresses and the stresses originated by the heat while braking tension arise. Heat stresses effective in the rim and web are being the cyclic one. All these stresses provoke in the wheel elasto-plastic and heating effects, fatigue processes in the rim and web, undercut flange and tread deterioration. Different kinds of the damages appear in the wheel: tread wear (modification of rim profile on the tread), the defects of the heating origin (creeps, infusions, braking dents, thermal cracks), fatigue spading and fragile cracks.

The integrated approach to the mechanism of the railway wheels wear includes the study of the structural changes, which occur in the superficial layers and the analysis of the wear particles. Interest toward the investigation of the wear mechanism which has quickened recently is connected not only to the necessity of the reduction related losses but also with the development of the sufficient manes of forecasting wheels durability, reliability in service especially under extreme conditions (high loads, high speed, increased temperature loadings on the continuous grades etc.).

The subject and research methods

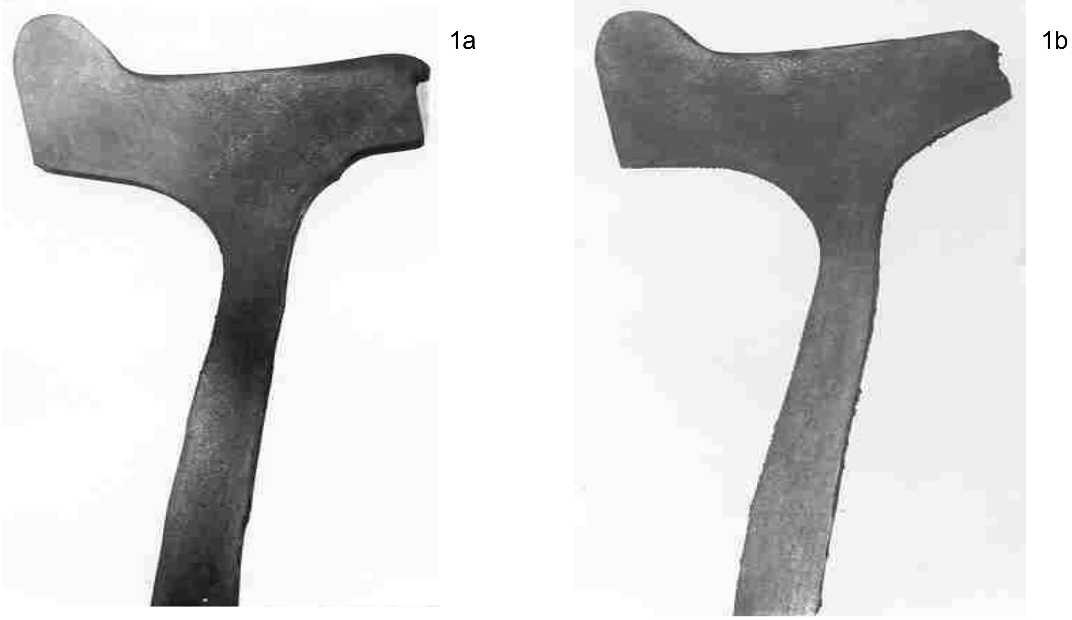
The important role in the understanding of the wear mechanism belongs to the investigation of the changes occurred in superficial layers of the rims during the service. The changes are connected with the development of the plastic displacements because of the action of the external loadings, heating stresses while braking as well as creation of "the white layers" when the metal is getting warm from heating while braking and drastically cools while brakes cessation. The worn wheels of different designs were studied: standard wheels with the cone-and-plate tread having the inclinations 1:20 and 1:7 [1] (wheel #.1) and the wheel with the complex-curvilinear tread developed at NMAU (wheel #2) [1]. The wheels were in the operation under the passenger train for more than 5 years. The chemical composition of the wheels is given in the table 1.

Table 1. Chemical composition of wheel steel of the wheels under question (volume.%)

Wheel	C	Mn	Si	S	P	Cr	Ni	Cu
1	0,59	0,72	0,31	0,025	0,012	0,14	0,15	0,20
2	0,57	0,78	0,34	0,023	0,012	0,14	0,16	0,21

The cross – section templates were cut from the wheels and on the section the character of their structure in the width of the rim was studied. Microstructural analysis was carried out on the optical microscope "Neophot-21". The peculiarities of the steel fine structure and locations density in the superficial layer were determined with the help of the electronic-microscopic (transmission microscope "Tesla") and X-ray structure analysis.

Visually inspected wheel # 1 with the badly worn flange had revealed on the tread the defects like creep, metal galling, liquation, buildup of the steel from the tread to the outer side face of the rim, fatigue – corrosion wear. The buildup of the steel resulted in the distortion of the wheel profile during operation (fig. 1a). From the creep to the deeper layers of the rim the numerous cracks initiated accompanied by the steel bearing zone and corrosion of the steel. Microstructure analysis of the cross-section template of the wheel #2 with the complex-curvilinear tread did not reveal any distortion of the profile (fig. 1 b). On the surface there is a small creep, the traces of corrosive destruction and small buildup of the steel to the outer side face of the rim.


1a

1b

Fig. 1. Macrostructure of wheels # 1(a) and 6 (b) with worn rim

While investigating changes of the chemical composition by the tread the elements content was determined by the laser spectral analysis on the devise MSL – 3 with the parallel grinding to the tread in every 5 mµ.

Investigation results and discussion

The microstructure of all the wheels rims close to the tread is characterized by the existing of the zone of the strained grains and the areas of the “white layer”. The appearance of the strained grains zones is connected with the metal bearing because of the pressure from the rail in the contact zone. The plastic displacement in the thin surface layer occurred under the conditions of the relatively high pressure and the temperature cyclically change. The character of the microstructure evidences that the behavior of the plastic deformation is heterogeneous over the rim cross section related to the non-uniformed distribution of the contact stresses: it is known that in the cove zone they are higher than in the middle of the tread [2].

In coving zone of wheel #1 the grains are greatly elongated and grinded (fig. 2a), approaching the tread the grains are bigger, their elongation degree is slightly reduced and becomes progressively less while going inside the tread (fig. 2b). While moving off the middle part of the tread to the opposite side to the flange elongation degree of grains grows again and becomes significant by the edge of rim. The nature of the structure in this part of tread is evidencing substantial steel flow in this zone, leading to wheel profile change. In flow zone laminations are discovered, oriented parallel to the tread (fig. 2c). As a rule they are located at the border in between areas with sharply different microstructure and divide the zones of elongated and equiaxial grains. The flow occurred progressively, by layers, which were warped while their displacement. At the same time fatigue cracks appeared, promoting metal corrosion in layers. At the very edge of the flow to the side rim surface the lobes with deformed structure overhang (fig. 2d). They are also the evidence of fiberwise flow device. Between these layers and also between floating metal and side edge cracks are visible.

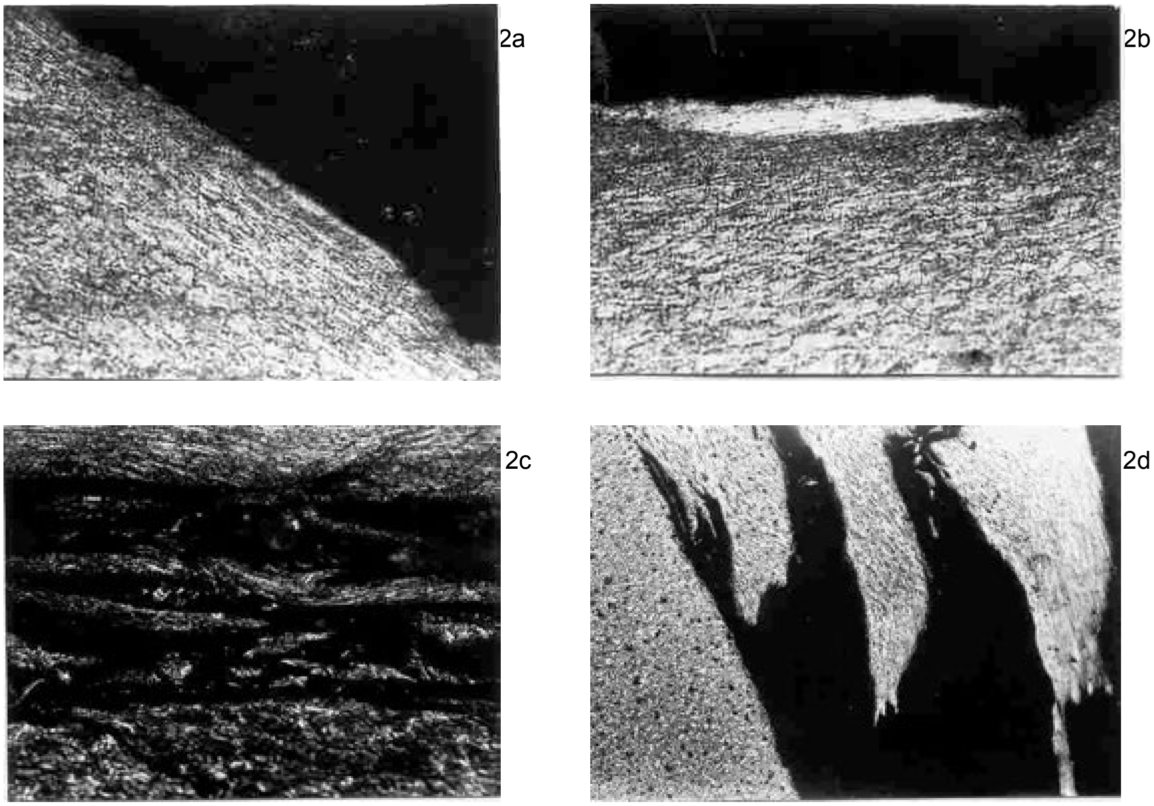


Fig. 2. Microstructure of different areas of worn tread of wheel 1; x200

The size value of grains elongation degree ε, of zone of plastic shears **h** and of dislocation density $\rho_{\perp}$ in different fields of tread of wheel #1 are given in table 2.

Table 2. Parameter Values of Microstructure ε, h and $\rho_{\perp}$ on tread of wheel 1

ε, %			*h*, μm			$\rho_{\perp}$, sm^{-2}		
cove	center	flow	cove	center	flow	cove	center	flow
65...75	22...25	90	300	30	600	$9{,}22 \cdot 10^{11}$	$3{,}732 \cdot 10^{9}$	$9{,}60 \cdot 10^{11}$

It should be noted that at operation on tread in conditions of deformative processes at rolling friction textures of rolling are formed, which are materialized as a result of joint action of normal and contact stresses. The examples of such textures, which are discovered in wheel #1 and then in the other wheels with cone-and-plate profile of tread: (223) $[03\bar{2}]$, (212) $[\bar{5}\bar{2}6]$, (112) $[\bar{1}\bar{3}2]$, (221)) $[11\bar{1}]$. In steel layer on the tread typical dislocation cellular substructure is shaped with gentle orientation of cellular webs towards the friction direction – band-pass substructure (fig. 3). Physical spreading of lines (110) is modified by depth from tread, which is related to different thickness of dislocations.

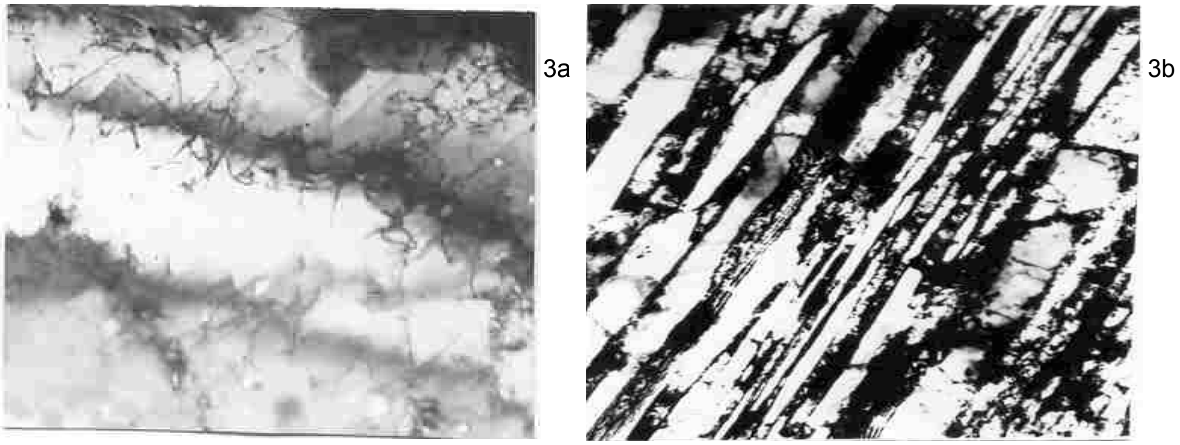


Fig.3. Dislocation substructure of steel near tread; x20000

The depth of zone of deformated grains edgewise of tread of wheel #1 is unequal (fig. 4). Plastic deformation spread innermost in flange cove area and in flow area near the rim edge. Elongation degree of grains allows to judge deformation degree of steel in surface coating of rim. The patterns of change of microhardness are similar. Dislocations thickness, defined by X-ray structure analysis is also unequal in different areas of tread. The allocation on the rim profile of parameters of intensive deformation of metal coating is indicated on fig. 4. Microhardness splashes were observed in the areas of occurrence of “white layer” structure.

The areas of “white layer” are structureless martensite (hardenite), it is a fatigue structural component, which is crumbled in the process of wheel service (see fig. 2b). “White layer” appears as a result of warming of thin surface layer of breaking heat till temperature beyond A_3 and subsequent quenching after break-shoes are switched-off. The width of “white layer” is 20-40 μm.

Microstructure nature of wheel #1 near tread in rolling direction is similar as for cross section considered above, however, elongation degree of grains in longitudinal direction is significantly higher. During analysis of structure in plate of rolling complex mode of steel stream is discovered in surface coating (fig. 5). There are areas with bent and curled grains in flow zone, where steel stream beard obviously rotational, turbulent nature.

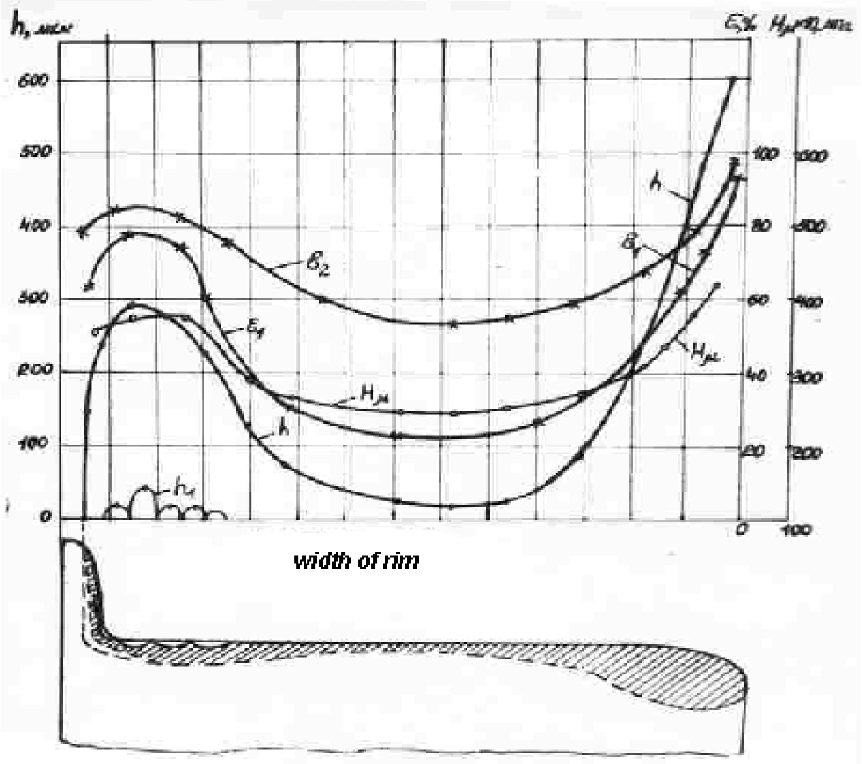


Fig. 4. Changing of deformation rate of grains across ε_1 and in rolling direction ε_2, microhardness Hμ and depth of plastic deformation area h in the width of wheel rim 1

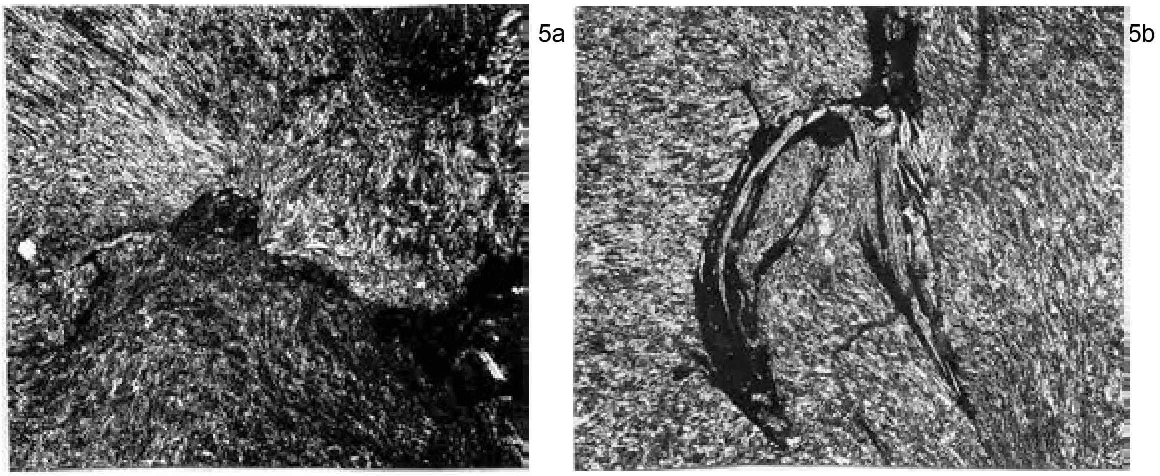
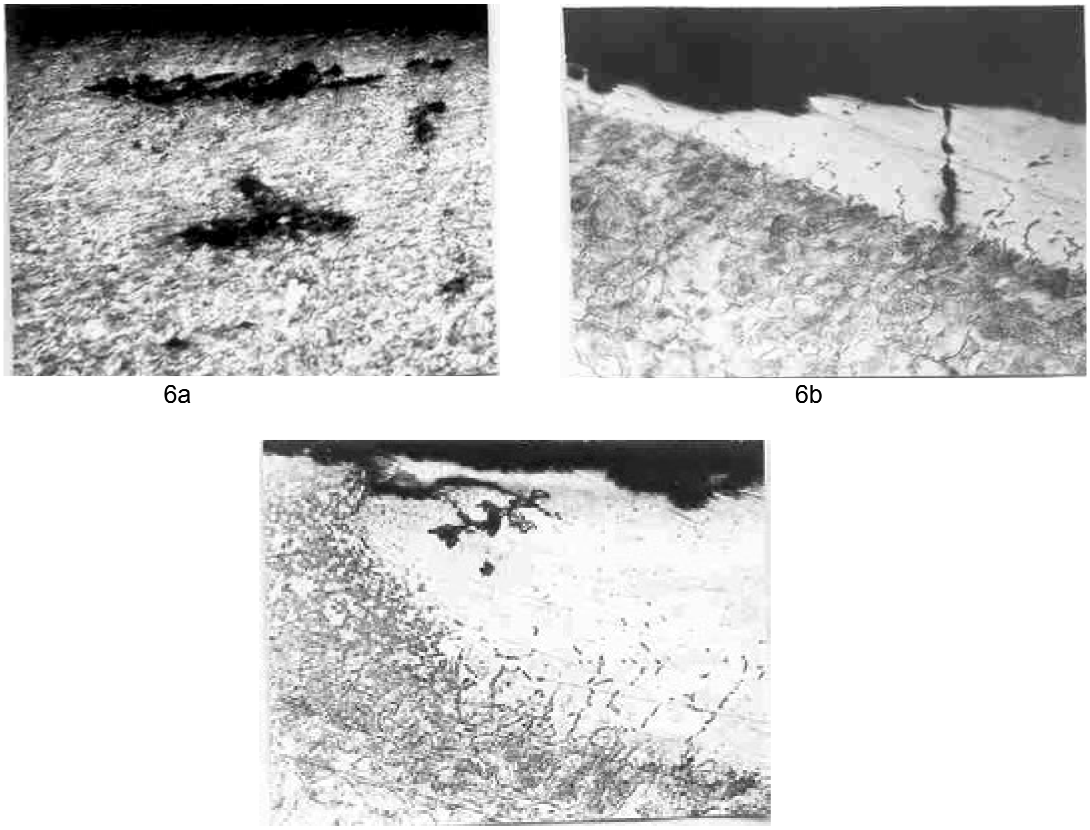

5a
5b

Fig. 5. Microstructure of worn rim of wheel 1 in plate of rolling; x 200

Rim microstructure examination in flow zones showed that the displacement of metal from inclination 1:20 to inclination 1:7 is inexpediently, as far as flowing occurs by layers and it is accompanied by complete turbulent steel stream. It results in increased wear out, occurrence of cracks, laminations and zones of heterogeneous deformation, scabbings, flows on hump retard. Therefore, existing geometry of tread with inclination 1:20 and 1:7 is far from geometrical perfection and it demands further change into curved surface, which has significantly smaller flow degree as long-term tests showed. The same imperfections to a greater or lesser extent are related to other cone treads.

The study of mechanism of wear of wheels tread with cone-and-plate profile was carried out. Along all tread microcracks and laminations occurred, leading to forming and delamination of wear fragments or to brittle failure in cove area which in practice causes mass rolled kinks of flanges of wheels. The great quantity of fragments is discovered on all width of rim and promotes rolled kink of flange and intensive flowing. It means intensive wear-out of wheel. Formation of wear-out fragments has different causes.

One of the main causes is passing of plastic deviations with significantly great degree of deformation, which has unequal mode. Just at the border of zones with different degree of deformation microcracks, delaminations, wear-out fragments appear (fig. 6a). The so-called “white layer” has increased fragility (fig. 6 b), moreover on its boundary with main structure considerable tensions occur, given by different physical and mechanical properties of zones with different structures. It contributes to crumbling of “white layer” (fig. 6c), therefore it is not practically continuous.



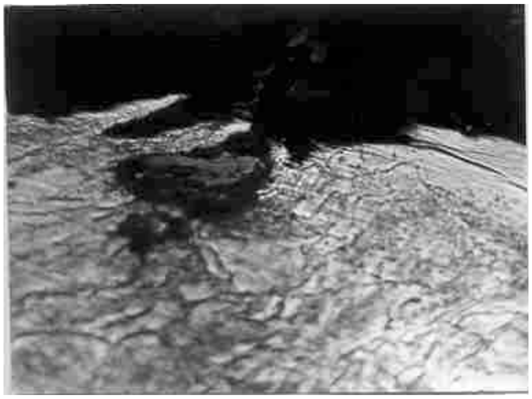
6a

6b

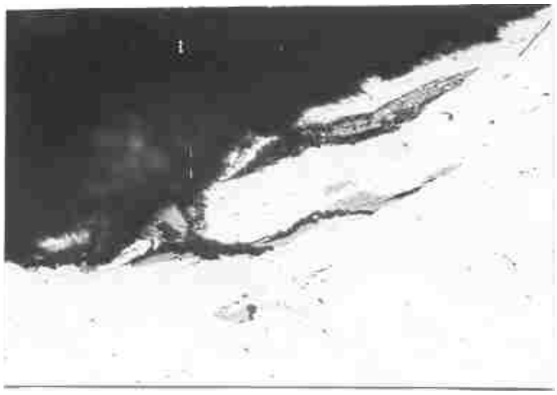
6c

Fig.6 Microcracks and delaminations near tread

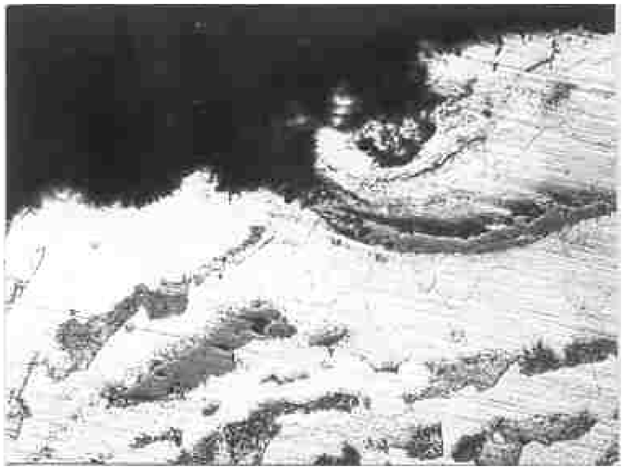
Formation of cracks and wear-out fragments also promotes oxidation and corrosive destruction of tread, at that the oxidation should be referred to formation of rough nonmetallic inclusions on tread. At presence of nonmetallic inclusions in surface layer, which have metallurgical origin, they become stress concentrator. Near inclusions in initial condition increased concentration of tensions already exists [3]. In the process of development of plastic deviations steel grains bend round inclusion (fig. 6d), and it conducts to unequal development of deformation and accumulation of tensions, which conduct to formation of microcracks (fig. 6e) and destruction of the inclusions. Around nonmetallic inclusions at emergency break application significant thermal stresses also arise, which reach critical size and they also are conductive to origination of cracks and wear-out fragments. It should be noted that nonmetallic inclusions are the center of local decarbonizing of steel which causes to structure inhomogeneity and involves inhomogeneous development of plastic displacement and also formation of microcracks (fig. 6f) and wear-out fragments.



6d

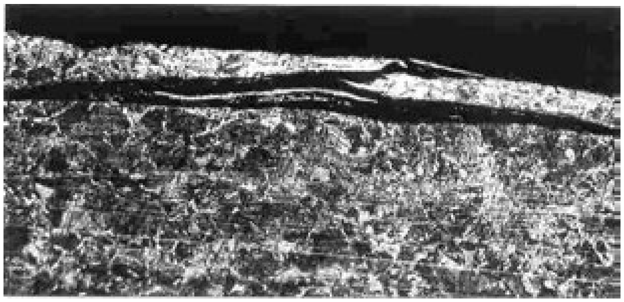


6e

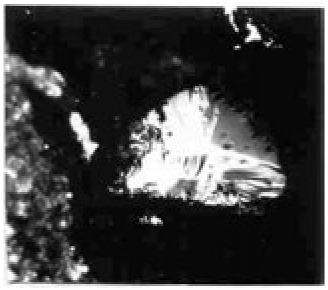


6f

Thus, multiple cyclic thermomechanical influence on tread of wheel at its interaction with rail conducts to accumulation of stresses and defects (microcracks, peelings, laminations) and it leads to formation of fragments of separation (fig. 7a, b). The most spread wear-out fragments are flakes and plates of different thickness. They are typical for normal conditions of wear-out [4] and their appearance connected with plastic deformation. According to theory of wear-out by “exfoliation”, at friction the maximum thickness of dislocation appears directly not at the surface but on some depth where prolonged cracks appear and they grow till critical size forming flakes which are exfoliated. The main part in this process refers to plastic acts conducting to accumulation of dislocations and cracks appearance parallel to the surface. Forming of flakes of wear-out goes by the way of adherent exfoliation.



7a



7b

Fig.7a,b. Wear-out fragments near tread

Sometimes wear-out fragments are in the form of loops, curls similar to chips during cutting (fig. 7c). Such fragments precede to damage and they are disclosed mainly on tread before local destruction. Wear-out fragments are also disclosed in the form of splinters with acute edges of irregular form (fig. 7d). Such fragments usually originate at very high pressures and their origin may be connected with forming of small fatigue cracks in surface coats of rims and their coming out on surface is the beginning of forming of wear-out fragments.

7c

7d

Fig.7,c,d. Wear-out fragments near tread

Results of analysis of microcracks, exfoliations and wear-out fragments showed that wear-out of treads of railway wheels occurs by several mechanisms and it is multiple-factor process.

Comparative researches of structural modifications near complex curvilinear tread of wearied rim (wheel #2) were conducted. In the cove zone the grains are elongated and crumbled up (fig. 8a), while coming out on tread surface elongation degree of grains is decreased (fig. 8b). While moving off the middle of tread elongation degree of grains increases again (fig. 8c) and it becomes significant near the edge of rim. Near external side rim border the little flow occurred (fig. 8d), where exfoliation is disclosed, areas of oxidation of steel and microcracks.

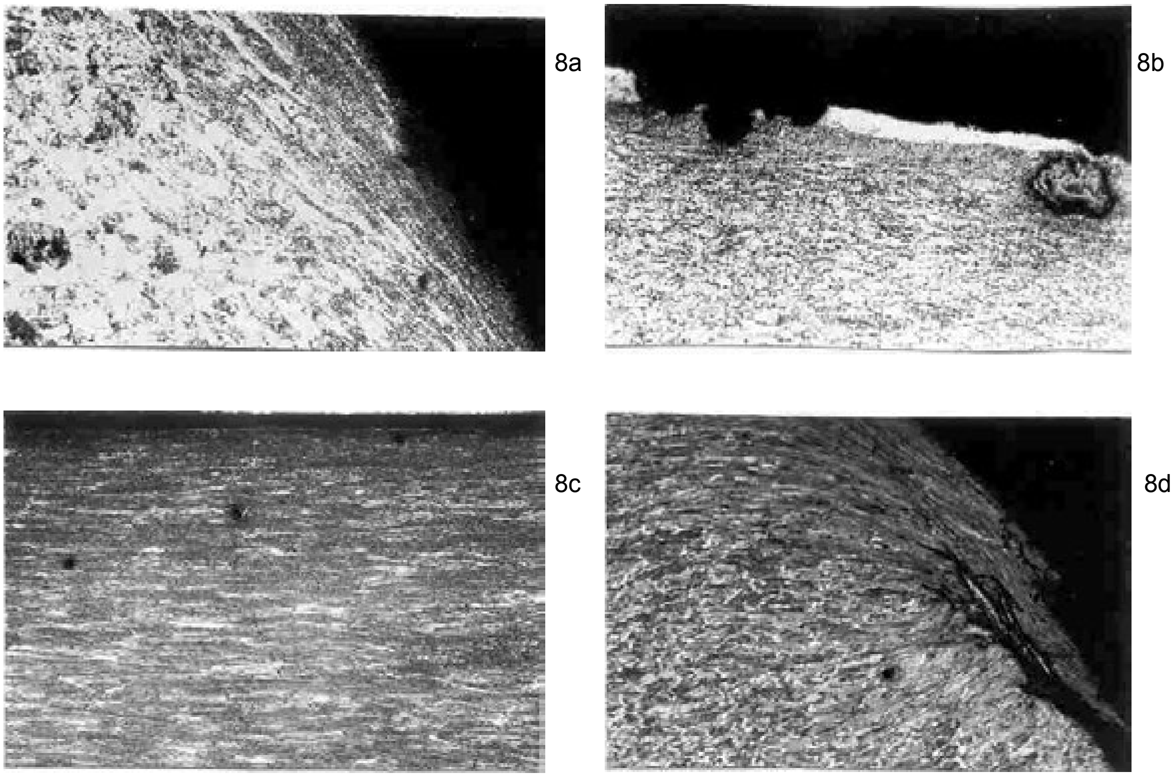


Fig.8. Microstructure near tread of worn rim of wheel 2 in the cross section; x200

Table 5. Parameters Values of Microstructure ε, h and ρ⊥ on Tread of Wheel #2

ε, %			*h*, μm			$\rho_{\perp}$, sm^{-2}		
Cove	center	flow	cove	center	flow	Cove	center	flow
60	10	80	180	20-40	420	$6{,}54\cdot10^{10}$	$6{,}41\cdot10^{8}$	$8{,}0\cdot10^{11}$

On fig. 9 and table 5 parameters of zone of structural modifications in wheel #2 are mentioned. As of the wheels with plane conical tread, deformation zone innermost spread in the places of coving and flow of wheel #6. The mode of changes of microhardness of steel by width of rim is similar. Sharp jump of microhardness on distance 2/3 of flange width connected with presence of “white layer” zone. The results of definition of dislocation thickness showed that their quantity is also maximum in cove and flow zones (table 5).

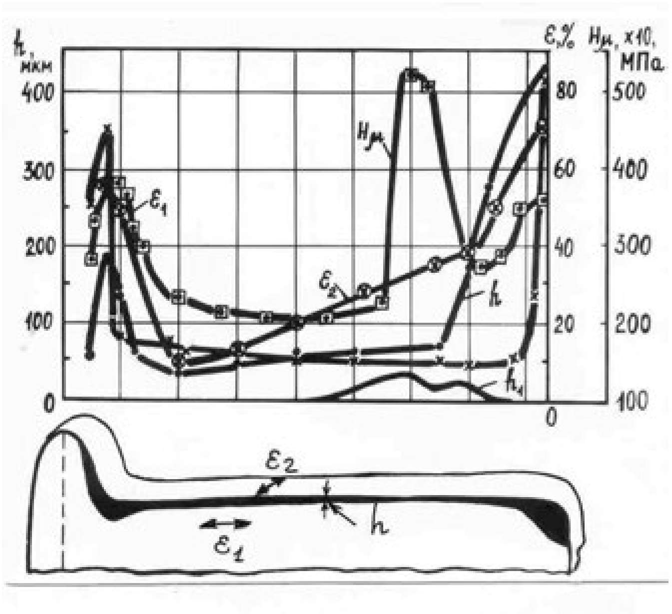


Fig. 9. Changing of deformation rate of grains across ε_1 and in rolling direction ε_2, microhardness Hμ and depth of plastic deformation area h in the width of wheel rim 2

Steel microstructure in plain of rolling is characterized by presence of equalaxial grains and stains of “white layer”, only in zone of grain flow the grains are elongated. Zones of turbulent steel streams were not observed.

Comparative analysis of microstructure of wheels with plain cone (wheel #1) and complex curvilinear profile of tread (wheel #2) showed that qualitative structural changes in rims are similar but parameters of these zones are different and depend on wheel design (geometry of tread). Research of structural changes indicates on imperfection of plain cone tread (with inclinations 1:20 and 1:7) contributing heterogeneous development of plastic displacements in surface layer and not similar degree of deformation of grains in different zones. Behavior of intensive plastic displacements in conditions of action of high enough contact stresses leads to intensive wear-out of wheels with plain cone profile of tread. Especially dangerous processes which are running in cove zone and conducting to rolled kink of flanges. At the present time this problem is very actual.

It should be noted that plastic displacements near tread can not be considered only as negative phenomenon. On the first stage they promote extra earning of wheels, arouse cold work hardening (hardening in the process of using – distinctive auto reinforcement), which permits to provide increased hardness and wear-resistance of rims.

Plastic displacements in surface layer of rim, thermocycling in the process of braking and interaction with ambient air create conditions for intensive development of diffusive processes, which may provoke changes of steel chemical composition. The analysis showed that steel chemical composition is modified in the process of using irregularly. At the distance from tread 5 μm maximum burnout of elements is due to cove and place adjoining to it right up till the middle of rim, at that distance the difference in chemical composition of steel is not significant. While passing external edge of rim elements content (except carbon) gradually increases and it almost comes out to the level of average steel composition near the very edge. Modification of elements contents in cove zone in comparison with chemical composition of steel, % (volum.): ΔC=0,37, ΔMn=0,34, ΔS=0,018, ΔSi=0,16,ΔP=0,008; at the edge of rim in flow zone: ΔC=0,13, ΔMn=0,02, ΔS=0,008, Δsi=0,01, ΔP=0,002. Thus, maximum "burnout" in cove zone near tread per elements composed 63% C, 48% Mn, 72% S, 47% Si, 77% P, in flow zone – 22% C, 4% Mn, 32% S, 3% Si, 17% P. While further grinding the content of elements gradually increases, however irregular mode of their “burnout” is kept. At distance 20 μm from tread in zone of cove and abutting areas right up till the middle and at approaching to its edge the content reaches the level of average contents of steel.

Depth of “burnout” zone of elements is 20…30 μm depending on the place by the width of rim. Observed mode of modifications of steel content is connected with changes in thin surface layer. The most strongly the elements “burnout” in the places of intensive plastic displacements and pronounced “white layer”, at that these two structural factors come forward in complete set, as far as intensive “burnout” of elements is not disclosed in flow zone in the other wheels in that zones of tread where “white layers” and zones of plastic displacements were absent.

Modifications of chemical composition of steel in surface layer of rim conditioned by presence of free surface (tread), serving as drain for dirt atoms and defects of crystal constitution, as motion of dislocations and lattice vacancy, facilitating diffusion, as steel temperature increasing while intensive braking and difference of chemical potentials of elements in steel and atmosphere.

Evidently, temperature field edgewise of rim in the process of using of wheels, especially while braking, has irregular character, which promotes irregularity of diffusive processes. The effect of disclosed phenomenon on reliability and safety of running is not studied deeply. In terms of reliability of wheels it is necessary to make researches on “burnout” optimization, on research of influence on this process of level of contact tensions in wheels with different geometry of tread, of system of breakings, of coefficient of coupling of wheel with rail etc. The one thing is clear, that modification of chemical compositions of steel in the thin surface layer promotes decreasing of mechanical properties, hardness, wear-out resistance of tread and this layer is necessary to be periodically removed, which occurs while regrinding.

List of literatures

1. V.P. Essaulov, A.I. Kozlovsky, A.T. Essaulov, M.I. Staroselet’skyy. Constructions of world railway wheels. Dnepropetrovsk, “Sich” Publicity, 1997,428p.
2. Yu. N. Taran, V.P. Essaulov, S.I. Gubenko. Increasing of wear resistance of railway wheels with different tread profiles. Metallurgical and metal mining industries. 2000, № 2, p.42–44.
3. S.I. Gubenko. Transformation of non-metallic inclusions in steel. M., Metallurgy, 1991, 225 p.
4. E.A. Marchenko. Nature of wear out of metal surfaces when friction.-M., Nauka, 1979, 118p.