The deformation-topographic method for the study of the tribotechnical indicators of the working bodies of rotary excavators

Y I Gustov¹*, I V Gadolina², A A Yushkov³

¹Moscow State University of Civil Engineering, Russia, 129337 Moscow, 26 Yaroslavl highway
²Blagonravov Mechanical Engineering Research Institute of the Russian Academy of Sciences, Russia, 101000 Moscow, 4 M. Kharitonyevskiy Pereulok
³Baumetall Grupp, Russia, 105120 Moscow, 10 Nizhnyaya Syromyatnichesky str
*E-mail: gustov.u.i@mgsu.ru

Abstract. The article describes the deformation-topographic method, developed on the basis of hypsographic and sclerobatic modeling of the microrelief of friction surfaces. Hypsographic modeling allows us to represent the microrelief of roughness of friction surfaces in the form of a normalized coordinate system "relative reference line - relative approximation" tp–£. Sclerobatic modeling allows to reproduce the diagrams of the distribution of microhardness along the normal to the friction surface of details and in the potential area of their worn layer.

1. Introduction
We consider the partial values of the micro-wear $D_a$ (the share of depressions) and the micrometall $D_m$ (the share of protusions) in the normalized coordinate system $t_p$–£ (see Figure 1). The area of partial micro-wear is located above the curve of the reference line $L_{r}$ (hypsogram), the share of the partial micrometall is located below the line $L_{r}$. For each partial value, we established the centers of gravity $C_a$ and $C_m$, respectively, through the pairs of medians. The line connecting the centers of gravity — the bicentroid $L_o$ — intersects the curve of the reference line $L_{r}$ at the pole $P$. 

Rotary excavators are important part of the mining fleet. Their working bodies (buckets, teeth, etc.) could wear out intensively during the operation in different soil conditions [10, 13]. This leads to a significant decrease in the performance of excavators and the associated complex of machines and equipment [2, 3].

Thus, the increase in abrasive wear resistance and durability of the working bodies of rotary excavators seems to be an important issue [9, 11, 12]. The solution of related issues requires the study of other important tribological indicators associated with the wear resistance [4, 5, 6].

2. Methods

The partial values of microwear and micrometals are determined by the relationship of bicentroid segments to the length of bicentroids:

\[ D_a = C_a P/C_a C_m, \quad D_m = P C_m/C_a C_m = 1 - D_a. \]  

(1)

Using the partial values, we can determine the coefficient of motion friction (sliding) by the dependence:

\[ f = (1 - D_a)^{1/D_a} = D_m^{1/D_a}, \]  

(2)

From which, with unknown values of \( D_a \) and \( D_m \), but with a known coefficient of friction, we can find the partial microwear \( D_a \) by the method of selection and find the partial micrometall \( D_m \) by (1). The coefficient of incomplete friction force of the rest (coefficient of adhesion) is calculated from the tilt angle of the bicentroid:

\[ F_p = \frac{\tan \varphi}{\tan[(t_s/t_m)/(\varepsilon_m - \varepsilon_a)]}, \]  

(3)

where \( \varepsilon_a, t_s \) and \( \varepsilon_m, t_m \) – coordinates of the centers of gravity of \( D_a \) and \( D_m \) (see Figure 1).

By expressions (2) and (3), we can estimate the indicator of the adhesion of the detail surface to the ground \( P_\varepsilon = f_s/f \).

The partial values, determined by (2) with the method of selection with known values of the friction coefficient, make it possible to determine the degrees of tribo-deformation hardening (or softening) of the friction surfaces \( K_s \) and wear products \( K_d \) (see Figure 2).

The degree of hardening \( K_s \) is calculated by the formula:

\[ K_s = H_0/H_0 = \left(\frac{D_{my}}{D_m}\right)^{D_m/D_a} = (0.618/D_m)^{D_m/D_a}, \]  

(4)

where \( H_0, H_0 \) – respectively, the initial (technological) and operational microhardness of the detail surface; \( D_{my} \) – harmonic value of the partial micrometall in the golden proportion system [7].
The degree of tribodeformational hardening of wear products is estimated based on the following dependance:

at \( K_s > 1 \) (hardening of the friction surface)
\[
K_s = \frac{H_s}{H_w} = K_s [K_s^{0.5} + (K_s - 1)^{0.5}],
\]

(5)

at \( K_s < 1 \) (softening of the friction surface)
\[
K_s = K_s [K_s^{2} - (K_s - 1)^{2}],
\]

(6)

where \( H_s \) – limit microhardness of friction surface.

Friction temperatures of friction surfaces \( T_s \) and wear products \( T_a \) are calculated by the formulas:
\[
T_s = T_0 + \Delta T_s = T_0 + \ln K_s/\lambda_s,
\]

(7)

\[
T_a = T_0 + \Delta T_a = T_0 + \ln K_s/\lambda_s,
\]

(8)

where \( T_0 \) – ambient temperature; \( \Delta T_s \) and \( \Delta T_a \) – the temperature increment of the friction surface and wear products due to friction and wear of the details respectively; \( \lambda = 2.15 \times 10^3, \) \(^1/\circ\)C – average temperature coefficient for steels and alloys.

Efficiency coefficients of the friction bodies (detail - abrasive) can be determined by the expression:
\[
\eta = 1/(1 + 2fL_p/L_tpp),
\]

(9)

where \( t_{pp} \) – relative reference line at the pole approximation \( \epsilon_p \) (see. Figure 1), which is calculated depending on
\[
t_{pp} = 1/(1 + 2D_a).
\]

(10)

With established practical equality \( 2f = t_{pp} \) expression (9) takes the form
\[
\eta = 1/(1 + L_r).
\]

(11)

Hyposogram \( L_r \) length can be measured instrumentally (for example, with an odometer) or calculated by the formula
\[
L_r = 1.4142 \left( D_{max}/D_{min} \right)^{DaDm},
\]

(12)

where \( D_{max} = D_a \) at \( D_a > D_m \), \( D_{min} = D_m \), at \( D_a < D_m \).

To assess the wear resistance of materials of the working bodies of excavators, we use a complex criterion in the form of:
\[
\epsilon = 1/\ D_d \eta.
\]

(13)

3. Results

Basing on the known coefficients of sliding friction of the teeth of rotary excavators [3, 4, 5], we obtained the following values of tribotechnical indicators (table 1).

| Soil type | \( f \) | \( D_a \) | \( K_s \) | \( K_a \) | \( \Delta T_s, ^\circ\)C | \( \Delta T_a, ^\circ\)C | \( L_r \) | \( \eta, \% \) | \( \epsilon \) |
|-----------|------|------|------|------|-----------------|-----------------|------|-------|------|
| Peat      | 0.25 | 0.5  | 1.236| 1.975| 98.55           | 316.5           | 1.4142| 41.4  | 19.32|
| Loam      | 0.3  | 0.32 | 0.816| 0.516| 94.58           | 307.7           | 1.66 | 37.5  | 27.78|
| Sludge    | 0.25 | 0.5  | 1.23 | 1.975| 98.55           | 316.5           | 1.4142| 41.4  | 19.32|
| Clay      | 0.35 | 0.09 | 0.020| 0.019| 1819.5          | 1838.0          | 1.709 | 36.9  | 86.03|
| Clay      | 0.3  | 0.32 | 0.816| 0.516| 94.58           | 307.7           | 1.666 | 37.5  | 27.78|

According to the table values of tribotechnical indicators, we can make the following conclusions:

1. During the operation in peat soil and in sludge, the teeth experience tribodeformational hardening of the friction surface \( (K_s = 1.236) \) and wear products \( (K_a = 1.975) \). The corresponding friction temperatures are \( \Delta T_s = 98.55 \) and \( \Delta T_a = 316.5 \) oC. The efficiency \( (\eta = 41.4\%) \) corresponds to the values typical for dry friction conditions, around 40% [7, 8].

2. During the operation in loam and in clay sandstone, the teeth experience tribodeformational softening \( (K_s = 0.816 \) and \( K_a = 0.516) \). The corresponding friction temperatures are of the surface and wear products are 94.58 and 307.7 oC, respectively. In this case, the efficiency of the friction pair “tooth-soil” is 37.5%, which corresponds to the conditions of dry friction.
3. Operation in clay conditions leads to significant tribodeformational softening of surface layers and teeth wear products (\(K_s = 0.02\) and \(K_a = 0.019\)), accompanied by frictional heating to temperatures of 1522 and 1542 °C, respectively. The efficiency is equal to 36.9%.

4. Comparison of the wear resistance criterion values \(\varepsilon\) shows the greatest abrasive wear resistance of teeth when working in clay (\(\varepsilon = 86.03\)), the smallest - in peat and sludge (\(\varepsilon = 19.32\)); intermediate value (\(\varepsilon = 27.78\)) - in loam and in clay sandstone. The abnormal value (\(\varepsilon = 496.28\)) confirms the conclusion about the absence of friction between the teeth in the siltstone.

Basing on the table values of the partial values \(D_s\) and \(D_m=1-D_s\), we can construct a normalized system of relative reference lines and approximations \(t_p - \varepsilon\) based on the approximating function,

\[
t_p = \varepsilon \frac{D_{ai}}{D_{mi}},
\]

(14)

Figure 3 shows the \(t_p - \varepsilon\) system for an excavator when operating in peat and sludge with a friction coefficient of 0.25 and a partial microwear and micrometall values of 0.5 each.

![Figure 3](image)

**Figure 3.** \(t_p - \varepsilon\) system for an excavator when operating in peat and sludge.

Relying on this system, we can note the following:

1. At equal partial values, the dependence of relative reference lines on relative approximations (hypsogram) is linear.
2. The coefficients of the centers of gravity of the partial microwear, the pole and the partial micrometall are fixed by the values \(\varepsilon_a = 0.333\) \(t_s = 0.666\); \(\varepsilon_p = 0.5\) \(t_pp = 0.5\); \(\varepsilon_m = 0.666\) \(t_m = 0.333\).
3. The length of the bicentroids is \(L_{\beta} = 0.4709\), the length of the hypsogram is \(L_{\gamma} = 1.4142\). The relation \(\gamma = L_{\gamma}/L_{\beta} = 3.0\) is a constant of the system.
4. The tangent of the bicentroid slope (\(\varphi = 45^\circ\)) equals to 1.0, characterizes the friction coefficient - the coefficient of incomplete rest friction force \(f_p\). The coefficient of sliding friction is \(f = 0.25\). The ratio \(f_p/f = 4.0\).
5. The degrees of tribodeformational hardening of friction surfaces and wear products are \(K_s = 1.236\) and \(K_a = 1.975\), the corresponding frictional temperatures are \(\Delta T_s = 98.5\) and \(\Delta T_a = 316.5^\circ C\). The efficiency at the tooth contacting with the soil is \(\eta = 41.4\%\). A complex criterion for wear resistance is characterized by the value \(\varepsilon = 19.32\).
6. The values of the tribotechnical indicators obtained from the \(t_p - \varepsilon\) system (see Figure 2) coincide with the values of Table 1.

Figure 4 shows the \(t_p - \varepsilon\) system for teeth during operation in loam and clay sandstone. The analysis of this system allowed us to get the following tribotechnical indicators (Table 2).
**Figure 4.** $t_p - \varepsilon$ system for an excavator bucket teeth when operating in loam and clay sandstone.

**Table 2.** Tribomechanical characteristics of the teeth during the operation in loam and clay sandstone.

| $K_s$ | $K_a$ | $D_a$ | $\varepsilon_a$ | $t_{pa}$ | $t_a$ | $\varepsilon_p$ | $t_{pp}$ | $\varepsilon_m$ |
|-------|-------|-------|-----------------|---------|-------|-----------------|---------|--------------|
| 0.835 | 0.56  | 0.35  | 0.295           | 0.275   | 0.785 | 0.385           | 0.64    | 0.565        |

Comparison of the values of tables 1 and 2 shows satisfactory coincidence of values $D_a$ (0.32 and 0.35) with discrepancy $\Delta=8.6\%$; friction coefficient $f$ (0.30 and 0.294) at $\Delta=2.0\%$; hypsogram length $L_\gamma$ (1.666 and 1.50) at $\Delta=10.7\%$; degree of tribodeformational softening $K_s$ (0.816 and 0.835) at $\Delta=2.3\%$; $K_a$ (0.516 and 0.566) at $\Delta=8.5\%$; complex wear resistance criterion $\varepsilon$ (27.78 and 23.65) at $\Delta=17.5\%$.

The results from the table 2 allow us to determine the friction fatigue $t$ by the formula:

$$ t = \ln(1/\varepsilon_a) / \ln(\varepsilon_p/\varepsilon_a), $$

(15)

The value of friction fatigue is 4.58.

This value indicates the wear of the teeth on the multi-cycle fatigue mechanism. [14, 15].

Test of the wear mechanism by the established dependences shows that the low-cycle fatigue mechanism is possible with the condition:

$$ L_\gamma = 1.4142 + (0.05 - 0.1D_a)^{0.5} $$

(16)

It is performed (see Table 2) with a slight divergence of the values $L_\gamma$ ($\Delta=2.4\%$). The divergence of $L_\gamma$ from Table 1 is $\Delta=11.8\%$.

Basing on the conditions (15) and (16), we can assume that the wear of teeth in these soils occurs by the mixed mechanism of low-and multi-cycle fatigue.

Figure 5 illustrates $t_p - \varepsilon$ system for teeth during operation in clay. In this case we obtained the following values of tribotechnical indicators (Table 3).
Figure 5. $t_\varphi$–$\varepsilon$ system for an excavator bucket teeth when operating in clay.

Table 3. Tribomechanical characteristics of the teeth during the operation in clay.

| $\Delta T_s$ | $\Delta T_a$ | $D_a$ | $\varepsilon_a$ | $t_{pa}$ | $t_a$ | $\varepsilon_p$ | $t_{pp}$ | $\varepsilon_m$ | $t_{pm}$ |
|-------------|-------------|------|-----------------|--------|------|-----------------|--------|-------------|--------|
| 1522        | 1544        | 0.104| 0.23            | 0.86   | 0.92 | 0.26            | 0.87   | 0.505       | 0.93   |

A comparison of the calculated (see table 1) and graphic (see figure 5) values shows the following:

1. The values of the partial micro-wear $D_a = 0.09\%$ and $D_a = 0.104$ almost coincide (discrepancy $\Delta = 13.5\%$), the same with the length of the hypsogram $L_\gamma = 1.709$ and $L_\gamma = 1.71$ ($\Delta = 0.06\%$); friction coefficient $f = 0.35$ and $f = 0.348$ ($\Delta = 0.57\,^\circ$); Efficiency ($\Delta = 0\%$); complex wear resistance criterion $\varepsilon = 86.03$ and $\varepsilon = 74.88$ ($\Delta = 14.9\%$).

2. Indicators of tribodeformational softening $K_s = 0.02$ and $K_a = 0.019$ are of the same order as the graphic values $K_s = 0.04$ and $K_a = 0.036$. The corresponding friction temperatures have the values $\Delta T_s = 1819.5$, $\Delta T_a = 1838\,^\circ$ C and $\Delta T_s = 1522$, $\Delta T_a = 1542\,^\circ$ C with discrepancies $\Delta s = 19.5\%$ and $\Delta a = 19.2\%$.

3. The frictional fatigue is $t = 12$, that indicates the wear of the teeth by the mechanism of multicycle fatigue. Verification by the $L_\gamma$ hypsogram and partial microwear condition confirms it.

The value of $L_\gamma = 1.71$ and the calculated $L_\gamma = 1.74$ with a discrepancy $\Delta = 1.75\%$ confirms the conclusion about the wear mechanism.

4. Conclusion

1. The deformation-topographic method of studying the microrelief of friction surfaces makes it possible to determine the principal tribomechanical parameters for a given coefficient of sliding friction of the working bodies of ground-moving equipment in various soil conditions.

2. Relying on the initial coefficient of sliding friction, we can determine the partial values of micro-wear and micrometals. They are basic indicators of friction surfaces microtopography for calculating the estimated tribomechanical characteristics, establishing wear mechanisms and criteria for wear resistance of teeth.
3. By means of the proposed approximating power function, we reproduce the curve of the reference line in the normalized coordinate system “relative reference line - relative approximation”. Its characteristic indicators help to find the target tribotechnical values.

4. Comparison of tribotechnical indicators calculated by a given friction coefficient with the same indicators of the normalized coordinate system showed their satisfactory numerical coincidence. This confirms the validity of the application of the deformation-topographic method.

5. The paper shows the mechanisms of wear and complex criteria for wear resistance of the teeth of rotary excavators during operation in different soil conditions.

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