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TRIBOLOGICAL PROPERTIES OF SURFACE LAYER WITH BORON

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Abstract

The aim of the present work is to determine the influence of technologically produced boron surface layers on the friction parameters in the sliding pairs under the conditions of mixed friction. The tribological evaluation included ion nitrided, pack borided, laser borided, quenched and tempered surface layers and TiB2 coating deposited on 38CrAlMo5-10, 46Cr2 and 30MnB4 steels. Modified surface layers of annular samples were matched under test conditions with counter-sample made from AlSn20 bearing alloy. Tested sliding pairs were lubricated 15W/40 Lotos mineral engine oil. The tribological tests were conducted on a T-05 block on ring tester. The applied steel surface layer modification with boron allow creating surface layers with pre-determined tribological characteristics required for the elements of kinematic pairs operating in the conditions of sliding friction. Pack boronizing reduces the friction coefficient during the start-up of the frictional pair and the maximum start-up resistance level is similar to the levels of pairs with nitrided surface layers. Paper present comparison between surface roughness of annular sample and countersample before and after test, influence of surface treatment annular sample on change of friction coefficient vs. rotation speed and load, influence of surface treatment annular sample on moment of friction in function load of kinematics pair, influence of surface treatment annular sample on friction forces and temperature depending on load, as well as influence of surface treatment annular sample on wear of AlSn20 bearing alloy under various load conditions.

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

1. Introduction

The surface of engineering components is subjected to higher stresses and greater fatigue, abrasion and corrosive damages than the interior. Therefore, more than 90 pct of the service failures of engineering components initiate at the surface. Surface modification techniques are employed to improve the resistance to failure by producing a hard and wear resistance layer around a soft and tough core. Two major classes of treatments available for enhancing the surface properties are thermal and thermochemical. Thermal treatment, such as flame and induction hardening, modify the microstructure without modifying the surface chemistry, whereas in thermochemical methods, the surface chemistry is altered.

Boronizing transforms the surface of engineering elements into a metallic boride layer. The boride layer is formed by diffusion of boron atoms in the base metal at high temperature [1-4]. Diffusion of boron into the surface of various metals and alloys results in the formation of metallic borides which provide extremely hard (up to 2000HV), wear and corrosion resistant surface [5, 6]. This treatment is a thermochemical treatment in which a material is kept in a boron-giving environmental from 850 to 1000^{o}C for 2-10 h [2, 7]. Various processes adopted for boronizing include pack boriding, molten salt boriding, vacuum boriding, laser boriding, etc. The resulting layer may consist of either single-phase boride (FeB or FeB_2) or polyphase boride layer (FeB and FeB_2). The tribological properties variations of FeB and FeB_2 layers depends on physical state of boride source used, boronizing temperature, treatment time, and properties of the boronized material [8]. Industrial boriding can be carried out on most ferrous and non-ferrous materials. Boronizing is very effective, especially on grey and ductile iron or low alloy steel with chromium.

If boronizing applied to a material surface the resultant boride layer increases the wear resistance considerably. Furthermore, it decreases the friction coefficient [7]. The use of ceramics materials for many tribological applications has increased considerably over pas two decades. This is effect of the unique combination of properties this materials, such as low bulk density, high corrosion resistance, low thermal expansion and high hardness over a wide range if temperature. Titanium diboride (TiB_2) belongs to this group of materials and is well know for its high hardness, high melting point, the relatively high strength, high chemical stability at height temperature and high wear resistance [9, 10]. Titanium diboride is promising class of advanced materials which have a great potential for tribological application.

The current boronizing processes allow obtaining surface layers of high hardness and high resistance to corrosion and wear, with low brittleness and no tendencies towards cracking [3]. However, the operation characteristics of these layers depend on the chemical composition, the structure of the surface layer, the method and parameters of their production, as well as any possible thermal treatment. The modification of the surface layer with boron should be selected upon the required operating characteristics and the operating conditions of the kinematic sliding pair [4-7]. Thus, it is crucial to determine the influence the boron modification of the sliding pair elements has on the operating conditions and wear during the mixed friction.

2. Experimental details

The aim of this work is to determine the influence of technologically produced boron surface layers on the friction parameters in the kinematic pairs under the conditions of sliding friction. The tribological tests were conducted on a T-05 block on ring tester (Fig. 1).

Fig. 1. The sliding pair; 1-annual sample, 2-counter-sample

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Three types of steel were used in the creation of annular samples, 38CrAlMo5-10, 46Cr2 and 30MnB4. Annular samples from 38CrAlMo5-10 steel were ion nitrided in the atmosphere H2 + N2, in the temperature of 500°C and in the time of 6h. Annular samples from 46Cr2 steel were borided in powder, in the temperature of 950°C in the time of 8h, and then were isothermally hardening. In the boronizing process of the following composition was used, B4C (30%), Al2O3 (68%), NH4Cl and NaF). Annular samples from 46Cr2 steel were also laser borided, with the use of CO_2 laser (power of beam P=2 kW, spot diameter d=4 mm, energy density 160 W/mm^2, tracking speed v=16 mm/s, gas carrier –argon). The boronizing process consisted in covering the annular sample with the layer of amorphous boron and liquid glass, and melting with the laser beam. Also, the annular samples from steel 46Cr2 were covered with the TiB_2 coating using PVD method (temperature 400°C, time 40min, pressure in ionization chamber p=2.5 x 10^{-2} bar). Annular sampler from 30MnB4 steel were hardening and tempering, hardening in the temperature of 800°C and drawing temper in the temperature of 450°C. Modified surface layers of annular samples were matched under test conditions with counter samples made from AlSn20 bearing alloy. Tested sliding pairs were lubricated 15W/40 Lotos mineral engine oil.

Tab. 1. Surface roughness of annular sample and countersample before test [μm]

Parameter of surface roughness	Annular sample					Counter sample AlSn20
	ion nitrided	pack borided	quenched and tempered	TiB_2 layer	laser boride	
R_a	0.32	0.42	0.29	0.51	0.30	0.34
R_z	2.5	4.9	2.1	4.4	2.7	3.2
S_m	52	88	38	41	55	70

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

Parameter of surface roughness	Annular sample		Countersample	
	Value [μm]	Change [%]	Value [μm]	Change [%]
ion nitrided surface layer				
R_a	0.36	13	0.44	29
R_z	2.7	8	4.9	40
S_m	68	31	82	17
pack borided surface layer				
R_a	0.59	39	0.58	71
R_z	4.2	-15	3.9	11
S_m	97	10	135	93
quenched and tempered surface layer				
R_a	0.39	33	0.42	20
R_z	2.9	36	4.5	29
S_m	51	33	78	11
TiB_2 coating				
R_a	0.48	-6	0.47	38
R_z	3.2	-27	3.7	6
S_m	44	7	89	27
laser borided surface layer				
R_a	0.36	20	0.65	91
R_z	3.2	19	4.1	17
S_m	97	76	98	40

4. Results and discussion

After the finish of the tests, the annular samples and the counter samples surface roughness measurements have exhibited significant changes on the surface layer. The annular samples' surface roughness parameters R_a, R_z i S_m have increased by values varying from several to several dozen percent (Tab. 2) in comparison to the initial value (Tab. 1). The measurement results do not allow determining one unique function connecting these changes with the configuration of the surface layer. However, some specific trends of changes in the selected surface roughness parameters R_a, R_z i S_m can be determined in a number of specific sliding pairs. The sliding pairs with nitrided, laser borided, and quenched and tempered surface layer annular samples revealed an increase in all of 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 6% decrease in the R_a parameter. The counter-sample surface roughness measurements revealed greater changes in the surface layer structure after the tests than the parameters observed on the co-operating annular samples' surface layers. The only exception is the association with the quenched and tempered surface layer, where the counter-sample surface roughness values measured are lower than the ones measured before testing. The most significant changes can be observed in the R_a and S_m parameters, which increased by several dozen percent, especially in correlation with the pack borided surface layer (71 and 93%) and laser borided surface layer (91 and 40%). The R_z parameter reveals a smaller increase, between ten and twenty in association with the pack borided surface layers and coating TiB_2. The R_z values in pairs with quenched and tempered surface layers increased by 29% and in pair with nitrided surface layers increased about 40%.

The surface roughness parameters measured tells 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 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 disequilibrium is observed in associations with the pack borided annular samples, where a large difference occurs between the final surface roughness of the annular samples and the counter-samples. These changes are created due to a variable distribution of micro-hardness on the annular sample's cylinder generator, which enhances the deformation of apexes, as an effect of friction wear and plastic deformation under the singular pressure and the temperature rise. The friction processes do not have to lead to a decrease in the peak-to-valley height of the surfaces cooperating within a pair to their initial values, but they shape the surface roughness of the ground-in surface layer as an individual characteristic of the association composition and the pair's operating conditions [13].

The co-operation of a kinematic sliding pair is characterised by the large dynamics of the measured parameters' values, due to external forces. Determination of these changes' tendencies is especially important 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 sliding speed (Fig. 2). The registered charts present the typical courses of the friction coefficient for the 'ring-block' frictional pairs under the load of 20 MPa. During the first start-up phase, a rapid increase in the frictional resistance occurs, followed by its significant drop. The registered courses of the friction coefficient for the higher sliding speeds are diversified. There are sliding pairs, with an increase in the sliding speed of the annular sample, which cause the increase in the friction coefficient. These variations occur in the pairs with nitrided and laser borided surface layers, after exceeding the sliding speed of 0.6 m/s and after 0.2 m/s for the pairs with the TiB_2 coating. The measured value of the friction coefficient level in the associations with thepack borided and TiB2 coating equals approximately 0.11. As for the pairs with 30MnB4 steel annular samples, an increase in the sliding speeds leads to the stabilisation of the friction coefficient values, while the pack borided pairs exhibited a decrease in this value (to its lowest possible level $\mu=0.02$) along with an increase in the sliding speed.

Another significant aspect pertaining to kinematic 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 nitrided, pack borided and quenched and tempered surface layer, which have similar values of approximately 8 Nm (at 20MPa). Significant increases of the friction moment (by about 20%) occur in pairs with TiB_2 coating and laser boronizing surface layer of annular samples. Similar moment changes are observed at the pressure of 10 and 15 MPa. The pairs with nitrided surface layers and coating TiB_2 reach the friction moment value at about 2 Nm under singular pressures (at 5 MPa), while the pairs with pack borided surface layers have the friction resistance values higher by 15%.

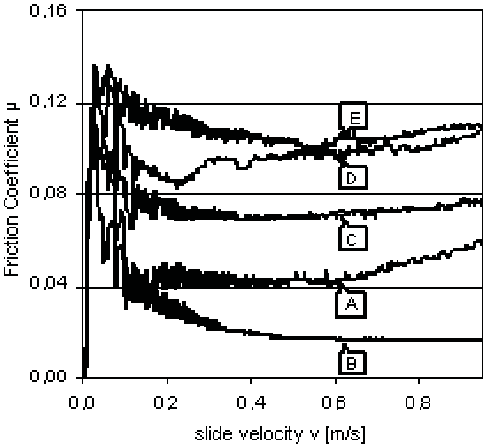

Fig. 2. Influence of surface treatment annular sample on change of friction coefficient vs. rotation speed and load 20MPa; A–ion nitrided, B– pack borided, C–quenched and tempered, D–coating TiB_2, E– laser borided

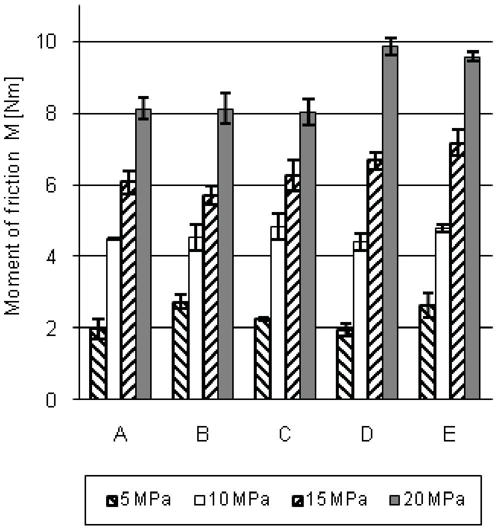

Fig. 3. Influence of surface treatment annular sample on moment of friction in function load of kinematics pair; A–ion nitrided, B– pack borided, C–quenched and tempered, D–coating TiB_2, E– laser borided

The observation of the friction parameter changes during the start-up phase tells about the behaviour of the system during its further work. 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 physical chemical processes and the changes in the friction surface micro-geometry due to the adaptation of the system to the conditions of external forces [14, 15]. In kinematic 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 coat, due to the existing tribochemical changes. These changes are shaped by the existing load state of the kinematic sliding pair, the temperature levels and the chemical reaction occurring within the area of friction. As an effect of the changes in the oil chemical composition and the synthesis of new chemical compounds, a boundary layer is created, which strengthens the anti-wear layer by changing its structure and decreases the movement resistances. These changes lead to the further decrease in the friction resistance, accompanied by the increase in the sliding speed of the annular sample [14, 15].

Significant changes of the friction force and temperature values within the friction area occur under singular pressures p=5, 10, 15 and 20 MPa (Fig. 4). The friction-force level values for the pairs with ion nitrided, pack borided, quenched and tempered samples are similar and do not exceed 200 N (at 200 MPa). Its value for the laser boronizing pairs is 270 N and amounts to 341 N for the TiB_2 pairs. The lowest friction force values at low-pressure conditions (at 5 MPa) were measured in pairs with nitrided and pack borided surface layer pairs. At the pressure of 10 MPa, the friction force increases by 50% in pairs with pack borided surface layer in comparison to the pairs with nitrided surface 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 quenched and tempered, laser borided surface layer 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 quenched and tempered surface layer (below 80^oC). The highest temperature values were noted for the pairs with the TiB_2 coating (about 111^oC) and pack borided surface layer (104^oC). The change of the surface pressure affects the temperature increase within the pair's adhesion area proportionally. In the nitrided and pack borided surface layer pairs, the intensity of the temperature increase is smaller for the low-pressure range (5-10 MPa) than for the higher pressures (10-20 MPa). In the surface layer of all other pairs tested, however, the changes tend to be quite the

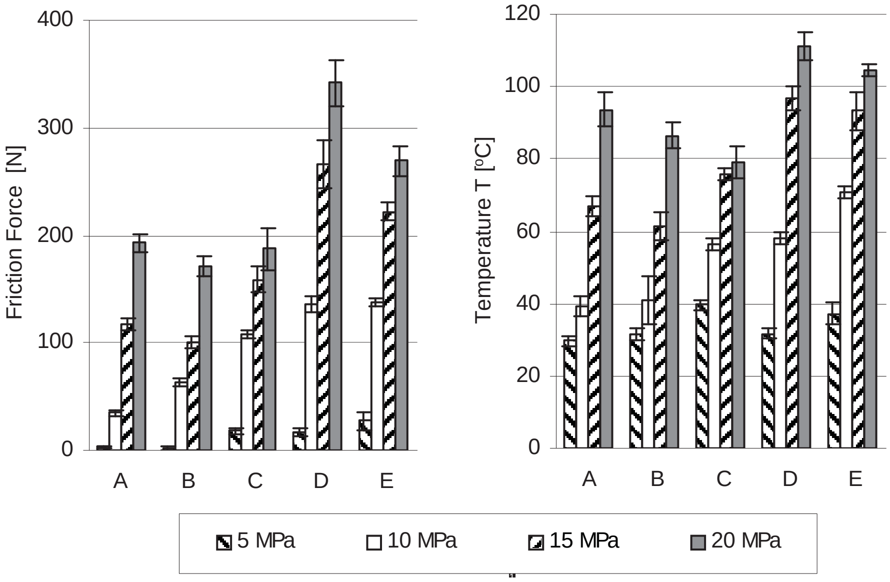

Fig. 4. Influence of surface treatment annular sample on friction forces and temperature depending on load (rotation speed 100 rpm); A–ion nitrided, B– pack borided, C–quenched and tempered, D–coating TiB_2, E– laser borided

opposite; higher singular pressures will decrease the intensity of the temperature increase within the friction area.

The registered courses of the friction force and temperature 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 stabilised forcing upon the start-up, and to the time flow, explain whether the system allows for a long-term and reliable operation or not. In the initial period of the pair's operation, there is always an intense increase in the friction coefficient, followed by its drop and stabilisation or increase. The stabilisation of the friction resistances indicates the adaptation of the pair composition to the existing forces and the generation of stable anti-wear and anti-seizure layers. The layers ensure the separation of the co-operating surface layer areas and a reduced rate of direct adhesion between the surface irregularities [14]. These conditions create a state of equilibrium between the processes of layer destruction and creation within the tribochemical processes occurring in the friction pair. The changes of the friction resistance and temperature allow assessing the probability of the kinematic sliding pair's failure caused by the acting external forces and the emergency use of the pair [15].

These load conditions were also used for the wear measurements of the AlSn20 bearing alloy. The lowest wear was measured for pairs with nitrided, pack borided and quenched and tempered surface layer and did not exceed 0.01 mg of the bearing alloy's mass, while the value dispersion was below 20% (Fig. 5). The pairs with the TiB_2 coating and laser borided surface layer exhibit almost twice the wear above, amounting to 0.015 mg for the laser borided surface layer and 0.018 mg for the TiB_2 coating.

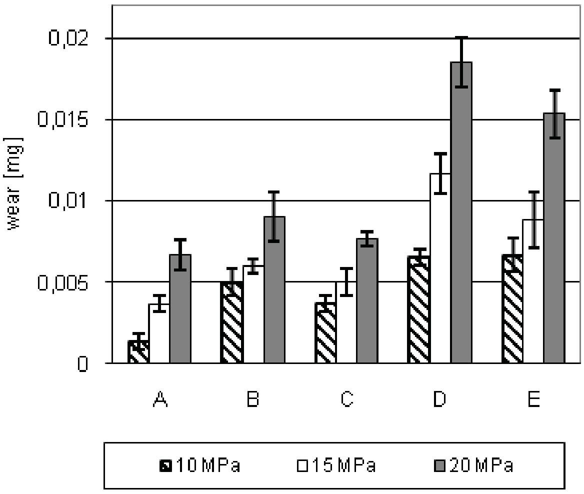

Fig. 5. Influence of surface treatment annular sample on wear of AlSn20 bearing alloy under various load conditions: A–ion nitrided, B– pack borided, C–quenched and tempered, D–coating TiB_2, E– laser borided

The occurring differences in the wear of bearing alloy and the absence of measurable surface layer annular sample wear changes are the effect of the interaction between the co-operating surface layers, as well as of the physical chemical 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, which 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, transmission of one element's particles onto the other, electron emissions and the corrosion current flow [16]. The material transmission processes were observed mostly in pack boronizing annular samples and samples with TiB_2 coating. 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. These changes may lead to smoothening of the surface and removal of its irregularities with 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. This increases the bearing alloy wear, especially because the created TiB_2 coating is characterised by a non-uniform and undirected distribution of the peak-to-valley height. 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 [17].

5. Conclusions

The following conclusions may be arrived at on the basis of the experimental tests performed and analysis of their results:

1. The applied steel surface layer modification with boron allow creating surface layers with pre-determined tribological characteristics required for the elements of kinematic sliding pairs operating in the conditions of mixed friction.
2. The process surface layers on annular samples, generated by nitride-, boron- and thermal-hardening, as well as by PVD, did not demonstrate measurable wear.
3. Boron-hardening reduces the friction coefficient during the start-up of the frictional pair and the maximum start-up resistance level is similar to the levels of pairs with nitrided surface layers.
4. The use of thermally-hardened 30MnB4 steel in kinematic sliding pairs ensures the operating parameters and bearing alloy wear ratio are similar to the sets with nitrided steel.
5. The highest friction resistance and bearing alloy wear levels were measured in sliding pairs with laser boronizing samples and with the TiB_2 coating.

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