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Frictional and Morphological Characteristics of Ion Plated Soft, Metallic Films

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FRICTIONAL AND MORPHOLOGICAL CHARACTERISTICS OF ION PLATED SOFT, METALLIC FILMS

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ABSTRACT

Ion plated metallic films in contrast to films applied by other deposition techniques offer a lower friction coefficient, longer endurance lives and exhibit a gradual increase in friction coefficient after the film has been worn off. The friction coefficients of metallic films are affected by the degree of adherence, thickness and nucleation and growth characteristics. The effective film thickness for the minimum friction coefficient was established for Au and Pb films. The nucleation and growth characteristics during ion plating lead to a fine, continuous crystalline structure, which contributes to a lower friction coefficient.

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INTRODUCTION

The friction between two sliding, rotating or rubbing surfaces is governed by the adhesion theory of friction where the frictional force (F) is determined by the shear strength (s) and the real area of contact (A), namely $F = As$. To obtain low friction between two sliding surfaces A or s or both should be small. This means that tribological materials of high hardness and low shear strength are most suitable. However, this is not possible in practice - metals of high hardness always have high shear strengths. Consequently, the application of thin layers of soft metallic films on a hard surface is one of the alternatives.

Thin ion plated metallic lubricating films such as gold and lead have been shown to perform better than thermally evaporated ones, particularly in spaceborn bearings of satellite mechanisms such as solar array drives, de-spin assemblies and gimbals. The ion plated films for these applications have definite advantages in that they give reduced coefficients of friction and wear, and extended endurance life. They also alter the mode of debris generation and reduced torque noise (refs. 1 and 2).

When two surfaces are brought together in relative motion, the frictional force arises from asperity deformation, adhesion and the plowing of the film and wear debris. A simple approach to the sliding process indicates, that the lower the shear strength of the soft metallic film and higher hardness of the substrate the lower the friction. During sliding, the normal load is supported by the real area of contact under the pressure (p) whereas the tangential force will be governed by the shear strength (s) of the thin, soft metallic film. As a result the friction coefficient is defined as $\mu = s/p$. The extent to which the coefficient of friction can be lowered depends primarily upon film thickness, surface roughness, degree of localized deformation, mechanical properties of the film relative to those of its substrate and the deposition technique

Thin, soft metallic film lubrication is effective for wear reduction when adhesive wear predominates, but is of little value in abrasive wear, therefore the most important requirement is strong adherence. Ion plated metallic films have exceptionally strong adherence which is attributed to a gradual film/substrate transition regardless of film/substrate compatibility. It is well known that the friction of thin metallic films is affected by shear strength, thickness, surface hardness and roughness. It is also influenced by physicochemical phenomena such as oxidation and diffusion under certain sliding conditions (refs. 3 to 5).

The objective of this paper is to explain the improved tribological characteristics of ion plated films of gold and lead in terms of adherence and surface strengthening effects, film thickness, nucleation and growth characteristics. The friction tests were conducted in vacuum with highly polished 440C stainless steel surfaces, in a pin and disk specimen configuration.

EXPERIMENTAL PROCEDURE

The ion plating chamber used in this study has been previously described (ref. 6). The plating conditions used are those most commonly encountered in commercial ion plating. A negative potential of 3-5 kV was applied to the specimen with a substrate current density of 0.3-0.8 mA/cm^2 in argon at a pressure of 20 m Torr. The specimen-to-boat distance was 10 cm, and the specimens were 440C stainless steel disks 6.4 cm in diameter with a hardness of $R_c = 55$. The surfaces were polished by standard metallographic techniques to a surface finish of about 0.02 μm CLA (centerline finish). Before ion plating, the surfaces were cleaned by d.c. sputtering for 10 minutes. Films of Au and Pb ranging in thickness from 0.02 to 10 μm were ion plated onto the highly polished steel surfaces. The film thickness was obtained either by sectioning and microscopic measurement or for films less than 1 μm by interference microscopy.

Friction testing of the ion plated films was done in a vacuum pin and disk apparatus with a 400C stainless steel pin (4.75-mm-radius) sliding on a ion plated disk. The friction tests were conducted at a constant speed of 1.52 m/min and a normal load of 2.45 N in a vacuum of 2×10^{-3} Torr.

RESULTS AND DISCUSSION

Adhesion and Surface Strengthening Effects

The primary requirement for effective thin film lubrication is strong adherence. Ion plated films provide such an adherence and have an unusual ability to withstand interfacial stresses. The excellent adherence is attributed to the vapor flux consisting of a small portion of energetic ions and large portion of energetic neutrals, which have a kinetic energy distribution from thermal up to the voltage applied to the discharge. The average energy of ions and neutrals were estimated to be of the order of 100 eV (ref. 7).

The graded interface which is formed is not only responsible for the excellent adherence, but also affects the mechanical behavior, due to a structural alteration of the crystal lattice in the surface and subsurface regions and the subsequent effects of dislocation interactions. The surface strengthening effects are basically blocking mechanisms, in which the coating acts as a barrier to the egress of dislocations near the surface. The film strengthening effects are shown in figures 1(a) and (b), where a 2000 Å thick ion plated copper film increases the yield, tensile, and fatigue strength accordingly.

FILM THICKNESS EFFECTS

Thin metallic film lubrication is basically due to the shear or displacement which takes place between the soft layers and not between the substrate surfaces. However, the film thickness has a very pronounced effect on the coefficient of friction as was first shown by Bowden and Tabor with vapor deposited thin films of indium on tool steel, with a minimum friction being achieved with a film approximately 1000 to 10,000 Å in thickness (ref. 8). Very few experimental studies are reported with the soft metallic films with respect to thickness effects on the friction coefficient. In this investigation the thickness effects on the friction coefficient of ion plated Au and Pb films were investigated, and the results are shown in figures 2(a) and (b). The effective film thickness for Au films was 2000 to 3500 Å and they displayed a friction coefficient of 0.1, whereas effective Pb films were 1800 to 2500 Å in thickness and displayed a coefficient of friction of 0.085.

Based on the friction coefficient, the variation of film thickness can be divided into two regions as shown in figure 3. The ultra thin and the thin film region with an effective or critical film thickness at which the friction coefficient reaches a minimum value. In the ultra thin region the increase in the friction coefficient is associated with a breakthrough in the film by mating asperities. In the thin film region, as the film thickness increases the load carrying capacity of the substrate surface decreases and an increase in the apparent area of contact leads to a higher friction coefficient. The relationship between the critical film thickness and the minimum friction coefficient is affected by the surface roughness and the deposition technique selected. With rough surfaces the friction coefficient increases continuously as the film thickness increases without going through a minimum (ref. 4).

The ion plated soft films displayed a somewhat lower friction and minimum, and have a lower friction coefficient at a lower film thickness when compared to films deposited by other depostion techniques.

Nucleation and Growth Characteristics

In ion plating the evaporant flux of energetic ions and neutrals transfer energy, momentum and charge to the substrate and the depositing film surface. These effects produce several unique nucleation and growth characteristics as determined by transmission electron microscopy (TEM). Standard copper mesh grids coated with thin, continuous carbon films were ion plated and vapor deposited with gold and lead films and examined by TEM. Typical TEM micrographs of ion plated Pb film in the initial stages of nucleation are shown in figures 4(a) and (b). A high degree of uniformity exists in the network of island formation. The islands are packed with small crystallites 30-60 Å in size, and the space between the islands consists of even smaller crystallites (10–30 Å) and are less dense as shown in figure 4(b). The nucleation and growth characteristics of a typical vapor deposited Pb film is shown in figure 5. A comparison of the micrographs of figures 4(b) and 5 reveal a pronounced difference in the formation of the nucleation islands, in terms of size and symmetry. As a result the microstructure for ion plated Pb films consists of a fine uniform crystallite structure where the vapor deposited film has a high degree of non-uniformity in the crystallite size and shape. A similar effect is shown by Au in figures 6(a) and (b). Surface diffusion apparently plays a much smaller part during ion plating. It is well known, that low adatom mobility leads to amorphous or fine grained structure. During ion plating, the evaporant ions and energetic neutrals have a strong surface interaction thereby limiting the surface mobility and at the same time increasing nucleation density which leads to accelerated nucleation growth and coalescence by the nuclei. As a result, these factors contribute to a continuous film formation with a minimum degree of lattice misfit at lower nominal thickness.

FRICTION CHARACTERISTICS

The ion plated lubricating metallic films always show better performance than the vapor deposited ones in terms of a lower friction coefficient, longer endurance life and lower wear. Typical friction curves for ion plated and vapor deposited films about 2100 Å thick are shown in figure 7. The increased endurance life of the ion plated film is attributed to the excellent adherence. Films which are not ion plated, generally do not possess such a strong adherence and do not have a graded interface, and will display a film failure by peeling and chipping. The lower friction coefficient can be attributed to the small crystalline size, shape and the increased cohesive strength. It has been also observed that the ion plated metallic films have a more gradual increase in the friction coefficient once it has worn through the film. As a result, catastrophic or abrupt failures are not observed with the ion plated films. This can be explained in terms of the graded interface which prevents an abrupt seizure.

CONCLUSIONS

The tribological characteristics such as the friction coefficient and endurance life of ion plated Au and Pb films were investigated in terms of film adherence, thickness, nucleation and growth characteristics. The film thickness effects for Au and Pb films on the friction coefficient were established. A minimum friction coefficient was determined for each critical film thickness. The nucleation and growth characteristics during ion plating are influenced by the increased nucleation density which leads to the formation of a fine, continuous grain structure. Ion plated gold and lead films display a lower friction coefficient and longer endurance lives when compared to vapor deposited Au and Pb films.

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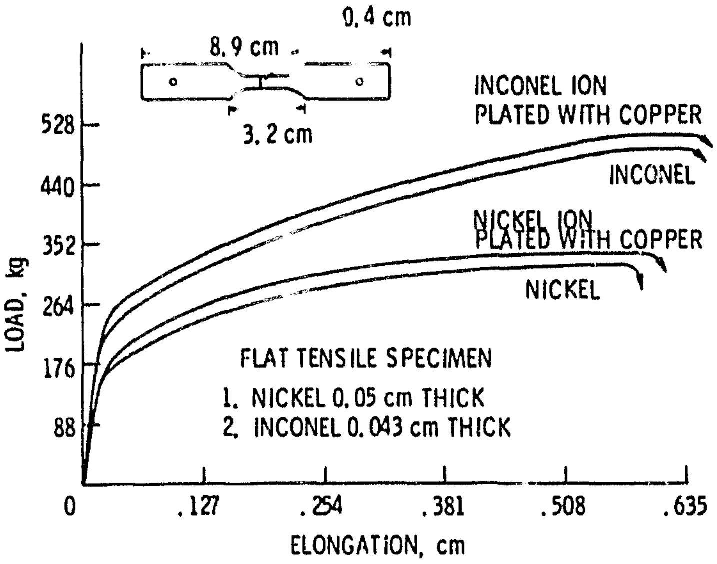


Figure 1(a). - Load elongation curves during tensile tests.

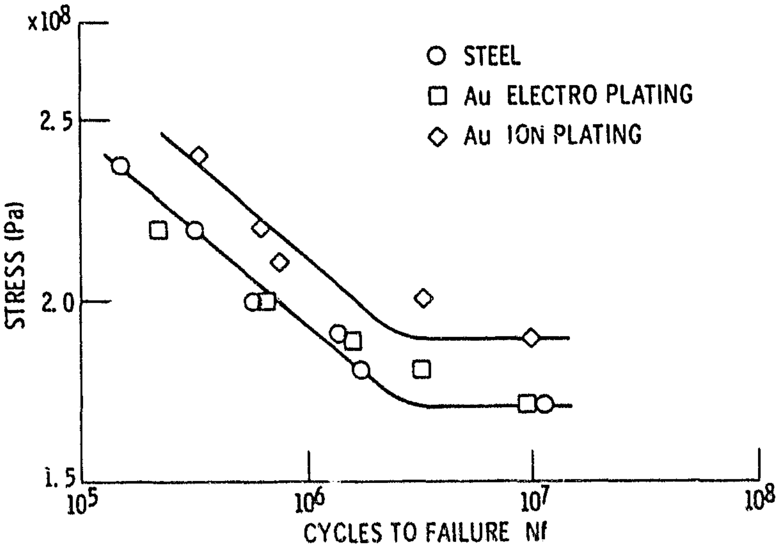


Figure 1(b) - Effect of ion plating on the fatigue property of low carbon steel

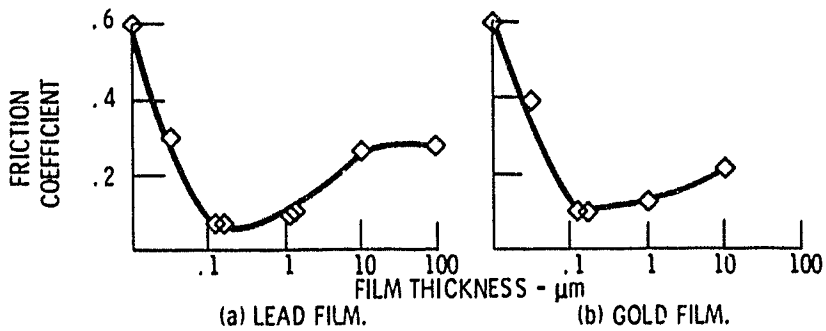


Figure 2. - The variation of friction coefficient with film thickness.

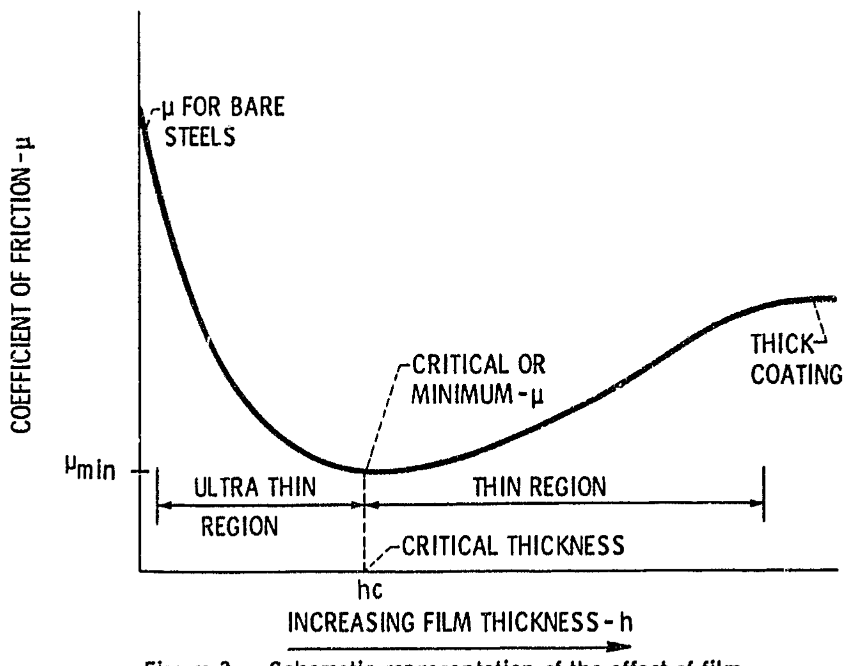


Figure 3. - Schematic representation of the effect of film thickness on the friction coefficient of low shear strength metallic films on steel.

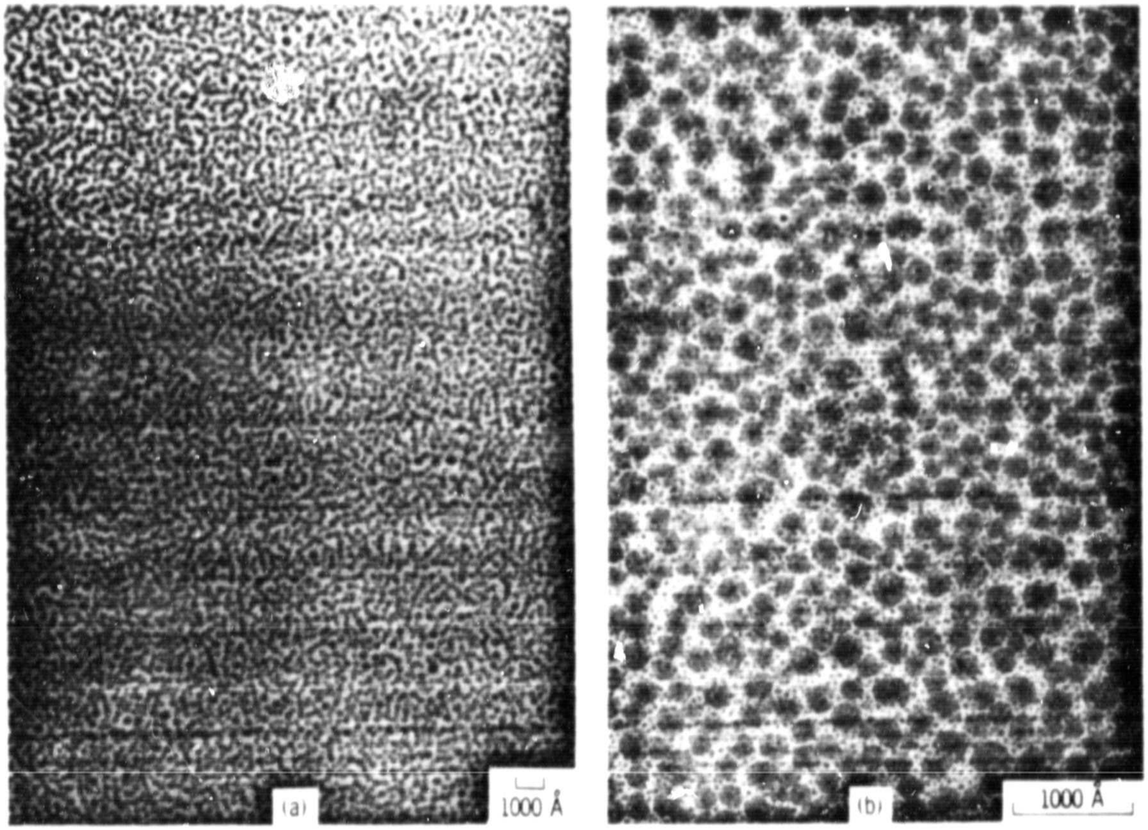


Figure 4. - TEM micrographs of ion plated lead film in the early stages of nucleation.

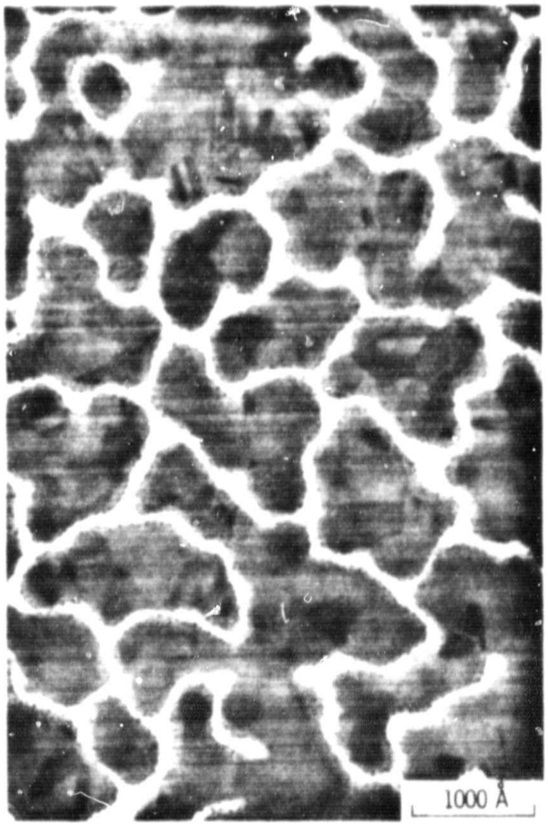
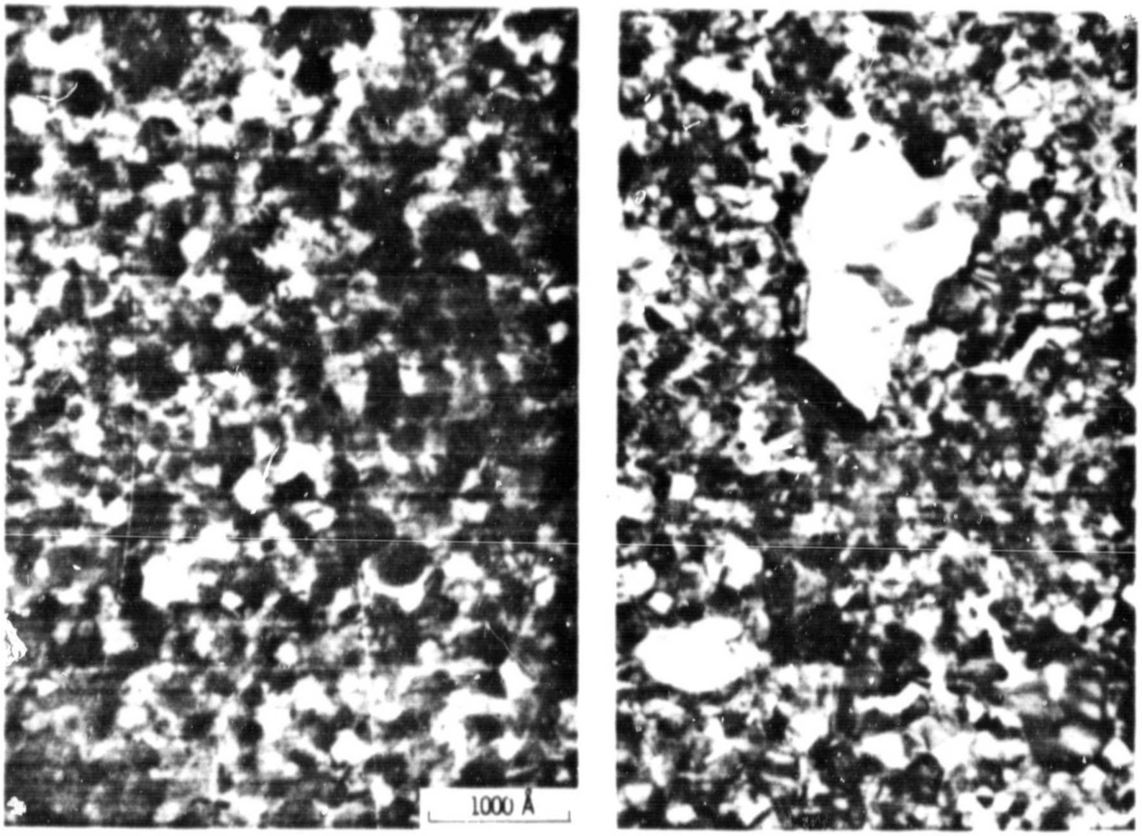


Figure 5. - TEM micrograph of vapor deposited lead film in the early stages of nucleation.



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

Figure 6. - TEM micrograph of the crystalline structure of gold film.