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# Evaluation of apparent Young's modulus of the composite polymer layers used as sliding surfaces in hydrodynamic thrust bearings

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## Abstract

Hydrodynamic bearings with a polymer sliding layer are able to operate in severe conditions, mainly due to favourable properties of the polymers. The goal of this research was to evaluate apparent Young's modulus of two types of the polymer composite layers used for sliding surfaces in hydrodynamic bearings, as a function of temperature. The Young's modulus was evaluated on the basis of compression tests carried out on samples obtained from thrust bearing pads. Measurements were accompanied by additional FEM calculations, reproducing the experiment.

The results presented in the paper prove that apparent Young's moduli of the studied types of the composite layers depend significantly on temperature and their values differ from existing information in available data on polymers.

## 1. Introduction

Polymer layers have been used as sliding surfaces in hydrodynamic thrust bearings for more than 40 years. The first application described in literature known to the authors was reported by Baiborodov et al. [1], and it was an implementation of PTFE (*polytetrafluoroethylene*) polymer layered thrust bearing in 250 MW hydrogenerator of the Bratskaya water power plant (1974). The bearing operated under specific pressure of 6 MPa, and after modernization showed good performance in all modes of hydrogenerator operation. Previously, frequent failures had been noticed [2]. In this application, an original invention of bonding polymer layer to the steel base using copper wire matrix was utilized. This bonding method was developed for journal bearings in the 1960's [3]. Excellent performance of the bearings with polymer layers – PTFE, but also PEEK (*polyetheretherketone*) was confirmed by several other applications in large thrust bearings all over the world, e.g. Japan [4], Great Britain [5] and Switzerland [6], or in smaller bearings of pumps or turbochargers [7]. Currently, two types of polymer materials are most frequently used for sliding layers: PTFE

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and PEEK. Both materials display stiffness and thermal conductive coefficients at considerably lower levels than Babbitt. Data for pure polymers according to [8] is collected in Table 1 (Babbitt data is also appended for comparison, according to [9]).

| | ***PTFE*** | ***PEEK*** | ***Babbitt*** |
|---|---|---|---|
| Young's modulus* (at 23 $^{o}$C) [GPa] | 0.34 | 3.56 | 53.0 |
| Coefficient of thermal conductivity [W/mK] | 0.40 | 0.25 | 40.0 |

*evaluated in tension tests

Table 1. Selected properties of the most commonly used materials for sliding surfaces in hydrodynamic bearings.

Due to low wear resistance of pure polymers, and also in order to increase dimensional stability and creep behaviour, fillers and additives are usually added to the polymers, for example carbon or glass fiber or graphite [10]. They help to increase wear resistance [4], [11], but simultaneously can alter the mechanical properties of the polymer, as it was shown e.g. for PEEK in [12]. Additionally, polymers are prone to creep, especially PTFE shows quite large amount of creep under compression, as reported in [9], while PEEK based composites did not show almost any creep ([6], [12]).

The use of the bearings with polymer sliding layers has proved to have many advantages over conventional, white-metal (Babbitt) lined bearings. Significantly lower stiffness of the polymers allows for a concave shape to develop on the bearing sliding surface [13], which is close to optimal [14]. Considerable compliance of the polymers compared to Babbitt bearings also allows better load sharing between bearing pads. Depending on conditions and design, polymer lined bearings can operate under larger specific loads than Babbitt lined bearings. According to various sources, the increase of allowable specific loads varies from 1.5 times ([15]) to 3 ([7]) times. This is due to the thermal insulation of the polymer layer, which reduces thermal crowning of the pad. Besides many advantages, polymers used for sliding layers also show some disadvantages. The mechanical properties of the polymers depend significantly on temperature, and can change depending on the range of temperatures encountered during usual bearing operation [2], [9]. Thermal insulation of the lining lowers the temperature in the pad base to a level closer to the oil bath temperature, which makes classical temperature diagnostic methods useless. A low, uniform pad temperature is not seen as favourable in centrally pivoted pads, where thermal pad crowning play an important role in generating hydrodynamic effect. Because of poor adhesion properties of the polymers, they need a special intermediate layer for firm bonding to the pad steel base. Two bonding types are widely in use, wire mesh or porous bronze sintered to the steel pad base. In both cases, bonding is achieved by pressing a sheet of the polymer against the intermediate layer.

Following the successful application of polymer materials for sliding surfaces of hydrodynamic thrust bearings, they also became an object of experimental and theoretical research. Experimental research in the area of thrust bearings was conducted mainly for PTFE-based linings [9], [16], [17], [18]. Generally, it proved that polymer lined bearings show higher measured temperatures in the oil film, lower maximum oil film pressure and lower circumferential tilt angle in comparison to Babbitted bearings.

Theoretical research of thrust bearings with polymer layers is not common. There are only several works analyzing influence of the polymer layer on hydrodynamic thrust bearing performance ([9], [18], [19], [20], [21], [22]). This can be due to the problems with convergence of calculations caused by significant deformations of the polymer layer. Furthermore, there is a lack of data concerning mechanical properties of the polymer composite layer, which is necessary for calculations. In the paper by Ettles et al. [9] the results of a very simple compression test of the polymer layer made of PTFE are presented. According to these results, the measured deflection of the PTFE based composite layer (with copper wire mesh as a bonding) at 13.7 MPa was equal to 0.1 – 0.15 mm. In this work for bearing calculations, Young’s modulus equal to 0.11 GPa (representative for composite) was applied. This value was later used also by other researchers [19], [20]. Pure polymer data seems insufficient, since the intermediate layer can change the resilience of the polymer composite lining significantly and as a consequence influence the results of the analysis. The effect of using fillers and additives can be similar. It is also expected that stiffness of the lining can change significantly along with temperature changes, which was not taken into account in any of the published research known to the authors.

## 2. Goal of the research

During the operation of hydrodynamic bearings the sliding layer is exposed to compression caused by the oil film pressure and also to shearing caused by the lubricant. Additionally, the temperature of the sliding surface increases due to oil shearing and heat generation in the oil gap. Sliding surface (and lining) temperature is not uniform, in the tilting pad thrust bearing, it is hotter close to the trailing edge and cooler close to the leading edge. These are natural phenomena when hydrodynamic bearings are in operation. Therefore, it seems reasonable to evaluate properties of the polymer-based lining as a function of temperature.

The goal of the research was to assess apparent (representative) Young’s modulus of the polymer composite layer used for sliding layers in hydrodynamic thrust bearings as a function of temperature. Since the bonding intermediate layer has a complex structure, and its details cannot be modeled separately, the apparent (representative) Young’s modulus of the whole composite layer, consisting of polymer, pure or filled, and an intermediate layer was evaluated.

This was achieved with the compression tests of the samples cut out from the thrust bearings pads lined with two different layers: PTFE-based and PEEK-based composites, and additional FEM calculations reproducing the experiment. Tests were carried out for four temperatures in the range of 25 $^{o}$C – 120 $^{o}$C. Temperatures for tests were selected to cover real bearing operational temperatures, taking into account also equipment limitations. Lower bound of the temperature (25 $^{o}$C) was selected to be close to the bearing oil temperature characteristic for cold start–ups in winter period. Upper temperature bound (120 $^{o}$C) was limited by extensometer resistance. Two additional temperatures were also applied in tests, to make possible following the Young’s modulus changes as a temperature function. The results of this research are meant to improve input data in further theoretical researches of polymer-lined bearings and also to compare properties of the both types of most widely used polymer composites under compression in a relatively wide range of temperatures relevant for the bearings operation.

The described method can also be helpful for other researchers to repeat the procedure in order to obtain data for other kinds of polymer composite lining in which different composition of a polymer or another type of bonding is used.

## 3. Materials and methods

Young’s modulus of the polymers (in compression tests) can be measured with the use of standardized method according to EN ISO 604: 2003 standard [23]. This requires beam-shaped samples with rectangular cross section (4 mm x10 mm) and length 50 mm. Taking into account, that polymer layer thickness is usually no more than 2-5 mm, it is not possible to use standard size specimen to evaluate Young’s modulus of the bearing lining. Additionally, the standard method will not allow to consider a contribution of the bonding to the stiffness of the whole composite layer. That was a reason why, this original, non standardized method was applied to evaluate apparent Young’s modulus of the polymer sliding layer. It was based on compression tests on non standarized samples cut out from thrust bearing pads. However, the results of compression tests could not be used directly to assess apparent Young’s modulus of the lining, due to a lack of a uniaxial stress state in the polymer layer of the sample. In consequence, numerical calculations were used to interpret the obtained experimental data.

### 3.1. Compression tests

For the purpose of this research, two cylinder-shaped samples were cut out from two pads covered with polymer composite layer (Figure 1). Samples dimensions: diameter d = 15 mm and height h = 13 mm. The PTFE-based composite was made from pure PTFE. It had the bonding layer made of steel wire mesh welded to the steel base – this composite material will be further referred to as the PTFE lining or PTFE layer. The PEEK-based sample was composed of PEEK with carbon fiber and a small amount of PTFE as a filler. Its intermediate layer was made of porous bronze sintered onto a steel backing. This composite material will be further referred to as the PEEK lining or the PEEK layer. The thickness of both the composite layers in the samples is the same as in the real bearing pad i.e. the face of the polymer layer was not machined.

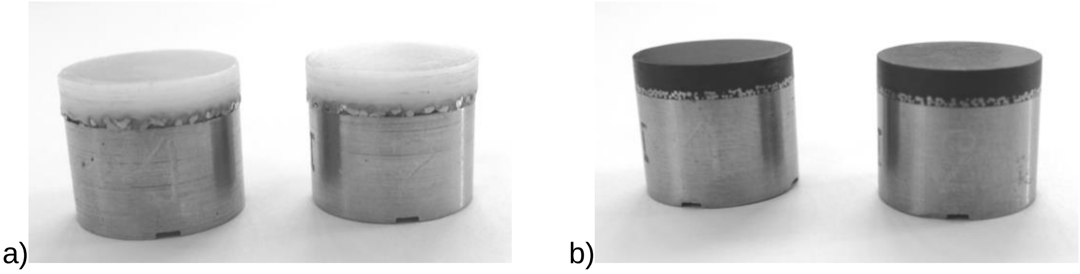

Figure 1. Samples cut out from bearing pads; a) lined with PTFE composite, b) lined with PEEK composite layer.

Thickness of the PTFE lining was $h_{PTFE}$ = 3.7 mm and thickness of the PEEK lining was $h_{PEEK}$ = 3.2 mm. Before compression tests, samples were kept immersed in turbine ISO VG-32 oil under the pressure (p = 4 MPa) at room temperature for about one month, to simulate conditions encountered by the lining in a real thrust bearing. After finishing this long compression period, samples were immediately subjected to compression tests with the use of universal testing machine (MTS, Figure 2 a). For the tests in elevated temperatures, a heating chamber was used. Tests were carried out at 25 °C, 60 °C, 100 °C and 120 °C in order to cover the range relevant for fluid film bearings operation.

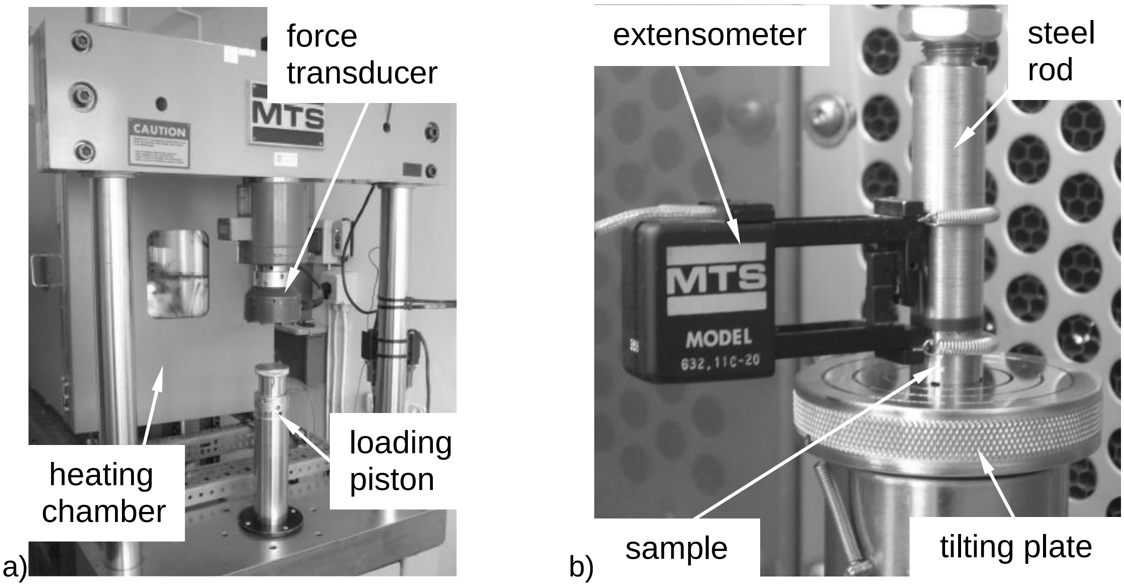

Figure 2. Equipment used during compression tests: a) general view of the universal testing machine; b) PEEK lined sample under compression inside heating chamber.

During compression tests three parameters were measured. Temperature in the heating chamber i.e. temperature of the sample was measured with the use of a thermocouple. Sample deformation was measured with the use of a precise extensometer - MTS, type 632.11C-20, base 25 mm, range up to 0.5 mm, accuracy ± 0.2 μm - confirmed by calibration measurements. Applied force was measured with the use of two types of force transducers - an MTS sensor, type 661.18D-02, measuring range up to 2 500 N (force transducer class 0.5). For the tests at 100 $^{o}$C and 120 $^{o}$C, a transducer with a larger measuring range was used, MTS type 661.20F-03, measuring range up to 10 000 N, (force transducer class 0.5). Maximum average sample compression stress was ~14 MPa, when up to 2500 N of force was applied, which is within the range of oil film pressure values in the bearings during operation. When 10000 N was applied, the maximum average stress increased to 56 MPa. The intention of using larger loads at highest temperatures was to test lining behaviour in overload conditions. Each sample was compressed 4 times at each temperature level. During the tests, the sample was placed upon a tilting plate and pressed with the use of the loading piston against a steel rod, connected to the force transducer (Figure 2 b). Minimum non-zero value of the load (100 N) was necessary to keep the sample (and extensometer connected to it) in its position before the start of the test. The load increase was very slow and the rate was 1000 N/min. Tests at 25 $^{o}$C and 60 $^{o}$C were carried out up to the maximum force of 2500 N. In some cases, especially for PTFE lining, before reaching maximum load, nonlinear dependence between force and lining deflection was observed. As nonlinearity was noticed, tests were stopped, to avoid damaging the sample. At 100 $^{o}$C it was assumed to apply a maximum load of ~3600 N (~20 MPa) in the tests of the PEEK lining, while PTFE lining tests were stopped when nonlinearity was observed. At 120 $^{o}$C two initial compression tests were carried out as at 100 $^{o}$C. The last two tests were carried out until much higher loads (in the case of the PEEK layer, up to 10 000 N) or to exceed the measuring range of the extensometer (in the case of the PTFE layer, where the deflection was more than 0.5 mm). The data was recorded with the frequency of 20 Hz.

The deflection measured with the use of the extensometer contains two components: deflection of the lining and steel parts (rod and sample base). Deformation of steel parts, calculated according to Hooke’s law and the known mechanical properties of steel. This was subtracted from the received measurement data. The correction component was ~1.5 μm in the case of the PEEK lining under 2500 N.

The diagrams showing polymer lining deformation for different temperatures as a function of the applied force were obtained from the results of compression tests.

### 3.2. Numerical reproduction of the experiment

The aim of the theoretical analysis was to reproduce the experiment with the use of a Finite Element Method (FEM). Changes in the polymer composite layer deformation were evaluated as a function of Young's modulus of composite lining in a series of calculations. To complete this, a simple 2D axisymmetric FEM model was developed using Ansys software (Figure 3) [24]. With the use of FEM model, behaviour of the specimens under compression were analyzed. The model contained a half slice of the specimen cross-section composed of two layers: the steel body and polymer composite layer including the polymer and the intermediate bonding layer. Dimensions of the specimen (including the thickness of the polymer) were assumed equal to the measured ones (see part 3.1).

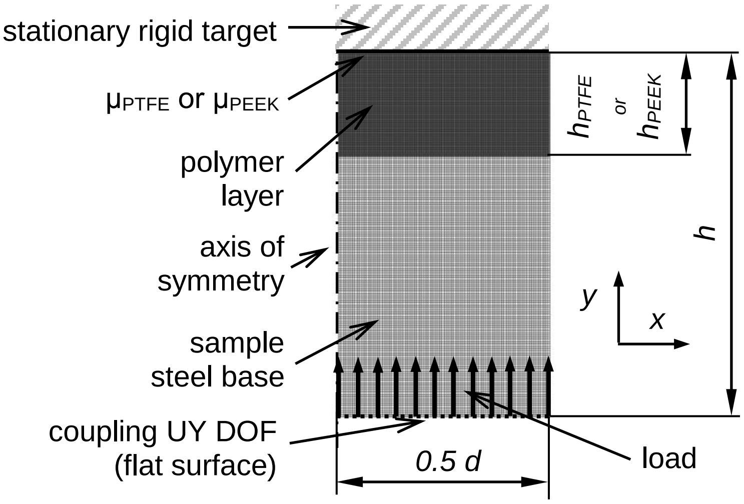

Figure 3. FEM model of the sample with polymer layer.

Both ends of the sample were in contact with other elements during compression tests, and were able to slide, but the lower end, with steel to steel contact, was not within the zone measured by the extensometer (see Figure 2 b). Contact elements were introduced between the lining face and target surface (rigid-deformable contact type, CONTA171 elements), which allowed the lining to slide in relation to the rigid target surface. Since the friction coefficient value between the lining and the steel has an impact on the results of the analysis, it was decided to measure it before the calculations for both composite materials. Measurements were completed with the use of a SOOG test stand, described in detail in [25]. Measured values of the static friction coefficient of the polymer face against the steel were $\mu_{PTFE}$ = ~0.14 and $\mu_{PEEK}$ = ~0.20, and these values were used as the input in FEM calculations. At the bottom of the sample the load was applied. Nodes placed at this surface were also coupled, to have equal displacement in y direction (flat surface). For the calculations steel properties were assumed as: Young's modulus $E_s = 2.1 \times 10^5$ MPa, Poisson ratio $v_s = 0.33$. It was also assumed, that the composite polymer layer fulfilled Hooke's law, with Poisson ratio for the PTFE layer of $v_{PTFE} = 0.46$ ([20]) and for the PEEK layer of

$\nu_{PEEK} = 0.40$ ([26]). A four node axisymmetric PLANE182 element was used. The FEM model contained 14720 plane and ~100 contact elements.

### 3.3. Evaluation of the apparent Young's modulus of the lining

An example of compression tests results is shown in Figure 4. Initial curvature of the compression tests results (visible especially in the case of the PEEK lining) was caused by initial imperfections of the lining surface flatness and also by its irregular thermal expansion during heating of the specimens.

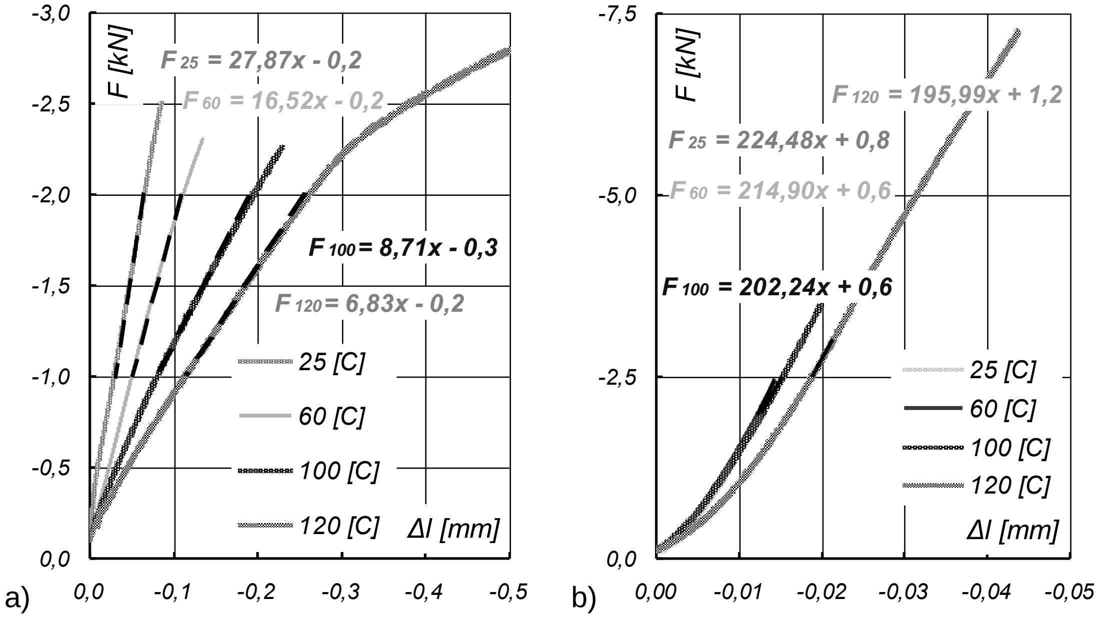

Figure 4. Example results of compression tests; a) obtained for PTFE lined sample no 1 (3rd repetition); b) obtained for PEEK lined sample no 1 (3rd repetition) – results at 25 °C, 60 °C and 100 °C are close each other.

This decreased the measured stiffness of the lining at the beginning of the tests and according to EN ISO standard recommendation [23] this part of the results, should not be used to evaluate Young's modulus of the polymer. This assumption was also included in the proposed method, however the influence of the initial shape of the lining surface on the evaluated apparent Young's modulus was analysed and the results are also summarized in section 4.4 of this paper.

To evaluate representative deflection of the polymer layer with the use of measurement results (excluding initial nonlinearity and comparable for both specimens and materials), linear regression was used. It was assumed, that regression function in the case of PTFE lining was defined for the loads in the range of 1 to 2 kN, while in the case of the PEEK lining in the range of 2 to 2.5 kN and 2.5 to 3 kN in case of tests at 120 °C (in order to avoid the initial nonlinearity). In Figure 4 regression lines and their equations were also shown (with dotted black lines in case of the PTFE and with solid black lines in case of the PEEK). The obtained equations of the regression lines were used to assess representative polymer lining deflection under the load (excluding nonlinearity). These results were compared with the calculated deflections of the lining (model described in part 3.2). FEM calculations were carried out for different values of Young’s modulus of the composite polymer layer until the calculated deflection was the same as the measured one. The value for which these two results were the same was considered to be an apparent Young’s modulus of the polymer lining – as explained before – representative for the whole composite layer including the polymer and the intermediate bonding layer.

## 4. Results and Discussion

The methodology described in the previous section was used to evaluate apparent Young’s modulus of the composite polymer layers as a function of temperature. In this section detailed description of the measurements and calculations results is provided together with the discussion, devoted to measurements uncertainty of Young’s modulus values for analyzed polymer linings.

### 4.1. Results of compression tests

During compression tests, both polymers showed different behavior. The PEEK lining showed very small deformations even under a large load (maximum ~63 μm under the load of 10 kN). The measured deformations of the PTFE lining were larger by the order of magnitude (see Figure 4) than the deformations of the PEEK lining. During the tests at 120 °C, both PTFE samples showed significant nonlinearity (see Figure 5 a), very similar to the results presented in [27].

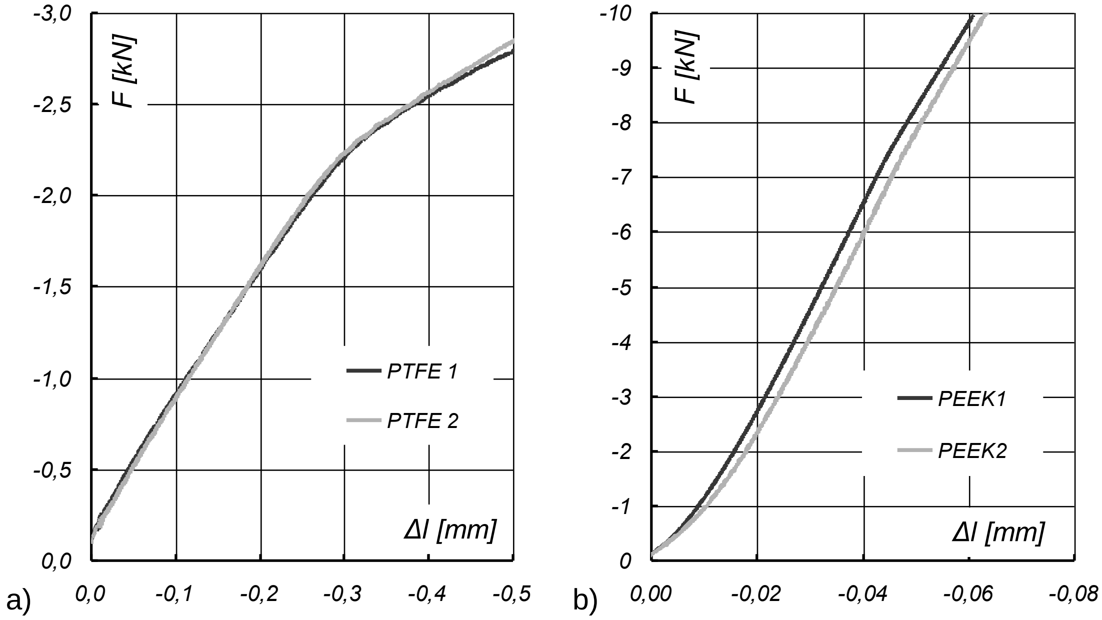

Figure 5. Comparison of the compression results obtained for both samples at 120 C°;
a) PTFE lined sample (3rd repetition), b) PEEK lined sample (4th repetition).

The initial slope of the force-deformation dependence for the PTFE samples changed after reaching ~2.2 kN. Beyond this point, the increase of the load caused much greater deformations of the composite layer. Additionally, after compression the PTFE lining showed high permanent deformation (noticed with the use of extensometer after the individual compression tests). It even exceeded 130 μm for tests no. 3 and 4 at 120 C° with a relatively light load (~3 kN). At lower temperatures, creep values were lower, and decreased systematically with each repetition of compression. In case of the PEEK-based composite (Figure 5 b), visible nonlinearity was noticed only above ~7 kN (p = ~40 MPa). For most of the PEEK measurements no creep was noticed. A small amount of creep was measured only after tests at the highest temperature (maximum ~5 μm after the test at 10 kN).

Because of the tendency of the PTFE-layer to creep, the course of compression tests at the initial stage was different to the PEEK course (Figure 5). In all the results of compression for the PEEK layer, initial curvature was visible, while in case of the PTFE layer, it was visible only in the results of the first repetition at temperatures 25 °C and 60 °C. This was due to PTFE creep, due to which the specimen's surface mirrored the counter surface shape. In case of higher temperatures (100 °C and 120 °C) the initial curvature of compression test result was not visible, probably due to the fact that tests did not start from zero force. The initial value of the force was probably adequate to cause creep of the PTFE lining composite before measurements at the highest temperatures.

Comparing results for both tested specimens of each material similar behaviour during compression can be observed. Larger differences during the tests were visible for the PEEK layer (see Figure 5). This was probably caused by the different initial shape of the samples' surfaces, which influenced the course of the compression at the beginning - different shape of the graphs for both samples.

Table 2 and Figure 6 show averaged measured compression results obtained with the use of regression equations. The results were obtained for the last two repetitions (nos. 3 and 4) of the compression test for each specimen. The results of initial repetitions were omitted because of noticeable creep of the PTFE layer (it was significantly smaller for third and fourth repetition). Deflection of the layers was evaluated on the assumption that compression force was equal to 2000 N. Measured deformation of the lining did not differ too much compared to the results for the same material. Maximum relative difference was lower than 10% (for the PEEK lining at 60 °C).

Significantly larger deformations were observed for the PTFE lining. Its deflection was about 290 μm at 120 °C, which is four times greater than the deformation at 25 °C (~72 μm). The PEEK lining behaved differently. It became deformed by only about 10.2 – 10.7 μm at 120 °C, and it was only ~2 μm (less than 20%) more in comparison to the deformation at 25 °C. It should also be mentioned, that after compression tests at 120 °C, on the surface of the PTFE lined samples, imprints of the steel rod were clearly visible. This is evidence of nonlinear behaviour of the polymer and significant amount of creep (samples were damaged). This was not noticed for the PEEK lining after the tests.

| sample | temperature | | | |
|---|---|---|---|---|
| | 25 °C | 60 °C | 100 °C | 120 °C |
| PTFE 1 | 71.6 μm | 119.4 μm | 228.3 μm | 290.5 μm |
| PTFE 2 | 72.2 μm | 113.8 μm | 212.9 μm | 285.2 μm |
| PEEK 1 | 8.78 μm | 9.26 μm | 9.92 μm | 10.24 μm |
| PEEK 2 | 9.29 μm | 10.12 μm | 10.32 μm | 10.69 μm |

Table 2. Average deflection (3rd and 4th repetition) of the polymer layer, results of measurements determined with the use of regression lines.

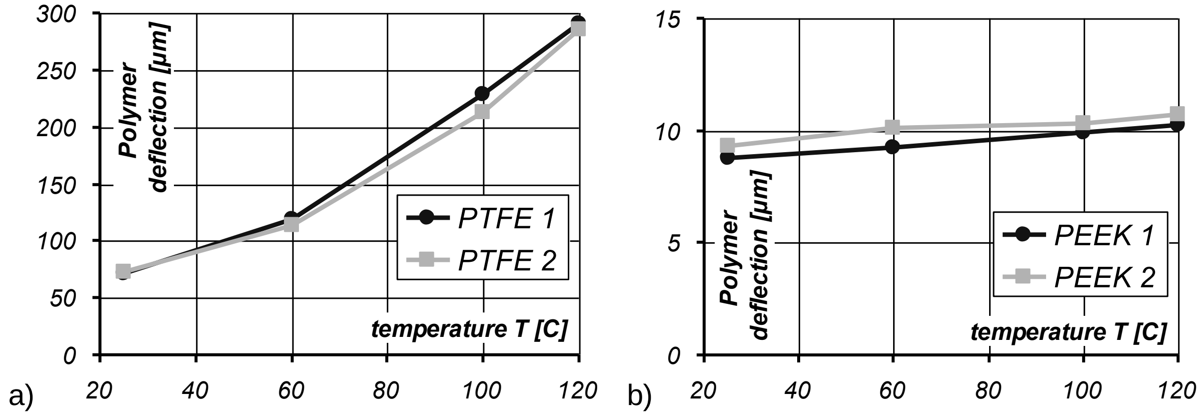

Figure 6. Average measured deflection of the polymer layer as a function of temperature.

## 4.2. Results of FEM analysis

As described in part 3.2, recalculation of the results of the measurements was carried out in order to avoid the influence of non-uniaxial stress in the polymer lining during experiments, which did not allow for direct evaluation of the Young's modulus value on the basis of measurement of the axial deformation only. In Figure 7 axial deformation of the polymer layer as a function of apparent polymer composite Young's modulus is shown for both linings (results of FEM calculations, model described in part 3.2).

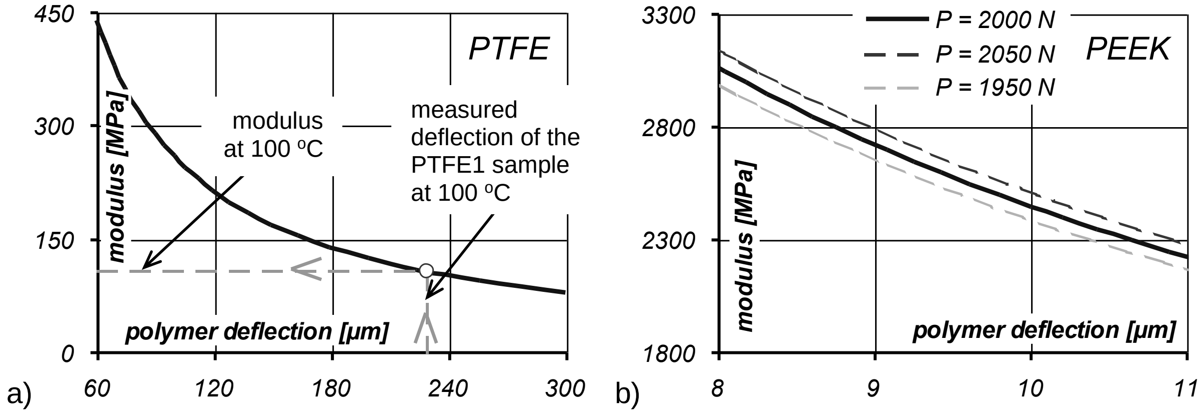

Figure 7. Calculated deflection of the polymer layer [μm] as a function of assumed value of Young's modulus, a) PTFE lined sample, b) PEEK lined sample – result for 3 values of load.

Analyzed range of polymer layer modulus was selected in such a way, that calculated results of polymer deformation cover the measured values range (equal to 60 – 300 µm for PTFE lined sample and 8 – 11 µm for PEEK lined sample; results in Table 2).

For both analyzed cases, obtained results showed nonlinear dependence between specimen deformation and assumed Young's modulus. This is due to a complex stress pattern in the layer and also the influence of sliding with friction at the polymer steel interface.

In Figure 8 an example of the FEM calculation results of the samples under compression is shown for one assumed value of the Young's modulus of the composite lining.

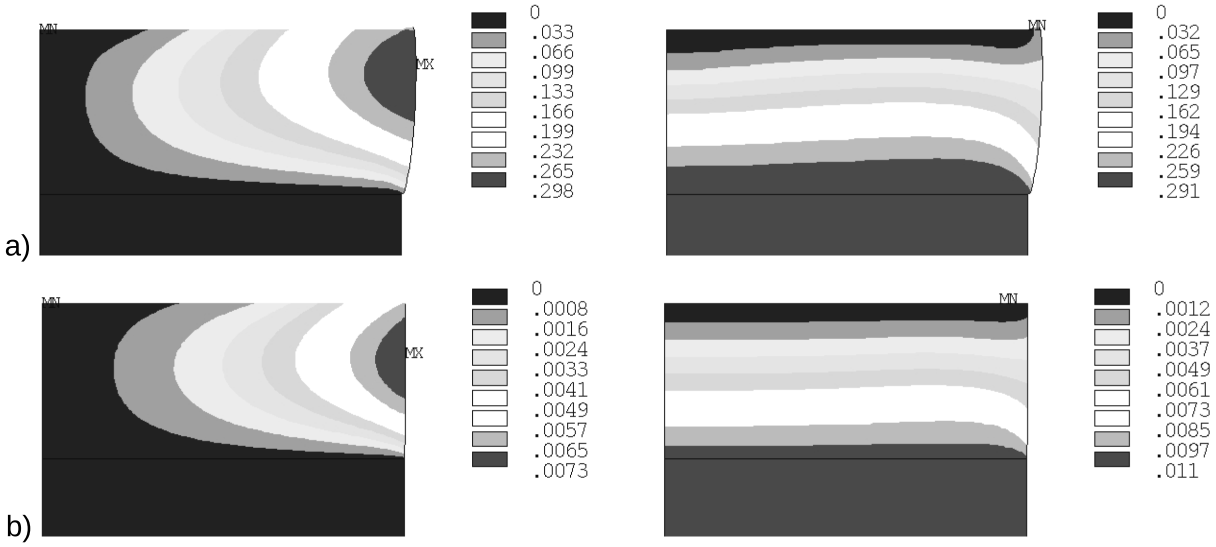

Figure 8. Example results of the sample lining FEM calculations under compression; radial (left-hand side) and axial (right-hand side) deformation [mm] obtained for 120 °C case; a) PTFE polymer layer (E = 83 MPa), b) PEEK polymer layer (E = 2390 MPa).

In Figure 8 radial and axial deformations for the PTFE lining are plotted (the result obtained for E = 83 MPa), while in Figure 8 b for the PEEK lining (E = 2390 MPa). Generally, in both results the same trends were visible. Compressed compliant polymer layer reduced its thickness and had a tendency to form a barrel shape (enlarged diameter, clearly visible in case of the PTFE-based sample result). Radial deformations of the layer close to sample axis were small and increased closer to the outer diameter of the sample. Maximum radial deformation was calculated at the outer lining diameter, closer to the sliding sample surface. Radial deformations of the layer bonded to the steel part were small, while at the sliding surface influence of friction was visible, which restricted the free movement of the sliding layer in a horizontal direction. In the case of axial deformations, lines representing the same value of deformation were almost parallel to the counter surface (target surface) especially close to the sample axis. This was disturbed at the outer diameter of the sample by the influence of the bonding of the layer to the steel part and at the end of the sample by sliding.

## 4.3. Apparent Young’s modulus of the linings

Apparent Young’s modulus of the tested linings was evaluated with the use of measurements and FEM calculations results. Measured deformation of the polymer layer (collected in Table 2) was used together with calculated deformation of the layer as a function of Young’s modulus, as shown in Figure 7. In the results of FEM calculations, measured deflection of the layer (from Table 2) was searched on the horizontal axis and next, the value of Young’s modulus corresponding to this deflection was read on the vertical axis. An example of this operation is shown in Figure 7 a for result obtained for the PTFE 1 sample at 100 °C. Evaluated apparent Young’s modulus of the layers as a function of temperature for the tested samples is collected in Table 3 and in Figure 9.

| sample | temperature | | | |
|---|---|---|---|---|
| | 25 °C | 60 °C | 100 °C | 120 °C |
| PTFE 1 | 363 | 214 | 107 | 83 |
| PTFE 2 | 359 | 225 | 116 | 85 |
| PEEK 1 | 2790 | 2640 | 2470 | 2390 |
| PEEK 2 | 2640 | 2420 | 2370 | 2290 |
| ratio PEEK / PTFE | 7.3 – 7.8 | 10.8 – 12.4 | 20.5 – 23.1 | 26.9 – 28.8 |

Table 3. Apparent Young’s modulus [MPa] of the polymer based linings as a function of temperature.

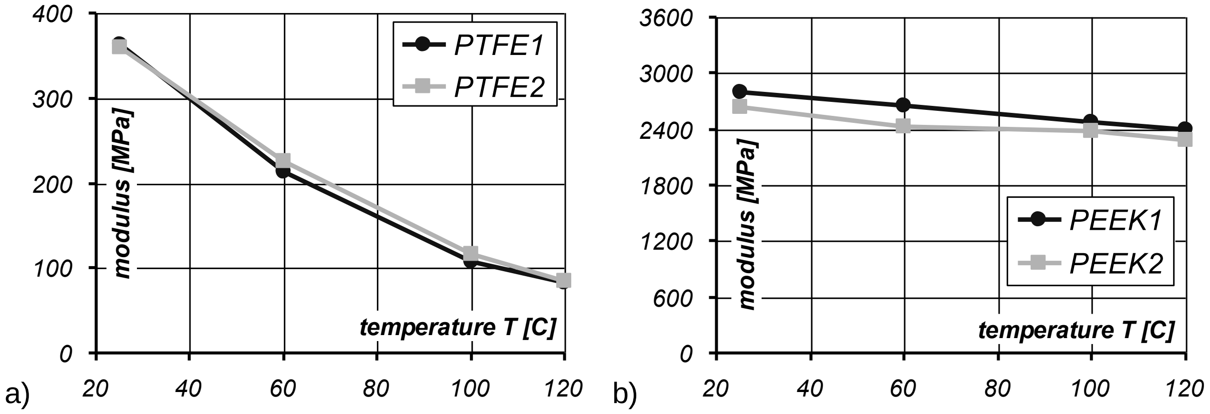

Figure 9. Apparent Young’s modulus [MPa] of the polymer composite layers as a function of temperature; a) PTFE lining, b) PEEK lining.

Values of Young’s modulus obtained for the PTFE lining do not differ much for both tested samples. Maximum relative difference of ~8.5 %, was observed, while in the case of the PEEK lined samples, the maximum difference was ~9.3 %. As expected, for both tested materials, apparent Young’s modulus of lining decreased with increased temperature. The PTFE lining decreased its average Young’s modulus from ~361 MPa at 25 °C to ~84 MPa at 120 °C. It means that the factor of modulus decrease with temperature (25 °C – 120 °C) is ~4.3. Much smaller decrease of Young’s modulus with temperature was noticed for the PEEK lining. Its value was ~2715 MPa at 25 °C and ~2340 MPa at 120 °C, so the decrease factor was ~1.16 only.

Comparing apparent Young's modulus changes as a function of temperature for both materials, significant differences were visible. With the increase of the temperature, stiffness of the PTFE-based polymer layer decreased much more than the PEEK-based lining. The ratio between the average value of the modulus of the sliding layers (E PEEK / E PTFE) at 25 $^{o}$C was ~7.5. It increased with higher temperatures, and reached its maximum value of ~27.9 at the highest temperature of the test (120 $^{o}$C).

The obtained values of apparent Young's modulus were different compared to data available in literature or used in other research. The values obtained for PTFE linings at 25 $^{o}$C are close to the literature data for pure polymer (Table 1) and simultaneously much larger compared to the values used in the other research ([9], [19]). This difference (0.11 GPa [9] compared to 0.36 GPa obtained in the present study) came probably from the different structure of the composite layer in both analyzed cases. In the work of Ettles et al. [9], the tested PTFE lining was made of a 5 mm thick pure PTFE plate clamped against a matrix of copper wire matting. The PTFE plate was pressed into a matrix of about 1.0 – 1.5 mm and thus formed a bond between the layers of the composite. The same technique was used for the lining tested in the present study, but the intermediate layer was made of a regular shaped steel wire mesh, which thickness was smaller (~0.5 mm) compared to the layer described in [9]. This must have influenced the resulting (representative) stiffness of the lining. In the case of the PEEK lining, the obtained value of the apparent Young's modulus was lower compared to catalogue data (Table 1). Reduction of the layer modulus is probably caused by the presence of the intermediate layer (bonding, layer of porous bronze in this case), which could be assumed as an additional elastic element (spring) deforming under the load.

### 4.4. Accuracy of the assessed Young's modulus

The accuracy of the assessed values of the Young's modulus for the polymer-based lining depends on the accuracy of the sensors used for measurements and on the relevance of assumptions of the proposed methodology. In this section both factors are analyzed to assess maximum inaccuracy of the value of the evaluated modulus.

In the case of sensor accuracy, both force and deflection values were measured with precision equipment. The maximum measuring error for the extensometer was assessed as ± 0.2 μm (in the whole measurement range). The maximum inaccuracy of the force measurement was assumed, on the basis of the class of the sensor (0.5) and its measurement range (maximum 10 kN), to be ± 50 N. Calibration of the equipment performed before the tests confirmed their precision.

The influence of the sensor's errors on apparent Young's modulus was evaluated with the use of previously described methodology (paragraph 4.3), assuming that deflection of the layer (Table 2) differed from the measured value by the extensometer measurement inaccuracy (± 0.2 μm). Calculations of the lining deflection as a function of modulus were also carried out for compression force varying by the value of force sensor maximum measurement error (± 50 N). Example of the result for the PEEK lining is shown with two dashed lines in Figure 7 b.

The largest error of the evaluated Young's modulus, caused by the sensor accuracy, was expected in the cases with the lowest measured values of layer deflection, because then the relative error of deflection measurement is the largest. According to the calculations the maximum error is 139 MPa in case of the PEEK samples (sample PEEK 1 at 25 $^{o}$C, P = 2050 N, $\Delta l = 8.58$ μm) and 10.2 MPa in case of PTFE samples (sample PTFE 1 at 25 $^{o}$C, P = 2050 N, $\Delta l = 71.4$ μm). The error of the evaluated Young's modulus decreased with the increase of the measured lining deflection, and at 120 $^{0}$C it was 108 MPa and 2.4 MPa for the PEEK lined samples and the PTFE lined samples respectively. Finally, the relative error of the Young's modulus assessed for linings caused by sensor accuracy can be evaluated as being ~ 3 % for the PTFE samples and ~ 5 % for the PEEK samples.

In addition to measurement errors, also the initial geometry imperfections may cause some errors, as the calculations reproducing the experiments were carried out with the assumption that the polymer surfaces were ideally flat. Moreover thermal expansion may cause additional curvature of the sample surface. An appropriate error analysis was performed. It was assumed that the sample surface was convex with the height of 10 μm. With such an assumption the relative error caused by thermal expansion and surface geometry deviation was evaluated as ~5.5 % for the PTFE lining, and 3% for the PEEK lining.

Summarizing all the analyzed sources of errors, the maximum difference of the assessed Young's modulus for the lining does not exceed 10 %.

A factor which was not analyzed is the repeatability of manufacturing process – it is possible that pads/specimens from different production batches can have varied properties, also in case of large bearing pads it is possible that the properties are not uniform all over the pads. Such a study was not carried our because of unavailability of a larger number and/or variety of polymer composite material samples.

Evaluated values of apparent Young's modulus are based on the results of measurements carried out for two samples of each material only. This is not enough to provide statistically sound results for various production batches. The results however, allowed to observe the trends of the changes of the measured values with temperature. The values of the apparent Young's modulus of the linings were very similar for both of the analyzed samples of each polymer, while there were significant differences between the PEEK and the PTFE composite polymer layers.

## 5. Conclusions

In this work, the methodology to evaluate Young's modulus for a polymer based sliding layer as a function of temperature is proposed and discussed. The proposed methodology was applied to two types of polymer linings often applied as linings for fluid film bearings: a PTFE-based layer and a PEEK-based layer. The tests were conducted within a temperature range of 25 °C – 120 °C. The proposed methodology made it possible to include a contribution of the stiffness of the bonding intermediate layer to the resultant apparent Young's modulus of the whole polymer composite lining.

As expected, evaluated Young's modulus of the polymer composites decreased with the increase of temperature, but the scale of this effect was different depending on the material. The apparent Young's modulus for the composite linings was different from catalogue data. This is probably due to the bonding layer.

Obtained data is limited to the bonding methods specifically used in these tests. Different manufacturing techniques of thrust-bearing pads in either material are likely to yield different apparent modulus numbers.

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