VACUUM EFFECTS ON THE MECHANICAL BEHAVIOUR OF A NEW TELESCOPIC ACTUATOR FOR ACCURATE MANOEUVRING AND POSITIONING IN SPACE

G. Allegri[¶], S. Corradi[¶], J.Leofanti[¶], M. Marchetti[§§], P. Tromboni[§]

School of Aerospace Engineering
University of Rome "La Sapienza"
Via Eudossiana 16, 00184 Rome, Italy
Tel. +39.06.44585800 / Fax +39.06.44585670
*e-mail:*mario.marchetti@uniroma1.it

ABSTRACT

The aim of this research is to study the behaviour of recirculating ball-screws, utilized for a new kind of linear telescopic space appendage (boom) of satellite DeSat, some of them were without lubricant (dry) and some lubricated by solid lubricant films containing WC/C. Steel and Titanium ball-screws were studied. The high reliability, already widely checked in the aeronautical and industrial production, make this mechanism particularly attractive for a new generation of space applications. The requirements, imposed by the space environment as well as by mechanical stresses, have led to a first geometrical configuration and material choice which are presented on this paper. First attempts on the calculation of vacuum effects on friction of ball screws when subjected to thermal-vacuum are here reported and commented.

1. INTRODUCTION

Among the major causes of mechanical anomalies, vacuum tribology-related malfunctions have received central attention due to the continued occurrence of spacecraft failures. Phenomena such as the increase of frictional forces between moving parts and the binding of metallic parts in high-vacuum environments are sometimes very difficult to examine in full scale on the ground [1], and only limited prototype verification is conducted in orbit. Responding to the strong need for the improvement of space mechanism and tribology research work, thermal-vacuum tests have been set up for ball screw mechanisms.

The thermal-vacuum apparatus of University of Rome (SAS) is intended to provide fundamental data on the performance of mechanical components and materials in high vacuum for validating space mechanism designs (Fig. 1): its dimensions 1.5(diameter)x3 m. allows to perform experimental tests and measure the variation of the life and efficiency of the proposed actuator during deployment and stowing.

Noise, resistance torque, lubricant degradation and surface wear are the main parameters to be observed during experimental analyses and represent the focus of the work, as well as other factors such as metal seizure in high vacuum, distortion due to high temperature gradients and the combined effect of space environmental factors on the deterioration of material surfaces, which are not fully understood.

This paper reports only the first steps of the ongoing work on ball screw space mechanisms at University of Rome "La Sapienza".

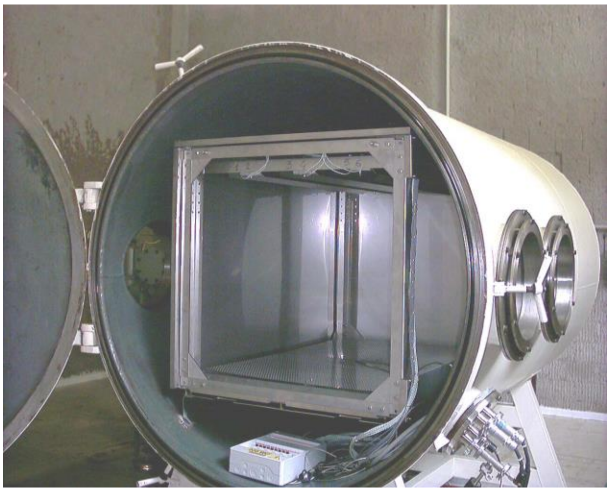

Fig. 1: The thermal-vacuum apparatus (SAS) of University of Rome "La Sapienza"

In 1999 the above mentioned departments of University of Rome "La Sapienza" have started a R/D project within the frame of the Italian Space Agency programme, to design an innovative type of linear actuator for space applications, based on the well known Recirculating Ball Screw technology.

The program involved the coordinated efforts of students and researchers, organized in a working unit supported for its activities by the industrial know-how of Umbra Cuscinetti S.p.A., a world leader in the market of actuators for aerospace applications. The DeSat program was focused around a highly

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§: Postgraduate students
¶: PhD Researcher
§§: Full Professor

sophisticated Telescopic Ball Screw (TBS) Boom, with characteristics in terms of stiffness, mass properties, efficiency, position accuracy and stability that set it at the top positions among similar mechanisms already on the market. In particular the boom has a modular design that makes it suitable for a wide range of applications, with possible spin-offs in the aviation industry, industrial vehicle market, micro electronics.

Rotating parts of space mechanisms are supported by sliding and rolling bearings. Among them a ball-screw provides a unique function: changing linear motion to rotation or vice versa with high energy efficiency. However, the friction and wear mechanism for a ball-screw for space use, when lubricated by a solid lubricant, remains unsolved. Tribological behaviour of a ball-screw is of particular interest because it operates under a rolling-sliding frictional condition which is somewhat different from rolling or sliding friction.

In the proposed telescopic structure, each element shows both an internal and an external threads representing, at the same time, a screw and a nut and consisting in a set of elements, with circular cross section, nested inside each other, with a variable overlapping length. Its geometry and mechanical characteristics strongly depend upon stresses distribution both in launch and operating environments.

Possible utilisation of the proposed system may fall in different areas, ranging from platform to, mostly, payload applications: precise off platform positioning of devices and instruments and successive micrometric adjustments are the main goals for all the cases as either radar or GPS interferometry, sensor measurements or attitude control manoeuvres, etc.
According to this, a dedicated research unit was created to attend to all the design activities involved with the ground test campaign and the on-orbit mission definition. Concerning the ground simulations of the boom predicted interactions with LEO environment, the experimental campaign is arranged by reproducing in a controlled ultra high vacuum chamber (SAS) the main conditions that could likely affect the mechanism functionality.

2. TELESCOPIC BALL SCREWS

The recirculating ball screws are mechanisms [2] which can transform rotary to linear motion and vice versa, transmitting power. The principal elements of the mechanism are the screw and the nut, both with threaded zone, and the balls. Contact between the screw threads and the nut threads is mediated by the balls which roll along suitably shaped race-tracks. At the end of the path allowed by the race-track, the balls are re-circulated by a variety of systems (trunnions) which bring them back to the beginning of the working path. Their main characteristics are summarized through the following points:

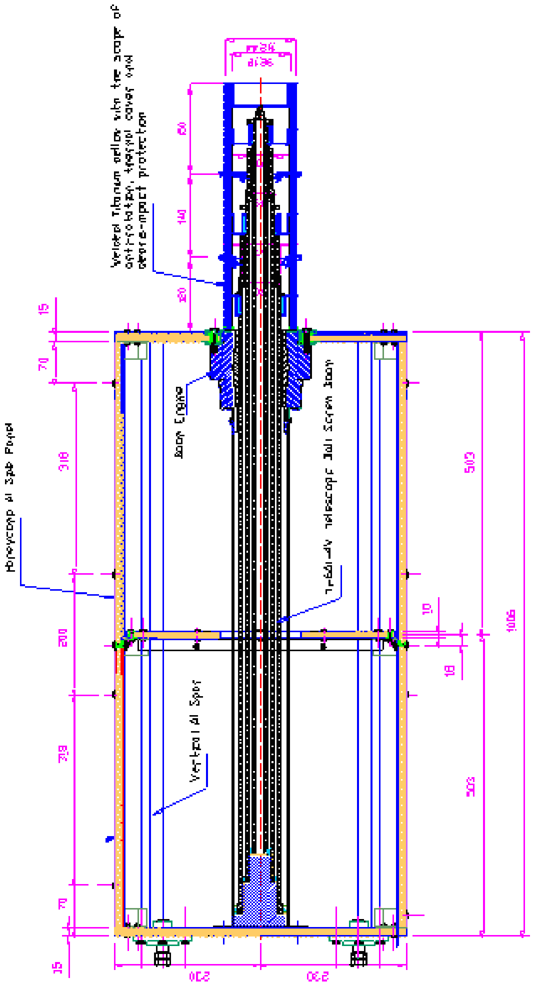

Fig. 2: Longitudinal section of satellite DeSat with titanium boom and bellow

- balls roll in the threading between screw and nut and the screw angle provides the axial movement;
- the missing cage causes contact stresses between balls which are normally not present in usual ball screws;
- in the recirculating part, which is the most critical point of the design, balls are unloaded and pushed along by the following one;
- contact pressures are generally higher on screw than on nut because of the different diameter but nut threading, which is always loaded, are more subjected to fatigue;
- nut deformability provides a non uniform distributed load between threads;
- screw open air exposure makes particularly critical some aspects as cleaning and lubrication content.

Specific characteristics of the ballscrews are: high precision, low or zero backlash and extremely high efficiency (90-94%); for aeronautical purposes hollow screw have been developed.

Fig. 3: Titanium Telescopic Ball Screw

In the deployment mechanism [2] the system provides a deployment through a Telescopic Ball Screw (TBS) (Fig. 3) which may operate either in dry conditions or lubricated via solid film. Dry mechanisms allow simplicity of design and represent a good opportunity for non inspectionable space applications which require long-life affordability [3]. In fact in the case of low cycle number, the absence of lubricant and the utilisation of an Alternate Design (AD) characterised by ceramic balls with different diameters are the ideal solution. The combination of stainless steel (Cronidur 30) screws and ceramic balls in alternate configuration has been adopted on many airplanes. 7000 cycles in landing and taking off have been reached in a test without lubricant before exceeding the upper limit values for backlash and the lower for efficiency. Despite these advantages, high deployment control and positioning - in radar interferometry, for example - require infinitesimal adjustments which may necessitate to decrease local wear through contact lubrication; in this case, Teflon, MoS_2, WC/C and solid paste could be utilised [4,5].

One of the most remarkable recent advancements in bearing technology is the utilization of hybrid and silicon nitride bearings. Hybrid bearings consist of steel races and silicon nitride balls. Solid-film-lubricated hybrid bearings have been applied to touchdown bearings in turbomolecular pumps. In addition, hybrid bearings are worthy of note because of their low dust-generation characteristics. Silicon nitride bearings have the drawback of high manufacturing costs compared with hybrids but they are needed for high-temperature applications up to 650°C.

Bearings are normally made of AISI 440C stainless steel but hybrid bearings, which use silicon nitride balls and steel races, have become common. For high temperature applications, tool steel such as M50 is used up to 400°C. At higher temperatures silicon nitride is more attractive than steel since it does not seize immediately after the solid-lubricant film has worn off . The use of material other than steel, like silicon nitride or titanium-nitride-coated balls, was proved to be effective in prolonging wear life [6].

The telescopic appendage is composed of several Titanium circular elements, which in stowed position are nested inside each other, and of a canister whose main role is to contain the whole stowed system. Its geometry and mechanical characteristics strongly depend upon stresses distribution both in launch and operating environments, but generally all the mission requirements can be summarised as follows:

- providing the necessary stiffness to satisfy the minimum dynamic characteristics in stowed configuration;
- reducing out-of-plane deployed oscillations to minimise overloads on ball screws;
- deploying smoothly, avoiding sudden releases and shocks;
- designing joints which can take care of different coefficients of thermal expansion;
- limiting sub-components and parts to facilitate assembling and inspectioning;
- providing the possibility to test the mechanism on ground.

3. SPACE LUBRICANTS

A solid lubricant is defined as “any material used as a thin film or a powder on a surface to provide protection from damage during relative movement and to reduce friction and wear.” Solid lubrication is achieved by using self-lubricating solids or by imposing a solid material having low shear strength and high wear resistance between the interacting surfaces in relative motion. The imposed solid material may be a coating, a loose powder, or a dispersion in oils and greases.

In the field of vacuum tribology dry solid lubricants are used when liquid lubricants do not meet the advanced requirements of modern technology. They are less expensive than oil and grease lubrication systems for many applications. Solid lubricants also reduce weight, simplify lubrication, and improve materials and processes.

Changes in critical environmental conditions, such as pressure, temperature, and radiation, affect lubricant efficiency (Fig. 4) [7]. Solid lubricants may be preferred to liquid or gas films for several reasons. In high-vacuum environments, in space-vacuum environments, in food-pro-cessing machines, or in semiconductor manu-facturing equipment a liquid lubricant would evaporate and contaminate the product, such as optical and electronic equipment or food. At high temperatures liquid lubricants decompose or oxidize; suitable dry solid lubricants can extend the operating temperatures of sliding systems beyond 250 or 300°C while maintaining relatively low coefficients of friction. At cryogenic temperatures liquid lubricants are highly viscous and are not effective. Under radiation or corrosive environments liquid lubricants decompose or will be contaminated.

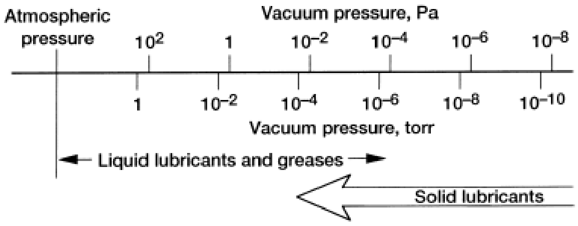

Fig. 4: Ranges of application of solid lubricants in high-vacuum

Further, in the weight-conscious aerospace industry dry solid lubricants lead to substantial weight savings relative to the use of liquid lubricants. The elimination (or limited use) of liquid lubricants and their replacement by solid lubricants reduce aircraft or spacecraft weight and therefore have a dramatic impact on mission extent and craft maneuverability [5].

The simplest kind of solid lubricating film is formed when a low-friction solid lubricant, such as molybdenum disulfide (MoS_2), is suspended in a carrier and applied to the surface like a normal lubricant. The carrier may be a volatile solvent, a grease, or any of several other types of material. After the carrier is squeezed out or evaporates from the surfaces, a layer of MoS_2 provides lubrication.

In addition to MoS_2, tungsten disulfide (WS_2), polytetrafluoroethylene (PTFE), polyethylene, and a number of other materials are used to form solid films[8,9]. Sometimes, combinations of several materials, each contributing specific properties to the film, are used. Because of recent innovations in the physical and chemical vapour deposition processes, solid lubricating materials, such as diamond, diamond-like carbon (DLC), MoS_2 ,WS_2 , and PTFE films, are grown economically on ceramics, polymers, and metals and used as solid lubricating films [10,11].

A new coating made of amorphous carbon with tungsten carbide inclusions (referred to as a WC/C coating) is here utilised: it has proved its worth in situations where all other surface coating systems fall.

This WC/C coating is applied by a PVD (Phisical Vapor Deposition) process – more precisely by reactive sputtering. In this process, the coating material is expelled from targets (WC plates) in high vacuum by ion bombardment and deposited on the parts being coated.

This high-vacuum technology makes it possible to obtain coating properties that cannot be imparted under an atmosphere (thermal spraying) or with gases or baths (nitriding, galvanizing). These properties include:

- Controlled material composition. Amorphous carbon films have the lowest friction of all hard surfaces.
- Extreme precision. PVD coatings are only a few µm thick. They replicate work piece surfaces exactly, thereby eliminating the need for subsequent machining.
- Maximal load-carrying. High vacuum deposition avoids contamination of all kinds. As a consequence, there is a metallurgical bond to the substrate, leading to high coating adhesion and load-carrying capability (PVD coatings such as TiN are traditionally employed on severely stressed tools).

Technical data of the WC/C (BALINIT C) coating are as follows:

Hardeness	24-28 GPa
Coefficient of friction	0.1-0.2
Coating thickness	1-4 µm
Coating temperature	max 250°C (480°F)
Oxidation resistance	300°C (572°F)
Color	black/gray

The hardness of WC and other carbide coatings is as high as 24–28 GPa. At the same time, the hardness of WS_2 and other solid lubricants (MoS_2 , graphite, lead) is generally below the 3 GPa level. This creates the potential for low wear rates and longer endurance even for high stressed ball screws for space applications, providing they maintain low friction coefficients similar to solid lubricants.

As far as optimal wear protection is concerned, the key combination of properties offered by the WC/C coating is low friction with high hardness. The sliding properties of the WC/C coating are not attained by conventional surface treatments, such as nitriding, nitrocarburizing, or chemical nickel-plaiting, or bronzes. This point is seen particularly in the dry friction behavior of these surfaces.

Precision positioning (as off-platform for interferometry measurements) cannot be attained on a long term basis with rapidly wearing bronzes. Case-hardened worms and worm mechanism do not have low enough friction, so they seize prematurely. Application of the WC/C coating to worms and worm wheels made of steel protects against both seizure and abrasion.

Solid lubricants designed for vacuum tribology applications must not only display low coefficients of friction (0.01 to 0.1) but also maintain good durability and environmental stability. The ability of a lubricant to allow rubbing surfaces to operate under load without scuffing, scoring, galling, seizing, welding, or any other manifestation of material destruction in hostile environments is an important lubricant property. For solid lubricant films to be durable under sliding conditions they must have low wear rates and high interfacial adhesion strength between the films and the substrates.

Solid film lubricants have finite wear lives or endurance lives.

4. EXPERIMENT

Two different kind of telescopic ball screws (TBS) have been set up for experimental analyses under thermal-vacuum: steel (AISI 440C) and Ti-6Al-4V ball screws, both in the unlubricated, bare conditions and in WC/C film lubricated conditions. The balls were made of Si_3N_4 in an Alternate Design.

The TBS specimens (Fig. 5) have been exposed to thermal-vacuum environment within the SAS simulator: the pressure inside the chamber has been 10^{-2} mbar during the tests. These level of pressure corresponds to an altitude of about 150 Km for undisturbed space environment: though this altitude could appear to be low if compared to standard perigee height for LEO mission, it must be considered that the environmental pressure close to a spacecraft is about two order of magnitude higher than for undisturbed space, due to materials outgassing and to the geometry of the fluid-dynamic field surrounding the spacecraft itself. For example, at 250 Km height, the level of pressure inside the Space Shuttle cargo bay is about 10^{-2} - 10^{-3} mbar, while the external pressure for undisturbed LEO neutral gas environment is close to 10^{-5} mbar. This points out that the vacuum level which is reached inside the SAS simulator can represent also a typical environmental conditions for space mechanism, especially during long-term manned mission, whose orbital perigee is generally lower than 500 Km.

Fig. 5: TBS specimens

The SAS simulator provides also the capability of performing thermal vacuum exposures, with temperature ranging from room temperature up to 150°C: the solar radiation is simulated by means of quartz radiating tubes, coupled with UV lamps. The total amount of irradiative power transmitted to exposed specimens is about 1500 W/m^2, so very close to the solar irradiation in LEO orbit: the system can also perform thermal cycling with an assigned profile between room temperature and its maximum operating temperature. The TBS specimens have been exposed to the SAS environment for 200 hours: during the exposure stage 100 thermal cycles between 70°C and 120 °C have been performed, each lasting two hours. The temperature profile applied to the specimens is quite different from that featuring LEO environment, since in actual space conditions temperatures vary in the range between –70°C and +100°C with a period of about 90 minutes. Nevertheless the thermal cycling profile here considered can affect the efficiency of the mechanisms, since the diffusion bonding of metallic surfaces is promoted by the temperature in vacuum conditions: however the entity of this effect must be assessed by efficiency experimental tests.

Efficiency tests have been performed for both material (AISI 440C and Ti-6Al-4V) and for both lubrication (dry and WC/C) before and after termal-vacuum exposure.

Efficiency is defined as the rate of energy transferred to the system and the energy kept by the system:

$$\eta = \frac{E_{OUT}}{E_{IN}}$$

Test bench measures the efficiency by the comparison of the inward torque and the outward torque:

$$\eta = \frac{C_{OUT}}{C_{IN}}$$

The outward torque is measured by a torquemeter, the inward torque is given by the axial load.

The test bench prepared for efficiency test is formed by three fundamental components:

- ✓ *Mechanical equipment* (support structures, engine for the movement of the ballscrew, reference known bulk)
- ✓ *Test equipment* (load cell for the measurement of the resistant ball screw torque)
- ✓ *Electronic equipment* (personal computer with acquirement board connected to the load cells that permits the knowledge of $\eta_{avar.}$ e η_{min}, and the knowledge of the *ripple*, i.e. the maximum variation between these two values and produces the η-diagram versus stroke)

TEST PROCEDURE

The ball screw is fixed by a pliers to a shaft connected to the engine; the nut is fixed on a mobile trolley and settled on its right place. The engine transmits a torque to the ball screw, which wheels round at a defined angular speed. The nut, fixed on the trolley, cannot wheel and moves backwards and forwards. This movement is contrasted by the force of gravity acting on the reference bulk, transmitted to the nut by steel rope and by the trolley. An apposite computing software gives the efficiency value versus the ball screw stroke, working out the values of the resistant torque generated by the force F and the torque generated by the engine and measured by the torque meter. The rotation speed was 79.5 r.p.m. the applied tension load on the ball screw was 400 N.

5. RESULTS AND DISCUSSION

UNLUBRICATED AISI 440C BALL SCREW

Six specimens of unlubricated ball screws before exposure have shown an average efficiency of 98.47 % and a variance of 0.74 (Fig. 6).

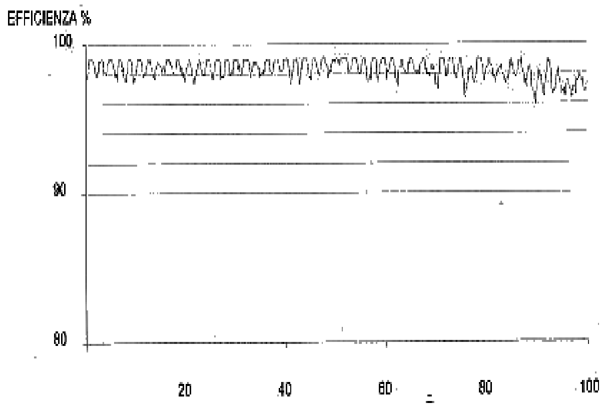

Fig. 6: Efficiency vs stroke for an unlubricated, bare steel ball screw **before** thermal-vacuum exposure

After exposure, a soft plunge in efficiency was recorded passing from the previous values to 94.53 for the average efficiency, denoting a fall of around 4 %, and to 0.77 for the variance (Fig. 7).

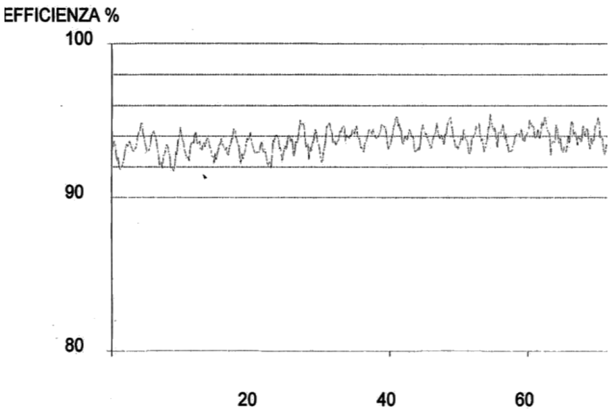

Fig. 7: Efficiency vs stroke for an unlubricated, bare steel ball screw **after** thermal-vacuum exposure

UNLUBRICATED Ti-6Al-4V BALL SCREW

Despite steel behaviour, Titanium dry lubricated ball screw show a deep plunge in efficiency and a boom of its variance after thermal-vacuum exposure. In fact the average efficiency passes from 97.61% to 91.3%, denoting a fall of around 7%, while the efficiency variance increased sharply from 0.83 to 3.1 (Fig. 8,9).

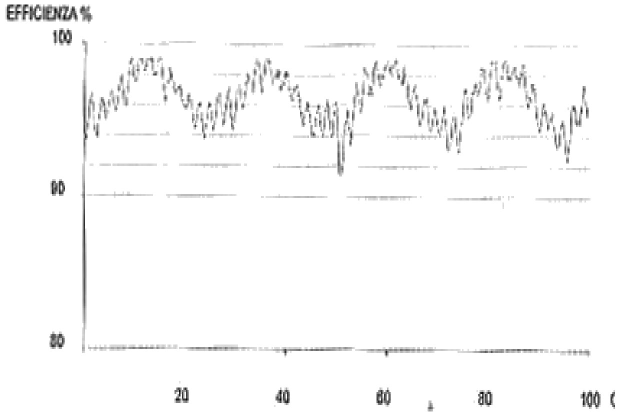

Fig. 8: Efficiency vs stroke for an unlubricated, bare Ti-6Al-4V ball screw **before** thermal-vacuum exposure

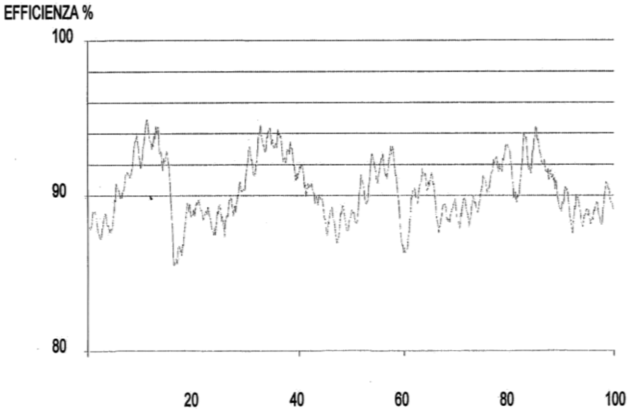

Fig. 9: Efficiency vs stroke for an unlubricated, bare Ti-6Al-4V ball screw **after** thermal-vacuum exposure

LUBRICATED AISI 440C BALL SCREW

Six specimens of WC/C lubricated steel ball screws before exposure have shown an average efficiency of 95.4 % and a variance of 2.31 (Fig. 10), denoting that, with respect of the unlubricated ball screw, WC/C deposition increases surface roughness and friction. This is confirmed by other researchers which denote a surface roughness of 0.15 and 0.20 μm. for 2.5–3.0 μm thick coatings. In general, surface roughness increased with WC/C coating thickness .

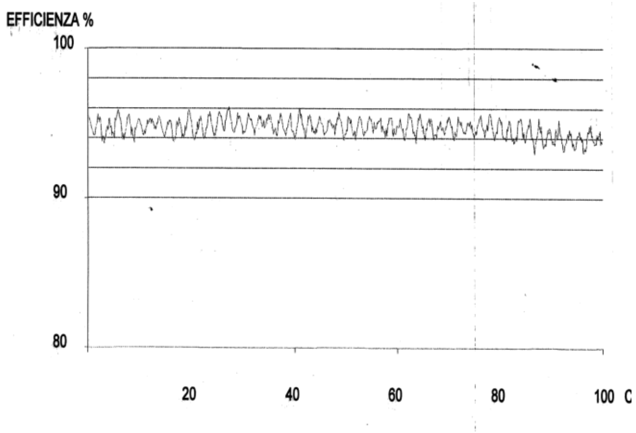

Fig. 10: Efficiency vs stroke for a WC/C lubricated steel ball screw **before** thermal-vacuum exposure

LUBRICATED Ti-6Al-4V BALL SCREW

Also in this case, six specimens of WC/C lubricated Ti-6Al-4V ball screws have been tested. Before exposure they have shown an average efficiency of 92.55 % and a variance of 2.47 (Fig. 11), denoting that, with respect of the unlubricated ball screw, WC/C deposition increases surface roughness and friction.

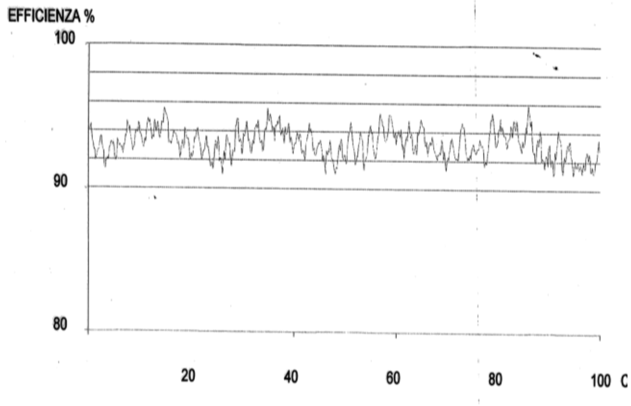

Fig. 11: Efficiency vs stroke for a lubricated Ti-6Al-4V ball screw **before** thermal-vacuum exposure

For the various possible applications of such a coating it is important to understand how the properties of the substrate (type, hardness, surface roughness etc.) influence the deposition procedure of the WC\C coating, the interface characteristics and especially the final property of the coating geometry.

6. CONCLUSIONS

In most space applications where the applied load is low, a coefficient of friction up to 0.025 might be acceptable; however, the high torque and high temperature for a boom application would not be permitted. This means that bearings for use in high-load conditions should have low-torque characteristics, and thus effective solid film lubrication is mandatory. Consequently the life of the bearings should be defined as the time of lubricant film failure.

The presence of oxides and contaminants on the surfaces of the bare Ti-6Al-4V and steel ball screws (Fig. 12) contributed to the low initial coefficient of friction, respectively 0.024 and 0.016. After thermal-vacuum exposure, the coefficient of friction rapidly increased for both materials reaching an equilibrium value of 0.087 for Ti-6Al-4V and 0.055 for steel. This type of friction is due to strong metallic interactions, particularly adhesion, which occur at the interface when the oxides and contaminants have been removed from the alloy surfaces by ultra-vacuum.

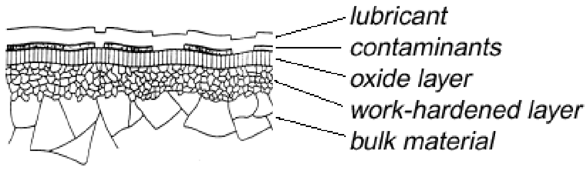

Fig. 12: General surface composition

The interfacial bond strength between bare metal and ceramic surfaces is generally greater than the cohesive bond strength in the metal. Thus, fracture of the cohesive bonds in the metal results when shearing occurs. These strong interfacial bonds and the shearing fracture in the metal are the main causes of the observed plunge in efficiency.

Therefore, during the exposure to high vacuum, cohesive bonds formed between the metallic surface and the ceramic spheres: this adhesion is not prevented by superficial oxides layers on metals, since diffusion bonding can easily occur due to high temperature and local thermo-elastic compressive stresses. After surfaces micro-welding has occurred at contact zones, these metallic-ceramic bonds are not affected by the subsequent shift from high vacuum conditions to the standard atmospheric environment. The bonds are broken only during efficiency testing on mechanical bench, when a moving torque is applied to the TBS: however the failure of the micro-welding regions between metals and ceramics affects the efficiency of the whole mechanisms. In fact the post-exposure raising of the friction coefficients for both steel and titanium is perhaps dependent on a local increase of surface roughness after breakage of the welding zones, where, at the beginning of the efficiency test, thin layers of metal are torn by the ceramic spheres.

It should be noted that tribological behaviour of a ball-screw is a particular case because it operates under a rolling-sliding frictional condition which is somewhat different from rolling or sliding friction.

Furthermore, because of the marked difference in the ductility of ceramics and metals, solid-state contact in thermal-vacuum between the two materials may have resulted in considerable plastic deformation of the softer metal, lowering efficiency especially for Ti-6Al-4V. In general, the responses of the Titanium specimens denoted larger variance than those of the steel specimens. This is to be expected as the relative softness of the Titanium leads to greater amounts of plastic deformation of the microscopic rough contact areas.

What here experimented and found confirmed what found by other researchers [12], i.e. all the clean metal-ceramic couples exhibit a correlation between the surface and bulk properties of the metal (e.g., its Young's and shear moduli, its bond strength, and the chemistry of the contacting materials) and the adhesion, friction, and wear behaviour of the metal. All of the following decrease with an increase in the Young's modulus and the shear modulus of the metal or with a decrease in the chemical activity of the metal: adhesion, coefficient of friction, metal wear, and metal transfer to the ceramic.

In other words, the coefficient of friction, which reflects interfacial adhesion, decreased with an increase in the shear modulus of the metal [12]. This shows that the shear modulus of the metal plays an important role in the friction behaviour of clean metal-ceramic couples. Similar friction-shear modulus relationships have been noted with other hard materials (such as diamond, silicon carbide, Ni-Zn ferrite, and boron nitride) in sliding contact with metals.

Titanium, which in vacuum is chemically very active, exhibits very strong interfacial adhesive bonding to ceramic. In contrast, steel have relatively low coefficients of friction; thus, the more chemically active the metals, the higher the coefficient of friction.

After exposure lubricated ball screws tests are under progress.

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