

ORIGINAL STUDY

CALCULATION AND EXPERIMENTAL STUDY OF THE REAL CONTACT AREA, CONTACT PRESSURE, AND COEFFICIENT OF FRICTION

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Abstract. The study investigates the formation of the real area of contact and the corresponding contact pressure during the tribological interaction of rough surfaces. Particular attention is given to the distinction between the nominal area, contour area, and real area of direct contact, taking into account the waviness and roughness of the surface profile. A calculation approach based on the geometric and statistical characteristics of the surface microrelief is used to estimate the transition from the nominal contact area to the actual areas involved in load transfer. The contact pressure in the zones of direct interaction is evaluated considering the deformation of surface asperities and their mechanical characteristics. The calculated parameters of the real contact are compared with the experimental characteristics obtained during tribological testing. The analysis demonstrates the importance of considering the actual contact conditions when interpreting tribological test results and evaluating the stress state of contacting surfaces. The proposed approach provides a basis for a more physically justified assessment of contact interaction and the subsequent analysis of friction and wear processes.

Keywords: real contact area; nominal contact area; contact pressure; surface roughness; waviness; asperities; friction; wear; tribological interaction.

1. Introduction

Friction and wear are among the key factors determining the reliability, durability, and serviceability of machine and mechanism components. During the relative motion of contacting surfaces, a complex set of interrelated physicomachanical processes occurs within the contact zone, including elastic and plastic deformation of asperities, destruction of surface layers, changes in surface microgeometry, and formation of wear debris. The combination of these processes generates a complex stress-strain state in the contact zone and directly determines the nature of frictional interaction [1]. Therefore, establishing the regularities governing real contact formation is of considerable importance for evaluating the tribological characteristics of materials.

Classical tribometric test configurations, such as ball-on-disk and pin-on-disk, are widely used for the experimental investigation of friction and wear processes. These configurations make it possible to determine the coefficient of friction, wear volume, and wear intensity under different conditions of relative motion and loading. However, the tribological characteristics recorded during testing are the result of processes occurring directly within the real contact zones, whose geometry and state differ substantially from the parameters determined by the initial nominal geometry of the mating surfaces.

The theoretical description of contact interaction is traditionally based on the classical Hertz theory, which allows the main characteristics of contact between elastic bodies to be determined as a function of their geometry, mechanical properties, and applied load. At the same time, the application of idealized contact models to real tribological systems requires consideration of the characteristics of the surface layer. D. H.

Received 22 September 2026; revised 25 September 2026; accepted 27 September 2026.
Published online 30 September 2026

DOI: <https://doi.org/10.66310/WDZS9519>

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Buckley emphasized the significant role of surface microgeometry, surface films, and adhesive interactions in the formation of real contact. This indicates the need to consider the contact surface as a multilevel system in which the geometrical parameters of the mating surfaces are complemented by the characteristics of their surface microrelief [1].

Real machine-component surfaces are characterized by a combination of irregularities of different scales, heights, shapes, and spatial distributions. Therefore, the interaction between mating surfaces does not occur over the entire nominal area but through a set of localized contact regions formed by the most prominent elements of the surface microrelief. This approach is particularly important when investigating the surfaces of hardened components. The formation of a hardened surface layer is accompanied by changes not only in hardness and mechanical properties but also in the microgeometry of the material. Surface roughness and waviness parameters determine the distribution of material along the profile height and, consequently, the conditions under which individual asperities are successively brought into contact. Under applied loading, asperities may undergo elastic, elastic–plastic, or plastic deformation, resulting in changes in the real contact area together with variations in pressure within the local interaction zones.

Consequently, the use of only nominal pressure, determined as the ratio of the applied load to the geometrical contact area, does not provide a complete characterization of the stress state of the real contact. A more informative approach is the sequential consideration of the nominal, contour, and real contact areas, which makes it possible to evaluate changes in contact pressure during the transition from the macroscopic geometrical level to the level of direct interaction between asperities [2]. In this context, the real contact pressure can be considered one of the key parameters linking surface microgeometry with the mechanics of contact interaction.

Changes in the real contact area and corresponding contact pressure are directly reflected in the nature of frictional interaction. During actual sliding, individual microcontacts continuously form, deform, and break down, accompanied by load redistribution and changes in the interaction conditions of the surface layers. This, in turn, determines the development of tangential force and the coefficient of friction and, during prolonged interaction, the nature and intensity of wear.

Thus, a more complete description of the tribological behavior of contacting surfaces requires consideration not only of their nominal geometry and average roughness parameters but also of the regularities governing the formation of the real contact area and real contact pressure, taking into account the surface microgeometry [3]. Such an approach makes it possible to relate the geometrical characteristics of real contact to its stress–strain state and subsequent friction and wear processes.

The aim of this study is to establish the regularities governing the formation of the real contact area and real contact pressure during the tribological interaction of rough surfaces, taking into account their microgeometry, and to investigate the relationship of these characteristics with the contact stress state, coefficient of friction.

2. Materials and methods

Surface roughness and waviness were measured before and after TEPT using a Surtronic S-100 [S-116 / S-128] portable contact profilometer (Taylor Hobson, AMETEK, UK). The instrument was equipped with a skidded inductive pickup and a diamond stylus with a tip radius of 5 μm and a stylus force of 150–300 mg. Measurements were performed at a traverse speed of 1 mm/s using a Gaussian filter, with a cut-off length of 0.8 mm and an evaluation length of 4.0 mm, in accordance with ISO 4287 and ISO 4288. The arithmetic mean roughness, R_a , and maximum profile height, R_z , were determined.

Tribological tests were conducted using a TRB3 tribometer (Anton Paar, Austria) according to the pin-on-disk configuration specified in ASTM G99 [4]. During relative sliding of the disk against the pin, a tangential friction force F_t was generated in the direction opposite to the relative motion of the contacting surfaces. The pin was mounted on a precision elastic lever connected to a force sensor. Under the action of the tangential friction force, the lever underwent a small elastic deflection, which was detected by the sensor and converted into the corresponding friction force F_t .

The coefficient of friction was determined from the measured tangential force and the applied normal load F_n according to:

$$\mu = \frac{F_n}{F_t}, \quad (1)$$

where F_t is the tangential friction force and F is the applied normal load.

The pin was made of cylindrical 12X18H10T stainless steel with a diameter of 8 mm, while 40X steel was used as the disk material. The chemical compositions of the investigated steels are presented below. A normal load of 5 N was applied to the contacting surfaces. The disk rotation corresponded to a sliding speed of 3 cm/s, and the total sliding distance was 60 m (Fig. 1).

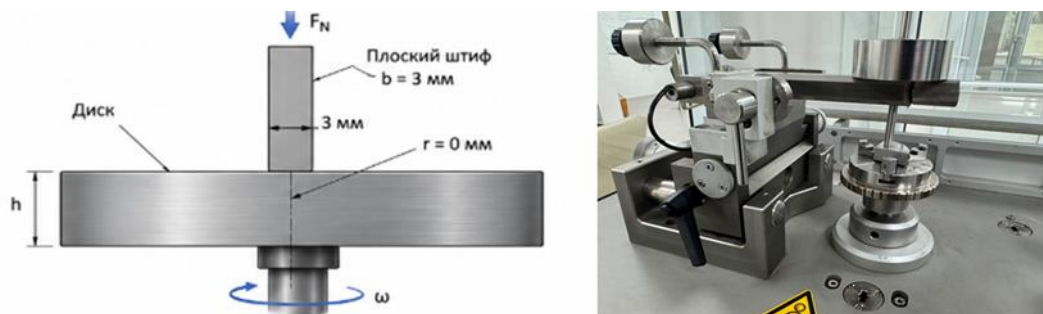


Fig. 1. Schematic representation of the pin-on-disk friction model.

Tensile tests were performed using a Shimadzu AGS-X universal testing machine at room temperature in accordance with ISO 6892-1. The specimens were subjected to uniaxial tensile loading until fracture, with continuous recording of the applied load and deformation. The yield strength and ultimate tensile strength (σ) were determined from the obtained stress–strain data to characterize the mechanical properties of the investigated materials. The ultimate tensile strength was determined from the maximum tensile load recorded during the test.

Table 1 presents the initial experimental data characterizing the properties of the investigated materials after testing.

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Parameter	Value
Arithmetic mean deviation, R_a	0.06578 μm
Profile peak height, R_p	0.2219 μm
Maximum profile height, R_{max}	1.082 μm
Total cutoff length, $\sum \Delta l$	0.25 mm
Sampling length, l	0.8 mm
Hardness of 40X steel, HB	270 kgf/mm ²
Elastic modulus of 40X steel, E	2×10^6 kgf/cm ²
Poisson's ratio of 40X steel, μ	0.30
Mean normal stress, σ_0	1400 kgf/cm ²
Frictional interaction parameter, β_f	0.004
Yield strength, σ_T	780 kgf/cm ²
Parameter of the unit process, t	2
Fracture strain, ε_0	0.16
Waviness height, W_f	4 μm
Waviness radius, R_w	50 mm
Waviness exponent, ν_w	2
Relative elongation, δ	$\approx 40\%$
Hardness of 12X18H10T steel, HB	$\approx 170\text{--}179$ HB
Temperature	20–25 $^{\circ}\text{C}$

2.1 Method for Determining the Contour Contact Pressure

In technical literature, four main types of deviations from the nominal surface geometry are traditionally distinguished: macrodeviations, waviness, roughness, and sub-roughness. Figure 2 shows the surface waviness profile and its main geometric parameters, including the maximum profile height R_{max} , maximum waviness height W_{max} , waviness peak height W_p and waviness spacing S_w .

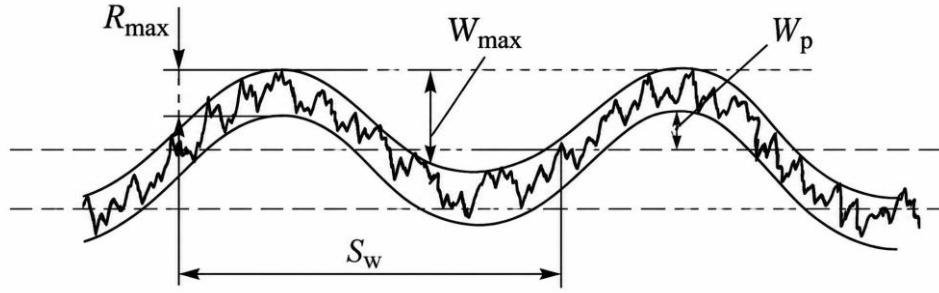


Fig. 2. Surface waviness profile and its main geometric parameters.

During contact interaction between the specimen and the counterbody, the real contact area differs substantially from the nominal contact area (Fig. 3) [5].

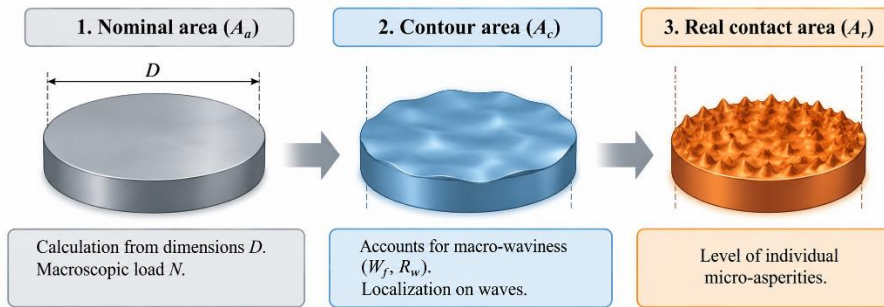


Fig. 3. Surface microrelief parameters and the regularities governing contact area formation.

A single parameter, R_a , representing the arithmetic mean deviation of the surface profile, is insufficient for a comprehensive description of the real contact surface. Surfaces characterized by identical R_a values may differ substantially in their microrelief characteristics and load-bearing capacity. This difference is primarily associated with the distribution of material along the height of surface irregularities, as well as with the shape and density of asperities, which directly determine the conditions under which real microcontacts are formed.

Therefore, a more comprehensive description of the contact properties of a surface requires consideration not only of the average height of surface irregularities but also of the distribution of material along the height of the surface microrelief [6]. One approach to such a description is the use of the bearing area curve (Abbott–Firestone curve), which relates the degree of approach of the mating surfaces to the change in the area of material brought into contact.

In the initial stage of contact, the variation of the bearing area curve parameters with the profile section depth can be approximated by a power-law function:

$$t_p = b\varepsilon^\nu, \quad (2)$$

$\varepsilon = a/R_{\max}$ is the relative approach of the contacting surfaces.

The exponent ν in this relationship characterizes the manner and rate at which the material area changes with increasing depth into the surface microrelief. Within the considered calculation approach, its value is determined from the parameters obtained from the surface profilogram:

$$\nu = 2t_p \frac{R_p}{R_a} - 1 \quad (3)$$

$$b = t_p \left(\frac{R_{\{\max\}}}{R_p} \right)^\nu \quad (4)$$

The surface characteristics used as input parameters are R_p , R_a , and $R_{\max}$. From a physical standpoint, the exponent ν reflects the geometric characteristics and distribution of surface asperity peaks. Variations in ν characterize differences in the rate at which the real contact area develops as the mating surfaces approach each other. Therefore, the combined consideration of R_a and R_a provides a more comprehensive

characterization of the surface microgeometry and its contact behavior than the use of either parameter individually [7].

For an integrated description of the height and geometric characteristics of the surface microrelief, a dimensionless parameter Δ is introduced, combining the corresponding surface parameters:

$$\Delta = \frac{R_{\{max\}}}{r_{eq} b^{\frac{1}{\nu}}} \quad (5)$$

Consequently, a decrease in Δ corresponds to a reduction in the concentration of local geometric interaction. The nominal contact pressure is determined using the classical equation:

$$p_a = N/Aa, \quad (6)$$

where N is the normal load and Aa is the nominal contact area.

After converting the applied load to the required system of units, the nominal contact pressure is determined as the ratio of the applied load to the nominal contact area. However, this quantity represents an averaged characteristic of the contact and does not reflect the actual pressure arising directly within the zones of asperity-to-asperity interaction.

The next level of contact is represented by the contour contact area A_c , whose formation is governed by the deformation of macro-irregularities and surface waviness under the applied load. For its calculation, the N. B. Demkin approach is employed [8].

$$A_c = A_a k_w k_v \left[\frac{2R_w}{HB} * \theta p_a \right]^{\nu_w/\nu_w+1.95} \quad (7)$$

where k_v and k_w are tabulated coefficients; R_w is the radius of waviness, ν_w is the waviness exponent, p_a is the nominal contact pressure, HB is the material hardness, and E_r is the reduced elastic modulus of the contact pair.

The contour contact pressure is then calculated as follows:

$$p_c = N/A_c, \quad (8)$$

Thus, the transition from nominal contact pressure to contour contact pressure reflects the redistribution of the applied load over a reduced contact area. At this stage, an increase in the average pressure acting on the surface becomes evident as a consequence of the reduction in the effective contact area (Fig. 4).

The mean real contact pressure in the zones of direct interaction between elastically deformed asperities is determined by the following expression [8]:

$$p_r = 0.4 \cdot E_r \cdot \Delta^{(2\nu+1)} \frac{W_t^{0.1}}{R_w} \quad (9)$$

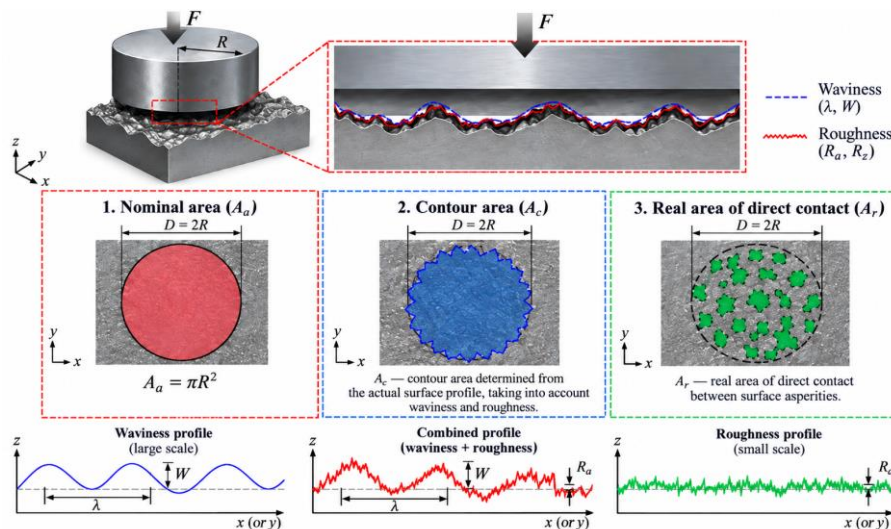


Fig. 4. Schematic representation of nominal, contour, and real contact areas of a rough surface.

3. Results and discussion

For the investigated surface condition, the calculated values were $p_c = 2.02 \cdot 10^7$ kgf/cm² for the contour contact pressure and $p_r = 1.18 \cdot 10^5$ kgf/cm² for the real contact pressure. Comparison of the obtained value of p_r with the material hardness, $HB = 270$ kgf/mm², indicates that the contact interaction within the adopted calculation model is predominantly plastic [9].

This result is of particular importance for the subsequent evaluation of the coefficient of friction, since under predominantly plastic contact conditions the resistance to relative motion is determined by the combined contribution of the adhesive component arising in the zones of real contact and the deformation component associated with the penetration and displacement of asperities on the mating surfaces. Based on the established nature of the contact interaction, the coefficient of friction is subsequently determined using the following relationship [5]:

$$f = \left(\frac{\tau_0}{H_B} \right) + \beta_f + 0,52 \sqrt{\Delta \left(\frac{p_c}{H_B} \right)^{\frac{1}{4}}} \quad (10)$$

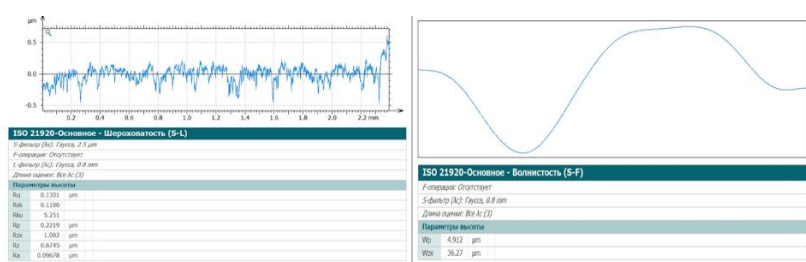


Fig. 5. Roughness and waviness profiles of the investigated surface obtained by profilometric analysis.

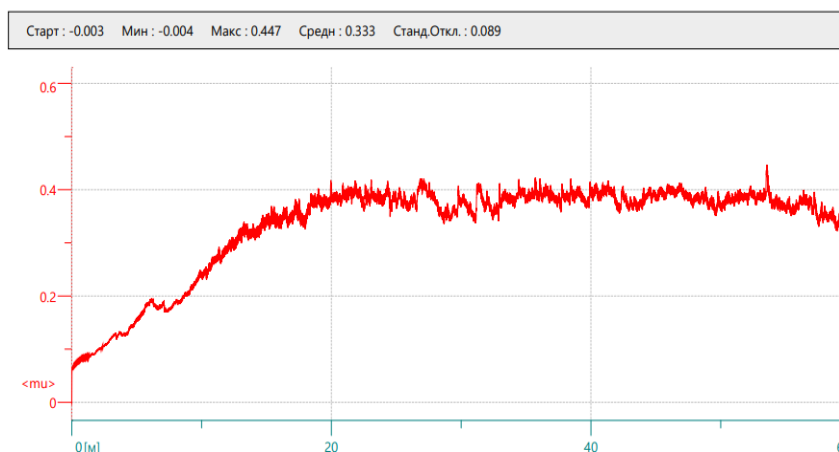


Fig. 6. Variation of the coefficient of friction as a function of sliding distance.

For 40X steel, the calculated coefficient of friction was 0.3527, whereas the experimental value obtained using the TRB3 tribometer was 0.3330. The close agreement between these values indicates that the proposed calculation procedure accounts for the main factors governing the frictional interaction of the investigated surface (Fig. 5-6). At the same time, the calculated value is slightly higher than the experimental one, which can be attributed to the difference between the idealized representation of individual microcontacts in the calculation model and the actual friction process [10].

The discrepancy between the calculated and experimental results may be associated with differences in the representation of the contacting surface. In the calculation model, the actual surface topography is described by a set of averaged parameters; therefore, the individual characteristics of particular asperities are not fully accounted for. Under experimental conditions, real contact is formed by a large number of asperities differing in height, geometrical shape, and local mechanical state. During relative sliding, individual contact regions continuously form, deform, and break down, accompanied by continuous redistribution of the contact load. Consequently, the experimentally recorded parameters may exhibit fluctuations that are not reproduced by the stationary calculation model based on an averaged representation of the surface.

4. Conclusion

The conducted study demonstrated that the assessment of the tribological interaction of contacting surfaces requires consideration not only of the nominal geometry of the mating surfaces but also of the actual state of their surface microrelief. It was established that the real contact area is formed by a set of individual asperities, resulting in real contact pressure that can differ substantially from both nominal and contour contact pressure.

The calculation analysis showed that consideration of surface roughness and waviness parameters provides a more physically justified assessment of contact-load distribution and asperity deformation. With increasing approach of the contacting surfaces, new regions of the surface microrelief are successively brought into contact, accompanied by changes in the real contact area and the corresponding contact pressure.

Comparison of the calculated and experimental results confirmed a relationship between the state of real contact and the frictional behavior of the surfaces. The observed discrepancies are associated with the fact that the calculation model employs an averaged description of the surface microgeometry, whereas under actual sliding conditions the composition and mechanical state of individual microcontacts continuously change.

Thus, real contact pressure is one of the key parameters governing the stress state of the contact zone and the frictional interaction of contacting surfaces. Its combined consideration with surface roughness parameters, real contact area, and coefficient of friction provides a more comprehensive description of the mechanisms governing tribological behavior and can be used as a basis for the calculation-based assessment of surface wear intensity.

Funding

This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant No. AP23490355)

Conflict of interest

The authors declare that they have no competing interests.

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