SPECIALIZED HYBRID ROLLING BEARINGS FOR SPACE USE – PROJECT ROLOKOS


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ABSTRACT
The primary objective of the project is to transfer the accumulated knowledge onto a specific product – a specialized hybrid rolling bearing. In order to ensure a clearance-free operation and initial preload, bearings often require the application of thrust force which is less beneficial for the functioning of the bearing than radial force. A new type of an enhanced rolling bearing was designed to work under thrust force in a vacuum environment. The outer ring raceway takes on the shape of a spherical cap, which enables to correct errors which might occur during the bearing rings assembly. Additionally, the outer ring has a groove which increases the durability and decreases the resistance forces. The project included development works whose main aim was to increase the wear resistance and decrease the friction levels of the metallic materials chosen for the construction of the hybrid bearing, that is Ti6Al4V alloy and 440C steel.

1. SELECTION OF BEARINGS AND MATERIALS
For the study there were chosen angular contact ball bearings, transferring both radial and thrust load, which are in the middle of the range of the bearings’ standard dimensions. The inner diameter amounts to 17 mm, the outer to 35 mm and width to 10 mm. As a rolling element there were selected balls with diameter 3/16” (4,7625 mm). The bearing’s contact angle equals α=30°. Proposals for changes in the bearing’s internal construction concerned:
- Design of the bearing’s outer raceway in the shape of a spherical cap with a radius of 14,73 mm, the radius of which is on the bearing’s axis, what ensures the bearing’s axially regardless of mounting defects.
- Design of the grooves on the outer ring’s surface.

Two types of materials were chosen:
- high chromium content steel X105CrMo17 (440C) characterizing with high hardness (1% C) and very high corrosion resistance (19% Cr),
- two-phase titanium alloy Ti6Al4V characterizing with low density and paramagnetic features unlike martensitic steel.

Steel 440C was hardened at a temperature of around 1000°C and tempered at low-temperature of 150°C. Titanium alloy Ti6Al4V was applied in the annealed state after plastic processing of equiaxed structure, so the one that is offered by the majority of suppliers. As the material for separator there were selected three materials, i.e. PEEK and polyimides with PTFE and MoS2 filling. In the prepared bearing there were applied commercial balls made of two materials ZrO2 and Si3N4 characterizing with the highest class of precision available on the market.

2. LAYERS AND SURFACE ENGINEERING TECHNOLOGIES APPLIED
For surface hardening of the selected metallic materials there was applied ion plasma nitriding process enabling to produce diffusion layers with gradient change of properties. On such diffusion layers there were produced series of surface coatings with thickness from 0,2μm to 3μm:
- hard, anti-wear coatings with low coefficients of friction:
  - carbon-based a-C:H(N) coating in RFCVD processes,
  - TiAlN in reactive magnetron sputtering processes,
  - carbon-base titanium doped Ti-C:H coating in reactive magnetron sputtering processes,
- solid lubricants coatings:
  - soft metals:
    - Pb in vacuum evaporation deposition processes,
    - Ag in electrochemical deposition processes,
  - MoS2 in magnetron sputtering processes.

3. OPTIMIZATION OF TRIBOLOGICAL PROPERTIES
At the first stage of surface treatment, titanium alloy Ti6Al4V and 440C steel were subject to the process of active screen plasma nitriding with application of a method which was developed at the Faculty of Materials Science and Engineering of the Warsaw University of Technology (WIM PW). Generation of
nitrided layers, with surface zone of compounds TiN+Ti2N+TiN, on the polished alloy Ti6Al4V increased the material’s surface hardness by 100%, i.e. from the level of 380HV0.2 to 780HV0.2. Simultaneously, its generation did not increase surface roughness over Ra<0.1μm required for application of ready raceway’s elements. In the case of 440C steel the parameters of nitriding were chosen in such a way that would allow to avoid formation of surface zone of hard nitrides and to obtain diffusion zone so that it would not decrease material’s fatigue strength when only surface hardness would increase. There was obtained a slight increase in surface hardness by 25% from the level of 670HV0.2 to 800HV0.2, while keeping very low surface roughness after nitriding process at the level of Ra<0.06μm.

The most favourable properties at the stage of optimization were exhibited by composite layers with thin h<1μm thick surface coatings produced on nitrided layers, which characterized with better adhesion and lower influence on final surface roughness (it was obtained Ra<0.1μm).

Generation of composite layers, based on the initial plasma nitriding allowed to achieve much better results in case of Ti6Al4V alloy, which performed better in the majority of tests, than coatings produced on untreated raw state material. These differences between nitrided and untreated state were not so significant in the case of 440C steel.

Further production of the below mentioned coatings was abandoned after optimization stage:

- carbon-based a-C:H(N) coatings, because it was not managed to obtain coatings with appropriate features guaranteeing good adhesion and stability of properties during long-standing activity, the coatings delaminated especially on the substrates hardened after nitriding processes,

- hard TiAlN coatings, the results of which differed significantly from other tested coatings, demonstrating very high wear level, what was the effect of their very low ground adhesion, spalling and remaining in the track of friction of hard particles playing a role of an abrasive in material wear.

The lowest wear resistance against friction among the analyzed solutions showed coatings of soft metals Pb and Ag, which without any additional processes of surface modification degraded very quickly.

4. TRIBOLOGICAL AND LABORATORY TESTS OF BEARINGS

Tests of tribological properties of the materials selected for the construction of the specialized rolling bearing were conducted at the Institute for Sustainable Technologies of the National Research Institute (ITE PIB) in Radom, where the tests were performed in the air under laboratory conditions, and in Space Research Centre of the Polish Academy of Sciences (CBK PAN), where the tests were conducted under vacuum conditions 5x10⁻⁵ mBar. Tests were performed at a standard temperature of 30°C for all friction couples and once better material for balls was chosen also at -80°C and 120°C under vacuum conditions. Tests were conducted for material pairs assumed for cooperation in the designed bearing, i.e. ball-raceway and ball-separator.

Materials chosen for the balls of the designed bearing were ZrO2 and Si3N4, TECASINT 2391 and 1041 were chosen as the material for separator serving as polyimide with 15% and 30% MoS2 filling. Despite very similar mechanical properties of the balls made of ZrO2 (1200HV10 and K1C=12,1) and Si3N4 (1390HV10 and K1C=11,6), in friction couples with alloy Ti6Al4V, 440C steel and the produced composite layers, the balls presented decidedly different tribological properties. Both under laboratory and vacuum conditions, more beneficial features presented ZrO2 balls, which characterized with lower coefficient of friction during the tests as well as with lower wear after the tests, despite lower hardness than Si3N4 balls. From the perspective of tribological properties in sliding friction, the application of Si3N4 balls should be recommended only if the material cooperating is 440C steel without surface layers, only in such a case the analyzed parameters were better than in the case of ZrO2 balls.

The composite layers contributed to a significant improvement of tribological properties of 440C steel and Ti6Al4V alloy under laboratory and vacuum conditions, excluding layers with Ti-C:H coating.

(a)
The most beneficial tribological properties of 440C steel and Ti6Al4V alloy were achieved as a result of combining nitrided layer with MoS$_2$ coating, which presented very low coefficient of friction $\mu_\text{ZrO}_2=0.04$ under vacuum conditions and only slightly higher $\mu_\text{ZrO}_2=0.15$ under laboratory conditions. Changes in temperature did not cause deterioration of these features. Very good tribological properties under laboratory conditions presented composite layers with Ti-C:H coating produced on alloy Ti6Al4V and the carbon based coating Ti-C:H produced independently on 440C steel, providing lower coefficient of friction $\mu_\text{ZrO}_2=0.11$ than MoS$_2$ and higher wear resistance in laboratory environment. Unfortunately tribological properties of the Ti-C:H coating in a vacuum environment strictly depend on the level of hydrogenation of the coating and they change rapidly from the value of $\mu=0.1$ to $\mu=0.9$. As a consequence, under vacuum conditions there were achieved extreme values of coefficient of friction as well as the level of wear, demonstrating that the coatings differed slightly from each other with hydrogen content, but it was significant for its tribological properties. Producing composite layers with coatings made of soft metals Pb and Ag improved tribological properties of 440C steel and Ti6Al4V alloy, but in a lesser extent than in the case of layers with coatings made of MoS$_2$ and Ti-C:H. This effect was particularly visible in a vacuum environment, because under laboratory conditions lowering of coefficient of friction was limited by low wear resistance of the applied metals leading to a continuous growth of the friction coefficient along with a quantity of revolutions. Among the two metals applied as solid lubricant coatings, more beneficial properties presents silver, because its features do not change at low and high temperature. Lead, despite lower coefficient of friction at room and negative temperature, wears out decidedly faster at an increased temperature what limits its use at temperatures over 100°C.

In the Tribological Laboratory in the Institute of Micromechanics and Photonics of the Warsaw University of Technology there were conducted stability studies of the target bearings' construction without the coatings in the version with and without the groove with the separator made of TESCANIT 1041. Both bearings were tested under identical laboratory conditions with the bearing’s thrust load at the level of 34N and rotational speed of 200 rpm to 11,000 rpm. The bearing without a groove worked until destruction of a separator (Fig. 2) for 257 hours and made 64m revolutions. In the case of the bearing with a groove, researches were interrupted after 1600 hours of work and after 280 m revolutions without signs of exhaustion (Fig. 2). A review of the available literature shows that with a thrust load at the level of 30N no one managed to obtain so high durability.

**5. TEST OF BEARINGS UNDER SIMULATED SPACE CONDITIONS**

In order to ensure efficient conduct of the tests there were created two test facilities (Fig. 3). Test facilities were placed in the vacuum chamber in Space Research Centre of the Polish Academy of Sciences (CBK PAN), where the tests were performed.
Each facility was designed independently in order to enable simultaneous testing of the bearings under different conditions. Single test facility (Fig. 4) consists of a facility with bearings, a measuring system (torque measuring) and a drive.

5.1 Test facility with bearings
In a facility with bearings (Fig. 5) there is a cardcage with the bearing system. It can be taken out what simplifies replacement of the bearings. Tapered shape of the cardcage ensures proper surface adhesion, what is particularly important for thermal conductivity. Bearings are mounted in “O” scheme and loaded with axial force. Force can be adjusted in the range of 0 to 50N by a proper spring clamp. In order to ensure appropriate and the most exact temperature reading of the bearings, the cardcage was equipped with two temperature sensors. The facility was equipped with a cooling/heating housing. Both facilities are powered with a common cooling system (Fig. 5) (with option to connect only one facility) supplying liquid nitrogen to the housing. Liquid nitrogen is steadily distributed in the housing using duct in the shape of a bolt profile. Heating of the bearings goes in a radiative way with the use of a ceramic heater hanging around.
5.2 Tests of series of bearings under high vacuum conditions and at ambient temperature

There were conducted over 30 tests of the bearings under high vacuum conditions and at ambient temperature of around 20°C. Bearings were tested in pairs in a divergent system. During the test internal raceways of the bearings turned with a speed of 3000 revolutions per minute. The force load of the bearings along the axis amounted to 50N. Test was interrupted after 1m of revolutions performed by a pair of bearings. Tests were conducted for bearings made of 440C steel and alloy Ti6Al4V. Tests encompassed both bearings made of starting materials as well as bearings characterizing with the following material variants: Ti6Al4V nitried + Ti-C:H, 440C + Ti-C:H, Ti6Al4V nitried + MoS$_2$, Ti6Al4V nitried + Pb, 440C nitried + Pb. The two charts below (Fig. 6 and Fig. 7) present the results of the studies for bearings made of steel and titanium alloy. The bearings with Ti-C:H and MoS$_2$ coatings made of steel as well as titanium alloy gave the best performance after the tests under vacuum conditions at ambient temperature. These bearings were selected to further tests at an increased temperature. Additionally, there was conducted a long-lasting test for the most promising type of bearings. The long-lasting test differs from the nominal one with a quantity of revolutions. In the long-lasting test the bearings carried out 20 m of revolutions. Below there is a register of the test presenting torque of a pair of bearings. Torque at the level of zero near 9 m results from a temporary lack of register of the torque on the sensor.
Figure 8. The register of a long-lasting test in vacuum at 20°C (20 m of revolutions)

5.3 Test of series of bearings under high vacuum conditions and temperature range of: -160 ÷ +200°C

The most promising variants of construction and materials of the bearings were checked during vacuum tests at a very low and a very high temperature. The remaining parameters of the tests were unchanged. First of all, it was decided to perform the tests at an increased 200°C temperature, because it is the most requiring when taking into account work and wear resistance. Below there is chart presenting average friction torque of a pair of bearings depending on the construction and material. The test of the steel bearing nitrided and coated with MoS₂ turned out to be promising regarding test at a low temperature of -160°C. The average torque from the test of a pair of bearings equaled 1,919 mNm, the tests were finished typically after 1 m of revolutions with a result at the level of 3,239 mNm. This result is higher than at room temperature but still low.

5.4 FINDINGS FROM THE TESTS

The most beneficial results obtained for 1 m of revolutions in vacuum 5x10⁻⁵mbar (Tab. 1 below), the green colour indicates work temperature of 25°C, the blue one -160°C, thrust load of the bearing equals 50N, rotational speed equals 3000 rpm. The bearings’ axis X58L, X66P initially performed 1 m revolutions at the temperature of 25°C and then further 1 m of revolutions at the temperature of 200°C. Measurement of the separator’s wear concerns friction on the surface of the edge of the inner ring running separator as well as slots cooperating with the balls.

Resistance to motion and separator wear significantly influenced by PV [N/mm² x m/s] index of the cooperating materials of edge of the inner ring and separator. After researches there was conducted observation of surface of the rolling elements, raceway and separator in order to identify the mechanisms of the bearing’s wear. It has been concluded that the reason for a sudden increase in resistance to motion as a result of separator and raceway wear are:
- use of inappropriate materials e.g. hard products of the Ti-C:H coating wear cause significant increase in separator’s wear, also the lead coating considerably increases resistance to motion and wear of the separator,
- final grinding to obtain super finish of soft Ti6Al4V titanium alloy on the raceways did not assure the planned concentricity of the raceway (before final grinding the surface of titanium alloy should be hardened),
- exceeding the PV index of the cooperating separator with the edge of the inner ring (the material of a separator sediments on the edge of the inner ring).

6. CONCLUSIONS

Tests under vacuum conditions (1 m of revolutions) have not confirmed beneficial impact of the grooves in the raceway on the work of a bearing. There are plans to conduct long-lasting test, as it was performed under laboratory conditions, which demonstrated several fold higher endurance of the bearing with grooves. Among the tested material solutions, the most beneficial properties of the hybrid bearing was ensured by connection of raceways: made of 440C steel and alloy Ti6Al4V with composite layers: nitrated layer + MoS₂ coating with a cooperation of ZrO₂ balls placed in separator made of TECASINT 2391. It should be emphasized that both bearings made of so distinct materials demonstrated very similar parameters of work during the conducted vacuum tests. The basic difference that has been observed between the raceway’s materials were significant differences in the speed of the separator wear, that probably result from the presence of hard nitrides (TiN,Ti₂N) zone in the nitrated layer produced on Ti6Al4V alloy. During wear of nitrated layer the supplied products of wear in the form of hard particles of nitrides constitute additional abrading what
Table 1. The tests’ results

<table>
<thead>
<tr>
<th>CONSTRUCTION / RINGS</th>
<th>Ti6Al4V nitrided + MoS2 [bearing’s designation, first 600 sec., total, last 600 sec.] bearing’s resistance to motion in Nmm</th>
<th>Wear of separator in mg</th>
<th>440C nitrided + MoS2 [bearings’ designation, first 600 sec., total, last 600 sec.] the bearing resistance to motion in Nmm</th>
<th>Wear of separator in mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>WITHOUT GROOVES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TX34 TX26</td>
<td>0.625 0.472 0.620 4.81 4.72</td>
<td>X31 X76</td>
<td>0.358 0.475 0.330 1.16 1.00</td>
<td></td>
</tr>
<tr>
<td>TX27 TX32</td>
<td>0.427 1.251 1.327 5.18 5.30</td>
<td>X29 X75</td>
<td>2.322 1.270 0.737 0.65 0.24</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>X28 X30</td>
<td>0.272 1.919 3.239 2.78 2.37</td>
<td></td>
</tr>
</tbody>
</table>

intensifies the processes of material wear. This mechanism is confirmed by the results obtained for particular types of coatings where it was also observed the highest level of separator wear in cooperation with raceways covered with super hard layers Ti-C:H but lower for lubricant coatings both Pb and MoS₂. The above arrangements show that an optimal solution as for the material for the hybrid bearing’s raceway is the application of composite layers consisting of diffusion layers without zone of nitrides compounds as well as lubricant coatings characterizing with low hardness. In the case of application of anti-wear layers and coatings characterizing with high hardness, it is recommended to apply separators made of hard to reach and expensive materials Duroid 5813 and PGM-HT characterizing with higher wear resistance and with an addition of glass wool and MoS₂ filling.

7. ACKNOWLEDGMENTS

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