NASA Technical Memorandum 101304

Status and Directions of Modified Tribological Surfaces by Ion Processes

Talivaldis Spalvins
Lewis Research Center
Cleveland, Ohio

Prepared for the
First International Conference on Plasma Surface Engineering
sponsored by Deutsche Gesellschaft für Metallkunde
Garmisch-Partenkirchen, Federal Republic of Germany, September 19–23, 1988

NASA

Status and Directions of Modified Tribological Surfaces by Ion Processes

Talivaldis Spalvins, National Aeronautics and Space Administration,
Lewis Research Center, Cleveland, Ohio 44135 U.S.A.

E-4294

Introduction

In any tribo-system, where touching surfaces are in relative sliding, rotating, rolling or oscillating motion, the primary interactions leading to deterioration and consequently to failure occur at the contacts. What happens when two contacting surfaces are in relative motion depends on the surface tribo-contacts, the lubricant and the environment. The tribological requirements for improved performance, life and reliability have increased dramatically in line with the higher demands placed on the high-performance precision space mechanisms, gas turbines, rockets and advanced concept engines of the aerospace and aeropropulsion fields. The critical space applications have to operate under severe environmental conditions such as: variable temperature, radiation exposure, and a variety of atmospheres from the ultra-high vacuum of space to highly oxidizing or corrosive environments at high temperatures. Since conventional liquid lubricants (oils and greases) in many of these applications decompose and evaporate, the use of dry or solid lubricants would be a logical choice. Unfortunately, there is no universal solid lubricant available which can perform under all of these adverse conditions.

It is critical to select the most suitable lubricant and utilize the most promising deposition modification techniques, since tribological behavior is greatly affected by coating adherence, coherence and morphology. To simplify tribo-material selection, it is convenient to divide the solid lubricants into two broad categories based on their operational environment: (1) Lubricants for spacecraft mechanisms used exclusively in ultra high vacuum with temperature variations from +150 to -120 °C; and, (2) Lubricants for space power systems and aircraft propulsion systems where high speed mechanical components (e.g., bearings) operate under high temperature, corrosive conditions. In addition to selecting the appropriate solid lubricant, it is equally important to select the most promising deposition technique. For tribological performance, the ion assisted deposition/modification techniques offer the greatest potential to custom tailor adherent, lubricating coatings with optimized chemical-structural surface properties independent of the bulk properties. The advantages of the ion assisted deposition processes lie in their high flexibility to tailor surface and film properties in ways not available with other deposition techniques. The purpose of this paper is to critically review the present practices and new approaches initiated to deposit/modify tribological surfaces by the various ion assisted deposition processes, in terms of structure-property-performance interrelationships. These interrelationships which are determined by structural and chemical characterization and frictional and wear behavior, dictate the performance or failure of a tribosystem.

Ion Assisted Surface Methodologies

The ion assisted surface treatments for tribological control can be classified in three categories:

1. Ion Assisted Deposition
   Physical Vapor Deposition (PVD): sputtering and ion plating
   Chemical Vapor Deposition (CVD): plasma enhanced deposition
2. Ion Beam Techniques
   Ion implantation
   Ion beam mixing
   Ion beam enhanced deposition
3. Plasma Thermochemical Processes
   Ion nitriding
   Ion carburizing
   Ion boriding
   Ion oxidation

Depending on deposition energies and surface interactions, the above process can be classified as processes that produce distinct overlay coatings (ion assisted deposition) and processes forming no discrete coating but which modify the surface of the bulk (ion implantation, plasma thermochemical processes). In this paper, the structure-property-performance interrelationships affecting tribological performance of surfaces deposited by the ion assisted deposition techniques or modified by the ion beam techniques will be addressed. Surface modifications by the plasma thermochemical processes will not be discussed in this paper.

Principles of Solid Film Lubrication

When two touching surfaces are in relative motion, or tribo-contact, what happens depends on the characteristics of the surfaces, the environmental conditions, and the lubricant. Friction originates in the deformation and shearing or surface asperities [1,2]. Adhesive wear occurs when both the surface and subsurface interact. According to the adhesion theory of friction the frictional force, F, is determined by the shear strength, s, and the real area of contact, A, according to F = As, as shown in Figure 1. For friction to be low, either A and s or both must be small. This means that the most suitable materials must have high hardness and low shear strength. However, this generally is not achievable with monolithic materials.

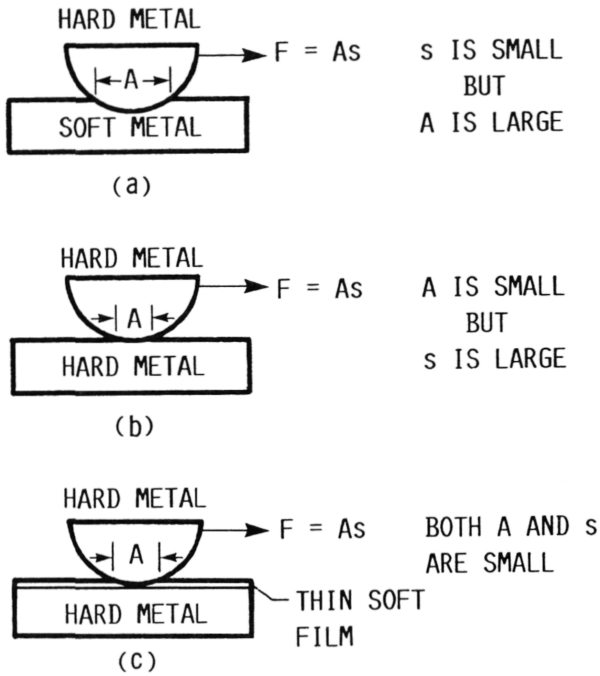


FIGURE 1. - SURFACE BEHAVIOR OF TRIBO-CONTACTS TO METAL HARDNESS.

For instance, when a hard metal slides tangentially on a soft metal, the friction force is a function of the real area which is large due to deformation as shown in Figure 1(a). Where two hard surfaces are in contact (e.g., SiC against SiC) as shown in Figure 1(b). The friction force is large because the shear strength is large due to the high elastic moduli of the two materials. However, by using thin layers of soft, low shear strength solid materials on hard, very smooth surfaces, friction and usually wear as well, can be reduced as shown in Figure 1(c).

This last combination of a soft layer on a hard surface has been widely explored and used not only in metal-metal tribocontacts but increasingly in studies of ceramic tribocontacts, primarily in highly oxidative environments. These new lubrication approaches are discussed in this paper.

The frictional properties of ceramic-ceramic, metal-metal and metal-ceramic tribocontacts in a vacuum environment are tabulated in Figure 2 [3]. The data presented indicate the marked difference in friction for the basic combinations of solids. It can be seen that the coefficient of friction due to adhesive bonding is the highest for metal-metal contacts and lowest for the ceramic-ceramic contacts. The conclusion can be drawn that the use of ceramic materials in the form of bulk and coatings in space or vacuum environments are beneficial from a tribological point of view.

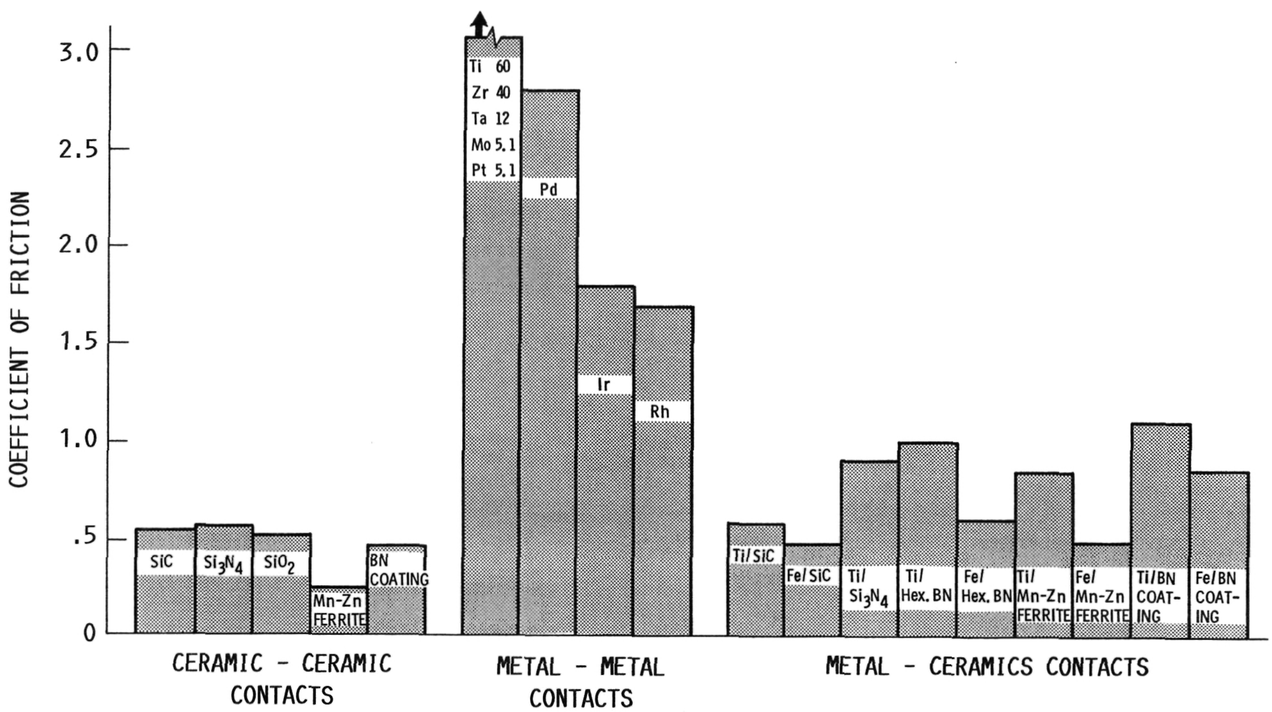


FIGURE 2. - COEFFICIENTS OF FRICTION FOR CLEAN SOLID-TO-SOLID INTERFACES. SINGLE PASS SLIDING IN VACUUM (30 nPa).

Soild Lubricants for Spacecraft Mechanisms

Many of the spacecraft-satellite moving mechancial assemblies and components require solid or dry film lubrication. The typical reasons for preferring dry lubrication is that viscosity of most liquid lubricants has a strong dependence on temperature, therefore affecting the tribo-contact behavior. Further, the use of solid lubrication can eliminate the need for fluid lubrication systems and thus reduce maintenance requirements. Solid lubricating films are used for spacecraft mechanisms such as solar array drives, antenna pointing and control systems, despin mechanisms, rack and pinion gears. The criteria for selecting a solid film lubricant are the following: (1) long term stability (3 to 10 years) in space without contamination by degassing or evaporation; (2) frictional properties are not to be influenced by temperature changes or by shear rate changes; (3) low torque noise and vibration levels over the mission life.

The triboelement surfaces in space mechanical components (bearings, gears gimbals, splines, etc.), because of their optimized design and precision tolerances, require very thin adherent films, typically 0.2 to 0.4 μm in thickness. Ion assisted deposition techniques, such as sputtering and ion plating, offer the best tribological performance. Since the tribological properties of these coatings are very sensitive to the deposition process parameters, the objective is to develop optimized lubricating films. Therefore, it is essential to investigate the structure-property-performance interrelationships with a fundamental understanding of coating/substrate interfaces and microstructures/microchemistries, in terms of the resultant tribological properties.

The major candidate lubricants used for space mechanisms can be classified as follows:

1. Layer Lattice Compounds: MoS_2, WS_2, $NbSe_2$ (sputtered) Au-Mo_2, Ni-MoS_2 (sputtered)
2. Soft Metals: Au, Ag, Pb (ion plated)
3. Double Layer Coating of MoS_2: MoS_2/Cr_3Si_2, Si_2, MoS_2/B_4C (sputtered)

Layer Lattice Compounds

Of the layer lattice compounds or dichalgogenides, sputtered MoS_2 films have been most widely used and investigated [4-10]. MoS_2 has been deposited by various sputtering modes (dc/rf diode, dc triode, dc/rf magnetron, ion beam, and ion beam mixing). However, the rf diode and rf magnetron sputtered films have found extensive uses as lubricants for high precision space mechanism components. For space applications MoS_2 also satisfies the thermal stability requirements since it has a high dissociation stability in vacuum, up to 930 °C as shown in Figure 3.

The unique characteristic of MoS_2 is its highly anisotropic hexagonal crystal layer structure as shown in Figure 4. The easy shear along the van der Waals

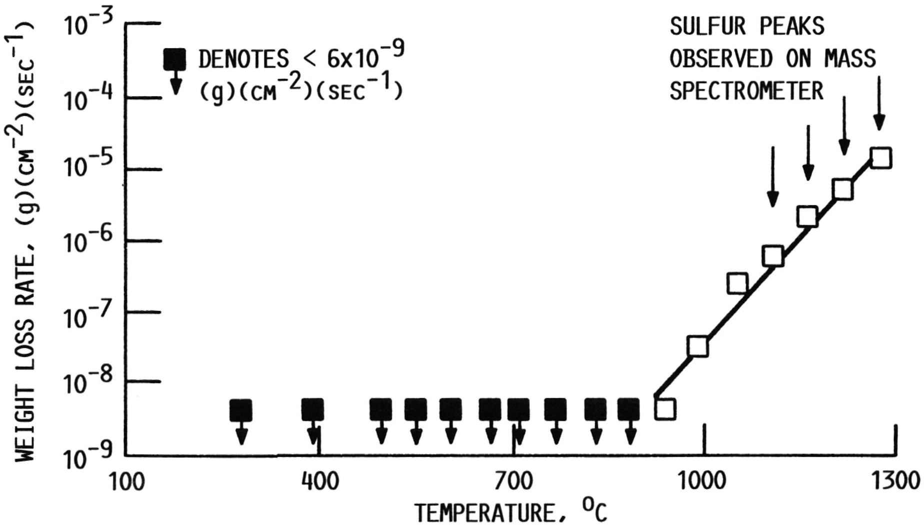


FIGURE 3. - WEIGHT LOSS RATE CURVES FOR MoS_2 WHEN HEATED IN VACUUM (10^{-9} TO 10^{-8} torr).

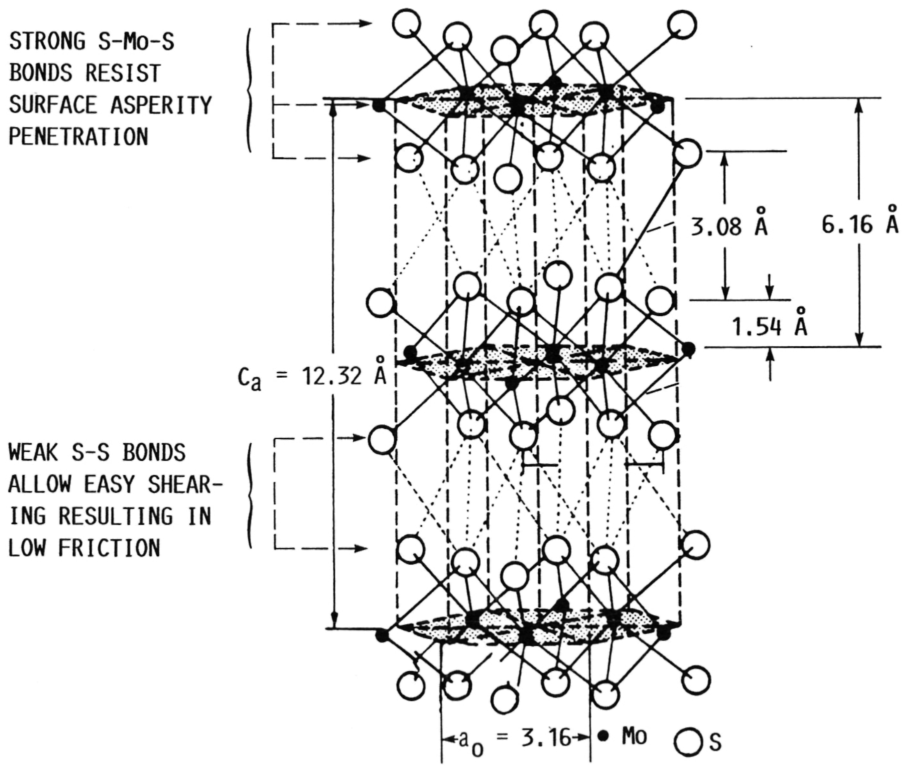


FIGURE 4. - STRUCTURE OF MoS_2.

bonded gap between the interlayers contributes to the low coefficient of friction. For mechanical sliding applications, the MoS_2 film has to satisfy two requirements: (1) strong adherence to the surface; and, (2) low shear strength to ensure low friction. The friction properties of sputtered films are also affected by the crystallographic transformation to an amorphous structure during sputtering and by anisotropic adsorption/oxidation during storage or exposure to atmospheric environment. For instance, sputtering MoS_2

on substrates at cryogenic or low temperatures should be avoided, since the sputtered species are quench condensed and an amorphous structure forms [4]. The amorphous structure has a short-range atomic order without the crystalline atomic periodicity. Thus the basis for easy interlayer shear is destroyed and the films display abrasive characteristics. A typical structural-friction diagram in Figure 5 illustrates how the particle size affects the coefficient of friction for MoS_2 films sputtered on substrates from -195 to 320 °C.

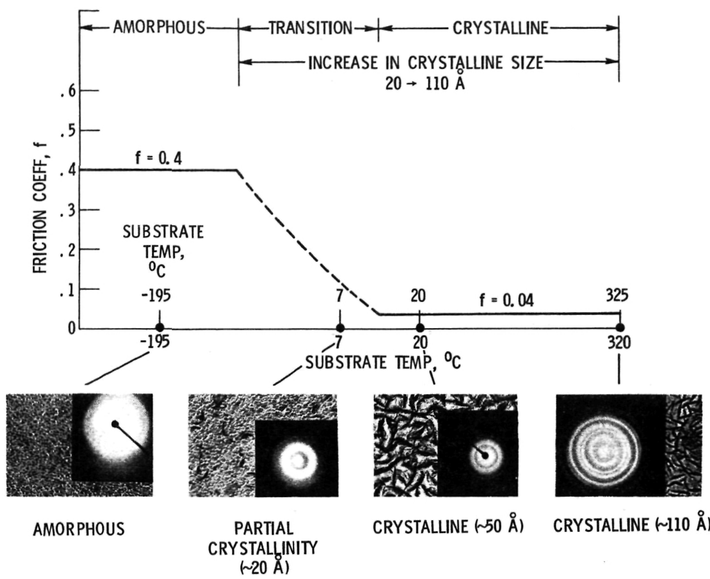


FIGURE 5. - SUBSTRATE TEMPERATURE EFFECTS ON MoS_2 FILM MORPHOLOGY AND FRICTION COEFFICIENT.

It is also important to recognize that sputtered MoS_2 films show their best performance in vacuum, inert gas or dry air, and should not be used under atmospheric conditions since humidity increases the coefficient of friction and thus reduces the endurance life. Sputtered MoS_2 films have the capacity to display ultra low coefficients of friction, 0.01 or less in vacuum, when the sputtering process parameters are optimized. Presently there is significant research activity under way to optimize sputtering process parameters which affect the frictional properties. Of particular interest is the crystallite reorientation during sliding or rolling, since best results are obtained when basal planes within the film reorient parallel to the substrate surface.

It is also important to identify the morphological growth patterns of the sputtered film, since the preferred or effective film thickness depends on the morphology. For instance, the effective film thickness for rf diode sputtered MoS_2 films was established in terms of the identified morphological growth zones during single pass sliding (pin-on-disk) as shown in Figure 6.

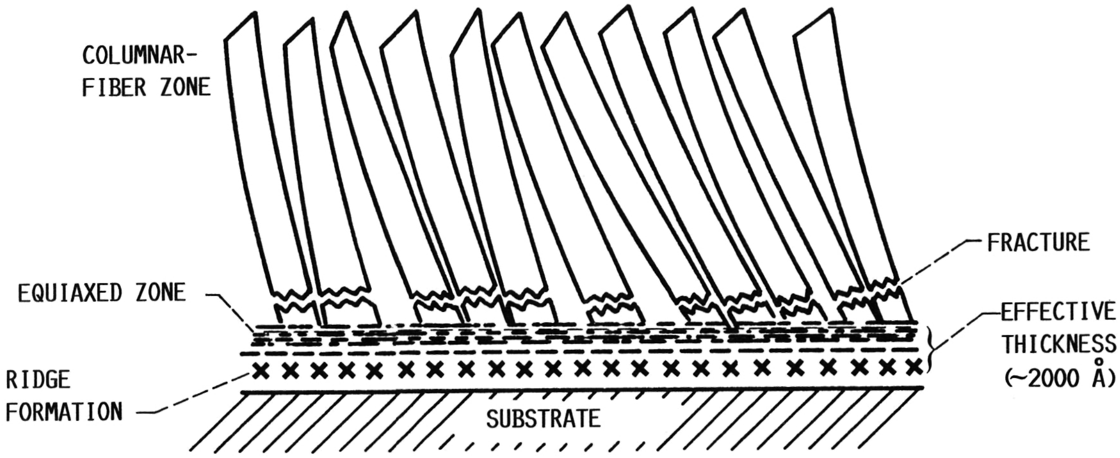


FIGURE 6. - FRACTURE DURING SLIDING OF SPUTTERED MoS_2 FILM WITH RESPECT TO MORPHOLOGICAL ZONES.

The results were that the film fracture - disintegration occurred in the columnar structure, indicating that the adhesive forces between the substrate and the MoS_2 film were stronger than the cohesive forces between the columnar fibers. Consequently, the lubrication was performed by the remaining surface film which was about 2000 Å thick.

Soft Metals

Ion plating utilizing a diode configuration is the preferred technique for deposition of thin (0.2 μm), soft metallic films (Au, Ag, Pb) either for spacecraft mechanical components or for terrestrial applications [11-16]. Ion plating technique has matured in the last decade primarily because of the demands of the aerospace industry.

Two important features of the process are: (1) the flux of high energy ions and neutrals which cause exceptionally strong adherence between the film and the substrate, and; (2) the high throwing power which provides the three-dimensional coverage to coat complex shapes.

The excellent adherence is caused mainly by atomistic mixing which generates a graded interface, i.e., one in which there is a gradual transition between the properties of the substrate and the coating. This can be shown by using X-Ray Photoelectron Spectroscopy (XPS) depth profiling, as in Figure 7 [17]. The interface formation can also be identified by making micro-Vickers measurements. The microhardness of an ion plated gold film, graded gold-nickel interface and nickel substrate as a function of distance from the surface is shown in Figure 8(a). The gold was gradually removed by argon ion sputtering

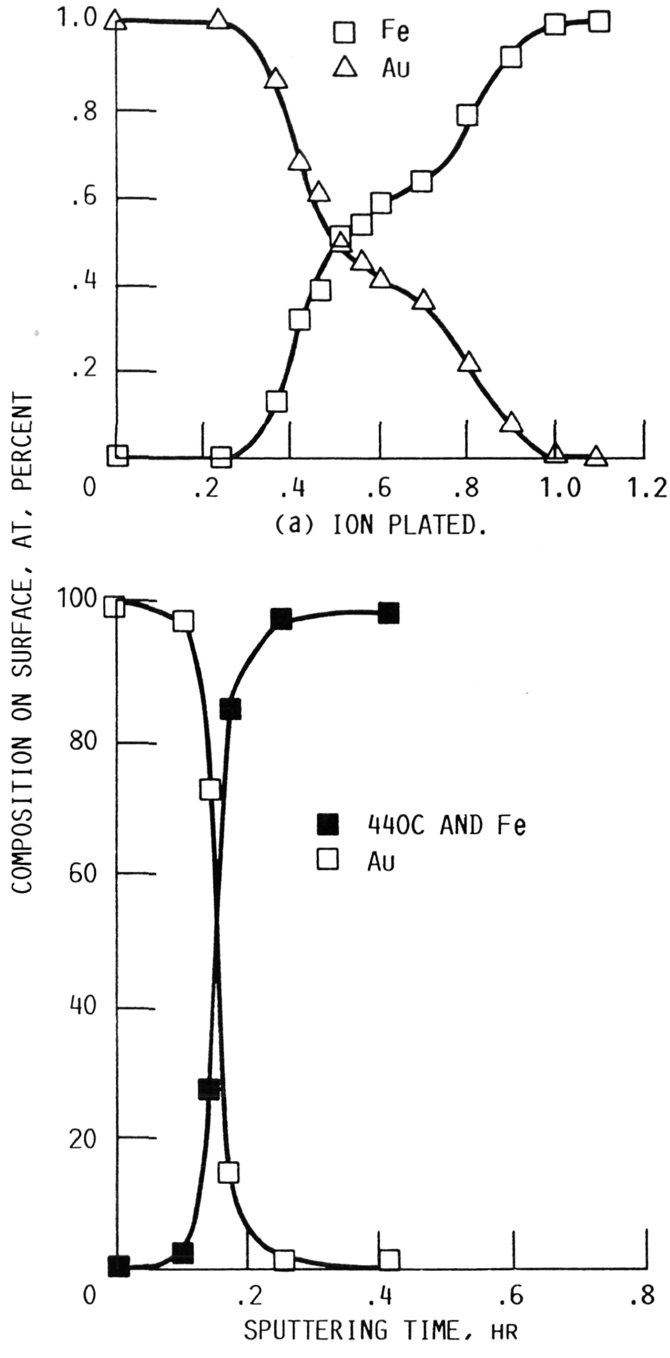
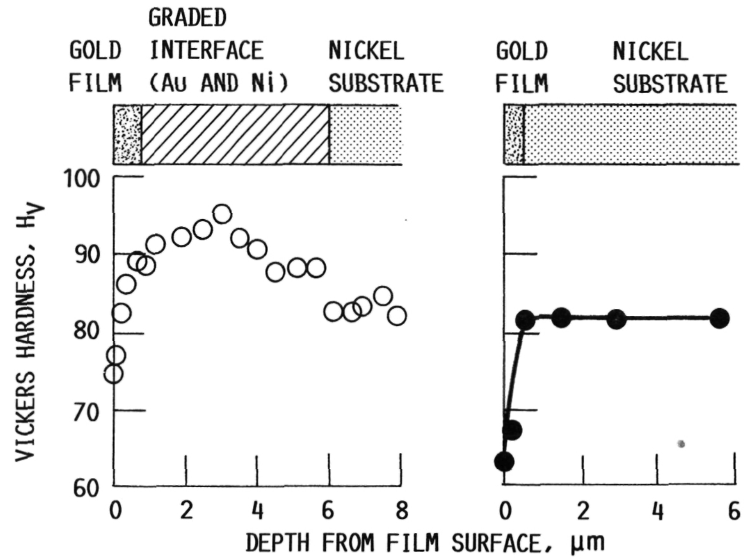


FIGURE 7. - ELEMENTAL DEPTH PROFILES FOR ION PLATED AND VAPOR DEPOSITED GOLD ON IRON.



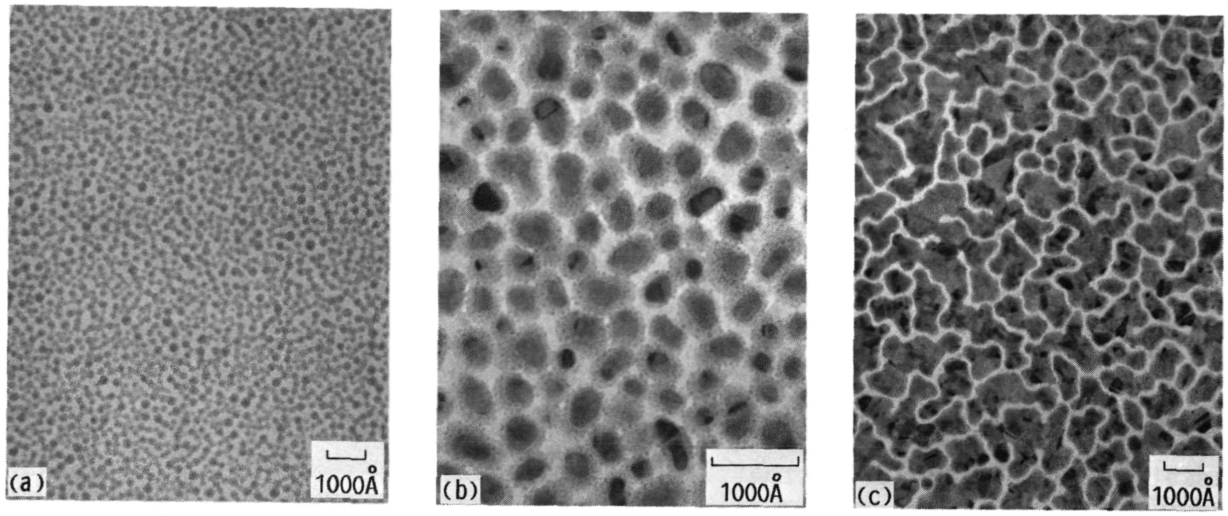
(a) ION-PLATED GOLD FILM. (b) VAPOR-DEPOSITED GOLD FILM.

FIGURE 8. - HARDNESS DEPTH PROFILES FOR GOLD ION PLATED AND VAPOR DEPOSITED ON NICKEL SUBSTRATE. HARDNESS MEASURING LOAD, 0.1 N.

prior to the microhardness determinations. Initially, the hardness was relatively low, in the gold film but gradually increased in the interface region and finally decreased again as the nickel substrate was reached. The higher hardness in the interface was due to alloying. The vapor deposited gold film on nickel shown in Figure 8(b) exhibited constant hardness, which is indicative of a sharp interface.

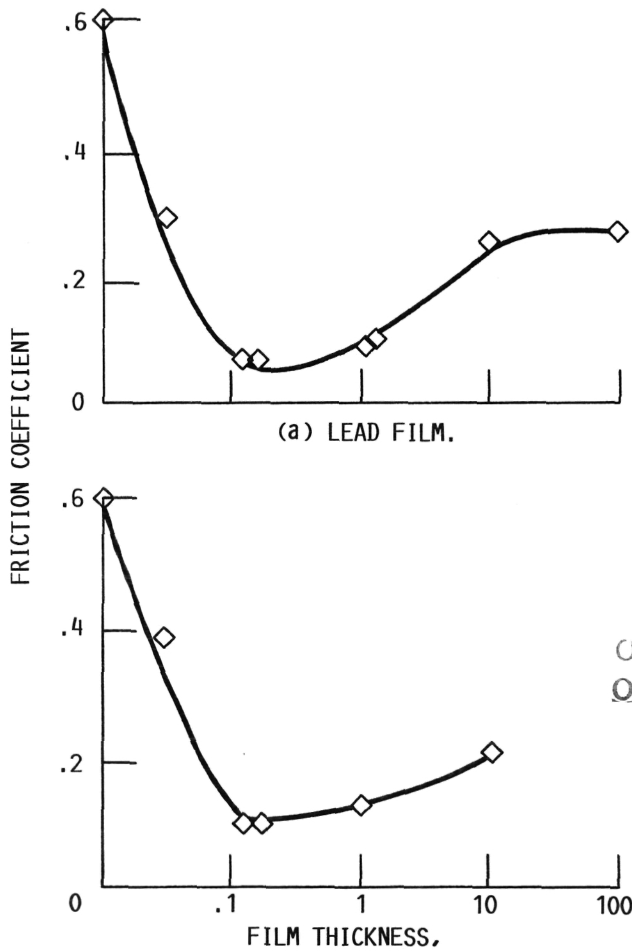
The ion plated metallic films, unlike the conventional vapor deposited ones, exhibit a distinct nucleation behavior as shown in Figure 9. The nuclei formed during ion plating exhibit these distinct characteristics: the nuclei are considerably smaller (150 Å), have a high density, and a uniform distribution. As deposition continues the nulei remain rounded with less than a 20 percent increase in size. Consequently, continuous films are formed in the 250 Å thickness range with uniform grain structure, high packing density, and minimum lattice misfit. It is therefore clear why ion plated metallic films display favorable morphological properties.

In thin film lubrication, the film thickness has a very pronounced effect on the coefficient of friction as shown in Figure 10 for ion plated Au and Pb films. The effective or minimum film thickness for Au and Pb films was about 2000-2500 Å with a minimum coefficient of friction of 0.1 and 0.085 respectively [8]. It has been suggested for Pb film lubrication that once the film



ION PLATED VAPOR DEPOSITED

FIGURE 9. - TEM MICROGRAPHS OF LEAD DURING NUCLEATION.



(b) GOLD FILM.

FIGURE 10. - THE VARIATION OF FRICTION COEFFICIENT WITH FILM THICKNESS (LOAD 2.45N; SPEED 1.52 $mmin^{-1}$; PRESSURE $2x10^{-3}$ torr; ROUGHNESS 0.02 μm).

has been plastically deformed down to a certain thickness, it will then start to behave elastically and deform with the substrate. This concept has been explained in terms of a very small shear stress in such a film.

Typical friction curves for ion plated and vapor deposited Au films 2000 Å thic as determined in a pin and disk tribotester under vacuum conditions are shown in Figure 11. The ion plated Au films had three distinct improvements over the vapor deposited ones: (1) increased endurance life, (2) lower coefficient of friction, and (3) avoidance of catastrophic failure. The increased endurance life is attributed to the superior adherence, the lower coefficient of friction to the these, cohesive small crystallite since and the optimum film thickness, and the gradual increase in the coefficient of friction after the film was worn off to the formation of the graded interface.

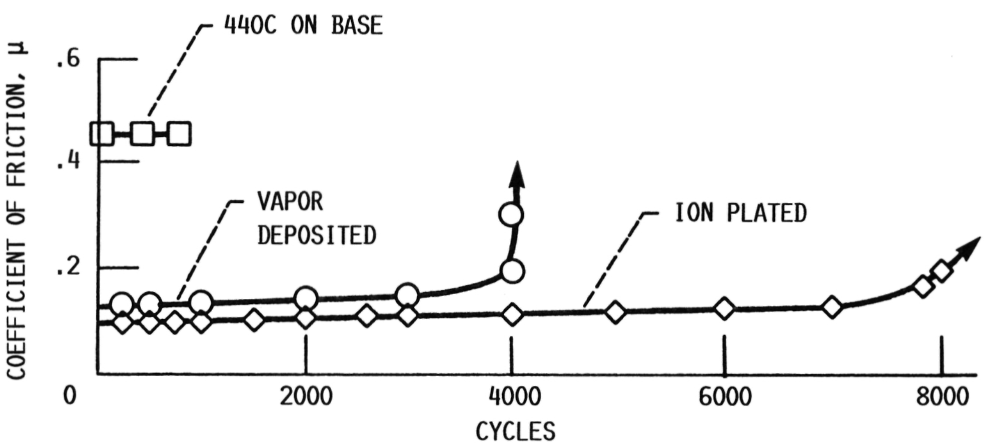


FIGURE 11. - COMPARISON OF COEFFICIENT OF FRICTION OF ION PLATED AND VAPOR DEPOSITED GOLD FILM ON 440C STEEL (LOAD, 2.45N; SPEED $0.26 ms^{-1}$; PRESSURE $2x10^{-3}$ torr, ROUGHNESS, 0.02 um).

Double Layer Coatings of MoS_2

These coatings are layer structures consisting of hard underlayer of BN, TiN, Cr_3Si_2, B_4C on a hard 440C steel substrate sputtered with MoS2 film as illustrated in Figure 12. The double layer coating approach originates from the concept that both friction and wear can be reduced by decreasing the extent of plastic deformation at or near the sliding counterfaces, which is a basic concept behind hard coatings used to resist plastic deformation.

Significant improvements were obtained with angular-contact, 440C stainless steel ball bearings sputtered with a 1000 Å thick underlayer of Cr_3Si_2 and 2000Å sputtered MoS_2 film [19]. These bearings, when evaluated in vacuum with a thrust load of 138 N at 1750 rpm, showed a remarkable endurance, over 1000 hr

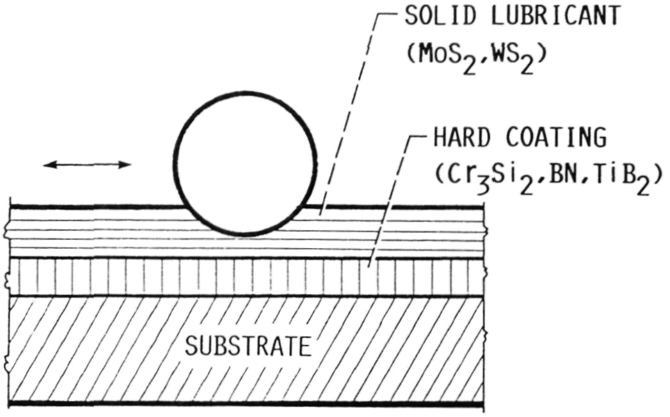


FIGURE 12. - DOUBLE LAYER COATINGS OF MoS_2.

as compared to about 200 hr for the same bearings sputtered only with a MoS_2 film. It should be acknowledged that this remarkable increase in endurance life is only applicable to rolling elements contact, but no sliding contacts.

Lubricants for Space Power and Aeropropulsion Systems

Aerospace machinery and energy efficient engines (adiabatic diesel, gas turbine and stirling) currently under development impose severe demands on the thermal/oxidative stability of lubricants, bearings and seal materials. The wide lubricating temperature range from ambient to 1000 °C in oxidative and corrosive environments with high loads and velocities create a severe tribological problem. For temperatures of 1000 °C and higher, metal bearings are being replaced by ceramics. These ceramics must either be self-lubricating or coated with a solid lubricant. Lubricants for high-temperature oxidative applications can be classified as follows:

(1) Ductile inorganic compounds: PbO, Cr_2O_3, B_2O_3, CaF_2, BaF_2
(2) Self-lubricating composite coatings: Ag-BaF_2/CaF_2 on metals
(3) Lubricious metal ion modified ceramics.

If one examines the maximum temperature capabilities, of presently known solid lubricants in Figure 13, it is clear that all of these lubricants have limitations in providing lubrication from ambient to high temperatures near 1100 °C. The organic polymers, layer lattice compounds and soft metals are effective lubricant below approximately 500 °C. The ductile inorganic compounds (oxides, fluorides) do not lubricate below 400 °C, but provide effective lubrication at the higher temperatures. To fill the existing need for a lubricant which can lubricate from a cold start condition up to the maximum operating temperature, a research program was conducted at NASA Lewis to develop self-lubricating composite coatings.

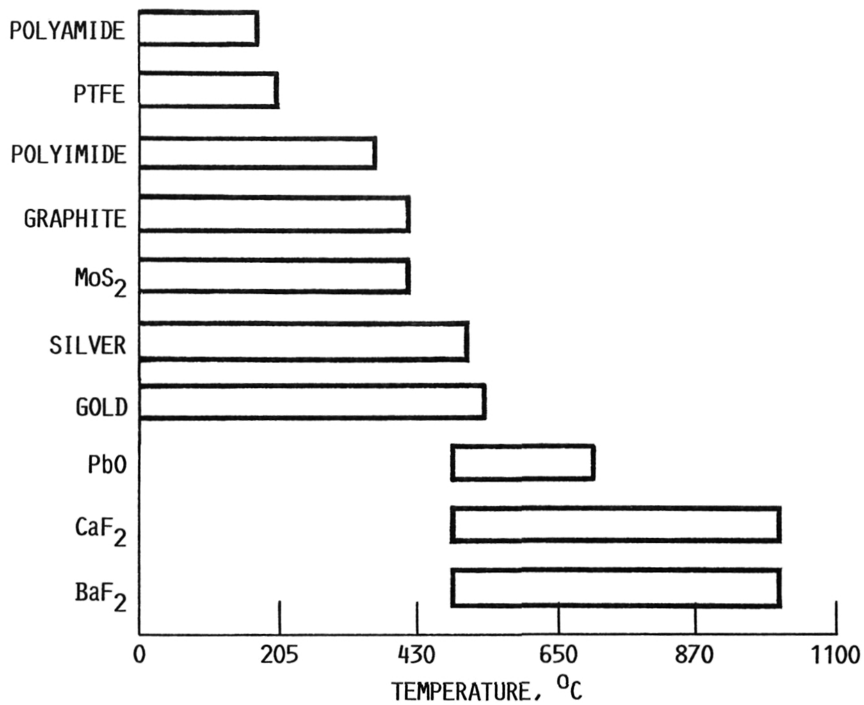


FIGURE 13. - COMPARISON OF THERMAL STABILITY OF SOLID LUBRICANT MATERIALS.

Self-Lubricating Composite Coatings

Development of the self-lubricating composite coating was based on the mixing of two or more solid lubricants to cover the whole temperature range [20-23]. For instance, the combination of stable fluorides and silver offered unexplored potentials. How temperature affects the microhardness and friction coefficients of these coating materials is shown in Figure 14. Silver is very soft at room temperature and is a good thin-film lubricant from ambient temperatures up to 500 °C. CaF_2 and BaF_2 does not lubricate below 400 °C but provide lubrication at the higher temperatures. During use Ag and the fluorides act synergistically and provide a low friction coefficient (0.2) over a wide temperature range, but have inadequate wear resistance for some long-duration applications. The wear resistance is dramatically improved by using a metal-bonded chromium carbide matrix dispersed with Ag and CaF_2/BaF_2 eutectic, which is designed PS200. The exact composition and the microstructure are shown in Figure 15. During plasma spraying of the composite coating the Ag and BaF_2/CaF_2 eutectic are dispersed throughout the metal bonded chromium carbide matrix. Ag alone is lubricative to about 500 °C, while the fluorides are lubricative from 400 to 900 °C. As a result, this composite coating lubricates from room temperature to 900 °C.

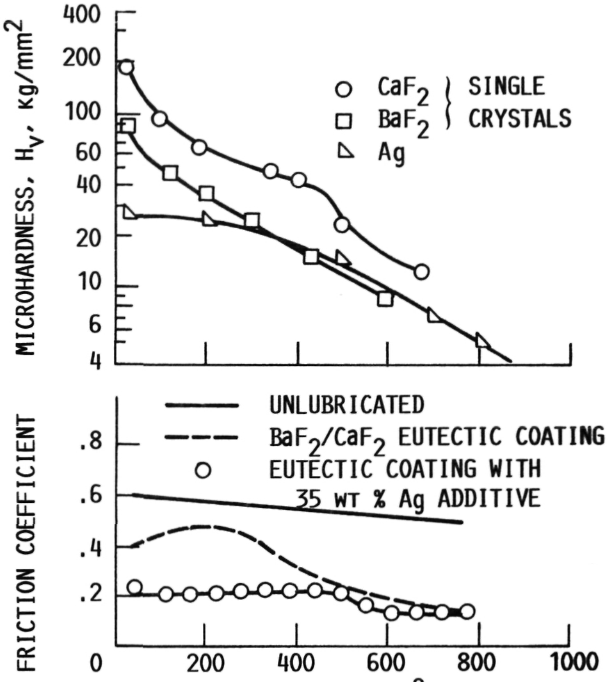
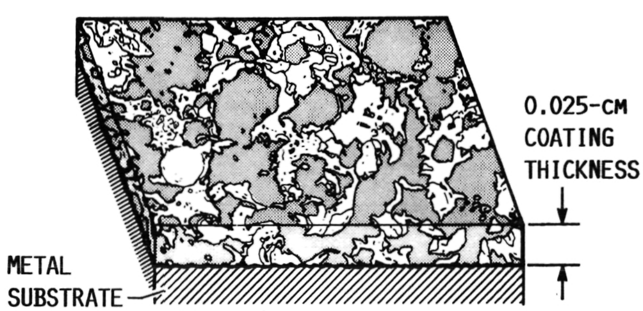


FIGURE 14. - EFFECT OF TEMPERATURE ON MICROHARDNESS AND FRICTION COEFFICIENTS OF COATING MATERIALS. (ACKN. H. SLINEY.)



COMPOSITION	FUNCTION
32% Ni ALLOY 48% Ca_3C_2	WEAR AND OXIDATION RESISTANCE
10% Ag	LOW-TEMPERATURE LUBRICATION
10% BaF_2/CaF_2 EUTECTIC	HIGH-TEMPERATURE LUBRICATION

- LUBRICATES IN AIR, HELIUM, OR HYDROGEN TO 900 ^oC

FIGURE 15. - PS200 - A PLASMA-SPRAYED COMPOSITE SOLID LUBRICANT COATING.

The basic materials properties needed in developing new self-lubricating composite coatings for a wide temperature range were established by the following characteristics: plasticity, low yield strength in shear, low hardness and thermochemical stability at the temperatures and in the environment of interest. Being a composite it can be tailored to a wide variety of required operational conditions by changing the formulation. The PS200 coating is presently applied by plasma spraying, but the ion assisted deposition techniques offer great promise for depositing and mixing the complex materials combinations with greater accuracy and control.

Lubricious Metal Ion Modified Ceramics

Ceramic coatings and ceramic tribo-components are finding use in an ever increasing number of aeropropulsion applications where the temperature has exceeded the high temperature capabilities of metals. In many of these applications the tribo-contacts are in an unlubricated state, due to the breakdown of conventional lubricants. Structural ceramics such as carbides (SiC, TiC) nitrides (Si_3N_4) and oxides (Al_2O_3, ZrO_2) are being increasingly used for machine elements in advanced low heat rejection engines. The successful use of these ceramics is often limited by tribological problems. While monolithic ceramic coatings mitigate wear, they generally have high friction coefficients. When low friction is required in addition to low wear some type of surface lubrication is necessary. For instance, the coefficient of friction can range from 0.2 for TiC against TiC in air, to over 0.8 for ZrO_2 against ZrO_2 in inert gas and the measured wear rates have been unacceptably high.

It is well established that the surface chemistry of the contacting ceramic tribo-components determines the tribological behavior of ceramics [24-25]. Tests conducted in high temperature oxidizing environments show the formation on wear surfaces of a thin oxide layer which subsequently can serve as a lubricant to reduce both the coefficient of friction and the wear rate. Forming soft oxide layers with low shear strength on ceramic surfaces may mitigate another problem, that of tensile stresses at the contact which can otherwise initiate cracks in the surface region. Thus, the critical load required to initiate surface-subsurface fracture of ceramics under sliding or rubbing conditions may be increased.

It has been shown that the high temperature tribological properties of ceramic surfaces can be favorably modified by ion beam techniques such as ion implantation and ion beam mixing [26-28]. The structural ceramics (Si_3N_4, SiC, ZrO_2) were ion implanted and ion beam mixed with Cr, Co, Ni or a double layer of Ti and Ni, and subsequently tribotested in a pin and disk configuration under oxidative conditions at a temperature of 800 °C. For certain of these material combinations the lubricious oxide films showed remarkable results.

The ion beam techniques offer the ability to modify the surface with essentially any metal ions and impose accurate controls on implantation/mixing depth and surface structure. The surface concentration profiles from implantation versus mixing depth for ion implantation and ion beam mixing are shown in Figure 16. At present the ion beam mixing technique may be more suitable for tribological surface modification, since the modified layer lies on top of the substrate, rather than below the surface.

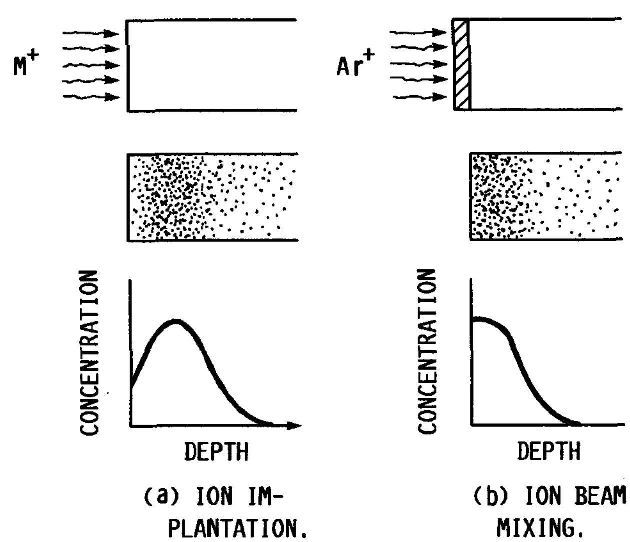


FIGURE 16. - SURFACE MODIFICATION BY ION BEAMS.

Of all the coated components, only Ti-Ni applied to Si_3N_4 and ZrO_2 disks by ion beam mixing showed a dramatic improvement in frictional properties when in sliding contact with a TiC rider. The friction results of the most promising combinations are shown in Table 1 [29]. The unmodified sliding couples displayed a high coefficient of friction, whereas the modified surfaces displayed coefficients of friction as low as 0.06 due to lubricious oxide formation in the 800 °C oxidizing environment. It should also be emphasized that the coefficient of friction is very sensitive to the precise nature of the selected sliding couples, and the test conditions.

TABLE 1. - COEFFICIENT OF FRICTION, μ_F, FOR ION IMPLANTED CERAMIC-CERAMIC PAIRS

[800 °C Oxidizing Environment, Ackn. Lankford, Wei, Kossowsky (Ref. 29).]

Rider	Disk, implant	μ_F
TiC	Si_3N_4 (Ti-Ni)	0.09
TiC cermet	Si_3N_4 (Ti-Ni)	.22
TiC	PSZ (Ti-Ni)	.25
TiC cermet	PSZ (Ti-Ni)	.06
TiC	PSZ (Co)	>.25
TiC cermet	PSZ (Co)	[a].06
TiC	Si_3N_4	.14
TiC	Unmodified Si_3N_4	-.6
TiC cermet	Unmodified PSZ	-.4

[a]Modified layer worn away.

Concluding Remarks

To meet the technological challenges of aerospace technology such as propulsion, power and sensitive spacecraft mechanisms it is imperative to create new, more durable and reliable tribo-materials which can withstand high temperatures, high vacuum and greater stresses and loads. To prevent tribological breakdown and consequent mechanical failures, the selection and mode of application of the proper lubricant or wear resistant coating is of paramount importance. The selection of an appropriate lubricant can be based on the operational conditions. On this basis, two categories of solid lubricants are distinguished. Lubricants essentially for vacuum and space environments and lubricants for high temperature oxidizing-corrosive environments.

In the application of lubricants to the components, most of the readily achievable advances have been made from the newly emerging ion assisted deposition/modification techniques. These techniques offer great flexibility and are capable of tailoring tribologically favorable surfaces with exceptionally good performance. With the ever increasing demand on tribo-systems to function under high temperature oxidative conditions, new approaches have been developed such as mixing, forming or synthesizing self lubricating composite or self forming lubricius oxide surfaces.

It is also important to emphasize that the monolithic ceramic surfaces in tribo-contacts need lubrication. In ceramic tribo-contacts to minimize tensile stresses, which eventually lead to microcracking, future tribomaterials or coatings may be fiber reinforced.

References

1. F.P. Bowden, D. Tabor: "Friction and Lubrication of Solids," Part I, Clarendon Press, Oxford (1950) 111.
2. D.H. Buckley: "Surface Effects in Adhesion, Friction, Wear, and Lubrication," Elsevier (1981) 324.
3. K. Miyoshi, D.H. Buckley, T. Spalvins: J. Vac. Sci. Technol. A 3 (1985) 2340.
4. T. Spalvins: ASLE Trans. 17 (1973) 1.
5. R.I. Christy: Thin Solid Films 73 (1980) 299.
6. T. Spalvins: Thin Solid Films 96 (1982) 17.
7. H. Dimigen, H. Hubsch, P. Willich, K. Reichelt: Thin Solid Films 129 (1985) 79.
8. B.C. Stupp: Thin Solid Films 84 (1981) 257.
9. P.D. Fleischauer: Thin Solid Films 154 (1987) 309.
10. T. Spalvins: J. Vac. Sci. Technol. A 5 (1987) 212.
11. D.M. Mattox: "Deposition Technologies for Films and Coatings," R.F. Bunshah, ed., Noyes Publishing (1982).
12. T. Spalvins: J. Vac. Sci. Technol. 17 (1980) 315.
13. A. Mathews: J. Vac. Sci. Technol. A 3 (1985) 2354.
14. T. Spalvins: "Ion Plating and Implantation: Applications to Materials," R.F. Hackman, ed., American Society for Metals, Metals Park, OH (1985) 39.
15. K. Parker: Vacuum 37 (1987) 303.
16. M.J. Todd: Tribol. Int. 15 (1982) 331.
17. K. Miyoshi, T. Spalvins, D.H. Buckley: Thin Solid Films 108 (1983) 199.
18. T. Spalvins, B. Buzek: Thin Solid Films 84 (1981) 267.
19. T. Spalvins: NASA TM X-3193 (1975).
20. H.E. Sliney: J. Vac. Sci. Technol. A 4 (1986) 2629.
21. C. Della Corte, H. Sliney: ASLE Trans. 30 (1986) 77.
22. C. Della Corte, H.E. Sliney: Lubr. Eng. 44 (1988) 338.
23. H.E. Sliney: NASA TM-100276 (1988).
24. D.H. Buckley, K. Miyoshi: Ceram. Eng. Sci. Proc. 6 (1985) 919.
25. C.S. Yust: Int. Met. Rev. 30 (1985) 141.

26. J. Lankford, W. Wei, R. Kossowsky: J. Mater. Sci. 22 (1987) 2069.
27. W. Wei, J. Lankford: J. Mater. Sci. 22 (1987) 2387.
28. W. Wei, J. Lankford, R. Kossowsky: Mater. Sci. Eng. 90 (1987) 307.
29. W. Wei, J. Lankford, I. Singer, R. Kossowsky: to be published in Thin Solid Films (1988).

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No.
NASA TM-101304

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Status and Directions of Modified Tribological Surfaces by Ion Processes

5. Report Date

6. Performing Organization Code

7. Author(s)
Talivaldis Spalvins

8. Performing Organization Report No.
E-4294

10. Work Unit No.
505-43-11

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Memorandum

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared for the First International Conference on Plasma Surface Engineering sponsored by Deutsche Gesellschaft für Metallkunde, Garmisch-Partenkirchen, Federal Republic of Germany, September 19-23, 1988.

16. Abstract
The purpose of this paper is to present an overview and recent advances in modifying contacting surfaces in motion by the various ion assisted surface coating/modification processes to reduce and control tribological failures. The ion assisted coating processes (sputtering, ion plating) and the surface modification processes (ion implantation, ion beam mixing and ion nitriding) offer the greatest potential to custom tailor and optimize the tribological performance. Hard, wear resistant and low shear coatings deposited by the ion assisted processes will be discussed. Primarily the recent advances of sputtered MoS_2 ion plated Au, Ag, Pb lubricating films and sputtered and ion plated hard, wear resistant TiN, HfN, TiC films will be described in terms of structural-property-performance interrelationships which lead to improved adhesion, cohesion, nucleation, morphological growth, density, film thickness as determined by structural and chemical characterization and frictional and wear behavior. Also, the recent tribological advances using the surface modification proceses such as ion implantation, ion beam mixing will be discussed with emphasis on the development of lubricious high temperature ceramic surfaces.

SOLID LUBRICANTS
ION PLATING
LUBRICATION
SPUTTERING
METAL FILM

TRIBOLOGY
SURFACE FINISHING
WEAR RESISTANCE
CERAMICS

17. Key Words (Suggested by Author(s))
Solid lubricants
Sputtering
Ion plating
Lubrication

18. Distribution Statement
Unclassified – Unlimited
Subject Category 31

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	22	A03

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161

National Aeronautics and
Space Administration

Lewis Research Center
Cleveland, Ohio 44135

Official Business
Penalty for Private Use $300

FOURTH CLASS MAIL

ADDRESS CORRECTION REQUESTED

U.S.MAIL

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA 451

NASA