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Tribological study of high bearing blended polymer-based coatings for air-conditioning and refrigeration compressors

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ABSTRACT

Deposition by spray techniques has made possible to coat different substrate materials found in engineering applications, such as air-conditioning and refrigeration compressors, with blended soft polymeric coatings based on polyetheretherketone (PEEK), polytetrafluoroethylene (PTFE), and fluorocarbons (FC). In this study, the tribological performance of four polymeric coatings (PEEK/PTFE, PTFE/MoS_2, FC, and PEEK/Ceramic against 52100 steel) was evaluated using a specialized tribometer simulating aggressive compressor conditions. Experimental results showed that PTFE/MoS_2, and PEEK/PTFE coating systems performed better in terms of their tribological performance compared to the other polymeric coatings under starved lubricated conditions (mixture of R-134a refrigerant and polyalkylene glycol lubricant). Under aggressive unlubricated conditions, scuffing was observed for all the coatings except PEEK/PTFE. By using time-of-flight secondary ion mass spectrometry (TOF-SIMS) and X-ray diffraction (XRD), it was found that the good performance of PEEK/PTFE was related to the formation of chemical species from the fragmentation of PTFE, PEEK, and its favorable interaction with the substrate, along with an increase in crystallization of PEEK during testing.

1. Introduction

Tribology has emerged as one of the fields that contributes to the solution of environmental problems through the development of products and solutions less hazardous or harmful to the atmosphere. Such solutions include the development of lighter tribomaterials to decrease the energy consumption in machine components, fuel in the transportation sector and appliances, and biodegradable oils that contribute to greener environments [1]. The air-conditioning and refrigeration industry has partially addressed this issue of greener technology shifting its attention towards advanced oil-less compressors, not only because it represents cleaner technology, but it would eliminate the adverse thermodynamic effects of the oil present in the refrigeration cycle [2]. Development of oil-less compressors requires the implementation of advanced materials, able to withstand unlubricated sliding conditions while maintaining friction and wear at acceptable levels [3]. Significant advances on the application and deposition of coating materials have been seen in the last decade. For example, spray techniques have made possible the reliable deposition of 10's of microns thick polymeric coatings based on polyetheretherketone (PEEK), polytetrafluoroethylene (PTFE), and fluorocarbons (FC) onto substrates that possess low surface energy, such as gray cast iron.

PTFE is characterized by low friction coefficient and high wear rates. It is believed that the low friction coefficient displayed by PTFE during sliding is related to the low shear strength of its long –(CF2–CF2)– chains [4]. This low friction coefficient along with its high melting point (327 °C) makes this polymer attractive for unlubricated sliding applications [5]. However, the continuous transfer of PTFE layers to the counterface and its easy removal make the wear rates of this material unacceptably high [6]. PEEK on the other hand, is a thermoplastic polymer that can be blended with PTFE to improve its wear performance. The good wear resistance of PEEK can be attributed to its stiff backbone chemical structure and high temperature stability which includes high melting point (335 °C) and high glass transition temperature (143 °C) [7]. Researchers showed that friction coefficient and wear rate values of blends of PEEK and PTFE (in bulk form) had minimum values when the blends contained approximately 10–20% of PTFE [8]. They concluded that 15% partial volume of PTFE was optimum to obtain friction coefficient values between 0.1 and 0.2 and wear rates between 10^{-6} and 10^{-5} $mm^3\,N^{-1}\,m^{-1}$ under 1 $m\,s^{-1}$ sliding conditions and 1 MPa contact pressure [8]. They explained that this reduction in friction and wear was due to the transfer of a continuous layer to the steel counter face. It was reported that at this volume, a continuous phase of PEEK with PTFE particles was present. The PTFE particles are responsible for the low friction (continuous transfer film) while the PEEK structure still provides good strength and wear resistance. Blended PTFE polymers were found to be suitable for applications where low friction and low wear were required, but only in situations of low normal loads. In situations of high starting normal loads, PEEK blends were found to be more suitable compared to PTFE blends [9].

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Despite the fact that the studies previously mentioned provide answers of the friction and wear behavior of PTFE and PEEK blends, tribological studies related to the performance of these polymers deposited onto substrates and in the presence of lubricants and refrigerants are limited. For instance, PTFE/MoS_2-based polymeric coating were found to have a friction coefficient below 0.2 along with a prolonged wear life in a range of temperatures from ambient up to 150 °C under unlubricated conditions [10]. It was reported that this polymeric coating can be potentially applied to small arm components that require absence of lubricant. In a different study, the temperature dependence on the tribological behavior of an amorphous PEEK deposited coating under dry sliding conditions was investigated [11]. It was reported that once temperature surpasses the glass transition temperature (T_g) and reaches 179 °C, the wear resistance increases. This improvement in wear resistance was attributed to an increase in stiffness due to the crystallization of PEEK. Regarding crystallinity of PEEK, different researchers have shown the rearrangement of polymer molecules to form crystalline grains at temperatures above T_g [12,13]. In the case of thermoplastic materials such as PEEK, spherical crystalline regions (lamellar structures also known as spherulites) are formed due to polymer crystallization. These lamellar structures, as organized regions, provide an increase in hardness and density to the disordered polymeric chains restricting their slippage and motion [14,15].

In recent compressor-specific work, the tribological performance of three different commercially available PTFE-based polymeric coatings in the presence of refrigerants was compared [16]. Two different PTFE/pyrrolidone coatings and a PTFE/MoS_2 coating were deposited onto gray cast iron and tested under unlubricated oscillatory conditions. It was found that during testing, the thickness of the coating was rapidly penetrated and most of the wear took place during the first few minutes of the test. In spite of the fact that the coatings were penetrated, the wear debris behaved as a third body and avoided scuffing, performing better than state-of-the art hard diamond-like carbon coatings. In a continuation of the aforementioned study, an evaluation of the effect of the substrate on the performance of the same three coatings was performed [17]. By using X-ray Photoelectron Spectroscopy (XPS) it was shown that in fact, the PTFE/MoS_2 coating was the only coating which did not show any sign of scuffing when coated on Al390-T6 substrate. They found that the metal fluorides formed as a result of fragmentation of PTFE and its interaction with the Al390-T6 substrate had a positive effect on the performance of PTFE/MoS_2 coating by improving its adhesion to the substrate.

Even though there are some studies on the performance of commercially available PTFE and PEEK deposited coatings in the presence of refrigerant, studies dealing with their friction and wear response in the presence of lubricant (in addition to refrigerant) are missing. The objective of this study is to measure the friction and wear behavior of different PEEK/PTFE (PEEK/PTFE), PTFE/MoS_2 (Fluorolon 325®), Fluorocarbon (Fluorocarbon 218®), and PEEK/Ceramic (PEEK/Ceramic) blend polymeric coatings under aggressive starved and unlubricated unidirectional sliding conditions at high temperature (100 °C). Experimental findings were supported by Scanning Electron Microscopy (SEM), Time-Of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS) and X-ray diffraction (XRD) analyses.

2. Materials and methods

2.1. Coating samples

Gray cast iron disks with an initial root-mean-square surface roughness (R_q) of 0.2–0.4 μm before grid blasting were used as the substrate for the deposition of the coatings. After grid blasting of the disk surface, R_q increased to 3.5 μm. These roughness measurements were performed using a contact profilometer (Tencor® P-15). Deposition of the coatings onto the surface of the disks after blasting was performed by an authorized vendor. The coatings were applied using a spray gun which deposits the coating on a previously treated substrate. The grid-blasting treatment on the surface of the disks (prior deposition of the coating) was performed by applying an 80-grit aluminum oxide abrasive which provides a stippled surface to enhance the mechanical bonding of the deposited coating.

In the case of PEEK/PTFE coating, the PEEK particles are distributed by Victrex scales Ltd (West Conshohocken, PA 19428, USA). The PEEK particles have an average size of ~10–12 μm and are semi-crystalline in nature [11]. Morpholine and xantham gum are mixed with the PEEK and PTFE particles into a liquid dispersion to inhibit rust and avoid sagging (formation of tears of the deposited coating), respectively. The gum particles are removed from the coating once the coating is baked (or cured) at 400 °C, leaving only PEEK and PTFE solid particles in the coating. Moreover, after baking the PTFE particles migrate to the top of the coating (i.e., positioned above PEEK). A similar process is employed for the deposition of the PTFE/MoS_2, FC, and PEEK/Ceramic. In the case of FC, a fluorinated ethylene propylene (FEP) resin is used to form the liquid dispersion. In PTFE/MoS_2 and PEEK/Ceramic coatings, the MoS_2 and the ceramic particles end up being evenly distributed throughout the thickness of the coating, after curing.

The cure and in-use temperature of the polymer coatings used in this work are listed in Table 1 along with their typical physical color [18]. Reduced Young's modulus and hardness measurements were obtained using the nanoindentation technique and are also listed in Table 1. Nanoindentation measurements were performed with a commercial nanoindenter instrument using a 90° cube corner and a Berkovich tip and a range of loads from 50 to 6000 μN. Four measurements were performed for each sample and the average and plus/minus one standard deviation values are reported in Table 1. The measured values are in agreement with the literature where Vickers micro hardness ranging from 10 to 16 (0.10–0.16 GPa) were measured on PEEK deposited on aluminum substrates [11,19]. This range in hardness was obtained by changing the cooling rates after baking, which provided differences in PEEK crystallinity.

2.2. High Pressure Tribometer

A High Pressure Tribometer (HPT) was used to perform controlled tribological experiments. The HPT uses a sliding configuration setup where the disk (Fig. 1 (a)) is the upper rotating part and the pin the lower stationary part. The pin used is an actual component found in typical automotive swash-plate air-conditioning compressors; it has a crowned contact geometry with a dimple at the center and is termed "shoe." The shoe holder is self-aligned to guarantee that the contact

Table 1
Physical properties of the polymeric coatings.

Property	PEEK/PTFE	PTFE/MoS_2	Fluorocarbon	PEEK/Ceramic
In-use temp. (°C)	260	260	232	260
Cure temp. (°C)	400	316	316	400
Reduced modulus (GPa)	6.08 ± 0.97	7.72 ± 1.30	4.88 ± 0.72	9.92 ± 1.91
Hardness (GPa)	0.17 ± 0.07	0.56 ± 0.10	0.35 ± 0.09	0.21 ± 0.07
Color	Light-blue	Dark-green	Black	Beige-tan