The relationship of microrelief indicators of the friction surfaces of mobile interfaces of construction equipment

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Abstract. The paper presents the relationships of microrelief indicators of the friction surfaces of mobile interfaces of a hydraulic excavator equipment and passenger elevator. The authors use partial micro-wear and micrometall as initial indicators of microrelief. These indicators are used to determine important operational tribomechanical characteristics. The article proposes an approximating function of the curve of the reference lines for the entire domain of relative approaches.

1. Introduction
The microrelief of friction surfaces can be represented by the normalized coordinate system “relative reference line - relative approximation” (Figure 1).

![Figure 1. Calculated curve of the reference line of the friction surface of the passenger elevator.](image-url)

Studies of this system allowed us to establish a number of dependencies between tribomechanical indicators of worn surfaces. At the same time, as the initial indicators, we consider the partial values of...
micro-wear and micrometall, corresponding to the fractions of micro-hollows and micro-protrusions of the profile on a certain profilographic base.

The theoretical and applied interest is caused by the relation of the initial (basic) indicators and their derivatives, which shows the self-organization (synergism) of the microrelief during friction and wear of surfaces.

The aim of the research is to establish the relationship between the indicators of the tribomechanical system “relative reference line - relative approximation” and to determine the operational characteristics of the used friction units.

To achieve this goal, we planned the following main tasks:
1) The determination of the pole coordinates \((\epsilon_p, t_{pp})\), the centers of gravity of the partial values of micro-wear \((\epsilon_a, t_a)\) and micro-metal \((\epsilon_m, t_m)\), as well as the relative values of the reference lines \((t_{pa}, t_{pm})\).
2) The determination of the length of the reference lines curve \((L_\gamma)\).
3) The determination of the degree of tribodeformational hardening (softening) of friction surfaces \((K_s)\) and wear products \((K_a)\).
4) The estimation of frictional temperatures of friction surfaces \((\Delta T_s)\) and wear particles \((\Delta T_p)\).
5) The determination of friction coefficients of motion and incomplete friction force of rest.
6) The evaluation of the efficiency of friction units \((\eta)\).
7) Approximation of the curve of the reference lines of friction surfaces.

2. Methods
We investigated the friction surfaces of hinge pairs of hydraulic excavator working equipment and traction sheaves of passenger elevator. We took the profilograms of worn surfaces by means of a profilograph - a profilometer PERTH-O-METER DWR-LP (Germany). Basing on the profilograms, we constructed a normalized coordinate system “relative reference lines - relative approximations” \(t_p - \epsilon\) (see Figure 1).

The curve of the reference lines \(L_\gamma\) - a pegelline - divides the coordinate system \(t_p - \epsilon\) into two parts. The upper part characterizes the partial micro-wear \(D_a\) (the share of hollows), the lower part - the partial micrometall \(D_m\) (the share of protusions) of the friction surface relief. The centers of gravity of the partial values \(C_a\) and \(C_m\) are determined by the intersection of the corresponding pairs of medians. The line connecting the centers of gravity - a bicentroid - crosses the line \(L_\gamma\) at the pole \(P\).

The fundamental partial values of \(D_a\) and \(D_m\) can be determined by the methods of base reference lines, geometric areas, bicentroid segments, and pole approximations [1-3].

The method of the base reference lines can be described as relation of the sum of the reference lines of the profilogram protrusions on all the approximations to the sum of the base lengths. In this case, the partial micrometal \(D_m\) and the microwear \(D_a\) are equal to:

\[
D_m = \sum t_{pi}/n, \quad D_a = 1 - D_m,
\]

where \(t_{pi} = \Delta x_i/L_\delta\) - relative reference line, \(n\) - number of approximations, \(L_\delta\) - profilographic base length.

The method of the geometric areas can be described in the following way: the partial values \(D_a\) and \(D_m\) are represented by a set of geometric figures (for example, squares, triangles, etc.), which sum of the areas in relation to the area of the \(t_p - \epsilon\) system is determined by the values of \(D_a\) and \(D_m\).

The method of bicentroid segments can be described as the division of segments before \((C_aP)\) and after \((C_mP)\) the pole by the bicentroid length \(L_\delta = C_aC_m:\)

\[
D_a = C_aP/C_aC_m, \quad D_m = C_mP/C_aC_m.
\]

The method of pole approximation consists of equating the partial micro-wear \(D_a\) to the numerical value of the pole approximation \(\epsilon_p\), i.e.:

\[
D_a = \epsilon_p, \quad D_m = 1 - \epsilon_p.
\]
The established correspondence (3) indicates the possible relations of tribomechanical indicators during the self-organization of the microlief.

In accordance with the goal of the study, we tested and analyzed the following relationships and dependencies.

We found the pole coordinates by the relations:

$$\varepsilon_p = D_a, \ t_{pp} = D_a^a/D_m. \ (4)$$

We found the coordinates of the center of gravity of a partial micrometall by expressions:

$$\varepsilon_m = D_a^a, \ t_a = D_a/D_m. \ (5)$$

We found the coordinates of the center of gravity of the partial microwear by dependencies:

$$\varepsilon_a = 0.565 \varepsilon_p, \ \varepsilon_a = \varepsilon_p \varepsilon_m, \ t_a = 0.5 \left(1 + \varepsilon_a^D_m \right). \ (6)$$

The relative values of the reference lines were calculated by the formulas:

$$t_{pa} = \varepsilon_a D_a/D_m, \ t_{pp} = \varepsilon_p D_a/D_m, \ t_{pm} = \varepsilon_m D_a/D_m. \ (7)$$

The length of the curve of the reference lines was determined by the dependence:

$$L_\gamma = 1.4142(D_{max}/D_{min})^{D_a/D_{max}}, \ (8)$$

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

The above linear indicators for (2) - (8) were determined by micrometry with a reference value of 0.5 mm with a scale bar and a KU-A brand odometer.

We determined the tribodeformational hardening of the friction surface \(K_s\) and wear products \(K_p\) by the formulas:

$$K_s = H/H_0 = [0.618/D_m]^{D_m/D_a} \ (9)$$

at \(K_s > 1 \) (hardening) \(K_s = H/H_0 = K_1^{0.5 + (K_s - 1)0.5}\)

at \(K_s < 1 \) (softening) \(K_s = H/H_0 = K_2^{0.5 + (K_s - 1)0.5}\) \ (10)

where \(H_0\) - initial metal microhardness, \(H_s\) - friction surface microhardness, \(H_a\) - microhardness of wear products.

The frictional temperatures of the friction surface \(T_s\) and wear products \(T_a\) are estimated by dependencies:

$$T_s = T_0 + D T_s = T_0 + \ln K_s/\lambda \ \ (11)$$

$$T_a = T_0 + D T_a = T_0 + \ln K_a/\lambda \ \ (12)$$

where \(T_0\) - ambient temperature, \(D T_s\) and \(D T_a\) - temperature increment, \(\lambda = 2.15 \times 10^{-3} 1/0\degree C\) - average temperature coefficient for steel and fusions [4].

The coefficient of friction of movement (slip) is determined by the expression:

$$f = D_m/\lambda = (1 - D_a) \lambda/D_a. \ \ (13)$$

The coefficient of static friction is estimated by the slope of the bicentroid (see figure 1):

$$f_p = \tan \phi = (a-m)/(\varepsilon m - \varepsilon a). \ \ (14)$$

The efficiency was estimated by the formula:

$$\eta = 1/(1 + L_\gamma). \ \ (15)$$

The curve of the reference lines \(L_\gamma\), depending on its type, can be approximated by the following partial functions [5]:

$$t_p = \varepsilon, \ t_p = b \varepsilon^v \ \ (16)$$

and general function:

$$t_p = \varepsilon^\varepsilon [t_p/(1 + \varepsilon_p - \varepsilon)^{1-\varepsilon}] \ \ (17)$$

3. Results

Figure 2 shows the normalized coordinate systems “relative reference line - relative approximation” \(t_p\), \(ε\) of worn hardened pins (a) and bushings (b) of the hinge of the working equipment of a hydraulic excavator.
Figure 2. Coordinate system $t_p - \varepsilon$ of worn hardened pins (a) and bushings surface microrelief. The initial partial sizes of microwear $D_a$ and micrometall $D_m$ and their derivative tribomechanical indicators are given in Table 1.

Table 1. Partial and derivative tribomechanical indicators of worn hardened parts of a hydraulic excavator hinge.

| Detail | $D_a$ | $f$ | $K_s$ | $K_a$ | $\Delta T_s$ | $\Delta T_a$ | $f_p$ | $t_a$ | $t_m$ | $\varepsilon$ | $\varepsilon_a$ | $L_\gamma$ | $L_\beta$ | $t_{pa}$ | $t_{pp}$ | $t_p$ | $\eta_\%$ |
|--------|-------|-----|-------|-------|-------------|-------------|-------|-------|-------|--------------|--------------|------------|--------|--------|--------|--------|-------|---------|
| Pin    | 0.5   | 0.2 | 1.2   | 1.9   | 98          | 316         | 0.7   | 0.6   | 0.3   | 0.6          | 0.3          | 1.4        | 0.4    | 0.2    | 0.4    | 0.7    | 40     |
| Bushi  | 0.5   | 0.2 | 1.3   | 2.2   | 125         | 372         | 0.5   | 0.5   | 0.3   | 0.7          | 0.2          | 1.5        | 0.4    | 0.1    | 0.4    | 0.6    | 39     |
| ng     | 65    | 29  | 1     | 6     | 8           | 24          | 24    | 72    | 53    | 24           | 72           | 8        | 8      | 84     | 69     | 57     |

Figure 3 shows the coordinate systems $t_p - \varepsilon$ of a worn-out borated pin (a) and a hardened bushing (b) of a hydraulic excavator hinge.

Table 2 presents the initial partial values of $D_a$ and $D_m$ and their derived tribomechanical indicators.

Figure 3. The coordinate system $t_p - \varepsilon$ of the microrelief of a worn-out borated pin (a) and a hardened bushing (b) of a hydraulic excavator hinge.
The calculated tribomechanical indicators are in satisfactory agreement with the experimental values for (3) - (7) showed satisfactory coincidence (see the differences of Δ in Table 4).

Thus, the partial values of microwear and micrometall and their derivative ratios make it possible to determine the main operational tribological characteristics of friction surfaces. According to the proposed approximating function, it becomes possible to build the calculated curve of the reference lines from the known coefficient of friction of motion (slip).

4. Conclusion

1) The basic indicators of the “relative reference line - relative approximation” system are the partial values of micro-wear and micrometall. On their basis, we can determine the operational tribomechanical characteristics of the mobile interfaces of machines and equipment.

2) The partial values of micro-wear and micrometall and the derived tribomechanical characteristics expressed through them testify to the self-organization of the process of friction and wear.

3) The proposed approximating general function of the curve of the reference lines is in qualitative and quantitative agreement with the experimental curves in the entire domain for determining the relative approximations.

4) The calculated tribomechanical indicators are in satisfactory agreement with the experimentally obtained characteristics. The developed method makes it possible to predict service tribomechanical

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**Table 2.** Tribomechanical indicators of worn-out borated pin and hardened bushing.

| Detail *   | Da    | tpp   | Lβ   | Ks    | Ka   | f     | t     | Lγ    | τp   | ΔTs, °C | ΔTa, °C | η , % | ΔTsλ, °C |
|------------|-------|-------|------|-------|------|-------|-------|-------|------|---------|---------|-------|---------|
| P-1        | 0.460 | 0.52  | 0.476| 1.167 | 1.738| 0.262 | 2.16  | 1.472 | 0.609| 60.0    | 215.0   | 40.5  | 137.5   |
| P-2        | 0.545 | 0.53  | 0.470| 1.291 | 2.163| 0.236 | 2.14  | 1.48  | 0.625| 99.4    | 300.0   | 40.3  | 199.7   |
| P-4        | 0.535 | 0.445| 0.470| 1.484 | 2.847| 0.239 | 2.47  | 1.45  | 0.699| 153.6   | 406.0   | 40.8  | 279.8   |
| P-5        | 0.455 | 0.535| 0.470| 1.163 | 1.772| 0.263 | 2.51  | 1.49  | 0.608| 58.8    | 211.0   | 40.0  | 134.9   |
| B-4        | 0.365 | 0.640| 0.485| 0.849 | 0.630| 0.297 | 3.66  | 1.50  | 0.957| 63.7    | 180.0   | 40.0  | 121.85  |
| B-5        | 0.525 | 0.520| 0.475| 1.269 | 2.90 | 0.242 | 2.30  | 1.47  | 0.773| 92.7    | 286.8   | 40.4  | 189.75  |
| B-7        | 0.320 | 0.620| 0.500| 0.816 | 0.571| 0.300 | 3.00  | 1.50  | 0.647| 79.1    | 217.9   | 40.0  | 148.5   |

*P - pin, B -bushing.

The graphs of the approximating functions (17) agree with the experimental curves of the reference lines (see figures 2 and 3). Knowing this, it is possible to construct a normalized coordinate system tp - ε without profiling the friction surfaces, but using, for example, the known friction coefficient.

For the pair “traction rope - traction elevator pulley” with the coefficient of sliding friction \( f = 0.276 \) [3], we obtained the following values of the reference lines tpi with given relative approaches \( ε i \) (table 3). To determine the partial micro-wear \( D_a = ε p \), we used the expression (13). Using the selection method with the known coefficient of friction we got \( D_a = 0.41 \) and \( D_a/D_m = 0.695 \).

**Table 3.** Values of the relative reference lines of the approximating function.

| ε i | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  | 0.6  | 0.7  | 0.8  | 0.9  | 1.0  |
|-----|------|------|------|------|------|------|------|------|------|------|
| tpi | 0.158| 0.281| 0.403| 0.526| 0.648| 0.763| 0.864| 0.945| 0.994| 1.0  |

The graph of the calculated curve of the reference lines of the friction surface of the traction pulley, built according to the data of Table 3, is presented in Figure 3. The resulting coordinate system \( t_p - ε \) is characterized by the indicators given in Table 4.

**Table 4.** Indicators of the coordinate system \( t_p - ε \) of the traction pulley friction surface.

| indicators | \( ε_a \) | \( ε_p \) | \( ε_m \) | tpa | tpp | tpm | e | ta | tm | Lβ | Ks | Ka | η , % |
|------------|----------|----------|----------|-----|-----|-----|---|----|----|----|----|----|------|
| calculated | 0.260    | 0.415    | 0.645    | 0.36| 0.545| 0.795| 0.665| 0.385| 0.480| 1.50| 1.08| 1.43| 40.0 |
| experimental| 0.275    | 0.410    | 0.600    | 0.40| 0.536| 0.730| 0.694| 0.400| 0.450| 1.54| 1.07| 1.39| 39.4 |
| Δ, %      | 5.8     | 1.2     | 7.5     | 11.1 | 1.7  | 8.8  | 4.4 | 3.9 | 6.7 | 2.7 | 0.9  | 2.9 | 1.5  |
indicators by the profile of the friction surface, as well as by the known or given coefficient of motion friction

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