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RESEARCH ARTICLE

Friction and wear performance of polyether ether ketone (PEEK) polymers in three lubrication regimes

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Abstract: This experimental study investigates the friction and wear of three coatings commonly used in industrial applications, particularly in hydrodynamic bearings. The three materials under investigation were Babbitt, polyether ether ketone (PEEK) reinforced with 15% carbon fibers, and PEEK reinforced with 20% carbon fibers. The first polymer material was extruded, while the other was produced by fused deposition modelling (FDM). The materials were subjected to sliding tests in a pin-on-disc configuration, with a steel ball serving as the counter surface. The tests were conducted at room temperature, with a load of 10 N and under three different lubrication conditions: dry, grease, and oil. The linear speed was set at 0.3 m/s for the dry and semi-solid lubrication tests, while for the oil tests, the speed was set at 0.25 m/s. The greases used had consistency grades of NGLI 000 and NGLI 2. An ISO VG 68 circulation oil was used for the oil lubrication tests. Additionally, thermodynamic analyses were performed under the most severe conditions (i.e., dry) to investigate the steel–Babbitt and steel–PEEK contact.

Keywords: hydrodynamic bearings; polyether ether ketone (PEEK) polymers; additive manufacturing; grease lubrication; sliding; oil lubrication; ball-on-disk; tribology

1 Introduction

Hydrodynamic bearings are commonly used in rotating industrial machines. Their operating principle is based on the storage of pressure in a thin layer of lubricant separating two sliding surfaces of the order of micrometers, thus minimizing wear to practically negligible rates. In real application, however, these ideal conditions are not always maintained. In dirty environments, bearings without lubrication or with grease lubrication are used [1]. The latter better withstand the presence of contaminants within the meatus. During stops and starts, the combination of high loads and low speeds makes the oil film unable to completely separate the sliding surfaces or shafts from the bearing surfaces, and the beginning of wear is unavoidable. The durability of bearings depends above all on their ability to resist wear under these operating conditions. Sn-based alloys, commonly known as Babbitt or white metals, are the traditional choice of material for lining a hydrodynamic bearing. Patented in the 19th century, Babbitt coatings are known for their low hardness, but this means that they have a rather low Young's modulus, as well as yield point, which is about 45.5 MPa at 20 °C and almost halved at 100 °C. These characteristics limit the so-called 'average specific load' of the bearings (i.e., the ratio of the load to the bearing's active surface) to values between 2 and 3 MPa, in order to avoid friction and damage to the bearing surface. The

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two fundamental characteristics of a bearing lining, which can come into direct contact with the shaft, are to have a low coefficient of friction and a hardness lower than that of the shaft. White metal is an alloy that differs in the percentages of other elements, mainly antimony and copper, and a non-negligible percentage of lead. For environmental reasons, white metal alloys no longer contain lead, cadmium, nickel, and arsenic, but generally keep their mechanical performance levels [2]. Sn-based coatings are also known to be able to incorporate the hard contaminant particles sometimes found in oil, preventing the continuation of abrasive degradation [3]. The low hardness, however, is not a beneficial property for the durability of Babbitt coatings and the low melting point limits their use at temperatures below 100 °C. The replacement of Babbitt coatings with polymer-based materials is becoming increasingly common due to the observed improvement in performance. One example is the use of polyether ether ketone (PEEK)-coated thrust bearings in hydroelectric power plants, which, according to an initial report [4], can withstand higher loads and service temperatures, as well as exempt operators from using oil lifting systems during start-up, a common practice to avoid premature wear of Babbitt bearings. Moreover, the enhanced load-carrying capacity of polymer-coated bearings, coming from their yielding characteristics, led to development of a concave interface. The last one improved lubricant retention and yielded hydrodynamic performance (pressure and oil film thickness) nearly indentical to that of Babbitt [5–7]. However, reports on the wear of oil or grease lubricated polymer-based coatings are not numerous. Early studies evaluated different fillers for politetrafluoroetilene (PTFE), including metal powders and fibers or whiskers [8, 9]. The authors ranked the composites in terms of wear rates in a block on (steel) ring tests with paraffin oil lubrication, identifying Ni powder and glass fibers as the most promising PTFE fillers. Graphite also seems to be a good reinforcing agent. As reported by Gheisari and Polycarpou [10], unless the lubricant is contaminated with hard Si particles, wear rates of graphite-reinforced PTFE cylindrical pins sliding against tool steel discs are not measurable. As demonstrated, reinforcing PEEK with glass fibers reduced wear rates to the limit of pure polymer, far exceeding carbon steel plates tested under the same conditions. Although the reports [8–11] are encouraging, they mainly concern the development of material formulations and the variable range of test conditions complicates comparisons. Consequently, bearing users wishing to replace Babbitt with composite liners are faced with a long list of commercially available candidates. Apart from practical reasons such as cost and simplicity of production, there is currently no way to classify the performance of coating materials according to their properties. The main issues of bearing coatings/layers are adhesion, maximum operating temperature, wear under dry/mixed lubrication, and thermal creep. The main issue for new materials is the compatibility with "conventional" lubricant products such as oils and greases.

It has been studied what happen in case of dry lubrication (absence of lubricants or insufficient lubrication in start up or shot down and in case of lubrication system failure). It has been studied, also, grease lubrication that could be used in the assembling phase. This work evaluates the tribological properties of bearing materials by means of dry, grease, and oil lubricated ball on disc tests. In this experimental activity, the characterization of PEEK and metallic Babbitt in terms of coefficient of friction (CoF) was performed using ball-on-disc (BoD) tests at room temperature for dry and boundary/mixed lubrication conditions. Furthermore, thermodynamic analyses of what happens in the steel–Babbitt and steel–PEEK contact were carried out in dry condition. Finally, the morphologies of the worn surfaces were examined post-test using a profilometer and scanning microscope.

2 Materials and methods

A CSM Instruments tribometer (CSM, Swiss) (a schematic representation of the machine is shown in Fig. 1) was used for friction and wear tests based on ASTM G99-17 and DIN 50324, where a 6.00 mm diameter steel (100Cr6) ball under 10 N load was rubbed against specimens of three different materials and different production method (see Table 1): Babbitt, PEEKcf15, and PEEKcf20. The load was chosen based on the knowledge acquired from previous experimental work [12], when with a lower load it was difficult to

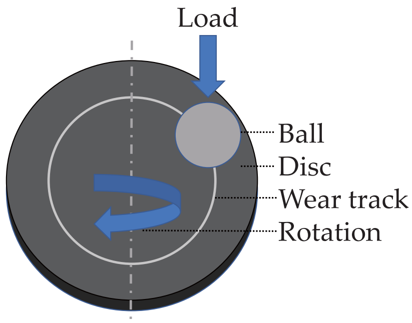

Fig. 1 Ball-on-disk scheme.

Table 1 Tested materials.

Type	Composition	Production	R_a
Coating	White metal—Grade 2 Babbitt (89Sn/7.5Sb/3.5Cu)	Lining	1.5 μm
Coating	Polymer—PEEK reinforce 15% carbon fiber	Injection molding	1.5 μm
Coating	Polymer—PEEK reinforce 20% carbon fiber	Fused deposition modeling (FDM)	3 μm

analyze the worn surface after the test. The materials were analyzed under three different lubrication conditions: dry, grease, and oil lubricated. The linear speed chosen for the experimentation is around 0.3 m/s (intermediate speed for the machine limits).

The boundary/mixed lubrication conditions were simulated using three products (see Table 2): two greases with different viscosity grades and a circulating fully formulated lubricant for oil lubrication. The graphs of the CoF curves as a function of sliding distance were obtained from the TriboX software version 4.1.I, installed in the tribometer to analyze the friction behavior of the samples. Before each test, the ball and the disc were cleaned in ethanol for 5 min.

Table 2 Lubricant products used for the tests.

Type	Sector	Grade
Oil	Industrial-bearings	ISO VG 68
Grease	Industrial-bearings	NLGI grade 000
Grease	Industrial-bearings	NLGI grade 2

3 Results and discussion

3.1 Dry tests

Dry tests are significant because they give an estimate of how well the material can withstand the load without lubrication. It may be the case, for example, that there is a problem with the lubrication system or in some cases when lubrication is not recommended due to environmental conditions (presence of dust in cement plants). For both PEEK samples the dry tests ended with an average CoF of about half that of the white metal. As shown in Fig. 2, the Babbitt test failed after a few meters. The PEEK samples exhibited two different behaviors: PEEKcf20 had a flat trend throughout the test, while PEEKcf15 grew linearly about halfway through the test and then stabilized at a higher value.

The huge gap in performance in dry conditions is due to the difference in the mechanical properties of the two types of materials tested: soft metal and plastic.

Soft metal is also called Babbitt or white metal and is an alloy with 80% tin, 10% Cu, and 3% copper. The plastic is a thermoplastic polymer and is based on PEEK with 15%/20% carbon fibre as a filler.

For Babbitt, there was adhesion evidenced by the scanning electronic microscopy (SEM) image in Fig. 3; whereas for PEEK, the Hertzian pressure is much lower because at the same external conditions (load and velocity) it has a Young's modulus approximately 90% lower and Poisson ratio 10% greater than white metal.

For PEEK-based materials, particularly PEEKcf20, we noticed from Alicona's measurements a lapping effect, i.e., a smoothing of the peaks in the material at the location of the wear track.

Some authors in the literature have noted the formation of tribofilm in dry condition using other tribometers (MTM) under more harsh external conditions [13].

3.2 Grease lubrication tests

Grease tests are intended to simulate a mixed/boundary lubrication condition, where there is no complete separation between the relative moving parts [14, 15].

Grease is typically a petroleum product consisting of up to 90% base oil, 10%–25% thickener, 0–10% solid lubricants, and 0.1%–4% additives. For these tests, two mineral-based lubricating greases were used. They both contain with antioxidants, anti-rust, extreme pressure (EP) additives, but one has a complex calcium-based thickener used for NGLI 000,

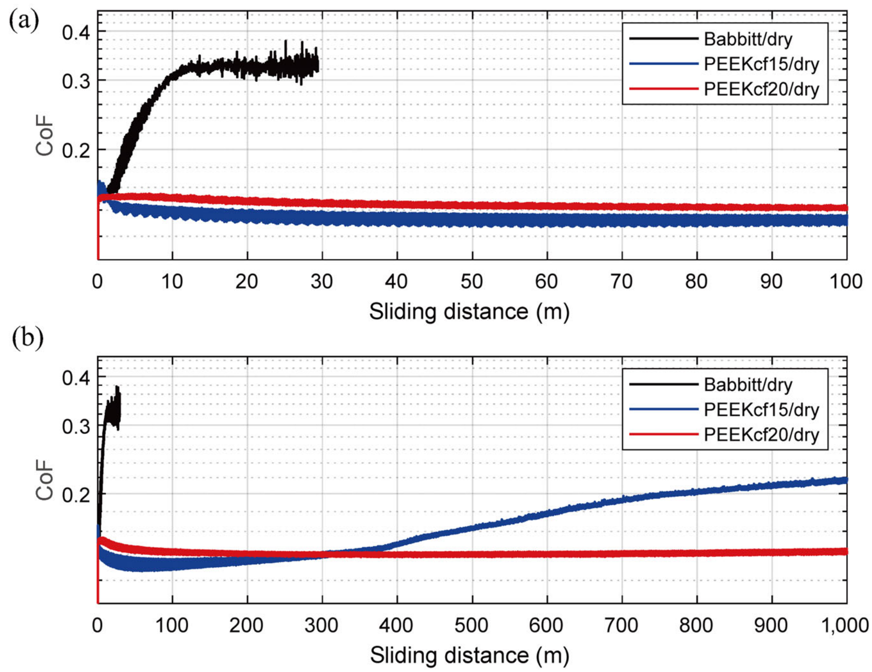

Fig. 2 Tests in dry condition with 10 N load applied and linear speed of 0.3 m/s. (a) Bottom overall curves and (b) top from start to 100 m (run-in phase).

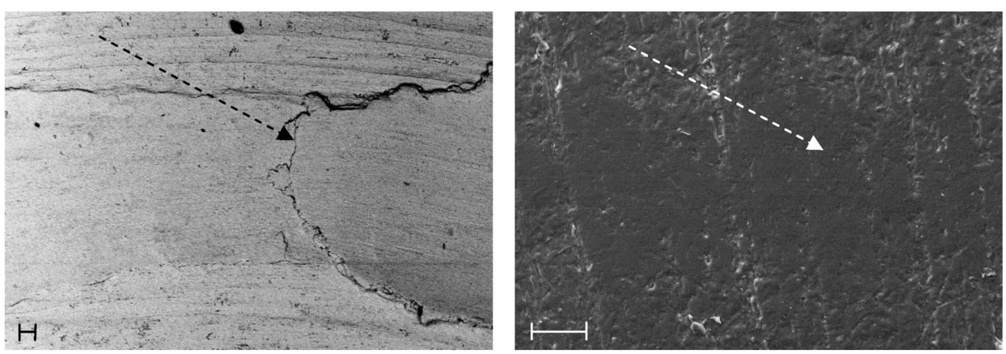

Fig. 3 Tests in oil lubrication condition with 10 N load applied and linear speed of 0.25 m/s.

while the other has a complex lithium-based thickener used for NGLI 2 grease.

The functioning of a grease can be imagined as a "sponge" that releases the base component under stress. The thickener is crucial as it allows the release and absorption of the base component. At room temperature, the base component released is at a high kinematic viscosity (>250 mm^2/s) and it can be defined this condition as semi-solid lubrication. Tests under grease lubrication conditions were concluded for all materials.

The two greases under these speed and load conditions succeeded in creating the lubricating film. CoF data for the Babbitt are more dispersed and show several peaks [16] (see Fig. 4) presumably due to formation of microcracking during the test; not sufficient to stop the test. The CoF curves for the PEEK test samples are more stable and show no peaks. For all materials, NGL 2 seems to perform better with lower friction. The ranking from the highest friction value, both considering grease at consistency 000 and grease at consistency 2, remains unchanged and is as follows: PEEKcf20, PEEKcf15, and Babbitt.

The worst surface finish of PEEKcf20 seems to be positive in grease lubrication at room temperature: there is a higher chance that the grease will be trapped in the valleys and when subjected to load can release the lubricant trapped in it.

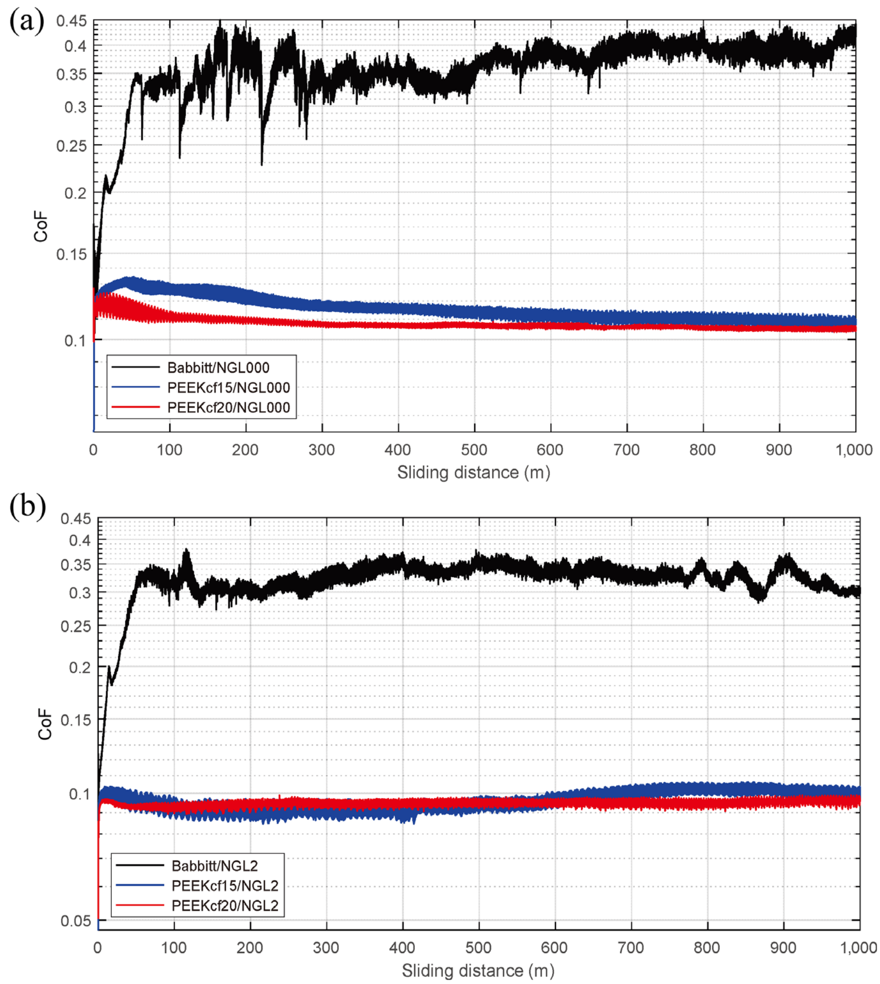

Fig. 4 Tests with grease lubrication using grease consistency (a) NGLI 000 and (b) NGLI 2.

Looking at Fig. 4(a) in the first moments there seems to be a higher average value for PEEKcf20 and then a steady state in the middle of the test which is maintained until the end with very similar values for both polymer-based specimens.

For the lithium-based grease, on the other hand, we find a flat trend for the entire duration of the test for PEEKcf20, while for the other soft material there is a trend that first falls slightly then rises again to stabilize in the last 200 meters.

According to Vásquez-Chacón work, grease lubrication is very sensitive to temperature and sample roughness; in case of material porosity, grease can be retained in the voids and thus release its base component under load.

We avoid smoothing the line (usually done in experimental works) and we keep the real curve shape because significant.

In the friction plot with grease lubrication, we have a curve thickener and many micro peaks for Babbitt than for PEEK-based materials, due to the micro seizure phenomena that occur.

We have found the same behaviour in oil screening test for FZG work where the tests did not abort before the end, but wear phenomena with micro-peaks in the friction profile occurred.

In SEM images below (Fig. 5), it is shown detailed of the worn track of Babbitt in dry and grease lubricated conditions with 10 N load applied.

In the dry condition, there is adhesion due to plastic deformation of the material, while in grease lubrication, it is sufficient meatus to reach the end of the test, but we can detect sign of microcracks in the work trace.

3.3 Oil lubrication tests

The three coatings were tested by using oil lubrication

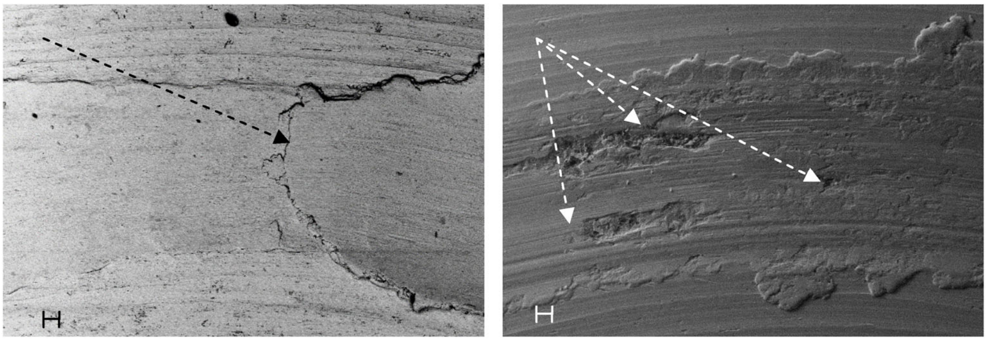

Fig. 5 Babbitt in dry (left) and grease(right) lubrication.

condition [17, 18] and all materials managed to reach the end of the test. The friction curve of the Babbitt is thicker, probably due to the contact between the ridges of the upper specimen and the one below, especially in the early stages.

As might be expected, the friction values in Fig. 6 are low and similar across the three materials, as after the first few meters the lubricant begins to play its role: it lubricates by interposing itself between the two moving parts and removing any debris in the contact area. The ranking from the lowest to the highest in terms of friction for the three materials is as follows: PEEKcf15, PEEKcf20, and Babbitt.

The differences are minimal and the gap between the three materials, going from dry, mixed, and finally fully lubricated condition, tends to narrow. We would have expected closer values under oil lubrication conditions. Calculation of the oil film thickness was done with the equation of Hamrock and Dowson [19]:

$$H_{\mathrm{min}} = 3.63U^{0.68}G^{0.49}W^{-0.073}(1-\mathrm{e}^{-0.68k}) \tag{1}$$

where H_{min} is the minimum oil film thickness, U is the speed parameter, G is the material parameter, and W is the load parameter.

The values of H_{min} for the three materials at a velocity of 0.25 m/s and a load of 10 N were divided by the root mean square (RMS) value of the test specimens (R_{a} is described in Table 1). For the 100Cr6 ball specimen, R_{a} of 0.02 μm was used.

We find lambda ratios of 0.05, 0.06, and 0.03 for Babbitt, PEEKcf15, and PEEKcf20, respectively. In all three cases, we are theoretically in the presence of boundary/mixed lubrication.

For the calculation, we considered a Poisson's ratio of 0.35 for Babbitt and 0.38 for PEEK; a Young's modulus of 53 and 3.8 GPa, and a kinematic viscosity at ambient temperature of 130 cSt.

For the two samples, despite the slight difference in the reinforcements of the two polymer-based materials, we find as the only distinguishing feature the differing roughness level due to the different production technique If we compare the polymer

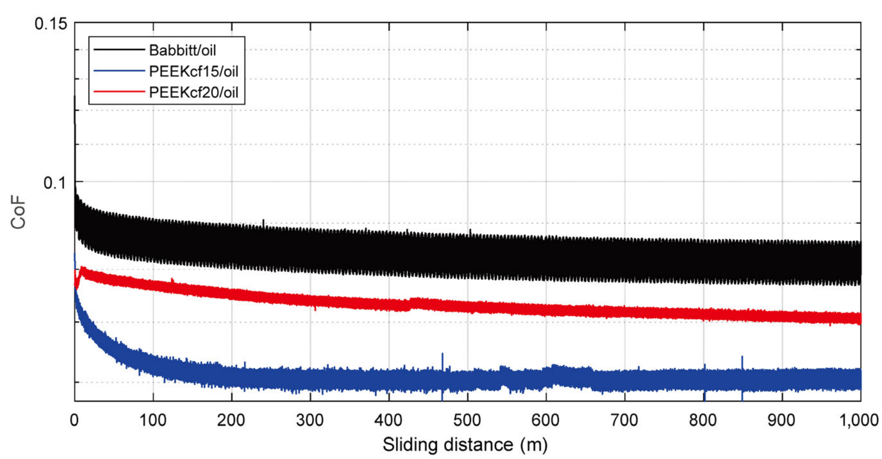

Fig. 6 Tests in oil lubrication condition with 10 N load applied and linear speed of 0.25 m/s.

specimens to the white metal one, the main differences are the following: mechanical and thermal properties.

White metal is a soft metal, whereas polymer is a plastic and therefore even softer.

Under boundary, mixed, and hydrodynamic conditions, there are different ways of conducting heat, as explained in the next chapter, which therefore cause the lubricant to heat up differently, as it has different rheological properties under the same external conditions.

Zhang et al. studied the boundary and mixed lubrication in block-on-ring (BoR) configuration and the ability of diesel to suppressed tribofilm formation changing lubrication quantity in PEEK–steel or PEEK composite–steel couplings.

To summarize the friction performance, Fig. 7 shows

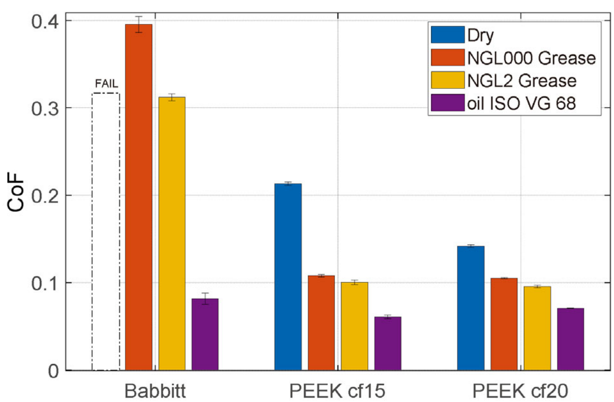

Fig. 7 CoF average calculated for the last 100 m with standard deviation.

the average CoF value for the three materials under the three different conditions: dry, with grease, and with oil lubrication.

3.4 Wear tests

The wear loss rate cannot be estimated by the volume loss using the transverse profile for all the three coatings. As shown in Fig. 8, wear is very slight for PEEK-based polymers.

The profilometer 2D scans and 3D optical scans agree that there is no material removal for PEEK linings. Presumably, only lapping and/or polishing occurs in PEEK-based samples.

The low friction and wear values (see Fig. 8) for PEEK can be explained by the film formation, studied by Tatsumi (2019), not observed in the experimentation.

3D confocal mapping images (see Fig. 9) have been carried out for the three samples in the most severe condition (dry test) and the roughness profile in the wear track has been analyzed for each.

In this case, as well, if for the Babbitt the wear depth is evident for the two peek specimens it is much less clear. In particular, if for the PEEKcf15 specimen it is measurable in the order of a few micro-metres for the PEEKcf20 it is of the same order of magnitude as the surface roughness.

To also analyze the depth of the wear mark, the surface samples were analyzed by profilometer scanning (Perthometer PGK from Mahr, Göttingen, Germany) and the results are shown in Fig. 8 for

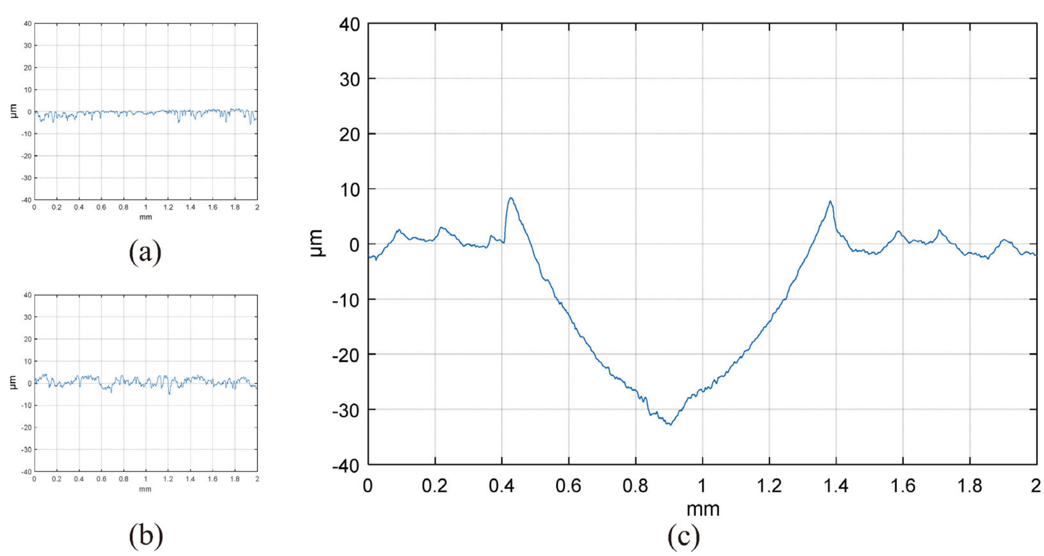

Fig. 8 Profilometer scans for (a) PEEKcf15, (b) PEEKcf20, and (c) Babbitt in dry condition.

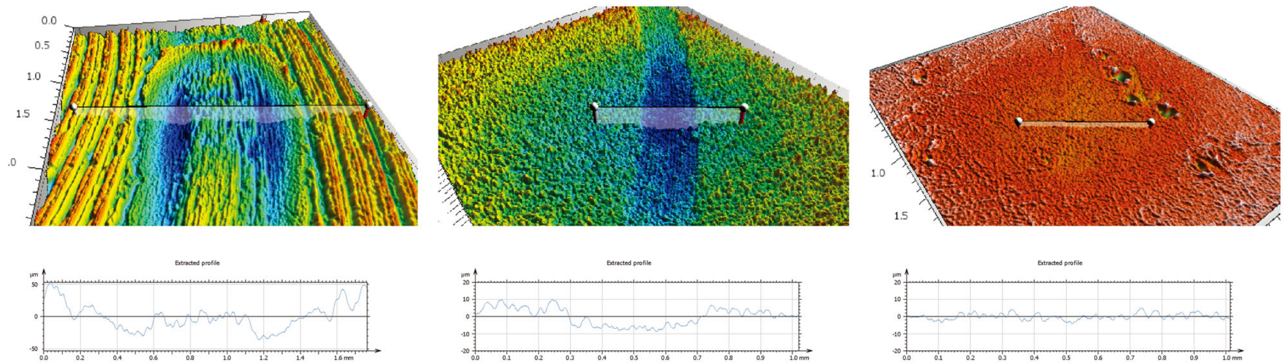

Fig. 9 Confocal 3D mapping and roughness measurement after dry tests from left: Babbitt, PEEKcf15, and PEEKcf20.

Babbitt metal, PEEKcf20, and PEEKcf15 coatings under dry conditions. Only for the Babbitt sample is the depth of the wear mark evident, while for the PEEK samples the depth is of the same order of magnitude as the surface roughness. After the dry test, a scan with an Alicona optical 3D measurement system of the wear mark was performed on PEEKcf20 sample.

In Fig. 10 (left side), starting from the top left and proceeding diagonally, an area can be seen where there is a different distribution of material ridges and presumably an improvement in the finish due to a lapping effect in the early stages of the dry test. In the roughness measurement (see Fig. 10 (right side)), a portion can be observed where the maxima deviate slightly from the mean value compared to the other measurement zones.

4 *In situ* thermal camera measurement

Analyses using an *in situ* thermal camera [20] were conducted to evaluate the thermal properties of materials in the absence of a meatus and during dry contact. The thermal images were obtained using a FLIR X690Xsc MWIR machine (FLIR, USA). The dry test performed on the Babbitt material was stopped after a few dozen meters due to seizing, whereas the PEEK material was tested up to 400 meters. The camera captures 30 frames per second (fps), and the two images depicted in Figs. 11 and 12 were taken before the test and after 1 min (equivalent to 18 m). Comparing the PEEK–steel (Fig. 11) and Babbitt–steel (Fig. 12) contacts, it is evident that they differ considerably. PEEK is an insulating material with a thermal conductivity of around 0.43 W/mK, causing a visible temperature rise in the circumferential wear track within a few moments (Fig. 11(b)). Conversely, the temperature increase is not apparent in the Babbitt tests, both inside and outside the wear track, since white metal, like many other metals, is a conductor with a thermal conductivity of approximately 55 W/mK [21]. This could be due to the temperature

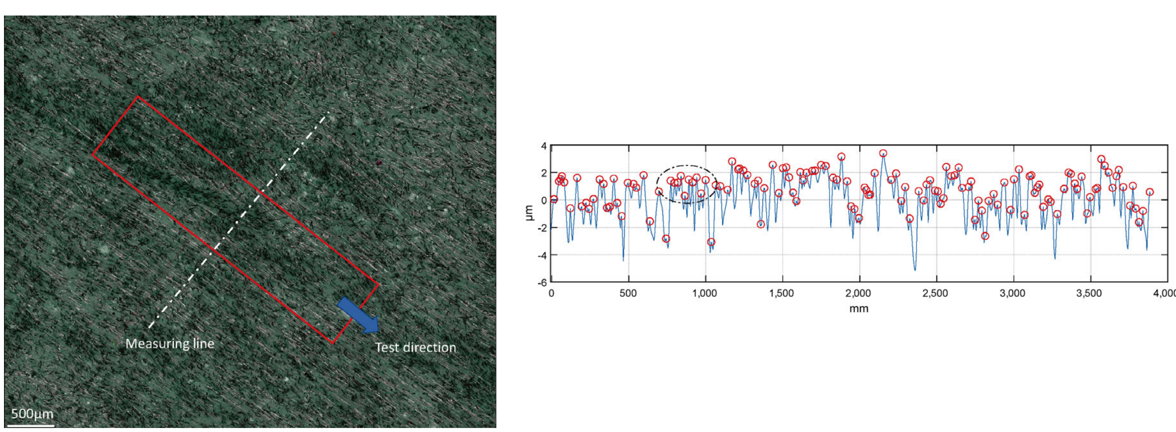

Fig. 10 Alicona 3D image (left) and roughness measurement (right).

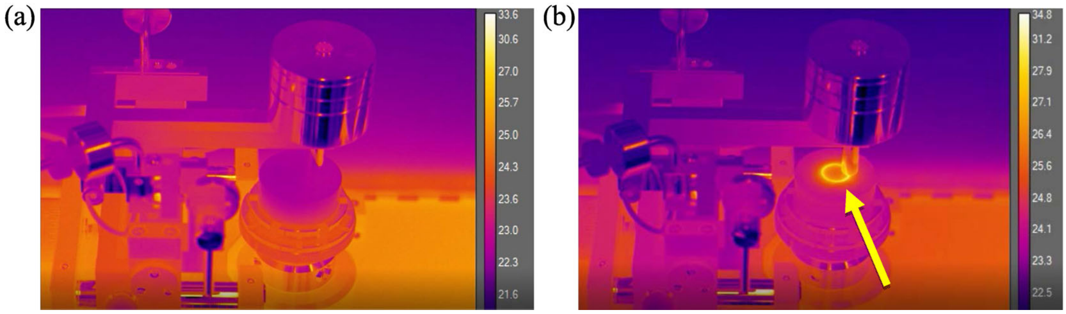

Fig. 11 *In situ* images for PEEKcf20 in dry (a) before test and (b) after some instants of time.

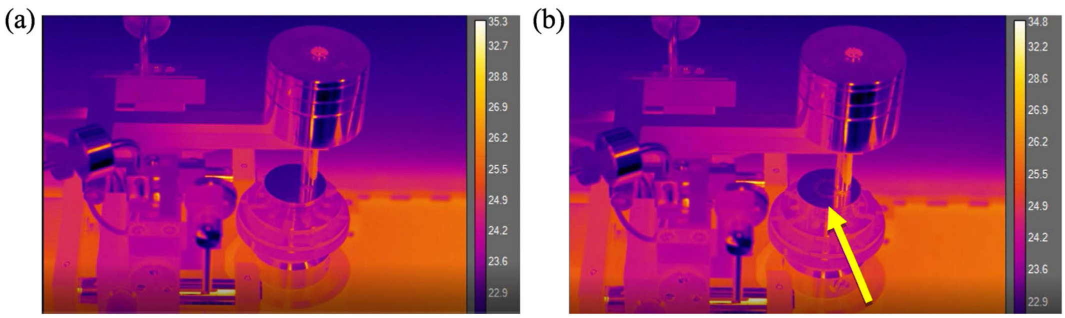

Fig. 12 *In situ* images for Babbitt in dry (a) before test and (b) after some instants of time.

increase in the contact zone being dispersed by conduction and convection from the metal disk. However, it's worth noting that the accuracy of thermal camera measurements can be influenced by various factors such as emissivity, distance, and ambient temperature. To ensure accurate measurements, emissivity values for the tested materials were carefully selected, and the camera was calibrated before each test. While the images provide valuable insights into the thermal behavior of the materials, more precise and comprehensive measurements are required to obtain a deeper understanding of the thermodynamics involved.

On the basis of this initial study, however, it is assumed that, in the case of lubricated contact, the higher temperature rise observed in the PEEK–steel contact can activate the additives in the lubricant. Proper formulation of the lubricant will have to be taken care of in order to avoid the possible degradation of the lubricant by oxidation, which will have to carry a higher thermal load.

5 Conclusions

The study focused on investigating the tribological performance of two polyether ether ketone (PEEK) materials reinforced with 15% and 20% carbon fibers, compared to the metallic Babbitt coating commonly used in hydrodynamic bearings. Tests were conducted using a ball-on-disc machine under different lubrication conditions, including dry, semi-solid, and oil lubrication. A load of 10 N was applied at room temperature, and friction and wear were measured.

Dry tests were conducted to simulate insufficient or light lubrication, as well as the start-up phase. The results showed that PEEK exhibited no wear, whether lubricated or unlubricated, in contrast to Babbitt, which displayed significant wear, especially under dry conditions. Microcracks were found to be the cause of the high dispersion and peaks in the friction profile for Babbitt compared to PEEK-based materials.

PEEK showed lower friction values than Babbitt in both lubricated and non-lubricated conditions, with the differences being more pronounced in the case of grease lubrication. Under dry conditions, the two PEEK-based coatings were able to reach the end of the test unlike the white metal sample. (1)The coefficient of friction (CoF) was studied in relation to surface modification and the wear mechanism, and the mean values of CoF were found to be 0.32 (failed test), 0.21, and 0.14 for Babbitt, PEEKcf15, and PEEKcf20, respectively, under dry conditions;

(2) in grease lubrication tests, the mean values of CoF were 0.39, 0.11, and 0.11 for Babbitt, PEEKcf15, and PEEKcf20, respectively, with NGLI 2. For NGLI 000 grease lubrication, the mean values of CoF were 0.31, 0.10, and 0.10 for Babbitt, PEEKcf15, and PEEKcf20, respectively; (3) in oil lubrication tests, the mean values of CoF were 0.08, 0.06, and 0.07 for Babbitt, PEEKcf15, and PEEKcf20, respectively.

Furthermore, both PEEK-based coatings demonstrated: (1) Low wear, with no material removal detected from the scanning images; (2) *in-situ* tests with a thermal imaging camera revealed a clear temperature increase in the contact area for PEEK, due to the polymer's insulating properties that reduce heat conduction.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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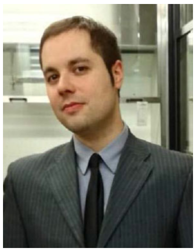
Davide MASSOCCHI. He got bachelor degree in mechanical engineering in 2016 and master degree in energy engineering at Politecnico di Milano in 2019. He is currently doing a Ph.D. in mechanical engineering in the Rotor Dynamics Group at Politecnico di Milano sponsored by Eni S.p.A. At Eni research center, he has carried out experimental studies using the following tribometers: SRV5, EHD2, MTM2, and FZG test bench. He has performed experimental works in dry and oil-lubricated conditions with ball-on-disc (BoD) at the mechanics department to assess the performance of lubricants and coatings. Vibration analysis for control based maintenance (CBM) predictive maintenance for experimental campaigns for rotating machines, e.g. roller bearings, tilting bearings, and fluid film bearings. Recently, experimental studies were conducted at Imperial College's Tribology Group under the supervision of Prof. REDDYHOFF and Prof. Daniele DINI.

Nora LECIS. She born in 1968, she is a confirmed researcher in metallurgy at Politecnico di Milano. She obtained a master degree in physics from the University of Milan in 1994 and a Ph.D. degree in metallurgical engineering from the Politecnico di Torino in 1997. She currently collaborates in the research activities carried out by the Department of Mechanics at the Materials for Advanced Applications section, mainly developing topics concerning: (1) Formulation and identification of operating parameters of baths for the electrodeposition of cobalt-based metal alloys for applications in magnetic recording and with good tribological characteristics; (2) study of the solidification of stainless steels, and the laboratory development of an activated sintering method; (3) study and characterisation of surface modifications of metallic materials obtained through thermochemical surface hardening treatments and/or deposition of thin films by vacuum (PVD) or thermal spray coating techniques, in particular the behaviour of components subjected to cyclic stress; and (4) optimisation of shape memory alloys for lightweight high-damping composites. She is secretary of the Coatings Technical Committee of the Italian Metallurgy Association (AIM). Since 2008 she has been in charge of the Mechanical Characterization of Coatings Laboratory of the Department of Mechanics at Politecnico di Milano.



Marco LATTUADA. He graduated with honours from Politecnico di Milano in chemical engineering in 2010 with a thesis on the development of catalytic systems for nitrogen oxides (NO_x) aftertreatment to be installed on cars in collaboration with Daimler. He has been with Eni since 2011 in the R&D unit that deals with the development and technical support of petroleum products. During his experience he had the opportunity to build up solid formulation and testing know-how on small/medium scale of lubricating oils, related to different applications (automotive, marine, transmission, industry). He served as Project Manager for life cycle assesment (LCA) studies on biolubricants. He boasts several scientific publications and participations in industry congresses. During his activity, he has developed contacts with manufacturers of vehicles and industrial machinery and companies supplying oil additives, as well as collaborations with Italian and foreign universities. He is currently in charge of Eni's Tribology laboratory and an active member of European Coordinating European Council (CEC) working groups for some tribological tests.

Davide SCAGLIA. He got a bachelor degree in mechanical engineering at the Politecnico di Milano in 2016, he obtained a master degree in energy engineering ("Power Production" degree course) in 2019. He is now the head of the Engineering Department of Eurobearings, a company that designs and manufactures hydrodynamic bearings for rotating machines (turbines, compressors, and generators). He is responsible for the mechanical design of the product as well as the research and development of anti-friction materials.

Steven CHATTERTON. He graduated with honors in mechanical engineering from the Politecnico di Milano in 2002. From 2002 to 2008, he held a research grant at the Politecnico di Milano concerning design methodologies for mechanical, hydraulic and pneumatic drives for the manufacturing industry. In 2008 he won the researcher competition for the scientific disciplinary field ING-IND/13. In the period following graduation, he conducted research on the kinematics and dynamics of parallel kinematic robots, developing kinematic synthesis, and optimization methods. In this area, he supervised the implementation of a prototype of parallel robots with 3 and 5 degrees of freedom in space with electric motor. In 2005, he began research into the control of the interaction force of manipulators with real and virtual environments, overseeing the design of an innovative redundant haptic interface with hybrid serial-parallel coupling. Research activities in the field of mechatronics and robotics have also involved collaboration with external companies for the design of automatic machines and the optimisation of articulated and cam mechanisms with high dynamic performance. Since 2009, he has been a member of the Rotor Dynamics Research Group of the Department of Mechanics. One line of research concerns the implementation of regression techniques for unbalance estimation in turbine rotors for power generation. In the field of gas and steam turbines, it deals with the analysis of dynamic phenomena typical of these machines such as tilting-pad bearing instability and vane snubbing phenomena. Another area of research concerns the torsional analysis of industrial compressors and the simulation of related vibration phenomena under unconventional operating conditions. In the field of mechanical transmissions, he was involved in the development of a high-speed train traction system test bench for diagnosing rolling bearing damage.

Paolo PENNACCHI. He graduated from the Politecnico di Milano in 1993 and was awarded a Ph.D. degree in applied mechanics in 1997. He attended specialized courses on "Kinematics and Dynamics of Multi-Body Mechanical Systems" in 1994 at International Centre for Mechanical Sciences (CISM) in Udine, on "Reliability Engineering and Software" in 1999, again at CISM in Udine, and on "Elements of Non-Linear Dynamics: Stability, Bifurcations and Chaos" in 2001 at Fondazione ENI Enrico Mattei and organised by Società Italiana Caos e Complessità (SICC). Since January 1999, he has been the recipient of a research grant for the research programme entitled "Vibration of Mechanical Systems (Diagnostics)" at the Department of Mechanics, Politecnico di Milano. On 1 September 2000, he took up his post as a researcher at the Department of Mechanics of the Politecnico di Milano. In September 2003, he was called as associate professor at the Faculty of Industrial Engineering of the Politecnico di Milano. Author of around 120 scientific publications and responsible for several research projects/contracts, his most recent research activity is in the field of rotor dynamics and identification and diagnostics. In recent years, he has also been involved in the study of dynamic loads during the operation of rotary positive displacement machines, noise control, the control of vibrating systems, biomechanics (in particular the biomechanical analysis of pedalling and the determination of mechanical parameters relating to the passenger of a vehicle), and the design of positive displacement machines such as diaphragm pumps, epitrochoidal lobe pumps, gear pumps, internal lobe pumps and screw pumps and compressors. He has also been involved in kinematics studies relating to the theory of conjugate profiles and the design of form tools for cutting particular three-dimensional profiles.