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The effect of electron irradiation on the tribological property of perfluoropolyether grease in vacuum

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ABSTRACT

A perfluoropolyether (PFPE) grease was exposed to 110 keV electron beam for fluence of 1×10^{15}, 5×10^{15} and 1×10^{16} e/cm^2 in vacuum. The friction and wear behaviour of the electron irradiated grease-lubricated 2Cr13 steel in vacuum was investigated by using a pin-on-disk type tribometer. The morphologies of the worn surfaces for the irradiated grease-lubricated 2Cr13 steel were observed by a scanning electron microscope (SEM). Gaseous products from the PFPE grease during the electron irradiation were monitored with a quadrupole mass spectrometer (QMS). The compositions and chemical states of grease samples before and after electron irradiation were analysed by Fourier transform infrared spectroscopy (FTIR) and X-ray photoelectron spectroscopy (XPS). Results show that the irradiated grease-lubricated 2Cr13 steel sliding against the same material in vacuum presents a high friction and a high wear. The QMS, XPS and FTIR analyses reveal that COF_2 gas, low molecular weight perfluoroethers and acid fluoride groups are formed due to decomposition when the PFPE grease is exposed to 110 keV electron beam in vacuum. Moreover, the base oil content of the PFPE grease decreases with increasing the electron irradiation fluence, leading to the loss of lubricating ability of the PFPE grease.

1. Introduction

Perflouropolyether (PFPE) grease as space lubricants has widespread applications in space mechanisms such as actuator bearings and gears due to its exceptional tribological performance, intrinsic stability to temperature and chemical attack [1–3]. Historically, the grease performed satisfactorily as early spacecraft placed few demands on their performance, since mission lifetimes were short and duty cycles were limited. However, now many spacecrafts have expected lifetimes of more than 10 years [4]. On the other hand, with recent improvements in many space components such as electronics, lubrication has become dominant cause of many mission failures and anomalies [5]. Improved lubrication of the mechanical system is a key to extended satellite life, resulting in more reliable and longer operating components. It is necessary and important to a more thoroughly understand of the various factors affecting lubrication phenomena that limit life of space mechanisms. This life requirement of more than 10 years introduces time-related lubrication degradation mechanisms, which must be considered. Thus, a number of studies concerning the tribological property of the unirradiated PFPE grease in vacuum have been reported [6,7]. The outer space abounds with varieties of charged particles. Electrons found in orbits designated as low earth orbit (LEO) have widely varying energy spectra from tens of keV to the GeV range [8], in which the keV-range electrons are the most significant components. Although liquid lubricants for space mechanism are not directly exposed to electron beam, evaporation and degradation induced by electron irradiation imply potential problems that must also be addressed in the design of mechanisms and selection of lubricants.

In the past few decades, certain attention has been focused on the effect of electron irradiation on the chemical and physical properties of PFPE oil [9,10]. Those studies revealed that possibilities of degradation of PFPE oils by electron beam were pointed out. For example, Pacansky et al. [10] has reported that when poly(perfluoropropylene oxide) (–(CF(CF_3)$CF_2O)_n$–) oil, was exposed to a 175 keV electron beam, its viscosity decreased as a function of increasing absorbed dose, due to decreasing molecular weight. Moreover, IR spectroscopy of the exposed the PFPE oil revealed that acid fluoride group (–COF) was the primary species

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formed. Since the reliability of PFPE grease for long term operation in space environment is not yet guaranteed, detailed research work is still required. Therefore, a study on degradation of PFPE grease induced by electron beam is important for some future spacecrafts, but only few data on electron exposures of PFPE grease are now available [11,12]. More important, the effect of electron irradiation on the tribological property of PFPE grease has so far received very little attention.

Therefore, for the space application, the aim of this paper is to investigate the effect of electron irradiation on the tribological property of perfluoropolyether grease in vacuum. The work is directed at gaining an understanding for friction and wear behaviour of the electron irradiated grease-lubricated 2Cr13 steel, with the secondary objective of elucidating the electron radiation induced changes in compositions of a PFPE grease.

2. Experimental

2.1. PFPE grease

A commercial perfluoropolyether (PFPE) grease for space applications was used in this study, consisting of PFPE base oil and small additive particles of polytetrafluoroethylene (PTFE). The grease has a wide operating temperature range: −80 to 204 °C. The PFPE base oil has a linear structure of $CF_3O(CF_2CF_2O)_m(CF_2O)_nCF_3$. Table 1 gives the physical properties of the PFPE base oil.

2.2. Electron irradiation experiments

Electron irradiation treatment was performed using an electron accelerator in Harbin Institute of Technology, China. The PFPE grease with a uniform thickness of 450 μm was smeared onto the 2Cr13 steel disks by means of a spatula after careful cleaning with acetone in order to analyze friction characteristics. The grease samples were perpendicularly irradiated by 110 keV electrons with 1×10^{12} cm^{-2} s^{-1} flux for fluence of 1×10^{15}, 5×10^{15} and 1×10^{16} e/cm^2, respectively. The tested chamber was kept in vacuum of about 1.3×10^{-4} Pa at room temperature. The energy for the electron irradiation experiments described here was chosen because it represents significant components of the electron spectra in LEO orbits. Also, tracking processes of the incident electrons were calculated using a commercial Geant-4 code, indicating that the 110 keV electrons could only penetrate the thin layer of grease with the thickness of approximately 110 μm.

2.3. Friction and wear tests

The sliding friction characteristics of the irradiated PFPE grease by 110 keV electrons were evaluated by using pin-on-disk type tribometer in vacuum pressure as low as 2×10^{-3} Pa at room temperature. Both the disks and pins are made from the same 2Cr13 martensitic stainless steel with the following chemical composition (in wt.%): C 0.16–0.25, Si ≤ 1.00, Mn ≤ 1.00, P ≤ 0.035, S ≤ 0.030 and Cr 12.00–14.00. The disk samples are in the diameter of 70 mm and thickness of 6 mm. The pin samples having length of 18 mm are a cylinder with semi-spherical face of 9 mm in diameter. The surfaces of all samples were carefully ground to a final surface of 0.28 μm (Ra). As the above mentioned, the PFPE grease with a uniform thickness was smeared onto the 2Cr13 steel disks before electron irradiation experiments. The 2Cr13 steel disk coated with the irradiated PFPE grease by electrons was fixed on a rotating shaft, while the pin was loaded by dead weight via a load arm. A normal force of 30 N and a sliding velocity of 0.4 m/s were chosen as testing parameters. Sliding distance was chosen as 1200 m to obtain stable friction and wear for the friction tests. Three friction and wear tests under the same condition were performed.

Table 1
Physical properties of base oils used for PFPE grease.

Parameter	Unit	Value
Average molecular weight	amu	9200
Specific gravity at 20	g/mL	1.84
Viscosity at 38 °C	cSt	160.50
Viscosity at 99 °C	cSt	48.40
Viscosity at −40 °C	cSt	6500
Viscosity index		350
Pour point	°C	−73
Vapor pressure at 20 °C	Pa	4×10^{-13}

2.4. Worn surfaces analyses

At the end of each friction and wear test, the disk was taken out of the vacuum chamber and cleaned in an ultrasonic wave bath with pure 1,1,2-trichlorotrifluoroethane (TCF) and acetone, respectively. The worn surface morphology of the cleaned disk sample was examined by means of a Quanta 200FEG type scanning electron microscope (SEM). The mean wear track widths of disks were measured using an Olympus-GX51 type optical microscope (OM).

2.5. PFPE grease analyses

Gaseous products from the PFPE grease during electron irradiation were monitored with a quadrupole mass spectrometer (QMS) (HAL/3F301RC type, made by Hiden, UK). The chemical compositions of PFPE grease samples after and before electron irradiation were analysed by an X-ray photoelectron spectroscope (XPS) (K-Alpha type, made by Thermo Scientific, USA) using an Al *Kα* source and Fourier transform infrared spectroscopy (FTIR) (Magna-IR 560 type, made by Nicolet, USA). Grease samples used for XPS and FTIR analyses were taken from the surface layer of the irradiated grease since the 110 keV electrons could not penetrate the PFPE grease with the thickness of 450 μm.

3. Result and discussion

3.1. Friction and wear behaviour

Fig. 1 shows the variations in friction coefficients with sliding distance for the PFPE grease-lubricated 2Cr13 steel sliding against

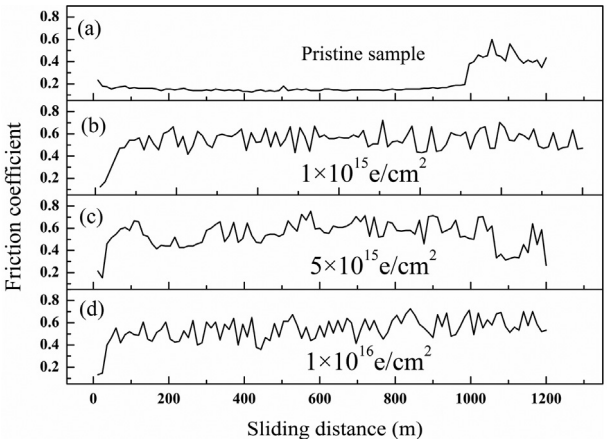

Fig. 1. Variations in friction coefficients with sliding distance for the PFPE grease-lubricated 2Cr13 steel sliding against the same material after the 110 keV electron irradiation in vacuum.