Tribology-Related Behaviour of Coated Titanium Ball Screw Mechanisms under Thermal-Vacuum Conditions

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ABSTRACT

Grade 5 Titanium telescopic ball screws have been tested under thermal-vacuum conditions in order to verify performances during on-orbit functioning. A solid multilayer film of Tungsten Carbide/Carbon (WC/C) was deposited on screw surfaces as a lubricant and was then compared with the case of no lubrication, which presently appears promising for many mechanisms. In order to compare experimental results, traditional stainless steel (AISI 4140) mechanisms were also tested and analyzed. The experimental results together with the analytical ones enable to calibrate a numerical contact non-linear model which has been useful for the comprehension of lubricant crack behaviour and propagation. The requisites imposed by the space environment, as well as by numerical contact mechanical stresses, have given useful information on a preliminary geometrical configuration and choice of materials, both of which are presented in this paper.

1. INTRODUCTION

In recent years, vacuum tribology-related malfunctions have received central attention due to the repeated 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. In answer to the urgent need for improvements in space mechanisms and tribology research work, thermal-vacuum tests have been set up here for ball screw mechanisms. Friction and wear mechanism for a ball-screw for space use, when lubricated by a solid lubricant, remains uncertain.

The recirculating ball screws are mechanisms[2] which can transform motion, from rotary to linear, and vice versa, transferring energy (Fig. 1). The main parts of the mechanism are the balls, the screw and the nut: the latter two with threaded zones. 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.

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

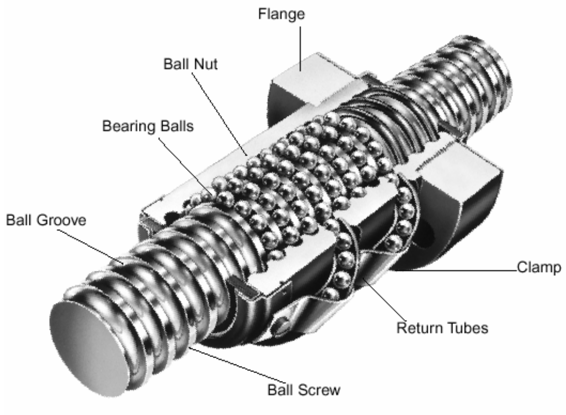

Fig. 1: Recirculating Ball Screws

The Recirculating Ball Screw may operate either with no lubrication (bare) or be lubricated via solid film. Bare mechanisms allow simplicity of design and represent a good choice for non-inspectionable space applications which require long-life affordability[3]. In fact in the case of a low number of cycles, the ideal solution is the absence of lubricant and the utilization of an Alternate Design (AD), characterized by balls of differing diameters. The combination of stainless steel screws and ceramic balls in alternate configuration has been adopted on many airplanes. In a test without lubricant, 7000 cycles of taking off and landing were reached before exceeding the upper limit values for backlash and the lower limit for efficiency. Despite these advantages, high deployment control and positioning - as in radar interferometry, for example - require infinitesimal adjustments, which may be necessary in order to decrease local wear through contact lubrication; in this case, Teflon, MoS_2 and solid paste are commonly utilized[4,5].

One of the most remarkable recent advances 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. Although silicon nitride bearings have the drawback of high manufacturing costs, when compared to those of hybrids, they are needed for high-temperature applications of up to 650°C.

Bearings are normally made of AISI 440C stainless steel; however, 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 materials other than steel, such as silicon nitride or titanium-nitride-coated balls, has proved to be effective in prolonging wear life[6]. The present work focuses on Titanium grade 5 and steel AISI 4140 recirculating ball screws in an Alternate Design of silicon nitride balls and steel balls.

2. COATINGS

In space applications, solid lubrication, which may appear as a coating, a loose powder, or a dispersion in oils and greases, is the preferred system; it involves the use of self-lubricating solids or imposing a solid material having low shear strength and high wear resistance between the interacting surfaces in relative motion. 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[7]. Solid lubricants may be preferred to liquid or gas films for several reasons.

In high-vacuum environments, in space-vacuum environments, in food-processing machines, or in semiconductor manufacturing equipment, a liquid lubricant would evaporate and contaminate products, 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 either decompose or are contaminated.

The weight savings, when compared to the use of liquid lubricants, is another important advantage. The elimination (or limited use) of liquid lubricants, and their replacement by solid lubricants, reduces aircraft or spacecraft weight and therefore has a dramatic impact on mission extent and craft maneuverability[5].

In the present work a low-friction solid lubricant, such as molybdenum disulfide (MoS_2), is utilized and applied to the surface as with a normal lubricant.

Generally, tungsten disulfide (WS_2), polyte-trafluoroethylene (PTFE), polyethylene, and a number of other materials may also be used to form solid films[8,9]. At times, combinations of several materials are used, each material contributing specific properties to the film. Due to 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].

Coating made of tungsten carbide/carbon (referred to as a WC/C coating), used here, has proved its worth in situations where all other surface coating systems fail. This WC/C coating is applied using a PVD (Physical Vapor Deposition) process - more precisely, by reactive sputtering. In this process, the coating material is expelled from targets (WC plates) in high vacuum via ion bombardment and then deposited on the parts being coated. This high-vacuum technology makes it possible to obtain coating properties that cannot be realized under an atmosphere (thermal spraying) or with gases or baths (nitriding, galvanizing). These properties include:

1. Controlled material composition. Amorphous carbon films possess the lowest friction of all hard surfaces.
2. Extreme precision. PVD coatings are only a few µm thick. They replicate work piece surfaces exactly, thereby eliminating the need for subsequent machining.
3. 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 coating are as follows:

Hardness	24-28 Gpa
Modulus of Elasticity	630 Gpa
Ultimate Tensile Strength	900 Mpa
Ultimate Compressive Strength	5.2 Gpa
Transverse Rupture Strength	2.0 Gpa
Poisson's Ratio	0.24
Coefficient of friction	0.1-0.2
Coating thickness	1-4 µm
Density	14.8 gr/cm^3
Color	black/gray

In this work, the adhesion between the coating and the substrate - both for the AISI 4140 steel and for the Ti-6Al-4V – has been improved by depositing an interlayer of Chromium and in particular of CrN. This helped to promote the deposition of such coatings onto structural components subjected to a high shear stress, as in the presented ball screws.

The microstructure of the coating system (Balzers, Balint C ®), when going from the interface with the substrate to the surface coating, is formed by a CrN interlayer, intermultilayer of WC and carbon and finally a WC layer (Fig. 2).

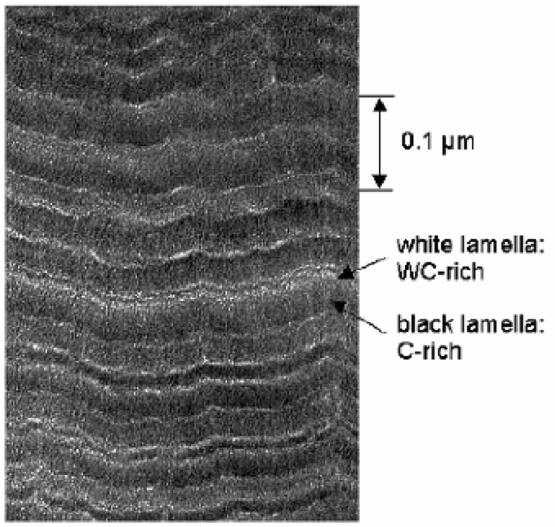

Fig. 2: TEM micrograph of the WC/C multilayer structure of Balint C ® here utilized as coating on ball screws

While the hardness of WS_2 and other solid lubricants (MoS_2 , graphite, lead) is generally below the 3 GPa level, the hardness of WC/C and other carbide coatings is as high as 24-28 GPa. This creates the potential for low wear rates and longer endurance, even for high-stressed ball screws for space applications, provided that these coatings maintain low friction coefficients, as with 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, chemical nickel-plaiting, or bronzes. This point can be noted 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 mechanisms do not have low enough friction, and as a result 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 demonstrate low coefficients of friction (between 0.01 and 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 as well as high interfacial adhesion strength between the films and the substrates. Solid film lubricants have finite wear lives or endurance lives.

3. EXPERIMENTS

Experimental analyses under thermal-vacuum conditions have been provided both for steel (AISI 4140) and Ti-6Al-4V ball screws, both in unlubricated bare conditions and in WC/C film lubricated conditions. The total number of balls were 32: 16 balls (2.381 mm. diameter) were made of Si_3N_4 in an Alternate Design with 16 AISI 4140 steel unloaded balls (2.366 mm. diameter).

The specimens (Fig. 3) were exposed to the thermal-vacuum environment, with a pressure of 10^{-2} mbar inside the chamber during the tests. This level of pressure corresponds to an altitude of about 150 Km for an undisturbed space environment. Although this altitude could appear to be low when compared to the standard perigee height for LEO missions, it must be considered that the environmental pressure close to a spacecraft is about two orders of magnitude higher than for undisturbed space, due to material outgassing and to the geometry of the fluid-dynamic field surrounding the spacecraft itself. For example, at a height of 250 Kms, the level of pressure inside the Space Shuttle cargo bay is about 10^{-2} - 10^{-3} mbar, while the external pressure for the undisturbed LEO neutral gas environment is close to 10^{-5} mbar.

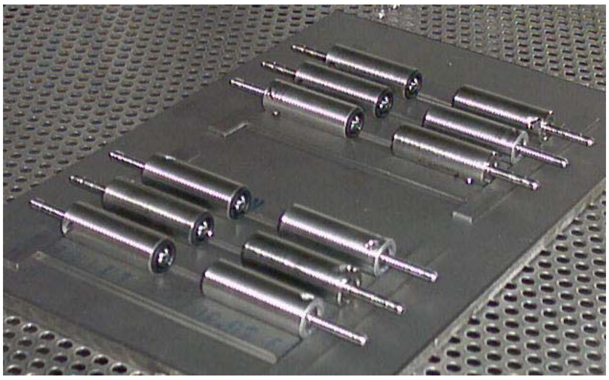

Fig. 3: Recirculating ball screw specimens

This demonstrates that the level of vacuum reached inside the utilised simulator can also represent typical environmental conditions for space mechanisms, particularly during long-term manned missions, in which the orbital perigee is generally lower than 500 Km.

The specimens were exposed to the simulator environment for a period of 200 hours during which 100 thermal cycles varying between 70°C and 120 °C were applied, each lasting two hours. The temperature profile applied to the specimens is quite different from that characyeristic of the 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.

4. EFFICIENCY AND SURFACE ANALYSIS

Upon visual inspection, running traces of the balls were observed in the grooves, but no abnormality was present, even if traces appeared larger in the case of Ti-6Al-4V substrate (Fig. 4). The total wear of the balls and grooves was evaluated by measuring the efficiency of the ball screws before and after the tests. Other analyses conducted on torque and various components of the ball screw revealed some variations.

The specimens denoted a slight drop in efficiency. In fact, exposure to the high vacuum causes the removal of the surface oxides and impurities which supply lubrication. This leads to an increase in friction between guides and balls and to a decrease in the overall efficiency (Tab. 1).

In order to assure better resistance to contact stresses, a solid film of WC/C was sprayed in the groove of the specimens. The WC/C deposition increases surface roughness and friction, with respect to the unlubricated ball screw. In general, surface roughness increases with increases in WC/C coating thickness. WC/C coating, in fact, prevents the removal of all the surface oxides and impurities, maintaining the friction coefficient constant.

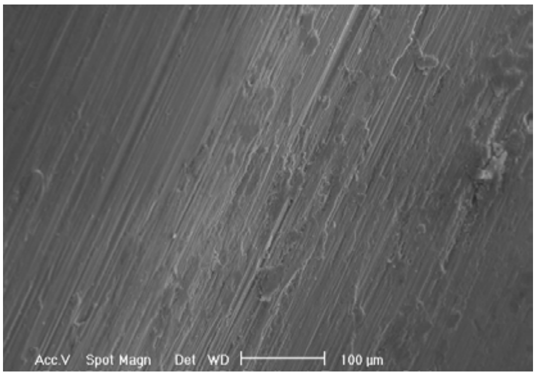

Fig. 4: SEM micrographs showing Ti-6Al-4V surface wear

Contrary to steel behaviour, demonstrate lower performances the Titanium bare ball screws; this may be due to the following two considerations: 1) as on the steel ball screws, following exposure to the high vacuum the surface oxides and impurities (which promote lubrication) are removed, leading to an increase of friction between guides and balls and to a decrease of the overall efficiency; 2) due to the marked difference in the ductility of ceramics and Ti-6Al-4V, solid-state contact between the two materials in thermal vacuum may have resulted in considerable plastic deformations of the softer metal, lowering efficiency (Tab. 1). Anyway, the worst case scenario is on the coated titanium surface: the extensive plastic deformations on Titanium give rise to coating detachments and debris production, lowering the overall efficiency and increasing the friction coefficient. All of these considerations are remarked later on.

Tab. 1: Efficiency values for ballscrews

	Efficiency before exposure	Efficiency after exposure
AISI 4140 without lubricant	98.4 %	94.5 %
Ti-6Al-4V without lubricant	97.6 %	91.3 %
AISI 4140 with lubricant	95.4 %	93.1 %
Ti-6Al-4V with lubricant	92.5 %	83.2 %

5. COATING STRESSES

Balls running between flat surfaces have small contact patches with each other and cannot transmit high loads. Thus ball-screw tracks usually have a curvature perpendicular to the balls' direction of movement, giving rise to a gothic groove profile. Track conformity, the dimensional relationship between ball and track, is expressed as the ratio of track radius to ball diameter. Therefore, track conformity of 0.5 means the ball fits exactly into the track curvature. Although this is desirable for optimum load bearing, track conformity of 0.5 is usually accompanied by excessive sliding between ball and track (sometimes referred to as differential slip) and cannot be used. Moreover, normal manufacturing tolerances of the ball-track shape make the contact patch move to any high spot, resulting in unpredictable contact angles. In this case conformity ratio is around 0.56 and contact angle θ is 45° (Fig. 5).

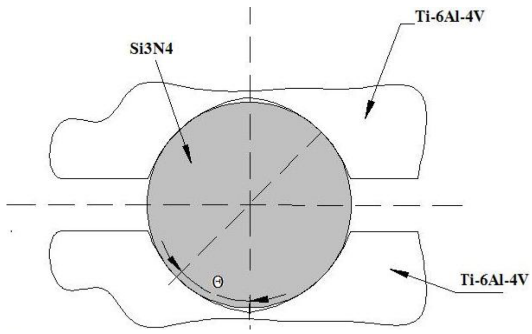

Fig. 5: Groove gothic profile

Numerical contact analyses, performed with MSC/MARC, were set up to better understand all the deformation events and the stresses on WC/C coating. A brick non linear model of a Si_3N_4 ball over a semicircular surface (Fig. 6), which takes into account a 2.4 µm coating and a substrate, has been utilised for all numerical analyses.

All the finite element numerical models have been first calibrated, in absence of lubricant, with Hertz point contact theoretical results, which suppose elastic and homogeneous bodies, isotropic materials, smooth surfaces and small curvatures.

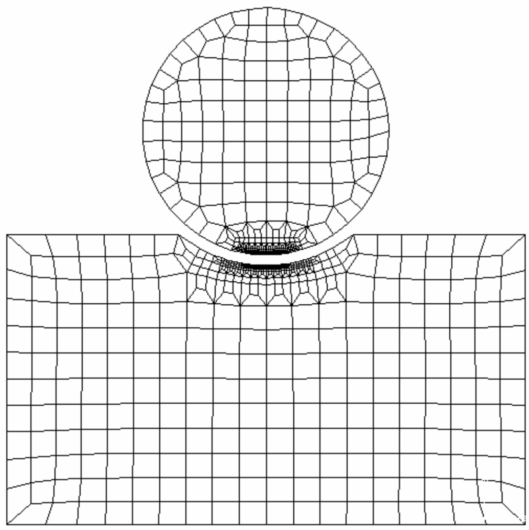

Fig. 6: A meshed 3D numerical model

The total preload acting on the larger Si_3N_4 spheres is 400 N, which corresponds to 40 N acting on each ball at a contact angle of 45° (Fig. 7).

The numerical models have been first calibrated with Hertz point contact pressure, respectively of 0.78 GPa for the Ti-6Al-4V and of 1.02 GPa for the AISI 4140, and successively a WC/C coating has been inserted in the model and analysed.

Results show that, as the substrate commences to experience a sufficiently high stress, the coating start flexing and bending to conform to the substrate deformation. This deformation history has major influence on the radial and tangential stress components of the lubrication coating at the contact zone:

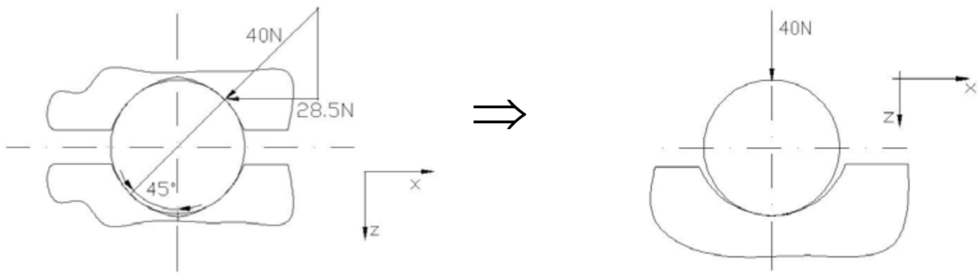

Fig. 7: Geometry and loading

particularly, for the case of steel substrate a value of 1.447 Gpa has been found on the coating (Fig. 8), and, for the case of Ti-6Al-4V substrate, a value of 1.563 Gpa (Fig. 9). This denotes that the coating on Titanium is more stressed than in the case of steel substrate, confirming that the more the substrate is flexible the more a solid lubricant film is suitable to crack.

Evidently for both spheres and substrate the maximum equivalent stress occurs just below the surface and may be taken to be 60% of the peak pressure. Finite element analyses also show that the coating and the substrate remain well below the respective admissible stress values, with margin of safety more than 2. Hertz stress values, which are often considered a valid reference for ball screw designer who are on the point of pre-dimensioning the bulk substrate, may only give a general indication.

Tab. 2: Stresses on ballscrews

	Hertz values	**Numerical values**
AISI 4140 without lubricant		
Substrate		
Peak pressure	1.02 GPa	1.02 GPa
Radial stress	0.826 GPa	0.826 GPa
Ti-6Al-4V without lubricant		
Substrate		
Peak pressure	0.78 GPa	0.78 GPa
Radial stress	0.62 GPa	0.62 GPa
AISI 4140 with lubricant		
Substrate		
Compressive stress	-	0.91 GPa
Radial stress	-	1.08 GPa
Coating		
Peak pressure	-	0.91 GPa
Radial stress	-	1.447 GPa
Ti-6Al-4V with lubricant		
Substrate		
Compressive stress	-	0.758 MPa
Radial stress	-	1.07 GPa
Coating		
Peak pressure	-	0.752 GPa
Radial stress	-	1.563 GPa

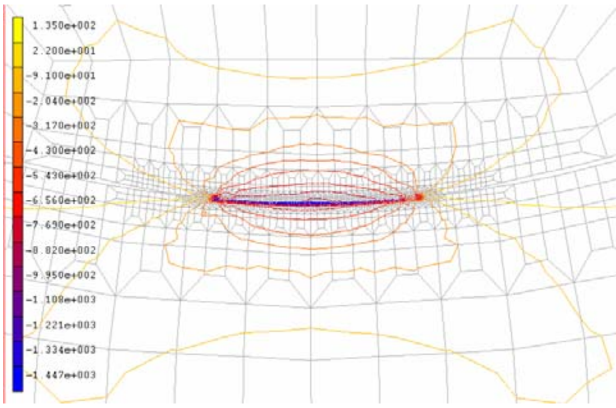

Fig. 8: Closed-up of the radial stresses between Si_3N_4 and AISI 4140

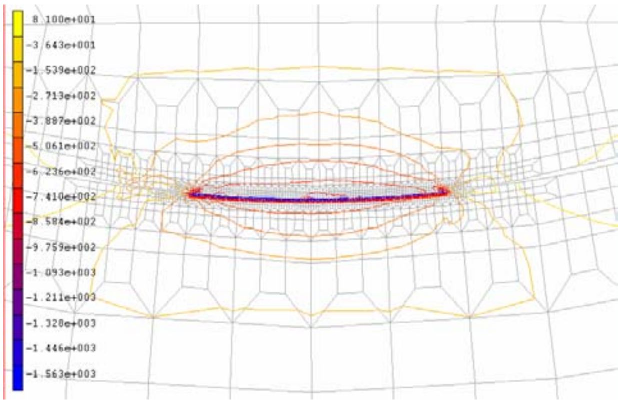

Fig. 9: Closed-up of the radial stresses between Si_3N_4 and Ti-6Al-4V

8. CONCLUDING REMARKS

Unlubricated Ball Screws:

In most space applications, where the applied loads are low, a coefficient of friction up to 0.1 might be acceptable; in many other applications, where high torque and high temperatures are present, it is necessary to lower the coefficient and stablize it over time. 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 necessary for lubricant film failure.

The experimental tests presented here have shown that high vacuum alone is responsible for the increase in the friction coefficient and for the lowering of efficiency in each case. The presence of oxides and contaminants on the surfaces of the bare Ti-6Al-4V and steel ball screws contributed to the low initial coefficient of friction. After vacuum exposure, the coefficient of friction rapidly increased for each material. 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 the ultra-vacuum.

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 drop in efficiency.

Therefore, during exposure to high vacuum, cohesive bonds formed between the metallic surface and the ceramic spheres as also explained by other authors: this adhesion is not prevented by superficial oxides layers on metals, since diffusion bonding can easily occur in conditions of high temperature and local thermo-elastic compressive stresses. After surface micro-welding has occurred at contact zones, the bonds are broken during efficiency testing on the mechanical bench, when a moving torque is applied to specimens. However the failure of the micro-welding regions between metals and ceramics affects the efficiency of the whole mechanisms. In fact, the post-exposure increases in the friction coefficients for both steel and titanium may depend on a local increase of surface roughness after breakage of the welding zones, where thin layers of metal are torn by the ceramic spheres at the beginning of the efficiency test.

Furthermore, given the marked difference in the ductility of ceramics and Ti-6Al-4V, solid-state contact in thermal-vacuum between the two materials may have resulted in considerable plastic deformation of the softer metal, decreasing efficiency. 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 plastic deformation of the microscopic rough contact areas.

Lubricated Ball Screws:
In this case, the presence of lubricant prevents the microwelding between spheres and grooves but may cause, in case of large deformation due to thermal loads, the coating to detach from the substrate, thereby creating unwanted hard wear debris. The authors suppose that this is the mechanism that happened here, which lowers especially the Ti-6Al-4V ball-screw efficiency.

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