



The William Blum Lectures

#29 - Morton Antler - 1988



The 29th William Blum Lecture
Presented at the 75th AESF Annual Convention (SUR/FIN 1988)
in Los Angeles, California
June 27, 1988

The Tribology of Contact Finishes for Electronic Connectors

by
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Recipient of the 1987 William Blum
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Editor's Note: Originally published as *Plating & Surface Finishing*, 75 (10), 46-53 (1988) and 75 (11), 28-32 (1988), this article is re-publication of the 29th William Blum Lecture, presented at the 75th AESF Annual Convention, SUR/FIN 1988, in Los Angeles, California on June 27, 1988.

ABSTRACT

This paper was originally published in two parts on the tribology of electrical contact finishes. The subjects covered in the first installment include friction, mechanical wear, fretting corrosion and frictional polymerization - all vital processes that affect the performance of contact finishes in electronic connectors. The dominant wear mechanisms (i.e., adhesion, abrasion and fretting) are also discussed. Substrate and lubrication effects on the tribology of contact finishes are elaborated on in the second part of this lecture. An Appendix summarizing the salient points in both of these papers is presented at the end.

Part I: Mechanisms of Friction and Wear

Introduction

An electric contact is the heart of separable connectors and printed circuit boards, instrument slip rings, switches and other current-carrying devices. These components are designed to allow the engagement or disconnection of an electronic assembly or to permit one contact surface to be moved while it touches another. Because the contact resistance between mating surfaces must be low, gold and other noble metals are used extensively. Tin and tin-lead solder are exceptions because their deformability allows insulating surface oxide films to be readily broken when contact is established.

The main applications of contact-containing components have been for telecommunication equipment, computers, aircraft and aerospace devices, various instruments and military hardware. However, the use of consumer products that contain large numbers of separable contacts is growing rapidly, especially in the automotive and entertainment fields. In developing finishing technologies for the noble metals, the high cost, limited availability and general unsuitability of these metals as structural contact materials have been the major challenges.

In this paper, metal finishing is interpreted broadly to embrace the diverse processes of electroplating, electroless plating, cladding and a variety of physical coating and surface-modification methods such as ion plating and ion implantation. Finishing can be extended to post-plating passivation treatments for porous deposits and even to contact lubrication when the application of a lubricant is made on the plating line directly following metal deposition.

Tribology* is important because contact coatings are generally thin, and it is necessary to maintain the integrity of the deposit during sliding to minimize exposure of base underplatings and substrates. The requirement for low friction is becoming more

Tribology is the science and technology of interacting surfaces in relative motion. It is derived from the Greek *tribos* which means *rubbing*. It embraces the study of friction, lubrication, mechanical wear and practices (*e.g.*, design) that relate to this field. Tribology does not include other forms of metal loss such as corrosion and arc erosion, although some forms of wear have both a mechanical component and a chemical or electrical component (*e.g.*, fretting corrosion).

critical as the numbers of contacts in separable connectors increases. While resistance to corrosion and tarnishing and the thermal stability of contact resistance have always been of concern in the selection of finishes, it is not often realized that the tribological requirements of coatings have been of equal or greater importance in molding metal finishing practices. As will be discussed for electrodeposits, the incorporation of cobalt or nickel in gold electrodeposits, the practice of using a gold flash on palladium, and the use of nickel underplates developed largely because it was realized that these practices would improve the tribological performance of the contact finish.

The objective of this review is to present the tribological background behind modern practices in the metal finishing of contacts and provide guidelines for selecting finishes for electronic connectors. Some thoughts on the needs and possible future developments are also given.

Contact wear mechanisms

Mechanical wear involves loss of material as loose particles from solid surfaces. In special cases, the following are also classified as wear: dimensional changes or roughening due to metal transfer in the absence of loose-particle formation, the cracking of brittle coatings, and mechanically induced flow without measurable transfer or loss (*i.e.*, burnishing).

Adhesive wear occurs when surfaces undergo metal transfer. Adhesive bonds are formed between touching asperities that are stronger than the cohesive strength of the metal. This bond formation results in plucking of material, which then may be lost from the surface to which it transfers during subsequent traversals.

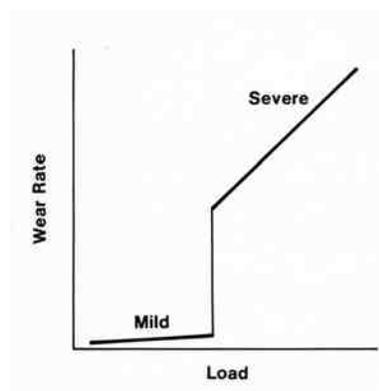


Figure 1 - Regimes of wear.

Many metal systems operate at widely different rates of adhesive wear, from mild to severe, and the scale of wear can change in a narrow range of load (Fig. 1). Below the transition load, wear debris is finely divided; above it, debris is coarse. Provided the surfaces are very clean, sliding with noble metals is in the severe regime even under small loads (*e.g.*, 1 g for pure gold plate and 10 g for cobalt-gold alloy deposits). In practice, the transition loads are related to the removal during sliding of adventitious contaminants such as adsorbed organic air pollutants. Such materials can be strikingly protective,¹ but, when repeat-pass sliding occurs too quickly for the contaminants to be renewed, the transition to severe wear will occur.

The severe adhesive wear of contact metals is a process called prow formation,² which can be described phenomenologically as follows for contacts of the same material. When the contacts are of different sizes, metal transfers from the part with the larger surface involved in sliding to that with the smaller surface (*e.g.*, from flat to rider in a rider-flat apparatus). A lump of work-hardened metal (the prow) builds up

and in turn wears the flat by continuous plastic shearing or cutting, while the rider does not wear (Fig. 2). Prows are lost from the rider by back transfer to the flat or as loose debris. Prows consist of thin, overlapping layers of metal (Fig. 2f, back transfer prow). If the rider always traverses virgin metal, prow formation continues indefinitely.

When contact members of the same material are identical in size and shape, an initial prow can come from either member. However, once transfer occurs, the receptor becomes the rider, and the opposing surface wears. With dissimilar metals, prows will form even when the flat is harder than the rider provided this difference is not greater by a factor of about 3. The friction and contact resistance of the system are determined by the prow metal. Thus, a palladium-plated rider sliding on a gold-plated flat behaves as does gold on gold, while a gold rider on palladium slides like palladium on itself.³

Another example is that of electrodeposited cobalt-gold mated to pure gold or to gold-silver alloys such as 70/30 Au-Ag. These wrought metals are much more prone to severe adhesive wear than the electrodeposit.⁴ If the larger surface involved in sliding is made of the more adhesive, wear-resistant metal, then the sliding performance of the couple will be superior to the sliding performance when the contact materials are reversed. For this reason, contacts of edge connectors for printed wiring boards made of wrought gold-silver alloys are generally acceptable when the board fingers are plated with cobalt-gold.

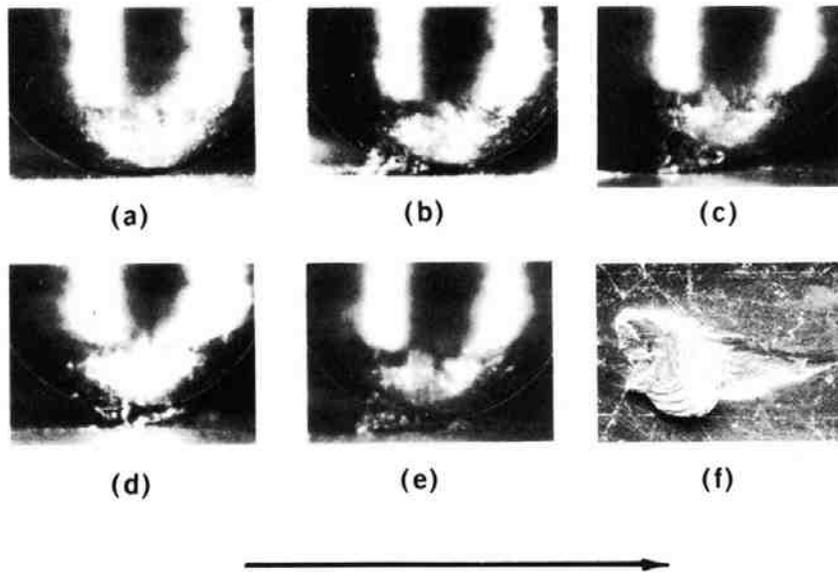


Figure 2 - Prow formation mechanism of sliding for a rider 3.2 mm in diameter on flat specimens with gold contacts and a 500-g load. Shown are (a) start of run, (b) well-developed prow, (c and d) loss of portion of prow by back-transfer to flat, (e) newly formed prow and (f) prow back-transferred to flat consisting of overlapping thin layers of metal. The arrow indicates the direction of movement of the flat.

Whenever dissimilar metals are mated and metal transfer occurs, the interfacial layer determines the behavior (including wear rate, coefficient of friction, contact resistance, and chemical properties); the equilibrium composition may take considerable repetitive sliding to develop; and the relative sizes of the contact regions of the members in the couple are as important as the metals themselves in determining the interfacial properties. This important concept extends beyond prow formation.

Prow formation occurs with gold, palladium, platinum, silver, copper, copper-beryllium alloys, phosphor bronzes, lead, aluminum, iron and many other metals. Metals that do not work harden, such as indium at room temperature, fail to form prows.

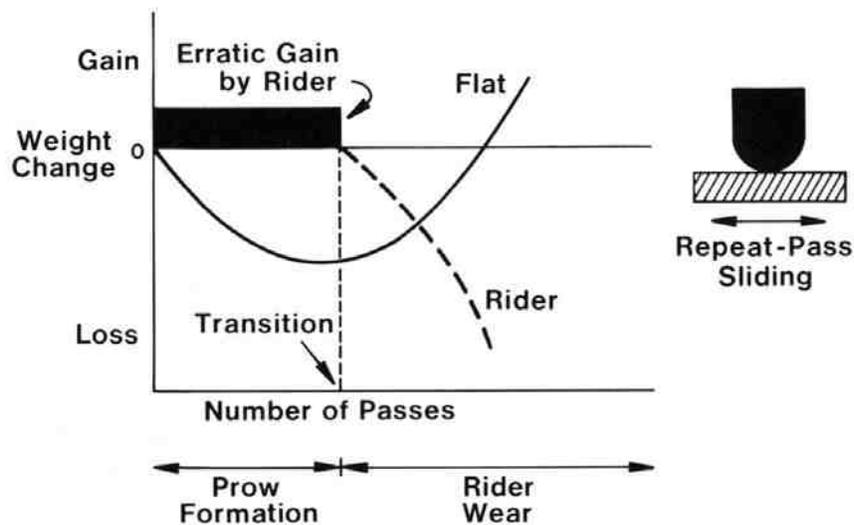


Figure 3 - Schematic diagram showing weight changes of rider and flat in repeat-pass sliding, from prow formation through the transition and into rider wear.

If the rider traverses the same track repetitively, prow formation eventually ceases and is replaced by rider wear, a mechanism in which the smaller contact surface wears. Rider wear occurs primarily by transfer to the flat with some loose-particle formation. In rider wear, the flat gains mass (Fig. 3). The transition is due to the accumulation of sufficient back-transfer prows on the flat to increase its hardness in all places to the level of extreme work hardening. When the surface of the flat reaches the hardness of prows, routing of the flat ceases and the rider begins to wear.

It has also been found that there is a roughness of the flat above which prow formation does not occur. This roughness is dependent on the load, hardness and ductility of the metal, and is related to the size of the prows. For pure gold, the critical roughness is 0.6 to 1.3 pm center line average (c.l.a.) at 100 g.⁵ The harder and less ductile the metal, the smaller is the critical roughness. This fact may explain why prow formation is unlikely to occur with rhodium, ruthenium and other hard, brittle electrodeposits. Because prow formation dominates the sliding of many contact metals in the severe regime, studies⁶ have been performed to determine the effects of load, numbers of traversals and track length on this process.

Adhesive wear of gold

Gold electrodeposits are the most widely used contact materials. Adhesive processes dominate their wear. The properties that control wear behavior were studied by the author.⁷ Table 1 lists typical mechanical-property data for gold plated with direct current. The ranking of different types of gold in order of increasing durability is based on several reports.^{5,8-10} Cobalt-hardened gold exhibits the best wear resistance. Gold-silver and gold-cadmium alloys are next in durability.

Table 1 - Properties of gold electrodeposits from direct current processes.

Type of gold	Type of bath	Alloy metal	Carbon, ^a %	Hardness, ^b kg/mm ²	Elongation, ^c %
Soft, pure acid matte	Cyanide, citrate buffered	None	0.01	50	> 10
24-karat hard gold ^d	Cyanide	None	0.01	200	> 10
AFHG ^e	Cyanide	None	0.06	180	2.5
Alloyed, alkaline non-cyanide bright	Sulfite	0.7% Cd ^f	None	135	5 - 10
Alloyed, alkaline cyanide bright	Cyanide	1.0% Ag	0.07	140	0.75
Hard, acid bright ^g	Cyanide	0.15% Co	0.15	180	< 0.4

^aDetermined by combustion microanalysis.

^bObtained from metallographic sections on thick deposits at 25 g.

^cVaries according to deposit thickness and method of measurement; values given are representative.

^dDescribed in Reference 9.

^eAdditive-free hard gold described in Reference 10.

^fMay contain small amounts of organic or metalloid brighteners.

^gNickel-hardened golds have properties comparable to those of this cobalt-hardened gold deposit. Deposits with similar characteristics are available from many commercial processes.

The reasons for differences in wear behavior have been the subject of conjecture. When hard golds, first the silver alkaline cyanide and then the cobalt- and nickel-hardened types, became available, it seemed that the superiority of their adhesive wear properties relative to the adhesive wear of soft, pure gold could be related to hardness. It later became apparent that this explanation was incomplete because tests with wrought gold alloys of comparable hardness showed the wrought gold to be inferior.¹¹ The discovery that a hard, relatively pure gold (Table 1, 24-Karat Hard Gold) wears poorly further underlined the inadequacy of the simple hardness theory.

A later suggestion¹¹ was that co-deposited polymeric organic materials¹² in the cobalt- and nickel-hardened golds were acting as lubricants. Table 1 lists typical carbon analyses of some golds as an indication of their polymer content. This explanation also proved inadequate once it was realized that some hard deposits that contain significant codeposited polymers were much more

prone to severe adhesive wear than the cobalt- and nickel-hardened gold electrodeposits. The silver alkaline cyanide and, especially, the additive-free hard gold (AFHG) are examples of this fact. It has also been found that even cobalt-hardened golds containing considerable polymers could wear by prow formation at low load provided their surfaces were scrupulously clean.

Two problems long stood in the way of a rational understanding of the wear of gold electrodeposits: (a) lack of information on the structure of Co-deposited polymers and (b) little physical-property information about the gold electrodeposits, other than the bulk hardness from sectioned deposits. Limited data are now available, and typical deposit ductilities are given in Table 1.

The structure of a cobalt-hardened gold deposit has been elucidated. The polymers consist in part of a complex cobalt cyanide compound,¹² which is uniformly distributed in the deposit as particles ranging in diameter from 2 to 7 nm.¹³ Some polymer particles may be larger.¹⁴ From physical metallurgy theories that describe the effects of finely divided particles on the mechanical properties of solids, both the hardness and the low ductility can be attributed to these codeposited materials.

It seems that the most durable deposits are those with fairly low ductility (*i.e.*, with elongations of about 0.4%). In addition to the cobalt-hardened, acid bright gold deposit in Table 1, polymer-containing 0.28% nickel-hardened gold and 1.3% cobalt plus 0.55% indium-hardened gold have similar durabilities and mechanical properties.⁵

A hypothesis for the ranking of gold deposits according to their adhesive wear resistance is based on the phenomenon of junction growth, which is controlled by the ductility and hardness of a solid. Junction growth¹⁴ occurs when adherent asperities undergo tangential stress. There is an increase in the area of asperity contact before the junction shears, particularly with ductile materials (Fig. 4). Junction growth causes high friction.

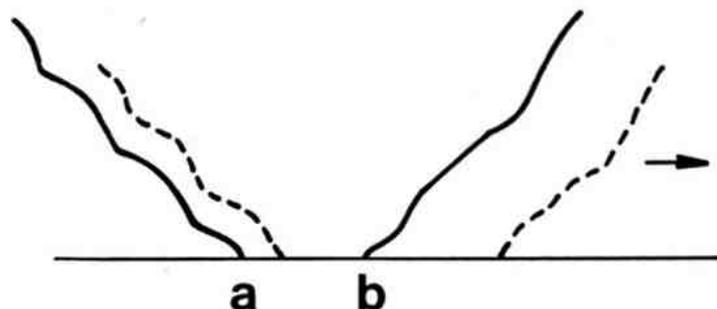


Figure 4 - Schematic representation of junction growth. Normal load deforms asperity so that contact occurs along line ab. When a tangential stress is imposed in the direction of the arrow, the junction grows, as shown by the dashed lines, and the two surfaces move together slightly.

The formation of prows with attendant transfer and the occasional loss of prows to form loose debris is closely related to junction growth, and a prow in its initiation and growth stages can be considered to be a single large junction.¹⁶ In summary, this view, coupled with friction theory, suggests that an interplay of three factors controls adhesive wear. For best performance, the contact finish should (a) be hard so as to limit the area of initial contact, (b) have low ductility to limit junction growth and (c) be lubricated to inhibit asperity adhesion.

Thus, high hardness alone, with or without codeposited polymers, is insufficient to provide good wear resistance (Table 1, 24-Karat Hard Gold and AFHG), while hardness coupled with relatively low ductility provides good performance. However, it is possible for a gold deposit to be so brittle that it would fracture under normal load.¹⁷ The efficacy of contact lubricants in compensating for the poor wear of ductile gold deposits, both hard and soft, is also well known.^{9,10,18}

It is possible to alter the composition, structure, and properties of gold electrodeposits by varying the current waveform during plating. For example, cobalt-hardened gold¹⁹ plated in a cyanide solution was substantially free of polymers compared with gold plated in the same solution using direct current. Both pulse- and de-plated deposits have been prepared with similar cobalt levels and hardness. However, bend tests showed that the de-plated, cobalt-hardened gold deposit was much less ductile, and

sliding tests showed the de-plated gold deposit was also significantly less prone to adhesive transfer and wear. This finding is in accord with the previous analysis, which shows that high ductility degrades adhesive wear resistance.

Recent developments

Gold plating processes often have relatively narrow "windows" from which electrodeposits with satisfactory tribological properties can be obtained, and this is especially true for high speed systems. In a recent study²⁰ with typical cobalt-gold and nickel-gold deposits, the solution compositions and bath operating conditions were varied, and the sliding characteristics of the deposits were evaluated using connector contacts in a tribotester having a rider-flat configuration. Both members were plated with 5 μm of gold, and sliding was at 150 g for 500 cycles. Figure 5 illustrates some of the results. The coefficient of friction is plotted against deposit potassium, solution cobalt, and plating current density. The line on the surface within which the crosses lie delineates the "good" wear region. Good wear resistance was synonymous with coefficients of friction of 0.26 or less and "bad" wear with larger values.

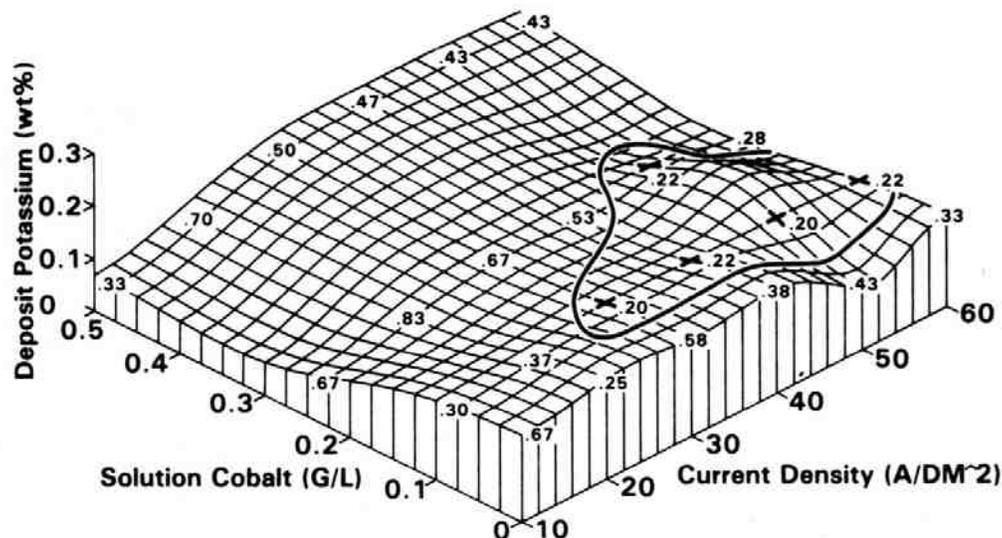


Figure 5 - Effect of cobalt concentration of electrolyte and cathode current density on potassium content of the deposit. The plus sign (+) represents experimental conditions resulting in "good" or "very good" wear. The numbers on the surface are the coefficients of friction.²⁰

The physical properties of these deposits were not determined, but they obviously depended on the process. Curves such as these can be used for plating process control because they define the operating window for deposition. This window yields gold deposits having satisfactory tribological characteristics. In a more general sense, it can be argued that the performance of a deposit is dependent on the process. This premise is true not only of gold but also of palladium, palladium-nickel, rhodium, tin-lead solder and any other engineering finish.

Abrasive wear

Two-body abrasive wear is caused by the plowing of a surface by an opposing contact material that is rough and substantially harder. When the abrader initially is a loose particle that can be embedded in one surface, wear is termed three-body abrasion. Displaced material can be removed in chip form, as in cutting, or can flow to the sides of the groove with little or no loose-particle formation.

Brittle fracture occurs with materials having low tensile strengths compared with their compressive strengths. The surface develops cracks across the wear track during sliding (Fig. 6). Many contact materials, including rhodium and cobalt-gold electrodeposits, are relatively brittle and likely to fracture when abraded.

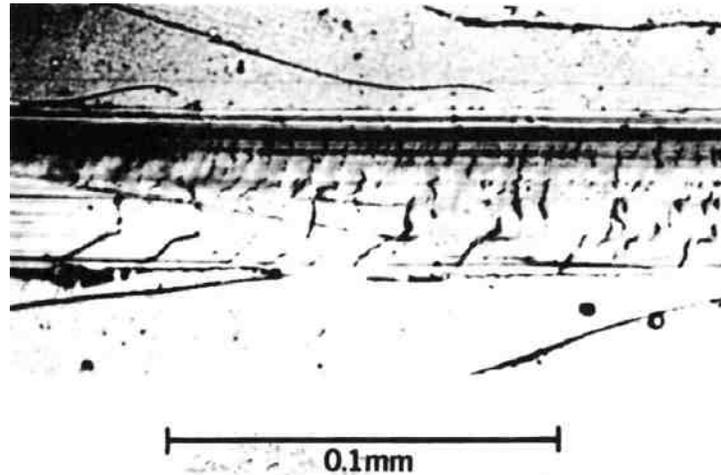


Figure 6 - Wear track on a 65/35 Sn-Ni electrodeposit 12 μm thick with a 0.43- μm -thick overplate of cobalt-gold alloy (diamond rider, 90° conical tip with a radius of 0.1 mm, single pass at a load of 200 g). Deposit shows brittle fracture.

As a class, wrought noble contact metals, such as cladding, are more ductile than their electroplated counterparts. Therefore, their abrasion resistance is superior. The two-body wear indices of a clad pure gold deposit and a cobalt-gold deposit with similar thicknesses were determined by drawing a diamond stylus across the deposits (Fig. 7). Electrography²¹ was used to measure wear. Electrographs are obtained by pressing moist, chemically treated paper against the worn specimen under the influence of a DC voltage. An imprint of the track appears in the paper, and colored spots reveal substrate regions that have been exposed. The ratio of the length of colored track to the total track length multiplied by 100 is defined as the wear index. Although the gold electrodeposit in Fig. 7 was supported by a hard underplate and substrate, the clad metal was clearly superior. By the same token, the adhesive wear resistance of clad pure gold is inferior to that of cobalt-gold electrodeposits.

For the majority of cases in which noble metal contacts are used, adhesive wear is more important than abrasive and brittle fracture wear. The selection of an electrical contact material generally should be made by first considering its adhesive wear properties. If it is practical to employ lubricants that can alleviate adhesive wear, then metals with superior abrasive wear characteristics can sometimes be used.

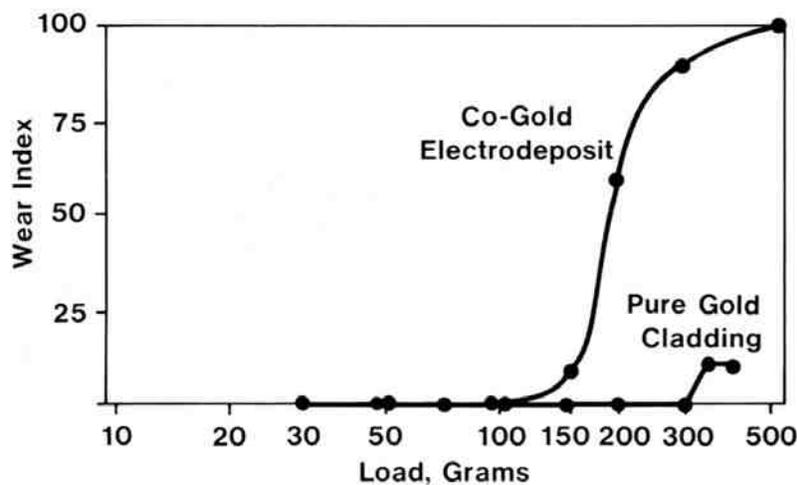


Figure 7 - Electrographic wear indexes from two-body, abrasive-wear runs with two 2- μm -thick gold coatings, namely, a cobalt-gold electrodeposit on a 2.5- μm -thick nickel underplate on a copper-beryllium substrate and a pure gold clad inlay with a nickel interliner on a copper-nickel-tin alloy substrate (single-pass runs at various loads with a conical diamond rider).

Fretting and fretting corrosion

Fretting wear occurs as a result of oscillatory movement of small amplitude, generally 130 μm or less.²² Because motion is limited, debris accumulates between the contacts rather than emerging free. The wear debris from base metals contains products of reaction with the environment (*e.g.*, oxides), and, in this case, the wear process is termed fretting corrosion. Small movements may occur when a component is subjected to vibration, mechanical shock or thermal excursions. Oxide debris can cause substantial increases in the contact resistance of electronic connectors having base metal contacts.

Laboratory fretting studies of contact materials are relatively new. It is difficult to determine the behavior of materials under fretting conditions with connectors or other components fixed to vibration tables because the mass, physical dimensions of the components and any equipment to which they are mounted, and the method of attaching electrical leads can either attenuate or exaggerate the forces exerted on the contacts. When the primary interest of the investigator is in the behavior of materials, it is desirable to exclude component effects by using an apparatus that forces movements under precisely controlled conditions. This point seems to have been overlooked in some of the research that led to contradictory claims about the fretting of contact finishes.^{23,24} Only when the behavior of an actual device is of interest is it appropriate to examine the device itself.

The author has used an apparatus (Fig. 8) in which a stationary rider (usually a ball, a contact rivet, or a copper rod with a hemispherical end - any of which can be plated by conventional methods) is dead weight loaded against a plated flat specimen mounted on a ball slide. A computer-controlled stepping motor displaces the slide over a small amplitude at a controlled frequency. Contact resistance is measured through leads with an appropriate electrical circuit and is recorded by the computer. This apparatus and experimental procedure have been described previously.²⁵

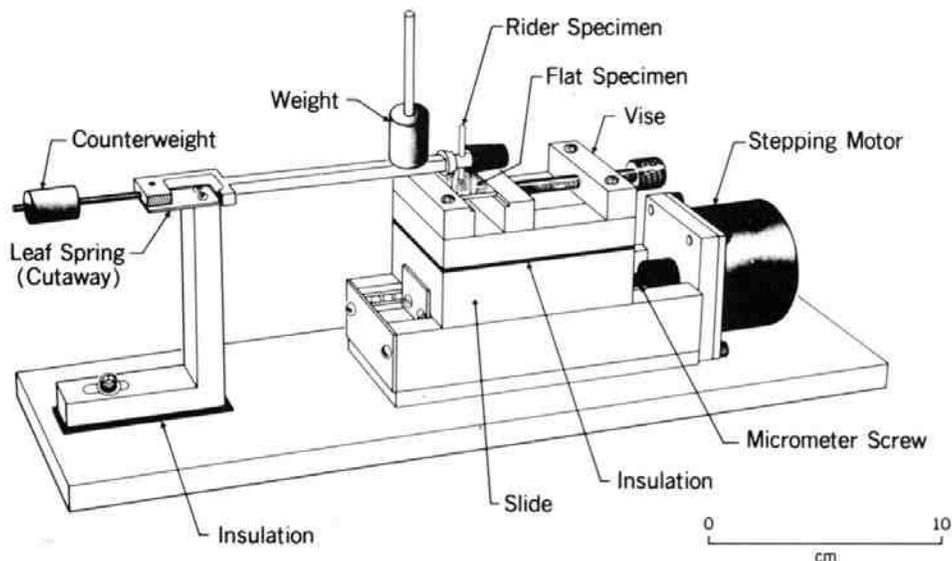


Figure 8 - Fretting test apparatus.

Typical data illustrating the contact-resistance instability of contacts plated with tin-lead solder are given in Fig. 9.²⁶ From an initial value of 0.001 Ω , contact resistance increases to 10 Ω in only a few thousand cycles of fretting at an amplitude of 10 μm . Furthermore, solder plate mated to gold degrades even more rapidly (Fig. 9). An explanation for the latter behavior based on the mechanics of oxide-film fracture has been given.²⁶ An oxide that transfers from the thin layer of solder to the much harder gold early during fretting was shown to be less readily fractured, thus having lower contact resistance, than oxides on base-metal contacts having identical hardness. The opposing contacts have identical hardness when the contacts are composed of the same material. Figure 10 is a worn contact surface from fretting tin-lead against itself. The wear spot is covered with a thick, insulating fudge of mixed tin and lead oxides, and debris is piled up around the periphery of the wear scar.

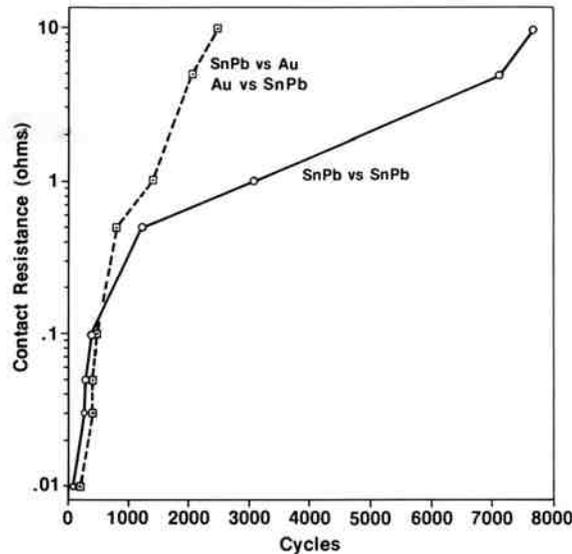


Figure 9 - Contact resistance vs. numbers of fretting cycles for tin-lead solder against itself compared to gold vs. tin-lead-plated contacts. The contacts were not lubricated (Wipe distance, 10 μ m; normal load, 50 g).

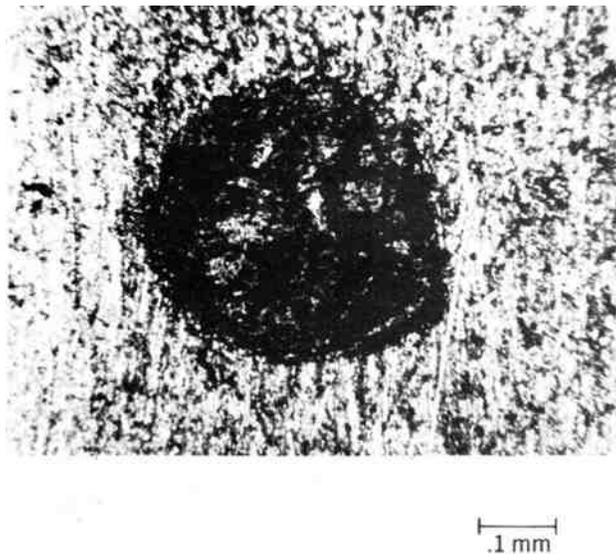


Figure 10 - Worn spot on tin-lead-plated contact after fretting.

It has also been found that fretting may be a cause of contact-resistance change in connectors with noble-metal contacts due to wearing out of the surface finish and resultant exposure of underlying base metal.²⁷ A comprehensive review of the electrical effects of fretting connector contact materials has been published previously.²⁸

Frictional polymerization

Frictional polymerization can occur during sliding and fretting with palladium, rhodium and other platinum-group contact metals and alloys²⁹ due to their catalytic activity. Adsorbed organic air pollutants are converted into complex, solid, insulating contaminants of high molecular weight. Movement enhances this effect, but its role may simply be to dislodge the reaction product, thus producing a continuous conversion to polymers in the area of slide.

Accumulation of frictional polymers, while resulting in the inhibition of wear, unfortunately causes the contact resistance to increase. An example of contact-resistance changes caused by frictional polymers in a fretting test is given in Fig. 11. Lightly loaded sliding contacts, such as instrument slip rings that operate in the 2- to 10-g load range, are particularly prone to be degraded by frictional polymers. Even more heavily loaded (50 to 200 g), separable connector contacts can be unreliable due to fretting when coated with catalytically active metals.

Gold-plated contacts have low and nearly invariant contact resistance until the gold is worn away when sliding under the same conditions as described in the preceding paragraph. A gold flash on palladium-plated contacts is only marginally useful in protecting them from contact-resistance degradation due to fretting in the system of gold-flashed palladium plate mated to itself,³⁰ although a flash of cobalt-gold is slightly better than pure gold.²⁸ Fretting tests were conducted in room air using 80/20 Pd-Ni alloy mated to itself, a 20- μ m wipe, a 50-g load, and a frequency of 4 Hz (Fig. 11). It was determined that a gold flash on the electrodeposited alloy also is of only small benefit in extending the numbers of cycles of fretting before contact resistance increases. However, when any of these finishes is mated to a thick gold plate, solid pure gold or some solid gold alloys, contact resistance will remain stable for lengthy runs due to transfer from the gold contact to the palladium-plated part early in the run. This transfer converts the system to one that is all gold.²⁸ An exception occurs when the gold alloy is harder than the palladium; this situation causes transfer in the opposite direction and thereby creates³¹ an all-palladium interface.

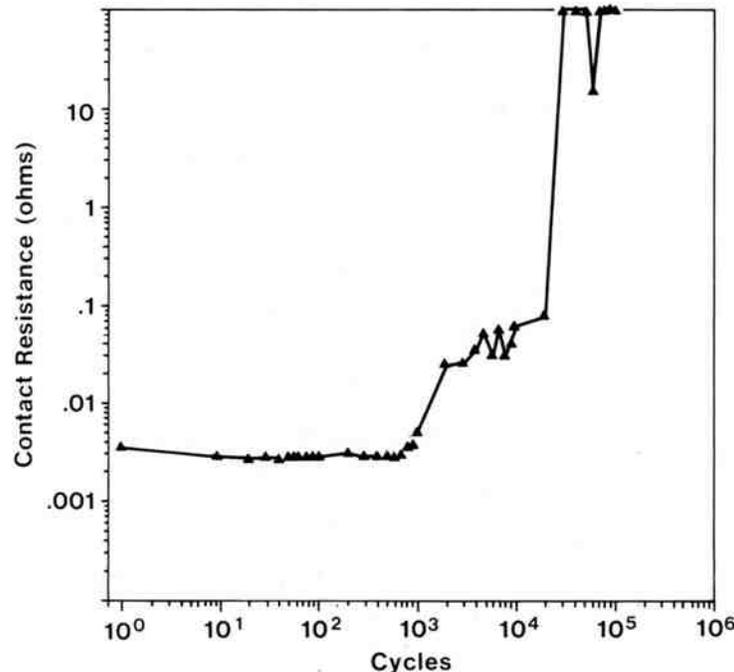


Figure 11 - Contact resistance vs. number of fretting cycles for a palladium rider (3.2 mm in diameter) tested against a palladium flat using a 20- μ m wipe, a 50-g load, and a frequency of 4 Hz. The increase in contact resistance is due to the formation of frictional polymers.

Summary - Part I

Friction, mechanical wear, fretting corrosion and frictional polymerization play vitally important roles in the performance of contact finishes in electronic connectors. Their tribological behavior largely determines contact plating practices. Adhesion, abrasion and fretting are dominant wear mechanisms. Adhesive wear involves metal transfer between sliding and stationary surfaces. Hardness and ductility are controlling factors. Abrasive wear occurs when there is a large difference in the hardness of the contact materials and one of the contact materials is relatively rough. Fretting results in the accumulation of wear debris in the contact zone. Fretting corrosion develops with base metals. Frictional polymers may form when platinum-group metals are involved. Fretting corrosion and frictional polymerization can cause high contact resistance.



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Part II: The Effects of Underplate, Topography and Lubrication

Introduction

High hardness and ductility are desirable in contrast to the low-ductility top coating preferred for minimal adhesive wear and friction. Fluids of certain chemical classes, such as the polyphenylethers, are often essential supplementary films that assure low sliding friction and acceptable adhesive and fretting wear. New, low-cost contact finishes under development may be successful in the less critical applications of consumer electronic components. Coatings applied by physical methods such as ion implantation and ion plating are of interest for critical applications.

Substrate effects

Hardness - Hard materials are more wear-resistant than soft materials, provided that other characteristics of the metal are the same. This fact originates in the reduction in real area of contact which accompanies increasing hardness. Therefore, with layered materials, increasing substrate and underplate hardness may be beneficial, particularly when the coatings are thin.

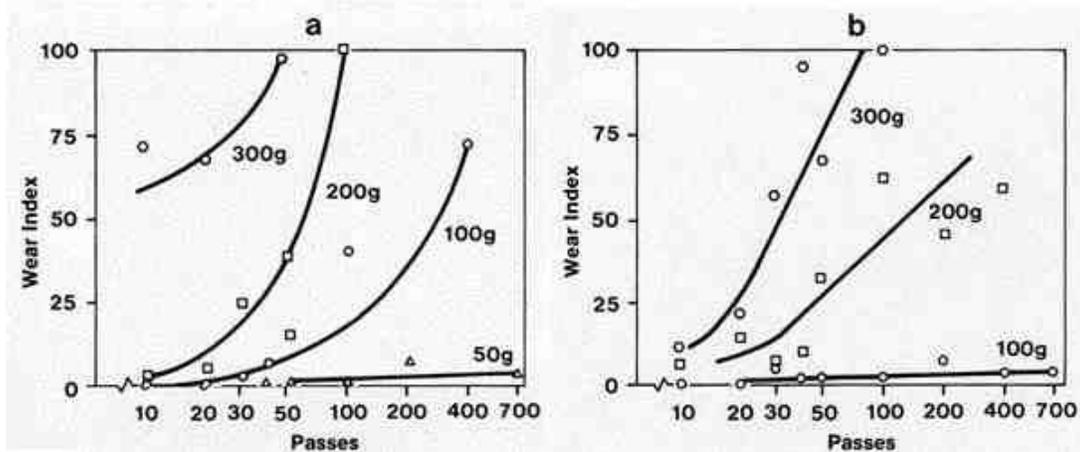


Figure 1 - Adhesive wear from runs with solid gold riders tested against a 3.3- μ m-thick cobalt-gold electrodeposit on copper (a) without and (b) with a 2.5- μ m-thick nickel underplate for the following loads: \square = 300 g; \square = 200 g; \circ = 100 g; Δ = 50 g.

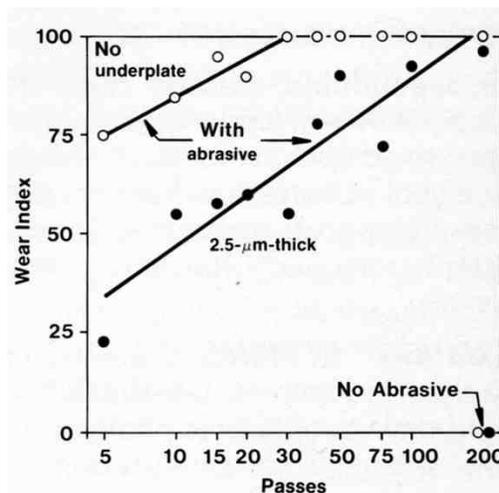


Figure 2 - Three-body abrasive wear runs with a 3.3- μ m-thick cobalt-gold electrodeposit on copper with and without a nickel underplate (lubricated; 50-g load; coarse silicon carbide particles sprinkled on the flat).

Examples of the value of a hard underplate (*e.g.*, nickel, 400 kg/mm²), are given in Fig. 1 for adhesive wear and in Fig. 2 for abrasive wear.¹ In Fig. 1, hemispherically-ended solid gold riders with a diameter of 3.2 mm were mated to cobalt-gold plated flats at a series of loads for various numbers of passes on tracks 1 cm long. Adhesive wear of gold was much reduced with the hard underplate. In Fig. 2, a solid rhodium rider with a circular flat contact area 0.5 mm in diameter was mated to a lubricated cobalt-gold plated flat. Equiaxed graded silicon carbide particles were sifted onto the flat. The motion was reciprocating. The figure shows the abrasive-wear-inhibiting ability of the nickel underplate. Hard underplatings have also been found to be effective in reducing the fretting wear of gold electrodeposits.²

Ductility - Underplates should be ductile so that they do not fracture during sliding, which would, in turn, cause porosity to develop in the gold or other metal finishes. For example, the brittleness of tin alloy containing 35% nickel underplate (elongation, 0.2%) has been the cause of failure of contacts plated with it despite its high hardness (700 kg/mm²). However, when the contact load is small enough so that the tin-nickel alloy remains intact during sliding, then a finish consisting of thin cobalt-gold on this underplate has very low wear and friction.³

Roughness - Smooth surfaces have been found to wear less than rough surfaces in both adhesive and abrasive wear.⁴ This is illustrated in Fig. 3, in which substrates were prepared at three levels of roughness (0.75, 0.38 and 0.1 μm c.l.a.) and were plated with the same mass of gold.

One reason why wear increases with increasing roughness is that it tends to occur preferentially on surface high spots. Thus, the gold is lost by wear first from the asperities. With smooth surfaces, wear is less localized than with rough surfaces, and more passes are required to achieve a given degree of wear.

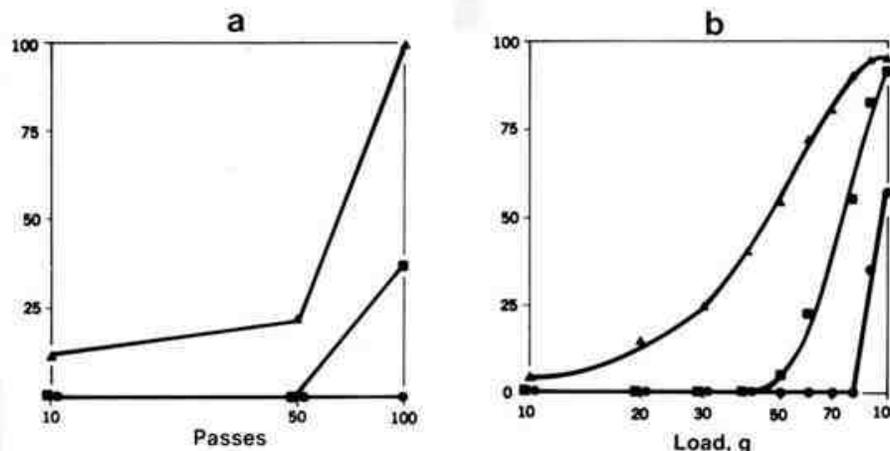


Figure 3 - Runs to determine the effect of surface roughness on wear for a 0.6-μm-thick cobalt-gold electrodeposit on a 1.5-μm-thick nickel underplate on copper flats abraded before plating to 3 levels of roughness (▲ 7.5 μm c.l.a.; ■ 0.38 μm c.l.a.; ● 0.1 μm c.l.a.). (a) adhesive wear with solid gold riders (100-g load); (b) two-body abrasive wear runs with a conical diamond rider (single pass).

Particular attention must be paid to roughness effects with nickel underplate. Nodular deposits can occur with poorly maintained baths, for example, as a result of inadequate filtration; to high current densities at edges and along scratches in the substrate surface; and with substrates that have particulate matter and precipitates on their surfaces. A nodular underplate will result in a nodular finish, and such surfaces can abrade an opposing contact that is softer. Since nodularity is also thickness-related, it is good practice to specify only as thick a nickel plating as is necessary to provide adequate support and the reduction in wear because of nickel's hardness for systems such as those illustrated in Figs. 1 and 2.

Adhesion - A plating will wear poorly if the stresses which result from sliding cause separation at the interface between the deposit and the underlying metal (whether it is an underplate or the substrate). The adhesion should be good even at the microlevel, and an example of a deposit having small non-adherent regions in the wear track is given in Fig. 4.

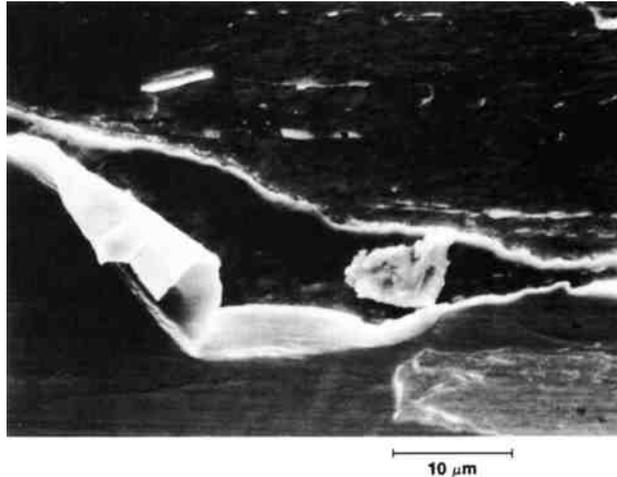


Figure 4 - Effect of sliding on a poorly adherent deposit. Plating is disrupted and porous. Two-body abrasion: 3.3 μm pure gold electrodeposit on copper. Diamond slider, one pass at 100 g.

Tribology of thin rim metallic contact lubricants

Thin films of some metals on thicker layers of other contact metals, or even of substrates which constitute the structure of the contact, have recently become commercially important. An example is the gold flashed palladium finish. When nickel is plated between the palladium and the substrate, the following terminology is used: gold flash is the plating; the palladium is the underplate; and nickel is the subplate. Strike deposits, which usually are used to promote adhesion between layers, are ignored in this discussion.

The primary function of the gold flash is to reduce friction and wear. It is an easily sheared coating, or metal film solid lubricant, for the palladium. The latter has intrinsically poor adhesive wear properties.⁶ This is readily understood by referring to Fig. 5. The hard palladium and nickel subplate support the load, with shear occurring in the gold layer. Pure gold, being soft, performs this function well, as expected. However, a cobalt-or nickel-gold has been found to be even better; they are relatively brittle and resist junction growth as described previously.⁷

A consequence of the physics of contact in Fig. 5 is that if the gold plating is soft and thicker than about 0.05 to 0.15 μm , friction and wear will rise with increasing thickness. If the gold is thinner than about 0.05 μm , friction also will rise with decreasing thickness. For the thin gold coating to be effective, the substrate must be very smooth. Wear and friction parallel each other very well. A practical example is given in Fig. 6, in which the rider contact was a gold-palladium-silver inlay (DG R-156), and the flats were plated in a range of thickness with pure and with cobalt-gold.⁸ The palladium underplate was 1.5 μm thick on a subplate of 1.25 μm of nickel.

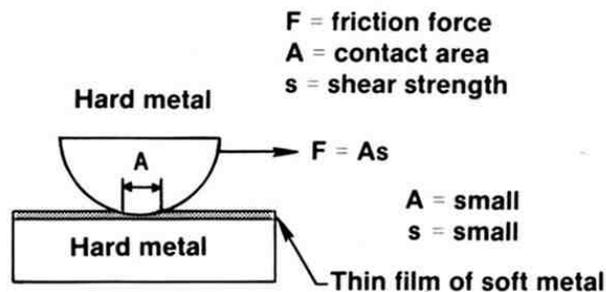


Figure 5 - The friction between metal surfaces can be lowered by depositing a thin film of a soft metal on a hard metal substrate (after Ref. 5). A coating of a metal that resists junction growth, such as electrodeposited cobalt-gold, will function in the same way as a soft metal film.

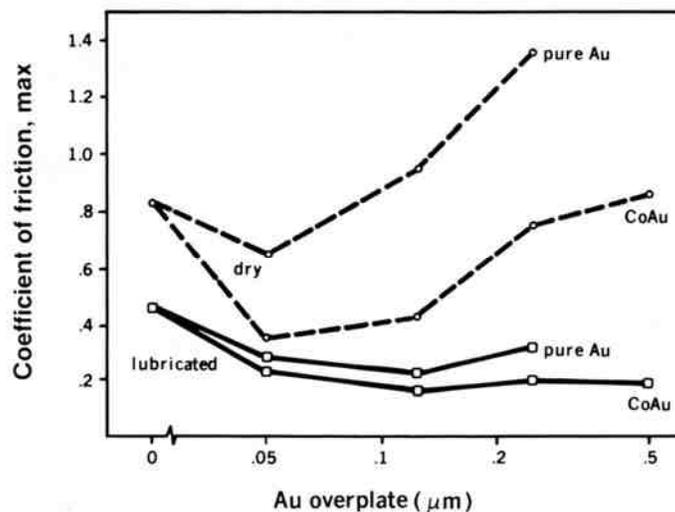


Figure 6 - Relationship between the maximum values coefficient of friction in runs with DG R-156 coated riders vs. coupons having gold on a palladium underplate with a nickel subplate. The variables were the type of gold plate (either pure or cobalt-hardened) and its thickness, and whether the flats were dry or were lubricated with a thin layer of a polyphenylether fluid.

Surfaces lubricated with a poly-phenylether fluid (discussed in the next section on organic lubricants) performed even better. Gold flash is commonly used on palladium nickel electrodeposits,⁹ and has been proposed for electroplated palladium silver,¹⁰ ruthenium,¹¹ nickel phosphorus¹² and other deposits.

Organic lubricants - Organic lubricants are widely used on electrical contacts. Their purposes are to: (a) lower friction; (b) control sliding wear; (c) inhibit corrosion in aggressive atmospheres; (d) reduce contact degradation resulting from the fretting corrosion of base metal finishes and substrates if the gold is worn through and (e) minimize contact resistance instability resulting from frictional polymers when the finish is a platinum group metal.

In the cases of (c) and (d), the lubricant blankets the surface, thereby retarding the formation of insulating oxides. In (e) the lubricant disperses the polymers, thereby preventing their accumulation on the contact. The subject of contact lubrication has been treated in detail by the author.^{13,14} Preferred lubricants are the 5- and 6-ring polyphenylether fluids with which contacts are coated by immersion and withdrawal, spraying, roller coating and other methods from dilute solutions in a volatile solvent such as inhibited 1,1,1-trichloroethane. Solutions of from 0.5 to 2 wt% of lubricant are commonly used for purposes (a), (b) and (c) above, and from 5 to 20 wt% for (d) and (e).

Lubricants are only marginally beneficial in reducing the friction and wear of tin and tin lead solder plated contact finishes. However, deposits having a hardness of at least 50 kg/mm², such as most cobalt- and nickel-golds, respond well to them.

Needs and future developments

The marked dependence of the tribological behaviors of gold electrodeposits on the solution chemistry and bath operating conditions from which the platings are obtained is undoubtedly true of most contact finishes, including the increasingly important gold-flashed palladium and palladium-nickel alloys. Deposit performance is, of course, ultimately dependent on their structures, compositions and mechanical properties. The tools and techniques exist to explore these relationships, but thus far the metallurgists, physicists and mechanical engineers who make up the body of research tribologists have largely ignored the challenge (and complexity) of studying layered systems. Much of the work that has been done is largely empirical, involves optimization of the finish for particular contact-containing components, and is conducted in the secrecy that is necessary to maintain the legitimate proprietary interests of its industrial sponsors. Nevertheless, there has been some recent academic interest in the basic tribology of contact finishes. One example is a study¹⁵ of mechanical stresses using finite element methods,

which has satisfactorily explained the author's observations¹ of the role of nickel underplate in reducing the adhesive wear of gold plate. Transmission electron microscopy has been proposed for studying the structural changes in golds that occur as a result of sliding.¹⁶ It seems appropriate for the American Electroplaters and Surface Finishers Society to identify new research projects on the tribology of contact finishes and to find university faculty interested in directing graduate level thesis research in this area. An AESF-sponsored fellowship through its Research Board on contact tribology would be timely.

Test Apparatus - It is desirable to standardize on apparatus for evaluating the tribological properties of contact finishes, including their wear, friction and fretting behaviors. Component hardware can be coated with experimental finishes, but hardware generally does not readily permit the variation of important sliding conditions, such as normal force and wipe distance. In addition, the complexity of many contact shapes and the unique ways in which contacts can be mated makes it difficult to analyze hardware test results and to apply the findings to other systems. For many years, the author has used classical tribometers which accommodate hemispherically ended riders, balls or rivets that are mated to flat coupons. Friction force and contact resistance are easy to measure with such apparatus. More recently, equipment which uses plated wires that are joined at right angles in a crossed rod configuration has been employed. American Society for Testing and Materials committees involved in contact work might consider writing guidelines for the design of wear test apparatus for materials, for their methods of use, and procedures for assessing wear.

Specifications on contact finishes - Since the tribological behaviors of finishes do not depend on simple characteristics such as composition and hardness, it follows that the plater and contact design engineer have, for the most part, been unable to write specifications having general utility. Platings are often called out in terms such as "Process X from Supplier Y has been found able to meet the requirements of the product," but (as in Fig. 7) can such a specification be divorced from the plating equipment that may be unique in a plant, and what else needs to be incorporated in these documents?¹⁷ Clearly, more work is needed to elevate our understanding of the properties of a contact finish on which tribological behavior depends.

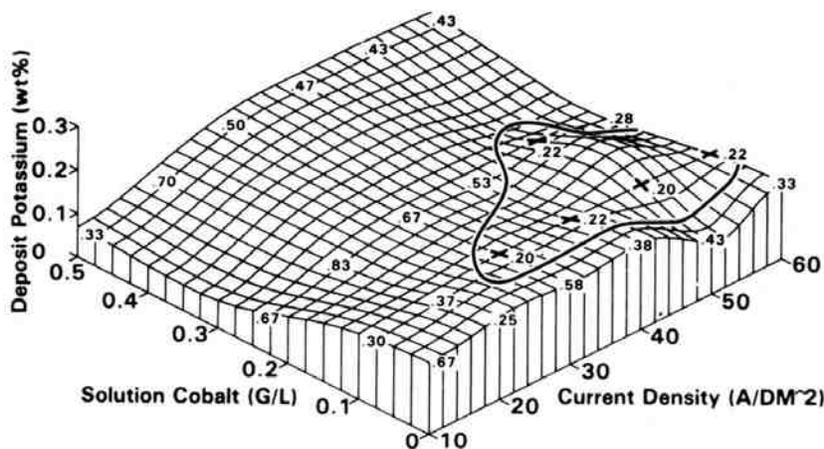


Figure 7 - Effect of cobalt concentration of electrolyte and cathode current density on potassium content of the deposit. (+) = experimental conditions resulting in "good" or "very good" wear. The numbers on the surface are the values of the coefficient of friction.

Cost reduction through new contact finishes

High reliability applications - Escalation in the price of gold began in 1972 when the need for electronic connectors was rapidly growing. Gold was the standard contact finish for high reliability, long-lived products. This spurred intense activity to reduce the dependence on this metal.¹⁸ The results of this research have been generally satisfactory. Selective plating, more realistic requirements concerning gold thickness and permissible as-plated porosity based on evaluations of field behaviors, better control of substrate roughness, and the acceptance of nickel underplate and of contact lubrication have all served to reduce the amount of gold that is necessary.



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Recently, however, there has been a lessening in the willingness to consider non-gold contact materials; and even palladium and palladium nickel finishes are tribologically unsatisfactory without a gold flash, as discussed earlier. This reluctance is because of the need for (a) connector miniaturization, (b) an increase in the numbers of contacts in a connector, which usually involves reduced contact normal loads and a greater susceptibility of the contact to degrade by surface contamination¹⁹ and by fretting, and (c) increasing demands for reliable performance. The precious metal costs as a percentage of the manufacturing expense of a connector and of the total costs of the equipment in which they are used have been significantly reduced in the past few years. It is questionable whether new contact materials are likely to be readily accepted for the large volume-high reliability connector applications in telecommunications, computers and many other products. This is reflected in the lesser activity today in new contact materials research. If the cost of gold and palladium again rise dramatically and rapidly, and if such higher costs persist, then this situation may change. In the meantime, we have seen the focus of studies in the contact field return to basic phenomena and away from the search for new materials. Tribological research on contact finishes should be a part of this new emphasis.

Consumer electronics - Tin and tin-lead solder plate have always been important contact finishes for connectors in consumer products where lesser reliabilities and shorter product lifetimes are acceptable. The factors responsible for the persistence of these base metal finishes in consumer product applications are that such connectors (a) involve smaller numbers of contacts needed, (b) permit higher minimum contact loads (100 to 200 g) compared to that which is usual for connectors having precious metal contacts, (c) allow higher coefficients of friction and (d) are acceptable with smaller numbers of insertions than generally are required in other applications.

Consumer electronics are much more cost-driven than traditional electronics, and so there may be a greater willingness to explore lower cost finishes than gold and palladium where tin and solder are unacceptable, for example, because of a need for connectors having many contacts. New work on lubricated gold-flashed nickel and nickel-phosphorus electrodeposits^{12,20} suggests that it may be possible to achieve improved tribological behaviors and acceptable ancillary properties that are usual for tin and tin-lead solder plate.

An additional area of new contact materials research may involve thin precious metal finishes that have been treated so as to passivate their surfaces to protect them from degradation in aggressive atmospheres. It may be possible to obtain satisfactory lower cost finishes in this way and to achieve acceptable tribological behaviors as well by the supplementary use of lubricants. Early studies in this area might profitably be extended.²¹

Physical deposits - Deposits produced by physical methods include vapor deposition, sputtering, ion plating and ion implantation. All of them involve vacuum or plasma-assisted environments which can be attained only with large investments in capital equipment. Nevertheless, ion plating and ion implantation have attracted considerable attention. Ion plating is commercially successful for aerospace ball bearings.²² These deposits do not have a sharp interface to the substrate. Rather, they are graded, which gives them better adhesion to some substrates than can be achieved by electrodeposition. Gold is a material of choice. It acts as a thin film solid lubricant much as does the gold flash on electroplated palladium and other deposits. Ion plated gold should be considered for critical contact applications where superior tribological performance is needed, especially when supplementary organic contact lubricants cannot be used.

Ion implanted contact materials have been explored in a cursory way.^{23,24} The results have been promising, and this technique for obtaining hard, wear-resistant surfaces having low contact resistance again suggests that applications may be developed in the future in which their high process costs can be justified.

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Appendix: Highlights of Parts 1 & 2

In order to provide added continuity between the two papers, Dr. Antler went further and prepared the following summary of the salient points discussed in the two articles.

1. Contact materials in electronic connectors, slip rings, switches and other components which serve low-voltage, low-current circuits in telecommunications, computer and similar applications are mainly electrodeposited finishes and claddings. Gold and its alloys are the most common, although palladium, tin, tin-lead alloys and a few other metals are used to some extent. The tribological properties of these materials control their functional behavior and reliability, and metal finishing practices, to a large extent, have been molded by tribological considerations.

2. Adhesive wear results from the formation of strong bonds at touching asperities, especially with clean surfaces. This can occur in mild or severe regimes according to load and can differ significantly in the extent of surface damage. The adhesive wear process, called prow formation, of many contact metals entails transfer from the member with the larger surface involved in sliding to that with the smaller surface, from which it subsequently can appear as loose debris. Prows consist of overlapping thin layers of metal.

When sliding occurs repeatedly in the same track, there is a transition to a process called rider wear in which, in the severe regime, only the smaller member loses metal by transfer. This transition depends on the material, load, track length and surface roughness, usually occurring within the expected lifetime of components.

3. Ductility is the key to determining whether high friction and wear by prow formation will occur. Golds, such as those containing cobalt from cyanide baths which have an elongation of about 0.4%, are less subject to prow formation and are, therefore, preferred to ductile finishes for sliding contacts. Codeposited polymers in these golds are believed to be responsible for their low ductility as well as their hardness.

4. Deposits can be so brittle, however, that they fracture during sliding. This is a cause of failure of the tin alloy electroplate containing 35% nickel, which has been used to some extent with a gold flash as a contact material.

5. Golds obtained at pulsed conditions appear to be more subject to adhesive wear than DC-plated golds which are obtained from the same baths.

6. Plating processes, especially from high speed systems, often have narrow "windows" from which deposits with satisfactory sliding properties can be obtained. A determination of these windows is necessary for plating process control.

7. Abrasive wear is caused by the plowing of a surface by an opposing member that is rough and substantially harder. Deposit nodularity is a type of roughness and should be avoided, especially with relatively hard metals such as nickel, which is commonly used as an underplate in contact finishes.

8. Fretting wear is the result of small amplitude oscillatory movement when mated contacts are subjected to vibration or other mechanical stresses. Wear debris accumulates between the contacts and, if base, will oxidize and cause the contact resistance to increase. In this case, the process is termed fretting corrosion.

9. Tin, tin-lead alloy, and other base metals are particularly subject to degrade by fretting. These finishes, when mated to gold contacts, have even less stable contact resistance behaviors during fretting than when the metals are mated to themselves.

10. Frictional polymerization occurs during the sliding and fretting of palladium and other platinum group contact metals. It results from the catalytically induced formation of tough organic films on the surface which originate in adsorbed air pollutants. These films are insulating and can be a cause of unreliability during fretting of connector contacts.

11. The gold flash commonly used on palladium and palladium-nickel alloy deposits is only marginally useful in protecting contacts from degradation resulting from frictional polymers when the finish is mated to itself. Fretting corrosion also occurs when noble contact finishes on base substrates wear through.

12. Palladium and gold-flashed palladium contacts mated to thick gold or gold alloys which are softer are stable during fretting. This is a result of metal transfer which converts the palladium contacts to all gold.
13. Hard ductile substrates and underplates are desirable, for they can lower adhesive, abrasive and brittle fracture wear and can minimize the rise of contact resistance during fretting in some cases when thin noble metal coatings are used.
14. Contact surfaces should be smooth when thin noble metal finishes are employed. In addition to minimizing as-plated porosity, such surfaces resist both adhesive and abrasive wear.
15. Non-adherent deposits wear poorly.
16. Thin films of relatively soft or of brittle metals, such as a pure- or a cobalt-gold flash on a harder substrate such as palladium, can reduce the friction and adhesive wear tendencies of the system. A gold flash has been proposed for use on ruthenium, nickel phosphorus and other experimental contact finishes.
17. Organic lubricants are widely used on electrical contacts. Their purposes are to (a) lower friction, (b) control sliding wear, (c) inhibit corrosion in aggressive atmospheres, (d) reduce contact degradation resulting from the fretting corrosion of base metal finishes and substrates if the gold is "worn through" and (e) minimize contact resistance instability attributable to frictional polymers when the finish is a platinum group metal.
18. Deposits obtained from physical processes, such as gold by ion plating or noble metals implanted with boron, nitrogen and other elements, are wear-resistant and may be useful in contact applications, especially when organic lubricants cannot be used.

About the author:

Most of this piece was written at the time Dr. Antler was announced as the recipient of the 1987 Scientific Achievement Award.



Dr. Morton Antler was named the 1987 recipient of the AESF Scientific Achievement Award during SUR/FIN 1987 in Chicago. The Scientific Achievement Award is the most prestigious of those conferred by the society. It is presented annually to recognize an individual who has made outstanding scientific contributions advancing the theory and practice of electroplating and allied sciences, raised the quality of products or processes, or enhanced the dignity of the profession.

Dr. Antler was born in New York, NY. He received his B.A. degree from New York University and a Ph.D. in chemistry from Cornell University, Ithaca, NY, in 1953. After several years of research in the automotive/petroleum industries on combustion science, lubrication technology, and corrosion engineering, in 1959 he joined International Business Machines Corp., Endicott, NY, where he began, and later as advisory chemist, led studies of electrical contact phenomena and materials. In 1963, he was appointed deputy director of research for the Burndy Corp., a manufacturer of electrical connectors, in Norwalk, CT, and in 1970 joined Bell Labs, Columbus, OH, where he continued his contact studies.

Dr. Antler's broad research interests cover physical, inorganic, analytical and surface chemistry, electrodeposition, corrosion, tribology and contact science. These studies for many years focused on the physical and engineering characteristics of electrical contact materials. They emphasized the properties and structure of electrodeposits and related materials such as claddings, weldments and ion-implanted metals. Dr. Antler was considered a pioneer in identifying the salient features of coatings to determine their performance and economic use in contact applications. New methodologies, particularly in the tribological evaluation of deposits and in their electrical resistance behavior, were devised in these studies and gained wide industry acceptance.

Dr. Antler published about 125 papers and patents. He lectured at many conferences and research laboratories in the U.S. and abroad. Dr. Antler was active in the organization and direction of numerous technical meetings, including service as general chairman of the Fifth AESF Plating in the Electronics Industry Symposium, in New York (1975) and the Ninth International Conference on Electrical Contacts, Chicago (1978). He was a member of the Steering Committee of AESF Research Project 25,



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"Properties of Gold Deposits for Electronic Uses," and served as a member of the Books and Symposia Committee (1971-1976). He coordinated the workshop sessions for the Fourth AESF Plating in the Electronics Industry Symposium and was active in organizing the annual IEEE Holm Conference and the biennial International Conference on Electric Contacts.

Dr. Antler taught courses on electrical contact materials and surface science sponsored by the American Society of Lubrication Engineers and the Institute of Printed Circuits. He was a lecturer for a course on electrical contacts sponsored by the Institute of Electrical and Electronics Engineers on the subjects of metallic coatings, chemistry, and tribology.

His honors include Precious Metal Plating Awards (1967 and 1970) of the AESF, the Alfred E. Hunt Memorial Award (1971) of the American Society of Lubrication Engineers, and the Special Recognition Award (1975) of the Electronic Connector Study Group. In 1980, he received the Ragnar Holm Scientific Achievement Award of the Holm Conference in recognition of his work on contact materials and phenomena for electronic connectors and related devices. He was among the first to receive a Distinguished Technical Staff Award (1982) from Bell Labs. In 1985, he was invited to deliver the keynote lecture at the Institution of Mechanical Engineers Conference at the University of Nottingham, England, where he discussed the electrical behavior of metallic coatings in contact during fretting motion. In 1986, he was appointed a fellow of the Institute of Electrical and Electronics Engineers for his outstanding contributions to the science and technology of contact materials, primarily electrodeposits. In 1987, he was honored by AT&T Bell Labs, with the Columbus Works Engineering Recognition Award for sterling professional contributions. He received the 1989 Holm Conference Armington Recognition Award for his continuous service to the conference.

Dr. Antler was a member of AESF, IEEE, the American Chemical Society, the American Society of Lubrication Engineers, ASTM and Sigma Xi. He was also Chair of the advisory group of the International Conferences on Electric Contacts and of IEEE's Components, Hybrids and Manufacturing Technology Society Technical Committee on Electric Contacts.

Dr. Antler passed away in January 1999.