DAMAGE OF THE WHEEL AND RAIL INTERACTING SURFACES AND THE RAIL CORRUGATION

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Abstract. ***The characteristic roll-slip phenomena between the wheel and the rail are prone to develop a rail corrugation. There are a lot of scientific works and opinions about rail corrugation, but some aspects of this phenomenon are still insufficiently studied.***

Studies have shown high sensitivity of the third body to the sliding speed, which for heavy loaded interacting surfaces, like wheel and rail, often destroys the third body. This leads to sharp increase in wear rate and other undesirable phenomena.

Was revealed the especially high sensitivity of various types of damage (scuffing, fatigue, plastic deformations) proceeding simultaneously in the contact zone to destruction degree of the third body.

The researches have shown that necessary conditions for the rail corrugation are periodic slipping of the interacting surfaces of wheels and rails, destruction of the third body, and seizure of separate places of the surfaces. The onset and degree of destruction of the third body were determined in the laboratory conditions. In the capacity of sliding sources are considered movement of the wheelset in curves, non-roundness of the wheel, and wheels of the wheelset with different diameters.

Keywords: ***third body, friction force, sliding speed, rail corrugation.***

1. INTRODUCTION

Typically, surfaces are covered with various types of natural and artificial coatings, which are components of the third body in the contact zone of interacting surfaces and they are subjected to high power and thermal loads. The thermal effects accompanying the process have direct influence on the deformation value, and volume of the deformed material, variation of the surface structure and physical and mechanical characteristics. This causes destruction of these coatings, activation of the physical and chemical processes proceeding between them and the surfaces, and generation of new coatings. Thus, during the interaction of surfaces, the processes of the third body destruction and restoration take place in the contact zone continuously. When continuity of the third body is disrupted in individual places the parts of the direct contact are cleansed from various coatings and boundary layers and are approached to each other, leading to seizure. Displacement of the coupled places of surfaces relative to each other causes disruption of these junctions' proceeds at the high shearing stresses that increases instability of the friction forces, transfer of the pulled-out material from one surface on the other, sharp change of roughness of these surfaces, and development of the process of catastrophic wear – scuffing. The shear deformation generated on the surface sharply decreases towards the depth and multiple repetitions

of such processes result in superficial plastic deformations, lamination, and fatigue damage, proceeding simultaneously.The damage scales and dominant types of damageproceed with various intensities and a dominant type of damage depend on the working conditions and ascertained visually.

It should be noted that some aspects of the rail corrugation as well as other types of wear are not studied sufficiently yet [1, 2] that hinders prevention of the undesired phenomena caused by it and rises heavy economic problems.

2. THE FEATURES OF THE WHEELSET MOVEMENT ON THE RAIL TRACK

Movement of wheelset in straight performs a zigzag movement close to the sinusoid which is accompanied by creeping. In the curves the inner wheel passes the shorter distance than the outer wheel causing deviation of the wheelset axis from the radial position. In such conditions, to return the wheelset into initial position it is necessary that one of wheel of the wheelset slide on the rail in the longitudinal direction. There are a lot of attempts to maintain more or less radial position of the wheelset [3, 4].

At moving of the wagon wheel-set in the curve its outer and inner wheels will travel the different distances (at pure rolling of the wheels) but due to the fact that at rotation through the given angle the difference between the lengths of the outer and inner rails is different for the curves with different radii of curvature and inclination of the wheel tread surface (1:20) is constant here also the wheel-set axle will deviate from the radial position and will be twisted at the same time(Fig. 1).

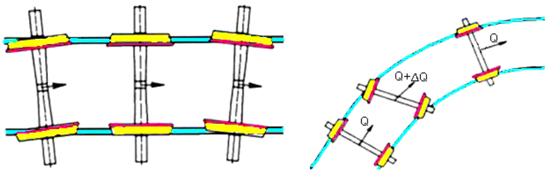


Fig. 1. Movement of the wheel-set in the straight and curve

The intermittent slipping of one of the wheels of the wheelset can cause the torsional vibrations of the wheelset shaft and the longitudinal vibrations of the vehicle (that have been identified as the flange noise [5]) and the respective wear of wheels and rails, like corrugation. The movement of a wheelset in the curve and a corrugated inner rail are shown in Fig. 2 [6].

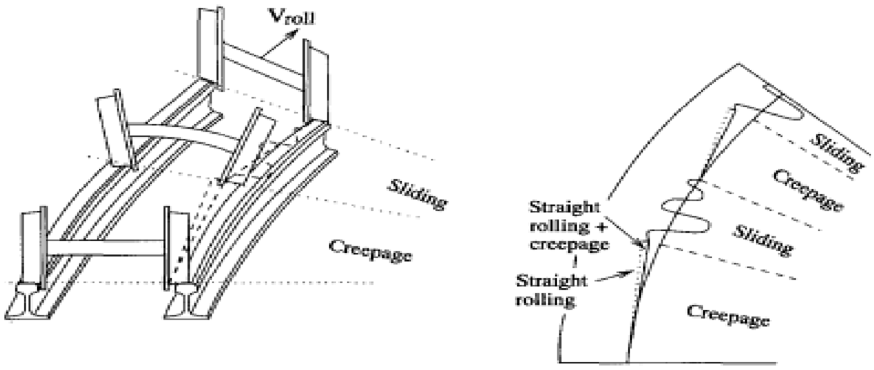


Fig. 2. Movement of a wheelset in the curve and a corrugated inner rail

The similar picture would be at difference of the tread surfaces or at various brake efforts of the wheelset. The wheel-rail contact is a simultaneous rolling and sliding contact, which can be divided into stick (no slip) and slip contacts. The slip zone of the contact of the tread surface is related to the traction force, creep, and geometry of the contact. The slip rate increases at movement in the curves, braking, and acceleration.

In Figure 3 is shown a rail with a trace left on it after the wheel climbing [7].

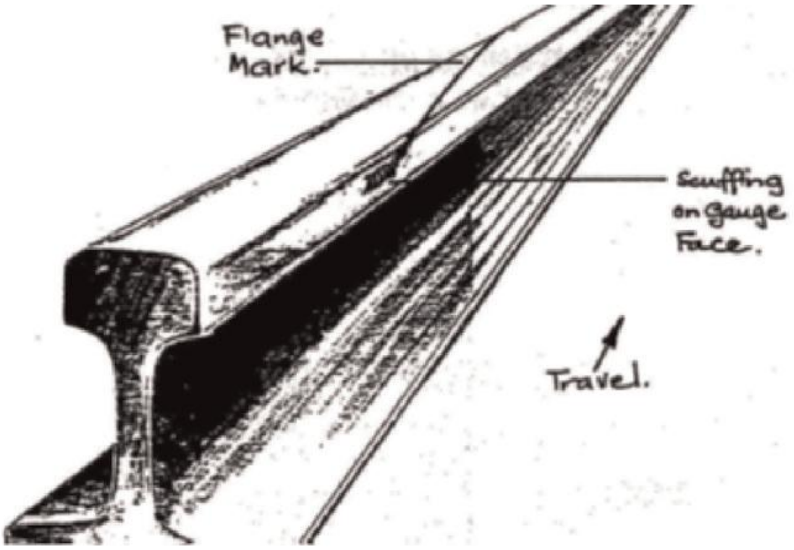


Fig. 3. The trace of the wheel climbing on the rail

The trace starts on the rail lateral surface and then passes on the rail tread surface.The mechanism of generation and development of this trace is not studiedsufficiently yet and needs additional researches [18]. Besides, according to thispaper, friction coefficient in the contact zone of the wheel and rail reaches 0.5 andmore at derailments.

The wheel climbing on the rail is also promoted by decreasing the rail radius ofcurvature and deviation of the axle of symmetry of the wheelset from radial position(increased angle of attack) that causes advancement of the wheel flange andrailhead lateral surface contact point.

As it is known, a vertical axis of symmetry of the rail is inclined by 20° accordingto the standard. Deflection of the rail in the opposite direction that decreases theangle of inclination of the wheel flange is especially dangerous for the wheelclimbing on the rail.

The tread surface of the wheel is conical which passes gradually into the flange surface through its root. Therefore, the difference between diameters of interacting surfaces inside of the contact zone, relative sliding, contact stresses, deformations and temperatures towards of the flange are greater. The sliding distances for the curves and straights and for elliptic wheels are determined and the numerical calculations are given.

3. MOVEMENT OF THE WAGON WHEELSET IN THE CURVE

At pure rolling of the free wheelset (without bogie) in the curved rail track with radius of curvature R of the internal rail, its axle will be inclined from radial position because both wheels

will have passed equal distances l. However, in the wagon wheelset rolling with velocity V, the outer wheel is constraint to maintain the radial position and pass greater distance $l + \Delta l$, rotating relative to the inner wheel in the clockwise direction if it is seen from axial direction A (Fig.4). At that, the wheelset axle is twisted through angle φ equal to the ratio of the difference Δl of the outer and inner arcs to the radius D/2 of the wheel tread surface, supposing that both wheels are rolling on the tread surfaces of equal diameters:

$$\varphi=\Delta l/(D/2) \quad (1)$$

From the drawing $\alpha = l/R=(l+\Delta l)/(R+\Delta R)=\Delta l/\Delta R$,

from where

$$\Delta l = l\Delta R/R, \quad (2)$$

and therefore

$$\varphi = 2l\Delta R/DR, \quad (3)$$

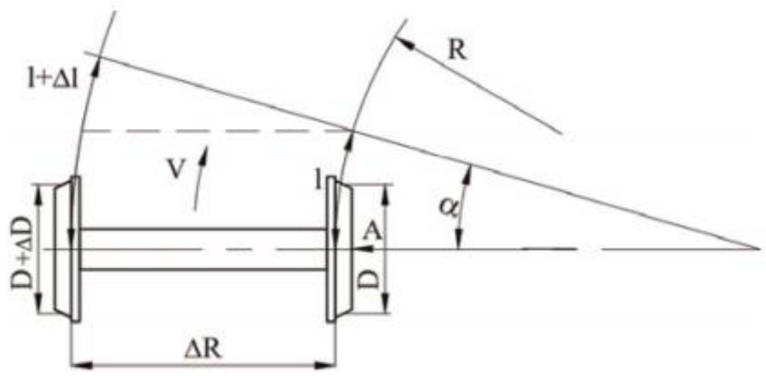


Fig. 4. Movement of wagon wheelset in the curve and wheelset shaft slope from the radial position

On the other hand, the maximum angle of twist of the wheelset axle φ_{max} depends on the friction force

$$F = fQ \quad (4)$$

and is calculated by the known, from the resistance of materials, formula

$$\varphi_{max}= ML/IpG, \quad (5)$$

where M is a torque caused by the friction force

$$M= FD/2 = fQD/2; \quad (6)$$

f - friction coefficient; Q - vertical load (half of the load on the wheelset) of the wheel on the rail; L - length of the wheelset axle; Ip, polar moment of inertia of the wheelset axle cross section; and G - modulus of rigidity (share modulus) of the axle material.

We determine distance between the worn-out segments of the rail or path l (at traveling this path, the wheels are rolling on the rail without sliding), at rolling of which the axle is twisted on the maximum angle φ_{max}, from (3) replacing φ by φ_{max}

$$l = DR\,\varphi_{max}/2\Delta R = MLDR/2IpG\Delta R \qquad (7)$$

and putting the found l into (2) we obtain difference of the paths passed by the outer and inner wheels at which the axle is twisted on the maximum angle φ_{max}

$$\Delta l = MLD/2IpG \qquad (8)$$

3. MOVEMENT OF THE WAGON WHEELSET WITH THE WHEELS OF DIFFERENT DIAMETERS IN THE STRAIGHT RAIL TRACK

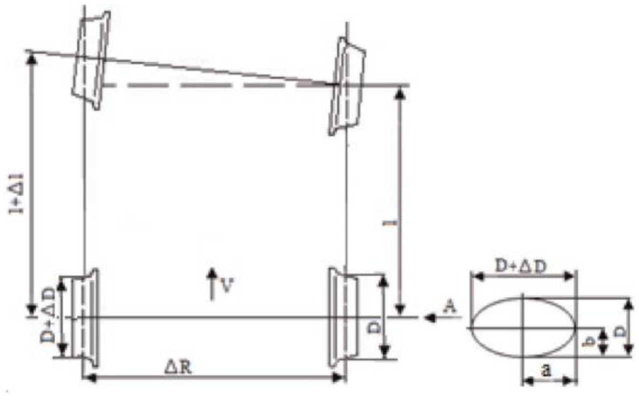
At rolling of the free wheelset (without bogie) with the wheels of different diameters D and D + ΔD in the straight rail track the distance l, the greater wheel passes a greater distance l + Δl, deflecting the wheelset axle from its perpendicular position relative to the rail track (Figure 2a). But in the wagon wheelset the axle being constraint to retain perpendicular position, the smaller wheel is forced to pass the same distance l + Δl and rotate relative to the greater wheel in the clockwise direction, if it is seen from axial direction A. At that, the wheelset axle is twisted through angle φ that is determined by formula (1), from where, considering (5), we obtain the value of Δl (see formula (8)) corresponding to the maximum angle of twist φ_{max}.

The following proportion can be written from the drawing: (l + Δl)/l = (D + ΔD)/D or Δl/l = ΔD/D, from which we obtain distance l between the worn-out segments at passing of which the wheelset axle will be twisted through angle φ_{max}:

$$l = \Delta l D/\Delta D = MLD^2/2IpG\Delta D \qquad (9)$$

5. MOVEMENT OF THE WAGON WHEELSET WITH ONE ELIPTICAL WHEEL IN THE STRAIGHT RAIL TRACK

Consider a free wheelset with one wheel of diameter D and other elliptical wheel with the small D and bigger D + ΔD diameters moving in the straight rail track (Figure 5, a and b).



a　　　　　　　　　　　　b

Fig. 5. Movement of the free wheelset in the straight rail track:
(a) with the wheels of different diameters or with one elliptical wheel; (b) parameters of ellipticity

At one revolution, these wheels will pass the different distances, correspondingly l and l + Δl, deflecting the wheelset axle from its perpendicular position relative to the rail track (Fig.4a). However, in the wagon wheelset the axle being constraint to retain perpendicular position, the

wheel with diameter D is forced to pass the same (greater) distance $l + \Delta l$ and rotate relative to the elliptical wheel in the clockwise direction if it is seen from axial direction A. At that, the wheelset axle is twisted through angle φ that is determined by formula (1).

The difference of distances passed by the wheels at one revolution is $\Delta l = L - \pi D$, where the length of the elliptical tread surface

$$L = \pi[3(a+b) - (3a+b)(a+3b)] \quad (10)$$

or

$$\Delta l = \pi[3(a+b) - (3a+b)(a+3b)] - \pi D . \quad (11)$$

The value Δl^I corresponding to maximum angle of twist $\varphi_{max}$is obtained considering formula (5)

$$\Delta l^I = \varphi_{max} D/2 = MLD/2I_pG . \quad (12)$$

The distance l at passing of which the wheelset axle will be twisted on the angle φ_{max} will be then

$$l = \pi D \Delta l^I /\Delta . \quad (13)$$

In all the three cases considered above, at removing or decrease of the torque M acting on the wheel that takes place at its vertical vibrations when the friction force F decreases, the angle of twist of the axle will start to decrease. Suppose φ_{max} falls down to zero during time t. This will take place at rotation of the inner wheel in the clockwise direction relative to the outer wheel on the angle φ_{max} since the flange of the outer wheel is pressed on the rail and the friction force arisen between the flange and rail additionally restricts its movement. Obviously, during this time t the inner wheel will roll and slide simultaneously on the rail and the rolling and sliding distance on the rail will be

$$Sr = Vt \ . \quad (14)$$

We note that the rolling and sliding distance on the wheel tread surface is

$$Sw = \Delta l + Sr, \quad (14')$$

or for the variant of the elliptical wheel

$$Sw = \Delta l^I + Sr \quad (15)$$

Here Δl or Δl^I is a sliding friction path and the wavelength of the worn-out rail (Fig. 3)

$$W = l + Sr. \quad (16)$$

This value of the wavelength assumes that at release of the inner wheel, the friction force acting on it from the rail is zero. When the friction force differs from zero, the wavelength will be less since its both components will decrease and its value depends on the friction force magnitude.

To determine time t, we present the wheelset as a one-mass torsional vibratory system (Fig.6,a), where C is a torsional rigidity of the wheelset axle and I, total moment of inertia of the inner wheel. Then, angle of twist φ_{max} will fall down to zero in conformity with a law of free vibrations of this vibratory system during the period P/4 (Fig. 6,b).

At that, period of free vibrations

$$P = 2\pi\sqrt{\frac{I}{C}} \tag{17}$$

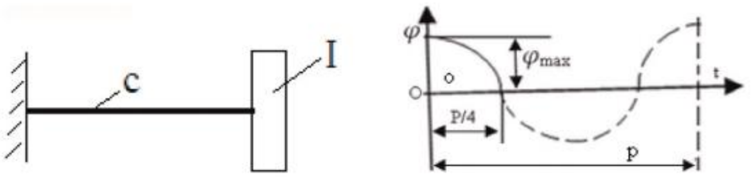
and consequently, time t will be

$$t = P/4 = \pi/2\sqrt{\frac{I}{C}} \tag{18}$$

The average velocity of the wheel contact point relative to the wheel center (Fig. 7)

$$Vw = D\varphi_{max}/\ 2t + Vr\ , \tag{19}$$

Where Vr = - V is a velocity of the rail contact point relative to the wheel center.



a b

Fig. 6. (a) One-mass torsional vibratory system; (b) graph of the system free vibrations

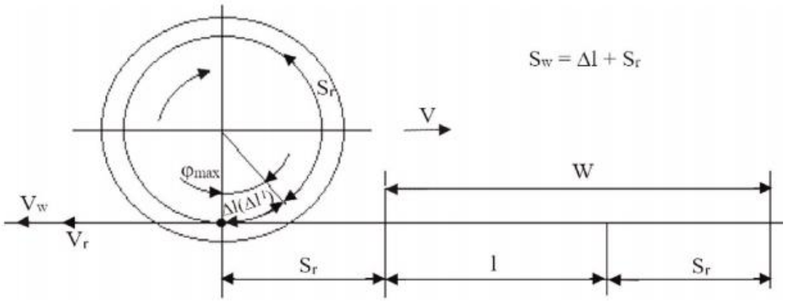


Fig. 7. The rolling and sliding distances on the rail and wheel

We note that maximum velocity of the wheel contact point relative to the wheelcenter.

$$V_w^I = -\frac{A\omega D}{2} + \mathrm{Vr} = -\varphi\max\sqrt{\frac{C}{I}} \times \frac{D}{2} + \mathrm{Vr} \tag{20}$$

where A = φ_{max} is an amplitude of the wheelset shaft torsion vibrations and $\omega = \sqrt{\frac{C}{I}}$ is cyclic frequency of vibrations.

Sliding velocity

$$V_{sl} = V_w - V_r (21)$$

Relative sliding velocities

$$\mathrm{Kr} = \frac{V_{sl}}{V_r} \times 100\% \text{ and } \mathrm{Kw} = \frac{V_{sl}}{V_w} \times 100\% \tag{21}$$

The depth of the worn-out layer a year of the rail segment Sr.

$$h = i\Delta lN, \tag{22}$$

where i is the wear intensity and N, number of cycles which is determined asfollows:

$$N = N_1N_2N_3N_4 \tag{23}$$

where N_1 is a number of the trains passing by a day; N_2, number of wagons inthe train; N_3, number of wheels on one side of the wagon; and N_4, number of daysa year.

6. CONDITIONS OF DERAILMENT

Possibility of derailment or the wheel's rolling up on the rail is estimated by thecriterion of the wheel flange contact point (point A, Figure 8) slipping down therail lateral surface, based on the condition of equilibrium of forces acting on thispoint [8, 9]. Lateral L and vertical V forces determined from the condition of equilibriumof these forces are:

$$L = N\sin\beta - F^{I}\cos\beta \tag{24}$$

$$V = N\cos\beta - F^{I}\sin\beta \tag{25}$$

where N is a normal force; $F^I = f^I N$, friction forcebetween the wheel flange and rail lateral surface; f^I, friction coefficient betweenthese surfaces; and β, angle of inclination of the wheel flange.

It should be noted that the forces acting on point A are interdependent andequalities (24) and (25) are only valid for limited values of forces L and V, since therise of the friction force F^I is limited by the friction coefficient f^I. Therefore, at acertain ratio of forces L and V, the friction force F^I can no longer balance thecontact point A, which will slip down on the rail lateral surface, and it is consideredon this ground that the wheel cannot roll up on the rail. At that, equalities (24) and (25) become inequalities from where a criterion of impossibility of the wheel rollingup on the rail or derailment is obtained [9]:

$$\frac{L}{V} \le \frac{\tan\beta - f^{I}}{1 + f^{I}\tan\beta} \tag{26}$$

However, at sign of equality (=) in (26) and to a certain extent at sign ofinequality (<) also, the wheel can rotate about contact point A and roll up on therail if such possibility exists or if moment of the force P acting on the wheel axleexceeds the moment of the vertical force V about contact point A (Figure 10). Inother words, under such condition, two-point (O, A) contact of the wheel passesinto one-point contact at A. In the first case (at sign =), the wheel will roll on theimmobile point A with pure rolling, and in the second case (at sign <), the wheelwill roll on the mobile point A creeping slowly down the rail lateral surface withcombined rolling and sliding. Both cases lead to the wheel climbing the rail andderailment.

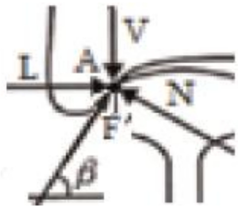


Fig. 8.Forces acting on the contact point A

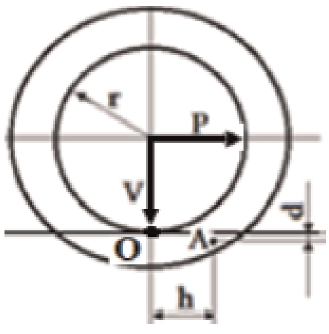


Fig. 9. Forces acting on the wheel axle

Therefore, it is necessary to provide the criterion (26) with additional conditionof impossibility of the wheel rolling on the contact point A, which, on the base of Fig. 9, can be written as

$$Vh \geq P(r + d), \qquad (27)$$

where h is the value of the climbing advance; r is the radius of the wheel rollingcircle; d is the vertical coordinate of the contact point A.

Force P acting on the wheel axle cannot exceed the sum of the friction forcesbetween the wheel and rail tread surfaces and between the wheel flange and raillateral surface:

$$P \leq F + F^{I} = fV + f^{I}N\,, \qquad (28)$$

where f and f^I are friction coefficients between the wheel and rail tread surfacesand the wheel flange and rail lateral surfaces correspondingly.

Determining N and V correspondingly from (24) and (26), substituting theminto (28) and then putting obtained P into (27), from the latter we obtain thefollowing criterion of impossibility of the derailment:

$$\frac{L}{V} \leq \frac{h\left(\sin\beta - f^{I}\cos\beta\right)}{(r+d)\left(f\cos\beta + f f^{I}\sin\beta + f^{I}\right)} \qquad (29)$$

If this criterion is not satisfied, the wheel starts to roll on the contact point Aand the contact between the wheel and rail tread surfaces is lost, or two-pointcontact at O and A passes into one-point contact at A. For obtaining a criterion ofimpossibility of the wheel rolling on the contact point A, it is necessary to put f = 0in (29), which gives.

$$\frac{L}{V} \leq \frac{h\left(\sin\beta - f^{I}\cos\beta\right)}{(r+d)f^{I}} \qquad (30)$$

The criteria (29) and (30) provide both, the wheel flange contact point slidingdown the rail lateral surface and impossibility of the wheel rolling on this point.Besides, the criterion (30) ensures less value (more conservative) of the allowableratio of the lateral and vertical forces L/V than criterion (27), while criterion (31),depending on the value of the climbing advance h, gives the ratio L/V less or morethan criterion (27). For illustration, consider two variants of numerical data of theparameters:

a. $\beta = 60^o$; f = 0.4; f^I =0.1; h = 62 mm and r + d = 485 mm;

b. $\beta = 60^o$; f = 0.4; f^I =0.1; h = 88 mm and r + d = 482 mm.

Allowable maximum ratios L/V for these variants calculated by the criteria (26),(29), and (30) are given in the following table:

Variant	Criterion (27)	Criterion (30)	Criterion (31)
a	1.39	0.31	1.04
b	1.39	0.44	1.47

For analysis of the obtained results, suppose that ratio L/V = 1.3, i.e., criterion (26) is satisfied and derailment is not possible. However, it is seen from the tablethat for variant (a) neither criteria (29), nor (30) are satisfied and both predictderailment. For variant (b), criterion (30) is not satisfied, or it predicts derailment,and criterion (31) is satisfied, i.e., by this criterion, derailment is not possible. Thismeans that the wheel starts to roll on the contact point A and two-point (O,

A)contact passes into one-point contact at A. Then, this contact point slides down therail lateral surface, the two-point contact restores, and so on, this process isrepeated. However, at passing from two-point (O, A) contact into one-point contactat A, the lateral and vertical forces on the steering surfaces increase. Typical forthese surfaces, increased relative sliding increases the power and thermal loads inthe contact of these surfaces, generating the convenient conditions for destructionof the third body. This results in sharp increase of the cohesion forces, scuffing, andfriction coefficient that promotes climbing of the wheel flange on the rail lateralsurface. This is confirmed by the numerous laboratory researches carried out by usas well as the trace of the wheel climbing on the railhead lateral surface (Figure 1)that has a form of scuffing.

Thus, it is expedient to estimate possibility of derailment by criterion (30), sinceit provides both, the wheel flange contact point sliding down the rail lateral surfaceand impossibility of the wheel rolling on the same point, and ensures less value(more conservative) of the allowable ratio of the lateral and vertical forces L/V thancriteria (30) and (26).

7. CONCLUSION

Prediction and avoiding of derailment are the most important problems to whichmany scientific works are devoted but the desirable results are notobtained yet. The survey of the literature and our experience show that the derailmentis especially influenced by the friction coefficient that is not predictable, andin contrast to other parameters, it varies in a wide range.

It is shown that for prediction of the friction coefficient and providing itsstability, it is necessary to provide the contact zone with the continuous and restorablethird body of due properties.The main results of the paper can be formed as follows:

- **A friction factor as well as other tribological properties of interacting surfacesdepends on the properties and degree of destruction of the third body;**
- **The sharp increase of the friction factor in the contact zone of steering surfacesindicates a beginning of the irreversible (progressive) destruction of the thirdbody that contributes to the wheel climbing on the rail;**
- **For avoidance of derailment, decreasing the wear rate and ensuring sufficientdurability of the rails, wheelsets, and brake shoes, a continuous or reversiblethird body must be provided in the contact zone;**
- **Destruction of the third body in the laboratory conditions is proposed todetermine by the flash of the friction moment or criterion of destruction of thethird body.**

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