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TRIBOLOGICAL PROPERTIES OF SLIDING PAIRS WITH SURFACE LAYER CONTAINING BORON UNDER MIXED FRICTION CONDITIONS

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Abstract

The aim of the present work is to determine the influence of surface layers containing boron on the friction parameters in sliding pairs under mixed friction conditions. The tribological evaluation included three production methods of surface layers with boron; pack boronizing, laser boronizing, and TiB_2 coating deposited on 46Cr2 steel. Modified surface layers of ring specimens with 46Cr2 steel were matched under test conditions with a counterpart made from AlSn20 bearing alloy. Tested sliding pairs were lubricated with 5W/40 Lotos synthetic engine oil. The applied modification technologies of the surface layer of steel allowed for obtaining construction materials with pre-determined tribological characteristics required for the elements of sliding pairs working undermixed friction conditions. The results showed differences in the wear of bearing alloy, as the effect of the interaction between the co-operating surface layers and of the physiochemical changes of their surfaces, induced by external forces. The TiB_2 coating generated the highest friction resistance and bearing alloy wear. The pack borided surface layer reduces the friction coefficient, the moment during the start-up of the frictional pair and the wear of the bearing material. The analysis of the surface layer indicated that the content of aluminum on pack borided ring specimens reached 21%, and on the TiB_2 coating, it exceeded 8%.

Keywords: *surface treatment, wear, sliding friction, boron, bearing alloy*

1. Introduction

The tribo-systems, with relative motion between interacting surfaces, are required to run smoothly even under severe operating conditions such as larger contact loads, higher speeds, and higher temperatures. The demand for increased performance of machine components has forced the use of substitute materials for sliding-contact especially under mixed friction conditions. The modification with boron can be carried out by means of various technologies, such as: diffusion of boron into the surface layer, creation of coatings containing boron or as an alloy addition in metallurgical processes [1].

Boronizing being a thermochemical process is widely used for boride-type coating. Borides formed on the steels surfaces increases their hardness (about 2000 HV), wear resistance and corrosion resistance [2, 3]. The tribological properties of these layers depend on a physical state of boride source used, boronizing temperature, treatment time, properties of the boronized materials, as well as any possible thermal treatment [4]. Current boronizing processes allow obtaining surface layers of high hardness, improved wear resistance, low coefficient of friction and with low brittleness and no tendencies towards cracking [5, 6].

Properties of metal borides coatings are very attractive because they can be used under severe operating conditions, whereas conventional tribo-metals exhibit performance difficulties at larger loads, higher speeds, and higher temperatures on low cost engineering materials. Titanium diboride (TiB_2) is a transition metal based refractory ceramic with a hexagonal structure and a metallic chemical bonding character. Recently TiB_2 has gained growing interest from industry and researchers due to its unique functional properties linked to its high hardness, high melting point, and high wear and corrosion resistance [7, 8]. Titanium diboride is a material which has a great potential for tribological application.

The modification of the material with boron should be selected upon the required operating characteristics and the operating conditions of the kinematic sliding pairs [3, 9]. Thus, it is crucial to determine the influence of the elements of sliding pairs modified with boron on the operating conditions and wear of the pairs during lubricated friction.

2. Experimental

In the experiments, three types of surface treatments were used in the creation of surface layers of ring specimens from 46Cr2 steel. The obtained layers were then matched under test conditions with counterparts made from AlSn20 bearing alloy. Ring specimens were borided in powder (B_4C (30%), Al_2O_3 (68%), NH_4Cl and NaF), in the temperature of 950°C in the time of 8h, and then were austempered. Ring specimens from 46Cr2 steel were also laser-borided, with the use of CO_2 laser (spot diameter of 4 mm, energy density of 160 W/mm^2, tracking speed of 16 mm/s, gas carrier – argon). Also, the ring specimens were covered with the TiB_2 coating using PVD method (temperature of 400°C, time of 40 min, pressure in ionization chamber of 2.5 x 10^{-3} MPa). The tribological tests were conducted on a T-05 block-on-ring tester (Fig. 1). Tested sliding pairs were lubricated with 15W/40 Lotos synthetic engine oil.

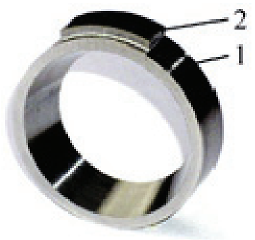

Fig. 1. The sliding pair: 1 – ring specimen, 2 – counterpart

3. Results

After the completion of the tests, the ring samples and the counterparts surface roughness measurements have exhibited significant changes on the surface layer (Tab. 2) in comparison with the initial value of parameters R_a, R_z and S_m (Tab. 1).

Tab. 1. Surface roughness of ring sample and counterpart before test [μm]

Parameter of surface roughness	Ring specimen			Counterpart AlSn20
	pack borided	TiB_2 coating	laser borided	
R_a	0.42	0.51	0.30	0.34
R_z	4.9	4.4	2.7	3.2
S_m	88	41	55	70

The measurement results do not allow one unique function connecting these changes to be determined with the configuration of the surface layer. However, some specific trends of changes in the selected surface roughness parameters R_a, R_z and S_m can be determined in a number of specific sliding pairs. The sliding pairs with laser borided surface layer ring samples revealed an increase in all the values of the parameters tested. The pack borided surface layer and TiB_2 coating samples exhibited a decrease of the R_z parameter after the tests. The TiB_2 coating samples also exhibited a 29% decrease in the R_a parameter. The most significant changes counter samples can be observed in the R_a and S_m parameters, which increased especially in correlation with the pack borided surface layer (59 and 74%) and laser borided surface layer (100 and 49%). The R_z parameter reveals a smaller increase and R_z values in pairs with pack borided surface layers. TiB_2 coating increased by 3% and in the pair with laser borided surface layers it increased by about 16%.

Tab. 2. Surface roughness of annular sample and counterpart after test

Parameter of surface roughness	Ring specimen		Counterpart	
	Value [μm]	Change[%]	Value[μm]	Change[%]
Pack borided surfacelayer				
R_a	0.54	29	0.54	59
R_z	3.4	–32	3.6	3
S_m	88	0	122	74
TiB_2 coating				
R_a	0.36	–29	0.43	26
R_z	2.8	–36	3.6	3
S_m	46	12	81	16
Laser borided surfacelayer				
R_a	0.34	13	0.68	100
R_z	3.4	26	4.05	16
S_m	99	80	104	49

The co-operation of a sliding pair is characterised by a large dynamics in the start-up stage of the frictional work. The assessment of the occurring changes is possible by registering the friction coefficient as a function of variable rotation speed (Fig. 2). During the first start-up phase, a rapid increase in the frictional resistance occurs, followed by its significant drop. Most of the sliding pairs under study are characterized by the decline of friction resistance coupled with the rise of the rotational speed of the ring sample. Under 5 MPa pressure, and after exceeding 100 rpm, the value of a friction coefficient in the sliding pairs with powder borided layers and with the TiB_2 coating significantly declines and it stabilizes at a level of approximately 0.0015. In the laser-borided sliding pairs, a considerable decline of friction resistance is noted after exceeding 280 rpm and in this case, it stabilizes at a level of approximately 0.006. In the friction pairs examined under a pressure of 10 to 20 MPa, the processes of rise, decline and stabilization of friction resistance can all be observed. The decline of friction resistance takes place mainly in the friction pairs with the powder-borided layers. And so, under a pressure of 10 MPa, a substantial decline of the friction coefficient from 0.04 to 0.02 takes place after exceeding 220 rpm of the ring samples. Under higher pressure, the exceeding of 320 rpm causes the stabilization of the friction coefficient and then, it amounts to 0.04 under 15 MPa pressure and 0.06 under 20 MPa pressure. In the sliding pairs with laser-borided layers, mostly stabilization of the friction coefficient can be observed. It is only under a pressure of 10 MPa and with 230 rpm, that a minimal value of the friction coefficient can be noted (0.04). In these sliding pairs, the highest values of friction resistance were registered. They amounted to 0,095 under a pressure of 15 MPa and 0.124 under a pressure of 20 MPa. In the friction pairs with the TiB_2 coating, the value of the friction coefficient declines to 0.045 under a pressure of 20 MPa (the lowest value of the friction coefficient amongst the sliding pairs under study), but after exceeding 400 rpm, it rises to the values observed in the sliding pairs with the powder-borided layer. Low values of the friction coefficient have been registered in the sliding pair with the TiB_2 coating under a pressure of 10 MPa, where up to 220 rpm, the value of the friction coefficient is the lowest among all pairs under study, and with a rotating speed of 430 rpm, the local minimum takes place. Under the 15 MPa pressure, the friction resistance in this friction pair is stable and the value of the friction coefficient amounts to 0.073.

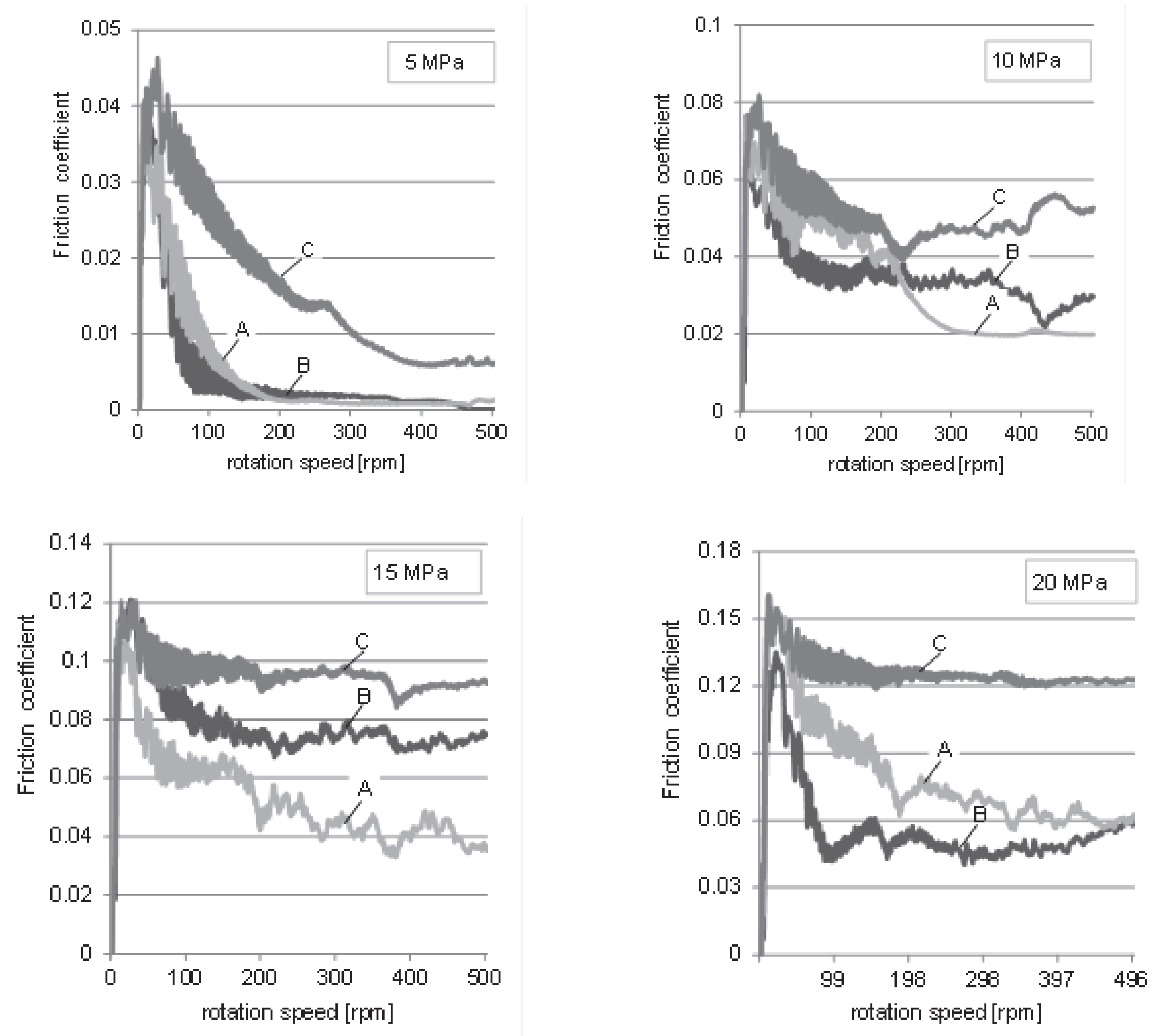

Fig. 2. Friction coefficient of ring specimens submitted to different surface treatment versus rotation speed: A – pack borided, B – coated TiB_2, C – laser borided

Another significant aspect pertaining to sliding pairs is to determine the value of the start-up moment (Fig. 3). During the tests, the lowest friction resistances were recorded for the pairs with TiB_2, which have similar values of approximately 9.7 Nm (at 20 MPa). Significant increases of the start-up moment (about 10%) occur in pairs with pack and laser borided surface layer of ring specimens. Similar moment changes are observed at pressures of 5 and 10 MPa in the pair with pack borided surface layer and TiB_2 coating of ring specimens. The pairs with laser surface layers have the friction resistance values higher by 15%. The pairs with TiB_2 at a pressure of 15 MPa showed a higher start-up moment than those recorded in other researched pairs.

Significant changes of the friction force and temperature values within the friction area occur under singular pressures of 5, 10, 15 and 20 MPa (Fig. 4). The friction-force level values for the pairs with pack borided samples do not exceed 240 N (at 200 MPa). Its value for the TiB_2 pairs is about 270 N and amounts to 300 N for the laser boronizing pairs. The lowest friction force values at low-pressure conditions (at 5 MPa) were measured in pairs with TiB_2 specimens. At a pressure of 10 MPa, the friction force increases by 50% in pairs with laser borided surface layer and TiB_2 coating in comparison to the pairs with pack borided layer. Further increase of pressure up to 15 MPa in a pair with pack borided surface layer decreases the tendency toward the rise of the friction force. The laser borided and TiB_2 coating pairs exhibit the intensity of changes within the pressure range of 5 to 10 MPa at a similar level. The temperature measurements following the conclusion of the tests have indicated the lowest heat in sliding pairs with the pack borided samples (about 96°C).

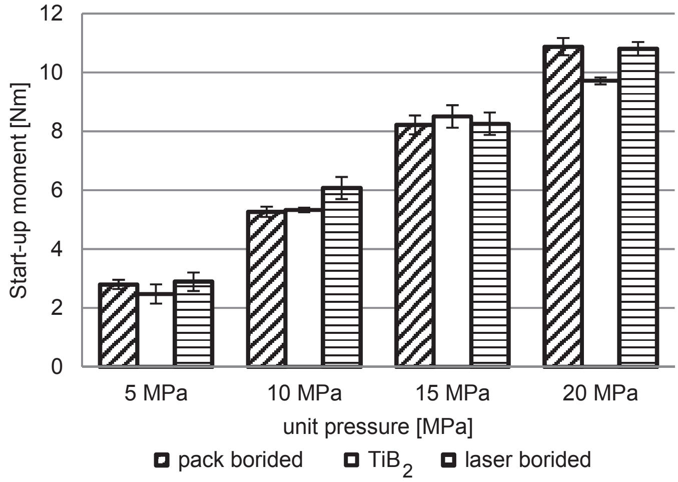

Fig. 3. Influence of surface modified ring specimen on start-up moment in function load of kinematics pair

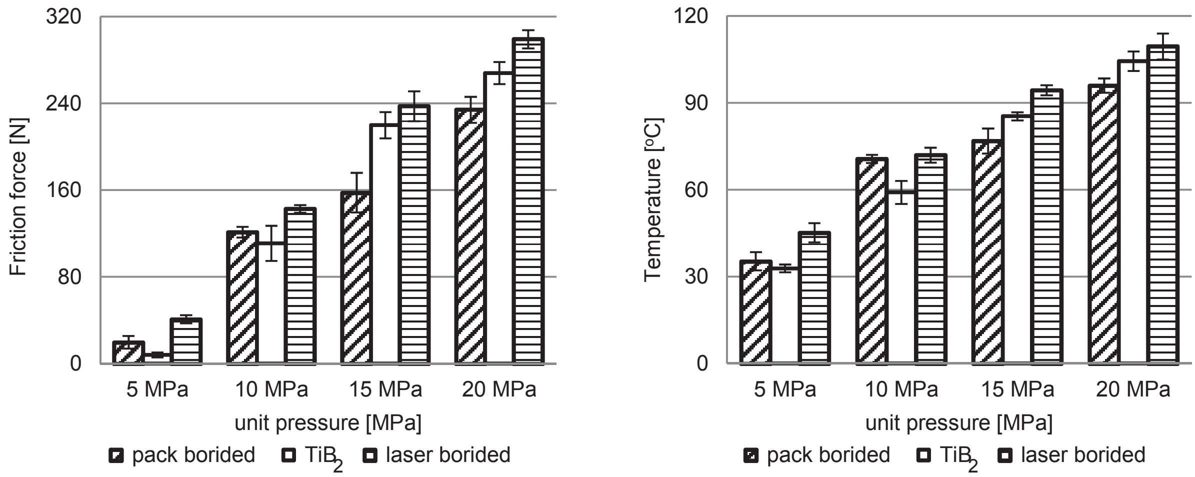

Fig. 4. Influence of surface treatment of ring specimen on friction forces and temperature depending on unit pressure and rotation speed of ring specimen (at 100 rpm and after 500 s)

The highest temperature values were noted for the pairs with the TiB_2 coating (about 104°C) and laser borided surface layer (109°C). The change of the surface pressure affects the temperature increase within the pair's adhesion area proportionally. In the pack borided surface layer pairs, the intensity of the temperature increase is higher for the low-pressure range (5–10 MPa) but smaller for pressures (10–20 MPa). In the surface layer of all other pairs tested, however, the changes tend to be quite the opposite; higher unit pressures will decrease the intensity of the temperature increase within the friction area.

The measurements of wear of the friction pair elements have indicated that boron-modified ring samples did not show the measurable linear wear, whereas, the wear rate of the cooperating counterparts from the ALSN20 alloy depends on the modified surface layer (Fig. 5). The wear rate describes the value of linear wear in relation to the duration of the time interval within which it occurred. The highest wear rate takes place in the sliding pairs with the TiB_2 coating. Also, an increase of wear has been registered in this sliding pair after exceeding 10 MPa. A similar character of the wear can be observed in the sliding pair with the laser-borided layer. However, the registered values of wear under small pressures from 5 to 15 MPa have shown that wear of the counterparts in the sliding pairs with the laser-borided sample and the powder-borided sample are comparable. The rise of pressure above 15 MPa causes a significant increase of the wear process in the sliding pair with the laser-borided sample.

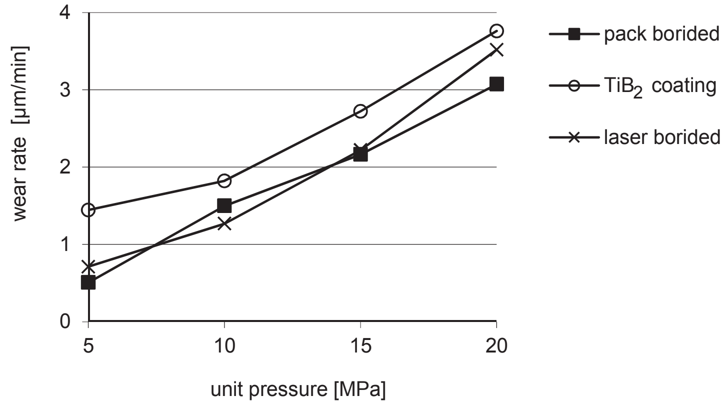

Fig. 5. Wear of counterpart with bearing alloy AlSn20 during cooperation with ring specimen (at 100 rpm)

The material transfer was observed in the sliding pairs with pack borided surface layer (Fig. 6) and TiB_2 coating (Fig. 7). The observation of the surface layer of the ring specimens demonstrated that a transfer occurred during the tests especially that of aluminum, the basic element of the AlSn20 bearing alloy. However, insubstantial amounts of zinc were also registered. Such a significant transfer of AlSn20 alloy material was not observed in the case of the sliding pairs with laser borided ring specimens. The pack borided ring specimens were unevenly covered with aluminum, whereas the ring specimens with TiB_2 coating were covered with an even layer of aluminum throughout the whole contact area of the sliding pairs. The percentage analysis showed that the content of aluminum on the surface layer of pack borided ring specimens reaches 21%, and on the TiB_2 coating, it exceeds 8%. The observation results of the ring specimens' surface layers indicated that aluminum has a strong tendency towards adhesion to surface layers tested during the sliding friction. Additionally, in the pack borided ring specimens, there could be observed an accumulation of aluminum in the areas where cracks appeared in the surface layer.

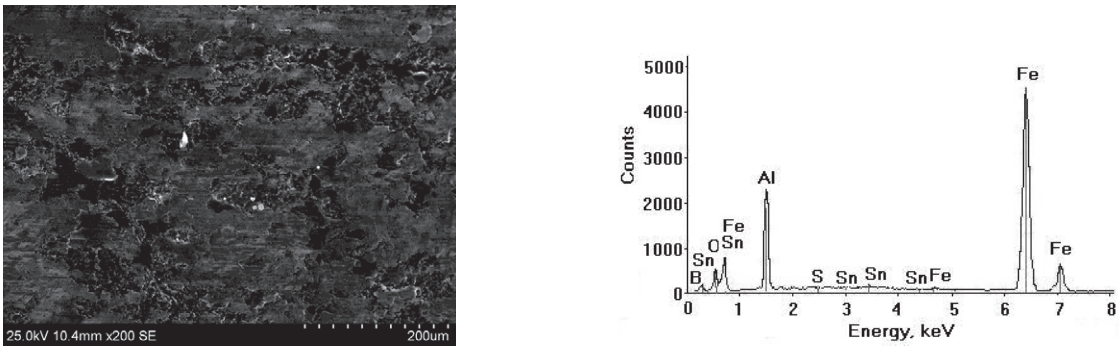

Fig. 6. SEM micrographs the pack borided surface layer and EDS analysis

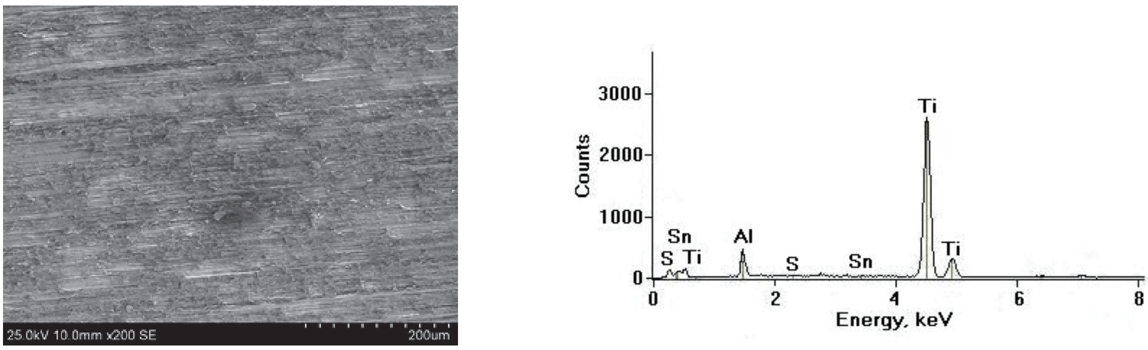

Fig. 7. SEM micrographs the TiB_2 coatings and EDS analysis

4. Discussion

The surface roughness parameters measured indicate about the intensity of friction and its influence on the shaping of the sliding pair's geometric structure. In effect of the processes occurring within the friction area under the external forces, the system processes the pre-existing geometric structures of both elements into a system with a structure which ensures the most favourable friction conditions. As a result of these changes, a structure is created which reflects the changes ensuring the given association of a certain optimal functionality, i.e. an operating surface layer is generated. In pairs where this kind of relationship does not exist and the load conditions, as well as the pair composition, cannot create a state of equilibrium, the effect is the destruction of a kinematic sliding pair [11, 12]

The changes of the friction coefficient during the start-up phase indicates the behaviour of the system during its further work until the modified layer is used up. The most favourable operating conditions are present 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. The value of the moment determines the energy demand of the system upon its start-up. Those sliding pairs which exhibited the tribochemical equilibrium within the shortest time generate optimal conditions for their further operation. The changes registered are the result of physiochemical processes and the changes in the friction surface micro-geometry due to the adaptation of the system to the conditions of external forces. In the sliding pairs, which exhibit a significant decrease in the friction coefficient, the improvement in the friction conditions depends on the increase in the effectiveness of the lubrication by the oil, due to the existing tribochemical changes. The stabilisation of the friction resistances and temperature indicates the adaptation of the pair to the existing forces and the generation of stable anti-wear and anti-seizure layers [13].

The wear of bearing alloy and the absence of measurable surface layer ring specimen wear changes are the effect of the interaction between the co-operating surface layers, as well as of the physiochemical changes of their surfaces, induced by external forces. These phenomena result from the elementary wear processes occurring within the contact area of the sliding pair, on the elementary surfaces of the cooperating layers. The lubrication factor is crucial for these processes, as it creates favourable or unfavourable friction conditions, depending on its transformation. These changes contribute to the generation of boundary layers on the layers created which are either highly resistant to ruptures or are quickly destroyed under variable operating conditions. The co-operation conditions also include the secondary phenomena of the friction and wear process. Among these are the effects of the wear products on the frictional surface layers, material transfer, electron emissions and the corrosion current flow [12].

The high wear of bearing alloy observed in pairs with the TiB_2 coating 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 [12]. 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 stabilises the wear process. However, the hard wear products created in the friction process induce chipping, slicing and grinding, which intensify the wear process. The examination of the rough layers indicates that the wear of the surface layer in the friction process depends not only on the peak-to-valley heights, but also on their shape and the direction of the machining lines. Decreased surface wear is observed with the greater surface roughness when the co-operating surface layers have the machining lines parallel to the sliding direction [11].

5. Conclusions

On the basis of this investigation, the results of this study can be summarised as follows:

1. The surface roughness shaped in the friction pair depends on the initial roughness, friction conditions and the applied surface treatment. The registered trends do not lead to the decrease

in surface roughness, but rather help to create an optimal geometrical structure and friction conditions for a given pair.

2. Pack borided surface layers decrease friction resistance during the start-up of the sliding pair, as well as lower the level of the friction force and temperature in the friction area.
3. In the sliding pairs with the TiB_2 coating were measured the highest friction resistance and bearing alloy wear, however no measurable wear of the coating itself was noted.
4. The material transfer had a significant impact on the friction and wear processes in the friction pairs with pack borided surface layers and in those with the TiB_2 coating. The percentage analysis showed that the content of aluminum on the surface layer of pack borided ring specimens reached 21%, and on the TiB_2 coating, it exceeded 8%.

References

[1] Taktak, S., *Tribological Behaviour of Borided Bearing Steels at Elevated Temperatures,* Surface and Coating Technology, Vol. 201, pp. 2230-2239, 2006.

[2] Bejar, M. A., Moreno, E., *Abrasive Wear Resistance of Boronized Carbon and Low-Alloy Steel*, Journal of Materials Processing Technology, Vol. 173, pp. 352-358, 2006.

[3] Duzcukoglu, H., Calik, A., Imrek, H., Karakas, M. S., *Examination of Pitting and Wear in Borided, Carburized, and Borocarburized AISI 8620 Gears*, Tribology Transations, Vol. 53, pp. 485-490, 2006.

[4] Pranay, H., Liang, M., Usta, A. H., *Wear and Surface Characterization of Boronized Pure Iron*, Journal of Tribology, Vol. 129, pp. 1-10, 2007.

[5] Atik, E. Yunker, U, Meric, C., *The Effect of Conventional Heat Treatment and Boronizing on Abrasive Wear and Corrosion of SAE 1010, SAE 1040, D2 and 304 Steels*, Tribolology International, Vol. 36, pp. 155-161, 2003.

[6] Lubas, J., *Practical Application of Boron-Modified Sliding Pairs in I.C. Engine*, Tribolology International, Vol. 43, pp. 2046-2050, 2010.

[7] Panish, N. Wangyao, P. Hannongbua, S. Sricharoenchai, P. Sun, Y., *Tribological Study of Nano-Multilayer Ultra-Hard Coatings Based on* TiB_2, Reviews on Advanced Materials Science, Vol. 13, pp. 117-124, 2006.

[8] Basu, B., Vleugels, J., Van Der Biest, O., *Fretting Wear Behavior of* TiB_2*-Based Materials Against bearing Steel Under Water and Oil Lubrication*, Wear, Vol. 250, pp. 631-641, 2001.

[9] Komvopoulos, K., Pernama, S. A., Ma, J., Yamaguchi, E. S., Ryason, P. R., *Synergistic Effects of Boron-, Sulfur-, and Phosphorus-Containing Lubricants in Boundary Lubrication of Steel Surfaces*, Tribolology Transations, Vol. 48, pp. 218-229, 2005.

[10] Nehme, G., Mourhatch, R., Aswath, P. B., *Effect of Contact Load and Lubricant Volume on the Properties of Tribofilms Formed Under Boundary Lubrication in a Fully Formulated Oil Under Extreme Load Conditions*, Wear, Vol. 268, pp. 1129-1147, 2010.

[11] Guha, D. Chowdhuri, R., *The Effect of Surface Roughness on the Temperature at the Contact Between Sliding Bodies*, Wear, Vol. 197, pp. 63-73, 1996.

[12] Schouwenaars, R. Jacobo, V. H., Ortiz, A., *Microstructure Aspect of Wear in Soft Tribological Alloys*, Wear, Vol. 263, pp. 727-735, 2007.

[13] Nehme, G., Mourhatch, R., Aswath, P. B., *Effect of Contact Load and Lubricant Volume on the Properties of Tribofilms Formed Under Boundary Lubrication in a Fully Formulated Oil Under Extreme Load Conditions*, Wear, Vol. 268, pp. 1129-1147, 2010.