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System Study of Wear Mechanism of Railway Wheel Tread Surface

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The effects of various factors on wear mechanism of railway wheel with cone-and-plate profile of tread surface was investigated. It was established that repeated cyclic thermomechanical effect on a tread surface under operation, as well as nonmetallic inclusions and corrosion products led to accumulation of stresses and defects, which resulted in formation of wear particles having various form, source and mechanism of formation.

Keywords: RAILWAY WHEEL, WEAR MECHANISM, FATIGUE PROCESSES, TREAD SURFACE, FRAGILITY, “WHITE LAYER”, NONMETALLIC INCLUSIONS, CORROSION

Introduction

Various factors affecting the wear mechanism of railway wheel tread surface while in service are discussed in this paper. The effect of plastic deformation in the surface layer of rim is considered in work [1]. However, the comprehensive approach to wear mechanism of railway wheels covers both investigation of structural changes in surface layers of wheel rim [2, 3] and analysis of wear particles and determination of their formation mechanism. The concept of fatigue character of surface layers failure is a general approach to analysis of wear particles [4]. The interest in studying the wear mechanism is related to necessity of loss reduction, development of effective methods to forecast the wheel durability, reliability control of wheel operation under real conditions including extreme (high loads and speeds, raised temperature loadings on lengthy down grades, etc.).

The fatigue processes on the tread surface are known to be related to the presence of nonmetallic inclusions, occurrence of plastic deformation zone and fragile parts of “white layer” and also corrosion damages of steel formed while in service [2, 3]. Phase and structural changes result in the formation of fatigue defects (cracks, wear particles) which cause destruction of a wheel rim. Thus, the wear mechanism of tread surface is caused by a set of mechanical, thermophysical and chemical phenomena, and is related to the formation of wear particles and microcracks in the intensive plastic deformation zone and areas of “white layer”, as well as near nonmetallic inclusions and corrosion damages of surface layers.

Methodology

The wear mechanism of wheels with cone-and-plate tread surface was investigated. Chemical compositions are presented in **Table 1**. Wheels 1 and 2 had been operated by a passenger train for about five years and are out of service because of wear limit.

Table 1. Chemical composition of wheel steel

Wheel No.	Content of element, %							
	C	Mn	Si	S	P	Cr	Ni	Cu
1	0.59	0.72	0.34	0.025	0.012	0.14	0.15	0.20
2	0.65	0.79	0.36	0.027	0.010	0.13	0.18	0.18
3-6	0.58	0.74	0.34	0.025	0.011	0.14	0.17	0.21

Wheels 3-6 were from one batch and had been operated by a passenger train for 1.5; 2.5; 4 and 5.5 years respectively. These wheels were applied to investigate the structural and phase transformations while in service.

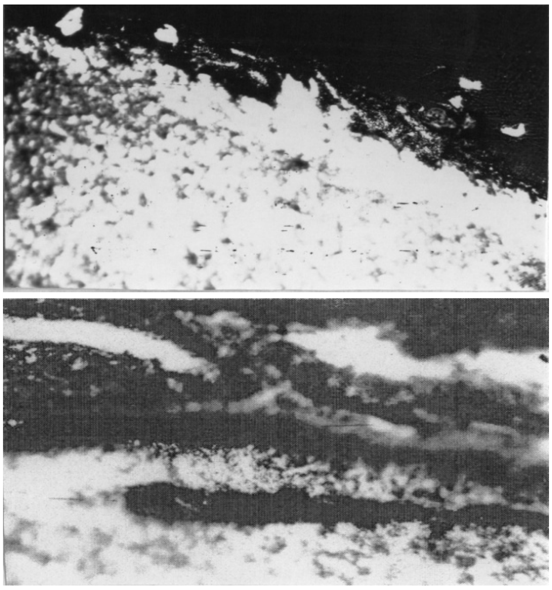
Nonmetallic inclusions and corrosion products were identified by means of following methods: metallographic – in the light and dark backgrounds and in polarizing light as well; micro X-ray spectrum, X-ray structure and petrographic method with the use of microscopes "Neophot-21" , MS-46 "Cameca", "Nanolab-7", DRON-2.0. Wear particles on the tread surface of railway wheels were studied by metallographic method using the optical microscope "Neophot-21" and scanning-electron microscope SEM-200.

Results and Discussion

One of the sources of wear particles formation on the tread surface is a so-called "white layer" which is characterized by increased fragility [2, 3]. There are substantial stresses on the interface "white layer" and the main structure of a wheel steel. These stresses are caused by various physical and mechanical properties of areas with different structures. Besides, localization of deformation of wheel rim surface layer is observed near the "white layer", which also promotes concentration of stresses on the interface "white layer" and the main structure of wheel steel. The latter results in chipping of "white layer", therefore it is almost always not continuous. The wear particles have the appearance of pieces with sharp edges of irregular shape (**Figure 1a**). Their occurrence can be related to the formation of small fatigue cracks in surface layers of wheel rims. When these cracks emerge, the formation of wear particles begins [4].

Steel is plastically deformed under fragile "white layer", and repulsive forces arise on the interface of specified structural components and affect moving dislocations [5]. There is an area with elevated density of dislocations providing deformation hardening near the interface of these structure zones. In turn, it can lead to occurrence of microcracks both along the interface "white layer" – deformed steel structure and at a distance from it parallel the tread surface (**Figure 1b**). There are a lot of extended laminations and wear particles under the "white layer" as a result of plastic deformation, which points to significant localization of deformation according to theory of "flaking off" wear [5].

Another reason for wear particles formation can be nonmetallic inclusions that have a metallurgical origin and are concentrators of stresses and deformations in a wheel steel [6-8]. Oxidation and corrosion damages of tread surface promote the formation of cracks and wear particles as well. These processes lead to the formation of rough inclusions of complex oxides straight on the tread surface. Hereafter, corrosion products will be called "nonmetallic inclusions" as their composition and structure are similar to some oxide inclusions in a wheel steel.



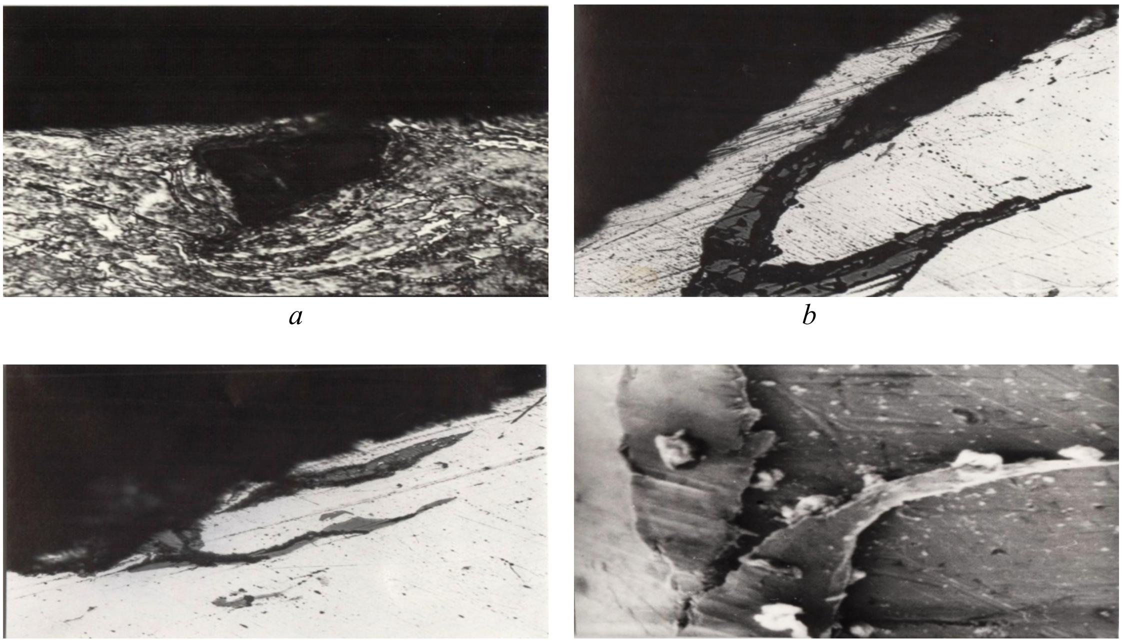
a

b

Figure 1. Wear particles (*a*) and chipping of "white layer" (*b*), x 1000

The investigations performed earlier [5] established that the presence of the second phase particles significantly raises the rate of microcracks formation and their coalescence during growth, which increases intensity of fatigue wear and wear under friction. Authors [5] explain this fact by retarding action of particles on moving dislocations and assume that effect of inclusions on wear particles formation is one of the most important mechanisms of defects formation under the wear. A depth of these defects formation is determined by a depth of particles of nonmetallic inclusions in relation to external surface.

It was determined in works [6-8] that nonmetallic inclusions of various types caused non-uniform progress of plastic deformation at various temperatures, rates and ways of deformation. The analysis of wheel steel microstructure near the tread surface has shown that nonmetallic inclusions and corrosion products promoted non-uniform growth of deformation, occurrence of turbulent flow zones (**Figure 2a**) and formation of areas with increased extent of



a *b* *c* *d*

Figure 2. Deformation localization (*a*) and formation of wear particles near nonmetallic inclusions and products of wheel steel corrosion (*b-d*) on a tread surface of railway wheels: *a, b* – x 400; *c, d* –x 200

deformation in relation to its average value in different areas across the rim width. The behavior of nonmetallic inclusions near the tread surface and under effect of stresses depends on their types, namely, whether they are plastic (sulfides) or are not inclined to plastic forming (oxides, silicates, carbonitrides of titanium). The laws of plastic deformation running in inclusions are the same as in metals or metal alloys in view of homological temperatures [6, 7].

A nonmetallic inclusion near the tread surface is in the stressed condition determined by a set of contact, dynamic and cyclic stresses. This inclusion is under the action of normal compression stresses – from the contact pressure of system wheel-rail; of axial shear stresses arising in a steel matrix in the process of its deformation; of friction stresses on the interface inclusion-matrix. The value of normal stresses depends on service conditions of a wheel, and that of shear stresses depends on ductility of wheel steel matrix determined by its structure and temperature. The temperature gradient arising near the tread surface leads to non-uniform distribution of deformations in steel matrix and of forces affecting the inclusion. The inclusions appear to be surrounded with non-uniform field of internal stresses that have long-ranged fields.

Thus, there is a certain scheme of stressed state near each inclusion. The ratios between values of various stresses in this scheme change constantly while a wheel is in service. The steel matrix is deformed with inclusion under these conditions. At high pressures and cyclically changing temperatures, the interaction of contacting surfaces of inclusion and steel matrix occurs by means of mechanical contact and diffusion processes.

Mechanical contact is established as a result of smoothing rough surfaces of inclusion and wheel steel matrix by means of contact friction between each other, which does not allow them to move. Such a friction is a kinematic dry sliding friction as it has no lubricant at forward motion of steel matrix grains on the surface of unwrought inclusion or between moving steel matrix and ductile inclusion. The conditions of formation of friction forces on phase boundary inclusion – matrix according to Amonton's law are analyzed in works [6, 7]. There is Equation (1) for distorting system steel matrix – inclusion that considers the effect of attractive forces between molecules of sliding bodies and their components on friction forces *F*. These attractive forces are caused by the type and structure of phase boundaries and related to definite surface energy and also to friction that arises when interphase dislocations and disclinations are moving (sliding):

$$F = \mu[N + S(\rho_o + \gamma_{i-m}/D_i + \nu\tau_d/\ell_1 + \omega\tau_d/\ell_2)] \quad \text{(Eq.1)}$$

where γ_{i-m} – the specific surface energy of interface inclusion-matrix; l_1 and l_2 – the length of mobile interphase dislocations and disclinations, respectively; v – Burgers vector of interphase dislocations; ω – the rotation vector of interphase disclinations; τ_d – the tangential stress of deformation origin that acts along the phase boundary; D_i – the size of inclusion; μ – the friction factor; ρ_0 – the intermolecular forces; μ and ρ_0 depend on chemical and phase compositions, types of crystal lattice of matrix and inclusion.

Obviously, the friction forces brake the flow of steel matrix around inclusion and are distributed on the interface non-uniformly. This non-uniformity is primarily caused by non-uniform distribution of normal and tangential stresses affecting the inclusion near the tread surface. The friction forces on the interface inclusion-matrix are determined by temperature and extent of deformation, shape and size of inclusion, and they rise with temperature drop and with increase of external stresses and inclusion size as well [6-8]. The temperature effect is expressed in terms of friction factor, the values of which are various for different temperatures. The effect of inclusion size and shape is determined by the contact area *S,* and the effect of extent of deformation by increase in density of interphase defects.

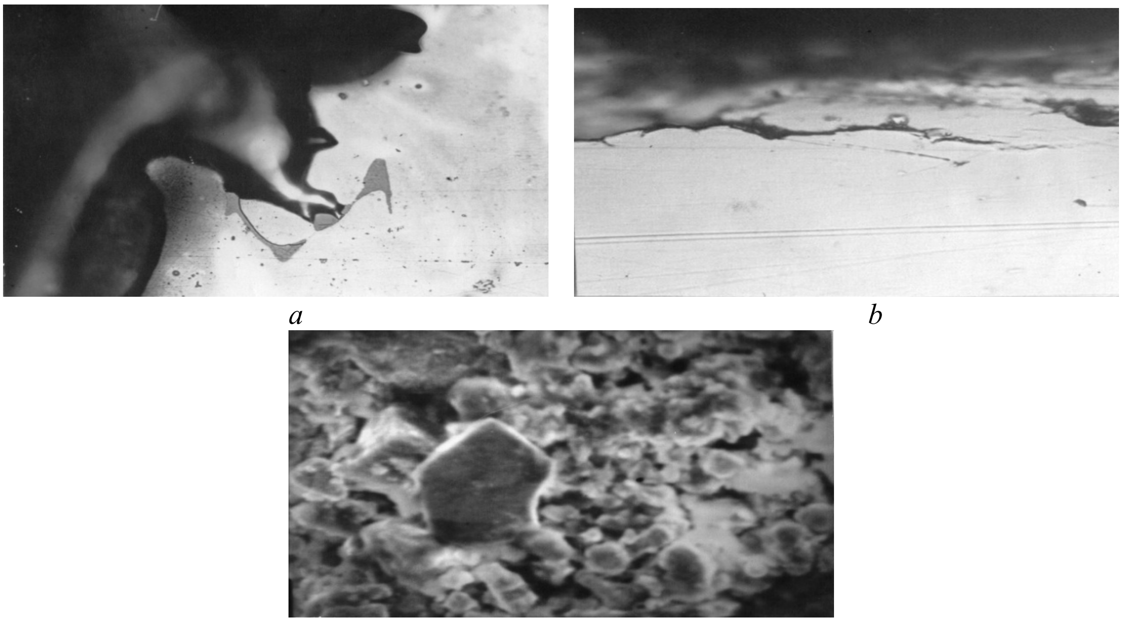
The contact friction intensifies the heterogeneity of wheel steel matrix deformation near inclusions because there are the elementary tangential forces of friction in each point of contact surface. This initiates additional tangential stresses on the phase boundary inclusion-matrix. These tangential stresses are directed oppositely sliding matrix in relation to the inclusion, which can affect not only the level of stresses but also the tension scheme [6, 7].

Characteristic fibrous grain structure of wheel steel is formed in the course of combined deformation of system inclusion-matrix near the tread surface. During deformation, each grain of perlite and ferrite is under the action of normal compression forces due to contact interaction wheel-rail. As a result, relaxing tangential stresses arise in the steel. Under their effect, the matrix flows in direction of floating movement, and grains of perlite and ferrite become elongated. Steel matrix is in a contact with inclusion, and friction forces arise on the phase boundary and break its flow. The fibers of deformed matrix round the inclusion which can be turned by moving matrix in direction of its flow. Consequently, couple stresses arise, and the typical vortex granular structure is formed (**Figure 2a**). The matrix fibers round the inclusion from one side if it is exposed on the surface or from two sides if it is near the tread surface. In the first case, the matrix fibers gradually "overlap" the inclusion (**Figure 2b**), curve and sometimes create loops or spirals (**Figure 2c**). In the second case, the matrix fibers round the inclusion from two sides, thus separation along the interface inclusion-matrix is possible (**Figure 2d**). The deformation is non-uniform: the fibers after the contact with inclusion stop, and elevated concentration of stresses occur in this place. And those matrix layers above and below are deformed in direction of wheel steel matrix flow. Thus, the compression and shear stresses are concentrated on the boundaries inclusion-matrix. These stresses can fracture the inclusion if they exceed a stress limit of inclusions at compression (**Figure 2b**).

At accelerated braking under conditions of great raise of temperature, it is necessary to consider a possible role of slipping lengthwise grain boundaries in austenite and lengthwise phase boundaries inclusion-matrix in deformation course near the tread surface [6, 7]. Besides, ductility of steel matrix in austenite condition increases as there is migration of grain boundaries and lineage boundaries under the effect of deforming stresses, and dynamic recrystallizing takes place in this way. It is known that there is local heating of metal at sliding of dislocations. Therefore, when a rake stops, the inclusions, which cause localization of flow shears and also break these processes as barriers on the way of movement of dislocations, promote additional local heating of matrix. This can cause the processes of dynamic recovery in matrix near inclusions at cold deformation.

Quite often nonmetallic inclusions are the centers of local decarbonization of steel, which causes structural heterogeneity and non-uniform flow shears, as well as formation of microcracks and wear particles.

It is necessary to consider one more aspect of effect of free-melting nonmetallic inclusions on the formation of wear particles near the tread surface under conditions of emergency breaking and local heating of tread surface up to the temperatures corresponding to austenite area of steel matrix, when partial melting and even complete melting of iron-manganese sulfides and sulfide eutectics are possible, i.e. appearance of a so-called *local sulfide red shortness* is possible [6]. It was determined that at temperature rise up to 980 °C and above, sulfides and their eutectics, at first, were melted near steel matrix interface, and after that they were completely melted and cavities filled with the melt occured. Partial melting of inclusions causes deformation localization in joining areas of matrix, which, in turn, stimulates the growth of cavities



a *b*

c

Figure 3. Formation of wear particles in areas of sulfide red shortness on the tread surface of railway wheels, x 600

and formation of cracks between them. The microcracks occur near these inclusions when extent of steel deformation ε_{cr} is reached. This extent of deformation depends on inclusion type and temperature. It sharply decreases as compared to ε_{cr} for solid inclusions, which indicates to red shortness in case of melting. The growth rate of cavities sharply increases in case of partial melting of inclusions. Therefore, under conditions of emergency train stop, when the tread surface is heated up to high temperatures, great localization of steel deformation takes place and a number of cracks appear as a result of melting of sulfide inclusions (**Figure 3a**), i.e. steel is fractured at relatively low extents of deformation. Thus, the conditions of steel matrix flow near the inclusions and of contact friction along phase boundaries inclusion-matrix are broken as described above for solid inclusions. The liquid layers are easily extended in parallel the tread surface (**Figure 3b**), the cracks progress between them and promote the formation of wear particles.

As a result of three mechanisms – galling of steel matrix grains on inclusions; separation along phase boundaries inclusion-matrix of steel under the action of friction forces and due to various plastic response of inclusions and matrix; partial melting of sulfide inclusions – the wear particles are formed and distorted during growth. The wear particles have a form of loops and spirals similar to chips when cutting near the nonmetallic inclusions and corrosion products of wheel steel (**Figure 2d**). They take this form thanks to residual stresses related to non-uniform distribution of dislocations through-the-thickness of wear particles formed near the inclusions [5]. According to [4], such wear particles occur before fracture and are observed mainly on the tread surface before local destruction. As for local sulfide red shortness of steel, there is a great number of wear particles of both spiral and compact irregular shape in the areas of tread surface where sulfide inclusions are partially melted (**Figure 3c**). This is caused by a great number of microcracks in these areas and by crushing of wear particles as a result of strong localization of deformation.

Considering the effect of corrosion products as nonmetallic inclusions upon the formation of wear particles, it is necessary to consider one more aspect of environment effect related to corrosion processes on fatigue failure on the tread surface of a railway wheel. It is known that initial stage of corrosion includes adsorption of atoms of elements from environment, which causes the effect of adsorption drop of product strength (P. A. Rebinder's effect) [9]. The flow shears arising in a surface layer of the rim, thermal cycling during braking and interaction with damp atmosphere create conditions for intensive development of diffusion processes which promote more intensive adsorption of elements from environment as compared to other areas of wheel surface. Obviously, adsorption-fatigue phenomena that lead to origin of fatigue cracks and wear particles take place on the tread surface of a railway wheel as well [4]. The presence of phase boundaries inclusion-steel matrix with their defect structure and stresses [7] as well as the formation of microcracks in them undoubtedly promote localization of effect of adsorption drop of tread surface strength near nonmetallic inclusions. This effect is characterized by drop in fracture surface work under the effect of formation of absorption layer [9]. Apparently, the power interpretation of effect of adsorption strength drop related to occurrence of disjoining forces in these boundaries that allow penetration of absorption layer into the depth from tread surface [9] is especially urgent for phase boundaries inclusion-matrix. This, in turn, promotes separation of inclusions from steel matrix and the formation of wear particles.

Conclusions

Wear particles in the form of pieces with sharp edges of irregular shape are formed at brittle fracture of "white layer". Their occurrence is related to formation of small fatigue cracks in surface layers of rim. The formation of wear particles starts when these cracks break the surface.

Those wear particles have the shape of loops and spirals near the nonmetallic inclusions and products of wheel steel corrosion. They are formed due to localization of deformation near inclusions and galling of matrix metal on inclusions, and also as a result of separation of phase boundaries inclusion-matrix. Such particles are observed mainly on a tread surface prior to local fracture.

In case of local sulfide red shortness, there are a number of wear particles of both spiral and compact irregular shape, which is caused by the presence of a great number of microcracks in these areas, and also by crushing of wear particles due to strong localization of deformation.

The results of analysis of microcracks, separations and wear particles as well as mechanisms of their formation have shown that wear of tread surface corresponds to complicated phenomenon and has several mechanisms (fatigue, absorption, corrosion, friction wear). It is a multifactor process.

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Системное исследование механизма износа поверхности катания железнодорожных колес

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Исследовано влияние комплекса факторов на механизм износа железнодорожных колес с плоскоконическим профилем поверхности катания. Установлено, что многократное циклическое термомеханическое воздействие на поверхность катания колеса при эксплуатации, а также неметаллические включения и продукты коррозии приводят к накоплению напряжений и дефектов, что способствует образованию частиц износа, имеющих разную форму, источник и механизм формирования.