The use of surface layer with boron in friction pairs lubricated by engine oils

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Abstract. The aim of the present work is to determine the influence of surface layers with boron and engine oil on the processes of friction and wear in friction pairs. The ring samples with borided surface layer cooperated under test conditions with counterparts made with CuPb30 and AlSn20 bearing alloys. During the tests, the friction pairs were lubricated with 15W/40 Lotos mineral oil and 5W/40 Lotos synthetic oil. The lubrication of friction area with Lotos mineral oil causes the reduction of the friction force, the temperature in the friction area and the wear of the bearing alloys under study, whereas the lubrication with Lotos synthetic oil reduces the changes in the geometrical structure of the cooperating friction pair elements. Lubrication of the friction area in the start-up phase of the friction pair by mineral oil causes faster stabilization of the friction conditions in the contact area than in the cause of lubrication of the friction pair by synthetic oil. The intensity of wear of the AlSn20 bearing alloy cooperating with the borided surface layer is three times smaller than the intensity of use of the CuPb30 alloy bearing.

1. Introduction

Design and modernization of the means of transport includes problems with the reliability and the durability of the construction. The reliability and durability of the construction is the result of the selection of appropriate forming technology of elements and components working in kinematics systems of the means of transport. Modern technology aims to create the elements working under maximum unit pressure, at high relative speeds of movable elements and high temperature of operation of kinematics systems. The implementation of these processes is possible by the application of surface layers with suitable tribological properties, such as wear resistance, low friction coefficient, corrosion resistance and seize resistance. The development of production processes of surface layers of kinematic elements of friction pairs and the knowledge of forming the selected parameters of these elements allows for the use surface layers with boron in a friction pair as an element affecting the performance characteristics. The modification of the surface layers with boron can be performed using various technologies: diffusion of boron in the surface layer of materials and their alloys, spraying coating containing boron and as an added element of metal alloy in metallurgical processes [8]. Boronizing is a thermochemical process that is widely used for boride-type coating. Borides formed in steel surfaces significantly increases their hardness (about 2,000 HV), wear resistance, and corrosion resistance [4, 7]. The tribological properties of these layers depend on the physical state of boride source used, boronizing temperature, treatment time, properties of the boronized materials, as well as any possible thermal treatment [10]. Boronizing is very effective, especially on grey and ductile iron.
or low-alloy steel with chromium [1, 2]. Current boronizing processes allow for obtaining surface layers with high hardness, improved wear resistance, and low friction coefficient [6, 8], with low brittleness and no tendencies toward cracking [2].

These properties cause the increasing interest in the use of these surface layers on the parts working under wearing conditions. However, the main interest in the literature is in the use of boron to form surface layer in the friction pairs operating under abrasive wear without lubrication.

The paper presents the influence of the type of engine oils on the conditions of friction and wear in the friction pairs with the elements containing boron in the surface layers. The tests were carried out under limited lubrication with the use of engine oil in order to determine the impact of the surface layer with boron and the lubricant on processes of friction and wear.

2. Experimental
The aim of the study is to determine the influence of the technological surface layer with boron on the friction parameters in sliding pairs under lubricated friction conditions. The research involves the determination of work parameters of friction pairs as a function of bearing material, engine oil and changeable parameters of the load of friction pairs. In the research, the friction pairs were composed of a ring sample and a counterpart made from bushing bearings (figure 1).

![Figure 1. Friction pair; 1-ring sample, 2 counterpart](image1)

Ring samples (figure 2a) were made of 46Cr2 steel and were borided in powder at a temperature of 950°C for 8 hours, and then were austempered. In the boronizing process, the powder of the following composition was used: B4C (30%), Al2O3 (68%), NH4Cl, and NaF. The borided layers obtained the characteristic structure (“tooth-shaped”) with a hardness of 2000 HV and a thickness of 40 μm (figure 3). The ring samples with borided layer cooperated during the test with the counterpart made from AlSn20 and CuPb30 bearing alloys (figure 2b) and the area of friction was lubricated with the engine oils: Lotos mineral 15W/40 and Lotos synthetic 5W/40.

Stand test was conducted on a T-05 block on ring tester. The tests were executed by following a specified algorithm, which included the initial running-in of the samples and the correct co-operation process at the pre-determined load parameters. The running-in was executed on a test site at a pressure of 5 MPa until a complete adhesion of the ring specimen and the counterpart was achieved. At the
starting phase, it was assumed that the pair would be accelerated from a speed of 0 to 500 rpm in 30 s and the friction coefficient was measured as a function of pressure. The friction force, the temperature in the friction area and the wear of materials of the elements of friction pairs were tested under pre-determined conditions: the ring specimen rotational speed of 100 rpm and the unit pressure of 5, 10, 15 and 20 MPa.

3. Results of research
The work of friction pairs during start-up stage was characterized by high dynamics of tribological processes as a consequence of external loads which had an important influence on lubrication conditions. Assessment of changes is possible by registering the friction coefficient as a function of variable velocity and configuration of friction pairs (bearing alloys and the type of engine oils)

![Figure 4. Friction coefficient in the friction pairs with the AlSn20 alloy counterpart lubricated by mineral oil and synthetic oil.](image)

![Figure 5. Friction coefficient in the friction pairs with the CuPb30 alloy counterpart lubricated by mineral oil and synthetic oil.](image)

The record of change of friction coefficient in the start-up phase of friction pairs showed a fast growth of friction resistance up to the point of achieving a maximum value and then a decrease of friction resistance was observed with the growth of velocity (figure 4, 5). In the friction pairs lubricated with the mineral oil a significant decrease of the friction coefficient were observed. In the
friction pairs with the AlSn20 bearing alloy counterparts the leveling of the compensation friction coefficient at the level $\mu \sim 0.05$ from speed of 0.5 m/s was observed (figure 4). But, in the case of friction pairs with the CuPb30 bearing alloy counterparts the scattering of the friction coefficient from $\mu = 0.06$ to $\mu = 0.095$ was observed. The lowest friction coefficient was recorded at the pressure of 5MPa, the maximum friction coefficient occurred at the pressure 10 MPa (figure 5). When used to lubricate the friction area the synthetic oil was observed to have had important change in the course of friction coefficient with reference to the registered in friction pairs lubricated with mineral oil. In the friction pairs with the AlSn20 bearing alloy counterparts stabilization of frictional resistance was observed, but there are two groups of pairs. At low unit pressures of 5-10 MPa there significant decrease of the friction coefficient below $\mu = 0.02$, and at high unit pressures of 15-20 MPa, the friction coefficient is stabilized at a level of $\mu = 0.06$ (figure 4). Important changes in the friction processes occurred in the friction pair with the CuPb30 bearing alloy counterparts which had high coefficient of friction; $\mu \sim 0.2$ for unit pressure from 10 to 20 MPa. In friction pairs at the pressure of 5 MPa, the friction coefficient stabilizes at the level of $\mu = 0.13$ (figure 5). In these pairs, at the unit pressure of 5-10 MPa, a significant decrease of the friction resistance was observed at the velocity 0.5-0.6 m/s, then the friction coefficient increased and then it stabilized itself.

![Graph](image.png)

**Figure 6.** Influence of the bearing alloy and the type of engine oil on the start-up moment in function of the load of a friction pair.

Another significant aspect pertaining to friction pairs is determination of the value of the start-up moment. The results of the measurements of the maximum the start-up moment differed significantly. The differences depended on the type of bearing alloys used and the type of engine oils applied to lubricate the friction area (figure 5). The use of the Lotus mineral oil in the lubrication of friction area generated a lower start-up moment in pairs with the CuPb30 bearing alloy counterparts as compared to the pairs with the AlSn20 bearing alloy counterparts. The use of the Lotos synthetic oil in friction pairs changed the friction conditions. In the pairs with the AlSn20 bearing alloy counterparts a lower start-up moment was observed than in the friction pairs with the CuPb30 bearing alloy counterparts. By analysing the value of the moment of friction significant differences can also be seen between the pairs with CuPb30 and AlSn20 bearing alloy counterparts. Under the conditions of lubrication by Lotos mineral oil, the difference in the start-up moment between the researched pairs is ~24% at the pressure of 5MPa and it decreased with the increase unit pressure and at the unit pressure of 15 MPa, the start-up moment was at the similar level. However, at the pressure of 20 MPa, the start-up moment was again higher in the pairs with AlSn20 counterparts by about 12% than in the pairs with CuPb30 counterparts. The use of the Lotos synthetic oil for lubrication generated lower start-up moment in the pairs with AlSn20 counterparts by about 10 % (at the pressure 5 MPa) than in pairs with CuPb30 counterparts. The increase of the unit pressure also caused the increase of the start-up moment and at the pressure of 20 MPa, the difference between the researched pairs was more than 35%. The recorded
maximum start-up moment can be the basis for the design of the friction pairs in terms of providing an adequate level of load at the time of start-up or creating adequate friction conditions. This allows one to determine the energy necessary to properly start the machine and allows for the design of friction pairs in terms of heat load. The differences between the start-up moment in the researched pairs are mainly the effect of the impact of the surface layer in the friction elements, the lubricant and the intensity of the formation of boundary layers which reduce the frictional resistance [9].

Figure 7. Influence bearing alloy and type of engine oil on friction forces and temperature depending on unit pressure (at 100 rpm and after 500 s).

The influence of engine oils on the friction conditions in the friction pairs with elements including boron in surface layers was tested under pre-determined conditions, at the ring specimen rotational speed of 100 rpm and at the jump unit pressure of 5, 10, 15 and 20 MPa. With the lubrication of the friction area by Lotus mineral oil, higher values of friction force were observed in friction pairs with the CuPb30 bearing alloy counterparts than in friction pairs with the AlSn20 bearing alloy counterparts. These changes were particularly important at lower unit pressures. An increase of the unit pressure caused a decrease of the percentage difference and when the unit pressures accounted for 20 MPa, the difference was 12%. A similar character of changes is observed during the recording of temperature in the friction area. The measurements showed higher temperature in friction pairs with the CuPb30 bearing alloy counterparts, compared to the friction pairs with the AlSn20 bearing alloy counterparts. Also, the difference of temperature between the researched friction pairs decreased with the increase of unit pressure (from 26% at the pressure of 5 MPa to 4% at the pressures of 20 MPa). The lubrication by Lotos synthetic oil generated higher friction force and temperature in friction pairs with the AlSn20 bearing alloy counterparts. The trend of these changes was observed at the unit pressure of above 10 MPa. At low unit pressures of 5 MPa, the friction forces and temperatures in friction pairs with the AlSn20 bearing alloy counterparts were lower than in the pairs with the CuPb30 bearing alloy counterparts. Under these conditions of lubrication in the friction pairs, the percentage difference between the friction pairs with the AlSn20 bearing alloy counterparts and the ones with the CuPb30 bearing alloy counterparts was 10% for friction force and 9% for temperature (at the pressures of 20 MPa).

In the friction contact area of the cooperating surface layers, the removal processes of the material occurred, caused by a relative movement of the friction elements. The results of the stand test have shown no measurable weight loss of the material of ring samples. Significant changes were observed only in the topography of the surface layer (Table 2). Instead, the measurement of wear of the bearing alloys has shown that the wear intensity of the AlSn20 alloy is significantly lower compared to the wear intensity of CuPb30 alloy (figure 5). Also, the application of the engine oils to the friction pairs has exerted an important influence on the wear of the bearing alloys - the use of mineral oil reduced the wear intensity of researched bearing alloys. In the conditions of lubrication by the mineral oil, the
wear intensity of the CuPb30 alloy is almost three times higher than that measured for the AlSn20 alloy. On the other hand, under the lubrication by the synthetic oil, the maximum difference in the value of wear intensity of the researched bearing alloys is ~ 250%.

![Figure 8. Wear intensity of bearing alloy material vs. unit pressure and type of engine oil used for lubrication of friction pairs.](image)

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| Parameter of surface roughness | Ring sample borided in powder | Counterpart |
|-------------------------------|-------------------------------|-------------|
|                               | CuPb30                        | AlSn20      |
| Ra                            | 0.42                          | 0.48        |
| Rz                            | 4.9                           | 3.0         |
| Ry                            | 5.3                           | 3.4         |
| Sm                            | 88                            | 48          |

The measurements of surface roughness of the friction pair elements after the tests revealed significant changes in the Ra, Rz and Sm parameters of roughness, as compared to the values of those parameters before the tests (Table 1). The measurements of the Ra parameter of ring sample showed that in the friction pair lubricated synthetic oil the Ra parameter was much smaller than in the friction pairs lubricated mineral oil (Table 2). Important change of Ra parameter was observed in the friction pairs with CuPb30 bearing alloy counterparts when were lubricated mineral oil - the Ra parameter increased by 37% compared to the surface roughness before the tests and when the friction pair was lubricated synthetic oil the Ra parameter increased by ~ 11%. Similar changes were observed when the Ry parameter was measured/while measuring the Ry parameter. During the co-operation of the friction pairs with the AlSn20 bearing alloy counterparts lubricated by the synthetic oil, a reduction/decrease of 5%. in the value of the Ry roughness parameter was observed. In the case of Rz
parameter, a reduction/decrease of surface roughness was observed, except for friction pairs with the CuPb30 bearing alloy counterparts lubricated by the mineral oil, where the Rz parameter of surface roughness increased by 12%. Measurements of Sm parameter have shown its growth in the case of lubrication by mineral oil, and in the case of synthetic oil, a minimal decrease of stabilization of the Sm parameter roughness was observed.

### Table 2. Surface roughness of ring samples after test.

| Parameter of surface roughness | Counterpart CuPb30 | Counterpart AlSn20 |
|--------------------------------|-------------------|--------------------|
|                                | Mineral oil       | Synthetic oil      |
| Value (μm) | Change (%) | Value (μm) | Change (%) | Value (μm) | Change (%) | Value (μm) | Change (%) |
| Ra        | 0.58      | 37        | 0.47      | 11        | 0.59      | 39        | 0.54      | 29        |
| Rz        | 5.5       | 12        | 4.9       | -1        | 4.2       | -15       | 3.4       | -32       |
| Ry        | 7.7       | 44        | 6.8       | 27        | 6.4       | 21        | 5.0       | -5        |
| Sm        | 92        | 4         | 86        | -3        | 97        | 10        | 88        | 0         |

### Table 3. Surface roughness of counterpart after test.

| Parameter of surface roughness | Mineral oil       | Synthetic oil      |
|--------------------------------|-------------------|--------------------|
|                                | CuPb30            | AlSn20             |
|                                | Value (μm) | Change (%) | Value (μm) | Change (%) | Value (μm) | Change (%) | Value (μm) | Change (%) |
| Ra        | 1.26      | 152        | 0.58      | 71        | 1.04      | 108       | 0.54      | 59        |
| Rz        | 8.9       | 197        | 3.9       | 11        | 8.0       | 167       | 3.6       | 3         |
| Ry        | 12.9      | 279        | 5.1       | 4         | 11.3      | 232       | 5.0       | 2         |
| Sm        | 150       | 213        | 135       | 93        | 113       | 135       | 122       | 74        |

The measurements of counterparts made of bearing alloys showed an increase of their surface roughness (Table 3). The surface layer measurements of the counterparts indicated more substantial changes than in the case of ring samples, the largest of them exceeding even several dozen percent. The biggest changes were recorded for the parameter Ry, which in the case of the Lotos mineral oil increased by 279%, and in the conditions of lubrication by the Lotos synthetic oil - by 232%. Also, significant changes were recorded for parameters Sm, Rm and Ra. The changes of parameters measured in the friction pairs with the AlSn20 bearing alloy counterparts were at a lower level and did not exceed 93%, while in the case of the Sm and Ra parameters – they reached 71%. The lowest change observed in the case of the Rz and Ry parameters amounted to a few percent (a maximum 11% in the conditions of lubrication by Lotos mineral oil). In the case of both materials, higher values of the surface roughness could be observed in the friction pairs lubricated by the Lotos mineral oil, in relation to the pairs lubricated by the Lotos synthetic oil.

### 4. Discussion

The start-up phase of sliding pairs indicates the behaviour of the system during its further work until the modified layer is used up. The most favourable operating conditions are presented in sliding pairs in which the friction coefficient increases in the initial stage of start-up, and then decreases significantly and stabilises itself at a constant level. Those sliding pairs which exhibited the tribochemical equilibrium within the shortest time generate optimal conditions for their further operation. The physiochemical processes and the changes in the surface microgeometry caused the adaptation of the system to the conditions of friction. The registered change of the friction force reveal the ability of the sliding pairs to adapt to the friction conditions in the extension of the pair’s operation time. The changes occurring in the reaction of the pair to the stabilization forces upon the start-up, and to the time flow, explain whether the system allows for a long-term and reliable operation or not. The stabilisation of the friction resistances indicates the adaptation of the pair to the existing forces and the
generation of stable anti-wear and anti-seizure layers. The created surface layers ensure a separation of the co-operating elements of friction pairs and a reduced rate of direct adhesion between the surface irregularities. These conditions create a state of equilibrium between the processes of layer destruction and creation within the tribochemical processes occurring in the friction pair [9].

The use of AlSn20 bearing alloy in friction pairs had an impact on the reduction of wear. This is mainly due to the continuous and homogeneous construction of the sliding layer of the AlSn20 bearing alloy, which enables formation of a hard, thin, continuous layer of aluminium oxide. However, in the case of the CuPb30 alloy, the high temperature in the contact area promotes the formation of brittle cracks in the layer of friction, and the organic acids in the oil cause leaching of lead, exposing the copper structure of the bearing material. In this situation, the products of wear caused by friction may accumulate in the resulting discontinuity areas of the friction layer and interact with the processes on the surface layer of the second element, which causes its cutting and enhances wear [11].

The differences in the wear of the bearing alloys and the absence of measurable wear of the surface layer ring specimen were the effect of the interaction between the cooperating surface layers, as well as of the physiochemical changes of their surfaces that were induced by external forces [9]. These phenomena result from the elementary wear processes that occurred within the contact area of the sliding pair on the elementary surfaces of the cooperating layers. The lubrication factor is crucial for these processes, because it creates favourable or unfavourable friction conditions depending on its transformation. These changes contribute to the generation of boundary layers on the surface layers of the cooperating elements that are either highly resistant to ruptures or are quickly destroyed under variable operating conditions [5]. The high wear of bearing alloy observed in pairs is explained by the increased initial surface roughness and the load of the system. Due to the influence of the hard areas on the areas of the second material, a stress concentration occurs, which leads to the interaction between the two surface layers and a more intense abrasion of the softer material [11]. These changes may lead to the smoothening of the surface and removal of its irregularities, which eliminates the potential sources of further material transfer and stabilizes the wear process. However, the hard wear products created in the friction process induce chipping, slicing, and grinding, which intensify the wear process [11].

The surface roughness parameters measured indicated the intensity of friction and its influence on the shaping of the sliding pair’s geometric structure. As an effect of the processes occurring within the friction area under the external forces, the system processes the preexisting geometric structures of both elements into a system with a structure that ensures the most favourable friction conditions [3]. As a result of these changes, a structure was created that reflected the changes, ensuring the given association of a certain optimal functionality; that is, an operating surface layer was generated. In pairs where this kind of relationship does not exist and the load conditions as well as pair composition cannot create a state of equilibrium, the effect is the destruction of a kinematic sliding pair [11].

5. Conclusions
The following conclusions may be drawn on the basis of the experimental test performed and the analysis of their results:
1. Lubrication of the friction area by Lotos mineral oil reduces start-up moment, friction force, temperature in the friction area and wear of tested bearing alloys;
2. Lubrication of the friction area in the start-up phase of the friction pair by mineral oil caused a faster stabilization of the friction conditions in the contact area than when synthetic oil was used for lubrication of the friction pair.
3. The intensity of wear of the AlSn20 bearing alloy cooperating with the borided surface layer is three times smaller than the intensity of wear of the CuPb30 bearing alloy;
4. The surface roughness of the ring samples and bearing alloy counterparts showed less change in the geometric structure of the friction pair elements lubricated by Lotus synthetic oil in relation to the friction pair elements lubricated by Lotus mineral oil;
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