Deformation processes within wheel-rail adhesion in contact area

A Yu Albagachiev 1, A M Keropyan 2

1 Moscow Technological University, 20 Stromynka St., 107996, Moscow; Mechanical Engineering Research Institute of the Russian Academy of Sciences, 4 M. Kharitonyevskiy Lane, 101990, Moscow, Russia
2 National University of Science and Technology (MISIS), 4 Lenin Av., 119049, Moscow, Russia

E-mail: am_kerop@mail.ru

Abstract. The study of working surface deformation during interaction of open-pit locomotive tires allowed defining outstanding features of phenomena occurring in the contact area of interacting surfaces. It was found that processes typical for plastic saturated contact occur in the area of wheel-rail interaction of industrial railway transport. In case of plastic deformation exposed to heavy loads typical for open-pit locomotives, upon all rough surfaces of the contour contact area being fully deformed, the frame on which they are found is exposed to plastic deformation. Plastic deformation of roughness within the contact area of interacting surfaces leads to the increase in the actual area of their contact and, therefore, increases the towing capacity of mining machines. Finally, the available data on deformation characteristics with regard to processes occurring in the contact area of wheel-rail interaction will allow making theoretical forecasts on the expected design value of friction coefficient and, therefore, the towing capacity of open-pit locomotives.

1. Introduction.

The contact between real rough surfaces is always discrete, i.e. it occurs in separate contact areas, and the actual area of contacting surfaces represents insignificant portion of the nominal contact area. At present, it is a common fact utilized by Russian and foreign experts in calculation of friction and wear. Fig. 1 shows the scheme of two rough surfaces in contact.

Roughness and waviness of contacting surfaces greatly influence the formation of actual contact area. Surface waviness defines areas where microasperities contact with each other. Such areas determine the so-called contour contact area (Fig. 1a) [1]. The value of contour area $A_c$ depends on geometry of contacting bodies and on loads within a contact area.

Besides the contour area, there is also nominal (geometrical) and actual (physical) contact areas [2].

Since contact inside every contour area occurs only in some points consisting of the actual contact area, actual contact area $A_r$ represents the sum of actual small areas of discrete contacts, i.e. point contacts of rough surface asperities resulting from deformations of separate rough zones and lying within a contour contact area.
In case of contact of two rough surfaces, not the highest asperities contact first, and those confronting such asperity on a conjugated surface in a way that the sum of heights of an asperity of the first surface and the opposite asperity of the second surface will be the highest. With the increase in $P$ load, all new pairs of opposing asperities with lesser sum of heights will be in contact (Fig. 1b). Thus the formed contact area will consist of zones located at different heights and at various angles. However, the difference in size of actual contact points from their plane projection parallel to the considered surfaces, is relatively small since angles of these zones do not exceed $3\text{–}10\,^\circ$, and, therefore, the increase in the area due to inclination of zones does not exceed $1.5\%$. Hence, for calculations it is possible to accept that all contact zones are located in one plane [1, pp. 33].

2. Results and discussion.

A contact that most likely occurs under huge loads at wheel-rail interaction of open-pit railway transport has some distinctive features. When the pressure is so high that almost all asperities come into contact this leads to further growth of the area alongside with the increase in load due to the increase in sizes of contact points of some asperities. A necessary condition to ensure interaction of all asperities within a plastic contact is equality of contour and nominal areas, i.e., $A_c = A_n$. However, this condition alone is not sufficient enough since the load has to be so big that the size of approximation exceeds the difference between the maximum and average height of roughness. Since the difference between the maximum and average height of roughness is usually higher for finely finished surfaces, almost all asperities will come in contact only at extremely high pressures. It is easy to satisfy this condition for surfaces treated via turning, chipping or milling with a finish ratio from Rz 20 to Rz 2.5 [2].

Multiple theoretical studies with confirmed experiment results state that the friction force between the interacting surfaces depends on many physical and mechanical properties of contacting surfaces and on their roughness [1, 3, 4].

For convenience of assessing the influence of surface roughness, the literature [1] introduces the concept of complex roughness indicator $\Delta$:

$$\Delta = \frac{h_{\text{max}}}{R b^\nu},$$

where $R$ – estimated curvature radius of roughness peaks determined as the average geometrical value of curvature radiuses of roughness peaks of working surface profile record in longitudinal and transverse directions, $R = \sqrt{r_{\text{long}} \cdot r_{\text{cross}}}$; $h_{\text{max}}$ – height of the biggest roughness; $b$ and $\nu$ – parameters of rough surface supporting curve.

Since the contact of real rough surfaces is discrete, i.e. has a point nature caused by interaction of certain asperities of microroughness, the friction force on each single asperity of contacting profiles according to molecular-mechanical theory of I.V. Kragelsky [3, 4] can be presented in the form of two summands:
\[ F_i = F_{i\text{mol}} + F_{i\text{mech}} \]  

(2)

where \( F_{i\text{mol}} \) – molecular component of the friction force and \( F_{i\text{mech}} \) – mechanical component of the friction force.

According to [1, 5], the position of asperities in the contact area is random and corresponds to the standard distribution law. At the same time, equivalent \( F_\Sigma \) of friction forces in the contact area will be equal to the sum of forces applied on single uneven surfaces:

\[ F_\Sigma = \Sigma F_i = \Sigma F_{i\text{mol}} + \Sigma F_{i\text{mech}} \]  

(3)

Thus, the total friction force depends on the actual interaction area of contacting surfaces [1, 5]. Therefore, the towing force of open-pit locomotives depends on the size of actual area within a contact area of interacting surfaces.

As a result of theoretical and experimental works [1, 3, 6-9, 19, 20], it was found that during contact interaction of rough surfaces, the following types of contact are possible: a) elastic unsaturated, b) elastic saturated, c) plastic saturated.

Depending on indicator \( \Delta \), contour loading \( p_c \) and physical and mechanical properties of contacting materials (\( \mu \) – Poisson’s ratio, \( \mu = 0.3 \); \( E \) – elasticity modulus, \( E = 2.1 \cdot 10^5 \text{ MPa} \)) findings presented in [3] show formulas to determine the nature of deformation in the contact area:

- for elastic nonsaturated contact:
  \[ 0 \leq \frac{p_c (1 - \mu^2)}{E} \leq 6 \cdot 10^{-2} \Delta^{1/2} ; \]  
  (4)

- for elastic saturated contact:
  \[ 6 \cdot 10^{-2} \Delta^{1/2} \leq \frac{p_c (1 - \mu^2)}{E} ; \]  
  (5)

- for plastic saturated contact:
  \[ 0.0625 \leq \frac{p_c}{HB} \leq 0.32 \alpha_t HB , \]  
  (6)

where \( \alpha_t \) – coefficient of hysteresis losses with monoaxial tension (compression).

For tempered steel, \( \alpha_t = 0.02 \) [3, pp. 30].

Contour loading is defined by the formula:

\[ p_c = N/A_c \]  

(7)

where \( N \) – loading on one locomotive wheel, \( N \); \( A_c \) – contour area of wheel-rail interaction. The experimental data [10] show that for load of 135,000 N (at axial load of 270,000 N typical for operating conditions of open-pit locomotives) \( A_c = 390 \text{ mm}^2 \), then \( p_c = 346.2 \text{ N/mm}^2 \).

The calculations made within the study show that for roughness \( R_t \) 6.3 and above, the deformation is elastic nonsaturated, and for unfinished surfaces when the roughness \( R_t \) 20 and below, the interaction demonstrates features typical for plastic saturated contact.

Therefore, the friction coefficients for elastic nonsaturated contact and plastic saturated contact, respectively, are defined by the below formulas [3]:
\[ f_1 = \frac{2.4\tau_0 (1 - \mu^2)^{0.8}}{p_c^{0.2} \Delta^{0.4} E^{0.8}} + \beta + 0.24\alpha \cdot \Delta^{0.2} \left( \frac{1 - \mu^2}{E} \right)^{0.2}; \]
\[ f_2 = \tau_0 / \text{HB} + \beta + 0.9\Delta^{1/2} \left( \frac{p_c}{\text{HB}} \right)^{1/2}, \]

where \( \tau_0 \) – tangential shearing strength of adhesive bond; \( \beta \) – pressure coefficient of molecular component of friction [11, pp. 205] characterizing increase in shearing strength on normal pressure [4, pp. 279]; \( \alpha \cdot \Delta \approx 2.5\alpha \) – coefficient of hysteresis losses of sliding roughness, \( \alpha = 0.02 \) [3, pp. 29-30].

Coefficients \( \tau_0 \) and \( \beta \) are also defined through experiments: for rough steel surfaces – \( \tau_0 = 1.256 \text{ MPa} \) (plastic contact), for clean surfaces – \( \tau_0 = 8.400 \text{ MPa} \) (elastic contact), \( \beta = 0.072 \) [3 (pp. 30 and 61), 13, 14, 15];

\( p_c \) – contour pressure; \( E \) – material elasticity modulus; \( \mu \) – Poisson’s ratio; \( \text{HB} \) – hardness of material.

The analysis of formula (8) allows making a conclusion that for nonsaturated elastic contact at \( p_c \) increases and complex indicator of roughness \( \Delta \), the molecular component of friction coefficient decrease.

It should be noted that the last summand in (8) characterizes mechanical (deformation) component of friction coefficient, which may be neglected for materials with high elasticity modulus, such as metals [16, pp. 30].

From formula (9) it follows that for plastic saturated contact at the increase in contour pressure and complex indicator of roughness, the friction coefficient and consequently the adhesion coefficient, increase.

3. Materials and methods.

Despite the fact that according to various criteria (roughness of contacting surfaces, high loadings in wheel-rail contact area, etc.), the plastic contact has to occur, it is possible to make additional calculations according to other criteria to confirm this hypothesis. According to [2, pp. 200], the elastic contact will occur if the following inequality is applicable for contacting surfaces:

\[ \alpha < K_m \sigma_y \left( 1 - \mu^2 \right) / E, \]

where \( \alpha \) – roughness inclination angle (radius); \( K_m \) – coefficient ranging from 2.5 to 5.0, \( \mu = 0.3 \) – Poisson’s ratio. For hardened steel \( \sigma_y = 1.020 \text{ MN/m}^2 \) (yield point), \( E = 2.1 \cdot 10^3 \text{ MH/m}^2 \) (elasticity modulus of contacting bodies), \( \alpha = 2.3^\circ \) [2, pp. 75].

For ease of comparison, \( \alpha \) is transferred to radians: \( \alpha = 2.3/57.3 = 0.04 \text{ rad} \).

The right part of a formula (4) for two values \( K_m \): 2.5 and 5.0 may be calculated.

Here \( K_m = 2.5 K_m \sigma_y \left( 1 - \mu^2 \right) / E = 0.011 \); where \( K_m = 5.0 \):

\[ K_m \sigma_y \left( 1 - \mu^2 \right) / E = 0.022. \]

The calculations show that at any \( K_m \) value, condition (10) is not fulfilled; therefore, it may be assumed that the plastic saturated contact occurs within wheel-rail interaction.

Typical values of coefficients \( b \) and \( v \) for surfaces with various finishing are given in Table 1 [2, pp. 53].

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1 Tangential strength of adhesive bond is understood as contact shearing stresses caused by molecular interaction in areas of actual contact [12, pp. 53].
Thus, considering the abovementioned wheel-rail interaction, the plastic contact shall be chosen provided it occurs along the contour area. In case of plastic deformation under the influence of enormous loads, after all rough surfaces of such contour area were considerably deformed, there is plastic deformation of foundation on which they are located. Therefore, it is possible to indicate the growth of contour area due to plastic deformation of underlying layers [1, 8, 9].

Experiments performed in real operating conditions resulted in graphic dependence of locomotive adhesion coefficient $\Psi$ at motion start on friction coefficient $f$ measured along the central part of wheel-rail interaction (Fig. 2) [17].

![Figure 2](image)

**Figure 2.** Dependence of adhesion coefficient of locomotive wheel pairs with the motion start and friction coefficient $f$ measured along the central part of wheel-rail interaction: 1 – VL8; 2 – VL23; 3 – VL60; 4 – VL60k; 5 – according to Collins and Prichard; 6 – direct proportionality between $f$ and $\Psi$

It should be noted that the experiments were conducted without sand supply, and friction properties of a railway for each speed interval changed in a wide interval alongside with changes of the friction coefficient [18].

The analysis of dependences obtained through experiments presented in Fig. 2 shows that curves $\Psi(f)$ for various locomotives are similar in form and change according to the Weber function. Analytical expression of the regression equation, shown in Fig. 2, is as follows [17].

$$\Psi = af^2 + bf + c,$$

(12)

where $a$, $b$, $c$ – regression coefficients different for various series of electric locomotives.

For various series of electric locomotives the values of friction coefficients $f$ thus calculated lie within 0.2-0.5 [17]. Equation (12) represents a parabola, the top of which defines value $\Psi_{\text{max}}$ corresponding to certain value $f$, which can be found through its differentiation and equalization of derivative to zero.
For studied locomotives the maximum calculated values of friction coefficients are given in Table 2.

Table 2. Maximum values of friction coefficients of electric locomotives

| Value                        | \( f_{ext} \) | \( f_{1\text{max}(VL8)} \) | \( f_{2\text{max}(VL60)} \) | \( f_{3\text{max}(VL60^{19})} \) | \( f_{4\text{max}(VL23)} \) |
|------------------------------|---------------|-----------------------------|-----------------------------|---------------------------------|-----------------------------|
| Friction coefficient        | 0.535         | 0.486                       | 0.507                       | 0.452                           | 0.437                       |
| Increase ratio              | -             | 9.16                        | 5.23                        | 15.51                           | 18.3                        |
| Average increase \( f \), % | 11.96         | -                           | -                           | -                               | -                           |

The analysis of maximum values of friction coefficients showed that when profiling rails with the roughness of \( R_z \), 20 \( \mu m \), the friction coefficient may increase by 12\% and, therefore, the wheel-rail adhesion coefficient may also increase.

4. Conclusions.

1. In the course of study, it was found that in the area of wheel-rail interaction of industrial railway transport there are processes typical for plastic saturated contact.

2. In case of plastic deformation under the influence of enormous loads, after all rough surfaces of such contour area were considerably deformed; there is plastic deformation of foundation on which they are located.

3. Plastic deformation of rough surfaces within a contact area of interacting surfaces leads to the increase in the actual area of their contact and, therefore, to the increase in adhesion coefficient of wheel-rail interaction and towing force of open-pit locomotives.

4. The study showed that when profiling rails (for instance, by rail grinding) thus ensuring roughness of \( R_z \), 20 \( \mu m \), the friction coefficient may be increased by 12\% and, therefore, the wheel-rail adhesion coefficient, as well as the locomotive towing force may also increase.

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