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LUBRICATION OF BEARING STEELS WITH ELECTROPLATED GOLD UNDER HEAVY LOADS

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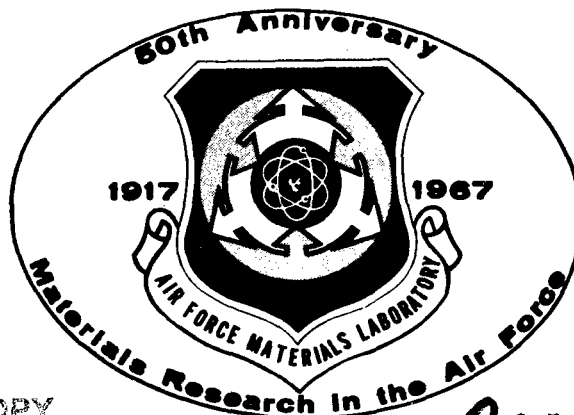
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LUBRICATION OF BEARING STEELS WITH ELECTROPLATED GOLD UNDER HEAVY LOADS

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FOREWORD

This report was prepared by the Fluid and Lubricant Materials Branch, Nonmetallic Materials Division, Air Force Materials Laboratory, with Dr. Tung Liu (MANL) as Project Engineer. The work was initiated under Project 7342, "Fundamental Research on Macromolecular Materials and Lubrication Phenomena," Task 734204, "Fundamental Investigation of Friction Lubrication and Wear." The work was administered by the Air Force Materials Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.

This report covers research conducted from January 1966 to September 1966. The manuscript was released by the authors in October 1966 for publication as a technical report.

This technical report has been reviewed and is approved.



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ABSTRACT

The lubricating action of electroplated gold for 52100 steel and 440C stainless steel in sliding motion under a 150-pound load was examined with a modified Alpha Tester (Model LFW-1). The advantage of gold plating was found to be entirely that of wear prevention while the sliding friction coefficient was not altered significantly. The wear lives of thick films were much longer than for thin films. A 20 μ film had a wear life of 150,000 revolutions. Too thick a film results in fatigue failure at the gold-steel interface. Silver, copper, and two gold alloys were found to be far less effective than pure gold as a lubricant while nickel was not at all effective. The failure of the plated film was usually marked by a rapid increase in wear rate. With thick gold alloy films, wear debris in the form of thin sheets were obtained in addition to the fine particles normally found with metallic films. The appearance of the wear tracks indicated that the gold films underwent considerable plastic deformation.

TABLE OF CONTENTS

SECTION	PAGE
I INTRODUCTION	1
II EXPERIMENTAL METHODS	2
III RESULTS	4
IV DISCUSSION	11
V CONCLUSIONS	13
REFERENCES	14

ILLUSTRATIONS

FIGURE		PAGE
1.	Schematic of Friction Force Recording System for Modified Alpha Tester	2
2.	Coefficient of Friction, Block Temperature, and Weight Loss of Specimens vs Number of Race Revolutions	7
3.	Sliding Areas of Block-Race Pairs	8
4.	Light Section Micrographs of Edges of Sliding Surfaces of Races	12

TABLES

TABLE		
I	Hardness of Races and Blocks	3
II	Plated Metals	3
III	Friction and Wear of Unlubricated Steels	5
IV	Wear Life of Gold Plated 52100 Steel	5
V	Friction and Wear Life of Different Metal Platings on Hard 52100 Races	6
VI	Friction and Wear Life of Gold Alloy Platings on Hard 52100 Races	9
VII	Friction and Wear Life of Gold and Gold Alloy Platings on Two Steels	10

SECTION I

INTRODUCTION

It has been established by Bowden and Tabor (Reference 1) that two sliding steel surfaces may be lubricated by a thin film of a soft metal such as lead or indium. According to the adhesion theory, this soft metallic film separates the steel surfaces and provides an easily sheared region, thereby reducing both the adhesive wear and the friction force. Gold, being soft, chemically inert, and high melting, has attracted the attention of friction and lubrication workers for its potential as a lubricant under high vacuum and high temperature environments (References 2 and 3). Evans and Flatley (References 4 through 6) showed that it is practical to use gold plating as a lubricant for miniature ball bearings. No extensive work on the durability of gold films for sliding bearings has been reported. This is likely due to the fact that the sliding coefficient of friction on gold film seldom falls below 0.1, the accepted range for boundary friction.

In an earlier work (Reference 7) the sliding friction of a spherical steel rider on a gold-plated steel flat was measured. The friction coefficient was found to depend on the material of the rider, film thickness, applied load, and to some extent on the substrate material. Under the most favorable conditions, the coefficient of friction reached values as low as 0.1 corresponding to theoretical values. The conditions of sliding (i.e., the load and speed) used during the work were relatively mild. The appearances of the wear tracks and scars gave limited indication of the failure mechanism.

The main purpose of this work was to clarify the wear mechanism of gold films in sliding. A relatively high load of 150 pounds was used in conjunction with a speed of 13.2 cm/sec to create a moderately severe sliding condition. Many of the experiments were carried out until failure occurred. The lubricating capability of gold was compared with several other metals and gold alloys.

SECTION II

EXPERIMENTAL METHODS

The sliding friction and wear measurements were carried out with a modified commercial Alpha Tester (Model LFW-1). The test specimens consisted of a rectangular block riding on the outer edge of a rotating disc coated with a soft metal. The disc was a Timken type cup. The linear sliding speed obtained with the 35 mm outside diameter race rotating at 72 rpm was 13.2 cm/sec. The normal load was applied by a dead weight through a lever system having a nominal mechanical advantage of 30. Initially, a contact was established as a line with a length of 6.35 mm. The friction force measuring device of the standard commercial model was replaced with a system as shown in Figure 1. The friction force experienced by the block is transmitted through a movable linkage to a horizontal shaft, which is guided horizontally by a ball bushing and connected to a proving ring equipped with a linear variable differential transformer (LVDT). Through the LVDT amplifier, the friction force signal was recorded on a two-channel strip chart recorder simultaneously with the block temperature. A high temperature grease was used to lubricate the tester bearings located near the specimens to minimize contamination of the sliding surfaces by the vapor of the grease.

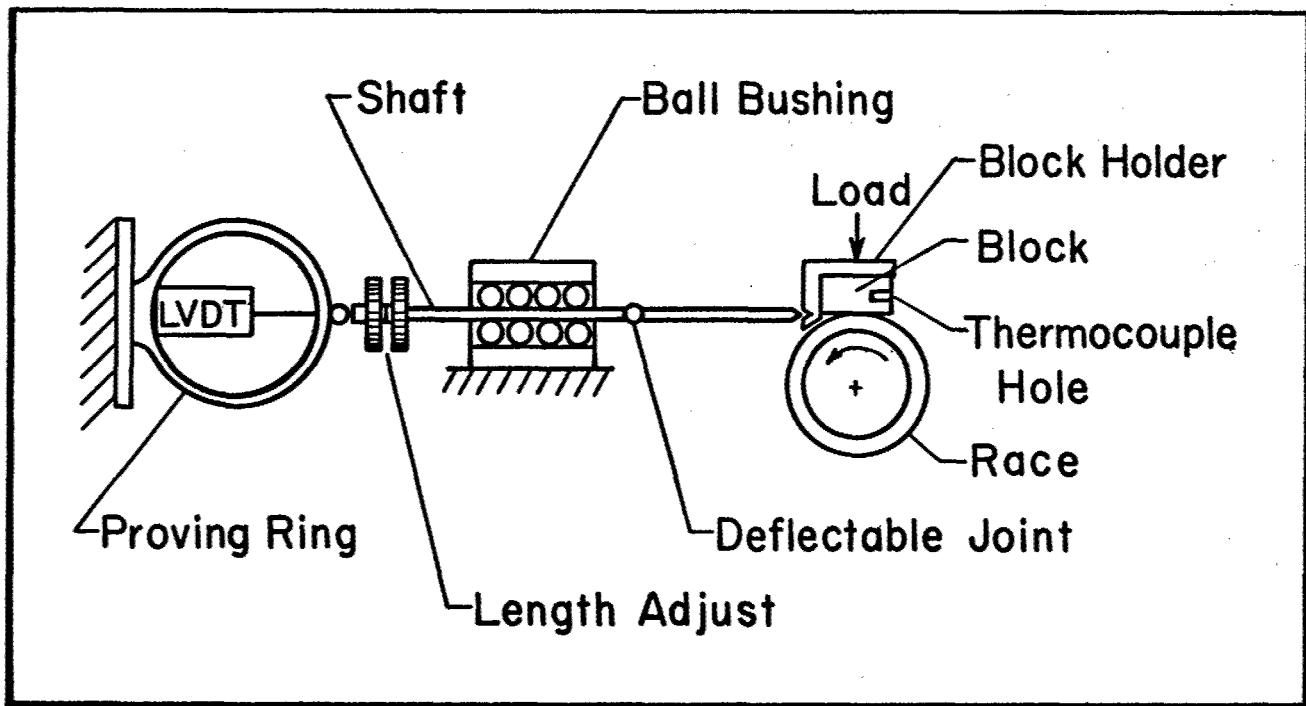


Figure 1. Schematic of Friction Force Recording System for Modified Alpha Tester

The races and the blocks were made of either 440C stainless or 52100 bearing steels. Both materials contain about one percent of carbon and had been hardened to martensitic structures. The hardness of the actual specimens used is shown in Table I.

TABLE I
HARDNESS OF RACES AND BLOCKS

Steel		Hardness (DPN)* at 500 g	
		Race	Block
Soft	52100	520	610
Hard	52100	790	790
440C	Stainless	715	680
*Maximum deviation was ± 15 units.			

Four metals - gold, silver, copper and nickel - and two gold alloys were used to electroplate the races used in this work. The plating was carried out by a commercial source using well established processes. According to the manufacturer, the pretreatment of the specimens (including nickel striking) and the plating process were carefully controlled to obtain products of the desired thickness, composition and hardness. The film thickness of nominally 5, 10, and 20 μ thick films of pure gold and gold alloy A plated on soft 52100 steel was checked with a magnetic gage and the variation of four measurements from the specified thickness was found to be less than 30 percent. A list of the plated metals and alloys is shown in Table II together with their compositions and hardness.

TABLE II
PLATED METALS

Metal	Hardness (DPN)*	Composition**
Gold	65	99.99+Au
Gold Alloy A	168	Sb 4%, balance gold
Gold Alloy B	209	Co, Ni, Tn 2-4%, balance gold
Silver	95	pure silver 99.9+
Copper	161	pure copper 99.9+
Nickel	316	pure nickel 99.9+
* Measured with 25 g load on 20 μ films.		
** Values given in Manufacturer's (Sel-Rex Corp, Nutley, N.J.) literature.		

The two gold alloys were selected from a field of four over a wide range of hardnesses. The other two were eliminated because of excessive wear, noise, and vibration in preliminary sliding runs.

The maximum surface roughness of the races prior to plating was 15 micro in. The rubbing surfaces of the block specimens were wet polished with 4/0 emery paper. Prior to each friction and wear run, the specimens were thoroughly cleaned with acetone and distilled water and degreased cathodically in a bath of 10 percent aqueous solution of trisodium phosphate.

The standard operating procedure was to initially apply a load of 30 lb (1lb weights x 30-1 mech adv). After each 50 revolutions, the load was increased by 30 lb until a total of 150 lb was reached. This stepwise loading procedure was selected to provide a smoother run-in to reduce vibrations. To facilitate comparison, it was assumed in calculating the number of revolutions of wear life that the wear in the initial stage varied with the product of load applied and number of revolutions divided by the final load. The first 200 revolutions were thus counted as 100. The test specimens were allowed to run under a 150-lb load with occasional interruptions to weigh the race and block on a semimicro analytical balance to 0.01 mg. Since wear rate is in general far from constant during its life and should be negligibly small until destructive wear begins, the test was terminated when the weight loss of the race exceeded one mg. The number of revolutions corresponding to one mg weight loss was estimated by graphical interpolation and reported as the wear life. It was desirable to have two weighings made fairly close to one mg weight loss of the race. Careful visual observation of the amount of debris collected on a sheet of white paper placed under the running specimens usually enabled one to stop the running at the desired time.

SECTION III

RESULTS

Some friction wear data of unlubricated steel specimens were obtained to serve as the base for comparison (Table III). Nine material combinations were taken from 440C stainless steel and 52100 steel at two levels of hardness. The coefficient of friction varied within a narrow range between 0.53 and 0.83 while the wear life deviated widely between the first three and the last six material combinations. Unlike the lubricated specimens (discussed later) the wear of the blocks is very high. The wear of the race is complicated by the mass transfer from the block to the race. Consequently, the accuracy of the wear life data for these unlubricated specimens was considerably poorer than for the lubricated specimens. With hard 52100 races, the wear life was much longer and was accompanied by dark-brown wear tracks and debris, presumably oxides.

TABLE III

FRICTION AND WEAR OF UNLUBRICATED STEELS

Block	Race	Coefficient of Friction	Wear * Life
Hard 52100	Hard 52000	0.78	750
Soft 52100	Hard 52100	0.70	300
440C	Hard 52100	0.83	330
Hard 52100	Soft 52100	0.68	46
Soft 52100	Soft 52100	0.55	20
440C	Soft 52100	0.64	40
Hard 52100	440C	0.53	9
Soft 52100	440C	0.58	3
440C	440C	0.76	2
*Number of revolutions corresponding to 1 mg weight loss of the race.			

In the last six material combinations, both the wear track and wear debris had bright metallic luster with no visible evidence of oxidation. It appears that the race material has a decisive influence in the type of unlubricated sliding. A series of experiments was conducted to compare the effect of 52100 steel substrate hardness on the lubricity of gold film. Three types of blocks, soft and hard 52100 steel, and 440C were run against gold plated soft and hard 52100 steel races. Four film thicknesses 0.2, 1, 5, and 20 μ were used in each material combination. Friction was not affected at all, and wear life as shown in Table IV was not significantly different except in thin films where hard races provide longer wear life just as in the unlubricated cases (Table III).

TABLE IV

WEAR LIFE OF GOLD PLATED 52100 STEEL

Film Thickness (μ)	BLOCK Soft 52100 Race		BLOCK Hard 52100 Race		BLOCK 440C Race	
	Soft 52100	Hard 52100	Soft 52100	Hard 52100	Soft 52100	Hard 52100
0.2	350	1,000	300	1,200	1,900	1,600
1	2,000	2,000	2,500	8,000	3,000	5,000
5	>33,000	32,000	8,000	>19,000	19,500	>70,000
20	150,000	>30,000	>35,000	>30,000	40,000	>25,000

The wear life of a typical thick gold film lubricated race was surprisingly high. On one occasion, a soft 52100 block running against a race made of similar material and plated with gold to a thickness of 20 μ lasted six days (with overnight interruptions) for a total wear life of 150,000 revolutions (Table IV and Figure 2). The coefficient of friction (Figure 2) after the initial rise stayed in the 0.80 to 1.02 range. It was realized that continuous running under controlled atmosphere is essential to obtain precise data. To obtain meaningful wear life data without consuming too much time from the present work carried out in the laboratory atmosphere, most of the long runs were terminated at the end of a day or two, well before the race showed any significant weight loss. Table IV shows the overwhelming effect of film thickness on the wear life while the choice of substrate hardness is relatively unimportant.

Since gold has a stronger affinity toward 52100 steel than 440C stainless steel, and because hard 52100 steel races provide longer wear life in unlubricated states, hard 52100 steel races were selected as the standard substrate for comparing the lubricating capabilities of various metallic films.

The relative effectiveness of an electroplated gold film as a lubricant under heavy loads was compared with three other metals - silver, copper and nickel. The experimental results are given in Table V.

TABLE V
FRICTION AND WEAR LIFE OF DIFFERENT METAL PLATINGS ON HARD 52100 RACES

Film Thickness (μ)	Block Hard Plating				Block 440C Plating			
	52100							
	Gold*	Silver	Copper	Nickel	Gold*	Silver	Copper	Nickel
0.2	1,200	300	500	700	1,600	300	300	130
1	8,000	100	600	100	5,000	800	1,100	50
5	>19,000	400	900	20	>70,000	1,600	1,200	10
20	>30,000	5,500	2,200	20	>25,000	4,900**	1,500	10
Coef of Friction	0.7-1.0	0.5-0.7	0.5-0.6	0.5-1.2	0.5-0.6	0.5-0.9	0.5-0.7	0.6-1.0
*Same data as shown in Table IV. **Failure was marked by peeling (Figure 3b).								

It is apparent that gold is far superior to the three other metals in achieving long wear life; in fact, the presence of nickel is detrimental when compared to that for unlubricated combinations (Table III). Again the coefficient of friction data failed to indicate any positive correlation between friction and wear. Photographs of the wear scars of the blocks and the wear tracks of the races plated with four different metals and gold alloy A and B after the sliding tests are shown in Figure 3 (a) through (f).

In a typical run, the sliding may be separated into three stages. During the initial run-in period, the friction and the block temperature gradually leveled off. A relatively smooth period followed, during which both the friction and block temperature remained virtually constant with very low wear.

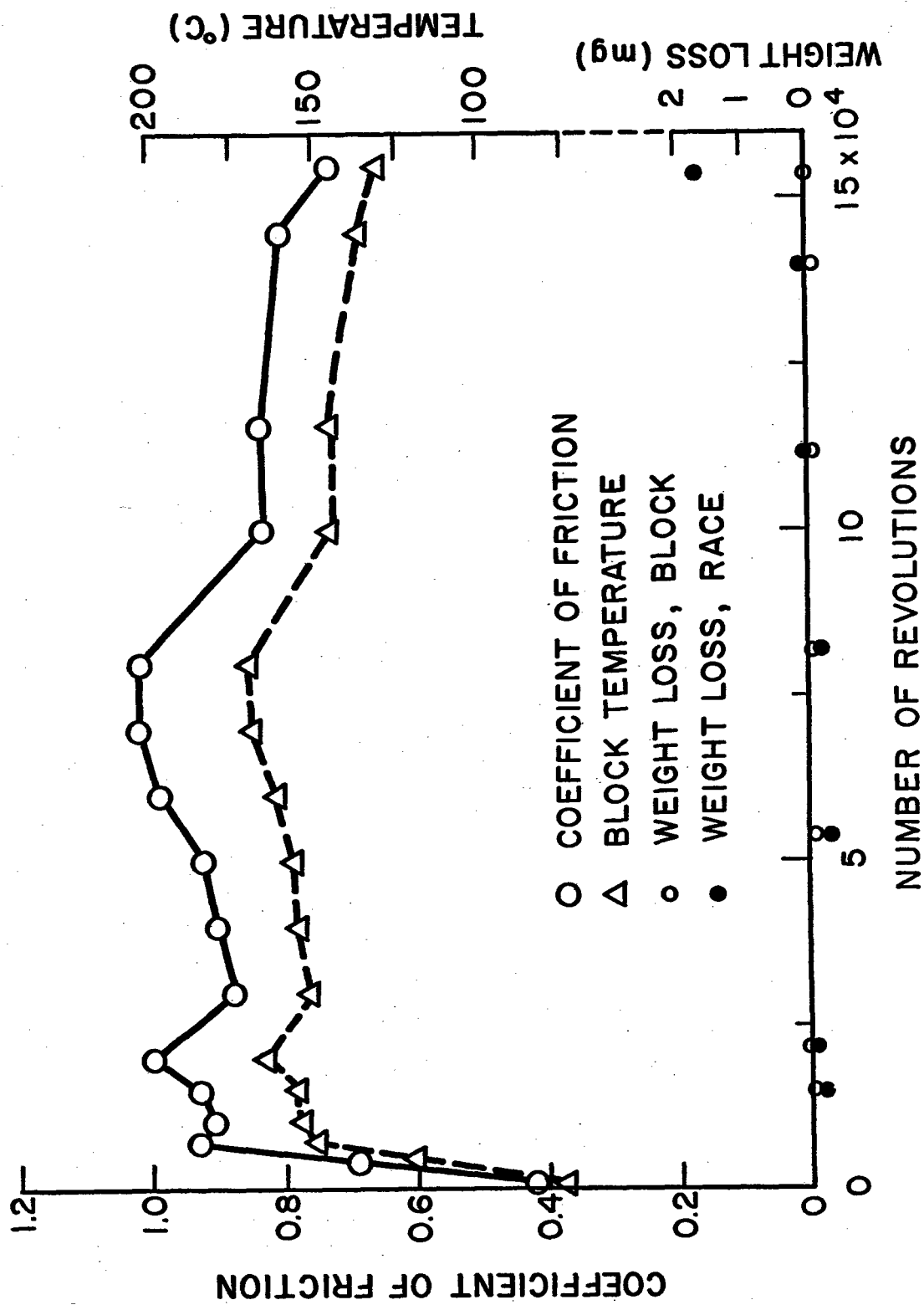


Figure 2. Coefficient of Friction, Block Temperature, and Weight Loss of Specimens vs Number of Race Revolutions (Block: Soft 52100; Race: 20 μ thick gold plated soft 52100)

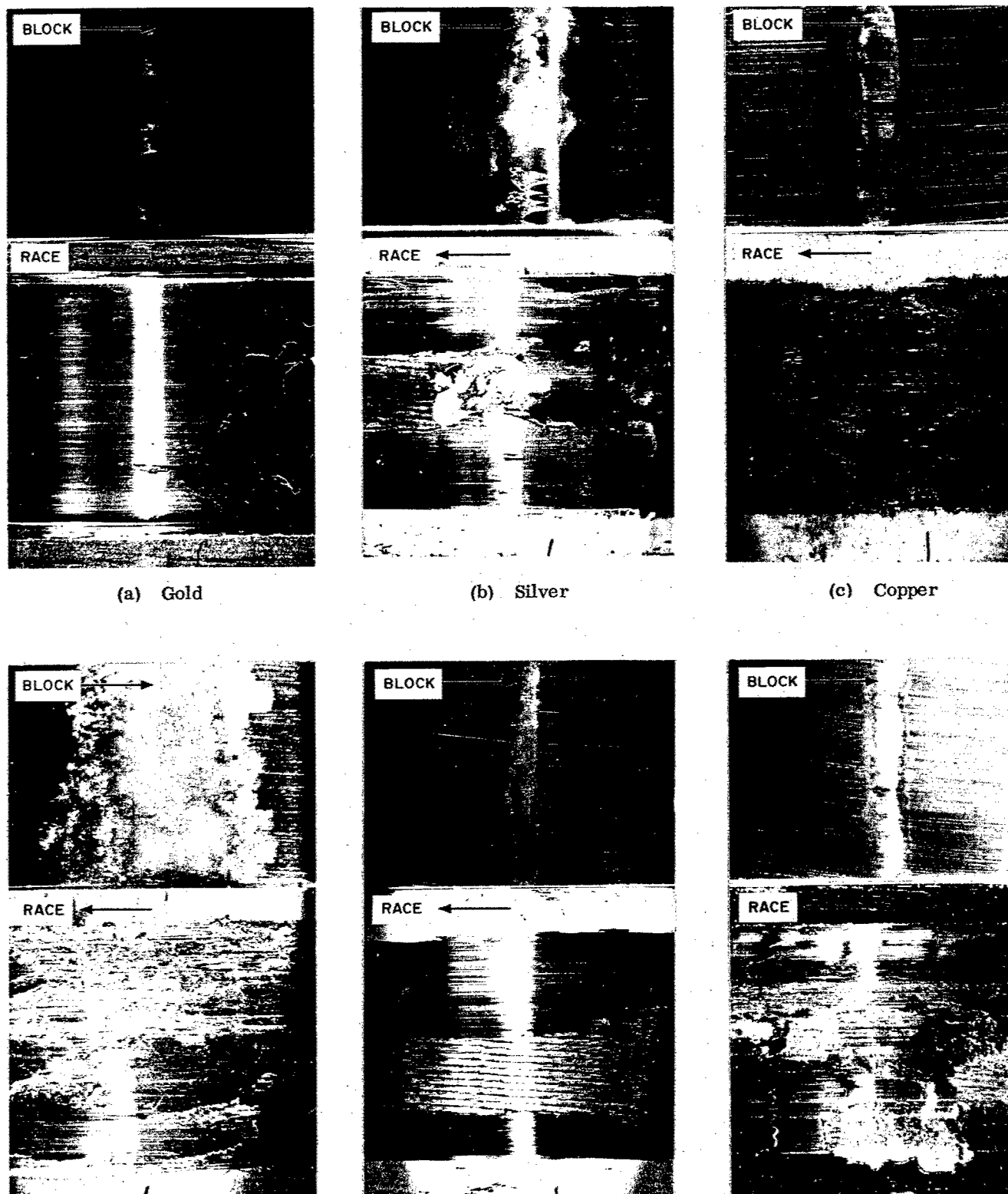


Figure 3. Sliding Areas of Block-Race Pairs (Arrows indicate moving direction of surfaces.)

The transition into the final stage usually came abruptly with a sudden increase in noise, vibration, and wear. The weight loss of the race normally stayed well below one mg until this final stage. Thus, the wear life data as reported in the number of revolutions per mg weight loss are definitely not the average rates of wear. The reduction in film thickness calculated from one mg weight loss of the race is actually very small:

Metal	Au	Ag	Cu	Ni
Thickness of One mg of metal (μ)	0.075	0.14	0.16	0.16

However, in the course of a long run, particularly with gold plating, considerable amount of metal may be pushed away from the contact zone. Figure 4 (a) shows the outline of the edge of the wear track of the gold plated race after running 30,000 revolutions against a hard 52100 steel block, taken with a light section microscope. It is clear that a considerable amount of gold was removed from the contact zone by plastic deformation. A small amount of gold sometimes fell down in the form of whiskers during a long run.

Two gold alloys were compared with pure gold as the lubricant for sliding steels. The results, shown in Table VI, clearly indicate that these alloys were not as effective as pure gold, especially in the thicker films where pure gold is extremely durable.

TABLE VI

FRICTION AND WEAR LIFE OF GOLD ALLOY PLATINGS ON HARD 52100 RACES

Film Thickness (μ)	Block: Hard 52100		Block: 440C	
	Plating		Plating	
	Alloy A	Alloy B	Alloy A	Alloy B
0.2	400	150	600	500
1	4,000	500	3,000	6,000
5	600*	50	900*	14,000
20	10*	5	1,100*	900**
Coef of Friction	0.6-0.7	0.6-0.7	0.5-0.6	0.4-0.5
*Failure was marked by peeling. **Blisters were visible on the race.				

Sliding surfaces after test are shown in Figure 3 (e) and (f). In Figure 3 (e), and also 3 (b), a portion of the plating on the race surface was completely removed. The original tool marks on the substrate became clearly visible.

With gold or other pure metal films, the wear debris is usually in the form of small particles. With thick gold alloy films (5 and 20 μ .) relatively large sheets of gold were found among the debris. With alloy A, the film appeared to peel off at the substrate interface. With alloy B, the separation appeared to be mostly within the gold film which frequently showed the signs of flaking or blistering.

Another series of experiments was performed to further investigate the effect of the film thickness on the wear life. Soft 52100 and 440C blocks were run against races of identical material plated with gold and its alloys.

The results are shown in Table VII. The experimental procedures used in these runs were somewhat different from the others.

TABLE VII
FRICTION AND WEAR LIFE OF GOLD AND GOLD ALLOY PLATINGS ON TWO STEELS

Film Thickness (μ)	Race and Block: Soft 52100				Race and Block: 440C Plating			
	Plating							
	Gold*		Alloy A	Alloy B	Gold*		Alloy A	Alloy B
0.1	350	400	500	450	900	1,050	800	1,100
0.2	500	900	700	700	500	1,300	1,200	1,400
0.5	1,100	3,500	3,400	3,000	450	6,700	200**	230
1	3,000	3,200	2,700	3,500	10,000	13,000	600**	500
2	11,000	13,000	4,000	100	4,400	18,000	800**	750**
5	>27,000	>30,000	10,000	50	6,500	>10,000	300**	500**
10	>8,000	>22,000	1,000**	20	>5,000	9,000	600**	80**
20	>27,000	>50,000	700**	10**	100**	>10,000	700**	30**
Coef of Friction	0.5-0.8		0.5-0.6	0.5-0.6	0.3-0.5		0.3-0.4	0.3-0.4
<div>*Two series of runs on gold film. **Failure was marked by peeling.</div>								

The block specimen surface was degreased but not polished prior to test; the load was 150 lb right from the start and the tester gave more vibration during sliding. Despite this, the data are in good agreement with those shown in Table IV. It is plain that the optimum film thickness varies with both the film and the substrate material.

SECTION IV

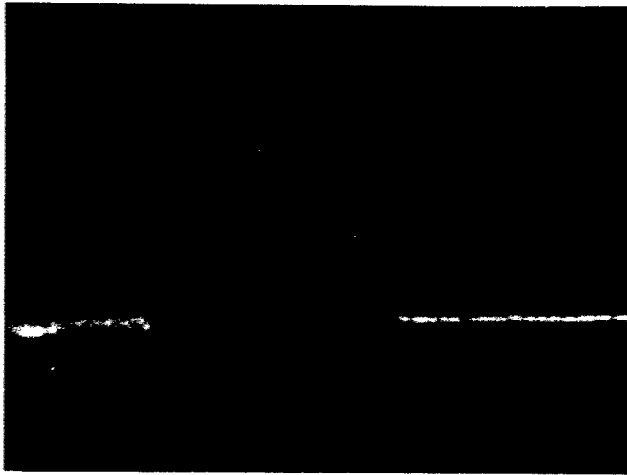
DISCUSSION

The experimental results on the lubrication of steels sliding under heavy loads by electroplated gold have shown that extremely long wear life may be obtained with $20\ \mu$ gold film. The friction force, on the other hand, remained about the same as for unlubricated steels. In the particular run previously described, wear life was 150,000 revolutions (one mg weight loss of the race), far longer than any other runs which were carried out to the end. The corresponding coefficient of friction of 0.80 to 1.02 (Figure 2) was much higher than the 0.55 obtained with unlubricated specimens. The high friction coefficient suggests that the actual contact area is relatively large. The beneficial influence of thick film implies that the separation between the steel block and race must be large for the gold film to develop its effectiveness. The conditions obviously do not fit the thin film lubrication mechanism explained by Bowden and Tabor (Reference 1). It has been found (Reference 7) that for slow sliding of steels lubricated with gold under a light load, a coefficient of friction of about 0.1 was occasionally reached. This value is in the range of those obtained with indium and lead. Thus, under a heavy load, the advantage of lubrication by a gold film is solely based on its wear protection quality as the conditions of minimum sliding friction were not met.

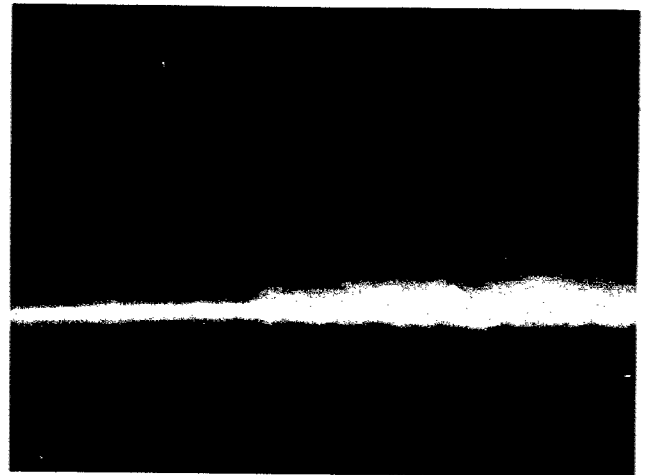
Three types of wear debris were observed in the experimental work. Besides the commonly observed irregularly shaped small particles, there are thin sheets and occasionally whiskers. The formation of whiskers is already mentioned as being the result of plastic deformation with gold being pushed out of the contact zone and followed by shearing. This thin sheet peeling off from the 52100 steel substrate (as gold alloys A and B, and silver) is likely a fatigue failure (Figure 3 (b) and (e)). Table VII shows that this mechanism also happened with pure gold film plated on 440C stainless steel. In the case of alloy B, with a soft 52100 substrate, a maximum wear life of 3,500 revolutions was obtained at a film thickness of $1\ \mu$, while a maximum of 1,400 revolutions was obtained with a $0.2\ \mu$ film on a 440C substrate. It may be summarized that this type of failure, if present, appears to impose an optimum thickness of film for a given set of material combinations as well as the running condition. Flaking failure within the film itself was observed with alloy B. This mechanism apparently causes a rapid dissipation of shear force throughout the film. The shear stress at the film-substrate interface is reduced, thereby inhibiting peeling failure.

The main task of attempting to explain the sliding mechanism appears in order. It has been indicated that the actual contact area during sliding is supposedly large and the steel specimens were well separated by a layer of gold. Using the hardness of gold before work hardening, $68\ \text{kg/mm}^2$, the actual contact area under a static load of 150 lb is calculated to be one mm^2 . While the length of contact remains a constant of 6.35 mm, the maximum width of contact area is 0.16 mm. The typical contact zone of a race plated with a $20\ \mu$ gold film was observed to be separated into several isolated patches with a total area around $2\ \text{mm}^2$. The radial displacement of the gold at the surface upon contact is estimated to be less than $1\ \mu$. Thus, the actual contact resembles that between steel and gold, or between two gold bodies when sufficient metal transfer had occurred. In other words, the presence of gold virtually substituted steel to steel contacts with steel to gold (or gold to gold) contacts. The formation of the enlarged contact area, which is presumably responsible for the large coefficient of friction (0.8-1.0), is most likely caused by plastic flow, essentially the phenomenon of junction growth first reported by McFarlane and Tabor (Reference 8). Gold, being highly malleable, is capable of undergoing considerably more plastic deformation without failure than other metals and alloys, and should provide longer wear life as a lubricating film. Silver and copper are also somewhat malleable and their films should achieve some lubrication.

Visual evidence of plastic flow of gold was also observed during the long runs. Occasionally a small amount of gold displaced to the outside of the wear track would reenter the contact area by slight lateral motion of the block, and subsequently spread out over the race upon repeated sliding. Figure 4 (a) shows the irregularly shaped, built-up edge of gold on a race after a long run. Figure 4 (b) shows that no built-up edge was evident in sliding over a film of gold alloy B.



(a) Gold



(b) Gold Alloy A

Figure 4. Light Section Micrographs of Edges of Sliding Surfaces of Races.
(Magnification: Vertical X 150; Horizontal X110)

SECTION V

CONCLUSIONS

The sliding friction and wear between a steel block and a Timken type cup plated with gold or other soft metal were measured under a load of 150 lb and at a linear speed of 13.2 cm/sec. The plating was performed by a commercial source and covered a film thickness range of 0.1 to 20 μ . The wear life was reported as the number of revolutions corresponding to one mg weight loss of the race, as this occurs normally at the onset of the rapid wear stage. Experimental results led to the following conclusions.

1. Gold plating may improve the wear life considerably, while the friction force cannot be significantly changed. Under the experimental conditions used, the sliding mechanism appeared different from that of other soft metal films.
2. Gold as a lubricant is more effective than silver, copper, and gold alloys. Observations show that gold films underwent considerably more plastic deformations than other materials.
3. Gold plating as a lubricant is most effective with high film thickness (at least 5 μ probably about 20 μ or higher) while gold alloys became less effective with higher film thickness.
4. Results on gold alloy films indicate that there are two basic failure mechanisms: rubbing off and peeling. With a gold alloy (or others to a lesser extent) film exceeding a certain thickness, relatively large sheets may peel off as wear debris, thus greatly shortening the wear life of the film.

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