THE ADVANTAGES AND LIMITATIONS OF SPUTTERED MOLYBDENUM DISULPHIDE AS A SPACE LUBRICANT.

E W Roberts
European Space Tribology Laboratory
AEA Technology, Risley
Warrington, Cheshire, U.K.

ABSTRACT

It is well established that thin films of molybdenum disulphide produced by the technique of sputtering can bring about remarkably low friction under vacuum. However the tribological properties of such films are highly sensitive to the conditions under which they are employed. These conditions, which encompass such variables as load, sliding speed and vacuum pressure, can be such as to preclude ultra-low-friction behaviour. The purpose of this paper is to examine critically the triblogical properties of sputtered MoS_2 under the varied conditions of operation likely to be experienced in space and from this basis arrive at an understanding of its advantages and limitations as a spacecraft lubricant.

Keywords: dry lubrication, molybdenum disulphide, vacuum lubrication, thin solid films, spacecraft mechanisms.

1. INTRODUCTION

Films of molybdenum disulphide produced by the technique of sputtering are exceptional in that, in vacuum, they can give rise to ultra-low friction (ULF). That is to say they can confer friction coefficients in the order 0.01. By any criterion, this is an extremely low level of friction and one which is appreciably lower than that obtainable with other solid lubricants. Sputtered molybdenum disulphide thus offers the prospect of spacecraft components in which frictional losses are minimal and the attendant frictional noise exceptionally low.

That is the prospect, but in reality this simple picture is made complex by MoS_2's sensitivity to operating conditions. Thus detailed tribological measurements indicate that the frictional properties of sputtered molybdenum disulphide are strongly dependent on such factors as contact load, sliding speed, continuity of operation and the gaseous composition of the vacuum environment in which the film is operated. It is only when the combination of these factors is favourable that true ultra-low friction is obtained and only in these circumstances therefore can it be exploited.

A fundamental limitation of any thin, solid film lubricant is its finite lifetime. Despite exhibiting comparatively long durability under pure sliding, sputtered molybdenum disulphide's limited lifetime places constraints on its uses in spacecraft. Furthermore the film endurance of sputtered molybdenum disulphide, as is the case with its frictional properties, is observed to be dependent on load and gaseous environment.

The purpose of this paper is to indicate the advantages of sputtered molybdenum disulphide and to identify and clarify its present limitations as a spaceraft lubricant. The approach taken will be to describe the fundamental, tribological properties of sputtered MoS_2 and how these vary with operating conditions. The implications that these effects have with regard to the suitability of employing sputtered MoS_2 for a given application are then discussed.

It is important to realise that whilst sputtered molybdenum disulphide does currently have limitations, a great deal of research work is being undertaken to devise ways of overcoming these shortcomings. In particular, several methods of enhancing the durability of MoS_2 films have been developed which should lengthen the lifetime of tribological components lubricated with sputtered MoS_2. These recent advances will be discussed.

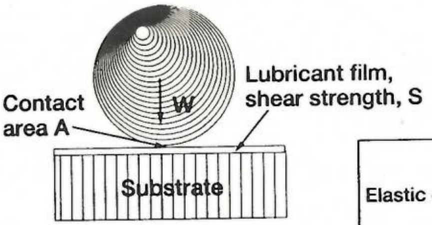
2. SPUTTERED MoS_2: HOW IT LUBRICATES.

2.1 Friction of thin, solid films.

Two fundamental criteria must be met in order to obtain low friction using solid lubricants. These are: (a) the lubricant must be applied to substrates which are hard (or have a high elastic constant) and (b) the lubricant must be applied in the

Fig. I

Principle of thin, solid film lubrication



$$F = S.A$$
$$F = \mu.W$$
$$\therefore \mu = \frac{S.A}{W}$$

Elastic deformation, $\mu = \frac{S.\pi}{W^{1/3}}\left(\frac{3R}{4E'}\right)^{2/3}$

Plastic deformation, $\mu = \frac{S}{H}$

form of thin (sub-micron) films. The need for these requirements can be understood by reference to Fig. 1. This depicts a flat, smooth substrate coated with a thin, solid lubricant. A ball is loaded against the coated face of the substrate (normal load, W) and is made to slide along it without rolling.

In the absence of a ploughing contribution the frictional resistance to motion arises from the adhesion between the ball and its counterface. This frictional force can be equated to the product of the the shear strength of the film (S) and the contact area (A). A simple expression for the friction coefficient can be derived from this relationship (Fig.1) which indicates that the friction coefficient is directly proportional to the product of the shear strength of the film and the contact area, and inversely proportional to the load. The contact area will be determined by the deformation characteristics of the ball and substrate (the deformation properties of the film need not enter the calculations since the film is too thin to contribute significantly to load carrying). Deformation will be either elastic (Hertzian) or plastic and expressions for the friction coefficient expected in both cases are given in Fig.1.

From these equations it becomes clear that in order for the solid lubricant to confer low friction then the following conditions must apply:

a) the film must have a low shear strength, S.
b) the film must be applied in the form of a thin film so that the load is supported by the ball and substrate.
c) the ball and substrate must be made from hard materials or materials of a high elastic constant.

2.2 Durability of thin, solid films.

We have identified above the conditions needed to bring about low friction. However a second and equally important requirement of the solid film is that of high durability. Of primary importance here is the adhesion of the film to the substrate, for if the film is poorly adhered then, under the actions of contact stresses, it will quickly be removed and lubrication will be lost. The means by which the film is applied and the nature of the substrate material are factors which affect adhesion. These factors are described below.

2.3 Friction and durability of sputtered MoS_2.

Since molybdenum disulphide has a low shear strength its potential as solid lubricant is high provided it can be deposited in the form of a thin film which can be made to adhere well to hard substrates.

The technique of sputtering is a means by which these two conditions can be fulfilled. Sputtering is a plasma-assisted, PVD (physical vapour deposition) technique in which film growth occurs atomistically. Adhesion is strong where atoms of molybdeum and sulphur form a chemical bond with the substrate - as is the case when MoS_2 is sputter deposited onto bearing steels (see below). Such bonding is further encouraged by cleaning the substrate by ion-etching (sputtering allows this) prior to film deposition. Sputtering also enables deposition to be carried out in a controlled manner, such that films of sub-micron thickness can be reproducibly produced. Because of their good adhesion to bearing steels, sputtered films of MoS_2 are tribologically superior (in vacuo) to films of MoS_2 produced either by burnishing or by using bonded spray techniques (Ref.1).

There exist several modes of sputtering (D.C; R.F; triode; magnetron), all of which can be employed to produce MoS_2 films. It is important to realise that films produced by different sputtering techniques may show differences in tribological behaviour (Ref. 2) which are not insignificant. For the purposes of this paper we will restrict our comments to films produced by the technique of magnetron sputtering, as employed at ESTL.

This affords higher deposition rates than that obtainable with other sputtering techniques.

3. FACTORS AFFECTING EFFICACY OF SPUTTERED MoS_2 LUBRICATION.

In assessing the tribological behaviour of sputtered MoS_2 and how this is affected by operating conditions, we are principally concerned with two parameters, namely friction coefficient and film durability. Below we examine how these two properties are influenced by substrate compatibility, environment and the mechanics of rubbing contacts.

3.1 The importance of substrate compatibility.

Following the arguments developed in section 2 it is to be expected that the substrate material will be instrumental in determining the friction and endurance of MoS2 films applied to it. This in fact is the case and can be illustrated by reference to Fig.2. In this, plots are shown of friction coefficient versus disc revolutions (as measured in a pin-on-disc apparatus in vacuum) of sputtered MoS_2 films applied to several bearing materials: a titanium alloy, two types of bearing steel (440C and 52100) and a hot-pressed silicon nitride. These results confirm that film friction is dependent on the deformation properties of the substrates in that the highest friction is observed when MoS_2 is applied to the titanium alloy (the softest of the four materials) whilst the lowest friction occurs when the lubricant is applied to silicon nitride, the hardest of the four substrates.

Fig.2 also demonstrates the very strong dependence of film durability on substrate material. Thus film endurance on silicon nitride is over two orders of magnitude longer than that of MoS_2 films applied to the titanium alloy. Evidence (Ref.1) that variations in film adhesion are responsible for these differences in endurance was obtained recently. This evidence showed that molybdenum and sulphur atoms do not bond strongly to the titanium alloy and hence adhesion is poor. MoS_2 bonding to steels and silicon nitride was demonstrated to be stronger, hence the longer film durabilities associated with MoS_2 films applied to such substrates.

3.2 The effect of environment.

It follows from the equations of friction derived in Fig.1 that if S, the shear strength of the lubricant film, is increased then a proportionate increase in friction coefficient results. Unfortunately the shear strength of MoS_2 is greatly increased when exposed to water vapour and indeed it is well documented (Ref.3) that the friction coefficient of MoS_2 in humid air (0.15 to 0.3) is considerably greater than that in vacuum. Whilst films run in humid air can recover their low friction properties in vacuum, the in-vacuo durability of such films is reduced such that the longer the "air-running" then the shorter the subsequent "in-vacuo" endurance. For this reason it is preferable not operate MoS_2 films at all in moist atmospheres.

The effects of water adsorption persist, albeit to a much lesser extent, under vacuum conditions. This arises because H_2O is usually the principal gaseous species within mechanisms on orbitting spacecraft (see for example Ref.4). This means that, even in the vacuum environment of spacecraft, very small, but influential, amounts of water vapour can be adsorbed by the MoS_2. This effect gives rise to a phenomenon which we have labelled the "dwell" effect. Thus, for example, it is observed (Ref.5) that when molybdenum disulphide films are allowed to dwell (that is, not subjected to sliding for a defined period) in high vacuum the friction coefficient is higher on recommencement of sliding (e.g friction coefficient on starting can be about four times higher than "run-in" value). This increase in starting friction is thought to result from the adsorption of sub-monolayer quantities of water molecules (Refs.3,5). With continued sliding these molecules are eventually removed (probably by friction-induced heating causing thermal desorption) and the friction coefficient decreases. The influence of water adsorption on MoS_2 lubricity is also thought to be responsible for the effect of sliding speed on film friction (see section 3.3 below).

In addition to being exposed to vacuum, spacecraft mechanisms are subject to large temperature fluctuations, ranging from cryogenic temperatures to several hundred Kelvin. It is observed that sputtered MoS_2 maintains its good lubricating properties in vacuum over an exceptionally wide range of temperatures. Indeed, recent results (Refs.6,7) indicate that its low-friction properties are conserved even at temperatures as low as 20K. Elsewhere (Ref.8) it is reported that molybdenum disulphide remains stable under vacuum up to about 1400K.

3.3 Contact load and sliding speed.

Finally, we need consider two other effects that bear on the tribological behaviour of sputtered MoS_2 in vacuum. These are the effects of contact load and sliding speed.

The equations of Fig.1 predict that, for elastically loaded contacts, friction coefficient should decrease with increasing load and indeed experiments confirm that this does occur (Ref.5). Increasing the contact load decreases the film lifetime in a manner that suggests that film durability varies with the inverse of load (Ref.5).

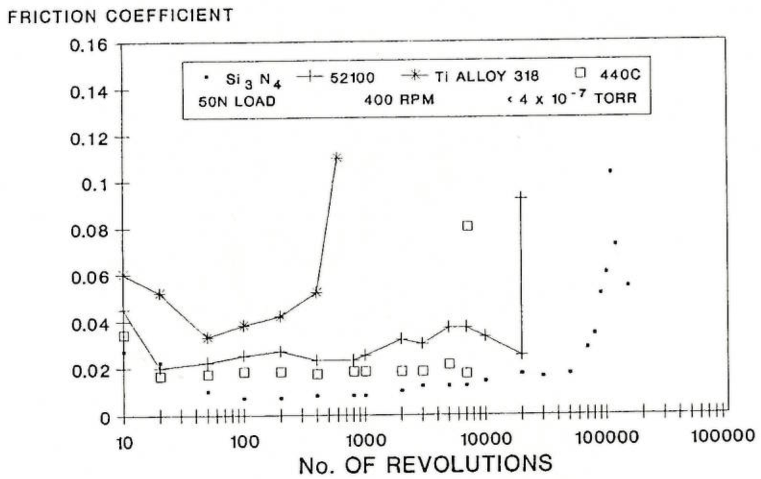


FIG. 2 : PIN ON DISC TESTS
MoS_2 ON VARIOUS SUBSTRATES

Table I

Advantages and Limitations of sputtered MoS_2

ADVANTAGES

- Low friction in vacuum and ULF achievable under favourable conditions
- Large temperature range of operation
- Long endurance under pure sliding

LIMITATIONS

- ULF not achieved at low loads and sliding speeds
- Friction higher after dwell in vacuum
- Friction increases with partial pressure of H_2O
- Finite film lifetime

The in-vacuo, friction coefficient of MoS_2 films is in general indedependent of sliding speed. However at very low speeds a dependency is observed in that the friction coefficient increases from 0.01 to about 0.04 (Ref.5). The effect has been attributed - as with the dwell effect - to water adsorption, the frictional heat generated at the low speeds involved being insufficient to desorb any adsorbed species.

4. ADVANTAGES AND LIMITATIONS

We are now in a position to identify the strengths and weaknesses of sputtered MoS_2 lubrication. And below we address what can be considered its advantages and limitations. Our observations are summarised in Table 1.

4.1 Advantages

It seems clear that a principal advantage of using sputtered MoS_2 as a lubricant in vacuum is its ability to reduce friction to levels which are lower than those obtainable with other solid lubricants. In general MoS_2 films applied to bearing steels give rise to friction coefficients which lie in the range 0.01 to 0.05. These values compare favourably with those obtained with lead films (0.1-0.25) (Ref.9) and PTFE (0.05-0.2). A further advantage is that sputtered MoS_2 maintains its lubricating properties over a range of temperature that is sufficiently wide to encompass most thermal conditions encountered in space. Additionally, sputtered MoS_2 exhibits comparatively long endurances when subjected to pure sliding motion (such films, for example, have durabilities which are appreciably greater than those of lead films).

4.2 Limitations

There is little doubt that sputtered MoS_2 is an excellent vacuum/space lubricant. However it is important that mechanism designers are made aware that whilst low friction is obtained in vacuum, ULF is only achievable when the conditions are favourably disposed (Table 1).

The sensitivity of MoS_2 to water vapour is at its most acute in humid air and this precludes all but the shortest period of in-air testing. Thus ground testing on MoS_2-lubricated components should be undertaken either in vacuum or in an inert atmosphere. This is undoubtedly seen by design and test engineers as a disincentive to lubricate components with MoS_2. However this is a guideline which must be observed if the full benefits of sputtered MoS_2 are to be realised.

The tendency of MoS_2 to exhibit a higher starting friction under vacuum (due to the dwell effect) means that applications involving intermittent operation cannot benefit from full ultra-low-friction lubrication.

A further limitation is finite film durability but this is a limitation of any thin, solid film lubricant. In fact, in this respect the durability of sputtered MoS_2 is good and compares very favourably with other solid films lubricants.

5. APPLICATIONS

5.1 Where motion is pure sliding.

Components whose surfaces are exposed to pure sliding include: cams, slides (Ref. 10), journal bearings (Ref.11), collars and screws. Such components are employed on latching mechanisms, deployment devices, solar array drive mechanisms and pointing mechanisms.

Since the performance of sputtered MoS_2 under pure sliding is superior to that of other thin, solid film lubricants (such as lead) then its employment in the above applications is to be recommended where substrate compatibility does not pose a problem. Furthermore because a substantial amount of data exists on sputter-deposited MoS_2 operating under purely sliding motion it should be possible to predict with reasonable accuracy the frictional forces generated in these various applications.

Devices such as latches and deployment mechanisms are often employed on a "one-shot" basis i.e in practice they are required to operate once and then only briefly. Under these conditions sputtered MoS_2 will not, in general, give rise to ultra-low friction (because of the "dwell" effect in vacuum) but will nevertheless provide low friction, the actual frictional forces being determined by contact loads and rubbing speed.

The wear of components subjected to fretting can be reduced through sputtering MoS_2 onto one of the counterfaces. MoS_2 has been shown to be a much more effective coating against fretting wear than coatings of soft metal films (Ref.12).

5.2 Where motion is sliding and rolling.

The low-friction properties of sputtered MoS2 can be used to bring about low torque in ball bearings (Ref.3) and high transmission efficiencies in gears (Ref.13). However the tribological behaviour of such lubricated components is rather difficult to predict.

In bearings this arises because calculations of bearing torque are made difficult by the dependence of MoS2 friction on load and sliding speed (in the ball-race microslip region slip occurs at different rates and therefore no single value of friction coefficient applies). At best one can obtain a spread of calculated torque values corresponding to a range of friction coefficients measured in a pin/disc apparatus. For this reason it is preferable where possible to measure the torque of individual components prior to their incorporation in a mechanism.

TABLE 2

TECHNIQUES FOR IMPROVING MoS2 FILM DURABILITY.

TECHNIQUE	LIFE ENHANCEMENT	REFERENCE
OPTIMISED SURFACE TEXTURE	up to x10	14
ION-BEAM MIXING	up to x5	15, 16
DOPED FILMS	up to x2	17
INTERLAYER (e.g TIN)	up to x10	18
LASER IRRADIATION	?	-

At present ball bearings lubricated with sputtered MoS2 have relatively short lives. Thus for example (ref.5) ED20 angular-contact ball bearings fitted with MoS2-coated steel cages and subjected to an axial load of 40N exhibit lifetimes of between 1 and 6 million revolutions (the actual lifetime depends on whether the balls are coated in addition to the races). Thus whilst such bearings exhibit very low torque, this can only be exploited in applications of short duration or low duty. The replacement of steel cages with PTFE/MoS2 composite cages lengthens lifetime appreciably (about tenfold) and experiments indicate that the low-torque performance is maintained. But there remains the possibility that lumpy transfer of PTFE might cause the development of higher torque spikes.

6. THE FUTURE: HOW LIMITATIONS MAY BE OVERCOME.

As we have seen, the useful lifetime of components lubricated with sputtered MoS_2 is limited by the durability of the film itself. This arises because wear-out of the film occurs much sooner than failure due to other causes such as tribo-component fatigue. It follows that if the durability of MoS_2 films could be increased then their range of application would broaden accordingly.

There are currently several lines of investigation which have this aim in mind. The approach taken is to seek improvements in film durability by modifications carried out to the substrate surface, the substrate/film interface or the bulk of the film itself.

As Table 2 indicates, significant enhancements in durabilities have been effected by: changing the surface texture of the substrate to which the film is applied (surface modification); penetrating the film with high energy ions so as to mix the atoms located at the interface (interface modification); and doping films by co-deposition with metals (bulk modification). Other techniques being investigated are the use of thin, hard interlayers (such as TiN) and exposure of films to pulsed lasers.

Whilst the above technologies are still under development it seems clear that they undoubtedly hold the promise of MoS_2 films with appreciably enhanced lifetimes. This, in turn, will broaden the range of applications which can benefit from the unique low-friction properties of this material.

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