Simulation modelling of tribotechnologies system and its parametric reliability assessment on tribotechnical parameters of the joints of sliding friction

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Abstract. The article discusses the formation of tribotechnical characteristics of cylindrical sliding friction joints by means of simulation. Experiments were conducted on physical models of joints. The parametric reliability of tribotechnological parameters of burnish operation were determined for the studied tribotechnological system.

1. Introduction

It is known that up to 80% of the technical devices fail due to wear and tear of the joints of parts. Improvement of wear resistance of joints is one of the most urgent and fundamental problems of modern engineering, and its solution is largely to be found in improving the processing technology of contacting surfaces of triboelements. Thus, the solution of the problem of effective tribotechnology methods development of the formation of functional surfaces of triboelements providing the desired quality characteristics with high reliability is so important [1 – 6].

The article considers the questions of formation of tribotechnical characteristics of burnishing process of the cylindrical friction pairs ‘Steel 45 – bronze CuSn5Zn5Pb5’ or ‘Steel 45 – antifriction cast iron grey ACiG-1’. Special attention was paid to the process of formation of tribotechnical characteristics depending on the processing conditions of the contacting surfaces and of some features of operation.

2. Materials and methods

The formation of the quality parameters determining the wear resistance of rubbing parts surfaces was carried out at the final stage of processing in the three-stage combined technological system (TS) of processing, that includes three main stages (Figure 1):

- Stage 1: ensures specified accuracy of part machining and the required geometrical parameters of surface quality for high-quality coating of materials for forming the running-films; main operation are finishing turning O11 or grinding O12;
- Stage 2: the coating on the parts surface of materials to obtain a soft running-film by friction O21 or by chemical methods O22 is provided;
- Stage 3: the microprofile is formed, excluding the process of microcut and providing the required physico-mechanical and operational properties of the surface (e.g., durability). Processing can be carried out by methods of surface plastic deformation (SPD), by diamond burnishing O31; by roll
burnishing $O_2$ etc.

In the study, in stage 1 parameters of parts surfaces quality were formed on a lathe finish turning with standard cutting inserted pieces, the cutting part of which is equipped with a composite 10 (geksanit R). In stage 2 of formation of the running-of films the finishing antifriction non-abrasive treatment (FANAT) of the work piece surface or chemical plating was applied.

The FANAT process was carried out using friction brass plating surfaces of parts with the use of surfactants (glycerin). The pressure in the contact area of the brass rod with the treated surface is 30 MPa; the processing speed is 20 m/min; the feed is 0.05 mm/rev.

In the process of a chemical copper plating the solution of copper chloride $CuCl_2$ in a mixture of 70% acetic acid and glycerin was applied to the on the degreased surface of the part rotating with a speed of 20 m/min. Uniform copper film was formed on the surface after 10 min of exposure of a part with constant speed of rotation.

At stage 3 of considered combined technologies the diamond burnishing by tools with elastic action with indenters, equipped with synthetic diamonds ASPK (carbonado, PSD) with a corner radius of 3.5 mm was used.

We studied the samples of steel 45 with hardness HRC 48...50, get by volume hardening. Samples were prepared in the form of step noses or rings. Models of liners were made of antifriction cast iron ACiG-1 or of bronze CuSn5Zn5Pb5. The unit model of sliding friction installed on the test bench is shown in Figure 2.

The parts surfaces were processed on a thread-turning machine 16K20 and on lathe and milling machining center mod. EX308 (TAKISAWA) in accordance with the plan of the experiment that is a regular fractional replica of type 2$^{12-8}$ of full factorial experiment of the type 2$^8$. The variation levels of the experiment factors are presented in table 1.

### Table 1. Factorial planning of experiment for formation of tribotechnical characteristics study in tribotechnological system.

| Fact or code | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | $X_8$ | $X_9$ | $X_{10}$ | $X_{11}$ | $X_{12}$ |
|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|----------|----------|----------|
| $V_T$        | 65    | 0.05  | 0.1   | 2.5   | 1.5    | 100   | 0.075 | 65    | 2     | 10       | 30       | 0.15     |
| $S_T$        | 200   | 0.15  | 0.25  | 1.62  | 3      | 300   | 0.15  | 100   | 5     | 50       | 50       | 0.25     |

Eight technological factors of processing were varied affecting to the formation of tribotechnical characteristics of friction pairs:

- modes of finish turning: $V_T$ – speed of steel 45 turning with composite 10, m/min.; $S_T$ – tool feeding, mm/rev; $t$ – cutting depth, mm;
- the rigidity of technological system $j$ at stages 1 and 3 of treatment, kN/mm;
– $M$ – the material of soft running-film on the surface of the shaft (for friction brass plating (FBP) the code is 3.0; for chemical copper plating (CCP) – 1.5);
– modes of diamond burnishing: $Q_{DB}$ – the force of diamond burnishing, N; $V_{DB}$ – the speed of diamond burnishing, m/min; $S_{DB}$ – the feed of diamond burnishing, mm/rev.

As factors, taking into account the operating conditions were adopted:
– $M_l$ – the liner material: for antifriction cast iron the code is 2; for bronze – 5;
– $V_R$ – the speed of the relative sliding of triboelements, m/min;
– $P_R$ – the value of nominal linear load on the tribojoint during running, N/mm;
– $\Delta P$ – the variation percentage of nominal linear load on the tribojoint during running when modeling dynamic operating conditions, %.

Studies of tribotechnical characteristics of joint were carried out on the installation, scheme of which is shown in Figure 2.

![Figure 2. Installation for tribotechnical tests: a – shafts models; b – rings models; c – model of assembly of a friction slip; d – installation diagram: 1 – plate, 2 – screw; 3 – body; 4 – pin; 5 – lead shank; 6 – bushing; 7 – shaft; 8 – bearing; 9, 12 – balls; 10 – dynamometer; 11 – indicator; 13 – nut; 14 – plate; 15 engine to convert rotary motion into reciprocating motion; 16 – slider; 17 – cam mechanism to transfer the load to the sample; 18 – bracket; 19 – pin; 20 – screw; 22 – bushing; 23 – locknut; 24 – stock; 25 – screws; 26 – cover; 27 – bushing; 29 – pin; 30 – cantilever beam](image)

In general, the experimental installation includes three modules:
1) main module A, in which a tested model of the friction pair, the drive, adjustable by speed, and dynamometer to create a static load are located;
2) module B to create a variable programmable load carrying dynamic loading according to the law: $P = P_{\text{rated}}(a + b\sin\omega t)$, where $a, b$ – the factors used to change the load $P$ according to a given harmonic law ($0 \leq a \leq 1, 0 \leq b \leq 1$).
3) module C of electronic count of the number of loading cycles, that is controlled by electric probe (on Figure 2 is not conventionally shown).

The running-in process of the samples was carried out in the conditions set forth in the plan of experiment, however, in the early running-in and after it the friction coefficient was measured at various speeds ($V_R = 10 – 90$ m/min) and loads ($P_R = 10 – 150$ N/mm). The registration of the measured characteristics envisaged the use of computer measuring system ‘Oscilloscope’, that is connected to the output of the strain gauge amplifier or the use of loopback oscilloscope and two-coordinate recorder.

3. Results and Discussion

The following tribotechnical properties were studied:
– \( f_1, f_0 \) – friction coefficients at the beginning and at the end of the running-in process;
– \( h_{01}, h_{02} \) – values of an initial wear of surface of the shaft (01) and the liner (02), \( \mu m \);
– \( L_{01}, L_{02} \) – running-in path for the shaft and the liner, m;
– \( I_1, I_2 \) – wear rate of the shaft and the liner surfaces.

Graphs of linear wear of the shafts and the friction coefficient depending on friction path are given in Figure 3. The graph shows the bounds for the 80% confidence intervals. In addition, micrographs of the topography of the shaft surfaces before and after running-in are showed. Color shades on all shades photomicrographs prove the presence of the running-film that in the conditions of the experiment remained on the surface both after diamond burnishing and after completion of running-in process.

Considering the dependence of the friction coefficient of running-in path, it should be borne in mind that their initial points \((L \to \text{min})\) correspond to the first registration. Naturally, that friction coefficient at \( L = 0 \) has a specific value close to registered, but not infinite as it may seem when considering curves 2, 4 (Figure 3).

As a result of processing of experimental data by the method described in [7], adequate physical-statistical simulation models of formation of tribotechnical characteristics (Cobb-Douglas models) were built:

\[
Y_i = b_0 K_1 K_2 T_T^a T_R^b S_T^c P_R^{b_1} P_T^{b_2} Q_{DB}^{b_3} Q_{DB}^{b_4} \Delta P^{b_5} 
\]

where \( Y_i \) – \( i \)-th tribotechnical characteristics; \( K_1, K_2 \) – coefficients taking into account the type of the running-film (FBP or CCP) and liner material (bronze (Br) or antifriction cast iron (ACi)); \( b_0, b_i \) – model coefficients.

Models parameters (1) and calculated values of Fisher criterion \( F_{calc} \) are presented in Table 2. \( F_{calc} \) compared with the table value at the significance level \( \alpha = 0.05 \) \( (F_{tab} = 6.59) \) proves the adequacy of models.
Analysis of factors influence of considered tribotechnological system on main tribotechnical characteristics \( (f_1, f_0, h_{01}) \) can be performed using Pareto charts (Figure 4). It should be noted that such factors of diamond burnishing, as \( Q_{DB} \) and \( S_{DB} \) have a strong positive impact on reducing the friction coefficient \( f_1 \). From the point of view of friction coefficients reduction \( f_1 \) and \( f_0 \), the running-in process should be running on forced mode, that is, at maximum permissible speed of relative sliding.

Table 2. Parameters of simulation models of formation of tribotechnical characteristics.

| Coef. | \( b_0 \) | \( K_1 \) | \( K_2 \) | \( b_1 \) | \( b_2 \) | \( b_3 \) | \( b_4 \) | \( b_5 \) | \( b_6 \) | \( b_{10} \) | \( b_{11} \) | \( b_{12} \) | \( F_{\text{calc}} \) |
|-------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| \( f_1 \) | 2.0 | 1.31 | 1.10 | 1.11 | 1.05 | -0.06 | 0.04 | -0.05 | 0.02 | -0.07 | 0.47 | -0.05 | -0.32 | -0.09 | 1.3 |
| \( f_0 \) | 2.82 | 1.64 | 1.20 | 0.92 | 0.96 | 0.03 | 0.20 | 0.19 | 0.11 | -0.14 | 0.28 | -0.03 | -0.35 | 0.03 | 0.62 | 0.5 |
| \( h_{01} \) | 3.74 | 1.20 | 1.07 | 1.23 | 1.09 | 0.31 | 0.15 | 0.02 | 0.04 | -0.38 | 0.32 | 0.68 | 0.05 | -0.74 | -0.19 | 5.6 |
| \( h_{02} \) | 8.08 | 1.10 | 1.04 | 1.28 | 1.11 | 0.07 | 0.27 | 0.09 | -0.07 | -0.16 | -0.04 | 0.05 | 0.04 | 0.10 | -0.40 | 4.7 |
| \( I_{1} \times 10^{-12} \) | 316 | 1.77 | 1.23 | 0.87 | 0.94 | 0.08 | 0.22 | 0.21 | 0.13 | -0.17 | 0.43 | -0.05 | -0.43 | -0.10 | 0.76 | 2.8 |
| \( I_{2} \times 10^{-11} \) | 147 | 1.80 | 1.24 | 0.94 | 0.97 | 0.08 | 0.22 | 0.14 | 0.14 | -0.13 | 0.25 | -0.06 | -0.4 | 0.02 | 0.64 | 2.1 |

Figure 4. Pareto charts of tribotechnological system factors effects on: a – friction coefficient \( f_1 \); b – friction coefficient \( f_0 \); c – value of shaft initial wear \( h_{01} \)

Detailed analysis of Pareto chart allows to identify a number of features, in particular, the increasing of the rigidity \( j \) of TS within experiment leads to the increase of all of the characteristics that is impractical. This, apparently, can be explained by the fact that machining of parts of TS with high stiffness leads to the surfaces, the quality parameters of which are higher than the required operating conditions. In this case, the running-in process must match the decrease in the level of these parameters to the operating.

Thus, the provision of the considered tribotechnical characteristics due to the factors of studied tribotechnological system is possible. At that the limits of support intervals for individual characteristics are shown in Figure 5 a, and the reliability \( P \) of their provision [7] in the symmetric relative \( \delta \)-interval is shown in Figure 5 b.

The most reliable is the ratio \( f_1/f_0 \) (at \( \delta = 0.1 P = 0.99 \)), and less reliable is the wear intensity \( I_1 \) и \( I_2 \) (at \( \delta = 0.1 P = 0.32 \) и 0.45, respectively). The high reliability has a friction coefficient after burning
at $\delta = 0.1$ $P = 0.76$.

Intensities of wear $I_1$ and $I_2$ have low reliability of technological provision, but their absolute value is quite low, so considered pairs refer to pairs of sliding friction with high abrasion class. The separation of influence factors on tribotechnical properties on technological and operational characteristics in this case can be considered as inappropriate because the uniform tribotechnological system is considered.

Figure 5. Diagram of variation (a) and the reliability provision $P$ (b) of tribotechnical characteristics depending on values $\delta$

4. Conclusion
An effective combined anti-friction technology for sliding friction surfaces treating of shafts of hardened steel, combining the finishing methods of machining, application of soft running-in film containing copper by friction or chemical means and the subsequent processing of the SPD is proved and developed. As a result of comprehensive research of tribotechnological system (surface treatment and conditions of joints of sliding friction burnish), a number of regularities of formation of parameters of wear resistance is established. The complex of adequate physical-statistical models ‘mode – property’ for tribotechnological system suitable for practical use is obtained.

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