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TRIBOLOGICAL CHARACTERISTICS OF THE SURFACE LAYER OF STEEL MODIFIED WITH BORON UNDER MIXED FRICTION CONDITIONS

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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 mixed friction conditions. 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 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 tribological evaluation included ion nitriding, powder-pack boronizing, laser boronizing, hardening and tempering surface layers and TiB_2 *coating deposited on ring samples. The ring samples were made from 38CrAlMo5-10, 46Cr2 and 30MnB4 steel. Modified surface layers of ring 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 sliding pairs operating under mixed friction conditions. 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 ion nitride surface layers.*

Keywords: *tribology, surface modification, boron surface layers, AlSn20 bearing alloy, friction coefficient*

1. Introduction

Therefore, more than 90 pct of the service failures of engineering components are initiated 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. The boride layer is formed by diffusion of boron atoms in the base metal at high temperature [1-3]. 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 [4, 5]. This treatment is a thermochemical treatment in which a material is kept in a boron-giving environmental from 850 to 1000^oC for 2-10 h [6]. Various processes adopted for boronizing include pack boriding, molten salt boriding, vacuum boriding, laser boriding, etc. If boronizing was applied to a material surface, the resultant boride layer increases the wear resistance considerably, there could even be observed a decrease the friction coefficient [6, 8]. Boride layers are also produced more and more often with the use of PVD method. The use of these methods 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 tribological properties borided layers depends on physical state of boride source used, boronizing temperature, treatment time, and properties of the boronized material and processes use for creation of surface layer [8].

The modification of the surface layer with boron should be selected upon the required operating characteristics and the operating conditions of the kinematic sliding pairs [4-6]. 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.

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

2. Experimental

In the tribological test used three types of steel in the creation of ring samples, 38CrAlMo5-10, 46Cr2 and 30MnB4 (Fig. 1). Ring samples from 38CrAlMo5-10 steel were ion nitriding in the atmosphere H_2 + N_2, in the temperature of 500°C and in the time of 6h. Ring samples from 46Cr2 steel were borided in powder, in the temperature of 950°C in the time of 8h, and then were isothermally quenched hardened. In the boronizing process powder of the following composition was used, B_4C (30%), Al_2O_3 (68%), NH_4Cl and NaF). Ring 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 ring sample with the layer of amorphous boron and liquid glass, and melting with the laser beam. Also, the ring samples from steel 46Cr2 were covered with the TiB2 coating using PVD method (temperature 400oC, time 40min, pressure in ionization chamber p=2,5 x 10-2 bar). Ring 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 ring samples were matched under test conditions with counter samples made from AlSn20 bearing alloy. The tribological tests were conducted on a T-05 block on ring tester and sliding pairs were lubricated 15W/40 Lotos mineral engine oil.

The surface layer produced by a powder-pack boronizing had a ‘needle’ boron configuration of 2000 HV0,1 of hardness and was 40 μm thick. A laser boron coating resulted with a molten layer with 0.5-1% boron content and variable micro-hardness along the cylinder’s generator (max. 1800HV). After thermal processing, the 30MnB4 steel samples attained a martensitic structure with 40HRC of hardness; a TiB_2 coating has a hardness value of about 3000 HV0,05, while a nitrided surface layer has a hardness of 1100 HV.

3. Results and discussion

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 kinematic sliding pairs, with an increase in the sliding speed of the ring sample, which cause the increase in the friction coefficient. These variations occur in the pairs with nitrided 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 the laser borided layer and TiB_2 coating equals approximately 0.11. As for the pairs with 30MnB4 steel ring samples, an increase in the sliding speeds leads to the stabilisation of the friction coefficient values, while the powder-park boronizing pairs exhibited a decrease in this value (to its lowest possible level μ=0.02) along with an increase in the sliding speed.

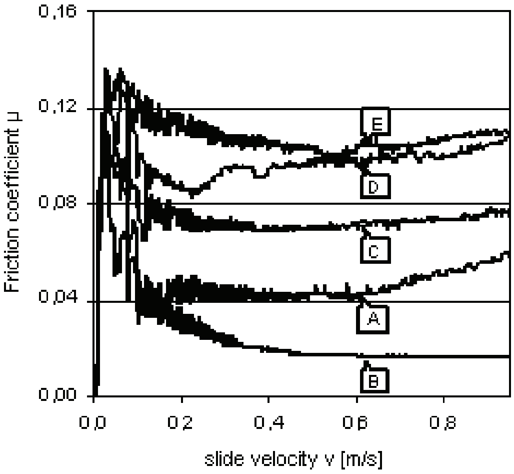

Fig. 2. Change of friction coefficient vs. rotation speed and load 20MPa, for surface treatment of ring sample; A–ion nitriding, B–powder-pack boronizing, C–quenched and tempered, D–coating TiB_2, E– laser boronizing

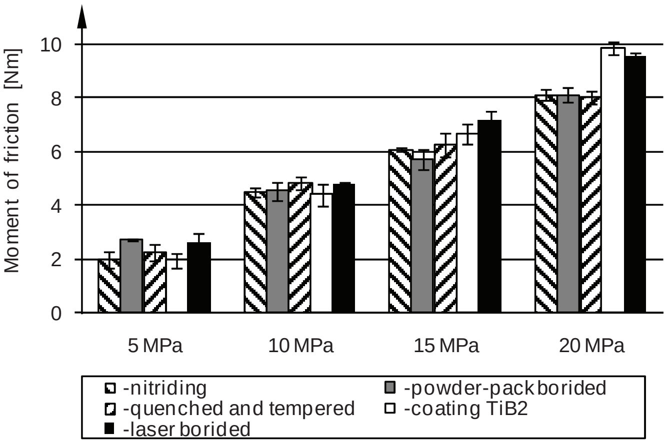

Fig. 3. Start-up moment in function load of kinematics pair and surface treatment of ring samples

Another significant aspect pertaining to kinematic sliding pairs is to determine the value of the start-up moment (Fig. 3). The load of a friction pairs has a significant influence on the value of the start-up moment, but no general correlation can be defined for the modified surface layers. With the smallest load (5 MPa), the lowest friction resistance occurred in the TiB_2 coating pairs and it was lower than that registered for pairs with a nitride sample, whereas the highest friction resistance was generated during start-up for pairs with laser-borided samples and samples borided in powder. With the load of 10 MPa, the value of friction resistance for pairs under study is at a comparable level (from 4.4 to 4.8 Nm). The load increase for pairs with laser-borided samples and samples with TiB_2 coating indicate tendencies towards a significant increase of friction coefficient in relation to the remaining pairs under study. With the load of 20 MPa, the highest friction resistance occurred in pairs with the TiB_2 coating (9.9 Nm) and in borided in powder sample (9.6), and its value is higher by 20% than in the remaining friction pairs. With such a load, similar friction resistance was also registered in pairs with nitride samples, samples borided in powder and quenched and tempered samples (8.0-8.1 Nm). With the load of 15 MPa, the lowest friction resistance was registered in the pairs with a sample borided in powder (5.7 Nm), and then in the pairs with a nitride sample, a quenched and tempered sample and a sample with the TiB_2 coating, whereas the highest values were observed in pairs with a laser-borided sample (7.2 Nm).

Changes of friction resistance during the start-up phase tell 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 [11, 12]. 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 layer by changing its structure and decrease the movement resistances. These changes lead to the further decrease in 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 friction resistance, accompanied by the increase in the sliding speed of the ring sample [11, 12]. The pairs with stable courses of the friction coefficient the surface layer of the element provides sliding characteristics, which allow the equilibrium of tribochemical phenomena within the contact area. This equilibrium allows inherent regulation of the processes occurring within the friction area, which stabilises the resistance values despite the increase in the sliding speed.

In order to determine the effect of the test duration on the friction processes, the measurements of friction coefficient were made in pre-determined load conditions (Fig. 4). With low load (10 MPa), an increase of friction coefficient can be observed Turing the cooperation of friction pairs under study. Under such load conditions, the lowest friction resistance was registered in pairs with a nitride sample and a sample borided in powder, while the highest friction resistance was observed in pairs with a TiB_2 coating sample With the load of 15 MPa, friction pairs with the samples borided in powder, nitride samples and quenched and tempered samples are characterized by a stable run of a friction coefficient. Whereas in pairs with laser-borided samples and samples with TiB_2 coating, a range of cooperation time can be defined, when there are changes of friction conditions registered in the form of significant/considerable increase or decrease of a friction coefficient. With the load of 20 MPa, there could be observed/delineated two groups of friction pairs with a different value of a friction coefficient. Samples with nitride layers, samples borided in powder and quenched and tempered samples (0.08-0.1) were applied in a group of pairs with a low friction coefficient, whereas considerably higher values of a friction coefficient were observed in pairs with laser-borided layer (~0.14) and with a TiB2 coating (0.17).

During the measurement of a friction coefficient versus the length of cooperation time of a friction pair, the measurements of maximum temperature around the friction area was also registered (Fig. 5). According to this cooperation parameter, it is possible to categorize unequivocally the type of modification technology applied to the friction conditions under study. The lowest temperatures occurred in friction pairs with samples borided in powder, where with the load of 10 MPa, the temperature was registered at 36°C, while the highest temperature for this pair was observed with the load of 20 MPa and it amounted to 75°C.

Other pairs with high temperature were pairs with TiB_2 coating, with a quenched and tempered layer and a nitride layer. On the other hand, the highest temperatures were registered in pairs with laser-borided samples, where with the load of 10 MPa the measured temperature was 79°C, and with the load of 20 MPa – 122°C. The temperature registered for pairs with samples borided in powder is lower by 20-40% in reference to the temperatures registered in pairs with the TiB_2 coating samples and the quenched and tempered samples.

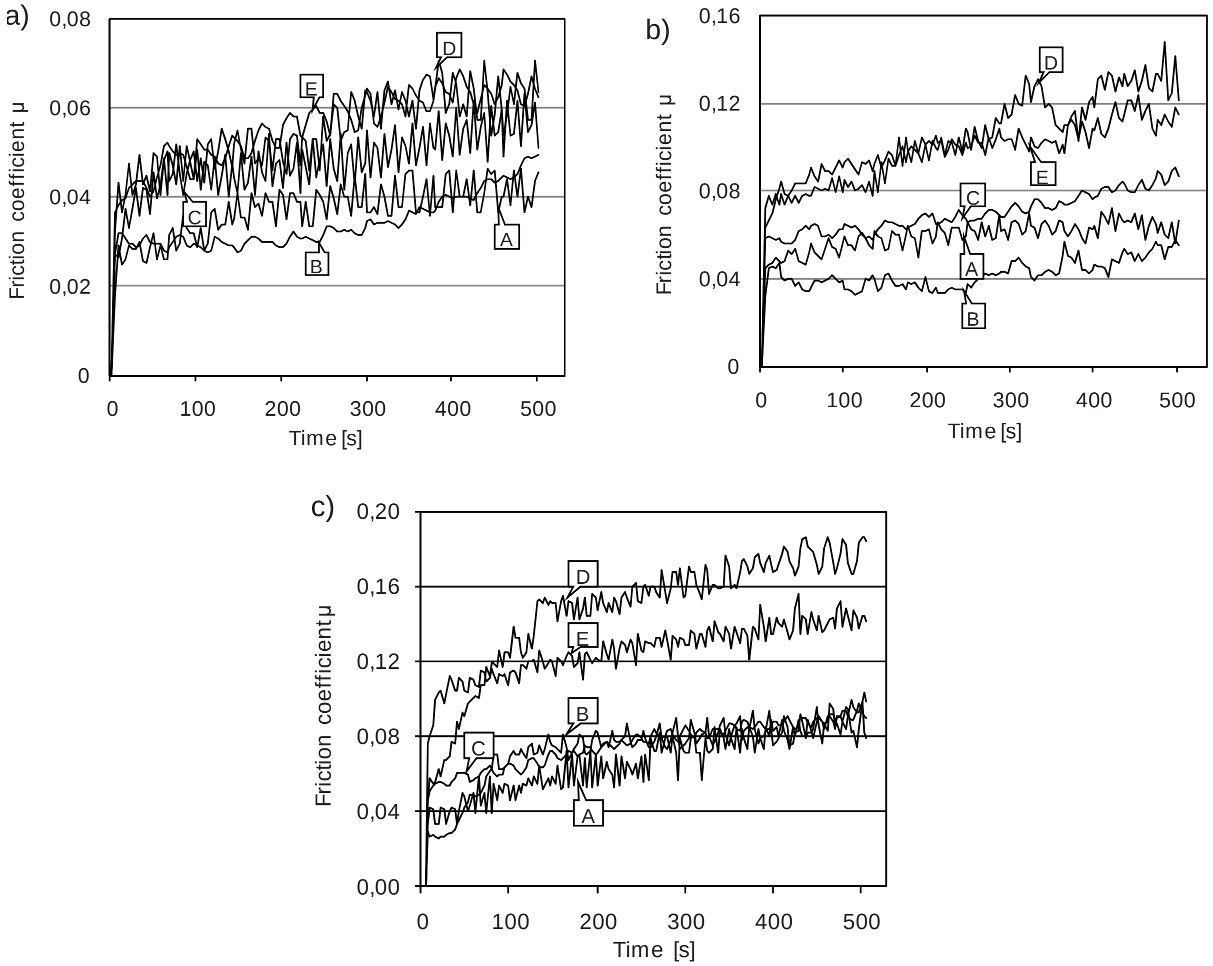

Fig. 4. Change of friction coefficient in function time of test and load a) 10 MPa, b) 15 MPa, c) 20 MPa; for surface treatment of ring samples: A–ion nitriding, B–powder pack boronizing, C– quenched and tempered, D–TiB_2, E– laser boronizing

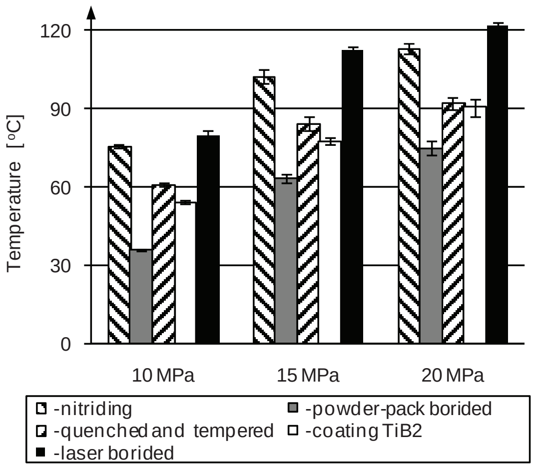

Fig. 5. Influence of surface treatment ring sample on temperature depending on load and rotation speed 100 rpm ring sample

The registered courses of the friction coefficient and temperature reveal the ability of the kinematic 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 [11]. 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 [12].

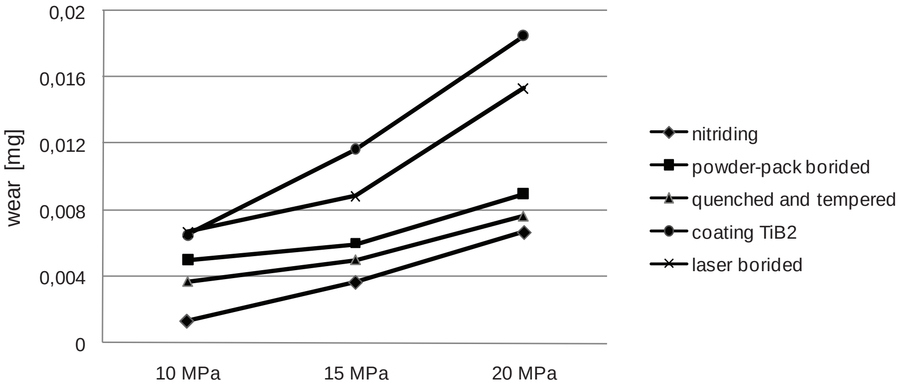

Fig. 6. Influence of surface treatment ring sample on wear of AlSn20 bearing alloy under various load conditions

These load conditions were also used for the wear measurements of the AlSn20 bearing alloy. The lowest wear was measured for pairs with nitriding, powder-pack boronizing, hardening and tempering samples and did not exceed 0,01 mg of the bearing alloy's mass, while the value dispersion was below 20% (at 20 MPa) (Fig. 6). The pairs with the TiB_2 coating and laser borided surface layer exhibit almost twice the wear of the AlSn20 above, amounting to 0,015 mg for the laser borided surface layer and 0,018 mg for the TiB2 coating (at 20 MPa). It is essential to note that in the case of pairs with the laser-borided samples, after exceeding 15 MPa, there occurred an intensive increase of wear of the bearing alloy.

The occurring differences in the wear of bearing alloy and the absence of measurable surface layer ring 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 kinematic 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 [13]. The material transmission processes were observed mostly in powder-pack boronizing and TiB_2 coating. Despite the presence of a lubricating factor, oxidation processes are also present in the mixed friction conditions and create oxides on the surface layers of the cooperating elements. The oxides lead to the decrease of the friction and wear factors within the friction processes; however, in unfavourable conditions, hard and brittle oxides increase the wear [14]. The high wear of bearing alloy observed in pairs with the TiB2 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. The phenomenon of macroscopic diffuse aluminium flow occurring in the section of the surface plastic deformation may lead to increased aluminium concentration, in the TiB_2 coating, adhering directly to the friction surfaces [15]. 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 [16].

4. Conclusions

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

1. Powder-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 ion nitrided surface layers.
2. The use of hardened and tempered 30MnB4 steel and powder-pack borided surface layers in sliding pairs ensures the operating parameters and bearing alloy wear ratio are similar to the sets with nitrided steel.
3. The temperature measurements in the friction area indicated an unequivocal categorization of the modified surface layers from the lowest temperature in pairs with a sample borided in powder, the TiB_2 coating sample, the quenched and tempered sample, and the nitride and laser-borided samples.
4. The highest friction resistance and bearing alloy wear levels were measured in sliding pairs with laser borided surface layer and the TiB_2 coating samples.
5. Modification with boron of steel allow creating surface layers with pre-determined tribological characteristics required for the elements of kinematic sliding pairs operating in the conditions of mixed friction.
6. The run of a friction coefficient indicated that a surface layer treatment has an impact on the character of work of a friction pair versus time, and the most unstable runs of friction resistance are generated by an applied TiB_2 coating.

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