THE INFLUENCE OF HARDNESS OF COOPERATING ELEMENTS ON PERFORMANCE PARAMETERS OF ROLLING KINEMATIC PAIRS

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Abstract
Hardness of an external surface is an important issue in a tribological approach. While the hardness of cooperating elements is a technological feature, it is directly connected with operating features. Two rolling kinematic pairs, with diversified hardness of elements, were accepted as a test object and underwent operating tests. In the article there was presented the analysis of external surface features (motion resistance as well as surface geometric structure) that influence its deformation affecting performance parameters of machines.

Key words: *surface geometric structure, moment of friction, roughness.*

INTRODUCTION

Knowledge on technological state and operational surface layer allows rational control of machine operational use. As a result, it is possible to increase life of machine and reduce the failure frequency.
Technological surface layer changes during the performance of individual treatments and operations provided in the manufacturing process and reaches a certain state upon its completion.
The next stage of the life cycle of a product after manufacture is the operation process characterized by the specific conditions determined by controllable factors and disturbances (uncontrollable ones). During machine operation the state of the surface layer (SL) constantly changes and it is a function of both the exploiting conditions and time (Kaczmarek & Wojciechowski, 1995, Grządziela, et al. 2015). As distinct from technological surface layer, for which relevant is the condition at the end of production state, for operation the current state of surface layer is essential, which is a consequence of the initial state.
Analysis of the extensive literature (Musiał, 2014, Blunt & Jiang, 2003, Dietrych, 1985, Oczoś & Liubimov, 2003, Frýza at al., 2015, Madej, at al., 2015) enabled to determine a set of the most important parameters that should characterize the surface layer ready for operation. According to the adopted order of importance with the diversification following the theory of machines three groups of technological features can be distinguished:

- material (MDF),
- geometrical (GDF),
- dynamical (DDF).

In tribological discussion the most important MDF is hardness of the surface layer. Hardness of cooperating elements is directly related with their performance parameters (Zwirlein & Schlicht, 1982, Łukasiewicz, at al., 2014, Czichos, at al., 1989, Hutchings, 2003, Kostek at al., 2015, Jin, at al., 2012, Kumar at al., 2000).
Characteristics of a kinematic pair are one of the factors of the relation algorithm between technological features and performance parameters of cooperating elements. The characteristics indicate differences in hardness occuring between cooperating surfaces. This feature has a big impact on the transformation of the surface layer which determines performance parameters of machines.
There are following performance parameters of cooperating kinematic pairs:

- wear (linear, volumetric, mass),
- friction (friction moment, resisting force),
- changes in the geometric surface structure.

Presented research results are a part of research related to the above functional characteristics of the surface layer. Below there is presented an analysis of kinematic pairs with diversified hardness of the surface layer regarding: movement resistance determined on the basis of changes of the value of friction moment and changes one of the parameters of the geometrical surface structure - *Ra*.

MATERIALS AND METHODS

Cylindrical roller bearings were the research object. Due to the nature of the load, kinematics of bearing components and the essence of operation of such kinematic pairs in real conditions, major changes appear on the inner ring and therefore during the studies there were observed changes taking place in those surfaces. Races of rolling bearings and rolling elements are made primarily from carbon-chromium steel which is normally subjected to heat treatment. As a result the material is hardened in the range of 55 to 65 HRC. Due to the widespread use of this type of steel in cylindrical rolling bearings specimens made of bearing steel with the designation 100Cr6 with a hardness of 55 HRC were accepted for tests while counter - specimens were made of the same steel but with hardness of 58 HRC - it was a one kinematic pair (with a small difference in hardness). The second kinematic pair (with a large difference in hardness) was the combination of the specimen of aluminum alloy EN AW-6082, and counter specimen the same as in the first combination. The chemical composition of materials used for tests was examined and shown in Tables 1 and 2. Testing of chemical composition were performed with a usage of the spectrometer made by SPECTRO, the SpectroMaxF model.

Tab. 1 The chemical composition of 100Cr6 steel (1.3505)

Si	Mg	Mn	Fe	Cr	Zn	Ti	Cu
investigated							
1,14	1,03	0,91	0,42	0,21	0,15	0,07	0,08
PN-EN 573-3							
0,7 – 1,3	0,6–1,2	0,4–1	≤ 0,5	≤ 0,25	≤ 0,2	≤ 0,1	≤ 0,1

Tab. 2 The chemical composition of EN AW-6082 aluminum alloy (3.2315)

Si	Mg	Mn	Fe	Cr	Zn	Ti	Cu
investigated							
1,14	1,03	0,91	0,42	0,21	0,15	0,07	0,08
PN-EN 573-3							
0,7 – 1,3	0,6–1,2	0,4–1	≤ 0,5	≤ 0,25	≤ 0,2	≤ 0,1	≤ 0,1

Operational tests were carried out with the use of the wear testing machine AMSLER 135. The rotational speed of the specimen was constant at 250 rev / min, the counter - specimen also rotated at a constant speed with a value causing slippage (sliding-rolling motion). In order to accelerate the process of wear, lubrication of combinations was made at the beginning of the test after precise cleaning of specimens and counter specimens using extraction naphtha. On such prepared surfaces there were applied and distributed 3 drops of paraffin. During research environmental conditions were controlled (temperature and relative humidity) in order not to influence the test results.
There were following variable parameters during the operational research:

– parameter describing the geometrical structure of the surface after turning: Ra_T [μm],
– load: P [N],
– time of test: τ [s].

In the experimental research there was used the Hartley PS/DS study plan (static, determined and multi-section one) – P: Ha 3(hK) (Górecka, 1995).

Central point of the plan had coordinates as follows:

– for combinations of aluminum-steel: Ra_T = 4,08 μm, P = 1128 N, τ = 18000 s,
– for combinations of steel-steel: Ra_T = 1,98 μm, P = 1128 N, τ = 18000 s.

The range and values of the load and the operating time of the combination were established on the basis of preliminary tests while the roughness was determined on the basis of the author's research results of the technological surface layer.

RESULTS AND DISCUSSION

Motion resistance expressed by the moment of friction is the main operating feature of rolling kinematic pairs. Dependance of the M_t moment on time τ, load P and roughness Ra_T of the tested tribological node of the combination aluminum- steel is shown in Fig. 1 and for steel- steel in Fig. 2.
On the base of on the figures it can be stated that in both cases the load influences friction the most in the examined nodes. Greater gradient of changes is characterized within a pair of steel - steel. Also, the analyzed values of moments of friction were twice bigger in that combination.

a) b)

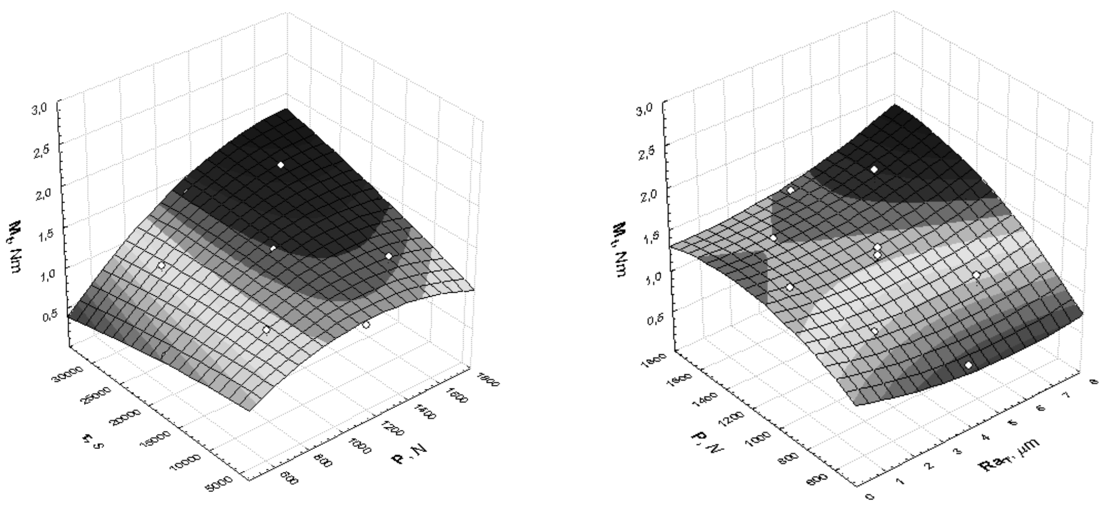

Fig. 1 Relationship chart of the friction moment M_t of the alloy aluminum-steel cooperating pair to: a) time τ and load P, b) load P and roughness Ra_T

a) b)

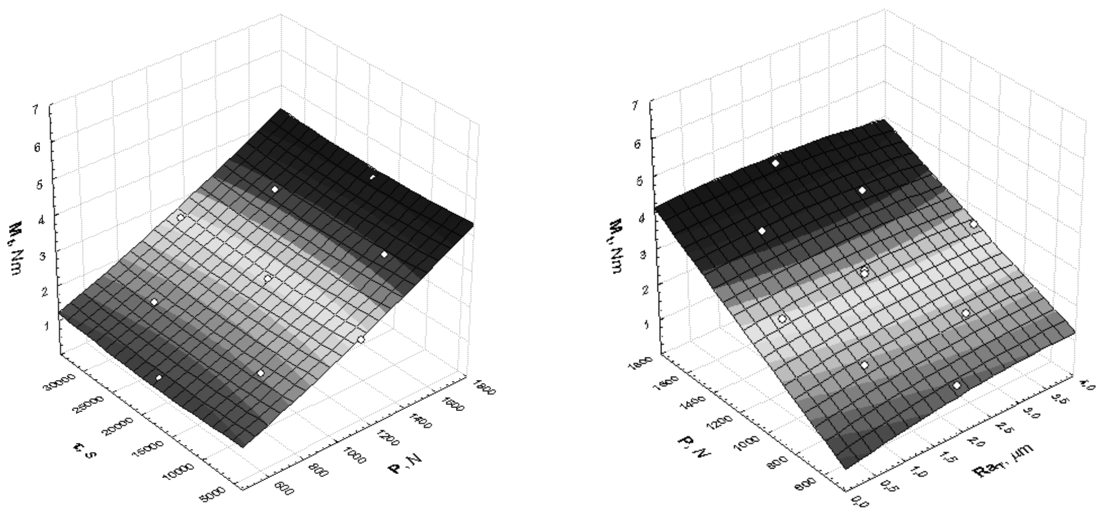

Fig. 2 Relationship chart of the friction moment M_t of the alloy steel-steel cooperating pair to: a) time τ and load P, b) load P and roughness Ra_T

The observed changes were described mathematically by the power function. Regression coefficients necessary in mathematical description of changes of the friction moment for the pair aluminium-steel are presented in Table 3. The rest of mathematical relationships were based on the observed regression coefficients.

Tab. 3 Regression coefficients and their statistical significance $M_t = f\ (Ra_T, P, \tau)$ for the kinematic pair aluminium-steel

	b₀	**b₁** *(Ra_T)*	**b₂** *(P)*	**b₃** *(τ)*
b_i	0,0164	0,0129	0,5492	0,0519
t-Stat	–4,1807	0,1807	5,1102	0,8285
p-value	0,0041	0,8617	0,0014	0,4347

Mathematical relationship taking into account data from Table 3 is defined as:

$$M_t = 0{,}0164 \cdot Ra_T^{0{,}0129} \cdot P^{0{,}5492} \cdot \tau^{0{,}0519} \qquad (1)$$

Wheareas for the pair steel – steel is expressed by the formula:

$$M_t = 0{,}0029 \cdot Ra_T^{-0{,}0394} \cdot P^{0{,}9733} \cdot \tau^{-0{,}0056} \qquad (2)$$

The surface roughness during operation Ra_E was the second of the analyzed parameters. Graph interpretation of variability of the factor for various combinations is shown in Figures 3 and 4.

a) b)

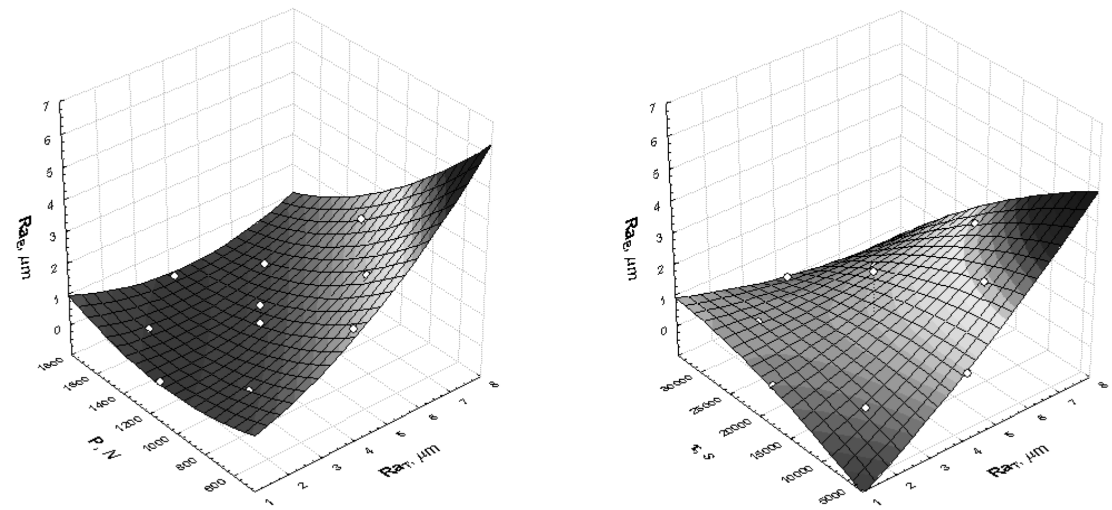

Fig. 3 Relationship chart of of roughness Ra_E of the alloy aluminum-steel cooperating pair to: a) time τ and load P, b) load P and roughness Ra_T

a) b)

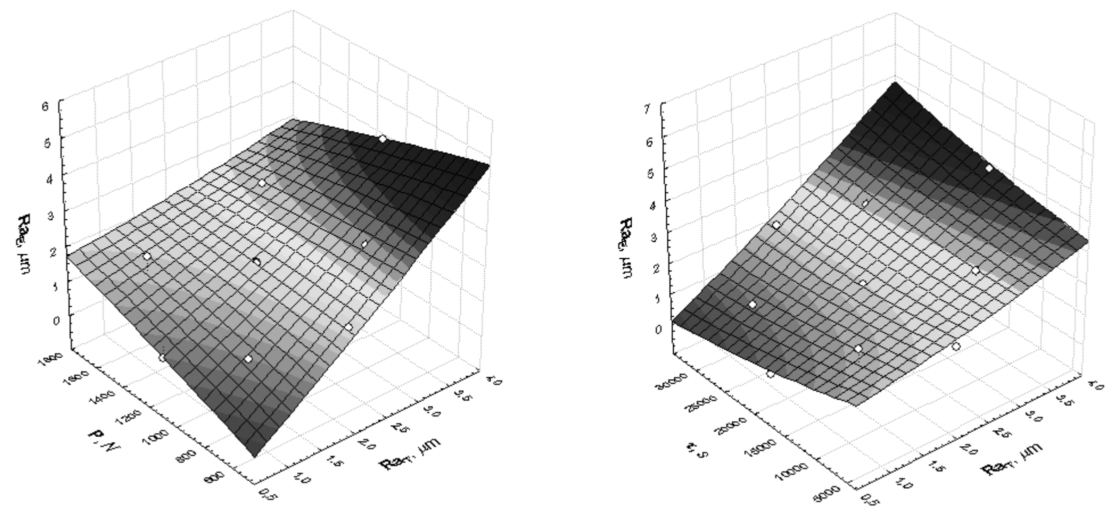

Fig. 4 Relationship chart of roughness Ra_E of the alloy steel-steel cooperating pair to: a) time τ and load P, b) load P and roughness Ra_T

On the basis of Figure 4 it should be noted that when the load was increasing the value of the parameter Ra_E was decreasing which is a result of flattening of surface vertices of the specimen made of aluminum alloy - Figure 5.

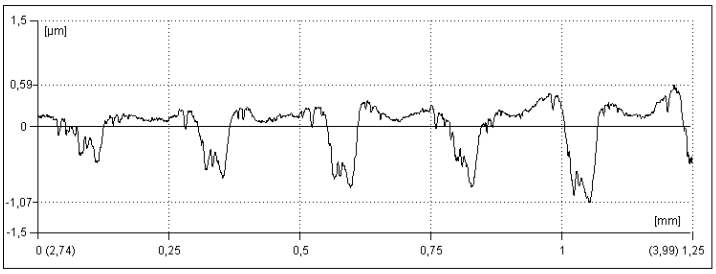

Fig. 5. Example of the surface roughness profile of the specimen EN AW-6082

The lower influence of the load was observed in the combination with similar hardness (steel-steel) where there was only a slight rounding of vertices of the tested surfaces – Figure 6.

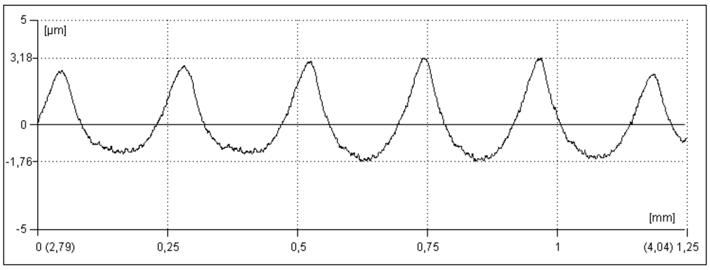

Fig. 6 Example of the surface roughness profile of the specimen 100Cr6

Mathematical description of surface roughness changes for the pair aluminium – steel is defined as (3):

$$Ra_E = 1473285 \cdot Ra_T^{1,0929} \cdot P^{-1,7509} \cdot \tau^{-0,3948} \quad (3)$$

The detailed form of equation of changes of the Ra_E parameters of the pair steel – steel is presented below (4):

$$Ra_E = 0,8931 \cdot Ra_T^{0,9052} \cdot P^{0,1525} \cdot \tau^{-0,0883} \quad (4)$$

CONCLUSIONS

The difference in hardness of cooperating elements has significant impact on performance parameters of kinematic pairs. Larger values of the moment of friction are present in the combination with similar hardness of elements which is mainly caused by the load. The load also determines changes in the combination with a large difference in surface hardness.

Comparing the surface roughness in the studied pairs the different nature of changes has to be noted. Along with the duration of tests the Ra_E value decreases for aluminum – steel specimens and increases for steel-steel specimens in the testing range.

Proper selection of the hardness of cooperating surfaces has impact on the lifespan and the failure rate of machines.

In order to verify research results, especially in order to apply them in practice, the authors consider to perform a set of tests in conditions of an accredited test laboratory on the base of their own experience (Szczutkowski, 2012, 2015)

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