THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 58, No. 2, February 1979
Printed in U.S.A.

Wear of Gold Electrodeposits: Effect of Substrate and of Nickel Underplate

By M. ANTLER and M. H. DROZDOWICZ

(Manuscript received May 8, 1978)

The adhesive and abrasive wear of electrodeposited gold was studied and the effect of a ductile hard underplate (nickel) and a hard substrate (beryllium copper) determined. Wearing conditions experienced by connector contacts were modeled with rider-on-flat apparatus. It was found that: (i) both the adhesive and abrasive wear of gold plate can be markedly reduced by hard substrates and underplates, (ii) thin film lubrication is effective when adhesive wear predominates, but is of little value in abrasive wear, (iii) there is a load-dependent minimum thickness of gold plate that will not wear through because of a change in mechanism which occurs during unlubricated sliding in the adhesive regime, (iv) sliding at mild conditions, as in the presence of a good boundary lubricant, occurs with lateral flow of gold which can close as-plated pores and wear-induced breaks produced early in a run, (v) pure (soft) gold platings may be able to resist abrasive wear at loads where hard golds fail by brittle fracture, and (vi) the prow formation mechanism adequately describes the adhesive wear of gold plate. Nickel underplate may be desirable on connector contacts to minimize the wear of gold plate, especially at high loads, with thin golds, where it is impractical to use lubricants and where abrasion is the dominant mechanism.

I. INTRODUCTION

This investigation concerns the wear of gold electrodeposits such as are used on the contacts of electronic connectors. The wear of contact finishes is important to connector reliability because, if base metal is exposed, oxide or corrosion films form which may lead to unacceptably high contact resistance.

Connector contact surfaces generally consist of gold platings hardened with from 0.1 to 0.5 weight percent of codeposited cobalt or nickel and having a thickness in the range of 0.5 to 5 μm. Underplatings of copper or ductile nickel are often used, chosen for their expected value in retarding substrate diffusion and for their effect in mitigating the formation of corrosion and tarnish films which can develop in aggressive environments at pores in the gold deposit. Wrought pure gold and silver-gold alloy weldments or claddings are also employed, generally on only one member of a contact pair. Among the common substrates are copper and copper alloys, as in the edge contacts of printed circuit boards and the spring elements of connectors. Lubricants may also be used to lower insertion forces and to reduce wear.

Prior research in the wear of gold has been summarized.[1] A role of underplate was found by Holden[2] and Solomon and Antler,[3] who recognized that contact finishes having low deformability are desirable and that the effective hardness of a multi-layer finish can be increased by the use of some underplatings, such as nickel. Studies with connectors have borne out their predictions,[4,5] but it is also common experience that nickel underplating may not change the wear of gold in some cases and, when associated with poor finishing practices which lead to nonadherent coatings or nodular surfaces, may even degrade wear behavior.

It was the objective of this work to determine the mechanisms by which nickel underplate and substrate metals control the wear of gold plate. If the role of underplate and substrate could be understood, the selection of contact materials might be better made than at present.

The wear of gold in connectors occurs by adhesion, abrasion, and brittle fracture.

Adhesive damage occurs when there is metal transfer. Adhesive bonds form that are stronger than the cohesive strength of the metal. These bonds lead to transfer and wear as sliding continues.

Wear generated by plowing of a surface by an opposing member which is rough and substantially harder is termed two-body abrasion. Loose hard particles between sliding surfaces causes three-body abrasion of one or both members. Abrasive wear of connector contacts originates in misalignment, parts having burrs or similar defects, work-hardened transfer and loose particles from adhesive wear, and foreign materials such as dusts and debris from connector structures or printed circuit boards. The abrasive wear of gold has been little studied.

Fracture wear occurs with brittle platings, especially when the substrate is deformable. The surface develops cracks during sliding and may result in catastrophic loss of the coating. Since the common cobalt- and nickel-hardened gold electrodeposits have elongations of less than one percent,[6] brittle fracture can be expected to contribute to the wear of gold contacts.

The experimental approach of this investigation was to model wearing conditions experienced by connector contacts using a rider-on-flat apparatus. It will be shown that: (*i*) both the adhesive and abrasive wear of gold plate can be markedly reduced by nickel underplate and by hard substrates, although small thicknesses of nickel may be ineffective, (*ii*) thin film lubrication is effective for wear reduction when adhesive wear predominates, but is of little value in abrasive wear, (*iii*) a load-dependent minimum thickness of gold plate will not wear through because of a change in mechanism which occurs during unlubricated sliding in the adhesive regime, (*iv*) sliding at mild conditions, as in the presence of a good boundary lubricant, occurs with significant lateral flow of gold which can close as-plated pores and wear-induced breaks produced early in a run, (*v*) pure (soft) gold platings may be able to resist abrasive wear at loads where hard golds fail by brittle fracture, and (*vi*) the prow formation mechanism adequately describes the adhesive wear of gold plate.

II. EXPERIMENTAL

2.1 Materials

2.1.1 Riders

In the study of adhesive wear, hemispherically ended smooth solid gold riders having a diameter of 3.2 mm were used. The purity of the gold was 99.99 percent, with a typical hardness of 65 KHN_{25}. A newly turned rider was employed for each run.

Riders used in three-body abrasion studies were 3.2-mm diameter solid rhodium rods, 99.9 percent pure, having a hardness of 370 KHN_{250}. The riders, which initially had hemispherical ends, were installed in the wear apparatus and then abraded with silicon carbide metallographic paper placed on the specimen table in place of the flat until a circular area of 0.5-mm diameter on the rider had been produced. Rhodium was used instead of gold to minimize embedding of powdered abrasive in the rider surface, and having flat mating surfaces assured that abrasive particles would be trapped between the specimens.

Runs in two-body abrasion were with a 90-degree conical diamond rider having a rounded tip with a radius of 0.1 mm.

2.1.2 Flats

The flats were a soft and a hard material, oxygen-free copper and beryllium copper alloy, respectively, and are described in Table I. They were randomly abraded on metallographic paper prior to plating.

Table I—Substrates

	Copper, Oxygen Free	Beryllium Copper
Size, cm	1.3 × 3.8	1.3 × 3.8
Thickness, mm	3.2	4.9
Composition, wt. %	99.95 Cu	97.9 Cu, 1.9 Be, 0.2 Ni or Co
Hardness, kg/mm^2 (cross-sections)	40–60 KHN_{25}	266 KHN_{25}
Roughness after plating, μm CLA	0.4 ± 0.08	0.2 ± 0.005

Platings were cobalt-hardened gold from an acid cyanide bath, pure gold from a citrate-buffered acid solution of $KAu(CN)_2$, and nickel from a sulfamate bath (Table II). The cobalt golds in three thicknesses and the pure gold were plated both with and without nickel underplate. The golds had low intrinsic porosity and thus were suitable to a chemical method (electrography) for assessing wear-through of the deposit. The cobalt gold contained codeposited polymer,[7] and was typical of platings used on connector contacts.

Immediately prior to a run, specimens were cleaned by immersion in multiple baths of reagent grade 1,1,1-trichloroethane and methanol.

2.1.3 Lubrication

Lubricant was a liquid polyphenyl ether, Monsanto OS-124.[8] It was applied to the cleaned flats by immersion and withdrawal at room temperature from a 0.5-percent solution in 1,1,1-trichloroethane. The solvent quickly evaporated, leaving a thin residual film of lubricant.

2.1.4 Abrasive

In three-body sliding, graded boron carbide powder consisting of equiaxed particles, approximately 50 μm across, was applied by sifting particles onto lubricated flats. About 50 percent of the specimen surface was covered with abrasive powder.

2.2 Apparatus

Two rider-flat machines were used. They were similar, involving dead-weight loading of a stationary rider against the moving flat. The riders were free to move vertically so as to accommodate wear debris, roughness, and other irregularities.

The machine for studying adhesive wear and three-body abrasive wear has been described earlier,[9] and was used in reciprocating mode. Contact members were observed during sliding at 30 diameters with a stereomicroscope. Test conditions were: tracks, slightly curved, with a

Table II—Electrodeposits

	Co Gold	Pure Gold	Nickel (Underplate)
Avg. thickness μm*	0.75, 2.0, 3.3	3.3	1.5, 2.5, 4.0
Composition, wt. % metals†	0.26 Co 0.20 K ‡	‡	
Carbon§	0.26 C		
Hardness, kg/mm^2¶	180 KHN_{25}	90 KHN_{25}	550 KHN_{10}

* Thickness determined from metallographic sections. Variability among replicate samples was ±15 percent.
† Analysis by atomic absorption method.
‡ Other metals not detected, or present in only trace amount.
§ Analysis by microcombustion.
¶ Hardness determined on metallographic sections.

length of 1 cm; average velocity, 0.3 cm/s; loads, 20–500g; numbers of passes (a to-and-fro traversal is two passes), usually from 10 to 700. Some runs were for 1 or 4 passes, and others continued for up to 4000 passes.

Two-body abrasion was studied by sliding for 1 pass. Test conditions were: tracks, straight, with a length of 1 cm; velocity, 0.25 cm/s; loads, 10–500g.

One to four runs were made at each test condition, and electrographic Wear Indexes, defined below, were calculated by averaging results from the individual experiments.

2.3 Determination of wear

Four different methods were employed to determine wear: surface examination with the light and scanning electron microscopes (SEM), electrography, profilometry, and metallographic sectioning across the wear track and observation of the section with the light and the scanning electron microscopes. The electrographic and profilometric methods are described in detail.

2.3.1 Electrography

Electrography[10,11] is useful for detecting loss of gold from a surface which results in exposure of base underplate or substrate. In this method, base metal at breaks in the gold is caused to transfer to chemically treated paper that is pressed against the specimen, its location signified by colored spots which appear in the paper. The procedure is given in the appendix to this paper.

Wear tracks were observed in the electrographic print at 10 diameters. Decorations consisted of discrete spots along the wear track and grew in number and size with increasing wear, e.g., in a series of runs with increasing numbers of passes. Often there were multiple spots across the width of a track. Figure 1 shows a typical electrographic print and the test specimen from which it was made.

It was convenient in quantifying wear to determine the ratio of length of track in the electrograph having decorated features to total track length. This ratio, multiplied by 100, is defined as the "Wear Index." Determinations of Wear Index could be made quickly with a calibrated eyepiece, and reproducibility in repeat observations of the same print was about 3 percent. This is less than the variability of wear from replicate runs.

2.3.2 Profilometry

Wear occurs with loss or displacement of metal, or, if transfer predominates, an increase in surface roughness. Since exposure of base metal is of most relevance in contact studies, a profilometric analysis

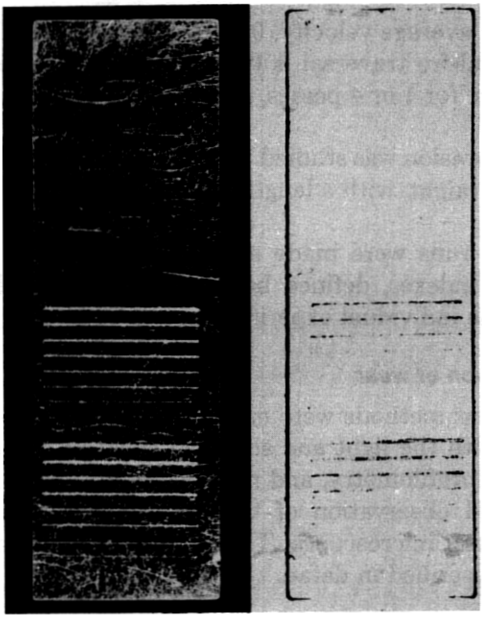

Fig. 1—Typical specimen and electrographic print.

was made which emphasized the maximum depth in the wear tracks compared to the level of unworn surface.

Three traversals across each wear track were made with a stylus instrument and charts of stylus excursions obtained. The average of the maximum depths in the three tracks with respect to the levels of the original specimen surface was then calculated. This is termed "depth of wear."

It was found that wear analysis by profilometry gave nearly the same results as analysis based on the electrographic Wear Index, as shown later for a typical case in unlubricated adhesive wear. Accordingly, profilometry was not used routinely because of its relative complexity.

III. OBSERVATIONS

3.1 Adhesive wear

3.1.1 Unlubricated

Solid gold riders and flats plated with several thicknesses of cobalt gold electrodeposits on copper, with and without nickel underplate, were used. The effect of nickel underplate was also determined with pure gold plate on copper and with cobalt gold plate on beryllium copper. The analysis of wear by electrography is given in Figs. 2, 3, and 4.

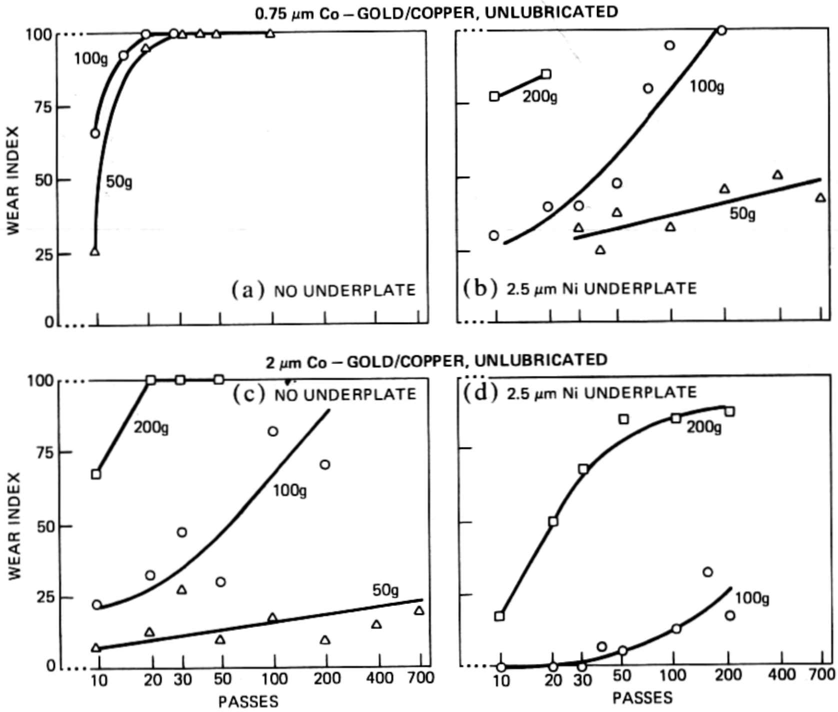

Fig. 2—Electrographic Wear Indexes from unlubricated adhesive wear runs with 0.75 and 2 μm cobalt gold electrodeposits on copper with and without 2.5 μm nickel underplate.

Figures 2a and 2b illustrate the large reduction in wear of 0.75-μm cobalt gold deposits obtained with nickel underplate. For example, a Wear Index of 100 occurs at 100g within 20 passes without the nickel, while 200 passes are required to produce equivalent wear with 2.5 μm of nickel. Figure 2c shows that roughly comparable wear results with 2 μm of cobalt gold plated directly on copper and with 0.75 μm of cobalt gold having nickel underplate, and Fig. 2d shows nickel is able to effect an equally dramatic reduction in the wear of 2-μm cobalt gold deposits.

Figure 3 continues this analysis with 3.3 μm of cobalt gold with nickel thickness being varied, including 1.5, 2.5, and 4-μm underplatings. In Fig. 3a, thick cobalt gold plate on copper is found to be more durable than thinner golds (Figs. 2a and 2c), but again nickel underplate is further able to reduce wear, although the improvement is less dramatic than when nickel is used with thinner gold finishes. Thus, at 200g a Wear Index of 50 is achieved in about 60 passes without nickel (Fig. 3a), and in about 120 passes with 2.5 μm of nickel (Fig. 3c). The sample having 1.5 μm of nickel underplate (Fig. 3b) is not substantially better at 200 and 300g than when nickel-free, although there is im-

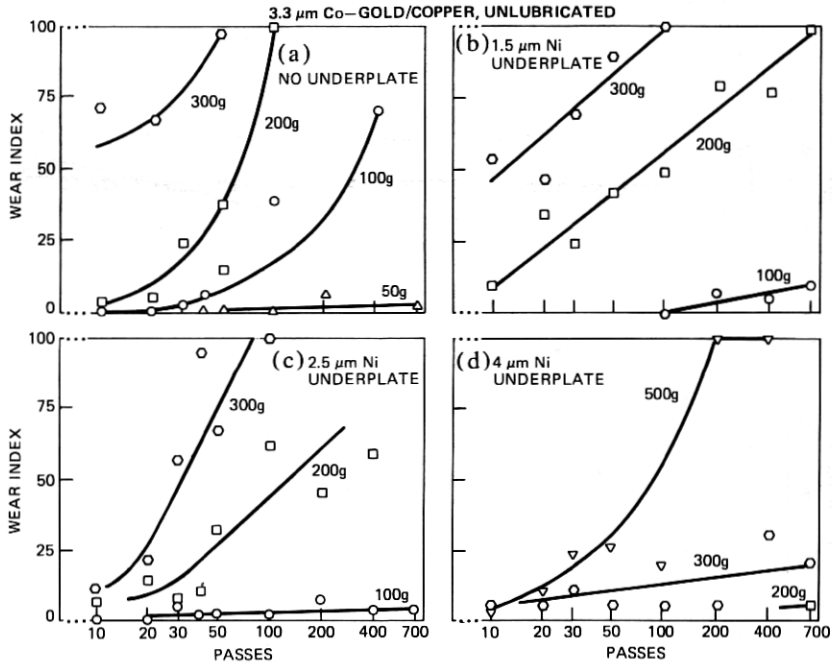

Fig. 3—Electrographic Wear Indexes from unlubricated adhesive wear runs with 3.3 μm cobalt gold electrodeposits on copper with various thicknesses of nickel underplate.

provement at 100g. On the other hand, the sample with the thickest nickel underplate in this study, 4 μm (Fig. 3d), is the most durable of the series with copper substrate; it was possible to slide at 500g, a load which caused catastrophic seizure when attempted with many of the other platings described in Figs. 2 and 3.

In Fig. 4a, the hard substrate, beryllium copper, is used with 2 μm of cobalt gold plate, and the results can be compared with Fig. 2c, cobalt gold on copper. Beryllium copper improves the wear of gold even more dramatically than does the intermediate (2.5 μm) thickness of nickel underplate (Fig. 2d) when on a copper substrate. Thus, Fig. 2c shows that at 200g a Wear Index of 100 was obtained within 20 passes with the copper substrate, while 700 passes were required for this to occur with beryllium copper. Most striking of all, 2.5 μm of nickel underplate on beryllium copper was able to reduce the Wear Index nearly to zero, even at 300g in runs to 700 passes (Fig. 4b).

Thick soft gold electrodeposits[12] have wear behavior indistinguishable from pure wrought gold, and the practice of making both contacts of pure gold has long been recognized to be impractical for unlubricated connectors, giving unacceptably high wear and friction. Figure 4c, with

3.3 μm of pure gold plate on copper, confirms that experience, a Wear Index of 100 occurring within 20 passes at 100 and 200g. On the other hand, 2.5 μm of nickel underplate was able to reduce wear considerably (Fig. 4d), a Wear Index of 100 at 200g not developing for up to 200 passes.

Historically, the original incentive to find golds for contact applications that were more durable than pure electrodeposits resulted in the development of the cobalt golds and similar hard platings. However, it is noteworthy that cobalt gold on nickel underplate is only slightly better than pure gold with the same underplate (Figs. 3c and 4d).

Figure 5 presents profilometric wear data for comparison with that from electrographic analysis, Fig. 2c, with 2-μm cobalt gold on copper. Results by both methods are strikingly similar. An additional finding, although expected, is that Wear Index does not rise sharply with numbers of passes until the depth of wear exceeds the thickness of the gold deposit. Subsequent analysis of sectioned samples revealed that a wear mechanism (prow formation with back transfer) was operating

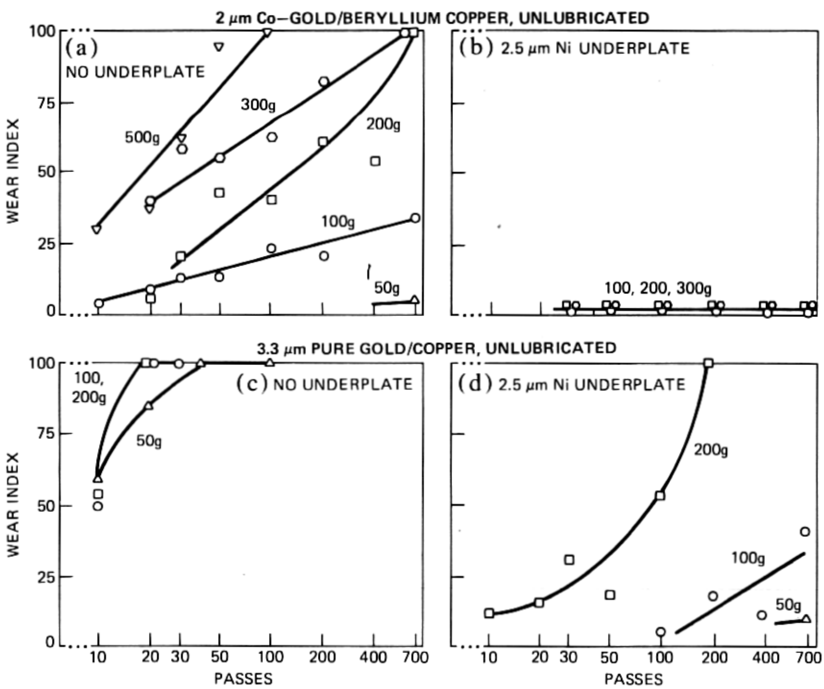

Fig. 4—Electrographic Wear Indexes from unlubricated adhesive wear runs. (a), (b) 2 μm cobalt gold electrodeposits on beryllium copper, with and without 2.5 μm nickel underplate. (c), (d) 3.3 μm pure gold electrodeposits on copper, with and without 2.5 μm nickel underplate.

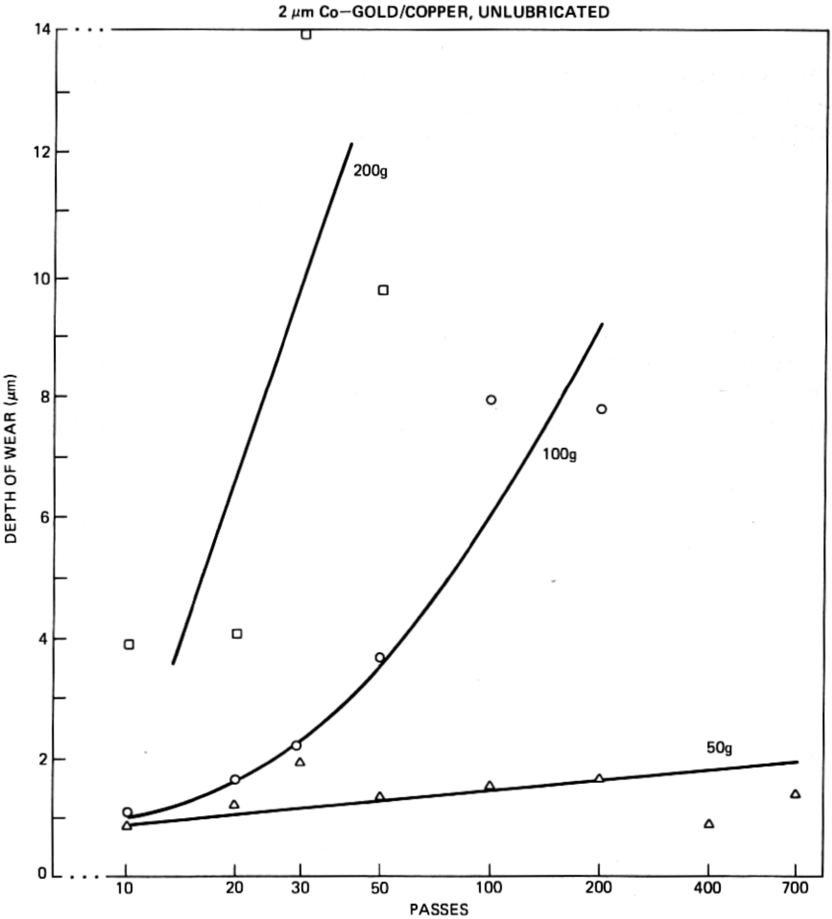

Fig. 5—Wear determined by profilometry from unlubricated adhesive wear runs with 2 μm cobalt gold electrodeposits on copper.

which permitted gold to persist in grooves in the wear track which are three to four times as deep as the thickness of the gold. This explains in part how Wear Indexes below 100 could be obtained in cases of severe roughening.

3.1.2 Lubricated

Adhesive wear was examined with a polyphenyl ether connector contact lubricant used in the telephone industry, as well as for connectors in computer and general-purpose applications. Boundary or elastohydrodynamic lubrication[13] prevailed, and there was good metallic contact and low contact resistance during sliding.[8] A high load, 500g, was used so as to promote adhesive wear because of the outstanding effectiveness of this lubricant.

Figure 6 presents the results with 3.3 μm of pure gold and 2 μm of cobalt gold, both on copper with and without 2.5 μm of nickel underplate. The data points are from independent runs. The overall conclusion is that the wear of all specimens is low in sliding for 700 passes. Additional runs with 2 μm of cobalt gold on copper at 500g for 1200 passes, and with 0.75 μm of cobalt gold on 2.5 μm nickel underplate at 200g for 4000 passes, discussed later, also gave little wear from microscopic examinations after test.

An unexpected result was the fall of the Wear Index with increasing numbers of passes following a rise early in sliding. This is most pronounced with the cobalt gold deposit (Fig. 6b) where the Wear Index was greater after 20 passes than after 700 passes. As shown later, this is attributable to self-healing which originates in the ability of the plating to flow laterally and to become burnished during sliding.

3.2 Abrasive wear

3.2.1 Two-body

Two-body abrasive wear of plated samples was studied with the pointed diamond rider in one pass at various loads, and the results

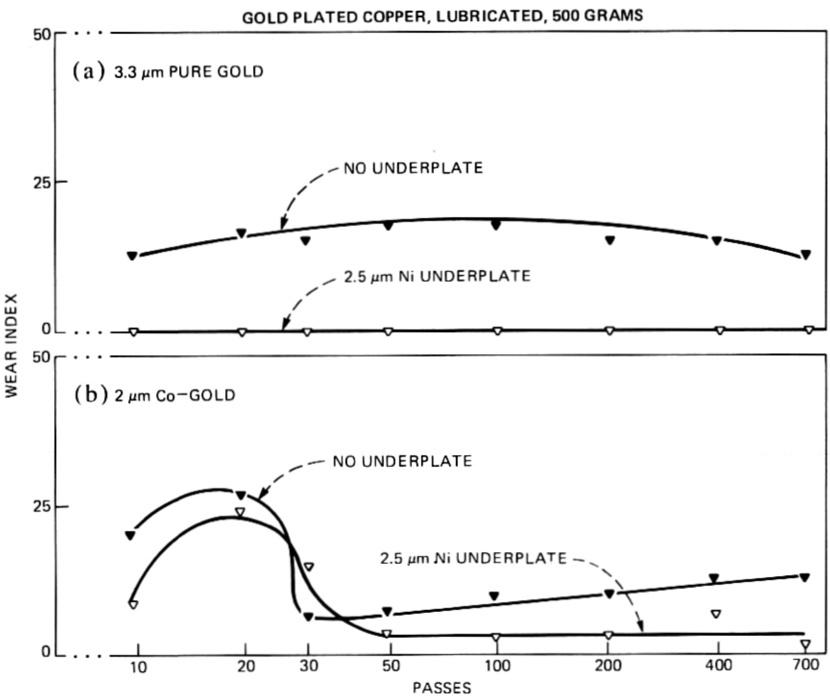

Fig. 6—Electrographic Wear Indexes from sliding at 500g with thin film of polyphenyl ether contact lubricant. (a) 3.3 μm pure gold electrodeposits on copper. (b) 2 μm cobalt gold electrodeposits on copper.

from electrographic analyses are given in Fig. 7. All curves have the same shape, a region in which the Wear Index increases little with increasing load until there is a precipitous break-through of the deposit. The point of inflection in the curves occurs at a Wear Index of 50 and a load that we term the "critical load for abrasive wear."

Increasing the thickness of the cobalt gold increases the critical load, for example, from 45 to 70g comparing 2 with 3.3-μm deposits on copper (Figs. 7a and 7b). Nickel underplate, 2.5-μm thick, increases the critical load from 45 to 90g with 2 μm of cobalt gold (Fig. 7a) and from 70 to 150g with 3.3 μm of cobalt gold plating (Fig. 7b). Likewise, a hard substrate, beryllium copper, increases the critical load from 45 to 150g with 2-μm cobalt gold deposits (Figs. 7a and 7c), and a further increase, from 150 to 200g, is obtained with nickel underplate on beryllium copper (Fig. 7c).

Critical load for 3.3 μm of pure gold on copper (Fig. 7d) was low, but this result is not representative; subsequent analysis, discussed later, revealed that the deposit was poorly adherent to the substrate. Most striking of all are the results with 3.3 μm of pure gold on 2.5-μm nickel underplate on copper (Fig. 7d), which gave the highest critical load, 250g, fully 100g greater than the value for the same thicknesses of cobalt gold and nickel underplate on copper.

Figure 7b shows the results with increasing thickness of nickel underplate on copper. There is no significant change of critical load with thin nickel, 1.5 μm, and the critical loads for 2.5 and 4 μm of

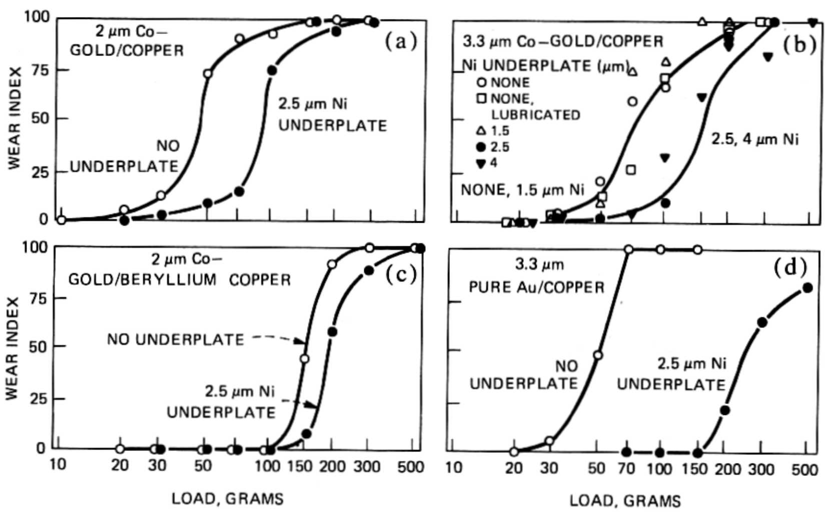

Fig. 7—Electrographic Wear Indexes from two-body abrasive wear runs with various gold electrodeposits, substrates, and underplates. Figure 7b shows no effect on wear by thin film lubricant, and 7d shows that results on specimen without underplate are poor because gold was non-adherent (see Fig. 15).

underplate are approximately the same. Finally, Fig. 7b shows that two-body abrasive wear is little affected by lubrication.

3.2.2 Three-body

Three-body abrasion was studied with 3.3-μm cobalt gold deposits, with and without 2.5 μm of nickel underplate. Runs at 50g were made to 200 passes, at which both samples had a Wear Index of 100 (Fig. 8). Control runs without abrasive gave a Wear Index of zero at 200 passes.

Nickel underplate markedly improved the durability of gold, five to ten times the sliding being required to attain comparable Wear Indexes.

IV. ANALYSIS AND DISCUSSION

4.1 Adhesive wear

The adhesive wear of gold has been extensively studied,[1] including the solid wrought metal, thick and thin electrodeposits in dry sliding, when adventitiously contaminated[7] and with liquid and solid lubri-

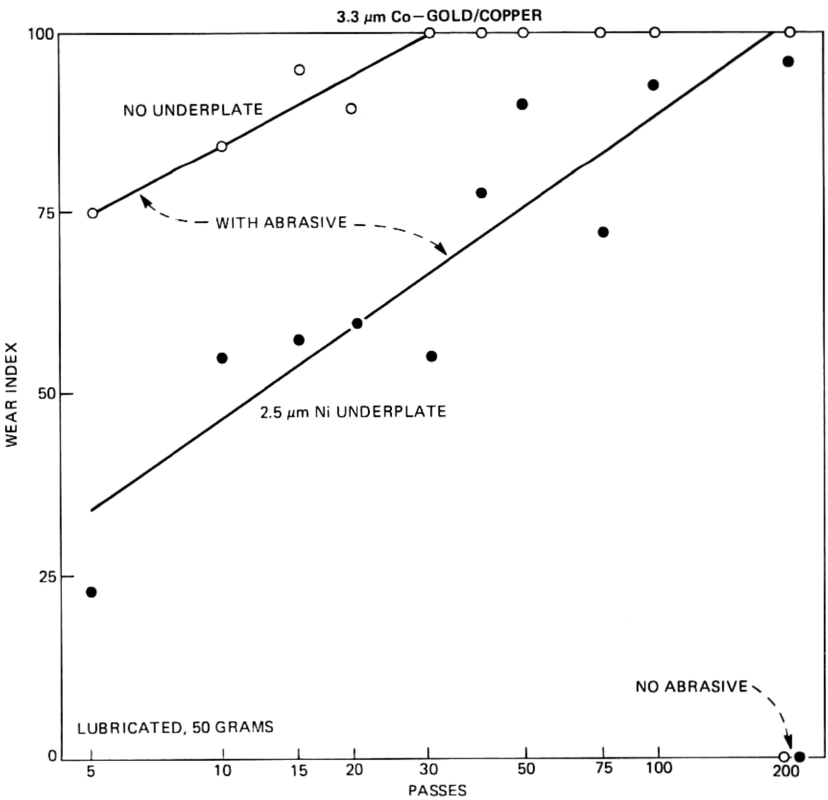

Fig. 8—Top: Electrographic Wear Indexes from runs with 3.3 μm cobalt gold electrodeposits on copper; three-body abrasion with coarse boron carbide, thin film lubricated.

cants. The present study of underplate and substrate variables shows that the mechanical properties of the basis material can have a profound effect on wear rate, although the mechanisms are the same. Details of sliding wear will be discussed, and as background, it is useful to summarize the present understanding of the adhesive wear of gold.

In connectors and other hardware, contact members are usually not identical in size and shape. Further, rubbing is generally localized to a small area on one surface and spread out on the other contact. In such situations, the unlubricated sliding of gold, and of many other metals, is characterized by unsymmetrical transfer, virtually all of the metal moving initially from one member to the other and not in both directions.

In a second step, the transferred metal is removed by back-transfer to the original part or is lost as loose debris.

These processes are readily observed with rider-flat apparatus in which the sliding members have the idealized geometry of a hemispherically ended rider contact that is pressed against a flat contact attached to a turntable. At the onset of rubbing, a lump of metal, called a prow, that comes from a flat, forms between and separates the specimens, as shown in Fig. 9. Sliding now continues at the junction between them. The prow projects against the direction of movement and gouges the opposing member. Routed solid becomes attached to the prow so that it grows in length.

A plausible explanation for the origin of the prow and why it is always located on the rider is that it is related to the difference in size of rubbing areas of the members. The population density of transfer particles (formed by breaking at other than the original interface of asperities of the specimens that have cold-welded together) is greater on the smaller part. Since compressive forces are large, the particles readily weld to each other and to the rider to form a prow. The prow is harder than either original surface because of the extreme degree to which it is worked in its transfer and growth.

Prows form on the smaller part in any arrangement of sliding members. For example, with edge connector contacts and printed circuit board fingers, prows form on the contact that corresponds to the rider in rider-on-flat systems.

When the rider traverses the same track repetitively, prow formation eventually ceases and is replaced by "rider wear," a process in which the member with the smaller surface involved in sliding loses metal. This is due to the accumulation of sufficient back-transfer prows on the flat to increase its hardness in all places to the level attainable by extreme work hardening. When the surface of the flat reaches the

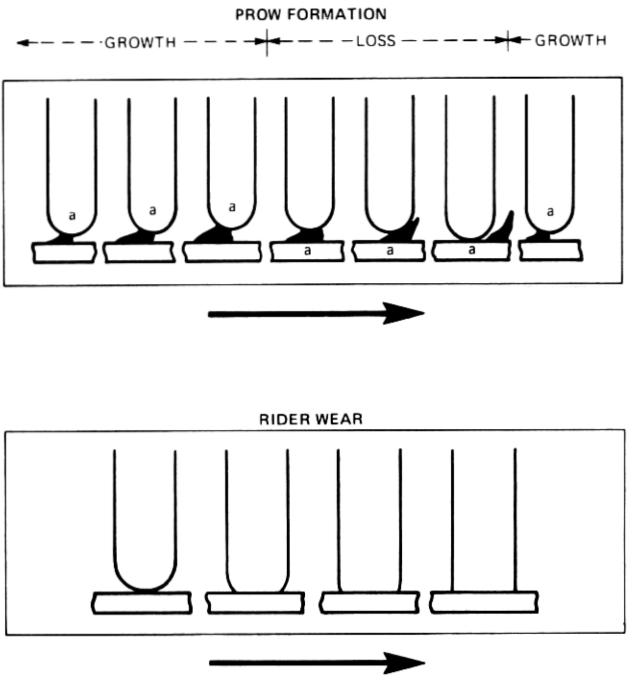

Fig. 9—Schematic representation of prow formation mechanism of adhesive wear. One of the processes by which rider loses prow and cold-welds to flat is shown. Letter "a" designates surface to which prow adheres. Arrow indicates direction of movement of the flat. Bottom: Schematic representation of rider wear mechanism.

hardness of the prow on the rider, routing of the flat ceases and a wear land appears on the rider. Figure 9 schematically shows progressive rider wear, with the rider shrinking in length as its hemispherical end wears away.

The number of passes to the transition from prow formation to rider wear is related to both track length (in unidirectional or reciprocating sliding) and to load. The shorter the track or higher the load, the more quickly will the transition come.

Past the transition, the flat gains mass and the rider loses metal by transfer to the flat or as loose debris.

Prow formation occurs with dissimilar metals, provided that the unworn flat is not excessively harder than the unworn rider. The flat provides prow metal which wears the flat in the usual way. Systems have also been observed with soft riders on hard flats in which transfer early in the run is by smearing of rider metal on the flat. Eventually, however, on repeat passes, the transfer metal is picked up by the rider and becomes so worked with resulting increase in its hardness that it begins to rout the flat. Prow formation ensues.

Figure 10 illustrates the prow formation mechanism and the effect of nickel underplate. The letter designations in the figure refer to vertical rows of photomicrographs: (a) to (d), 2 μm cobalt gold plate on copper and (e), 2 μm cobalt gold plate and 2.5 μm nickel underplate on copper.

Figure 10a, from initial sliding at a light load (20g, 1 pass), shows cold welding of asperities of the contact members and transfer of gold from rider (soft) to flat (hard). After a few additional passes, the direction of metal transfer reverses with the initiation of prow formation, as in Fig. 10b (20g, 15 passes) where minute fissures now appear in the gold plate with attendant loosening of a particle of the deposit. It should be noted that, at higher loads, prow formation occurs at the initiation of sliding, without preliminary wiping of rider metal on the flat. In Fig. 10c, prow formation continues with increasing loss of metal from the flat and the development of porosity (center of track) in the deposit. A secondary wear process involves plowing or abrasion of the flat by severely work-hardened prows which persist on the rider. This gives elongated wear features, often for the full length of the track (100g, 100 passes). Figure 10d shows further development of the process in (c) resulting in deep grooving of the track. The rider has acquired a large prow, and the wear track is extensively covered with coarse back-transferred metal (former prows). Both rider and flat have loose matter of varied size and shape, including equiaxed, plate-like, and roller-shaped wear particles. Not shown in the figure is the advanced stage of wear when prow formation ceases and rider wear occurs. The effect of nickel underplate on sliding in Fig. 10e is to reduce the scale of transfer and wear, with smaller prows, less debris, and lower Wear Indexes. The photographs in Fig. 10e were taken at sliding conditions and numbers of passes identical to those in (d). Hard underplates and substrates can also increase the effectiveness of marginal lubricants and of adventitious contamination.

A graphic illustration of the value of nickel underplate in increasing the durability of gold plate is given in Figure 11, based on data presented in Figs. 2 and 3. Figure 11a shows that the resistance to wear-through of gold plate increases dramatically when its thickness exceeds a particular value, about 3.5 μm for cobalt gold plated copper at 100g (unlubricated) calculated for a Wear Index of 50. This thickness increases with increasing load and for smaller Wear Indexes. With 2.5 μm of nickel underplate, the thickness of cobalt gold at which durability shows a sharp increase is only slightly in excess of 2 μm. In Fig. 11b, passes to the Wear Index of 50 is plotted against thickness of nickel underplate for 3.3 μm of cobalt gold. Again, a sharp rise in durability occurs at a characteristic nickel thickness, which becomes greater the

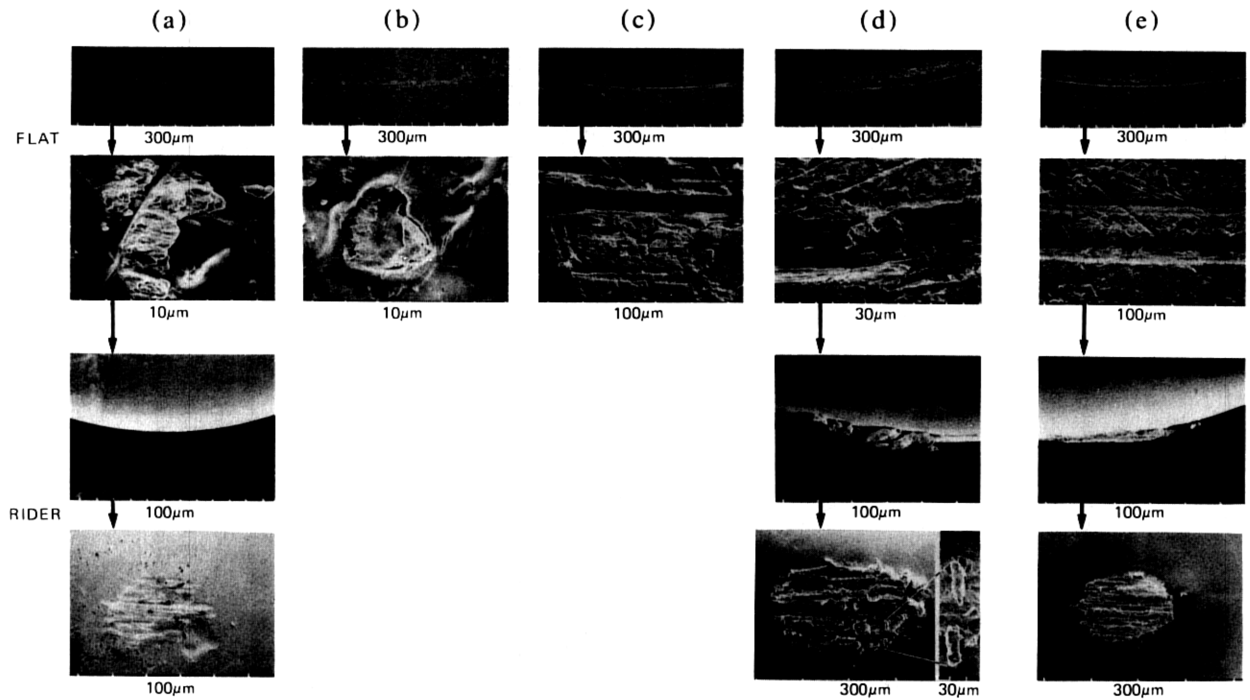

Fig. 10—Worn specimens from sliding in the absence of lubricants. Flats: 2 μm cobalt gold electrodeposits on copper. (a)-(d) Plated directly on substrate. (e) Plated with 2.5 μm nickel underplate. Riders: solid gold (views are at right angles and normal to the worn surface). (a) to (d) Runs of increasing severity. (d) and (e) At identical conditions of sliding, illustrating similarity of wear processes with significant attenuation in severity when nickel underplate is used. Scanning electron microscope numbers are distances between adjacent white markers.

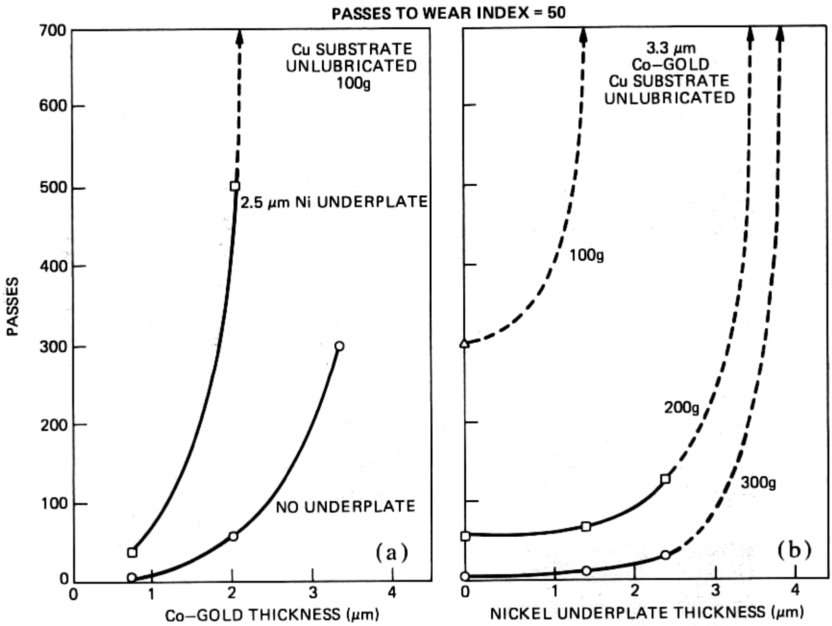

Fig. 11—Unlubricated sliding at adhesive wear conditions (passes to Wear Index = 50). (a) 0.75, 2, and 3.3 μm cobalt gold electrodeposits on copper. (b) 3.3 μm cobalt gold electrodeposits on copper with 0, 1.5, 2.5, and 4 μm nickel underplate. Arrows at ends of dashed curves indicate runs at 700 passes without achieving a Wear Index of 50.

larger the load. From Figs. 11a and 11b, the less the gold thickness, the thicker the nickel underplate has to be to obtain a given level of protection, e.g., against reaching a prescribed Wear Index at a designated load.

It has been shown that sliding occurs initially with considerable transfer, roughening, and wear of the flat. These processes diminish in severity to an equilibrium level as sliding continues.[14] The early stage of sliding is where most connectors operate during their lifetimes, common service requirements being 200 insertions and withdrawals (400 passes). The use of nickel underplate is a way to permit the high wearing conditions of early sliding to occur without excessive loss of gold, or with a lesser thickness of gold than otherwise would be required.

4.2 Lubricated sliding and burnishing

Lubricants are desirable for sliding contacts because they reduce the interaction of surfaces and, thereby, adhesive transfer and wear. If only a few scattered asperities continue to touch, contact resistance during sliding would be little different from that of stationary contacts. Connectors ordinarily do not carry current during engagement, and thus do not have the critical requirements for low wear and electrical noise of instrument slip rings and many other sliding metallic contacts.

It has been shown[8] that lubricants can be effective through a wide range of sliding conditions, and that adventitious contamination, although variable, may be adequate for some applications.[7]

Figure 12 illustrates surface changes from sliding with a good lubricant, a liquid polyphenyl ether, characterized by little transfer and wear and a marked tendency for the surfaces to become burnished. The photomicrographs are from copper flats plated with 2 μm of cobalt gold. In Fig. 12a, there are signs of burnishing of the flat with the simultaneous appearance of a few fine scratches and a small amount

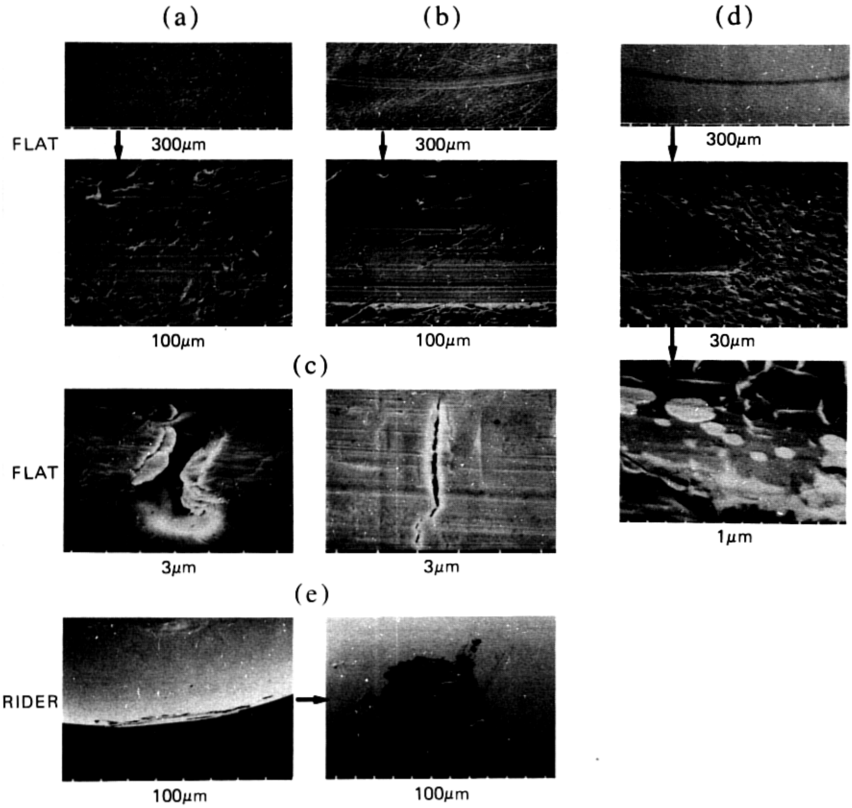

Fig. 12—Worn specimens from sliding with a thin film of liquid polyphenyl ether lubricant. (a), (b), (c) 2 μm cobalt gold electrodeposits on copper flats at 500g (a = 4 passes, b = 1200 passes, c = 10 passes). (d) 0.75 μm cobalt gold on 2.5 μm nickel underplate on copper flats (200g, 4000 passes). (e) gold rider from sliding against 2 μm cobalt gold plated copper flat (500g, 100 passes). Figures 12a, 12b, and 12d illustrate burnished surfaces due to lateral movement of metal on which are superimposed very fine scratches. Figure 12d has a nearly continuous gold layer (from electrographic testing), but so thin that contrast differences appear due to the underplate from the electron beam which has penetrated the gold. Figure 12c (left and right) are concurrent processes: left is burnishing in which a pit or pore initially present in the deposit is being closed, and right is a tiny fissure (rare) that has developed in the deposit. Figure 12e shows a small prow on the rider (views at right angles and normal to the tip).

of wear-induced porosity (500g, 4 passes). On further sliding (Fig. 12b), burnishing continues, with marked thinning of the gold plate evidenced by the grey striations in the track attributable to the copper substrate from SEM electron beam penetration of the overlying gold (500g, 1200 passes).

Figure 12c illustrates concurrent wear processes in gold plate: left, lateral flow of metal (burnishing) which has partially closed over a micropit or pore in the as-plated deposit; and right, a fine crack or tear (500g, 10 passes).

These phenomena are qualitatively the same with nickel underplate. Figure 12d, with 0.75 μm of cobalt gold on 2.5 μm nickel after prolonged sliding (200g, 4000 passes), shows the gold to be still nearly continuous, proven by little response in an electrographic test. The center photomicrograph shows that a small amount of fine loose debris has formed and accumulated mainly at the ends of the track. The wear track is concave along its width, most of the wear and metal flow occurring in the center because of the hemispherical shape of the rider. Figure 12d (bottom), the middle of the wear track (along its width) at high magnification, has a thin but continuous gold layer. The light patches are thicker gold in micro depressions of the unworn surface.

Figure 12e shows the gold rider after 100 passes at 500g against a 2 μm cobalt gold-plated copper flat, thinly coated with polyphenyl ether. Lubricant transferred to the rider was not removed prior to SEM study and appears as a dark stain. A small prow on the rider accounts in part for the small loss of metal by the flat and is the cause, along with loose debris, of the fine scratches in the cobalt gold plate.

It was found that burnishing and widening of the track proceeds more rapidly in the absence of intentional lubrication, if the samples are intrinsically low wearing. An example is 3.3 μm of cobalt gold on 2.5 μm of nickel underplate (Fig. 3c). A section was made across the wear track from a run for 40 passes at 200g, and 171 measurements of gold thickness were obtained at fixed increments, 45 outside the wear track and 126 within its boundaries. A probability plot (Fig. 13) of the two sets of measurements clearly reveals the extent of burnishing that has occurred; gold is displaced from the high spots to the low spots in the surface (inset), with some measurements less than 1 μm compared to the rather uniform 3.3 μm original deposit, and with measurements at the other end of the distribution greater than 5 μm. It can be seen, at the 50-percent point, the median gold thickness decreased in sliding by 0.1 μm, or 3 percent of the unworn value. The worn gold appeared as loose debris and transfer matter. The photomicrographs also show no change in thickness of nickel underplate during sliding. Fresh surface was not created by lateral flow of metal, since the gold deposit is dense and featureless.

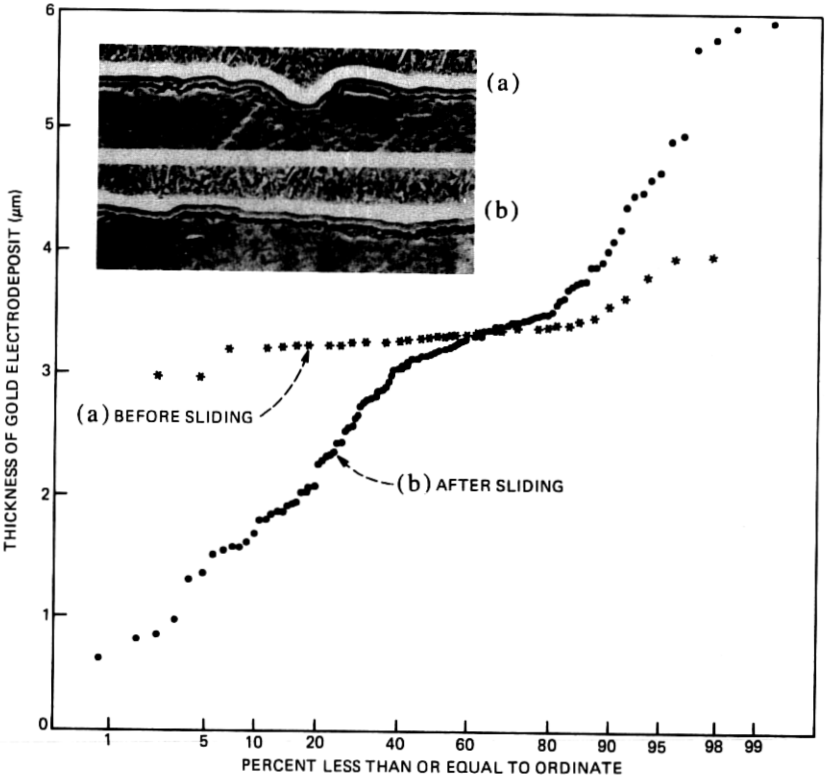

Fig. 13—Thickness distribution of gold plate. Cobalt gold electrodeposit on nickel underplate (3.3 and 2.5 μm average thicknesses) on copper. Section a, unworn flat, and section b across wear track from sliding at 100g, 40 passes with solid gold rider. The inset is an SEM photograph of the section showing a portion of the wear track. The gold plate is the light band, and the dark band below it is nickel underplate.

The evidence of burnishing in Figs. 12 and 13 show how the Wear Index can fall with continued sliding (Fig. 6). Remaining to be explained, however, is the increase in Wear Index from the initiation of the run, before significant burnishing has developed. The rise of the Wear Index is due to a brief period of severe wear, during which small-scale prow formation occurs. As the surfaces run in, contact pressure diminishes and conditions become more favorable for a hydrodynamic contribution to sliding by the contact lubricant.[13] Wear rate then becomes less and burnishing begins to predominate. The balance between adhesive wear, with attendant roughening and high friction, and burnishing having the opposite effect is delicate and can shift in the course of a single run.

4.3 Abrasive wear

4.3.1 Two-body

Figure 14 illustrates surface damage which occurs in two-body abrasion. The samples are arranged in order of decreasing surface damage (left to right) and increasing load (top to bottom). The samples are plated with 3.3 μm of gold: (a) cobalt gold on copper; (b) cobalt gold on 2.5 μm of nickel underplate, and (c) pure gold on 2.5 μm of nickel underplate. At light loads, relatively smooth depressions having horizontal striations appear which can completely alter the topography of the surface. Tensile cracks in the deposit develop at higher loads, characteristic of the material, and grow in size and number as the load is further increased. Porosity in the gold originates in these cracks, as well as from removal of gold by a cutting action which exposes the underlying metal.

Although the width of the wear tracks at a given load is greater with pure gold compared to those from an equal thickness of cobalt gold on

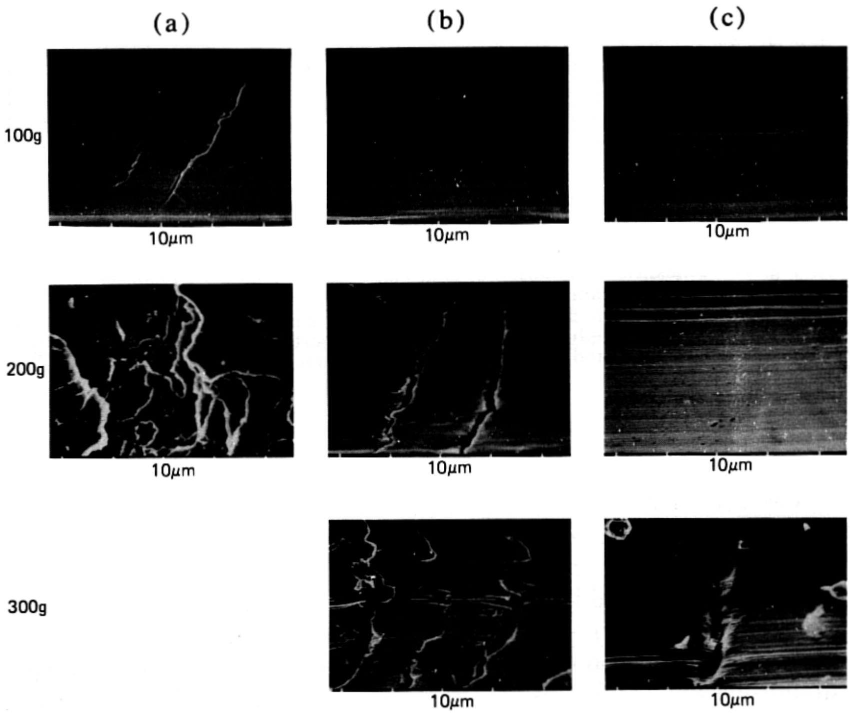

Fig. 14—Worn gold plated flats from single pass sliding with conical diamond rider (two-body abrasion) at various loads. (a) 3.3 μm cobalt gold electrodeposit on copper. (b) same as (a) with 2.5 μm ductile nickel underplate. (c) 3.3 μm pure gold electrodeposit on 2.5 μm nickel underplate on copper. Sliding in horizontal direction. Wear appears as smooth depressions in surface with tears in gold coating. Nickel underplate (b) reduces extent of tearing. Pure gold (c) resists tearing better than cobalt gold due to its greater ductility.

the same substrate because it is softer, the pure gold sample has significantly less porosity (see also Figs. 7b and 7d for 3.3 μm of gold plate on 2.5 μm nickel). This is attributable to its greater ductility with an elongation estimated to be 2 to 3 percent, compared to less than 1 percent for the cobalt gold.[6] It is apparent also that a hard ductile underplate (nickel) on a softer substrate (copper and beryllium copper) provides significant protection for the gold deposit (Figs. 7a, 7b, and 7c). Thus, both hardness of the composite of gold and underplate and the ductility of the gold control the resistance of the finish to two-body abrasive wear.

With pure gold plated directly on copper (Fig. 7d), the load range in which there is a steep rise of Wear Index is abnormally low compared to the load range for cobalt gold on copper (Fig. 7b). This was probably due to poor adhesion of the deposit on this particular sample which led to premature stripping, as shown in Fig. 15.

4.3.2 Three-body

To obtain three-body abrasion, particles were used that were substantially harder (2750 kg/mm^2) than the plating and too coarse to be buried in the valleys between the high spots of the specimen surface. As in two-body abrasion, the thin lubricant film probably did not

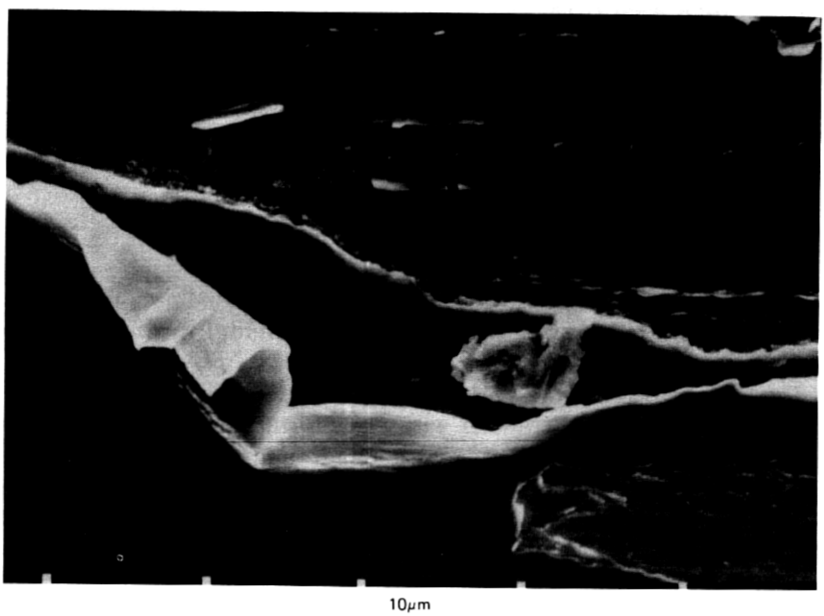

Fig. 15—Effect of sliding on poorly adherent deposit. Plating is disrupted and porous. Two-body abrasion: 3.3 μm pure gold electrodeposit on copper. Diamond rider, 1 pass at 100g (see Fig. 7d).

mitigate wear. The wear processes of two-body and three-body abrasion are identical, due to penetration of the gold surface under load with the development of porosity by plowing and tearing of the gold. A hard ductile underplate, nickel, is effective in reducing wear.

The rate of increase of Wear Index with numbers of passes (Fig. 8) is small, Wear Index doubling from about 45 to 90 between 10 and 100 passes with gold on nickel underplate. This is probably due to extensive rolling of the loose abrasive during which it would be ineffective in causing wear.

4.4 *Effect of hardness and ductility of contact material on its wear*

The hardness of a multilayer contact material reflects the hardness of the individual layers, depending on their thickness, load, and the shape and size of the indenter. In the present study, deposit thicknesses, loads, dimensions of the riders, and conditions of sliding were chosen so as to realistically model the wear processes of separable electronic connectors.

It was found that increasing the hardness of any of the layers of the contact material—gold plate, underplate, or substrate—could be beneficial in reducing wear. To a first approximation, the hardness of the samples determined normal to the surface with a Knoop indenter at a low load permitted ranking the composite contact materials in inverse order of their wear resistance in unlubricated sliding according to Figs. 2 to 4. Some measured hardnesses are given in Table III.

The dependence of adhesive wear on hardness is explained by all the common theories of wear. For example, the "adhesion" theory, attributed to Holm based on an atomic model, and the Archard version, based on asperity interactions,[15] give the relationship:

$$\text{Wear Volume } \alpha \frac{\text{(distance slid) (load)}}{\text{hardness}}.$$

Physically, an increase in hardness reduces the real area of contact and thus the numbers of junctions which can weld. Prow formation is a special case of adhesive wear.

In the lubricated adhesive wear experiments (Fig. 6), there was a small amount of metal transfer with prow formation early in the runs at high load, shown in Fig. 12e with cobalt gold-plated copper. Prow formation is attenuated by increasing the hardness of the composite contact material.

In the case of abrasive wear, increasing the hardness of the material will, in general, also improve its wear resistance because the depth of penetration of the surface is reduced, and with it the volume of metal carried away by plowing. However, ductility is also a factor in wear because even when the gold layer is not removed, it can crack if it is

Table III—Hardness of plated contact materials*

Co-Gold (μm)	Ni Underplate (μm)	Substrate	KHN_{25}	Depth of Penetration of Indenter (μm)†
2	None	Cu	57	2.6
2	2.5	Cu	64	2.5
3.3	2.5	Cu	95	2.0
3.3	4	Cu	134	1.7
2	2.5	Be-Cu	294	1.1

* Hardness determined normal to surface.

† Depth of penetration $= \dfrac{\text{length of diagonal, Knoop}}{30.53}$.

unable to yield plastically under the loaded slider. Thus, pure soft gold may be better able to resist abrasive wear than cobalt gold, as shown in Fig. 7 with nickel underplate. In the adhesive wear studies, prows that persisted on the rider were able to cause further wear in repeat pass sliding by secondary abrasion.

Although primary attention has been directed to the flat in this investigation, prior[1] observations permit statements to be made concerning wear behavior were the rider made of a material other than solid gold, such as cobalt gold-plated copper alloy. When wear of the flat occurs with the formation of prows, the material of the opposing contact is unimportant, the rider merely acting as a holder for the prow. The prow appears, grows, and breaks off as sliding continues but a new one immediately forms without damage to the rider. Eventually, however, when the transition to rider wear occurs, the rider begins to lose metal. The rider should be made of a hard material to reduce its wear rate, and nickel underplate is desirable.

A few connectors are designed so that their mating contacts have identical geometry. In this case, either member can accept prows with the other one wearing, and the role (rider or flat) played by a contact may change several times as sliding continues.

4.5 Application to hardware

An objective of this investigation was the determination of the role of nickel underplate and of substrates in the wear of gold plate so that guidelines could be developed in contact materials selection for electronic connectors. This study has shown that wear, determined by the development of porosity, can be reduced when a hard ductile underplate such as pure nickel is used. Increasing substrate hardness has the same beneficial effect, although in practice the substrate material is selected for reasons other than hardness, such as spring properties, formability, and conductivity. Thus, the underplate remains the only way that the hardness of a gold contact finish can be increased.

Advantages to the use of nickel underplate were demonstrated for all wear mechanisms: adhesion, two-body abrasion, three-body abrasion, and brittle fracture. It was also found that at the conditions of this study there was little advantage in using thin, i.e., 1.5 μm, nickel plating with thick (3.3 μm) gold, but that nickel deposits 2.5 μm or greater in thickness could be highly desirable. The benefits in using nickel underplate were found for a wide range of gold thickness, but were most striking with the thinnest golds.

It does not follow, however, that a satisfactory gold contact cannot be designed without a hard underplate. Depending on the numbers of insertions which are required, the level of porosity in the gold layer that can be tolerated and on other factors, performance may be adequate in its absence. For example, there is little reason to use nickel underplate with very thick (say, greater than 5 μm) gold deposits at loads typical of electronic connectors. Another example would be when abrasive wear is unlikely to occur, and good contact lubricants are employed to minimize adhesive wear. At the other extreme, when lubrication is not used or when particulate contamination of the contact occurs, as with glass fibers from the leading edge of a glass-epoxy printed circuit board, nickel underplate is especially desirable because of its ability to control both the adhesive and abrasive wear of gold plate.

When the application of the connector or printed circuit board cannot be controlled or is unknown, the best course is to specify nickel underplate. This recommendation is especially applicable when thin (below 1 μm) gold coatings are used.

V. ACKNOWLEDGMENT

Dale E. Heath contributed significantly to this investigation by his excellent metallographic work.

The assistance of the Sel-Rex Division, Oxy Metal Industries Corporation is acknowledged for plating the samples used in this study.

APPENDIX

Electrography

The procedure in this work was to use Kodak Dye Transfer Paper F that had been soaked for 15 to 45 minutes in an electrolyte-indicator solution of 20g of the disodium salt of dimethylglyoxime and 20g of sodium chloride in 1 liter of water. Excess liquid was removed by squeezing the paper between rubber rollers, and the paper pressed against the specimen at 70 kg/cm^2 between titanium electrodes. Current was applied from a constant voltage source at 2.0V dc for 1 minute. The papers were peeled from the samples and dried in an oven at 50°C. Colored spots (red for nickel and green for copper) signified exposed base metal. Spots were, however, somewhat larger than worn areas in the specimen to which they could be related due to spreading of the chemicals in the paper. The electrographic prints were made within 1 day of the wear runs.

Electrography can be made more or less severe by varying applied voltage. However, at about 4-V dc, the gold is stripped from the specimen.

It was found that there is no significant change in the surface of a worn deposit as a result of electrographic testing. Distinguishing surface features in a track were photographed with the SEM at various magnifications from 30 to 5000 diameters both before and after obtaining an electrograph. This finding is in agreement with an earlier[11] optical study at 13 to 75 diameters.

REFERENCES

1. M. Antler, "Tribological Properties of Gold for Electric Contacts," IEEE Trans. on Parts, Hybrids, and Packaging, *PHP-9* (1973), pp. 4–14.
2. C. A. Holden, "Wear Study of Electroplated Coatings for Contacts," Proc. Holm Seminar on Electrical Contacts, Illinois Inst. Tech., Chicago, Ill. (1967), pp. 1–19.
3. A. J. Solomon and M. Antler, "Mechanisms of Wear of Gold Plate," Plating, *57* (1970), pp. 812–816.
4. G. Horn and W. Merl, "Friction and Wear of Electroplated Hard Gold Deposits for Connectors," Proc. Sixth International Conference on Electrical Contact Phenomena, Illinois Inst. Tech., Chicago, Ill. (1972), pp. 65–72.
5. W. Burt and R. Zimmerman, "Wear Capabilities of Gold Over Copper and Nickel Underplates," Proc. Third Annual Connector Symposium, Electronic Connector Study Group, Inc., Cherry Hill, N.J. (1970), pp. 435–444.
6. J. M. Dueber and G. R. Lurie, "The Strength and Ductility of Some Gold Electrodeposits," Plating, *60* (1973), pp. 715–719.
7. M. Antler, "Wear of Gold Plate: Effect of Surface Films and Polymer Codeposits," IEEE Trans. on Parts, Hybrids, and Packaging, *PHP-10* (1974), pp. 11–17.
8. M. Antler, "The Lubrication of Gold," Wear, *6* (1962), pp. 44–65.
9. M. Antler, "Wear and Contact Resistance," Ch. 21 in *Properties of Electrodeposits—Their Measurement and Significance,* R. Sard, H. Leidheiser, Jr., and F. Ogburn, eds., Princeton: The Electrochemical Soc., 1975, pp. 353–373.
10. H. W. Hermance and H. V. Wadlow, "Electrography and Electrospot Testing," Ch. 25 in *Standard Methods of Chemical Analysis,* 6th ed., W. W. Scott, N. H. Furman, and F. J. Welcher, eds., New York: Van Nostrand, 1962, Vol. 3, Part A, pp. 500–520.
11. H. J. Noonan, "Electrographic Determination of Porosity in Gold Electrodeposits," Plating, *53* (1966), pp. 461–470.
12. M. Antler, "Wear of Electrodeposited Gold," ASLE Trans., *11* (1968), pp. 348–360.
13. W. E. Campbell, "The Lubrication of Electrical Contacts," IEEE Trans. on Components, Hybrids, and Manufacturing Technology, *CHMT-1* (1978), pp. 4–16.
14. M. Antler, "Stages in the Wear of a Prow-Forming Metal," ASLE Trans., *13* (1970), pp. 79–86.
15. E. R. Braithwaite, ed., *Lubrication and Lubricants,* New York: Elsevier, 1967, p. 58.