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Fretting experiments of advanced polymeric coatings and the effect of transfer films on their tribological behavior

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ABSTRACT

The tribological performance of PTFE and PEEK-based polymeric coatings was evaluated under aggressive small amplitude reciprocating (fretting) conditions. Such a condition is encountered in modern machinery, including air-conditioning and refrigeration compressors. Unlubricated step load-to-failure experiments to determine their scuffing resistance have been performed. It was found that the tribological performance depends on the transfer film formed on the counterface. The PTFE coatings were able to form stable and continuous transfer films on the counterface and exhibited lower friction coefficient and wear without catastrophic failures. In the presence of liquid lubricant, the coatings showed worse performance than under dry conditions because the lubricant prevented the formation of transfer films on the counterface.

1. Introduction

The sliding contact of polymers in the form of coatings against metallic counterfaces is becoming increasingly common in industrial applications due to improved coating processes on light weight substrates as well as favorable tribological behavior of polymeric coatings under moderate to severe contact conditions [1]. A type of motion encountered in industrial bearing contact applications is reciprocating motion with small amplitude of few mm to sub-mm, which is usually referred to as fretting motion. The tribological performance of polymeric coating contact surfaces in air-conditioning and refrigeration compressors experiencing such motion is of particular interest in this work, e.g., in a scroll compressor.

The tribological behavior of advanced blended bulk polymers has been extensively studied, and their superior tribological performance is usually attributed to their unique property of effective transfer film formation on the counterface during dry sliding [2–8]. Specifically, [2,3] showed that the retention of protective transfer films strongly adhered to the counterface is primarily responsible for the improvements in wear resistance. Studies about the effects of fillers on the tribological behavior of polymer composites also show that improved wear performance is related to how well the fillers improved the ability of composites to form transfer films [3,8,9]. The mechanism of transfer film development by abrasion of the softer polymeric material by the harder counter-surface metal asperities has been studied under somewhat idealistic conditions of low load, slow unidirectional sliding speed and smooth interfaces.

The mechanism and effectiveness of transfer film formation for polymeric coatings (versus bulk) has not been investigated and such a mechanism may or may not be the same as for bulk materials. The nature of the coatings is such that effective transfer film formation is critical since penetrating the thin polymeric coating will likely result in catastrophic failure as one would expose metal-to-metal contact (unless some sort of protective layer is formed). This is typically not the case for bulk polymers since there is an abundance of polymer material to replenish any worn transfer films. Note that the use of polymeric coatings versus bulk polymers in bearing applications in machinery can resolve issues associated with bulk polymers such as long-term stability and high cost.

Tribological studies of bearing-grade blended polymers in the form of coatings are scarce, compared to bulk polymers. Polycarpou and co-workers [1,10–12] reported tribological studies of polymeric coatings under specific refrigerant environments simulating air-conditioning and refrigeration compressor surfaces. These studies focused on unidirectional high speed sliding conditions (e.g., as encountered in swash-plate automotive air-conditioning compressors) and large oscillatory motion simulating the wrist-pin/bushing contact in reciprocating compressors. From these studies, it was shown that PTFE-based (versus PEEK-based) polymeric coatings exhibited superior tribological performance. In this work, two representative PTFE- and PEEK-based polymeric

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coatings were tribologically tested using unlubricated (dry) and liquid lubricated fretting test conditions, under aggressive normal loads, to examine their scuffing resistance limits. The mechanism of transfer film formation and the transfer film role on the sliding wear, were studied using Scanning Electron Microscopy (SEM) and profilometric roughness measurements.

2. Experimental

2.1. Coating systems

Gray cast iron (Dura-Bar® G2), a commonly used material in compressors, was chosen as a substrate material. It has a bulk hardness is 2.2), a comman initial (as machined) surface roughness (R_q) of 0.3–0.5 µm (before grit-blasting). After grit-blasting with aluminum oxide (which was performed before depositing the polymeric coatings), R_q increased to 3.5 µm, which facilitated the deposition and strong adherence of the polymeric coatings on the substrate surface.

Two different commercially available PTFE- and PEEK-based coatings, namely, PTFE/Pyrrolidone (DuPont™ Teflon® 958-414) and PEEK/PTFE (1704 PEEK/PTFE®) were deposited on the grit-blasted substrates using a spray gun. Photographs of the resulting coatings are depicted in Fig. 1 and the physical properties of the coatings are given in Table 1. PTFE/Pyrrolidone coating showed a glossy and dark-green colored surface, while PEEK/PTFE has a dark gray colored and matte finish. The name of each coating shows their base material; their entire compositions including solvents are unknown as they are proprietary to the coating manufacturers and coating applicators. The entire deposition processes were performed by two authorized applicators, Orion Industries (for PTFE/Pyrrolidone) and Southwest Impreglon (for PEEK/PTFE). General information on the application method for these coatings can be found in Ref. [1] (for PTFE/Pyrrolidone) and Ref. [10] (for PEEK/PTFE), and the companies' websites.

The surface roughness (R_q) of the two coatings was measured using a stylus profilometer (Tencor P-15™) and summarized in Table 1. The PEEK/PTFE coating surface shows higher roughness (1.00 µm) than the PTFE/Pyrrolidone coating (0.61 µm), which can be attributed to the coating powder/particle size used. The thickness of the two coatings was measured using cross section SEM [1,10], and found to be 23 ± 5 µm and 40 ± 5 µm, respectively, for PTFE/ Pyrrolidone and PEEK/PTFE coatings. These values are thicker than typical hard coatings, such as diamond-like-carbon (DLC) and WC/C (2.5 µm [13]).

2.2. Tribological testing conditions

A high-pressure tribometer (HPT) enabling the application of a precisely controlled (closed loop) normal load (with error less than 2% of the applied load) and the measurement of in-situ friction coefficient on the pin-on-disk (coated) contact interface was used for the fretting experiments. The pin is placed on the lower stationary holder, which is directly mounted on a force transducer sensing both normal force and friction force, thus obtaining the friction coefficient. The coated disk is securely attached on the upper oscillating spindle, enabling fretting-type of motion at the interface. Further details of the HPT can be found in Refs. [10,11].

The pins were also made out of the same gray cast iron material as the substrates, and machined as seen in Fig. 2. In addition to the "standard" cylindrical pin having 6.3 mm diameter (of nominal flat contact area), a reduced diameter (3.2 mm) pin was also used to achieve higher contact pressure testing. The standard pins were used with a rigid pin holder to avoid excessive tilting and ensure finite fretting motion. The smaller pins were used in a self-aligned pin holder, while still maintaining flat surface contact and finite fretting motion. The roughness of the pin surfaces was 0.3-0.4 µm (smoother than the polymeric coating surfaces). The pins were used as received, without any coating.

Fretting motion with 3 mm translation amplitude and 4.4 Hz reciprocating frequency was imposed on the pin-on-disk interface, thus resulting in an average linear sliding speed of 26.4 mm/s. The applied normal load started from 133 N (30 lb), and progressively increased by 133 N every 2 min, up to 1334 N (300 lb) (20 min testing) to examine the scuffing resistance of the coatings. Assuming a nominally flat pin surface under the initial 133 N normal load, the corresponding initial contact pressures are 4.28 MPa and 16.58 MPa for the regular pin and the reduced diameter pin, respectively.

Testing was performed under conditions simulating a compressor environment, namely, inside an environmentally controlled chamber filled with 40 psi of R-134A refrigerant at room temperature. Table 2 summarizes the experimental conditions used in this work. Additionally, liquid lubricated testing was performed under exactly the same testing conditions to investigate the interaction between lubricant and the polymeric coatings under fretting conditions (the need for such testing is that even though polymeric coatings are envisioned to replace liquid

Table 1
Coating physical properties (for thickness, ± is for min–max values; for all other cases, ± is the standard deviation).

	PTFE/Pyrrolidone	PEEK/PTFE
Color	Dark green	Dark gray
Thickness (µm)	23 ± 5	40 ± 5
R_q (µm)	0.61 ± 0.08	1.00 ± 0.03
Elastic modulus (GPa)	3.7 ± 0.1	4.5 ± 0.8
Hardness (MPa)	51 ± 3	42 ± 13

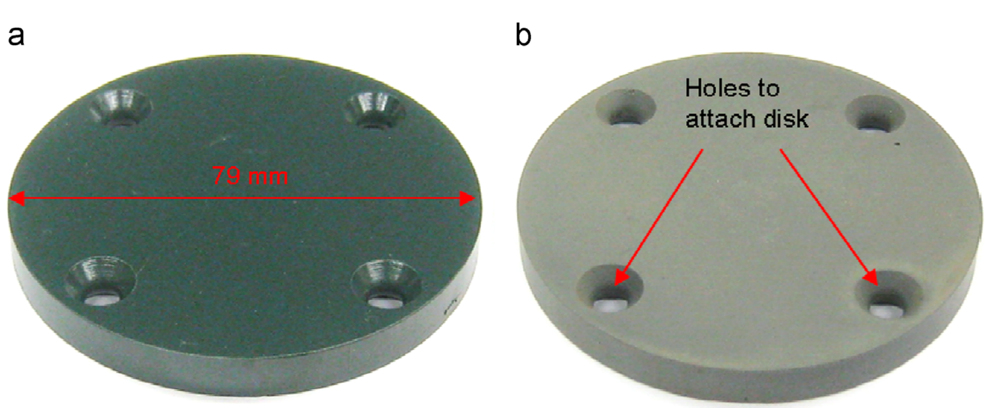

Fig. 1. Photographs of coated disk samples (coated on both sides, gray cast iron substrates): (a) PTFE/Pyrrolidone and (b) PEEK/PTFE.