Computer model of contact of rough surfaces of friction material in the friction nodes of lifting and transport machines

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Abstract. In this paper, there is proposed computer model of the contact of friction materials in the brake devices of building road machines and lifting transport machines. The contact surface is modelled by a microrelief composed of a set of elements in the form of rods. As a result of modelling, there are such contact characteristics as rapprochement, distribution of contact pressure, real contact area and the gap between the surfaces. The obtained dependencies are compared with the finite element method (FEM).

1. Introduction
When developing friction units of hoisting-transport machines and selecting friction materials for them, physical modeling of working conditions of materials on laboratory stands or friction machines is widely used. The main problem of physical modeling is the substantiation of the identity of the loading of friction materials in laboratory tests and natural conditions. This rationale is based on the correspondence of the external parameters of the friction process, most often such as: sliding speed, pressure on the nominal contact surface. In this case, the pressures on the real contact area in full-scale and on model specimens can significantly differ, with the same external parameters. Under other equal conditions, the more the sizes of the friction surfaces differ, the greater likelihood of a mismatch between the results of the friction process on small samples and the results of friction materials in full-scale friction nodes there is. It presents that the comparison of laboratory and field tests can be more adequate if when modeling the pressure distribution over the real contact areas is compared, rather than the average pressure over the nominal areas of the friction surface. This is possible, if deformations of microroughness under load are known.

Contact interaction of surfaces is the subject of contact mechanics [1-3]. When calculating the parameters of contact interaction, different surface models are used such as analytical, numerical. Examples of analytical models are the model of N B Demkin [1] and the model of J Greenwood and J Williamson. In this model, the surface roughness is modeled by hemispheres with the same radii of curvature. The distribution of irregularities in height relative to the plane of contact follows the Gaussian distribution function. Numerical models [4] in comparison with analytical ones allow taking into account additional factors and clarifying the description of contact interaction processes. This refinement is related to the distribution of sizes and shapes of individual irregularities of the contacting surfaces, the mechanism of deformation of the material of the surface layer, etc. Analyzing the existing models, it should be noted that they are difficult to apply for engineering calculations, since
either they do not provide the necessary accuracy of the contact area calculations, or they have a complex mathematical apparatus.

This article discusses computer models based on technical surfaces in C++ that differ from the ideal geometric shape in the form of roughness. The model is intended, first of all, to calculate the load on the contact, which is to calculate such mechanical characteristics of the contact as the magnitude of the contact deformation, the real contact area, the pressure distribution on the contact surface.

2. Model description

The model of the microsurface of the contact is represented by a set of elements in the form of rods located next to each other. The nature of the deformation of the protrusion changes during loading, the protrusions are first deformed elastically, then elastoplastically and, finally, plastically. The real contact points are crushing areas of individual protrusions. When deriving the calculated ratios, the following preliminary assumptions are made.

The rough surface model element is located on a rigid base. If a system of concentrated forces with a step \( s \) is applied to the surface of the body, then according to the Saint-Venant’s principal at a distance from the surface, commensurate with the value of \( s \), the stress distribution is the same as if a load distribution acted uniformly on the surface. Consequently, the dimensions of the layer with an inhomogeneous strain distribution are of the same order as \( s \). It could be considered that a concentrated force acts on each contact spot, then the dimensions of this layer can be estimated as about 100 μm, which is more than an order of magnitude higher than the roughness height. The stress in it is much lower than those that arise on the irregularities themselves, amounting to approximately 1/100 - 1/1000 part of them. Thus, the displacement due to deformation of the underlying material layer is less than the contact displacements 10 \(-10^2\) times than can be neglected in this calculation [4].

It is considered that close contacts do not affect each other. In practice, when using friction polymer materials, the pressure does not exceed ten kilograms per cm\(^2\), and even more rarely, by several tens of kilograms per cm\(^2\). In most drum and belt brakes, in which brake linings are made of friction polymer materials on a rubber, rubber resin and resin binder, pressures not exceeding 1 MPa [5] are used. Note, that at such pressures the density of contact spots is low. Thus, this assumption does not introduce significant errors in the calculations.

The contact characteristics are determined only by the shape of the gap between interacting bodies, instead of the contact of two rough surfaces, the contact of a rigid flat smooth surface with an elastic body having an equivalent roughness corresponding to the gap between unreformed surfaces can be considered which greatly simplifies the task. Thus, the general case of the process of interaction of solids with smooth and equivalent rough surfaces can also be taken into account. Many works have shown that the theoretical considerations underlying this approach are generally valid [6]. One of the main results of the calculations of G. Greenwood and J. Williamson is the conclusion, which is confirmed by experiment, that for many types of rough surfaces the average radius of the contact spot (excluding surface temperature) remains constant with increasing load, while the number of contact spots and the area of actual contact increases in proportion to the load [7]. We suggest using the contact model in the form of separate rods with a constant cross-section, mainly to assess the load on the contact, therefore, the assumptions made are justified.

In the general case, the maximum contact pressure \( q \), at which plastic deformation begins, can be represented by the expression [1]:

\[
q = C\sigma_y
\]  

(1)

where \( C \) - the coefficient, depending on the shape of the surface; \( \sigma_y \) - the yield strength of the material.

According to [2], it has a value in the range from 1.075 to 3. In the N B Demkin’s works, the value of \( C \) is close to 3. When calculating the actual pressure, we can take equal microhardness \( q = H \) is used, where H is the maximum Meyer’s hardness [8].

To create the model, the following tasks need to be done: determination of static characteristics describing microtopography of the surface; determination of the dependence of relative deformation on pressure; finding the deformation of the totality of irregularities.
2.1. Microsurface model

When generating a microsurface, the input parameters are the standard characteristics of microtopography of the contacting surfaces by GOST 2789 – 73.

The entire surface is divided into separate areas with a base length l. In numerical simulations, this separate area is approximated by an n x n matrix of bar elements having the same rectangular section, but different heights.

When generating a microsurface, the heights of the rods at the base length are satisfied with the following conditions:

Condition 1: The value is accepted in the range from 0 to R_{max};
Condition 2: The arithmetic mean of the differences in the heights of the rods and (R_{max}-R_p) in each row of the matrix must be equal to R_a;
Condition 3: The average value of the pitch of the profile irregularities within the base length is S_m;
Condition 4: The relative value of the sum of the lengths of elements whose height is greater than or equal to (R_{max} - R_p) to the base length l is t_1;
Condition 5: The relative value of the sum of the lengths of elements whose height is greater than or equal to 0.8R_{max} to the base length l is equal to t_{20}.

A microtopography model of a surface that satisfies all these conditions reproduces the real surface well, but the formation of the model takes a lot of time. Therefore, to save time, you can apply one of the following sets of conditions:

K1: Condition 1, Condition 2, Condition 4, Condition 5;
K2: Condition 1, Condition 2, Condition 3;
K3: Condition 1, Condition 2, Condition 4.

2.2. Model contact

It is assumed that one of the materials of the contact pair has significantly lower mechanical characteristics compared to the other. This means that only softer material is deformed. This corresponds to friction brakes and couplings in which steel or cast iron and friction plastics contact.

Features of the model:

- it is assumed that during loading the friction material is deformed first elastically, then elastoplasticity, and when the pressure in the contact reaches the maximum Brinell hardness - plastically;
- it is assumed that the contact area is determined by the mechanical characteristics of the friction material (softer);
- the mechanical characteristics of the material at different temperatures should be experimentally determined in advance;
- the contact of rough surfaces is discrete.

The main mechanical characteristics for use in the model are obtained from the experiments of the considered materials for compression by GOST 4651-2014 (ISO 604: 2002). According to the test results, the dependence function σ = f(ε) is created using the cubic spline. The program is implemented in C ++ [9]. In the model, the contact pressure at which plastic deformation begins, is equal to HB. It denotes the relative deformation in this case ε_k.

The computer model of the contact of rough surfaces works according to the following algorithm. For a given common normal load on a friction pair, the relative deformations of each protrusion are determined by the characteristics of the surface microgeometry. If the found value is less than ε_k, then the contact stress is found by the function σ = f(ε); if it is greater than or equal to ε_k, then the contact stress is equal to the hardness HB. For each protrusion, depending on its area and contact pressure, a load is determined. The sum of loads of all the protrusions should be equal to the specified load.

3. Result and discussion

Giving an example of modelling a rough surface by preliminary grinding, the roughness parameters according to the results in the book [1] are presented in table 1.
Table 1. Parameters of surface microgeometry.

|        | $R_{\text{max}}$ | $R_{a}$ | $R_{p}$ | $S_{m}$ | $l$ | $t_{20}$ | $t_{m}$ |
|--------|------------------|---------|---------|---------|-----|----------|----------|
| (μm)   | (μm)             | (μm)    | (μm)    | (μm)    | (mm)|          |          |
| 10     | 2.5              | 5       | 160     | 0.8     | 0.1 | 0.5      |          |

Figure 2 shows the curves of the supporting surfaces according to the formula presented by professors N B Demkin, I V Kragelkim and according to the sets of conditions K1, K2, K3. The curve calculated in our program according to the set of conditions K2 best fits the curve calculated by the formula recommended in [1].

As examples of the contact model, the contact model of the rough surface of the friction material 2339.62 with hardness HB = 23 MPa (the brakes of trucks) with a smooth steel surface is simulated. The stress diagram of material from a compression experiment at 20°C on machine QUASAR 50 is shown in figure 3. On table 2, the stress distribution over the actual contact areas at various nominal pressures is presented: 0.1; 0.5; 2.0; 3.0 MPa.

Figure 4 presents the simulation results, namely: the influence of the nominal pressure $q_{a}$ on the ratio of the real area to the nominal $A_{r}/A_{n}$; ratio of rapprochement to maximum roughness height $p/R_{\text{max}}$; real maximum pressure $q_{r}$ and gap between the surfaces.
Figure 3. The stress diagram of material.

Figure 4 confirms that in the range of generally accepted values of nominal pressures for this material, the real contact area is hundredths and tenths of the nominal area, which corresponds to the results given in many works. From the moment when the nominal pressure reaches 2.4 MPa, the maximum pressure on the real contact area changes little and corresponds to the hardness of the material. This can be explained by the fact that from this moment many individual contact spots are already in a state of plastic deformation and although gradually new protrusions come into contact, the actual maximum pressure changes little. In this case, only the area of the protrusions with maximum pressure on the contact increases. As the nominal pressure increases, the rapprochement increases and the gap volume decreases.

To verify the reliability of the developed simulation model, the stress-strain state of the contact was modeled by the finite element method. Modeling was performed using the APDL program (ANSYS). In figure 5 the dependences of the ratio \( p/R_{\text{max}} \) on the nominal pressure are presented, where \( p \) is the rapprochement. The solid line shows the FEM calculation result; round dots - the result of modeling under the condition that the transition from elasticity to plastic deformation is the hardness HB of the watched material; triangular points - the result of the simulation under the condition of transition from elastic to plastic deformation at stress equal to \( 2\sigma_y \); line with rhombuses - the result of the simulation under the condition of transition at stress equal to \( 3\sigma_y \). From figure 4 it shows that the simulation result using HB as a criterion for the transition from elastic to plastic deformation gives results close to the results of FEM calculations.
Figure 4. Effect of nominal pressure \( q_a \) on contact characteristics.

Figure 5. Comparison of simulation results with the finite element method.
4. Conclusions
Using standard characteristics of surface roughness allows to create computer models for calculating the distribution of pressure on the contact. The proposed model of the formation of the contact area allows to take into account the features of surface microgeometry and reflects the approximation of rough surfaces and the nature of the pressure distribution over microroughnesses. Such model of contact of friction material can be used to evaluate loads at actual contact areas, when collating the results of laboratory and full-scale tests of friction devices. This model of contact interaction has featured in comparison with the traditional approach. This is, firstly, the rejection of the assumption that the radii of curvature of the peaks of the bumps are the same and, secondly, the rejection of the need to know the law on the distribution of the vertices of the protrusions. In the future, the model is supposed to be used to calculate temperatures that occur during dry friction in the zone of real contact.

Notation
- \( R_p \) maximum height of the protrusion of the rough surface
- \( R_{\text{max}} \) full profile height
- \( R_a \) the arithmetic mean deviation of the rough surface profile
- \( t_m \) the relative reference length of the profile along the midline
- \( t_p \) the relative reference length of the profile, where \( p \) is the value of the profile section level, often equal to 20% of the total profile height (\( t_{20} \))
- \( l \) the base length
- \( S_m \) the average pitch of irregularities
- \( q_n \) nominal pressure
- \( q_r \) real pressure
- \( A_n \) nominal contact area
- \( A_r \) real contact area
- \( \eta \) relative area
- \( \varepsilon \) relative deformation
- \( \sigma \) contact stress
- \( p \) rapprochement
- \( V \) the gap between the surfaces
- \( \sigma_y \) yield strength

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