Friction materials operating under high stress, cryogenic temperature, and in vacuum

Z. Piec a, J. Nowacki b, *

a Massachusetts Institute of Technology–Plasma Science and Fusion Center M.I.T. Cambridge MA 02139, USA
b Institute of Materials Science and Engineering, Szczecin University of Technology, Al. Piastów 19, 70–310 Szczecin, Poland
* Corresponding author: E-mail address: jnowacki@ps.pl

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ABSTRACT

Purpose: of this paper was to select interfacial materials to provide friction coefficients less than \( \mu = 0.3 \) which remain at this level during the machine lifetime. This material must withstand cycling motion under pressures up to 80 MPa, at 77 K, and in vacuum of \( 10^{-4} \) Pa.

Design/methodology/approach: In the described work, experiments were conducted to determine the friction coefficient and the wear of several low friction materials. The test rig consists of a cryogenic sample holder enclosed in vacuum chamber installed into a servo-hydraulic test machine (M.T.S.). The friction coefficients have been measured cycling the samples (1,960 mm\(^2\)) for about 38,000 cycles at normal pressure up to 80 MPa, sliding speed of 0.1 m/min, at 77 K, and under vacuum of \( 10^{-4} \) Pa.

Findings: The Fiberslip B40 (woven multifilament of PTFE and glass) was selected as the best candidate material. It exhibited a friction coefficient of approximately \( \mu = 0.22 \), and low wear rate was obtained. The maximum value of the friction coefficient is reached after few thousand cycles and then remains fairly constant.

Research limitations/implications: Further studies on relative sliding/sticking at magnets interfaces as well as predicting the heating due to frictional forces are required.

Practical implications: application of the selected material is possible in large friction interfaces operating under high compression stress, cryogenic temperature, and in vacuum one can meet in nuclear power stations.

Originality/value: The experimental program verified the testing methodology, and techniques selected for measurement of coefficient of friction and wear for the friction pairs with large contact area, which are operated at temperature of 77 K, under high contact pressure and in vacuum.

Keywords: Composites; Wear resistance; Metallography; Materials design; Quality assessment

1. Introduction

Thermonuclear fusion is a possible new energy source. The device, in which fusion can be obtained, a thermonuclear reactor, allows the isotopes of hydrogen to be heated until they ionise to form plasma, and releases energy in the form of neutron radiation. One of the most developed methods to contain and control plasma is with magnetic field, which is produced by large resistive or super conducting magnets. Specially shaped magnetic fields hold and compress the ionised atoms together while the atoms are heated. One of the important aspects in construction of thermonuclear devices (tokamaks) is the proper understanding and optimisation of friction processes between magnets and the structural components, which are shown on Figure 1 on example of the International Thermonuclear Experimental Reactor (ITER), which was developed in collaboration between the European Union (EU), Japan (JA), the Russian Federation (RF), and the USA.
The evaluation of results from cyclic friction testing under vacuum, at temperature 77 K and under high bearing stress, showed that by applying friction materials containing polytetrafluoroethylene (PTFE) a low coefficient of friction $\mu = 0.2$ can be obtained. One material that constantly showed stable friction, low wear and, as a result, reduction of induced frictional heat, was Fiberslip B-40. This material is produced by technology of weaving a filaments of Teflon (low mechanical properties) with filaments of glass to assure high mechanical properties, high resistance to compressive load, and low friction wear. Total friction distance of 500 m was obtained with stable friction. This exceeds (about five times) the construction requirement of a typical experimental fusion reactor. The test results showed that cryogenic temperature operation causes a rise of friction coefficient in the range of contact stresses up to 80 MPa by factor of about five. It was also concluded that a vacuum level of $10^{-4}$ Pa has no effect on values of coefficient of friction both at a temperature of 293 K and at 77 K for the indicated low friction material.

The results obtained for parameters of friction and wear for selected friction material pairs, were introduced to the global computer model for a typical tokamak reactor [2]. The model permits an investigation of local effects of friction parameters at large friction interfaces, or distributions and quantity of frictional heat along the interfaces. In the above model, the friction interfaces, Central Solenoid (CS) and inner and outer cylinders, were divided to a set of finite number of units (discs and rings) being held in equilibrium by a set of elements (springs) with axial stiffness and torsional stiffness.

The friction parameters obtained in experiments, i.e. values of friction coefficient as a function of the sliding distance, and dynamic parameters, i.e. frequency of friction cycling or sliding velocity, were applied to each interacting set of discs and rings. As a result the local values of displacement between components, fluctuation of stresses in the components, frictional heat as a function of friction parameters were evaluated. Based on the characteristics obtained from the model it was concluded that the selected friction pair Fiberslip B-40 and AISI 316LN will satisfy the operational requirements for the friction interfaces typical for an experimental thermonuclear reactor.

2. Selected aspects of friction coefficient and wear at 77 K

Some sources define the coefficient of friction ($\mu$) as a property of a specific friction pair. It is a general statement because other parameters have an influence on values of $\mu$. Such parameters include: value of compression load, operational temperature, atmosphere in which given materials are operated, displacement velocity, and frequency of cycles. If one of the materials in a friction pair is a polymer composite, the kind of strengthening material (e.g. filaments of glass, metallic or ceramic powder) and techniques in which the composite has been strengthened also has an effect. The main material properties that influence the value of friction forces of a material pair are penetration hardness and shear strength of the weaker material at given temperature. For example the penetration hardness for...
Teflon increases about 13 times at 77K (450 HB) and the shear strength increases about 6 times (72 MPa) [1]. Friction between polymer and steel materials is a result of two phenomena. The first is adhesion at the boundary layer where a connection at the points of contact occurs. The adhesive component of the friction coefficient $\mu_a$ for unfilled polymers is generally related to the intermolecular shear strength of the boundary layer. Based on the theory of King and Tabor the intermolecular shear strength, $s$, is often different than the bulk mass shear strength, $S$, because of influences of internal adhesion of molecular chains of polymer to a counter face and the presence of large hydrostatic stresses at the interface. In conclusion, they introduced a correction factor, $c$, $s = c x S$, for unfilled Teflon this coefficient is equal $c = 0$, 3. A special case of adhesive friction is a situation where a thin layer in the form of a film with low shear strength is formed between surfaces displaced with friction. The coefficient of friction under this condition is a sum of two components: one is related to the shear strength and penetration hardness of the area covered by film and the second is to the geometrical parameters at the intermolecular junctions.

The second component influencing the value of the coefficient of friction is an effect where protruding points of the rough surface of a harder material penetrates into the softer surface of the material with which it is in contact. This component is commonly known as abrasive friction. In this case, the material, which is in front of the point of depression, has to be physically pushed in the direction of movement and finally causes abrasion of the material with lower hardness. The specific case of abrasion is when foreign particles of hard material are trapped at the friction interface. Because abrasion generally leads to higher friction and wear, surface preparation plays a very important role. Precautions are also needed that free particles of hard materials are not left at a friction interface.

Influence of cryogenic temperatures on properties of polymer materials can be summarized as follows. In general, most material properties increase at 77K. The parameters that have trends to decrease are: plasticity, mechanical strain, coefficient of expansion, and specific heat. Some of parameters such as: impact strength, adhesive shear strength, or thermal conductivity may increase or decrease for different polymers. It was also observed that below 153 K (-120°C), which is the temperature of the Glass State for polytetrafluoroethylene PTFE, the fluctuation of the coefficient of friction is low. The effect of compressive stress on the specific static friction force, $f = F/A_r$ (A_r real contact area) for PTFE was evaluated. The general trend for polymers is an increase of the specific static friction force with increase in contact stress. Pure Teflon and Teflon in composites tested at 77K, showed the same characteristic and is described later in this document.

Earlier results of investigations [12] for aeronautical applications showed that the presence of vacuum with level of $10^{-5}$ Pa influences the process of friction, however, the level of vacuum in a typical tokamak is about half lower (about $10^{-5}$ Pa). A vacuum level of $10^{-4}$ Pa was found to have a low effect on the value of measured coefficients of friction. Similar low effects were observed in results of investigations at 293 K and 77 K.

These results are discussed later in this document. Published results describing the amount of time that is required to form a self-protecting film on interacting surfaces in vacuum confirmed above statement. For a vacuum of $10^{-4}$ Pa, the time required to form a protective film is about 2.5 hours which is shorter then the total time needed for preparation of the apparatus for testing (time for assembly, cool down, and pump down). For that reason, a protective layer was built up even before testing was started, and, since the time of experiments was long, protective layer existed through the tests.

An additional factor influencing the process of friction and wear in a thermonuclear reactor is the effect of radiation. Analysis of results of investigations for Joint European Torus (JET) experimental reactor showed that irradiation of PTFE (expected during operation of typical thermonuclear reactor) is not destructive, however, it is not without effect [4]. It was shown that irradiation of Fiberslip B-40 samples with Gamma rays to a level of $10^7$ rad increases wear in the first phase of friction cycles (running in phase), but has lower effect in regular phase of wear.

Other sources [12] indicate that the influence of radiation on the coefficient of friction and wear in the phase of running in is minimized in the presence of vacuum. Expected level of radiation in ITER is below $10^9$ rad and is expected in final phase of operation of a system, from this reason use of friction composite material based on PTFE is acceptable.

Three aspects of the counter face surface, which influences the value of wear, are: counter face material, hardness, and surface roughness. It was found [9, 11] that by increasing hardness of a counter face the friction wear is reduced, therefore a harder counter face is preferred. Changing the roughness of the counter face has an important effect on values of wear both in phase of running in and during stabilized friction. In both phases, the value of wear is higher at higher roughness.

The main goal in design of a friction interface with large contact area (e.g. about 100 m²) is the assurance of the required coefficient of friction, low frictional wear, and stability of friction. Most undesirable phenomena, which should be eliminated, are popularly known as "stick-slip". This depends on the mechanism of friction and wear, and on the stiffness of the system in which friction sliding takes place.

Results published by researchers [1] evaluating friction materials showed that materials characterized by a low difference in values of static and kinetic coefficients of friction assure stable friction and eliminate the occurrence of "stick-slip". Experimental results described in the next paragraphs show that samples of Fiberslip B-40 material showed similar characteristics and justify the selection of this material.

### 3. Material and mechanical aspects in construction of thermonuclear systems

The main elements of the new generation of experiments are large super conducting magnets, which produce magnetic fields up to 13 Tesla. As a result of the interaction of strong magnetic fields with high intensity current, large electromagnetic forces ($F = I x B$) are generated. This results in high compression stresses at interfaces between magnets and their relative displacement with friction. The friction interfaces of thermonuclear reactor experiments are subjected to thousands of friction cycles under vacuum $10^{-3}$ Pa, at cryogenic temperatures...
down to 4.2 K and compression stress of about 80 MPa. Proper design of super conducting magnets will demand expansion of many mutually dependent thermal, mechanical, and electric aspects, and assurances of fatigue endurance of materials. Stable working of friction interfaces with smooth displacement can assure predictable operation.

Optimisation of friction coefficient at friction interfaces of a magnet system reduces heat generated as a result of friction and lowers the cost of the cooling systems. Most important aspects in construction and operation of super conducting magnets are: assurance of thermal stabilization of superconductors, minimization of stresses in structural components, and minimization of stresses in electrical insulation.

The results of a computer simulation showed negative effects of friction processes for $\mu > 0.3$, resulting in high stresses in mechanical components of Toroidal Field (TF) magnets and unacceptable shear stresses in electrical insulation on the conductor in the Central Solenoid (CS) magnet. Optimisation of stresses in electrical insulation and optimisation of generated frictional heat are the main aspects in construction of magnets, and was the subject of analysis in ITER. The requirement was to assure a coefficient of friction $\mu < 0.3$ and stable friction over a sliding distance of minimum 200 m (cyclic movement with ± 5 mm stroke) under compression stress up to 80 MPa at 77K in vacuum of $10^{-5}$ Pa.

### 4. Solid lubricants for use at 77 K, under high compression, and in vacuum

Several studies have been completed on the development of solid friction materials for use in bearings and gears that have to operate under conditions where conventional greases or oil cannot be tolerated. Most friction materials such as liquids or greases lose lubricating properties at 77K. They freeze or decompose in the presence of vacuum, which causes evaporation of the volatile components of grease. The best solution is the use of dry solid lubricants, where a solid friction material covers a friction surface.

An example of material, which is based on PTFE warp strengthened with woven glass fibers, is Fiberslip B-40 produced by AMPEP, Clevedon, UK. This composite material has a bearing surface of woven PTFE that provides a low coefficient of friction and a high degree of chemical inertness. Because of its unique method of construction the poor mechanical properties inherent in bulk PTFE have been overcome. Fiberslip B-40 is so woven that predominantly multifilament PTFE yarns are present at the bearing surface while glass and PTFE are exposed on the reverse side, as shown on Figure 2.

A supporting layer consisting of a glass fiber fabric impregnated with a phenolic resin is bonded under heat and pressure to the Fiberslip fabric to produce the laminate. This material is produced in the form of sheets with thickness 0.5 and 0.3 mm, has very high compression strength about 290 MPa, and low coefficient of friction, $\mu = 0.03$ to 0.04, at 293 K. Fiberslip B-40 was fabricated for needs of aeronautics.

Based on the friction properties given by the producer and the results obtained from testing at 293 K, under contact stress of 41MPa, this material was considered as a potential candidate for investigations at cryogenic temperatures. The main characteristics of this material at room temperature are that both coefficient of friction and wear changes drastically in the phase of running in, about the first 100 m of sliding distance. The friction coefficient dropped from about $\mu = 0.1$ to $\mu = 0.03$ to 0.06 and than remained stable.

![Fig. 2. Examples of two of the main types of dry-bearing liners [10]](image)

As a result of radiation, the wear in the phase of running in increased by about 150%, however, this value stabilized in regular phase of friction. The influence of counter face roughness on value of wear was very significant. It increased five times for irradiated and twice for uniradiated samples. The lowest wear for Fiberslip B-40 can be reached at a counter face roughness of $Ra = 0.05 \mu m$. Surface roughness of $Ra = 0.1$ to 0.2 $\mu m$ reduces its lifetime two times and $Ra = 0.2$ to 0.3 $\mu m$ reduces it three times.

### 5. Experimental verification

The initial elaboration of testing methods, development of the test apparatus, and selection of materials for testing at cryogenic temperature under high contact stress began in 1990 at MIT for this program. A test apparatus was built, as shown on Figure 3.

The apparatus was capable to provide cyclic displacement with low amplitude, and was equipped with a special system of self-aligning devices. This is the essential feature, which needed to be applied to an investigative device that operates under large compression stresses.

The main goal was to assure equal distribution of normal load on the sample surface and to eliminate additional force components that may affect friction forces. Another important characteristic of this testing system was its large stiffness. This feature helped to eliminate the “stick – slip” phenomena of friction and improves interpretation of results, especially for cyclic tests.
with short stroke i.e. up to ± 5 mm. The signals from all instrumentation units, which were calibrated before installation in the test apparatus, were transformed by a data acquisition system controlled by computer. The results of an initial investigation on benchmark materials i.e. Teflon, confirmed proper operation of the test apparatus and the instrumentation tools.

Several materials were selected for the compression stress tests under of 253 MPa at 293K and 77K. The composition of these materials and obtained results are described in Table 1. Seven candidate materials were finally selected for cyclic testing at 77 K. These were: Fiberslip B-40 and Ampep X - 140 (both Ampep), Fiberglide #6 and Fibriloid (both BFM Transport Dynamics Corp.), X-1200S (Kahr-Bearing), as well as the DU#1 (Garlock-Bearing), and Lubrite HPF (Merriman Inc), which were, tested in the earlier single stroke tests. All tests were conducted with a face compression of 253 MPa.

Based on the results from the first stage of testing, Fiberslip B-40 was selected as the most promising from standpoint of friction proprieties. The second material, which satisfied the requirement, was Ampep X-140, however, the large content of glass at the friction surface was found destructive to the counter face surface due to the high hardness of glass at 77 K (Rc = 60). Charts with friction coefficients as a function of quantity of cycles for the tested materials are given in Figure 4.

The results showed that Fiberslip B-40 is the material, which meets the experimental requirement. It exhibits a low coefficient of friction $\mu < 0.1$ that is stable in the range of required sliding distance (~3,000 cycles). Another characteristic feature of this material is that the value of static coefficient of friction is similar to the kinetic coefficient of friction; $\mu_s = 0.073$ while $\mu_k = 0.068$, A material with such a characteristic assures smooth frictional displacement and eliminates the occurrence of "stick - slip". It was shown previously by Rabinowicz and Iwasa based on their results from investigation of Teflon and other polymer materials at cryogenic temperatures. The remaining tested materials did not satisfy the requirements of this program.

### Table 1. Candidate materials plus results of compression test at 293 K and 77 K

<table>
<thead>
<tr>
<th>Material</th>
<th>Material composition and form</th>
<th>Results at 293 K</th>
<th>Results at 77 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unfilled Teflon</td>
<td>Sheet 1.5 mm thick, One side etched for bonding</td>
<td>Failed by extrusion</td>
<td>Failed by extrusion</td>
</tr>
<tr>
<td>Multifill 427E and 426</td>
<td>A bland of PTFE and a combination of fillers, epoxy-glass backing. Sheet, 0.75 mm thick</td>
<td>Failed by extrusion</td>
<td>Marginal</td>
</tr>
<tr>
<td>Tyvek 10</td>
<td>Polyolefin fiber-reinforced sheet 0.25 mm thick</td>
<td>Marginal, tendency to tear</td>
<td>Marginal</td>
</tr>
<tr>
<td>DU #1</td>
<td>Sheet steel backing, porous bronze surface impregnated with Teflon and lead</td>
<td>Sufficient</td>
<td>Sufficient (higher strength)</td>
</tr>
<tr>
<td>X-1200 S</td>
<td>Bronze-PTFE lubricating layers, bonded to Steel backing surface</td>
<td>Sufficient</td>
<td>Sufficient (higher strength)</td>
</tr>
<tr>
<td>Fiberslip B-40</td>
<td>Glass fiber reinforced woven multifilament of PTFE. Sheet 0.3 mm thick</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Ampep X-140</td>
<td>Glass fiber reinforced woven multifilament of PTFE. More glass at the surface then in Fiberslip B-40 Sheet 0.3 mm thick</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Lubrite HPF</td>
<td>Woven-fiber pad containing PTFE fibers 0.85 mm thick</td>
<td>Failed, peels</td>
<td>Peels</td>
</tr>
<tr>
<td>Permalon 327</td>
<td>Air-drying resin with colloidal Teflon. Sprayed 1 mm thick</td>
<td>Failed at high stress level</td>
<td>Marginal</td>
</tr>
<tr>
<td>Aerolon M</td>
<td>Resin bonded colloidal MoS$_2$ sprayed 1 mm thick</td>
<td>Failed at high stress level</td>
<td>Marginal</td>
</tr>
</tbody>
</table>

Microscopic observations of the Fiberslip B-40 surfaces were performed before and after cyclic tests. The samples examined before beginning of cycling showed the distinct woven structure of the friction surface with exhibited groups of PTFE filaments. The photomicrographs made after the test showed that filaments of Teflon became compacted as a result of compression, and smeared (equally distributed) in the direction of motion, as shown in Figure 5. The second observed characterization is similar to the wearing processes for the PTFE at 293K and at 77K. In both cases, characteristics of adhesive and abrasive wear were observed. The process of adhesive wear is typical for PTFE at room temperature.
It was found that the damage done to the friction surface is local. It is due to the cyclic nature of motion with a short stroke (±5 mm) in which the destructive effects of wear are not distributed along large distances, but they are contained locally.

Part of the investigation was to evaluate friction characteristics in an atmosphere with moist air. Two samples of Fiberslip B-40 were subjected to three thousand cycles at 77 K in dry air, and then left for 48 hours in moist atmosphere. Before repeating the test, water vapor was observed with a magnifier glass on the friction surface of the sample. The system was then cooled again to 77 K and tested. Testing of the moist sample of Fiberslip B-40 at 77 K caused strong vibrations of the test apparatus, and the friction surface was worn out completely after about 100 cycles. A drastic influence of moisture that was left of the porous structure of the sample was observed. Especially large damage was found on the edges of samples, which were perpendicular to the direction of motion. A typical cycle characteristic and photomicrographs of tested samples are shown in Figure 6. As result of cool down to 77 K and high compression, the moisture was trapped and crystallized creating micro crystals of ice, which translocated during cycles and damaged the surfaces of the friction material by abrasion. To eliminate this condition or to lower the moisture level, nitrogen gas was pumped in the environment surrounding the friction head in close proximity to the tested sample. This was started before applying the normal load and continued during the cycling phase of testing.

The investigation at MIT showed that two materials, Fiberslip B-40 and Ampep X-140, consistently assured coefficients of friction below \( \mu < 0.1 \) and low friction wear up to 6,000 cycles with the stroke of ±5 mm at 77 K and under the compression stress of 253 MPa. Other tested materials did not satisfy the requirements of the test program. Most of the examined materials did not meet requirements, however, they showed lower values of wear at temperature 77 K. This is due to higher strength properties of polymers at cryogenic temperature. Some of the rejected materials can still find use in applications operating at 77 K where lower compression stress is applied.

In the second phase of the investigation, the methodology for testing of friction materials in vacuum, under compression stress up to 80 MPa, and at 77 K was developed. New materials were introduced in addition to those tested in the first phase and a list is included in the main text. Several new materials, which previously were not available or omitted, were taken into account and are described.

A specially developed friction head enclosed in a vacuum chamber for testing of friction materials, shown in Figure 7 was specially constructed for the ITER program in the tribology laboratory Ente per le Nouve Tecnologie L’ Energy e L’ Ambiente(ENEA) in Brasimone, Italy.

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Fig. 4. Static friction coefficient vs. number of cycles at 77K

Fig. 5. Photomicrograph (100 x) of Fiberslip B-40 before test (left) and after 3,000 cycles (right), at 77 K, and normal load of 253 MPa, stroke 5 mm

Fig. 6. Typical stroke curve for Fiberslip B-40 tested at 77 K, 253 MPa, 5 mm with accumulated frost
The vacuum chamber [4] was equipped with two horizontal, in line, hydraulic cylinders capable of about 18 tons each. They produced up to 100 MPa of compression stress on the surface of the samples. A turbo molecular vacuum pump and a measuring system assured reaching and maintaining vacuum at $10^{-4}$ Pa. Cooling of the samples was by conduction from liquid nitrogen circulating through a system of channels located in the friction head. The temperature of samples and of the friction head was registered at several points by thermocouples. The main characteristic of the friction head is its high stiffness. It holds two identical samples of material, is enclosed in a vacuum chamber, and produces simultaneous motion of two samples against the counter face material.

Based on the results of analysis it was shown that the sample shape in the form of a ring with rounded edges tested against a dimensionally larger counter face produces the lowest level of stress concentration on the edges. The plasticity of the friction material and use of self-aligning systems reduced the edge stresses on the samples and assured equal distribution of the normal load. The selected shape of the friction material sample was a flat ring with external diameter of 64 mm and internal diameter of 40 mm (contact area about 1.960 mm$^2$). It was moved cyclically against the polished flat surface made of stainless steel 316LN. The drawing of the sample and the counter face is shown on Figure 8.

The friction head was first cooled to 77 K under an initial compression of 10 MPa and vacuum of $10^{-4}$ Pa, and then compression was increased to 80 MPa. The samples were tested with an average speed of 0.1 m/min for 19,000 cycles with a stroke of $\pm$ 6 mm. In the second stage of the investigation, new samples were tested for 38,000 cycles. The results from both investigations are described in Table 2.

Through the experimental selection of materials it was found that among the examined friction pairs, the composite Fiberslip B-40 in a pair with stainless steel AISI 316LN, showed a stable coefficient of friction, stable movement, low wear, and low generated heat in comparison with other investigated materials.

The analysis of the friction data for Fiberslip B-40 showed that during the cyclic test, the values of friction forces stabilized after about 2,500 cycles, as shown in Figure 9. Among the other investigated materials, ALCRO 1 exhibited a higher friction coefficient than allowable. The second examined material, Vespel SP3, showed a very low coefficient of friction ($\mu = 0.09$), but the characteristic of friction for this material was very unstable. The coefficient of wear was also high. This characteristic of VESPEL SP3 is not acceptable in a device that requires operation of friction interfaces with stable characteristic over friction distances of several hundred meters.

**Table 2. Summary of friction test results, based on data from [3]**

<table>
<thead>
<tr>
<th>Sample / test phase</th>
<th>Contact load (MPa)</th>
<th>Number of cycles</th>
<th>Coefficient of friction $\mu$</th>
<th>Weight reduction (g)</th>
<th>Thickness reduction (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiberslip B-40 / 1</td>
<td>80</td>
<td>19,000</td>
<td>0.22</td>
<td>0.048</td>
<td>0.019</td>
</tr>
<tr>
<td>Vespel SP3 / 1</td>
<td>80</td>
<td>19,000</td>
<td>0.09</td>
<td>0.384</td>
<td>0.033</td>
</tr>
<tr>
<td>ALCRO 1 (CuAl10Ni5Fe4) / 1</td>
<td>80</td>
<td>19,000</td>
<td>0.3</td>
<td>0.133</td>
<td>0.009</td>
</tr>
<tr>
<td>Fiberslip B-40 / 2</td>
<td>80</td>
<td>38,000</td>
<td>0.19</td>
<td>0.087</td>
<td>0.029</td>
</tr>
<tr>
<td>Vespel SP3 / 2</td>
<td>80</td>
<td>38,000</td>
<td>0.05</td>
<td>0.850</td>
<td>0.13</td>
</tr>
<tr>
<td>ALCRO 1 (CuAl10Ni5Fe4) / 2</td>
<td>300</td>
<td>8,300</td>
<td>0.36</td>
<td>0.090</td>
<td>0.029</td>
</tr>
</tbody>
</table>
Friction Coefficient vs Number of Cycles / Fiberslip B-40

Temperature: -190 °C
Vacuum: 3.2 x 10^{-4} Pa
Contact pressure: 80

Friction Coefficient vs Number of Cycles / Vespel SP3

Temperature: -190 °C
Vacuum: 2.2 x 10^{-4} Pa
Contact pressure: 80

Fig. 9. Friction coefficient vs. number of cycles Fiberslip B-40 compared with Vespel SP3.

The influence of compression load on values of friction coefficient for Fiberslip B-40 tested in vacuum are shown on Figure 10 and Figure 11. The tests that were performed at 293 K showed about a 10% increase of friction coefficient under influence of vacuum with a level of 10^{-4} Pa.

Fig. 10. Coefficient of friction vs. normal load, Fiberslip B-40 at RT and vacuum.

The results obtained from the tests performed with compression ranging from 20 to 80 MPa, at 77 K, and in vacuum, showed an increase of friction coefficient by a factor of five (compared with RT data). Analysis of results showed that the effect of vacuum of 10^{-4} Pa on this increase is low. In both cases with higher compression the friction was lower.

The analysis of results for static and kinetic coefficient of friction showed low differences, about 5%. This characteristic assures that Fiberslip B-40 will provide a stable process of friction. The coefficient of friction remained stable at a level below $\mu = 0.2$ after about 2,000 cycles. The temperature of Fiberslip B-40 samples during testing showed a progressive temperature increase during the first few hundred cycles. After this period, the temperature stabilized. The time required for that stabilization was dependent on the frequency of cycles.

A sample tested with pulse frequency of 0.4 Hz experienced a temperature increase from 77 K to 95 K during the first hundred cycles. Lowering this frequency to 0.3 Hz resulted in normalization of temperature on the level of 95 K after seven hundred cycles. The frequency of 0.3 Hz was selected in order to reduce the testing time.

The microscopic pictures of the Fiberslip B-40 sample surface and the surface of the counter face after testing at 77 K and in vacuum of the level 10^{-4} Pa are shown on Figure 12. It was concluded that the influence of adhesive wear is lower under vacuum. The presence of vacuum minimized the amount of moisture in the porous structure of the tested material and improves conditions of abrasive wear. Microscopic photographs showed an equally distributed transfer of Fiberslip B-40 particles to the surface of the counter face.

The combination of cryogenic temperature and vacuum increased the friction resistance to sliding under high compression. Friction properties of the selected friction pair, Fiberslip B-40 against stainless steel AISI 316LN, at temperature 77 K, in vacuum of 10^{-4} Pa, under compression stress up to 80 MPa, are promising with respect to values of friction coefficient, amount of generated frictional heat, stability of sliding motion, and low level of wear.
6. Discussion about results

Covering surfaces of friction interfaces of large electromagnets or super conducting magnets in a tokamak by composite material based on a PTFE warp reinforced with glass fabric provides the required operational lifetime of the components. By combining the low friction properties of PTFE filaments with high mechanical properties of glass filaments, a stable characterization of friction through the required sliding distance was demonstrated. Teflon in its pure form is a polymer material investigated for many years for use as lubricant at cryogenic applications under low normal load. Using the technology of weaving Teflon filaments with glass filaments, applied in the production of Fiberslip B-40, allows applications with high compression stresses up to 250 MPa.

Based on experimental results and analysis, it was shown that the friction pair Fiberslip B-40 against AISI 316LN would work properly under extreme conditions such as cryogenic temperatures, vacuum, and high compression stress. It will allow reduction of operating stresses in the components of friction interfaces and reduction of generated friction heat. By knowing characteristics of the friction pair, the amount of generated friction heat and distribution along the interface can be estimated and optimised.

One of the main characteristics of all tested friction pairs was that their friction coefficient decreased with increase of the compressive stress. The behaviour was observed both at 293 K and at 77 K. It was found that introduction of cryogenic temperature (77 K) increases the friction coefficient of selected friction pair (Fiberslip B-40 vs. AISI 316LN) by factor of six at the lower level of compression (26 MPa). This factor was decreasing linearly to the value of three for the stress of 100 MPa.

The experimental results obtained in the second phase of testing; in vacuum 10^{-5} Pa, shown low effect of this level of vacuum on the values of coefficient of friction. The published data shown similar behaviour. It was concluded that the preparation time required for setting the experiment (time needed for: installation of a samples, cool down to 77 K, reaching the vacuum of 10^{-5} Pa) and time required to perform the experiment was long enough for formation of monomolecular film on the surface of the counter face. The level of residual pressure was low enough that these films could continue formation even during the experiment. It was also observed that vacuum has a positive effect on reduction of abrasive wear, the reason for this behaviour is that vacuum eliminates a water vapour from the micro porous structure of the sample surface, and drays the glass fibers from any moisture absorbed from the air [5 – 8].

It was shown that one of the main characteristics of selected friction pair is that the values of static and kinetic coefficients of friction are similar and stable in the range of sliding distance. Earlier investigations by Rabinovicz and Iwas shown that friction pair being characterized with above feature assure stable work and eliminates process of friction type" stick-slip". One of the characteristics of pure Teflon is a low adhesion, this kind of material is often recommended for the friction interfaces operating cyclically and with high frequencies e.g. friction interfaces of airplanes. The initial test performed with pure Teflon showed similar values of static and kinetic coefficient of friction and high stiffness of the test apparatus. These characteristics, low difference between static and kinetic coefficient of friction and high stiffness of the system are two of the main parameters, which eliminate the “stick-slip” phenomena of friction.

The results of testing and analysis for the friction pair Fiberslip B-40 with AISI 316LN, at room temperature have given a good understanding of their friction properties. By adding the characteristics obtained through the programs discussed in this document, which included cryogenic temperatures, and vacuum, a wider range of characteristics is provided. Also, the characteristics for the materials which did not satisfy the requirements of the investigation discussed here, may be a useful source for designers of systems operating at less extreme conditions.

The test results obtained through the program at the selected temperature of 77 K are similar to these obtained earlier for pure Teflon at 4.2 K. The analogy between these results suggest that selected friction pair Fiberslip B-40 - AISI 316LN may be applied at a system which is operated at the temperature below 77 K.

The adhesive wear which is a characteristic for the pure Teflon at 293 K was still observed at the temperature of 77 K. It was found that the wear process at 77 K is a combination of adhesive and abrasive wears. During the experimental it was also shown how destructive effect has presence of moisture on the surface of the sample, it increases the abrasive factor of wear. During cool down the trapped moisture forms micro crystals of ice, which destroys the samples surface. This effect is minimized or eliminated if selected friction interface is operated in vacuum. Assuring the dry atmosphere and clean moisture free surfaces of the friction interfaces is always recommended at 77 K [8].

Application of experimental results into the mathematical formulas and analytical model [2] allowed performing optimisation of the friction parameters of analysed interfaces. The results of calculation and performed analysis confirmed positive effect of selected friction pair Fiberslip B-40 - AISI 316LN on operational performance of the system. The proposed pair also meets one of the main requirement of the test program which was to assure stable coefficient of friction below $\mu = 0.3$ through the lifetime of the experiment. This guarantee reduction of the stresses in the components of thermonuclear experimental reactors below the level allowable by the design criteria.
7. Conclusions

It was shown that application of Fiberslip B-40 as lubricating material at magnet friction interfaces of an experimental thermonuclear reactor allows:

1. low values of friction coefficient, and stable friction,
2. lower wear in comparison with other investigated materials.

The experimental program verified the testing methodology, and techniques selected for measurement of coefficient of friction and wear for the friction pairs with large contact area, which are operated at temperature of 77 K, under high contact pressure and in vacuum. The high stiffness of the magnet system in a thermonuclear reactor, for which the selected pair was evaluated, was reflected during the test program in high stiffness of the test apparatus.

Low difference between values of static and kinetic coefficient of friction, not exceeding 10%, obtained for the friction pair Fiberslip B-40 – AISI 316LN provides stability of friction processes and elimination of "stick-slip"

The experiments showed a low effect of vacuum (level of 10⁻⁶ Pa) on the value of friction coefficient for the selected friction pair both at 293 K and at cryogenic temperature. It was concluded that the preparation time required for setting experiment was sufficient for formation of monomolecular film on the surface of the AISI 316LN. The level of residual pressure was low enough that these films could continue formation during the experiment.

The wear characteristics of Fiberslip B-40 tested against the counter face made of stainless steel AISI 316LN showed analogy at both temperatures 293 K and 77 K. The process is a combination of adhesive and abrasive wear, which is a result of tribological characteristic of Teflon in above temperatures, and due to the presence of glass fibers in the structure of the selected materials. Higher roughness of the counter face surface reduces lifetime of the Fiberslip B-40 material.

The presence of water vapour or other moisture on the surface of the low friction material has a drastic effect on the surface wear if the friction interface is operated at cryogenic temperature without vacuum. The abrasive portion of wear is reduced in vacuum; it is due to elimination of moisture from the microspores structure of selected material.

The results of experiments and estimates calculated based on the obtained data were applied to an analytic model and confirmed good operational properties of the selected friction pair under the specified operational conditions. It was concluded based on the characteristics obtained from analytical analysis for selected friction pair, that there is a close relation between the stress level in structural components of the magnets, amount of generated friction heat, and it distribution at the evaluated interfaces. The parameters of this relation can be optimised by application of selected friction pair Fiberslip B-40 - AISI 316LN in the friction interfaces between magnets of the thermonuclear reactor.

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