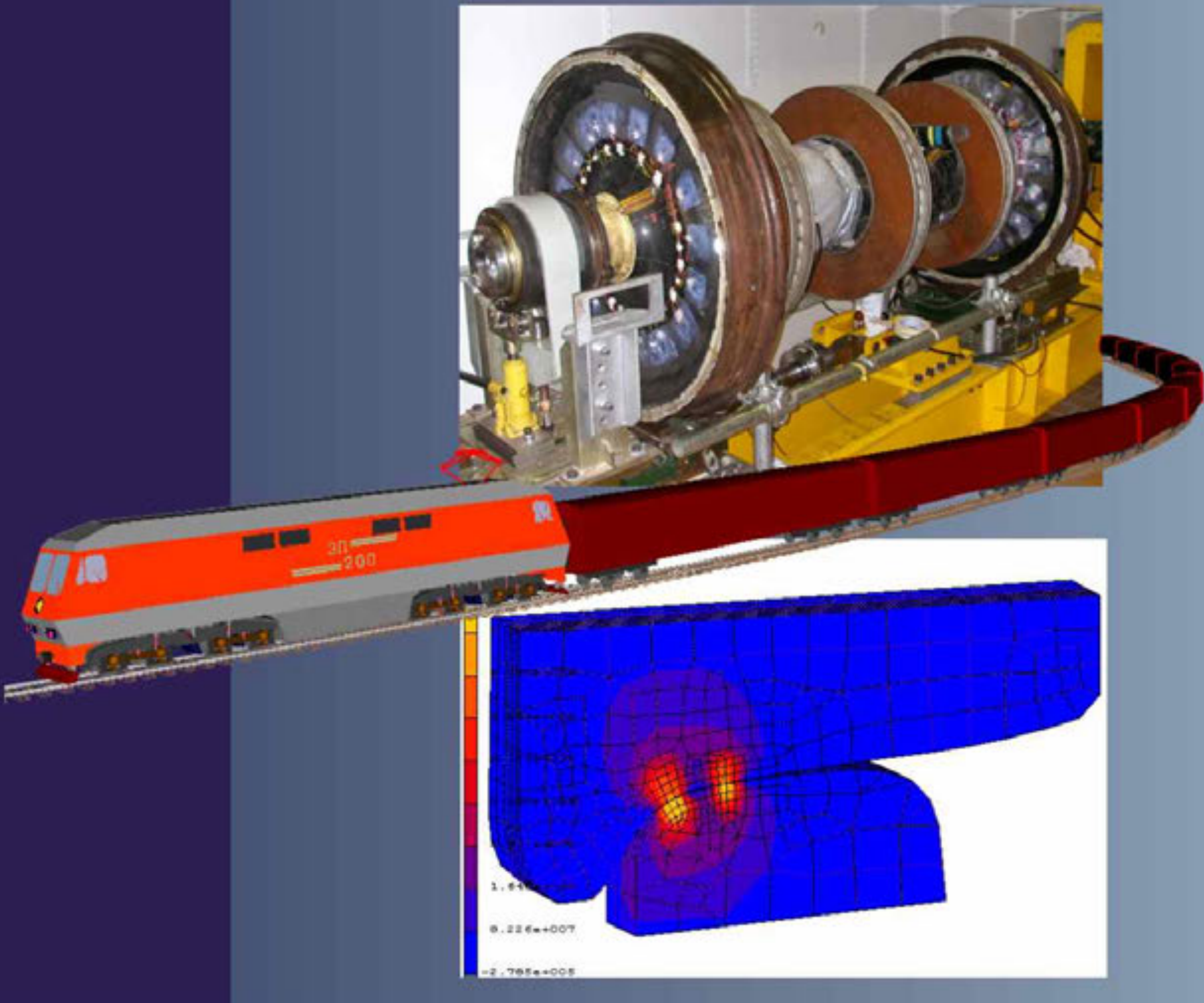
Aleksander SŁADKOWSKI

RAIL VEHICLE DYNAMICS AND ASSOCIATED PROBLEMS



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RAIL VEHICLE DYNAMICS
AND ASSOCIATED PROBLEMS

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CONTENTS

S. GUBENKO[1], A. SŁADKOWSKI[2]

THE INFLUENCE OF THE CONTACT STRESS ON THE STRUCTURAL CHANGES OF RAILWAY WHEEL STEEL

Summary. Structural and chemical changes near to a working surface of railway wheels with a different profiles of this surface, occurring onstream are investigated. The influence of structural changes in steel is established on formation of microdestructions and wear of working surfaces. Advantages of a new curvilinear profile of a working surface are shown. The comparison with results of FEM calculation is carried out.

1. INTRODUCTION

Quality of wheel metal in many respects defines traffic safety of trains. The railway wheel has a complex configuration. Each of its elements (a rim, a disk, a nave) has its own functions and is under influence of stresses. The complex of vertical, traction and lateral forces acts on a wheel. The level of stresses caused by these forces is high enough. These stresses cause plastic deformations in a wheel, promote fatigue processes in a rim and a disk, a wheel flange wear and to destruct a working surface. In a wheel at exploitation arise a various sort of damage arises: wear of a working surface of driving (change of a profile of a rim surface near a taping line), defects of thermal influence (flats, fettled layers, scaled fragments, thermal cracks), fatigue spalling, cleavages. The essential constructive requirements are brougt to wheels. Reduction of rigidity of a disk and increase of its elasticity promote increase of stability of train movement at high speeds and improve dynamics of interaction of a wheel and a rail. It is expedient to apply wheels to high-speed movement with smaller weight of a rim and the increased elastic properties of a disk.

Temperature stresses determine plastic shears on section of a wheel. Intensity of thermal loadings depends on construction of a wheel, speed of movement, type, size and material brake shoes, a way and a mode of braking. The disk of a railway wheel should be elastic and capable to perceive loading of a rolling stock and to cooperate through a rim with rigid tracks. One of the reasons why deformations occur in a disk at operation is high brake loadings owing to friction brake shoes at which heat in a rim and a disk is allocated and there are thermal stresses. These thermal effects cause high radial stretching stresses in a disk. When the rim of a wheel is heated up at emergency or long braking, any part of a disk can treat to action of the stresses exceeding stresses from other external loadings. These stresses are imposed on variable mechanical stresses (from action of radial loading, lateral forces, the traction or brake moments) and there is complex stressed - deformed condition of a disk where fatigue damages can appear.

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The thermal and deformation phenomena in a wheel at exploitation inevitably cause processes of ageing (dynamic and static), those affecting a level of properties of steel (yield point raises first of all) and constructional strength of wheels. If the contents in steel of carbon raises, the effect of ageing is more displaced. Besides this process is influenced with a level of stresses and a degree of plastic shears, density of dislocations in steel. Apparently, the contribution of deformation - thermal ageing to a level of stability of wheel properties at exploitation is comparable with the contribution of plastic processes.

Operating conditions of railway wheels were recently complicated due to the increase of rigidity of ways as a result of use of heavier and high-strength rails, ferro-concrete cross ties and a large ballast; applications of the composite brake shoes, having a high constant of friction and a low heat conductivity; increases of speed of movement and an intensification of use of a rolling stock; works in severe climatic conditions from -60 up to +50 ^{o}C; increases of loadings at an axis of cars till 25-27 tons and locomotives up to 30 tons.

The analysis of the operating conditions of railway wheels has allowed to formulate the following requirements to wheel steel [1]. Smelting of steel and technological process of manufacturing of wheels should provide absence of metallurgical defects in a wheel. Steel should provide such important characteristics of wheels as high strength, wear resistance, viscosity, cold resistance, thermostability, fatigue strength, plasticity. These characteristics are reached by reception high-quality vacuum-degassed deoxidized steel, optimization of its chemical composition, strengthening thermal processing. In a ready wheel it is very important to provide presence of compressing stresses in a surface layer of a rim and low stresses in critical parts of a wheel that causes increase of its constructional strength and reduces danger of destruction at operation.

The requirements which are produced to composition and structure of wheel steel, are totally concerned with a wheel rim. For guarantee of a high complex of mechanical and operational properties a rim subjects to thermal processing which guarantees uniformity of structure and properties of comparable parts of one wheel and all the wheels of one consignment. Hardening of a rim is carried out from temperature A_3+25 ^{o}C; at sharp cooling receive products of austenite disintegration with a lamellar structure (finely differentiated pearlite). After hardening for removal of internal stresses wheels are subjected to tempering at temperature 500 ^{o}C and to controllable cooling on quiet air. In work [1] it is established, that the wheel steel having in thermally strengthened condition a lamellar structure of a carbide phase has high resistance to wear in an interval of values of hardness 250-450 HB. In the steel having structure of tempered martensite, high resistance to wear is observed only at increase of hardness up to 350-450 HB. The steel having after thermal processing structure granular pearlite (cementite) even with disperse carbide fragments has smaller wear resistance and resistance to fatigue failure, than steel with lamellar pearlite. It is necessary to notify, that opportunities of increase of a complex of rim properties by regulation of their structural condition at thermal processing are not exhausted. At development of high-strength wheels, apparently, it is necessary to pass to other structure, in particular to bottom bainite as for manufacturers of wheels there is an actual problem of guaranteeing of hardness of a rim 360-400 HB on the depth of 30 mm from a working surface.

The complex approach to the mechanism of wear process of railway wheels includes studying the structural changes occurring in surface layers, and the analysis of a wear fragments. The variety of operating conditions of the friction pairs allows to assert, that the general approach can be a representation about the fatigue nature of destruction of surface layers. Such approach is necessary as at choice of a chemical composition of steels for friction pairs of a wheel – a rail in view of their cyclic strength and longevity, and at the development of new designs of wheels in a view of conditions of their exploitation. Interest to study the wear mechanism, which has sharply increased in the last years, is connected not only with the necessity to reduce the losses connected with the wear, but also with development of effective methods of forecasting of the wheel longevity, maintenance of reliability of their work, especially in extreme conditions (the big loadings, the high speeds, the raised temperature loadings on long falling gradient, etc.).

At exploitation the working surface of a railway wheel due to combined action of external loadings, contact and thermal influences is in a complex stress condition. Owing to a corrugation and a roughness contact of surfaces of the friction pair wheel - rail is discrete, that results in heterogeneity of distribution of applied external loading, contact stresses, structural changes in a near surface zones and, as a result, to non-uniform wear. Presence of roughnesses on a working surface of a wheel and a rail causes at movement the loads of impact character which grow at increase of the movement speed. Destruction of a working surface of wheels occurs under action of fatigue processes, stresses from which collect in metal owing to contact with the rails, braking shoes, and as a result thermal phenomena. Fatigue processes are connected with occurrence near to a working surface of a zone of plastic deformation and sites, so-called "a white layer", which differs brittleness. These structural changes cause occurrence of defects of a fatigue nature (cracks, fragments of the wear), which bring to the destruction of a rim, to very dangerous wear of a flange and change of the profile of a wheel as a result of displacement of layers of metal along a working surface. The mechanism of the wear of a working surface represents a set of mechanical, thermal physical and chemical phenomena and is connected with a formation of the wear fragments and microcracks in places of intensive plastic deformation and in sites of "a white layer".

On a working surface can be formed various damages (flats, gallings, "zoned hardenings", wear as the result of the abrasion of surfaces, fatigue scaled places due to variable contact stresses, brake scaled places at spalling of metal under influence of sliding between a wheel and a rail, scabbings near to impurities and zones of segregation). Brake scaled places are formed under special conditions of the braking causing jamming of wheels and their sliding on rails that results in heating of a contact zone above temperatures A_1 and even A_3, then at sharp cooling the sites of hard and brittle "white layer" are formed. The galling of metal occurs at rolling of wheels on a rail owing to slip; thus except for normal pressure due to the vertical loading in places of contact there are significant tangent stresses. Damages of brake type are not the same type defects.

2. OBJECTS AND TECHNIQUES OF RESEARCH

The important role in understanding of the wear mechanism of wheels is presented a research of the changes occuring at exploitation process in surface layers of wheel rims. These changes are connected with a development of plastic shears due to action of external loadings, thermal stresses at braking and also formation of the "white layers" at heating metal from heat of braking and sharp cooling at switching-off of brakes. The worn out wheels of different designs are investigated: standard wheels [2] with the working surface having slopes 1:20 and 1:7 (wheels 1-5), and also a wheel with a curvilinear working surface [3], developed in DMetI (National Metallurgical Academy of Ukraine). Wheels 1 and 6 have worked more than 5 years under passenger structure. As a result of the turning thermally processed layer has been completely removed, wheels 2-5 worked different term with the purpose of studying of the kinetics of development of structural changes near a working surface. A chemical composition of the steels for the investigated wheels it is resulted in tab. 1.

Tab.1

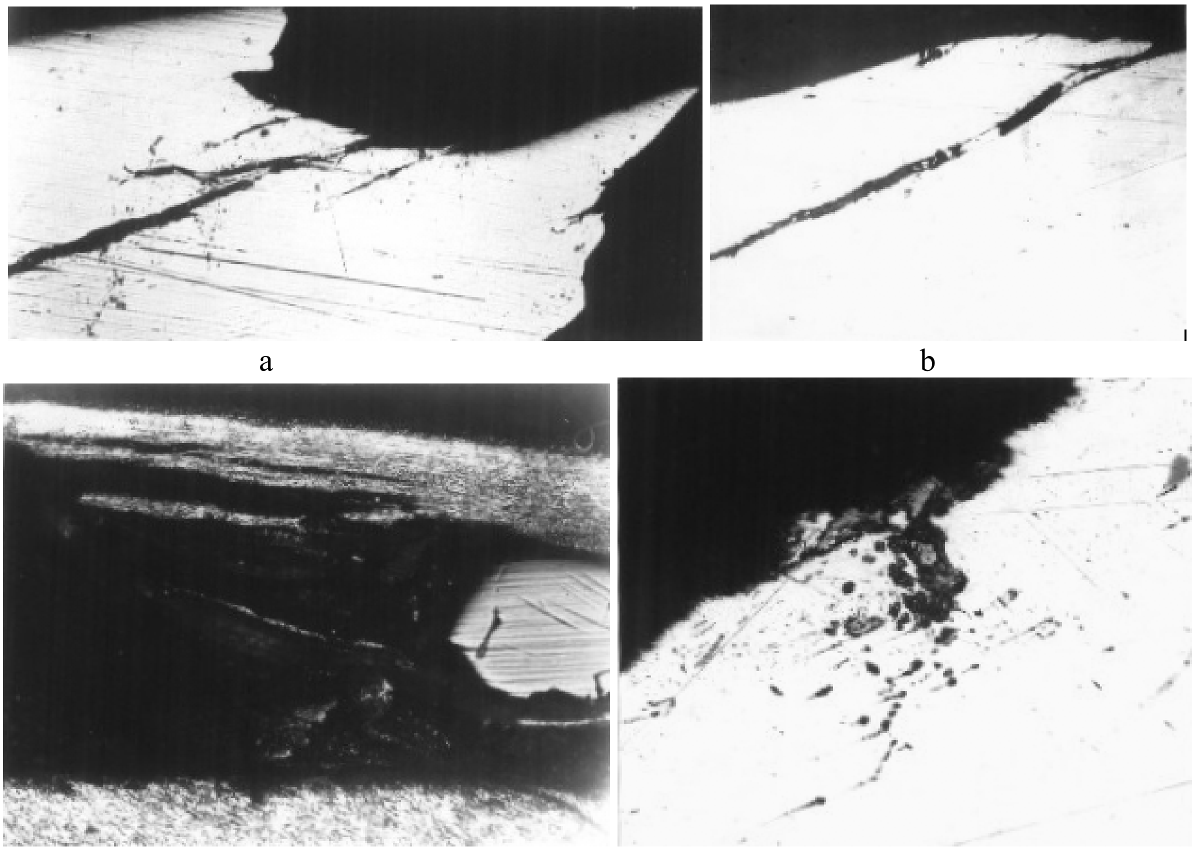
Chemical composition of the steels for the investigated wheels (%)

No of wheel	C	Mn	Si	S	P	Cr	Ni	Cu
1-5	0,59	0,72	0,31	0,025	0,012	0,14	0,15	0,20
6	0,57	0,78	0,34	0,023	0,012	0,14	0,16	0,21

As we see, chemical compositions of steels are similar, that allows to compare the results of research correctly. The cross templates cut out from wheels and characters of their structure on width of a rim in this section are studied. The microstructural analysis is carried out using an optical microscope "Neophot-21". Parameters of structural heterogeneity of steel (depth of zones with various structure, a degree of grains deformation) are defined. Microhardness of steel in a thin superficial layer measured on device PMT-3 at loading 0.5N on indentor. 8...15 measurements are carried out in each structural zone. Results of measurement of structure parameters and microhardness are processed by a statistical method. Character of thin structure of steel and density of dislocations in a surface layer defined at electron microscopic research (transmission electron microscope "Tesla"), and also by X-ray structure analysis by means of recording of roentgenograms on X-ray diffractometer DRON-2,0.

At visual inspection of a wheel 1 with very much worn rim such defects, as flats, galling of metal, exfoliations, overflows of metal from a working surface on an external lateral side of a rim, fatigue-corrosion wear are found out on a working surface. As a result of overflow there was a distortion of a wheel profile onstream (fig. 1a). The numerous cracks diverge from flats in deep layers of a rim (fig. 2a, b), accompanying with the zones of contortion metal (fig. 2c). On fig. 2d the example of steel erosion is resulted.

Fig. 1. Macrostructure of a wheel No 1 with the worn rim

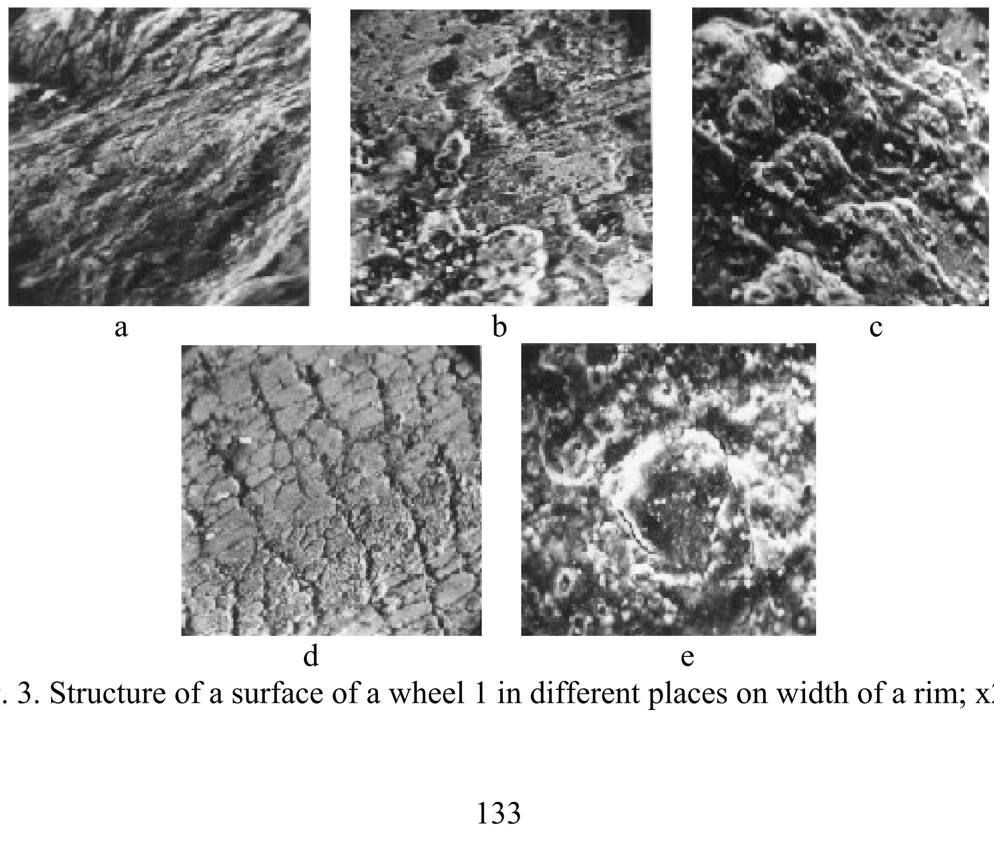


a b

c d

Fig. 2. Cracks (a-c) and corrosion destruction (d) in a flat zone; x100

Relief of a working surface of highly worn wheel 1 investigated visually, at small increase at a polarizing stereoscopic microscope and at the big increases at raster electronic microscope JSM-35. Results of research have shown, that the relief of a working surface on a section of a rim is not identical (fig. 3).

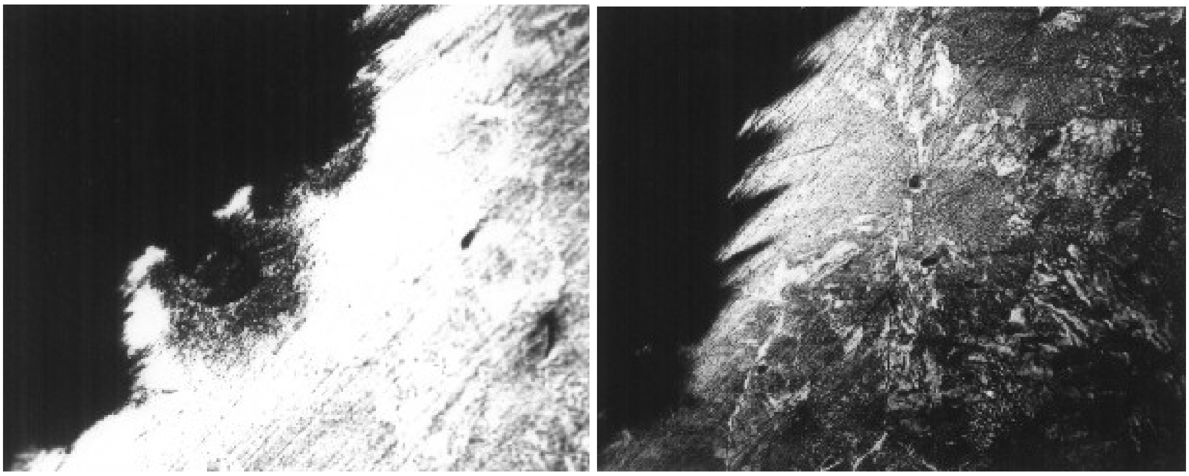


a b c

d e

Fig. 3. Structure of a surface of a wheel 1 in different places on width of a rim; x200

On a surface cambers and cavities are present, and it's the most roughness is most vastly expressed in a zone of overflow (fig. 3a) and on a flange (fig. 3b). At the big magnification cellular character of structure of a working surface is shown. It is especially precisely seen in a zone of gorge and on a lateral surface of a flange (fig. 3c, d). The sizes of cells correspond to the sizes of steel grains. In the structure of a relief of a working surface cracks (fig. 3e) are visible. Evidently, the cellular structure was showed owing to thermal etching due to heat arising at friction of a wheel about a rail. The relief of a working surface of a wheel in cross section is shown on fig. 4; along all working surface lugs and cavities are visible.



a b

Fig. 4. Relief of a working surface of the worn rim; x200

The macrostructural analysis of the cross template of a wheel with a curvilinear working surface has not revealed distortion of a wheel profile (fig. 5). On a surface there are a small flat, traces of corrosion destruction and small overflow of metal on an external lateral side of a rim.

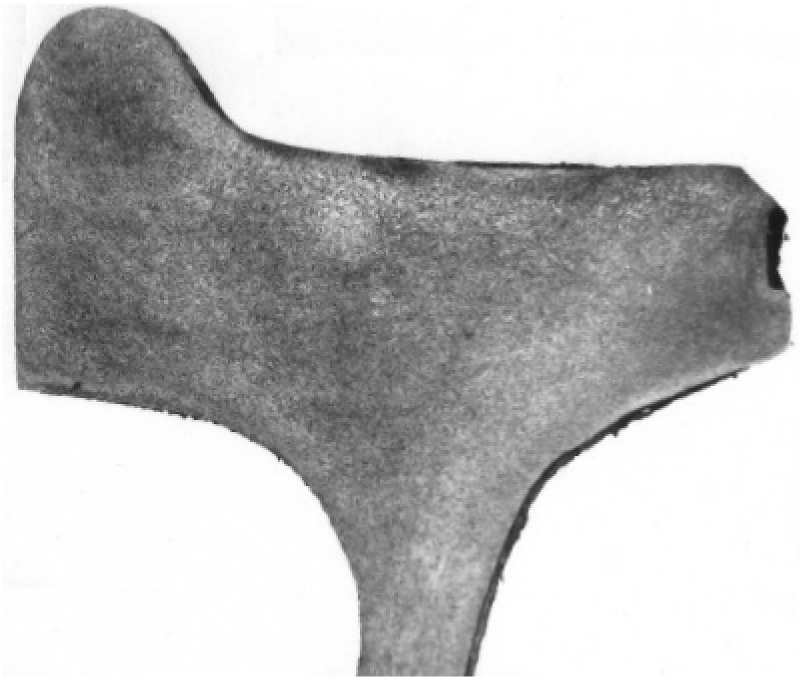


Fig. 5. Macrostructure of a wheel No 6 with the worn rim

At research of change of a chemical composition of steel near a working surface the contents of elements defined the laser spectral analysis on the plant MSL-3, carrying out grinding in parallel to a working surface every 5 microns. Spectra of researched samples are compared with reference. For each spectrum with the help of microphotometer MF-4 a difference of nigrescence homologous pairs of element – iron is defined. Using spectra of standards, calibrating schedules are built in coordinates a difference of nigrescence - the logarithm of concentration for each element on which unknown concentration in percentage is defined. Researches carried out on the same samples in which structural changes are studied.

3. RESULTS OF RESEARCH AND THEIR DISCUSSION

The rims microstructure for all wheels near to a working surface is characterized by presence of a zone of the deformed grains and sites of a "white layer ". Appearance of a zone of the deformed grains is connected with contortion of metal in contact with a rail under loading. Plastic shears in a thin superficial layer have passed in conditions concerning high pressures and cyclically changing temperature. Character of a microstructure is evidence of non-uniform passing of plastic deformation on section of a rim that is connected with a non-uniform distribution of contact stresses: it is known, that in a zone of the flange gorge they are higher, than in the middle of a working surface [4].

At the beginning structural changes near to a working surface of heavily worn rim of a wheel 1 are studied. In a zone of the flange gorge grains are considerably extended and crushed (fig. 6a, b), at an egress on a working surface a grain is larger, the degree of elongation of them is reduced a little and becomes ever less at the approach to the middle of a working surface (fig. 6c, d). At distance from the middle of a working surface to a flange direction the degree of grains elongation grows and becomes significant at edge of a rim (fig. 6e, f). Character of a structure in this part of a working surface is evidence of significant flow of steel in this zone, resulted in a change of a wheel profile. In a zone of overflow the stratifications oriented in parallel to a working surface (fig. 6f) are found out. As a rule, they are situated on a border between areas with sharply various microstructure and are divided zones of the extended and equiaxial grains. Overflow occurred gradually by layers, which were deformed at the displacement. Thus there were the brittle cracks in them promoting destruction of metal in layers. At the edge of the overflow on a lateral side of a rim the petals with heavily deformed structure are overhang (fig. 6g). They are also evidence of the layerwise mechanism of the overflow. Cracks are visible between these layers and also between overflow metal and a lateral side.

Parameters of a degree of grains elongation ε, depths of a zone of plastic shears h and density of dislocations $\rho_{\perp}$ in different sites of a working surface of a wheel 1 are showed in tab. 2.

Tab.2

Values of parameters of a microstructure ε, h and $\rho_{\perp}$ on a working surface of a wheel No 1

ε, %			h, μm			$\rho_{\perp}$, cm^{-2}		
gorge of a flange	middle	overflow	gorge of a flange	middle	overflow	gorge of a flange	middle	overflow
65...75	22...25	90	300	30	600	$9{,}22\cdot10^{11}$	$3{,}732\cdot10^{9}$	$9{,}60\cdot10^{11}$

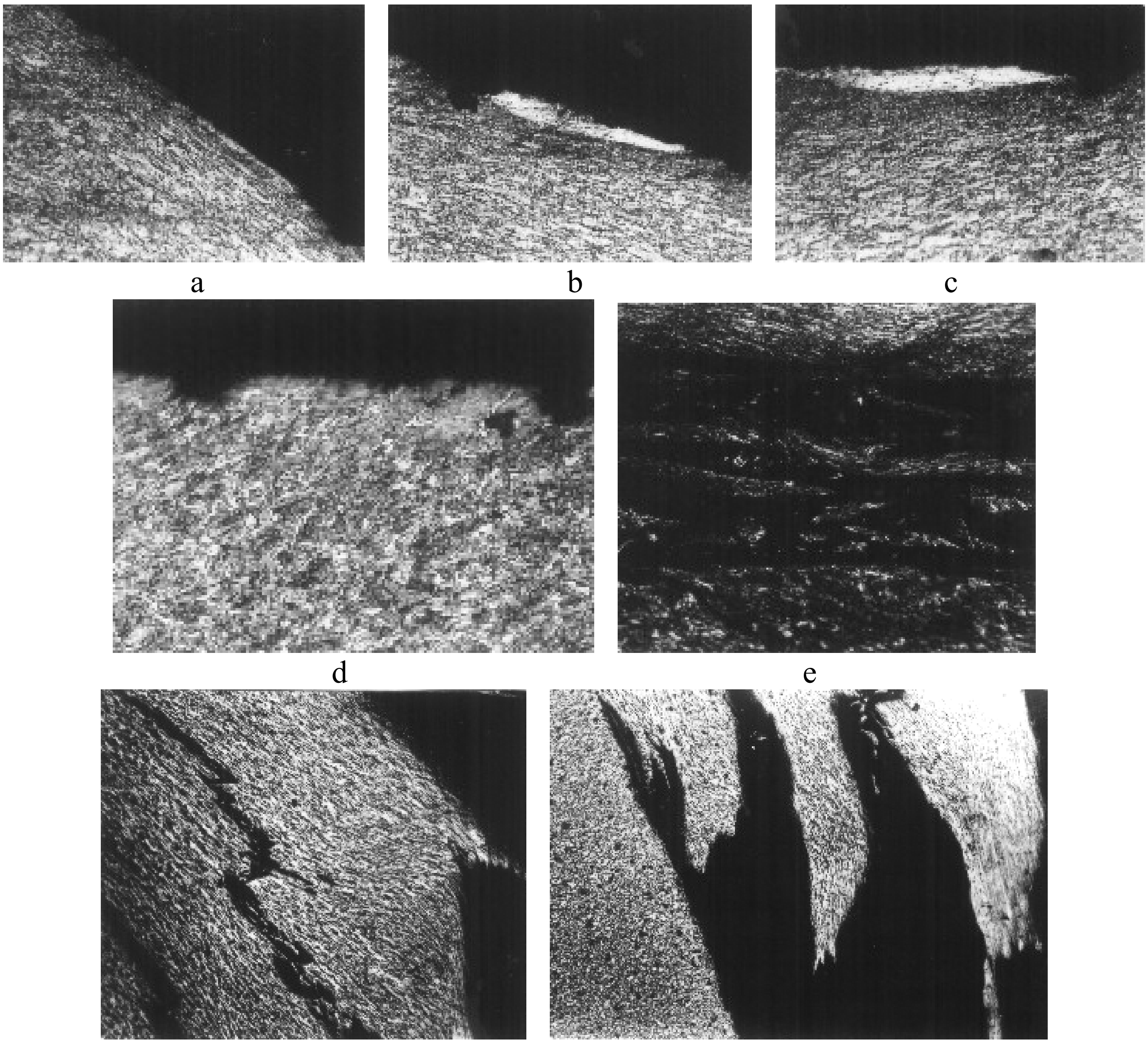
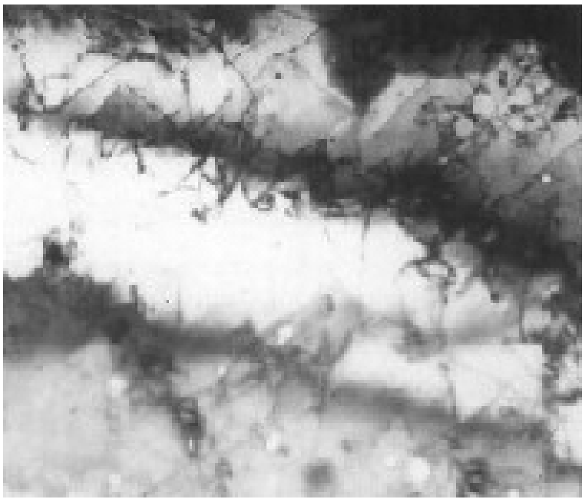


Fig. 6. The microstructure of different sites of the worn working surface of a wheel No 1; x200

It is necessary to note, that at operation in conditions of the rolling friction rolling textures on a working surface are formed which are realized as a result of the action of contact stresses. Examples of such textures which are revealed in a wheel 1, and then in other wheels with a standard profile of a working surface: (223) $[03\bar{2}]$, (212) $[\bar{5}\bar{2}6]$, (112) $[\bar{1}\bar{3}2]$, (221) $[11\bar{1}]$. In the deformed layer of metal on a working surface the typical cellular dislocation arrangement with small orientation of cell walls in a friction direction was generated - a strip substructure (fig. 7). Physical widening of lines (110) varies on the depth from a working surface that is connected with different density of dislocations.

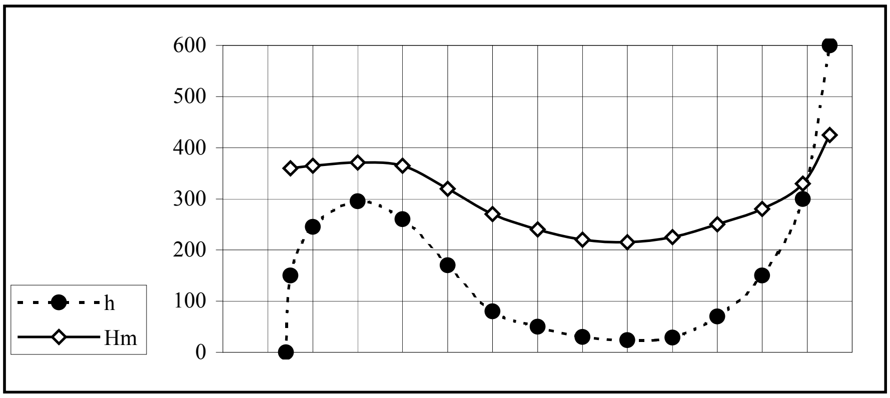
Depth of a zone of the deformed grains on width of a wheel rim No 1 was unequal (fig. 8). Most deeply plastic deformation was distributed in a place of a flange gorge and in a zone of overflow at the edge of a rim. The degree of elongation of grains allows to judge about the degree of steel deformation in a surface layer of a rim. In a zone of a flange gorge sizes ε reach 65...75 %, then are reduced up to 22...25 % in the middle of a working surface and considerably grow (up to 90 %) in a zone of overflow. Character of change of microhardness is similar. The density of dislocations determined by a X-ray structure analysis, also is not identical in various places of a working surface. On fig. 8 distribution of parameters is resulted for a layer of intensive deformation in a rim section. Bursts of microhardness are observed in places of occurrence of the "white layer" structure.

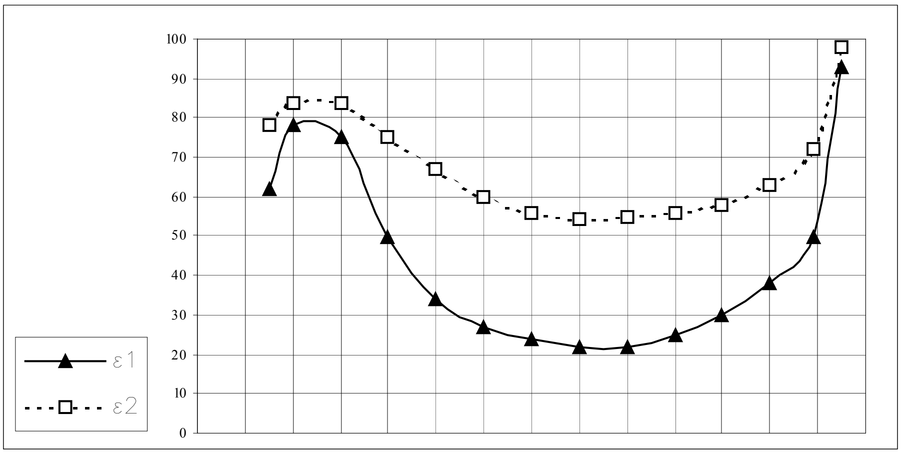


a

b

Fig. 7. The dislocation substructure of steel near to a working surface; x20000





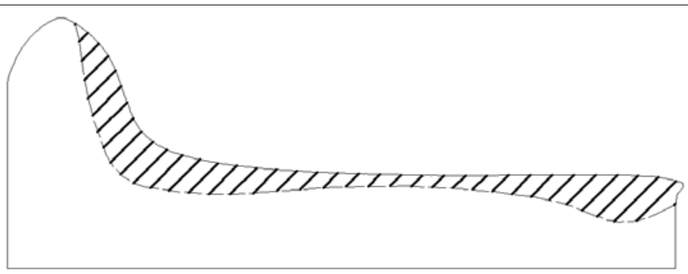
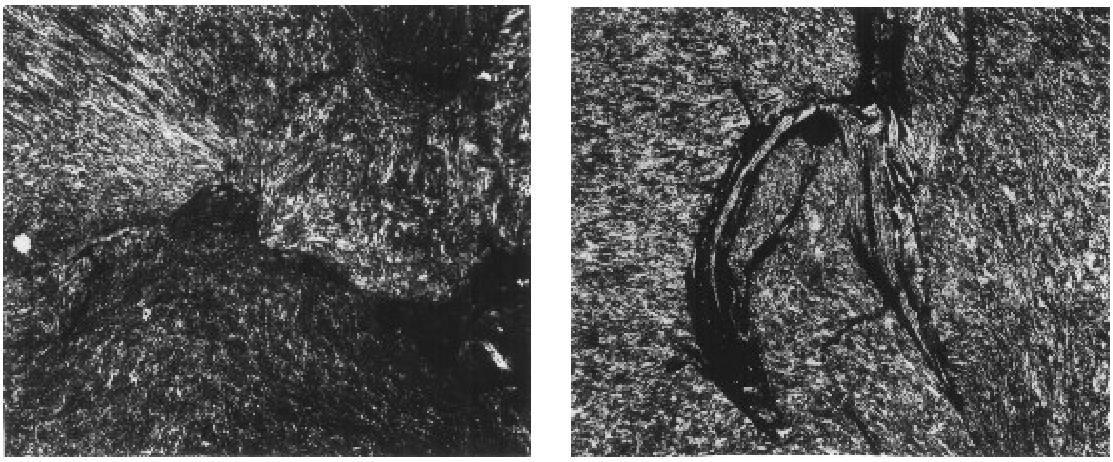


Fig. 8. Change of a degree of grains deformation across ε_1 and in a rolling direction ε_2 [%], microhardness H_μ [x10, MPa] and depths of a zone of plastic deformation h [μm] on width of a wheel No 1

Sites of a "white layer" represent unstructured martensite (hardenite). It is a brittle structural component which is painted during the work of a wheel (fig. 6c). There is a "white layer " owing to heating a thin surface layer from heat of braking up to temperature above A_3 and the subsequent sharp cooling after switching-off brake shoes. The width of a "white layer" equals 20 - 40 microns.

Character of a microstructure of a wheel No 1 near to a working surface in a rolling direction is similar considered above for cross section, however, a degree of elongation of grains in a longitudinal direction is much above. At studying of structure in a plane determined by the taping line a complex character of flow of steel in a surface layer is found (fig. 9). On an orientation of grains it is visible, that the flow of steel in a zone of a flange gorge and in the central part of a working surface had laminar character (fig. 9a) while in a zone of overflow there are areas with the curved and twisted grains where flow of steel had obviously vortical, turbulent character (fig. 9b). Between the zones with various orientation there were microcracks.



a b

Fig. 9. The microstructure of the worn rim of a wheel No 1 in a plane determined by the taping line; x200

Also kinetics of structural changes near to a working surface is investigated as owing to non-uniform distribution of contact stress on width wear of a rim occurs non-uniformly. For researches four wheels of one production lot, which has worked different term under passenger rolling-stock have been chosen: a wheel No 2 - 1,5 years, No 3 - 2,5 years, No 4 - 4 years, No 5 - 5,5 years. During exploitation wheels have turning on average in 8,5 months, therefore by the moment of research wheels have accordingly 2, 3, 5 or 7 turning, and after last turning have worked accordingly 1; 4,5; 5,5 and 5,5 months. In itself wheel turning has broken a continuity of work of wheels, and removal of the work-hardened layer have broken a continuity of kinetics of structural changes. Nevertheless, control of wheels is carried out onstream in view of all operations which they are subjected.

The lateral internal surface of a flange was subjected to plastic shears which gradually grew with increase in service life of wheels (tab. 3). It is necessary to note, that plastic shears in this zone are not the highest. Switch to a zone of a flange gorge is accompanied by increase in a degree of deformation, which intensively develops in this zone at all exploitation phases. The degree of deformation is high and corresponds to so-called big plastic deformations at all terms of operation - approximately at 70-80% (tab. 3), however with increase in service life depth of a zone of plastic deformation grows. This plastic deformation despite of removal of the work-hardened layer at turning covers more and more deep layers. At all stages there are fatigue cracks and wear fragments (fig. 10a, b), which are gradually separated from a surface.

Tab.3

Parameters of structural changes of wheels with different service life

Number of a wheel	Place of measurement	Degree of deformation ε, %	Depth of a zone of plastic deformation h, μm	Microhardness, H_μ, MPa
2	Surface of a flange	5–10	30	230
	Flange gorge	70	80	455
	The middle of a working surface	18	50	220
	Overflow	40	35	225
3	Surface of a flange	10	40	240
	Flange gorge	80	100	460
	The middle of a working surface	20	60	220
	Overflow	30–50	20–45	230
4	Surface of a flange	30	100	330
	Flange gorge	80	210	470
	The middle of a working surface	24	95	225
	Overflow	80	120	435
5	Surface of a flange	40	120	240
	Flange gorge	80	320	480
	The middle of a working surface	29	145	235
	Overflow	90	400–500	490

Switch to the middle of a working surface at all operation phases is characterized by change of intensity of deformation (tab. 3), which degree and depth of distribution is higher according to its service life. Here too observed occurrence of wear fragments and extended cracks (fig. 10c, d). At a leaving from the middle of a working surface the intensity of deformation again grows and is greater with increase of service life of a wheel that promotes wear of a working surface. As it has been shown above, overflow of metal on an external lateral surface of a rim occurs as a result of level-by-level flow and moving of metal from a working surface on a lateral side of a rim. At small service life this process occurs not so intensively and under overflow layers of metal the initial structure is precisely visible. In these sites occurrence of cracks is probable. With increase of service life process of overflow is sharply intensified, that is expressed in increase in a degree of deformation and depth of the deformed zone (tab. 3). The increasing quantity of layers hangs on an external lateral side of a rim, between layers there are cracks and extended stratifications (fig. 10e, f) and between layers metal has time to be oxidized essentially.

The value of steel microhardness (and hardness) in different sites of a working surface reflects the described heterogeneity of structural changes, but mainly constantly grows in each zone with increase of service life of a wheel (tab. 3).

The comparative analysis of parameters of thin structure of steel near to a working surface has shown, that the level of a stress condition of this layer of metal remains complex at all terms of exploitation (tab. 4) and precisely corresponds to the features of structural changes described above in different sites on the width of a rim. At all exploitation phases metal in a zone a flange gorge and on late service life in a zone of overflow is strained the most.

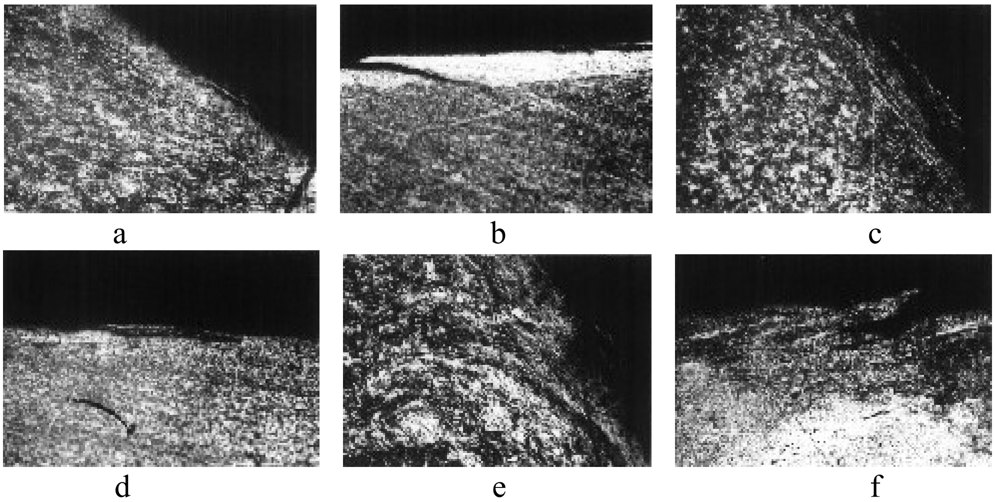


Fig. 10. The microstructure in zones of the flange gorge (a, b), the middle part (c, d) and the overflow (e, f) of wheels: No 2 (a, c); 3 (b, d); 4 (e); 5 (f); x200

Tab.4

Parameters of thin structure of steel near to a working surface of wheels with different service life

Number of a wheel	Place of measurement	The size of blocks of a mosaic, $a \times 10^{-5}$, cm	Microdistortions in a lattice, $\Delta a / a^{*}$	Density of dislocations, $\rho_{\perp}$, cm^{-2}
2	Surface of a flange	2,06	0,24	$4,6 \cdot 10^{10}$
	Flange gorge	2,38	0,31	$6,1 \cdot 10^{11}$
	The middle of a working surface	2,01	0,18	$6,3 \cdot 10^{10}$
	Overflow	2,08	0,19	$9,3 \cdot 10^{10}$
3	Surface of a flange	2,08	0,23	$8,3 \cdot 10^{10}$
	Flange gorge	2,63	0,32	$6,4 \cdot 10^{11}$
	The middle of a working surface	2,02	0,19	$6,8 \cdot 10^{10}$
	Overflow	2,34	0,22	$9,3 \cdot 10^{10}$
4	Surface of a flange	2,24	0,24	$9,1 \cdot 10^{10}$
	Flange gorge	2,75	0,33	$7,3 \cdot 10^{11}$
	The middle of a working surface	2,10	0,21	$7,1 \cdot 10^{10}$
	Overflow	2,53	0,32	$8,4 \cdot 10^{11}$
5	Surface of a flange	2,28	0,25	$9,4 \cdot 10^{11}$
	Flange gorge	2,86	0,34	$7,5 \cdot 10^{11}$
	The middle of a working surface	2,25	0,21	$7,2 \cdot 10^{10}$
	Overflow	2,93	0,34	$9,3 \cdot 10^{11}$

* - Initial size before exploitation

Thus, the analysis of the kinetics of structural changes near to a working surface of wheels with different service life has shown, that for a standard profile of a working surface the heavy wear already at early operation phases occurs in a zone of the flange gorge. On a slope

1:7 on early terms of operation overflow occurs insignificantly, but is sharply intensified with increase of the service life. The non-uniform wear of a rims occurs at all operation phases that is connected to non-uniform distribution and a high level of the contact stress.

Research of a rim microstructure in zones of overflow has shown, that displacement of metal from a slope 1:20 on a slope 1:7 is inexpedient, as overflow occurs by layers and is accompanied by complex turbulent flow of steel. It entails the increased wear, occurrence of cracks, stratifications and zones of non-uniform deformation, scabbings, overflows. Hence, the existing geometry of a working surface with slopes 1:20 and 1:7 is far from geometrical perfection and demands replacement by a curvilinear surface at which as has shown experience of long-term tests, the overflow occurs in much smaller degree. The same lacks of the greater or smaller measure are inherent also for other conic working surfaces.

Let's separately stop on studying of the mechanism of the wear of a working surface of the wheels with a standard profile. Along all working surface there are microcracks and the stratifications resulting in formation and separation of the wear fragments or fragile destruction in a zone of the flange gorge, that in practice causes mass wears of a wheel flanges. A plenty of wear fragments is found out on all width of a rim and promotes to wear of a flange and to intensive overflow, so to intensive wear of a wheel as a whole. Formation of the wear fragments has the different reasons.

One of the main reasons is passing of plastic shears with rather big degree of deformation which has non-uniform character. On borders of zones with a different degree of the deformation there are microcracks, separations, wear fragments (fig. 11a, b). So-called, the «white layer» has the increased fragility (fig. 11c) besides on border of its partition with the basic structure there are the significant stress caused by various physical and mechanical properties of zones with various structure. It promotes to a spalling of the «white layer» (fig. 11d), therefore practically always it is not continuous.

The formation of cracks and wear fragments is promoted also by oxidation and corrosion destruction of a working surface (fig. 11e), and oxidation should be attributed to the formation of rough nonmetallic inclusions on a working surface. At presence in a surface layer of nonmetallic inclusions, which have a metallurgical origin, they become the concentrators of a stress. Near inclusions in an initial condition already there is an increased concentration of the stresses [5]. At the process of the development of plastic shears the steel grain bend around inclusion (fig. 11f), that results in non-uniform development of deformation and accumulation of stress, which lead to formation of the microcracks (fig. 11g) and to destruction of the inclusions. Around inclusions at emergency braking there are also significant thermal stresses, which reach critical size and also promote crack nucleation and occurrence of the wear fragments. It is necessary to note, that nonmetallic inclusions quite often are the centers of the local decarbonization of a steel that causes structural heterogeneity and entails non-uniform development of plastic shears, and also formation of the microcracks (fig. 11h) and a wear fragments.

Thus, repeated cyclic thermomechanical influence on a working surface of a wheels at its interaction with a rails results in accumulation of stresses and defects (microcracks, stratifications, separations), that promotes formation of a separation fragments (fig. 12a, b). The most widespread fragments of wear represent flakes or plates of different thickness. They are characteristic for the normal conditions of a wear [6] and their occurrence is connected with a plastic deformation. According to the theory of “peeling” wear, at friction the maximal density of dislocations arises not on a surface, but on some depth where there are extended cracks, which grow till the critical size, forming exfoliated flakes. The leading role in this process concerns to the plastic acts resulting in accumulation of the dislocations and occurrence of a cracks parallel to a surface. The formation of a wear flakes occurs by viscous separation.

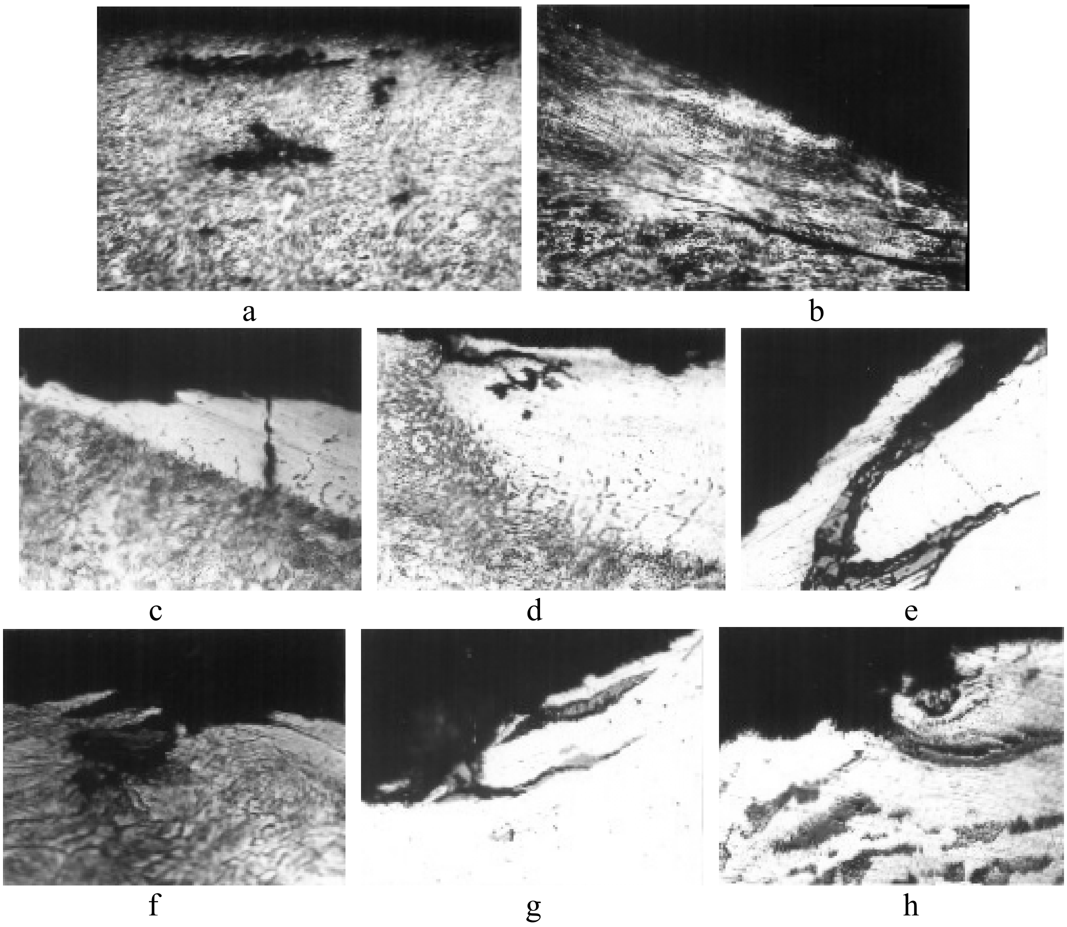


Fig. 11. Microcracks and stratifications near to a working surface

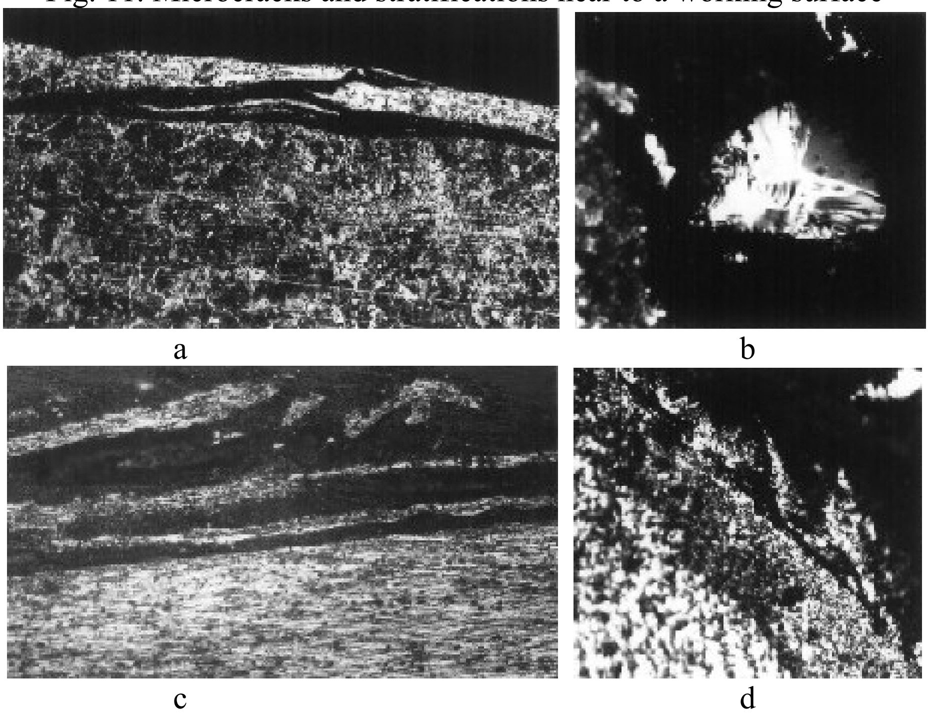


Fig. 12. The wear fragments near to a working surface

Sometimes the particles of a wear look as the loops or the spirals similar to a chips at the cutting (fig. 12c). Such particles precede the damage and are found out, mainly, on a working surface before the local destruction. The particles of a wear as fragments with sharp irregular-shaped edges (fig. 12d) are found out also. Such particles usually arise at very high pressures and their occurrence can be connected with formation in superficial layers of a rims fine fatigue cracks which exposure on a surface is the beginning of a formation of a wear particles.

The results of the analysis of a microcracks, exfoliations and wear particles have shown, that the wear of the working surfaces of a railway wheels occurs on a several mechanisms and is a multiple-factor process.

The comparative researches of a structural changes near the working surface of the worn out rim (a wheel No 6 with an initial DMetI profile of a working surface) are carried out. In the beginning metal was studied in the cross section of a rim. The grains in a flange gorge zone are extended and crushed (fig. 13a), at the rise on a working surface the degree of elongation of the grains decreases (fig. 13b, c). At the distance from the middle of the working surface the degree of elongation of the grains grows again (fig. 13d) and becomes significant at the edge of a rim (fig. 13e). The external lateral side of a rim had the small overflow (fig. 13f) where the exfoliations, the sites of the oxidized steel and the microcracks are found out.

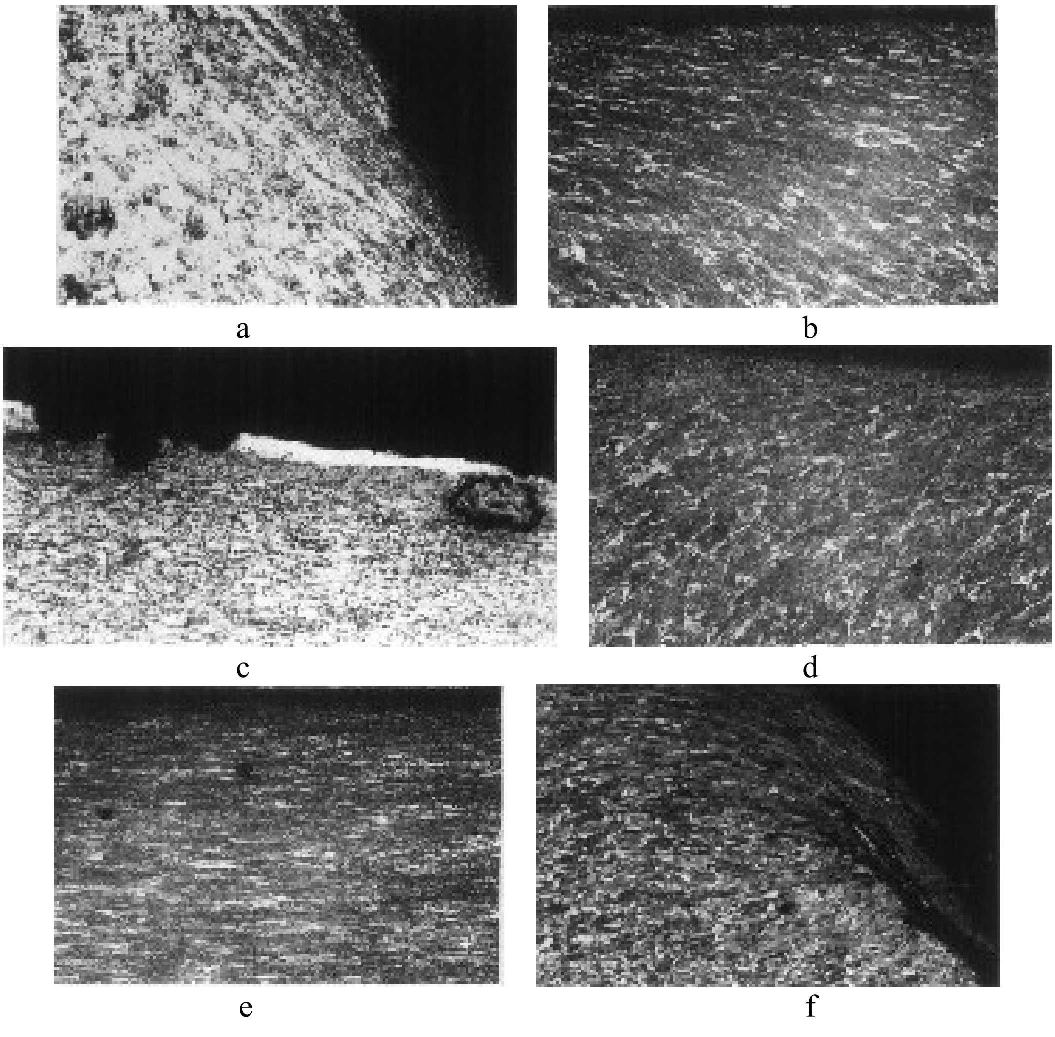


Fig. 13. The microstructure near to a working surface of the worn out rim of the wheel No 6 in a cross section, x200

The parameters of a zone of structural changes in a wheel No 6 are shown on fig. 14 and in tab. 5. As well as in the wheels with a standard working surface, in the wheel No 6 the zone of deformation was distributed most deeply in the places a flange gorge zone and an overflow.

The degree of the grain elongation in a cross section ε_1 changes on a width of a rim and in a flange zone reaches 60-70%, at transition to a working surface it is reduced in the average part up to 10% and again sharply grows up to 80% at approach to an external lateral side of a rim. The character of the change of a steel microhardness on the width of a rim is similar. The sharp growth of the microhardness at a distance of 2/3 width from a flange is connected with the presence of a site of "a white layer" (fig. 13c). The results of the analysis of a density of a dislocations have shown, that their quantity also is the maximum in a flange gorge zones and in a zones of the overflow (tab. 5).

Tab.5

Values of parameters of a microstructure ε, h and $\rho_\perp$ on a working surface of a wheel No 6

ε, %			h, μm			$\rho_\perp$, cm^{-2}		
gorge of a flange	middle	overflow	gorge of a flange	middle	overflow	gorge of a flange	middle	overflow
60	10	80	180	20…40	420	$6{,}54 \cdot 10^{11}$	$6{,}41 \cdot 10^{8}$	$8{,}0 \cdot 10^{11}$

Character of a steel microstructure near to a working surface of a wheel No 6 in the longitudinal planes directed perpendicularly to a working surface is similar to considered above for cross section of a rim though the degree of grain elongation ε_2 is higher, than ε_1 (fig. 14). The steel microstructure in a rolling plane is characterized by presence of the equiaxial grains and spots of "a white layer" (fig. 15a). The grains are extended only in a zone of the overflow (fig. 15b). The zones of the turbulent flow of a steel did not observe.

The comparative analysis of a microstructures of the wheels with a standard profile of the working surface (a wheel No 1) and with the profile DMetI (a wheel No 6) has shown, that qualitatively the structural changes in the rims are identical, but parameters of these zones are various and depend on a design of a wheel (a geometry of a working surface). The research of a structural changes specifies imperfection of a standard working surface (with biases 1:20 and 1:7) promoting non-uniform development of plastic shears in a superficial layer and a unequal degree of a deformation of the grains in the various zones. The passing of intensive plastic shears in the conditions of the action of the enough high contact stress results in an intensive wear of the wheels with a standard profile of a working surface. The processes proceeding in a zone of the flange gorge and resulting to a cutting of the flange are especially dangerous. This problem is very actual now.

It is necessary to note, that plastic shears near to a working surface cannot be considered only as the negative phenomenon. At the beginning they promote the formation of the run-in surface of the wheels, cause of the cold-hardening (hardening onstream - original autohardening), that allows to provide the raised hardness and wear resistance of the rims.

The plastic shears arising in a superficial layers of the rims, the temperature cycling during braking and the interaction with a surrounding atmosphere create conditions for intensive development of the diffusion processes which can entail the change of a chemistry of the steel. The analysis has shown, that the chemistry of a steel onstream varies non-uniformly (fig. 16). At the distance of 5 microns from the working surface (fig. 16a) the maximum of the burning out of the elements falls on the flange gorge and on the area adjoining to it down to the middle of a rim, and on this distance the difference in a chemistry of the steel is insignificant. At transition to the external edge of a rim the contents of the elements (except for a carbon) gradually grows and at the edge almost leaves on a level of an average structure of the steel. The change of the contents of the elements in a zone of the flange gorge in comparison with a chemistry of the steel in percentage (volumetric) is equal: ΔC=0,37, ΔMn=0,34, ΔS=0,018, ΔSi=0,16, ΔP=0,008; at the edge of a rim in a zone of the overflow: ΔC=0,13, ΔMn=0,02, ΔS=0,008, ΔSi=0,01, ΔP=0,002. Thus, the maximal "burning out" of elements in a zone of the flange gorge near the working surface has made 63% C, 48% Mn, 72% S, 47% Si, 77% P, and in a zone of the overflow - 22% C, 4% Mn, 32% S, 3% Si, 17% P. At the subsequent grinding the contents of the elements gradually grow, however non-uniform character of their "burning out" is kept. At the distance of 20 microns from a working surface (fig. 16b) in a zone of the flange gorge and in an adjoining areas down to the middle and at approach to its edge the contents of the elements reaches a level of average structure of the steel.

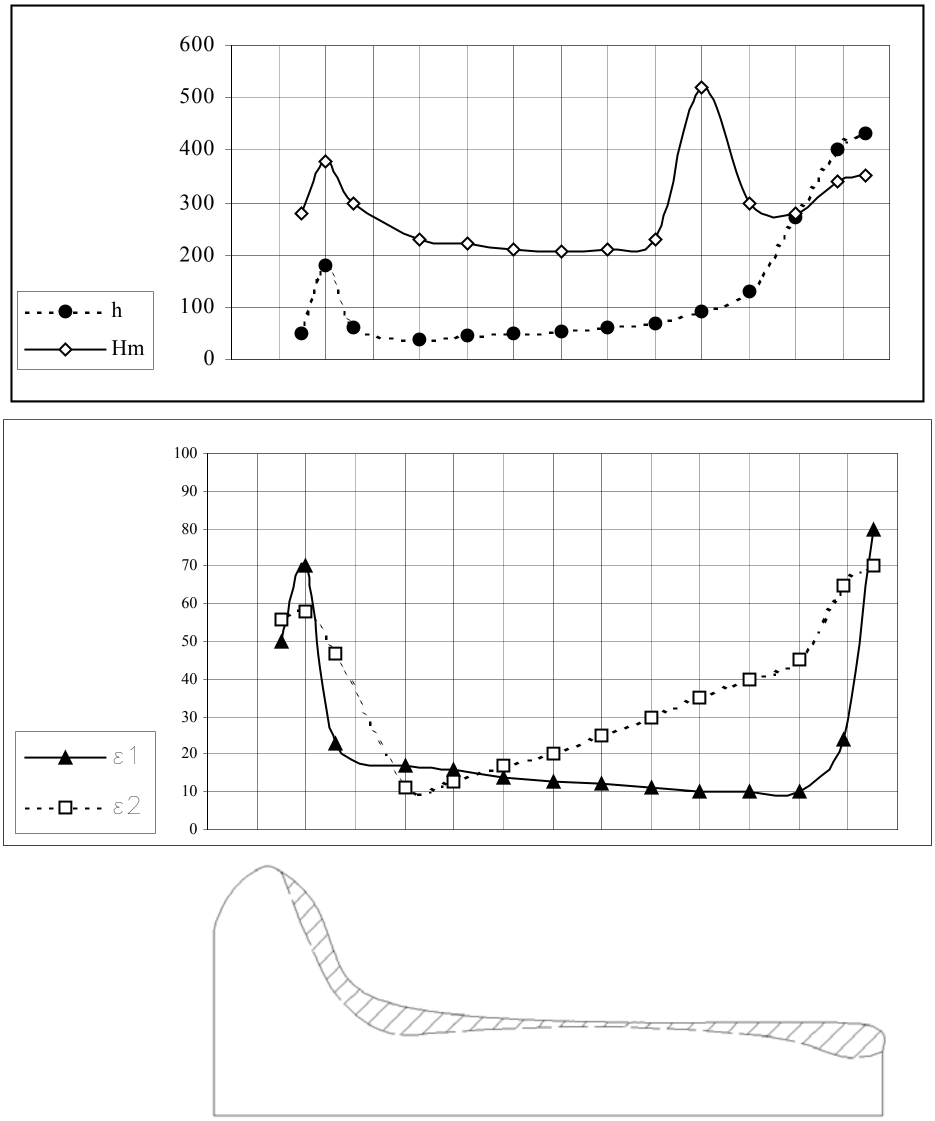
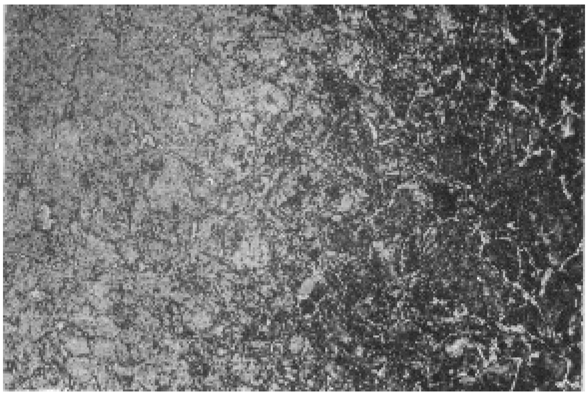


Fig. 14. Change of a degree of grains deformation across ε_1 and in a rolling direction ε_2 [%], microhardness H_μ [x10, MPa] and depths of a zone of plastic deformation h [μm] on width of a wheel No 6

The results of research have shown, that onstream the change of a chemistry of the steel on the working surface of the wheels occurs non-uniformly on the width of a rim. The elements "burn out" most intensively at the distance from the flange gorge up to the middle of a rim, and in the greater degree it is shown for a sulfur and a phosphorus. The depth of a zone of "burning out" of the elements makes up 20...30 microns depending on a place on the width of a rim. The observable character of the change of the steel chemistry is connected to the structural changes in a thin superficial layer. The elements "burn out" most heavily in the places of the intensive plastic shears and the pronounced "white layer" and these two structural factors act in a complex as it is not revealed the intensive "burning out" of the elements in a zone of the overflow in other wheels in those sites of the working surface where there was no the "white layer" and the zones of a plastic shears.



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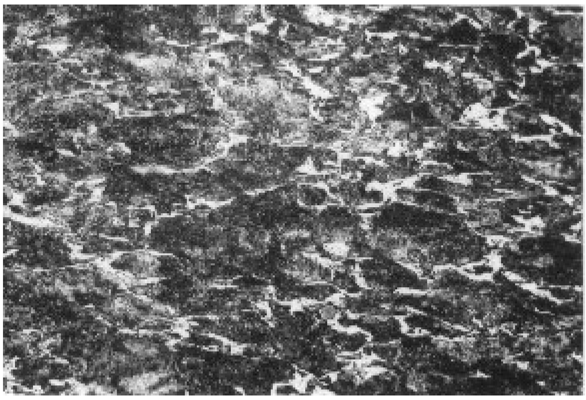


b

Fig. 15. The microstructure of the worn out rim of a wheel No 6 in a rolling plane; x200

The change of a steel chemistry in a superficial layer of a rim is caused by the presence of a free surface (a working surface) serving as a drain for the atoms of the impurities and the defects of a crystal structure, the movement of the dislocations and the vacancies during the plastic shears facilitating a diffusion, the rise in the steel temperature at the intensive braking and the difference of a chemical potentials of the elements in a steel and an atmosphere.

Apparently, the temperature field on the width of a rim onstream of the wheels, especial at the braking, has the non-uniform character that promotes the heterogeneity of a diffusion processes. The action of the found out phenomenon on the reliability and the traffic safety is not investigated deeply. The researches on an optimization of the "burning out" from the point of view of the reliability of a wheel operation, for the studying of the influence on this process of a level of the contact stress in a wheels with the different geometry of a working surface, the systems of a brakes, the traction coefficient of a wheel with a rail, etc. are necessary. One is clearly, that the change of a steel chemistry in a thin superficial layer promotes decrease of the strength properties, the hardness, the wear resistance of a working surface and this layer is necessary to delete periodically, as occurs at a wheel turning.

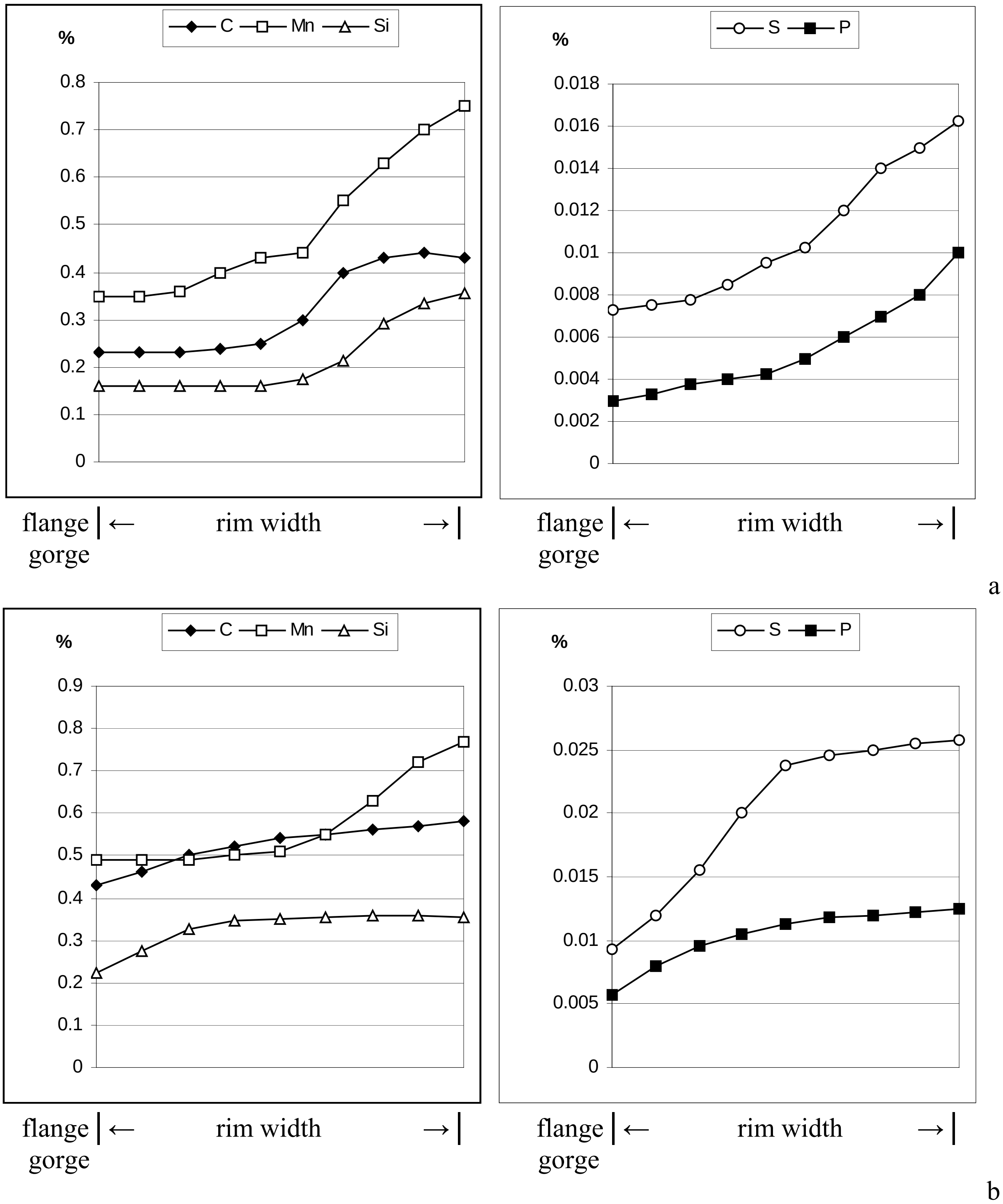


Fig. 16. The measurement of a steel chemistry of the standard wheel along a rim width on the depth of 5 microns (a) and on the depth of 20 microns (b)

The calculations with the use of the finite element method [7] have been carried out for the comparison with the results of the metallographic analysis. For this purpose the software of MSC.Software and, in particular, packages MSC.ADAMS/Rail and MSC.MARC was used. The first package is intended for multi body modelling of movement of the wagon in various sites of a track, for determining of the operating forces for each relative position of a wheel and a rail. The second package has allowed to investigate the contact interaction of wheels with real profiles of a tread surface. Thus the plastic deformation of the near contact areas was considered.

One of the main problems of the solution of the contact problems is the task of creating of the coordinated FE meshes [8]. To realize algorithm offered in the monograph [9], it is necessary to carry out the precomputation of the contact interaction based on the Quasi-Hertz method [3]. The arrangement and size of contact zones are defined for the set relative positions of interacting surfaces of a wheel and a rail, having real geometry including worn profiles. It is obvious, that such zones can have only the elliptic form, that in general not represent the facts. Nevertheless such approach allows to carry out the regular FE sampling of the near contact areas, having created mutually coordinated meshes of a wheel and a rail. The coordinated FE meshes of new wheel and rail with a standard profiles of a tread surfaces are shown on fig. 17. The position corresponding of two-point contact is considered. Accordingly, there are two zones coordinated regular meshes. One is in the area near the taping line, the second is in the flange area.

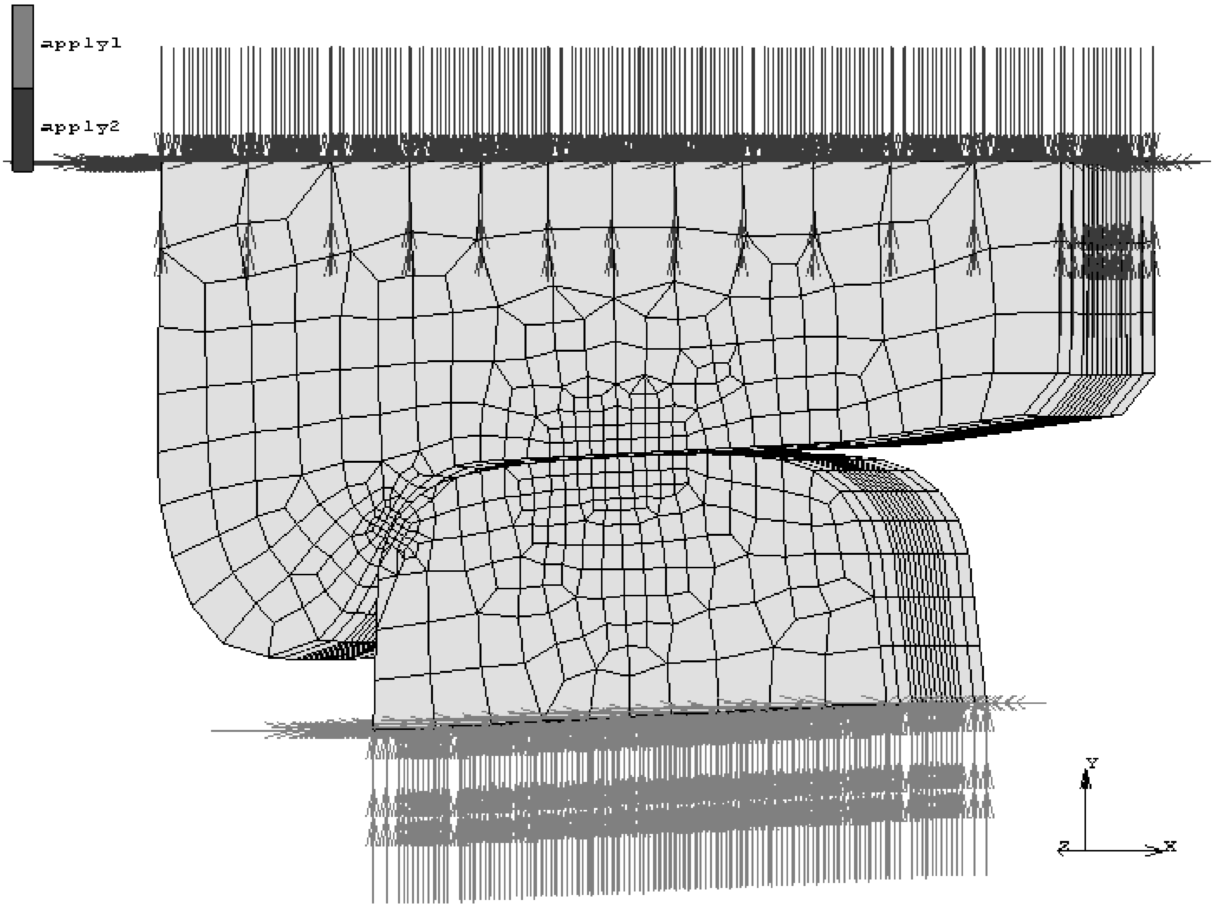


Fig. 17. An example of the coordinated FE meshes of a wheel and a rail. The boundary conditions set in the MSC.MARC software is shown also

The calculations [9] show that there are plastic deformations in the near contact layers of a wheel steel even at the action of the nominal loads. Such deformations in rails don't arise at the central contact owing to higher plastic limit. The maximal plastic deformations take place at contact in a flange area, therefore we shall consider interaction of the wheels with the standard profile and with the DMetI profile, which will contact with a new rail R65.

The distribution of the solid Von Mises stress at the contact of the considered wheels under action of the vertical force 125 kN is shown on fig. 18. As we see, according to the classical theory the maximal stress isn't on a contact surface, but is on some depth. The stress distributions are close to the Hertz distribution. Especially it concerns to the central zone of the first wheel.

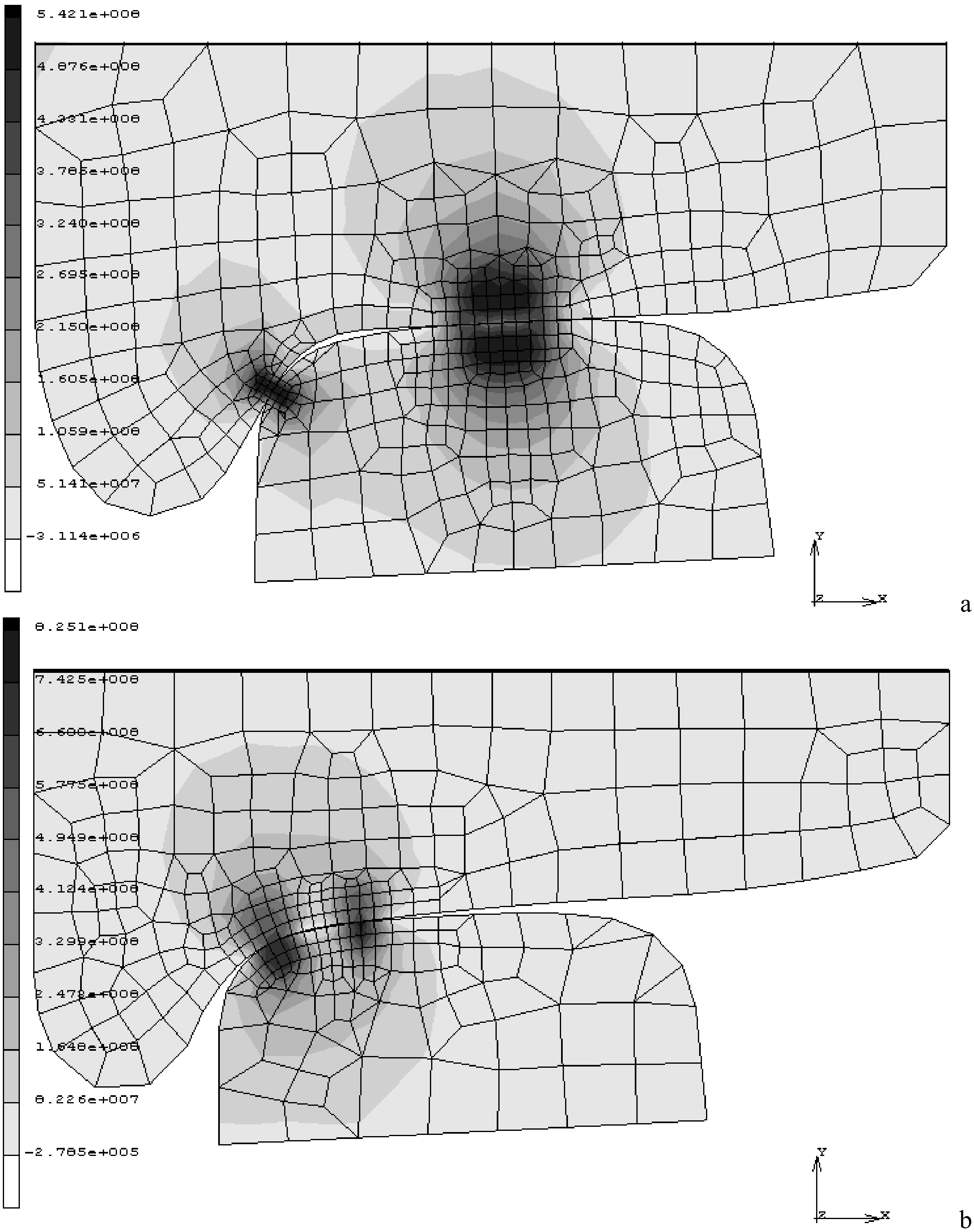
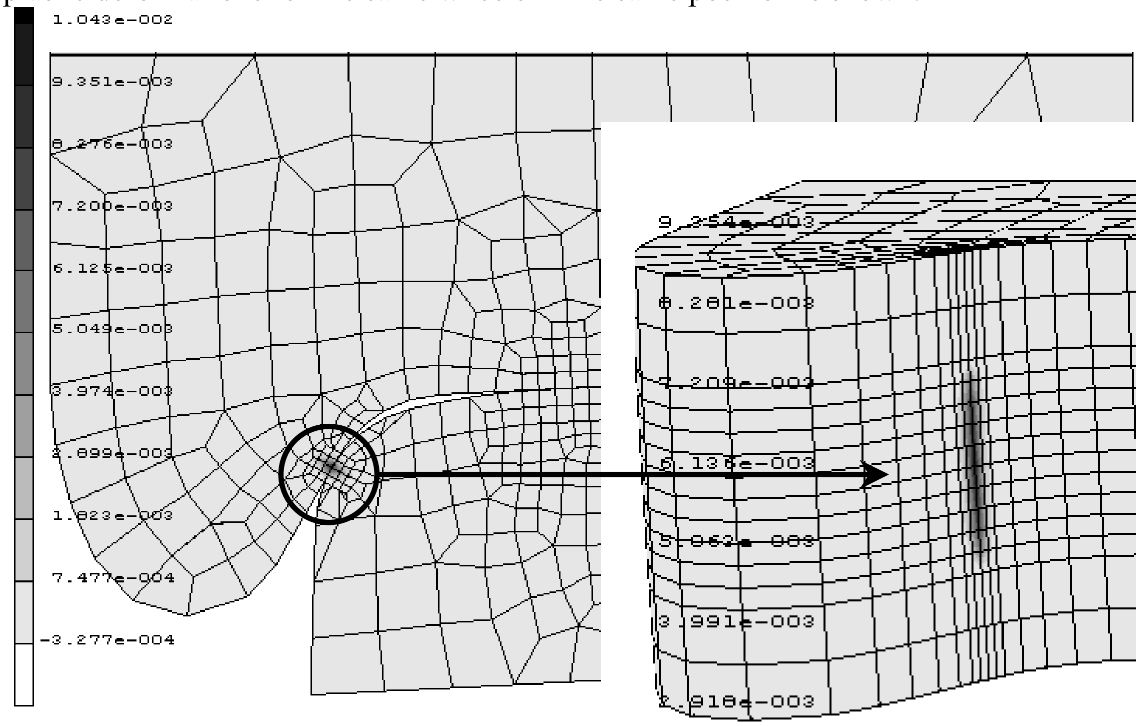


Fig. 18. The distribution of the solid Von Mises stress at the two-point contact of the rail R65 with the wheel GOST 9036-88 (a) and with the wheel DMetI (b)

The resulted stress distributions essentially differ. For a standard wheel exists two enough distant contact zones. One zone is in the central area, and the second in the flange area. For DMetI wheels these zones are pull as much as possible together and are in the transition zone between the central part and the flange.

If to consider only the given position and only the specified stress the comparison would be not in favour of the DMetI wheels. It is caused by that for the first contact pair the maximal stress is equal 542 MPa, and for the second - 825 MPa, i.e. there is the clear advantage of the wheels with a standard profile. However if to compare equivalent plastic strain, which appear as a result of action considered above stress it is not necessary to speak any more about a clear advantage of standard wheels. On fig. 19 comparison of equivalent plastic deformations for the same wheels in the same position is shown.



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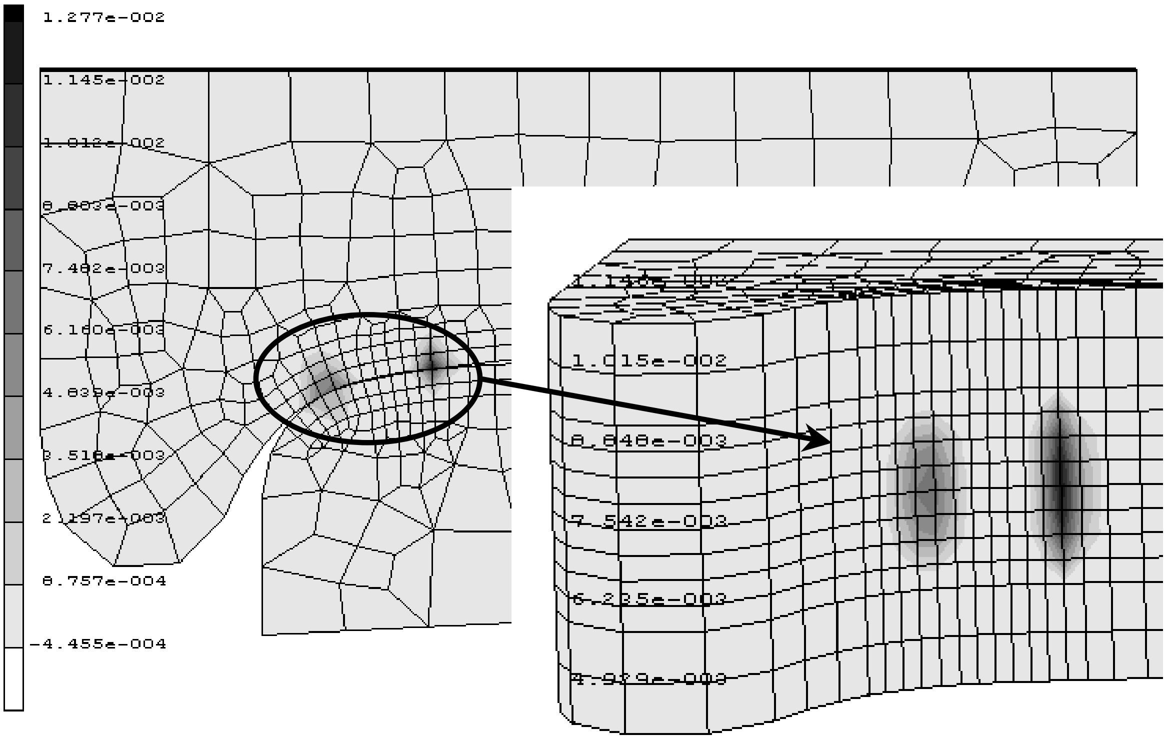


b

Fig. 19. The distribution of the equivalent plastic strain at the two-point contact of the rail R65 with the wheel GOST 9036-88 (a) and with the wheel DMetI (b)

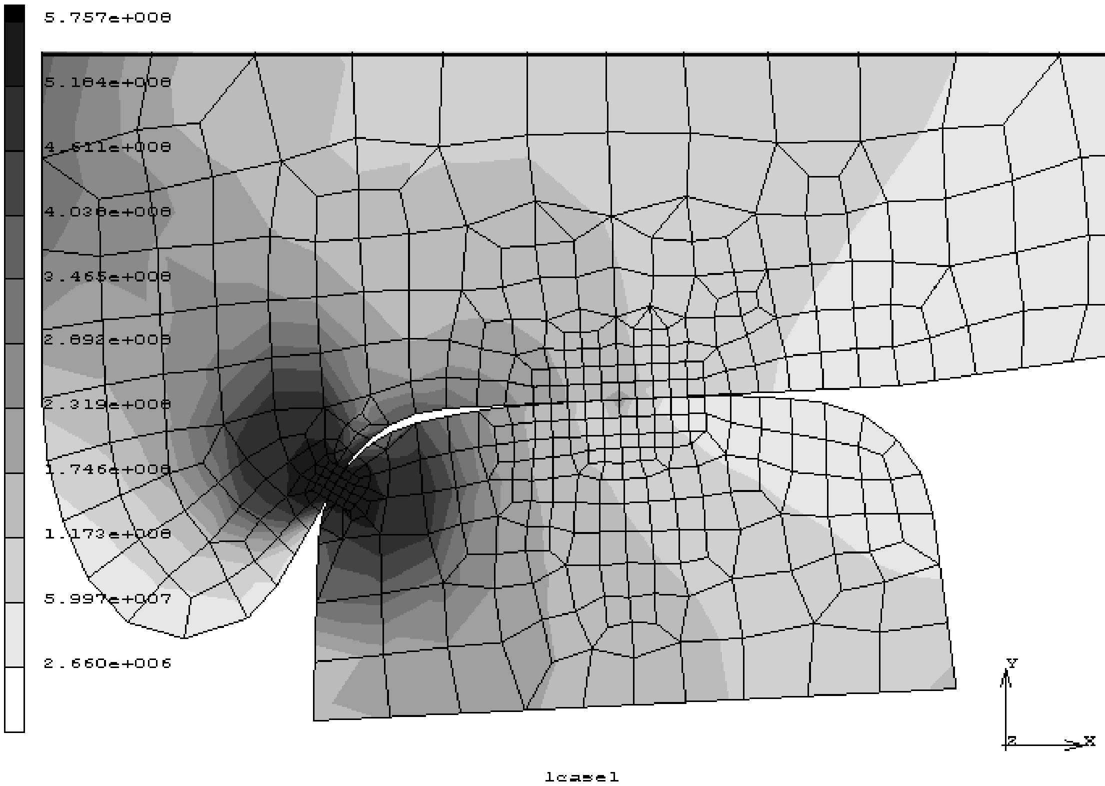
Here the essential difference of a deformation of the wheels with the considered profiles is visible. Rather small plastic deformations of the standard wheels in the central area stop at initiation of the flange contact zone. I.e. only one zone of the plastic deformation on a wheel flange exists, that is a main cause of the intensive wear of the flange.

The comparison of the numerical results for a plastic deformations does not give a significant advantage of the first profile. In particular, for the standard wheel such deformations are equal $1{,}043 \times 10^{-2}$, and for the wheel DMetI $1{,}277 \times 10^{-2}$. I.e. insignificant advantage of wheels with a standard profile for the given position exists, nevertheless it will be lost very fast in exploration. The form of the DMetI profiles is those, that they as though bend around a rail working surface. Their fast grinding occurs in exploration. Instead of the two-point contact for the given position of a wheel there is one contact zone with rather small level of the stress and accordingly the plastic deformation of a wheel steel decreases. It does not occur for the wheels with a standard profile.

However the position of each wheel when the two-point contact turns to the one-point flange contact is the most critical. Such position constantly arises at presence of the big lateral force that takes place at an entrance in curve sites of a track, at passage of the turnout or at presence of the cross-section roughnesses of a track. The stress distributions for the given case of contact is shown on fig. 20. We shall note, that at modelling of the given case the same vertical force 125 kN has been set.

In this case of the contact also it is possible to speak about advantage of a standard profile on a level of the Von Mises stress. In particular, the maximal solid Von Mises stress for the first wheel is equal 578 MPa, and for the second wheel is equal 826 MPa. Nevertheless the comparison of the equivalent plastic strain leads to absolutely opposite conclusion (fig. 21). As the result of the calculations it is defined, that for the given position of the wheelsets the equivalent plastic strain in the flange areas of a standard wheels reach size $2{,}706 \times 10^{-2}$, while for the wheels with a DMetI profiles their level is 1,44 times less, i.e. is equal $1{,}882 \times 10^{-2}$.

Thus, the results of the FEM calculations have confirmed validity a conclusion about advantage of the wheels with the DMetI profiles. As a result of the research carried out, the distribution of contact zones and also stress in them for various wheel and rail profiles have been defined. Investigation of intensity of the wear of wheelsets have been carried out. Recommendations for improvement to wagon wheels and locomotives are developed. For such profiles intensity of the wear, in particular in the region of the flange, decreases. Such profiles are now effectively used in re-profiling wheels of locomotives in Ukraine, Russia and other countries. According to the data of various maintenance depots, intensity of the wear has been shown to decrease by between 20 and 50 %. Similar results have been observed in the application of new profiles for railway tanks. The greatest efficiency has been observed in the use of the new profiles on industrial railway transport. As a result it was possible to reduce intensity of the wear of wheels on fleets of locomotives and wagons belonging to a number of the largest ore mining and processing industries.



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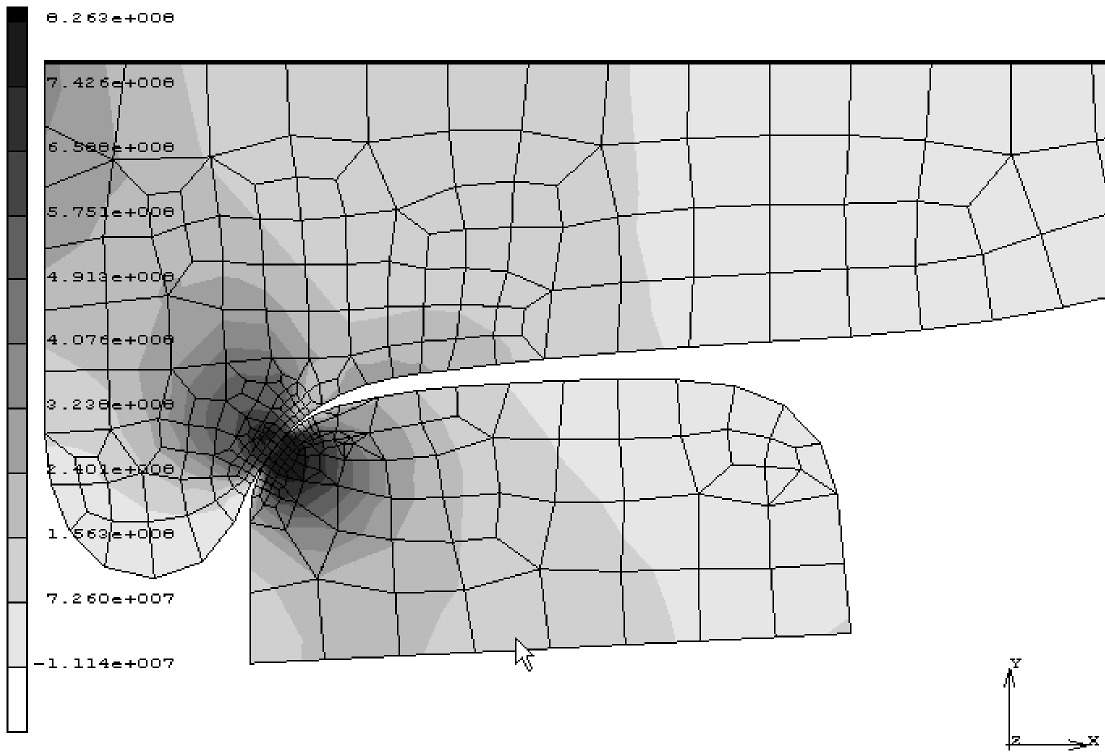

b

Fig. 20. The distribution of the solid Von Mises stress at the one-point contact of the rail R65 with the wheel GOST 9036-88 (a) and with the wheel DMetI (b)

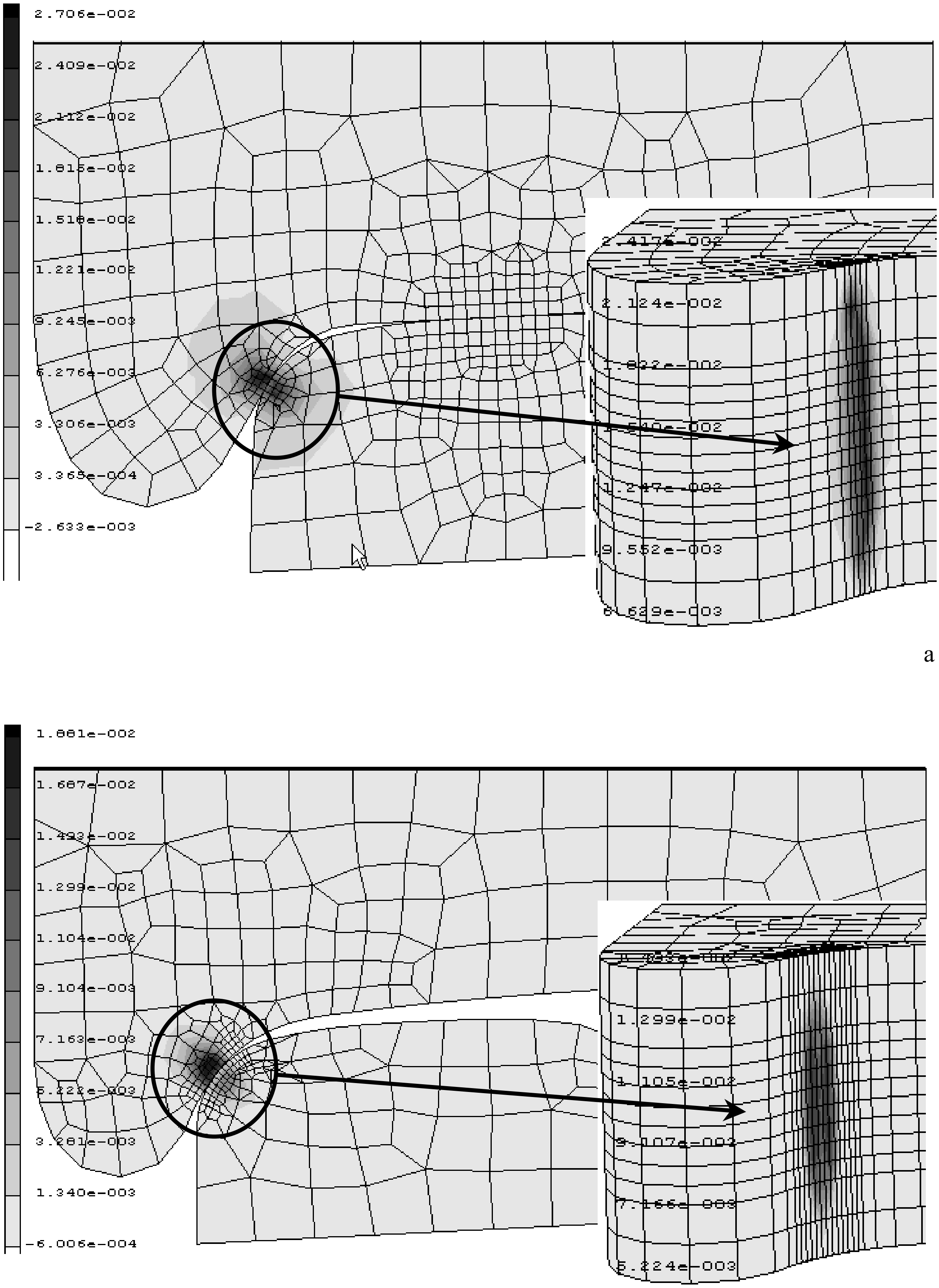

Fig. 21. The distribution of the equivalent plastic strain at the one-point contact of the rail R65 with the wheel GOST 9036-88 (a) and with the wheel DMetI (b)

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