Tribology of Solid Lubricant Coatings for Space Mechanisms and Cryo-turbopumps of Rocket Engine

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授　与　学　位	博士（工学）
学位授与年月日	平成19年3月14日
学位授与の根拠法規	学位規則第4条第2項
研究科，専攻の名称	東北大学大学院工学研究科，機械システムデザイン工学専攻
学位論文題目	Tribology of Solid Lubricant Coatings for Space Mechanisms and Cryo-turbopumps of Rocket Engine （宇宙機器とロケットエンジン用極低温ターボポンプのための固体潤滑材被膜のトライボロジー）
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論文内容要旨

Chapter 1. Introduction

The general problem for the lubrication of space systems is the lack of oxygen. The space vacuum environment challenges the lubrication of frictional contacts in low speed space mechanisms like solar array drives, slip ring units, payload steering mechanisms for long duration of 30 years, whereas the rocket-engine cryogenic turbopumps challenge the operation of bearings at high-speeds and in direct contact with cryogenic fluids (like liquid oxygen and liquid hydrogen).

Mechanism anomalies continue to occur and to be a cause of catastrophic mission failures. Several factors cause problems for space system mechanisms. The space environment produces wide temperature ranges, thermal gradients, and rapid changes in temperature, which can bind the moving parts of mechanisms. The need to improve space mechanism reliability is underscored by a long history of flight failures and anomalies caused by malfunctioning mechanisms on spacecraft and launch vehicles.

The lubrication options for space applications are very much limited mainly due to hard vacuum and extreme temperature conditions of inherent space environment. Different methods are adopted appropriately to lubricate the moving parts (rolling-element bearings, gears, seals, latches, bushings) either with liquid, grease or solid. For example, the high-speed turbopumps like those used in the Space Shuttle Main Engine (SSME) operate with the cryogen passing directly through the bearings. Oils and greases solidify at this temperature; therefore the only viable alternative is solid lubrication. Currently the low-speed spacecraft mechanisms successfully use ion plated Pb as the solid lubricant coating for the bearings and gears. It is noticed that different kinds of solid lubricant coatings are prevailing in various rocket engines of international space programs. The challenges for future space systems seems to be very high since missions are being planned that will require mechanisms to last for longer periods of time. For example, the design life of the International Space Station (ISS) is 30 years. In addition to Earth-orbiting spacecraft, lunar and planetary missions are being planned that will require systems capable of operating over wide temperature ranges, in a low-Oxygen atmosphere and in a dusty, corrosive environment on the planet Mars.

For meeting the above challenging tribological requirements a new high-current ion plated Pb coating has been developed. In order to improve the friction and wear properties of the conventional ion plated Pb coating on steel; the coating interlayer thickness has been improved, by processing the ion plating deposition at higher substrate voltage and current conditions. The effect of interlayer thickness on the endurance life, the friction and wear of ion plated Pb coatings were studied. For the experimental evaluation of friction and wear of the coatings at high speeds in liquid nitrogen, a ball-on-disk cryo-tribometer has been developed. The tribological evaluation of the new high-current ion plated Pb coating has been carried out with (1) the low-speed sliding test in ultra high vacuum ball-on-disk tribometer, (2) the low-speed rolling-sliding test in gaseous nitrogen, (3) the high-speed sliding test as well as (4) the rolling-sliding tests in liquid nitrogen. The lubrication and wear mechanism of the high-current ion plated Pb coating has also been studied.

Chapter 2. Development of high-speed ball-on-disk cryo-tribometer

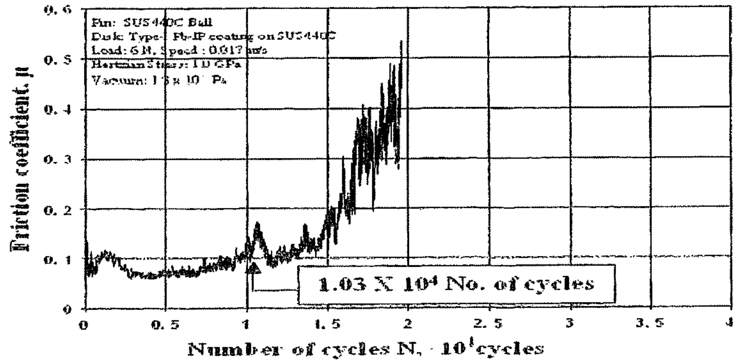
A high-speed ball-on-disk type cryotribometer has been designed to study friction and wear characteristics in sliding contacts under cryogenic fluid conditions at very high sliding speeds (0.50 to 45m/s). Also provision has been made for the rolling-sliding testing of a ball bearing under cryo-fluid immersed condition at a maximum speed of 36000 rpm. The cryogenic media used is liquid nitrogen. The unique feature of this tribometer is in regard to the flexible drive shaft arrangement, which enables to eliminate the vibration and shock from the drive motor transmitted to the friction force measurement.

Chapter 3. Friction and wear of solid lubricant coatings on steel at high-speed in liquid nitrogen.

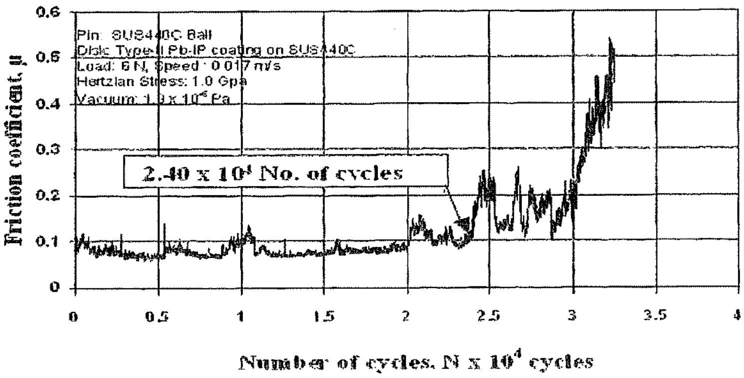
In order to evaluate and compare the friction and wear properties of the five different solid lubricant coating on SUS440C steel (high-current ion plated Pb, ion plated Au, Ion plated Ag, RF-Sputtered PTFE and sputter ion plated MoS_2Ti coatings on SUS440C steel against SUS440C steel ball in liquid nitrogen immersed conditions, number of tests at high sliding speeds and normal load conditions were conducted. The friction coefficient versus number of cycles of the above five different solid lubricant coatings on SUS440C steel disk against SUS440C steel balls in liquid nitrogen immersed condition shows that the friction coefficient of high-current ion plated Pb coating is comparable with that of ion plated gold and ion plated silver coatings. Also it was understood that there was no significant variation of friction coefficient of these solid lubricants with respect to different sliding speeds of V=0.67 to V=1.67m/s.

Chapter 4. Friction and wear of ion plated Pb coatings on steels at low speed in ultra high vacuum

The friction, wear and endurance life properties of both types of (Type-1 =conventional and Type-2 =high-current) ion plated Pb coatings on SUS440C and SUS17-4Ph steels are studied for the low-speed sliding test in ultra high vacuum ball-on-disk tribometer. As per Fig.1 of the accelerated life test of ion plated Pb coatings in ultra high vacuum, the high-current ion plated Pb coating on SUS440C steel has shown a increase in coating life of 240% of that of the conventional.



$\mu_{sliding}$ Vs No. of cycles of conventional ion plated Pb coating



$\mu_{sliding}$ Vs No. of cycles of high-current ion plated Pb coating

Fig. 1 Accelerated life test of ion plated Pb coatings on SUS440C steel in UHV

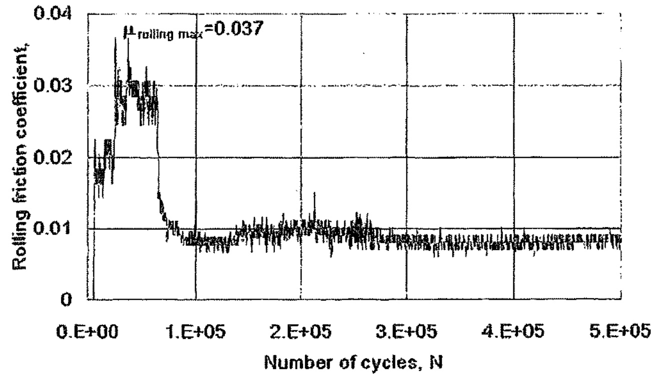
The comparison of interlayer thickness, friction coefficient, wear and endurance life of ion plated Pb coatings on SUS440C and SUS17-4PH steels in ultra high vacuum shows that due to thicker interlayer thickness of the high-current ion plated Pb coating its friction, wear and endurance life have improved in comparison with that of the conventional ion plated Pb coating.

Chapter 5. Tribological performance of ion plated Pb coating on steel ball bearing at high-speed in liquid nitrogen

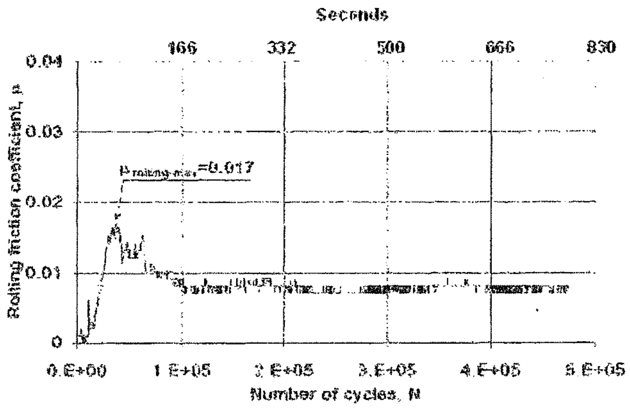
In order to assess the suitability of the high-current ion plated Pb coating for cryogenic applications in particular to cryo-turbopumps of liquid rocket engines, the performance evaluation of the typical rocket engine bearings (coated with the high-current ion plated Pb coating) in liquid nitrogen at 36,000 rpm has been carried out. It is observed that as in Fig.2, the friction coefficient of rolling sliding of high-current ion plated Pb coating is 50% less than that of the self-mated condition.

Chapter 6. Tribological performance of ion plated Pb coatings on steel ball bearing at low-speed in gaseous nitrogen

In order to assess the suitability of the high-current ion plated Pb coating for long duration applications in particular to low-speed mechanisms (like solar array drives) for 30 years of operation in space station, the performance evaluation of the typical bearings (of SUS440C steel) with ion plated Pb coatings in gaseous nitrogen at 1 rpm has been carried out. It is observed that as in Fig.3, the friction coefficient of rolling sliding of high-current ion plated Pb coating is 40% less than that of the conventional ion plated Pb coating with low value of $\mu_{rolling}$=0.0015 at the end of life test.



Ball bearing without coating

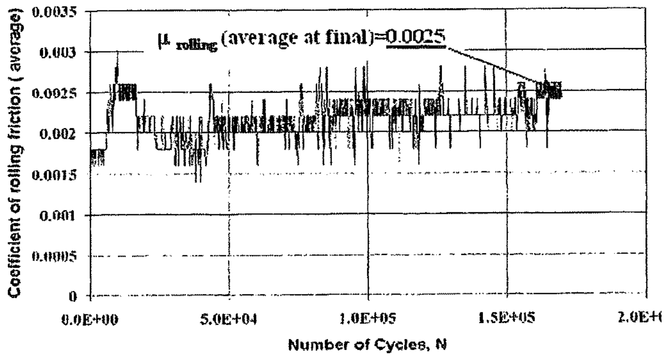


Ball bearing with high current ion plated Pb coating

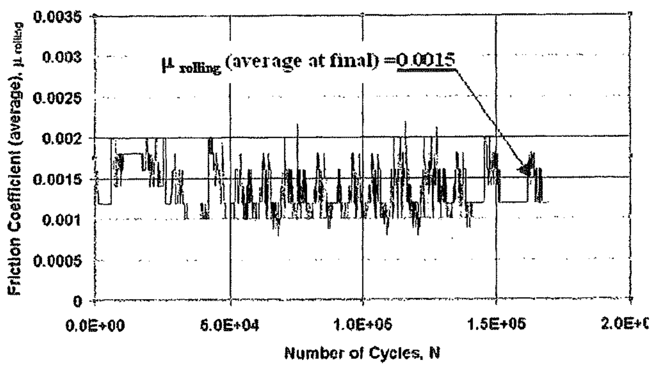
Fig. 2 Tribologicasl performance of SUS440C steel ball bearing without any coating at 36,000 rpm in liquid nitrogen

Chapter 7. Lubrication and wear mechanism of ion plated Pb coating

The improvement of friction, wear and endurance life properties of high-current ion plated Pb coating on steel is found to be due to the thicker interlayer thickness formation compared to that of the conventional ion plated Pb coating on steel. The wear scar of the high-current ion plated Pb coating on SUS440C and SUS17-4PH steels subjected to accelerated life-tests in ultra high vacuum showed the presence of Pb particles even after the end of life cycles.



μ Rolling Vs No. of cycles of conventional Pb-IP coating



μ Rolling Vs No. of cycles of high-current ion plated Pb coating

Fig. 3 Accelerated life test of SUS440C ball bearing with ion plated coatings in nitrogen gas

The wear of high-current ion plated Pb coating on SUS440C steel at high rolling sliding speed in liquid nitrogen showed absence of severe wear marks in comparison with the bearing without any coating. The micrographs of worn tracks of inner ring of bearing with high-current ion plated Pb coating (after $6.6x10^5$cycles) showed presence of Pb coating with uniform mild wear.

The ball wear scar with the high-current ion plated Pb coating on steel at high sliding speed in liquid nitrogen showed particles of Pb adhered to it. This confirms the presence of transfer film lubrication mechanism with this new high-current ion plated Pb coating.

Chapter 8. Conclusion

The above experimental results confirms that the newly developed high-current ion plated Pb coating on steel is a promising candidate for use in low-speed space mechanisms and rocket engine cryo-turbopumps.

論文審査結果の要旨

人工衛星や宇宙ステーションにおいて摩擦が関与する機構部分は鉛のイオンプレーティング被膜によって潤滑されていることが多い。この場合被膜の潤滑性と耐摩耗性の向上は宇宙機器のエネルギー消費を減らし、寿命を延ばすために、絶えず求められる課題である。本研究は現在用いられている鉛被膜の潤滑特性を更に向上させるために、従来に無い高圧大電流下で作製されたイオンプレーティングによる改良型鉛被膜について、種々の摩擦条件下における摩擦摩耗特性の評価を行い、それが宇宙機器用として有効であることを実証している。本論文は、これらの研究成果をまとめたものであり、全編8章からなる。

第1章は緒論であり、本研究の背景、目的および構成を述べている。

第2章では、極低温ターボポンプ用固体潤滑材被膜の摩擦と摩耗特性を評価するために作製した液体窒素中高速摩擦試験機の説明をしている。

第3章では、SUS440C鋼ディスク上に作製された改良型鉛被膜を含む金、銀、等5種類の固体被膜について液体窒素中0.67～1.67m/sのすべり摩擦試験を行い、開発した試験機の信頼性の確認をしている。更に改良型鉛被膜と他の固体被膜の潤滑特性の比較により改良型鉛被膜の長所を確認している。

第4章では、改良型鉛被膜が超高真空中0.017m/sのすべり摩擦において、従来の鉛被膜に比べほぼ等しい摩擦係数と約2.4倍の寿命を示すことを実証している。更に寿命の延長を可能にした鉛被膜の耐摩耗性の向上は被膜と下地間の中間層の厚さの増加によることを明らかにしている。これらは鉛被膜の特性の更なる改良のために極めて重要な基礎的知見である。

第5章では、改良型鉛被膜を付けたSUS440C鋼玉軸受の転がり摩擦係数が液体窒素中36000rpmの高速回転試験において、被膜をつけない場合の50%以下になることを実証している。これは実用のための有用な知見である。

第6章では、改良型鉛被膜を付けたSUS440C鋼玉軸受の転がり摩擦係数が1気圧の窒素ガス中1rpmの低速回転試験において、従来の鉛被膜をつけた軸受の場合の60%以下になることを実証している。これは実用のための有用な知見である。

第7章では、改良型鉛被膜を付けたSUS440C鋼ディスクとSUS17-4PH鋼ディスクの超高真空中0.017m/sのすべり摩擦において、摩耗率が従来の鉛被膜の場合に比べそれぞれ50%以下と30%以下になることを実証している。さらに、改良型鉛被膜を付けたSUS440Cディスクの液体窒素中1.67m/sのすべり摩擦における摩耗率は金、銀、等の被膜と同等であることを実証している。これらは、実用のために有用な知見である。

第8章は結論である。

以上要するに本論文は、新たに開発した改良型鉛被膜が超高真空中低速すべりと液体窒素中の玉軸受の高速回転の両方において、優れた潤滑性と耐摩耗性を示すことを実験により明らかにし、宇宙機器とロケットエンジン用極低温ターボポンプのための固体潤滑材被膜として有望であることを示すとともに、鉛被膜の更なる改良の指針を与えたものであり、機械システムデザイン工学及びトライボロジーの発展に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。