UDC 629.012.3 : 620.192.3 : 001.5

Effect of Plastic Deformation in Surface Layer of Wheel Rim on the Mechanism of Railway Wheel Wear in Service

S.I. Gubenko /D.Sc. (Eng.)/, **S.I. Pinchuk** /D.Sc. (Eng.)/, **E.V. Belaya**

National Metallurgical Academy of Ukraine
4 GagarinAve., Dnipropetrovsk 49600, Ukraine

Abstract

The wear mechanism of railway wheel with cone-and-plate profile of tread surface is investigated. It is established that repeated cyclic thermomechanical influence on a tread surface under operation leads to accumulation of stresses and defects, which results in formation of wear particles having the various form, source and mechanism of formation.

Keywords: *railway wheel, wear mechanism, fatigue processes, tread surface, fragility, density of dislocations, corrosion*

Introduction

The comprehensive approach to wear mechanism of railway wheels consists both in studying the structural changes in surface layers of wheel rim [1, 2] and in analysis of wear particles and determination of their formation mechanism. The variety of operating conditions of friction pairs enables to state that the concept of fatigue character of surface layers failure is considered to be general [3]. Such an approach is necessary when choosing chemical composition of steel of friction pair *wheel-rail* in view of their cyclical strength and durability and when developing the new designs of wheels in view of their operation conditions. The interest to investigation of the wear mechanism is related to necessity to reduce losses, to develop the effective methods for prediction of wheel durability, reliability control of their operation under real conditions including extreme ones (high loads and speeds, increased temperature loadings on lengthy down grades, etc.).

The fatigue processes are related to the presence of particles of nonmetallic inclusions near the tread surface, occurrence of plastic deformation zones and fragile parts of "white layer" and also to corrosion damages of steel formed during the service [1, 2]. The structural changes lead to formation of fatigue defects (cracks, wear particles) which cause destructions of a wheel rim (in this case, flange worn sharp is very dangerous) and also to change of wheel profile as a result of metal layers displacement along the tread surface. Thus, the mechanism of tread surface wear is caused by the set of mechanical, thermophysical and chemical phenomena, and it is related to the formation of wear particles and microcracks in places of intensive plastic deformation and areas of "white layer" and near to nonmetallic inclusions and corrosion damages of surface layers as well.

The results of investigation of the mechanism of wear particles formation on the tread surface of railway wheels during their operation are stated in present paper.

Materials and research techniques

The wear mechanism of wheels with cone-and-plate tread surface is investigated. The chemical compositions are presented in Table.

Table. 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 1 and 2 have been operated by a passenger train for about five years and are out of service because of limiting wear of wheel rims. Wheels 3-6 were from one batch and have been operated by a passenger train for 1.5, 2.5, 4 and 5.5 years respectively. These wheels were used for research of structural and phase transformations while in service.

Research results and their discussion

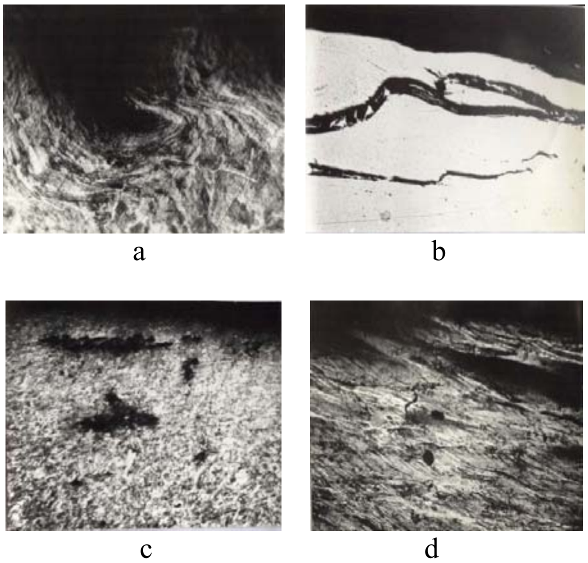
There are microcracks and segregations along the whole tread surface. They lead to formation and separation of wear particles and also to fracture failure in a throat zone. The latter causes flange worn sharps during their operation. The formation of wear particles can be caused by various factors. The form of particles depends on conditions of their formation.

One of the major reasons for wear particles formation is plastic shifts caused by rather high degree of metal deformation near the tread surface, that has a non-uniform pattern across the whole width of rim [1, 2]. There are microcracks (Figure a), separations, wear particles (Figure b) on the boundaries of zones with different deformation degree and in the areas of intensive and turbulent deformation. There are a lot of wear particles in the throat zone, which points to major localization of deformation and finally leads to flange worn sharp.

The wear particles appeared as a result of intensive plastic deformation near the tread surface have a form of plates with different thickness. They are typical for normal wear conditions [3].

According to wear theory [4], the maximum density of dislocations occurs in the process of friction not on the surface but at a definite depth where extended microcracks appear (Figure c) and grow till the critical size as a result of steel plastic yielding (Figure d). Thus, plastic yield of steel is localized in the area between cracks and tread surface, and the particles in the form of scales are formed.

The plastic acts are the most important in this process. They result in accumulation of dislocations and occurrence of microcracks parallel to the tread surface. Such microcracks do not cause the formation of wear particles for some period of time. They can grow and the new microcracks can be formed simultaneously. The wear scales are formed by means of viscous separation of metal at these cracks coalescence, this process is accompanied by plastic yield of steel near the tread surface.


a b

c d

Figure. The wear particles near the tread surface in the zone of intensive plastic deformation: a, b – x 100, c, d – x 200

The data regarding determination of dislocation density on the tread surface presented in papers [1, 2] highlight the growth of intensive deformation of rim surface layer while the wheels are in service.

The density of dislocations was determined after the subsequent grindings of 1, 2, 3 and 5 wheel surfaces on a various depth from 100 up to 200 μ. The value of this parameter was approximately at the level of 10^{10} -10^{11} cm^{-2}. Thus, the value of dislocation density at a depth from 100 up to 200 μ from the tread surface was in 2-3 times higher than that on the surface. Such a difference is related to end of moving dislocations in the process of plastic deformation. Besides, there is known the fact of "shielding" effect of external surface (in our case – tread surface) on moving dislocations [4]. The so-called *polarizing stress* σ_i affects moving dislocations at plastic deformation near the tread surface:

$$\sigma_i = G \cdot b / 4\pi (1-\nu), \qquad \text{(Eq. 1)}$$

where G – the shear modulus of wheel steel, b – Burgers' vector of dislocations, ν – Poisson's ratio of wheel steel.

Frictional constraint σ_{fr} and change of surface energy resist this force when dislocations move from the surface [4]. Solving the equations with frictional constraint σ_{fr}, we obtain an expression for thickness of wear particles a_p:

$$a_p = G^{\cdot} b / 4\pi (1-\nu) \sigma_{fr}, \qquad \text{(Eq. 2)}$$

The frictional constraint near the tread surface can be expressed approximately as follows:

$$\sigma_{fr} \approx G \varepsilon^2 c, \qquad \text{(Eq. 3)}$$

where ε – the degree of steel deformation; c – the concentration of impurity atoms; G – the shear modulus of wheel steel.

Obviously, when considering the features of plastic deformation of wheel steel near the tread surface, it is necessary to consider interaction of this surface with environment (in particular, with damp atmosphere), which leads to corrosion damages. Since the initial stage of corrosion includes adsorption of element atoms from the damp environment, it can cause the effect of adsorption simplification of plastic deformation near the tread surface (P.A.Rebinder 's effect) [5]. The phenomenon of plasticization of surface layers can be explained by influence of surface energy change on behavior of deformable solid, i.e. by decrease in the surface potential barrier, which affects behavior of dislocations in the boundary layer of wrought metal [5]. Apparently, the plasticization of tread surfaces of wheel and rail promotes smoothing of their roughness, admissible change of tread surface profile at the initial stages of operation. This accelerates the so-called *useful wear* which is necessary for acceleration of “running-in ability” process in the system “wheel-rail”.

Then, for the formation of surface defects (wear particles) it is necessary to achieve the final condition of steel strain hardening under conditions of changing stress action. This stage of deformation is accelerated under influence of tension-active medium [5]. In the process of formation and separation of wear particles, when fatigue failure of tread surface occurs and there are new "fresh" surfaces of progressive cracks, the active elements of damp environment are adsorbed on them. Such an adsorption penetration of surface-active components inside cracks has rather high rates [5], which leads to decrease in surface energy of cracks and simplifies their further propagation in the process of plastic deformation of steel. Besides, the processes of steel corrosion take place on the surface of wear particles, after which the oxidation products are often observed in steel. It is known that damp environment penetrates inside the formed cracks under the influence of capillary pressure at rather high rate [6]. Thermodynamic inevitability of the process of surface-active substances penetration in cracks is explained by decrease of surface energy inside the crack under influence of adsorption [6]. Thus, damp environment containing various lubricants, pollution, etc. has a negative effect upon endurance strength of tread surface owing to adsorption and corrosion phenomena.

According to research work [4], wear particles in the form of scales or plates of different thickness are formed at uniform distribution of dislocations through-their-thickness. After the formation, a few of these scaly particles get into the space between two tread surfaces of wheel and rail, after that they can be either destroyed with their form change or can get the "flat" form keeping the former size.

Obviously, wear of tread surface occurs by layers and each layer consists of a number of scales – wear particles. Their quantity N in each layer is in proportion to a number of microcracks formed in the process of plastic deformation. The rate of cracks coalescence and critical degree of deformation which are necessary for formation of uncoupled particles of wear depend on the depth of plastic deformation area with the maximum density of dislocations h_{cr}. This density h_{cr} is necessary for removal of the full layer containing N of wear particles. Similarly to calculations in paper [7], the total wear of tread surface under intensive plastic deformation can be expressed as follows:

$$W = N^w (h_{p.d..}{}^w / h_{cr}{}^w) A^w a_p{}^w + N^r (h_{p.d.}{}^r / h_{cr}{}^r) A^r a_p{}^r, \qquad \text{(Eq. 4)}$$

where N – the quantity of wear particles in the layer separated from the tread surface, a_p - the thickness of a wear particle, $h_{p.d..}$- the depth of plastic deformation zone, h_{cr} - the depth of plastic deformation zone with the maximum density of dislocations, w and r - the indices for wheel and rail, respectively.

Thickness of wear particle a_p is accepted to be equal to the depth of plastic deformation zone with the maximum density of dislocations h_{cr} (see Equation (2)). The average surface area of each wear particle depends on the real area of contact at wheel-rail interaction in view of roughness S_r:

$$S_p = cS_r, \qquad \text{(Eq. 5)}$$

where c – the coefficient of proportionality.

In paper [5], it is established that the value

S_r and number of roughnesses in the contact n are proportional to applied loading L, and n ~ Nk:

$$S_r \sim L^{0,09}\ ,\ n \sim L^{0,91}, \qquad \text{(Eq. 6)}$$

After substitution of Equations (2, 5, 6) in (4), we obtain:

$$W=b/4\pi\{[k^wG^w/\sigma_{fr}h_{cr}{}^w(1-\nu^w)]+[k^rG^r/\sigma_{fr}h_{cr}{}^r(1-\nu^r)\}Lh_{p.d.}{}^r, \qquad \text{(Eq. 7)}$$

where k^w and k^r – the constants depending on the surface roughness.

It follows from Equation (7) that the wear rate of tread surface is proportional to normal loading and depth of plastic deformation zone near the tread surface. Equation (7) can be written down as follows:

$$W=K\cdot L\cdot h_{p.d..}{}^k, \qquad \text{(Eq. 8)}$$

where K – the wear factor of tread surface at plastic deformation under conditions of friction in the system wheel-rail:

$$b\ /4\pi\{[k^w\ G^w/\sigma_{fr}\ h_{cr}{}^w\ (1-\nu^w)] + [k^r\ G^r/\sigma_{fr}\ h_{cr}{}^r\ (1-\nu^r)\ ]\}. \qquad \text{(Eq. 9)}$$

Thus, the wear rate decreases, when intensity of plastic deformation in the surface layer of wheel rim lowers.

Summary

The repeated cyclic thermomechanical influence on the tread surface at its interaction with a rail leads to accumulation of stresses and defects (microcracks, separations, detachments), which promotes the formation of wear particles with different form, source and mechanism of formation.

The most widespread wear particles look like scales or plates of different thickness. These wear scales are formed by means of viscous separation. They are typical for normal wear conditions and their occurrence is related to plastic deformation near the tread surface.

References

1. Yu.N Taran., V.P. Yesaulov, S.I. Gubenko Structurnyye izmeneniya v obodyakh zheleznodorozhnykh koles s raznym profilem poverkhnosti kataniya (*Structural Changes in Railway Wheel Treads with Various Tread Surface Profile)* // Izvestiya vuzov. Chernaya metallurgiya – 1989. – No. 9. - P. 101-105.
2. Yu.N Taran., V.P. Yesaulov, S.I. Gubenko Povyshenie iznosostoykosti zheleznodorozhnykh koles s raznym profilem poverkhnosti kataniya (*Increase of Wear Resistance of Railway Wheels with Various Tread Surface Profile)* // Metallurgicheskaya i gornorudnaya promyshlennost – 2000. – No. 2. - P. 42-44.
3. E.A. Marchenko O prirode iznosa poverkhnostey metallov pri trenii (*Nature of Deterioration of Metal Surfaces at Friction).*– M.: Nauka, 1979. – 118 p.
4. N.P. Suh The Delamination Theory of Wear. Wear, 1973, v. 23, n 1, pp. 111-124.
5. V.I. Likhtman, E.D. Shchukin, P.A. Rebinder Fiziko-khimicheskaya mekhanika materialov (*Physial and Chemical Mechanics of Materials*). - M.: Publ. of Academy of Sciences of USSR, 1962. – 303 p.
6. G.V. Karpenko Prochnost stali v korrozionnoy srede (S*teel Strength in Corrosion Medium*).- M.-K.: Mashgiz, 1963. – 187 p.
7. G.V. Akimov Teoriya i metody issledovaniya korozii metallov *(Theory and Methods of Metal Corrosion Studies*).– M.: Publ. of Academy of Sciences of USSR, 1945. – 195 p.

Received September, 2009

Влияние пластической деформации в поверхностном слое обода на механизм износа железнодорожных колес при эксплуатации

Губенко С.И. /д.т.н./, Пинчук С.И. /д.т.н./, Белая Е.В.

Исследован механизм износа железнодорожных колес с плоскоконическим профилем поверхности катания. Установлено, что многократное циклическое термомеханическое воздействие на поверхность катания колеса при эксплуатации приводит к накоплению напряжений и дефектов, что способствует образованию частиц износа, имеющих разную форму, источник и механизм формирования.