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U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Institute for Materials Science and Engineering
Metallurgy Division
Gaithersburg, MD 20899

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Prepared for:

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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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FINAL REPORT

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EXECUTIVE SUMMARY

Laboratory studies have been conducted of wear processes occurring in BEP currency and stamp printing operations. Conclusions were drawn on the principal modes of wear involved. Laboratory work was carried out to develop new wear test methods that could be used to evaluate materials such as improved chromium plating, and to determine the abrasiveness of printing ink constituents.

In the water wipe press, wear of chromium plated currency printing plates occurred primarily at the wiper roll contact. Particles in the ink were trapped at the contact between the PVC covered wiping roll and the printing plate surface. These particles caused abrasive scratching and polishing of the printing plate surface. According to our laboratory tests, factors which had a significant influence on wear rate were particle size, hardness and concentration, and the roughness of the PVC surface. Other factors which had a strong effect on wear were fluid film thickness at the wiper roll-printing plate contact (determined by contact pressure, ink rheology, and sliding speed) and the ability of the ink to form a protective solid film on the plate surface. Some ink constituents were found to form a transfer film on chromium in laboratory experiments.

Particles contained in the PVC wiper roll cover material did not cause significant wear of the printing plates. Large, hard, foreign particles which were occasionally embedded in the PVC material did cause scratching damage.

Among the inks received from BEP for study in this program, the wear rate of the highest wearing rate ink was 25 times greater than that of the lowest in laboratory wear tests. This indicated a potentially large difference in wear rates among printing inks.

For stamp inks a correlation was established between service behavior and laboratory results. An ink that caused severe scratching in service was also found in laboratory tests to produce severe scratching of chromium plating. It was noted that severe scratching did not necessarily correlate with a high wear rate.

Three laboratory tests were evaluated for use in the study of wear in the printing process. The rotating pin-on-disk test was found to be suitable both for the evaluation of the wear behavior of different printing inks and of different chromium plating. Appropriate test procedures were developed for both of these tasks. Preliminary experiments indicated that the flat-on-ring test could also be used for these tasks but further development was necessary. The GTA test was found to be unsuitable for determining ink abrasivity.

It was demonstrated that with various printing inks the wear rate of soft chromium plating was substantially greater than hard BEP type chromium plating. No appreciable difference was found between a transition type chromium plating and BEP type plating.

Recommendations for future laboratory work were made in the report. Development of a scratching test that would evaluate inks and chromium coatings for scratching tendencies is important. Development of an additional wear test that could be used both in the laboratory and in printing press operation is recommended. Improved wear measurement methods are needed particularly in the low wear regime. Fundamental studies are needed to better understand the role of all materials -- plate materials, inks, and wiping materials -- in the wear process.

TABLE OF CONTENTS

I. Introduction

Currency and postage stamp printing operations of the Bureau of Engraving and Printing (BEP) are carried out using many different printing technologies. Of major importance are those methods utilizing chromium plated engraved metal plates or cylinders. There are several different processes which limit the life of these metal surfaces; among them are wear, scratching, fatigue cracking, corrosion, and accidental damage. The study being reported here has examined the intaglio currency printing process and has determined that wear-out or unacceptable scratching of a plate takes place during the wiping step where excess ink is removed just before the impression is made. Wiping may take place by a sliding blade, by a rotating cylinder, or by a paper web. In all three cases, the motion is sliding under high pressure between the wiping body and the engraved plate. Other steps in the process such as inking and printing involve rolling with respect to the impression plate. There is no sliding, hence, there is no appreciable wear associated with those steps.

Electrodeposited coatings are widely used by industry to minimize or eliminate degradation caused by wear and corrosion. In the case of wear, coatings are frequently used to reduce abrasion which is the most prevalent mode of wear found in industrial service. While severe forms of abrasive wear are usually associated with industrial operations such as mining, many wear problems involve milder forms of abrasive wear caused by low concentrations of abrasives or by mildly abrasive materials. In some instances, wear may occur even in a lubricated system where abrasives are present as a contaminant in the lubricant. Since the wear rate under mildly abrasive conditions can be several orders of magnitude greater than the typical value for lubricated conditions, this form of wear can be a very serious problem. In many operations wear processes are complicated by the presence of fluids or gases that cause a certain amount of corrosion to take place. The rate of corrosion alone may be acceptably low for the materials involved, but the simultaneous occurrence of wear creates a significant problem. Corrosion and wear are usually synergistic in their effect, and the rate of material loss can increase greatly. The occurrence of both processes at the same time severely limits the designer's choice of suitable materials.

Studies carried out in our laboratory have shown that abrasion by the ink in the water-wipe intaglio currency printing process is primarily responsible for the printing plate wear. The wear is due to both hard and soft particles in the ink that are either intentionally added or accidentally incorporated as contaminants. There is also some corrosion which may enhance the wear process. Details of these findings are presented later in this report. The problem of wear can be minimized by attention during the printing operation to the wiping cylinder pressure, the wash solution chemistry and cleanliness, the wiper blade condition (these blades wipe the PVC roll surface continually), and the PVC roll surface condition. The ink formulation, and ink cleanliness in terms of particulate contaminants is also of major importance, as will be described later.

II. Wear of Service Components in Printing

A. General Considerations

Numerous discussions were held with BEP personnel to obtain information on the printing process and the performance of the press equipment. The NBS laboratory wear studies in this program were planned and carried out using conditions that reflect some of those that occur during printing. In particular, wear contact conditions such as load, speed, temperature, and environment, which are very important factors, were chosen so that we could compare the laboratory wear data with BEP service experience. Samples were requested of typical worn materials, inks, and wiping roll covers, in order to conduct a study of the wear modes involved. A previous study of worn plate surfaces carried out at the BEP laboratory offered evidence that abrasive wear was taking place during the printing cycle. The wear rates were relatively low and this suggested that the abrasive particles were small, perhaps comparable in hardness to the chromium plating, or were present in low concentrations. We also obtained specimens of new and worn wiper blades, used to scrape the PVC roll during operation. Wear studies on these steel wiper blades were a useful adjunct to studies of end sections of the plates themselves.

A study to identify important system considerations connected with wear during the currency printing process was conducted. The study considered the sliding conditions present in the currency printing process, the materials involved, possible wear modes, approaches to measure wear, and possible wear test approaches for laboratory use.

1. Sliding Conditions

A schematic drawing of the currency printing press system is shown in Fig. 1. Essentially, it consists of a rotating roll to which the printing plates are attached. The plates are chromium plated and contain the impressions which transmit the ink to the paper. Three auxiliary PVC rolls are used. One supplies ink to the plate; one removes the excess ink; and one loads the paper against the plate to receive the impression. The contact sites of primary concern are those that might cause the plates to wear. These are identified as 1, 2, 3, and 4 in Fig. 1 and are discussed in more detail in the following paragraphs.

(a) Inking Roll Contact

The plate roll and the inking roll turn in the same direction with the same surface speed so a rolling contact results. The ink temperature is 85°C so this would be the contact temperature. The load is adjustable but the actual values are unknown. The only wear on the printing plates would be due to ink flow or microslip resulting from the elastic deformation of the PVC roll. This wear is believed to be very small.

(b) Wiper Roll Contact

The wiper roll moves in a direction opposite to the drum so that pure sliding results at a velocity of 7.5 m/s. The temperature can be assumed to be 85°C. The load is unknown and probably varies since it is regularly adjusted by the operator. Since the rolls move in opposite directions there can be little or no ink film and, of course, none is desired since the function of the roll is to remove the ink.

Superimposed on the rolling motion is a translating motion which is parallel to the roll axis. This motion would have little additional effect on the wear process since the sliding distance is short. Wear tracks on the plate would merely appear at an angle rather than parallel to the rolling motion. The ink contains several different kinds of abrasives whose hardnesses are compared below with the roll and plate materials.

TABLE 1

Material	Hardness (kg/mm^2)
Iron Oxide	600
Silica	900
Calcium Carbonate	180
PVC	(Shore D50)
Chromium plating	800-1000

These first two materials would cause abrasive wear of the chromium plating. Thus, primary attention should be given to abrasive wear at this contact.

In abrasive wear several distinctions should be made:

- Three Body Wear vs. Two Body Wear
- Hardness of abrasive/Hardness of substrate ratio
- Particle size of the abrasive

Three body wear occurs when a hard particle is caught between two sliding surfaces. The particle may roll or slide depending on its shape and how firmly it is held by one or the other of the surfaces. With sliding, scratches may be produced and the wear process is one of normal abrasion. Since the particles are not rigidly held, the scratches may be short and tend to wander away from the direction of the sliding bodies. With rolling, wear may take place by a process of repeated indentations. Surface material is deformed and eventually broken away to form a wear particle. In three body wear the indentations are often concentrated at the converging inlet. If relatively soft and ductile surfaces are involved, particles or fragments of particles may become embedded in the material, and the wear behavior is more like two body abrasion. Under that condition, wear of the harder surface may be greater than that of the soft. Embedment is less likely to occur with soft but highly elastic materials such as the PVC cover used on the wiper roll. With brittle surfaces, cracking and chipping may occur. Three body wear rates are usually about 1/10 that of two body wear rates.

For the case of PVC sliding against chromium, wear is strongly dependent on the hardness of the PVC and the size of the abrasive particles, because these factors determine the particle protrusion distance, p, as shown in Fig. 2. With soft PVC or small particles the protrusion distance is small and very shallow scratches or indentations are produced. With very hard PVC, p is large but the particles are not trapped and rolling occurs. This is a much less efficient process with respect to wear than scratching.

Many factors other than those mentioned above are important. Examples are load, particle shape, particle concentration, the presence of a fluid film, and, of course, the relative hardnesses of the abrasive particles and the two surfaces. Studies have been reported which indicate that the amount of abrasive wear increases with the ratio, Ha/Hm, where Hm is the hardness of the wearing body and Ha is the hardness of the abrasive (Fig. 3). Two regions can be defined: soft abrasive wear and hard abrasive wear. Soft abrasive wear extends up to approximately Ha/Hm = 0.8. With soft abrasive wear a polishing type of wear occurs.[2] The ratio for iron oxide and chromium plating is about 600/900 = 0.67. Since the concentration of iron oxide in currency printing inks is likely to be much higher than that of harder particles, soft abrasive wear by iron oxide is probably significant. For soft abrasives, the particle size is of less importance than for hard particles since they can be broken up in the process. Polishing is not strictly abrasion but is also due to the repeated plastic deformation of the surfaces and to adhesive transfer of the metal to the iron oxide powder.

Polishing also may be the result of corrosive wear. Ink consists of a variety of chemicals and additives. In addition, the water wash process uses a solution of chemicals to remove the ink. PVC contains chlorine which is known to be corrosive in combination with metals. Corrosive wear rates may be of the same order of magnitude as abrasive wear rates so either is possibly of major concern.

(c) Printing Contact

In this contact the paper is pressed against the ink filled plate. A slight amount of slip is caused by deformation of the paper and the impression roll. Under these circumstances the important variable is the amount of microslip resulting from the deformation. Since the amount of slip is likely to be small, this contact would contribute very little to the wear of the chromium plating.

2. Measuring Wear

Mechanisms of wear are determined by identifying all of the constituents (materials, designs, operating conditions, environment) in the wearing process and by careful inspection of the wearing surface and the wear debris. Once the wear mode has been identified, it is necessary to set up test devices which will allow studies to be made which will establish the details. In running such test devices, it is desirable to establish a correlation with service. Usually this is done by showing the same relative ranking of a series of materials in both the test and the actual application. With the printing process this is almost impossible to do, so some other approach must be used. One such approach is to measure a wear rate in service and then to devise a test which nearly duplicates this wear rate. One possibility is to utilize the wiper blade that slides on the wiping PVC roll for this purpose.

The wiper blade rubs against the wiper roll, flooded with ink. This contact is located very close to the wiper roll-printing plate contact, and except for the load and velocity, the conditions at the two sites are almost identical. The blade is about three feet long which imposes some problems with sample preparation but these are not insurmountable. This would be an ideal test to evaluate materials but could not be used to evaluate other factors such as the abrasivity of the inks or the effects of changes in operating variables. The primary problem is that the load is not controlled and changes as wear takes place. Some modifications would have to be made in the loading system or a sufficient number of tests would have to be run to provide acceptable statistical control. If the wiper blade was chromium plated it could also be used to identify wear modes and to determine the relative significance between soft abrasive, hard abrasive, and corrosion wear. This blade could also be used to measure service wear coefficients to compare with bench tests. The blades wear rapidly so the total wear could be determined by weighing. The load, however, would have to be measured and controlled.

B. Printing Plate-End Examinations

A detailed understanding of the process by which printing plates wear is important for several reasons. In the development of improved electroplatings such an understanding can indicate which properties should be emphasized. It can indicate whether corrosion resistance, adhesion, or hardness should be improved. This is especially important since improvement in one property may result in the degradation of another. Identification of the controlling wear process will also assist in the development of a valid laboratory wear test. In addition, an understanding of the wear process may suggest relatively minor changes in present printing procedures that will result in significant improvement in plate wear life. The plate-ends were studied in order to develop an understanding of the wear process.

1. Paper Wipe Process

Several plate-ends sheared from plates used in paper wipe processes were received for study. Some of these plates were designated as having been removed from service due to chromium wear and others because of mechanical failure. In a few cases the chromium plating appeared to be worn away sufficiently to expose the nickel substrate at high points within color bars (engraved special features on the plates). In general, however, the chromium layer was still present over the plates surfaces. The worn surface of the chromium plating was similar in appearance to that of the wiping blades but the scratches were shallower.

2. Water Wipe Process

Seven plate-ends from plates used in water wipe presses were received for analysis. Information provided with each of the plate-ends included the ink color, total number of impressions, and for six of the plates, the reason for removal from service; no reason was given for one plate. Three of the plates had been used with black ink (bill faces) and the remaining four with green ink (bill backs). Only the plate-ends used with black ink contain color bars. The six plates for which information was provided were removed from service because of damage other than wear. Four experienced indentation damage presumably due to improper feeding of the currency paper, and two of the plates were removed because of fracture. The number of impressions to which the plates had been exposed ranged from 457,000 to 3,263,000. Examination of the color bars did not reveal areas where the chromium plating had been worn away to expose the nickel substrate nor was the chromium plating worn away at any other location on any of the plate-ends. The chromium plating thickness was measured at several locations on each of the plate-ends. The measurements were made on metallographically polished cross sections cut from the plate-ends. The thickness in an area within the margins that was not exposed to the printing or wiping action was compared to the thickness in the printing area. From these measurements the amount of wear was found to be quite small even for the plate that had been run for 3,263,000 impressions. Other features also indicated that the wear was quite small. In particular, scratches that were introduced during abrasive buffing after application of the chromium plating were still visible in the printing area.

Curiously however, at the edge of the plates outside of the area of contact with the currency paper but still within the area of contact with the wipe roll, the chromium was thinner (in one case by a factor of 3 for the plate that had 3,263,000 impressions) and buffing scratches were worn away. This indicates that wear can be a significant factor in plate life depending on circumstances of use. Further information on the details of the printing process are needed to develop an explanation for this effect.

Our studies indicate that consideration should be given to establishing the validity of analyses based only on studies of plate-ends. Wear which occurs in the plate end region may not be representative of that which occurs in the engraved part of the plate involved in printing bills. Indeed the wear may be generally uneven across the plate area. The latter possibility was suggested by the study of color bars on paper wipe plate-ends. There it was found that substantially less wear occurred at the leading edge of a color bar than at the trailing edge. The chromium plating was completely worn away on the front row of the color bar pattern but less than 50% on the back row. This kind of variation may occur in other parts of the plate. Thus chromium plating may be worn away at one location of the plate while very little wear is experienced at another location. It appears that it will be important to measure wear over various regions of the plating, including within the engraved areas. To that end it would be important to obtain samples from used printing plates taken from unengraved regions throughout the plate area.

C. Wiper Blade Wear

As discussed previously, the primary wiper blade is loaded against the PVC wiper roll; its function is to remove most of the ink from the PVC roll before subsequent cleaning stages. It is made of carbon steel. In service these blades wear rapidly. Discussion with one of the press operators indicated that the blades are replaced approximately once every 24 hours due to wear. Although the sliding speed at the wiper blade contact is less than that between the printing plate and the PVC wiping roll and the load may be different, the fact that the wiper blade and printing plates are otherwise exposed to more or less similar wear conditions against the wiper roll suggests that study of the wiper blade could provide valuable information on plate wear processes. Scratches of the order of a micrometer in depth were present on the edge of the blade (Fig. 4). This indicates that abrasive wear is a major if not the primary mode of wear sustained by the wiper blade. The hardness of the wiper blade (approximately 550 KHN) is significantly less than that of chromium electroplating (~900 KHN). Consequently, it would be worn more rapidly by abrasive particles. Measurements were made on wiper blades to obtain a wear rate value that might be related to that for printing plates.

Seven worn wiper blades were received from BEP. A record was also provided indicating the number of impressions that had been made with each blade in place. These data are shown in Table 2.

TABLE 2

WIPER BLADES RECEIVED FOR WEAR MEASUREMENT

#	Press	Ink	Impressions
1	402	Green	142,300
2	402	Green	313,396
3	402	Green	212,843
4	401	Black	143,836
5	401	Black	98,631
6	401	Black	52,686
7	401	Black	74,067

The wear of each blade was determined by measuring the wear scar width (Fig. 5) and using this value to determine wear volume from geometrical considerations. Actually, the wear scar width was found to vary along the length of the blade as shown in Fig. 6. Higher wear occurred at the blade ends than in the center. For each blade the total volume was determined by adding the volumes calculated at 2 cm intervals along on the blade. The specific wear (wear volume/impression) for each blade is shown in Fig. 7. An average value for the blades was 13.8×10^{-5} mm^3/impression.

The determination of the wear coefficient[1] requires a knowledge of the applied load in addition to the known quantities-wear

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[1] Defined by the relation:

$$\text{wear coefficient} = \frac{\text{(wear volume)*(hardness)}}{\text{(load)*(sliding distance)}}$$

volume, sliding distance, and blade hardness. Unfortunately, the applied load is not a quantity that can be determined directly from printing press operating or design information. However, by determining the blade wear rate as a function of load in a laboratory test simulating the press conditions, the service load could be determined indirectly. With that value, a wear coefficient for the blades in service could then be calculated.

D. PVC Wiper Roll Cover Properties

Studies were conducted on both new and used PVC roll cover material using scanning electron microscopy (SEM) and optical microscopy. Since the wiper roll slides on both the printing plates and the wiper blades, these studies revealed further information concerning the wear modes.

The composition of the PVC cover material is shown in Table 3. Two kinds of particles are present, calcium carbonate and graphite. Both are relatively soft. A photograph of the PVC surface is shown in Fig. 8. A large number of particles are seen. An analysis of several different surface regions showed that these particles were present at an average concentration of $340/mm^2$ and had an average size in the range of 4 to 22 µm.

Photographs of the worn PVC surface are shown in Fig. 9 and 10. Several features can be seen: cracks and pitting both of which are probably due to the wear process. Another feature is that the particles seem to be raised above the PVC matrix. This would take place if they wore at a slower rate than the PVC. In other words, the PVC is being abraded from around the harder solid particles.

An analysis of the composition was made of a large number of particles in both new and used PVC by means of energy dispersive x-ray analysis. It was concluded that most of the particles were either graphite or calcium carbonate from the original formulation; however, out of about 50 particles examined, two were of a different composition. One contained silicon and the other silicon, aluminum, and potassium (Fig. 11 and 12). These particles may be contaminants from materials used in the formulation or they may have entered the PVC during fabrication or handling. A photograph of the Si-Al-K containing particle is shown in Fig. 13.

Whatever the nature of the particles in the PVC, the primary question was whether they could scratch the chromium plated surface of the printing plate. A simple test was devised to answer this question. A pellet of PVC was mounted in the chuck of a hand grinder and run against chromium plating while lubricated with mineral oil. Although the test was run at various pressures there were no scratches in the chromium plating or evidence of wear. This suggests that the PVC itself should not damage the chromium plating. When run dry against the chromium plating the PVC was worn rapidly. Under these conditions there were some scratches in the chromium plating. Although this is not the condition that would be found in printing, this result does indicate that there may be some particles in the PVC that are capable of scratching chromium plating.

TABLE 3

PVC COMPOSITION (%)	
Polyvinyl Chloride	58
Dioctyl Phthalate	28
Monomer X980	9
t-Butyl Perbenzoate	.09
Ferro 837	1.2
Calcium Carbonate	2.9
Graphite	.9

E. Printing Ink Characteristics

Wear of chromium plating is primarily due to particles in the printing inks. The composition of an ink formulated by BEP is shown in Table 4. Samples of those ingredients which contained or consisted of solid particles were supplied by BEP and examined microscopically. It was found that for all ingredients the particles were small (<1 µm) except amorphous silica and synthaline green which contained larger particles (>1 µm). Photographs of particles from these materials are shown in Fig. 14 and 15. The important question is which of the ingredients might cause damage to the chromium plating. To answer this question a test similar to that described in the previous section was employed. Polishing cloth was attached to the end of a disk which was mounted in the chuck of a small high speed grinder. The particles listed in Table 4 were mixed with mineral oil and applied to the polishing cloth. The chromium plated surface of a plate-end was rubbed for several seconds. A new cloth was used for each particle material. At the conclusion of each test the chromium plated surface was examined under an optical microscope for evidence of damage. The results are given in Table 5.

The only ingredient which produced scratches was the flushed synthaline green. The titanium dioxide polished the surface while the calcium carbonate yielded no visible effect. The yellow iron oxide and the amorphous silica gave a transferred film. The film from yellow iron oxide was more or less continuous while the amorphous silica transferred in lumps

TABLE 4

Ink G-4716-MRE

Stock No.	Ingredients		Weight	Sub Total
295	Aqua Wipe Varnish	850-065	160.0	160.0
248	Cobalt Drier 5 1/2%		6.0	6.0
263	Lead Manganese Drier		6.0	6.0
281	Flushed Synthaline Green		28.0	28.0
-	#1840 Black Tint		12.0	12.0
292	Mineral Spirits		8.0	8.0
45	Titanium Dioxide		8.0	8.0
204	Yellow Iron Oxide		44.0	44.0
38	Calcium Carbonate (ultrafine)		120.0	120.0
154	Amorphous Silica		8.0	8.0

(Fig. 16). The lumps have the appearance of molten drops. Both of these materials contain water which reduces the hardness and increases the possibility of chemical effects. When the same test was conducted on ink which had been formulated according to Table 4, as might be expected, scratches were produced. The above analysis indicates that the source was probably the synthaline green. For comparison, tests were also conducted on three other materials. Quartz having a particle size on the order of 1 µm gave scratches. Submicron aluminum oxide on the other hand gave polishing like the hard (6.5 Mohs) titanium dioxide. The polishing effect is due to the small particle size. Black iron oxide, a principal ingredient of black currency ink, produced only a film.

This test demonstrates that two possible forms of wear can occur with inks, abrasive scratching and polishing wear. The relative amounts will depend upon the size of the particles and their concentrations at the interface.

III. Laboratory Wear Test Methods and Results

A. General Considerations

In order to devise a simulated laboratory bench test it is necessary to draw conclusions as to the mechanism of wear in service. From the previous discussions, a logical assumption would be that wear of the chromium platings is due to abrasive scratching and polishing by particles in the ink. The principal geometry involved is a cylindrical chromium plated surface sliding against a PVC surface in the presence of ink. A discussion of the important variables in this geometry follows.

TABLE 5

PARTICLE DAMAGE TO CHROMIUM PLATING

Powder	No Effect Visible	Scratches	Polishing	Transfer Film
Green ink G-4716-MRE		x		
Flushed Synthaline Green		x		
Titanium Dioxide			x	
Yellow Iron Oxide				x
Calcium Carbonate	x			
Amorphous Silica				x
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Quartz (.5 to 12 µm)*		x		
AL_2O_3 (sub micron)*			x	
Black Iron Oxide*				x

* Particles not found in G-4716-MRE

The contact geometry is shown in Fig. 17; cylinder (2) is the printing plate and body 1 is the PVC wiper roll. The ink is being drawn into the contact by body 2 and is wiped away by body 1. The controlling variables in the wear process are the amount of ink within the contact area, the length of the contact, the entrance angle, and the pressure in the contact.

The geometry and the materials can be duplicated in the bench test. The size of the cylinders would, however, be reduced. This reduction in size would change several important factors such as contact area and pressure. This change could reduce the wear rate since a particle passing through the contact would have much less area on which to act. The actual printing load is unknown and the pressure distribution across the plate surface is likewise unknown. This can be measured but would not necessarily remain constant with time. Another important variable is the amount of ink in the contact area. The purpose of the PVC wiper roll is to remove the excess ink. Because of its elasticity and long contact width this can be effectively accomplished; however, since the plates contain recesses a small amount of ink will be dragged into the contact and squeezed out. The squeezing out process contributes to the wear.

The change in stress, contact width, and the unknown amount of ink which is squeezed out make it difficult to simulate the printing wear process, that is, to obtain identical wear rates in a test rig and the application. However, this is not crucial if the primary purpose is to make a comparative evaluation of materials, and to evaluate the abrasivity of inks. Under these circumstances it is only necessary to ensure that the wear modes are the same and that the wear rate is rapid enough to conduct the evaluation in a reasonable length of time.

Three different laboratory tests were employed to evaluate wear and/or scratching of chromium plating by printing inks. These tests are referred to as 1) the rotating pin-on-disk test, 2) the flat-on-ring test, and 3) the Gravure Technical Association (GTA) test. The test machine, operating procedures, and the results obtained for each of these tests will be described in the following sections. Most of the development work was carried out on the rotating pin-on-disk test, primarily because much of the necessary equipment and considerable experience with the test had already been gained in connection with an earlier but unrelated study concerned with abrasive wear by lubricating greases containing hard particles.

The flat-on-ring test machine was designed and constructed specifically for this project. However, it was only available for use during the final phase of the project, and only a limited evaluation was conducted. Additional work is required before it will be known to what extent the test is suitable for the evaluation of printing inks and chromium plating. Important features and some possible difficulties with the test will be pointed out in the section discussing this test.

The GTA test is designed specifically to determine the abrasivity of printing inks. It is not applicable to the study of different types of chromium plating. Unfortunately, as our results will indicate, it is also not suitable for the evaluation of ink abrasivity.

B. Rotating Pin-On-Disk Test

Test Machine: A schematic drawing of the rotating pin-on-disk specimen configuration is shown in Fig. 18. A photograph of the test machine is shown in Fig. 19. The original design of this machine was due to Schiefer [5]. Schiefer's application was concerned with the wear of fabric materials. A unique feature of his design was that the rubbing motion was omnidirectional, that is, the fabric material was rubbed, not in a single direction, but in directions that were constantly changing as both the fabric, which was attached to the disk, and the abrading body, at the location of the pin in Fig. 18, were rotated. As illustrated in Fig. 18, this was achieved by mounting the rubbing bodies on two parallel but offset shafts. Rotation of both shafts is in the same sense. The rotational speeds however are slightly different. This is important because it changes what would otherwise be a circular path into a precessing orbit.

The Schiefer machine, configured for abrasion testing of fabric materials, is available commercially. Its application to the testing of fabric materials is described in ASTM D4158, "Abrasion Resistance of Textile Fabrics (Uniform Abrasion Method)". The pin and disk system which is illustrated in Fig. 18 is not the configuration used for fabric testing. The design used here had been developed in our laboratory for the investigation of wear by abrasive contaminants in lubricating greases [6]. In addition to the single pin holder which is shown in Fig. 18, a three pin holder has also been constructed. Photographs of both holders are shown in Fig. 20. With the three pin holder it is possible not only to obtain separate measurements of wear on three pins in a single test run, but by using pins with different types of chromium plating it is possible to compare the wear behavior of the different platings under nearly identical conditions.

The operating conditions used in most of the tests are listed in Table 6.

TABLE 6

Rotating Pin-On-Disk Operating Conditions

Pin Sliding Speed	63-64 cm/min
Load	15 N (5 N per pin with three pin holder)
Temperature	22+/- 1 C
Atmosphere	Air, Relative humidity, 30-65%

As mentioned above the pin and disk shafts rotate at slightly different speeds so that the sliding speed of the pin is not constant but oscillates between the values given in the table. Although the tests were conducted at room temperature, friction and stirring of the ink caused a small temperature rise, but by no more than 10°C.

The so-called pin specimens are ordinary 3/8 inch diameter steel bearing balls which are electroplated with the coating to be tested. The balls are clamped in the holder so that they can not rotate. In early experiments the chromium was deposited directly onto the steel ball. In later tests the ball was first plated with ~.005 inches of nickel (using BEP conditions) before depositing the chromium. This was done to simulate more closely the printing plate construction which is chromium on nickel. The nickel is considerably softer than the steel bearing material and could result in a different abrasion response, especially with larger scratches. Also, the structure of the chromium deposit is influenced by the substrate. Tests were not conducted specifically to determine if there were differences in chromium plating wear associated with the substrate used, and in the tests that were conducted, there was no indication that the substrate had a detectable effect.

The steel bearing balls serve as a very convenient substrate to use for the study of chromium plating wear. They can be purchased for a few cents a piece from bearing supply retailers. The bearing balls are manufactured from AISI 52100 steel. Composition, hardness, and surface finish are highly consistent from ball to ball. Moreover, the bearing application requires that the dimensions be maintained within very close standard tolerances. In each test only a small circular area about 1 mm in diameter is worn, so that a large number of tests can be conducted on a single plated ball. In one case nineteen tests were run on a ball, and there was area available for several more.

Initially, measurement of the amount of wear on the pin presented some difficulties. With a flat wear scar the simplest procedure is to measure the diameter of the scar and calculate the volume lost on the basis of geometry. With the soft elastic PVC counterface that was used in this investigation, the ball sinks into the surface, and the wear scar has a more or less spherical shape. The diameter of the contact area does not change much with wear. A measurement based on weight loss was impractical because often only a few nanograms were lost in a test run, particularly with slow wearing inks. However, the depth of wear was amenable to measurement using an electronic depth gage. Such instruments are routinely accurate to a fraction of a micrometer. For our measurements a Brown and Sharpe Model 599-1021 Electronic Gage** was employed; a similar instrument from another manufacturer could have been used.

It was deemed important to monitor periodically the amount of wear as the test progressed. Thus, changes in wear rate that

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**This particular commercial instrument is identified solely for the purpose of adequately describing the test system. It does not constitute an endorsement of the particular instrument.

might occur during a test run could be detected. Also, the effect of induced changes, for example by varying the load or introducing a different ink, could be determined. To accomplish this a fixture to hold the gage head was designed that could be placed directly on the pin holder without disturbing the ball. The outer surface of the holder served as the fixed reference level for the depth measurement. Repeated measurements on the same specimen showed a precision of about ± 0.05 µm.

An indication of the precision of the measurement method is demonstrated by the results plotted in Fig. 21. Here the ink that was used, compared to most of the other inks studied, exhibited a very low wear rate against chromium plating. The difference between each plotted point is the incremental amount of wear that occurred after 10,000 revolutions (1667 m sliding distance). It can be seen that wear depth increases monotonically with increasing distance and that the plotted points fall on a smooth curve through these points.

Test Results: More than 80 separate rotating pin-on-disk tests were conducted during the course of this program. A test run usually consisted of a number of increments of several thousand revolutions each. At the end of each increment, the thickness of material worn from the pin was measured as described above. The test increment was measured directly in terms of the number of revolutions. For most inks that increment is 10,000 revolutions; however, for faster wearing inks or more aggressive abrasive materials, a smaller increment has been used. Generally, it was desireable that at least a few tenths of a micrometer be worn away during each increment, but that the amount should not exceed one micrometer in order to have a sufficient number of data points to show the progress of wear. Because the ink became more viscous during testing as a result if drying, it was replaced with fresh ink after 10,000 revolutions.

For most tests, a total of about 5 µm of the 10-15 µm thick chromium plated layer on the pin was worn away. Because of the wide variation in the wear rates of different inks, as well as other factors that affect wear rate, tests ranging in length from a few thousand to 1.5 million revolutions have been conducted. In the latter case, several days were required to complete the test.

For an overall view of the rate at which printing inks wear chromium plating compared to other abrasive materials, data on printing inks, quartz particles, and aluminum oxide particles are summarized in Fig. 22. The printing inks include both stamp inks and currency inks and involve inks produced by both SICPA and BEP. The test conditions used to acquire the data shown in Fig. 22 are those given in Table 1. It can be seen that the wear rates, expressed in terms of volume per 1000 m sliding distance, extends over a range of nearly three orders of magnitude. The highest wear rate for inks was more than twenty-five times greater than the lowest. The wear rate obtained for quartz was substantially greater than that for most inks and the wear rate for aluminum oxide was greater than for quartz. Results obtained for quartz and aluminum oxide represent relatively simple systems consisting of a single particle type in mineral oil. On the other hand, printing inks consist of several different types of particles in a more complex fluid medium.

The different wear rates among these materials can be attributed to several factors. Among these are particle hardness (exemplified by the difference between quartz and aluminum oxide), particle size, concentration and shape. In addition to effects associated with particle properties, as will be discussed below, the nature of the fluid vehicle and the condition of the PVC counterface can have a substantial influence on wear rate.

Repeatability: If a test procedure is to be useful in comparing the wear response of different materials, it must operate at a satisfactory level of repeatability. In Fig. 23, results are plotted for three consecutive tests, all using a currency ink from the same container, the same chromium plated pin, and the same PVC counterface. In terms of the measured quantity, depth of wear, the repeatability appears to be good. In terms of volume lost the repeatability, ± 22%, is not as good but is still reasonable when compared to typical results obtained from laboratory wear tests in general. Figure 24 shows results from a second set of consecutive wear tests. The ink in this case was an intaglio stamp ink. Here, the wear rates, in terms of volume lost, differ by approximately a factor of two. Similar tests on different inks and chromium platings showed similar variations. Thus, it appears that one can not expect in separate tests to obtain repeatability that is better than a factor of two. If the PVC counterface or the chromium plated pin is changed between tests, even larger differences could be expected.

In a later section, a procedure will be described which largely avoids the poor repeatability demonstrated in separate tests and allows a relatively precise comparison to be made of the wear response of different inks. However, before taking up this topic and the discussion of the wear behaviors of the various inks studied in this program, results will be presented regarding some important factors that have a strong influence on the observed wear rate in this test.

Factors Affecting Wear Rate: A series of tests was conducted on an abrasive slurry consisting of quartz particles in mineral oil. These tests were initiated for the purpose of finding a standard reference fluid which could be used for the periodic calibration of the test. That is, by utilizing a standard fluid it was anticipated that variations in wear rate associated with factors such as the use of different PVC counterface materials or chromium plated pin specimens could be detected. However, it was found that the wear response of the quartz was rather unusual. Quartz particles and mineral oil were mixed in the proportions, one part quartz particles by weight to three parts mineral oil. The quartz particles, designated BCR 70, were a standard reference material prepared and distributed by the Commission of the European Communities. Approximately 95% by mass of the particles were specified to be within the size range, 0.5-12 µm, with a median size of 3.0 µm. The mineral oil (paraffinic) was obtained from Fisher Scientific Co. and had an indicated viscosity of 125-135 SUS. The viscosity of the 1:3 slurry of quartz particles and mineral oil was not measured but appeared similar to that of the inks tested when blended 4 parts by weight ink with one part of the same mineral oil.

Figure 25 shows the results of a test conducted on quartz particles. The wear rate is initially rapid, then becomes slower, and finally increases substantially. An initial decrease in wear rate has been observed in tests on printing inks, but it is not always seen. Among its causes are the smoothing of the slightly rough, nodular surface that is characteristic of the electrodeposited chromium and the geometric effect associated with the parabolic dependence between depth and volume when a flat is worn on the surface of a sphere. The rapid acceleration in wear depth that occurs later in the test, however, was not seen with inks. For the test shown in Fig. 25, a fresh mixture of quartz particles and mineral oil was introduced at the beginning and was not changed for the duration of the test, since there was not a problem of drying out as there was with printing inks. When a new test was run with the used slurry from a previous test, the response shown in Fig. 26 was obtained. Here the wear rate was rapid throughout the test. Although measurements were not made, it is conjectured that during the first test the quartz particles were fractured and the smaller, perhaps sharper, particles constituted a more efficient abrasive medium.

The basis for this hypothesis is as follows. To analyze the wear process one must consider the geometry of the contact and the particle size in relation to the film thickness, as is illustrated in Fig. 27. Large particles (A) are not likely to pass through the contact area and are pushed aside, although a few of these particles may get trapped in the entrance zone and be forced through. The occasional, large scratches seen on the pin surface can be attributed to these particles. Particles much smaller than the film thickness will pass through the contact region with little or no effect. Particles (B) with diameters equal to or slightly greater than the film thickness can enter the contact region and cause wear. The amount of wear caused by these particles will be a function of their concentration and their hardness in relation to the surface they slide against. Thus, in the above experiments, a large fraction of the quartz particles were probably larger than the film thickness and did not enter the contact area. However, large particles that did pass through the contact zone were susceptible to fracture. With time this could result in an increase in concentration of particles in the smaller, more damaging size range.

Although the quartz slurry revealed important features about the wear process, as the above discussion indicates, it probably is not suitable as a reference fluid. Further work will be required before such a fluid can be identified.

Effect of Counterface Roughness: The nature of the counterface surface can have a substantial affect on wear rate. If the counterface surface is rough, particles can be trapped in valleys or small holes and cause much greater wear. The number of large particles that enter the contact region is also likely to be greater. The first instance where the importance of counterface roughness was clearly indicated occurred when a test with quartz particles was conducted on a newly machined PVC counter face. The as-machined surface was significantly rougher than surfaces after lengthy periods of testing. In the test, a slurry of unused quartz particles was employed. The resulting wear rate was high and nearly constant throughout the test, being similar to that shown in Fig. 26. By the time a third test was conducted, the counterface had become much smoother, in fact, polished in appearance. Correspondingly, the wear behavior was again like that shown in Fig. 25.

It was not possible within the framework of the present program to conduct a thorough and systematic investigation of the influence of counterface roughness. However, several tests of an exploratory nature were conducted, that do indicate the manner in which counterface roughness can affect wear rate with different printing inks. Figure 28 shows wear rate results for tests with smooth and rough PVC surfaces. To obtain the rough surface the counterface was scratched with the edge of a file before each test increment. The ink used in Fig. 28 was one that had been found to produce a relatively high wear rate. (The results for different printing inks are discussed in the next section.) It can be seen that the wear rate was substantially greater for the rough counterface than the smooth counterface. This behavior was not always observed, however. When similar tests were run with a low wear rate BEP ink counterface roughness had little effect. It can be hypothesized that the difference in behavior for these two inks is related to the size of the particles which they contain. Large particles in the SICPA ink pass through the contact zone with less frequency when the counterface is smooth than when it is rough, so wear is less for the smooth surface. With relatively few large particles, as appears to be the case with the BEP ink, counterface roughness has little effect.

In addition to surface roughness, the mechanical properties of the counterface are also likely to have an effect on wear rate. The elastic modulus of the counterface will determine the contact area, which in turn affects the film thickness. Also the elastic modulus and hardness of the counterface will determine how well the particles are held and the force with which they are pressed against the pin. These factors were not investigated during our program.

Wear Characteristics of Currency Inks: Currency inks produced both by BEP and SICPA were received for study on several different occasions over the two year period of this project. The inks were usually delivered in pint or in one instance, gallon size metal containers. Usually but not always the inks were described by identification and lot numbers. A list of the inks received is given in Table 7. Early in the program no attempt was made to retard the drying out of the inks in the containers and it was found that the inks were no longer suitable for use after several weeks. Later the inks were covered with nitrogen and refrigerated. In this way the inks were suitable for use for several months. In addition, BEP prepared a special batch of inks without dryers. Drying of these inks did occur, however, by loss of volatile solvent.

TABLE 7

Date Received	Color	Identification
9/26/84	black	Cylinder wipe currency ink black
9/26/84	green	Cylinder wipe currency ink green
1/25/85	green	Project G-4716-MRE (without dryers)
3/01/85	black	Project BK-3280-373 (without dryers)
11/27/85	green	SICPA S10
11/27/85	black	SICPA S4
3/20/86	green	I-286 Cylinder wipe green S10 W-2181-06 Lot #2-003-2929
3/20/86	black	I-287 Cylinder wipe black S4 W-2180-66 Lot #2-003-3613
5/21/86	green	SICPA Intaglio CW green S10 Color 354100A Lot #2-003-4532
5/21/86	black	SICPA Intaglio CW black Color 374101G Lot #2-003-4740

As indicated in an earlier discussion, separately run tests were not capable of distinguishing between inks unless they differed markedly in wear rate. Even then care had to be taken to assure that the PVC counterface and chromium plating were as nearly similar as possible for each test. With these precautions it was possible to identify some inks that gave relatively low wear rates and some that gave relatively high wear rates. Inks that gave low wear rates were the BEP inks without dryers, BK3270-373 and G-4716-MRE, and the SICPA ink, S4 black Lot #2-003-3163. Inks that produced much greater wear rates were SICPA S4 black Lot #2-003-4740 and SICPA S10 green Lot #2-003-4532. Separate tests comparing SICPA S4 black Lot #'s 2-003-3163 and 2-003-4740 are shown in Fig. 29. On a wear volume basis these inks differed by almost a factor of 20. The same chromium plating, applied with BEP conditions, was used in both these tests. Among the other inks studied, there was no indication on the basis of separate tests that they were markedly high or low in their wear behavior.

The most reliable means to determine the relative differences in wear rates between inks was by alternating the inks in the same test run. Results using this method are shown in Fig. 30. Here SICPA S10 green Lot # 2-003-4532, a fast wearing ink, is compared with BEP G-4716-MRE w/o dryer, a slow wearing ink. In Fig. 30a the SICPA ink is used first. It is replaced by the BEP ink in the second segment and then used again in the final segment. In Fig. 30b, the BEP ink is used in the first and last segments and the SICPA ink is used in the middle segment. In both of these tests the wear rate was noticeably less for the BEP ink. This assessment can be made without reference to the actual wear rates of the inks. Thus differences in chromium plating and the PVC counterface material that might otherwise interfere with the test results are avoided. (It is of course possible that a different ranking would occur with different chromium plating or counterface materials.)

A major limitation of the above method is that it does not easily lend itself to the comparison of a large number of inks, especially if the evaluation is to be made over a long period of time. A means of avoiding this difficulty is to employ a standard ink or a reference fluid. The fluid may be an ink or preferably a simple slurry consisting of well characterized abrasive particles and a liquid. As discussed in the previous section, an attempt was made to use quartz particles and mineral oil as such a fluid, but the wear results were not consistent. It is thought that a fluid containing only a few of the major constituents of currency inks might be more satisfactory.

<u>Wear Characteristics of Intaglio Stamp Inks</u>: The wear behavior of three intaglio stamp inks was studied. These inks were identified as follows:

SICPA LOCKWOOD GREEN
SICPA BROWN
BEP BROWN

Service experience had indicated that these three inks differed significantly in abrasivity, with the SICPA lockwood green exhibiting the greatest abrasivity and the BEP brown the least.

The availability of these three inks was of considerable importance to our laboratory wear testing activity, since they provided the opportunity to study inks with known service performance. Rotating pin on disk test were conducted on these inks. The BEP brown and the SICPA lockwood green inks were about equal in wear rate while the SICPA brown ink was noticeably greater. Thus the ranking of the inks in terms of laboratory wear rate appears to differ from that determined by service abrasivity. However, on examining the worn chromium plated surfaces of the laboratory test specimens, it was found that very large scratches were present with SICPA lockwood green, smaller and perhaps fewer scratches were obtained with SICPA brown and very few scratches were seen with BEP brown, in apparent agreement with the service assessment of abrasivity. Photographs of the worn test specimen surfaces are shown in Fig. 31.

These results indicate that in the determination of ink abrasivity it is necessary to distinguish between wear rate and scratching as two separate processes that may limit the useful life of printing plates. The results also demonstrate that the presence of large scratches and a high wear rate do not necessarily correlate. This behavior is consistent with the fact that a given ink can contain a range of particles of different types, sizes, concentrations, and abrasivities. A high concentration of very small but highly abrasive particles may produce a high wear rate and yet yield a polished surface. On the other hand, a mixture consisting of a few large abrasive particles combined with a high concentration of less abrasive particles may give a lower wear rate but cause severe damage by scratching. In summary, these results indicate that printing inks should be analyzed both for scratching abrasion and for wear rate.

<u>Wear of Different Types of Chromium Plating</u>: In initial studies, several different types of chromium plating were examined. Separate tests were conducted using the same ink and PVC counterface for each chromium plating. With one exception, the scatter in the results far exceeded any difference that might have been attributed to differences in the chromium platings. The exception involved a chromium plating referred to as Armaloy. That plating was said to consist of an outer porous layer of electrodeposited chromium over an inner layer of dense, bright plating. Typical results on this chromium plating are shown in Fig. 32. The wear rate was initially very high and then decreased to a low rate. This behavior was attributed to the lower wear resistance of the outer porous layer compared to the underlying, dense chromium plating.

In order to obtain a more precise comparison of the wear rates of different types of chromium plating, a three pin holder was designed and constructed. With this device three of the same or different platings could be tested simultaneously under essentially identical conditions. The only exception is that each pin follows a different track on the counterface. However, by periodically exchanging positions of the pins in the holder, even this possible source of bias can be minimized.

To investigate the extent under rather extreme conditions to which different chromium platings might exhibit different wear behaviors with currency inks, pins were prepared with very soft chromium plating, approximately 500 HN versus approximately 900 KHN for standard BEP chromium plating. Results obtained with the soft chromium plating are compared with standard BEP chromium plating in Fig. 33. Here, the wear rate of the soft chromium plating is clearly much higher than the BEP chromium plating. When the test was repeated with a different currency ink, the results in relative terms were essentially the same. The soft plating wore much faster than the hard plating. These results clearly indicate that wear rate can be strongly dependent on the type of chromium plating under certain conditions.

Additional tests using the three pin holder were carried out to compare the behavior of "transition" chromium plating with BEP chromium plating. Transition chromium plating is deposited under different conditions than those used for BEP chromium. As a result, the crack density, microstructure and hardness differ. Figure 34 shows results from a test employing currency inks where two pins were plated with transition chromium and the third pin was plated with BEP chromium (wear results for the latter pin were shown previously in Fig. 30a). The results indicate that the BEP chromium has somewhat better wear resistance than the transition chromium. The difference is however relatively small compared to the expected variability in the test. One other test gave the same ranking but a third test indicated that the BEP chromium was intermediate between the two transition specimens. Therefore, it can not be concluded that there is a significant difference between these two different types of chromium plating in the rotating pin-on-disk test with printing ink.

Some comment should be made about the fact that these results differ both from those obtained by Lashmore et al.[1] and those obtained by Bolster et al. [4] at the Naval Research Laboratory. Lashmore et al. found that the transition chromium plating exhibited somewhat better wear resistance than the BEP type plating (prepared at NBS) while Bolster found that the BEP type plating prepared at NBS was substantially better than the transition plating but was not quite as good as the BEP chromium plating on a specimen cut from a printing plate. In the latter case, the chromium plating prepared by NBS according to BEP conditions was found to be substantially harder than the BEP plating on the printing plate. This probably accounts for the different wear behavior in this instance. On the other hand, assuming that the BEP and transition platings prepared at NBS and tested by the three groups were all the same, the different wear behaviors which were found are probably the result of differences in the tests employed. Lashmore et al. used a slurry containing 5 µm Al_2O_3 particles with the pH adjusted to 4.5 by means of ferric chloride, while Bolster et al. employed a slurry containing 30 µm quartz particles. Additionally, the load used by Bolster et al. was substantially lower than that used by Lashmore et al. These conditions, of course, differ from those used in the three pin-on-disk test where printing ink was used as the abrasive medium. Although the reasons for the different results are not known in terms of the wear mechanisms involved, the differences do indicate the strong influence that test conditions can have and emphasize the importance of selecting conditions that are relevant to the service conditions that are actually involved.

C. Flat-on-Ring Test

Test Machine and Procedure: The flat-on-ring configuration, shown schematically in Fig. 35, simulates more closely the contact geometry that exists between the wiping roll and printing plate than does the rotating pin-on-flat configuration. In the press, the sliding direction is nearly unidirectional except for a small periodic oscillation by a few degrees as a consequence of the axial motion of the wiping roll. With the flat-on-ring configuration sliding is unidirectional.

The ring for the flat-on-ring test is prepared from a 2.0 inch disk cut from PVC wiping roll cover material. The inner black and center white PVC layers are machined away leaving only the outer black layer with a thickness of about 0.09 inches. After drilling the necessary mounting holes in the disk, it is clamped between flanges on a motor driven shaft. The design is such that a ring of PVC material extends beyond the flange and comes into contact with the flat specimen.

A significant advantage of the flat-on-ring machine design is that the chromium plated flat specimens, which are in the form of 0.250 inch diameter disks, can be cut directly from the ends (or other regions) of printing plates. Thus, the actual materials used in the printing process can be used in the laboratory test and there is no need to prepare special specimens -- unless, of course, it is desired to study experimental coatings.

An additional feature of the flat-on-ring machine design is that the ring and flat are enclosed. During a test, the entire enclosure is filled with ink and only minimal exposure to the atmosphere occurs. Thus, drying of the ink due to solvent evaporation and exposure to oxygen in the air is minimized. In addition, the enclosure contains passages for fluid circulation to control temperature. Although this feature has not yet been put into use, it would permit tests to be conducted at ink temperatures that are normally encountered during press operation.

Other features that have been incorporated are a load cell to measure friction force and a variable speed drive. The capability to measure friction force is important in that film thickness, viscosity and/or ink rheological effects on wear rate may be investigated. The variable speed drive allows sliding speed to be studied as a variable that may influence wear rate.

A disadvantage of the flat-on-ring test is that only one specimen can be tested during a run, while with the rotating pin-on-disk machine three can be tested. Thus, the flat-on-ring test is not as well suited to the comparison of different types of coatings as is the rotating pin-on-flat test.

Operating conditions reported in the tests reported here are listed in Table 8.

TABLE 8

Flat-On-Ring Operating Conditions	
Sliding Speed	89 cm/s
Load	5 N
Temperature	22+/-1 C

Prior to each test, the PVC ring and surrounding enclosure was cleaned by swabbing with mineral spirits to remove old ink. The enclosure was entirely filled with 12 g of a mixture of ink and mineral oil (three parts ink to one part mineral oil by weight). The chromium plated specimen was briefly lapped on 6 µm diamond paste to produce a flat surface, ultrasonically cleaned with hexanes, and mounted for testing. The test was then started and run for the desired number of revolutions of the ring.

At the conclusion of the test, the volume worn from the chromium plated flat was measured. Intermediate measurements were not made as was done in case of the rotating pin-on-disk test. The measurement was carried out by means of an automated, computer controlled profilometer system. A series of parallel traces 20 µm apart was made across the worn region. The volume was then obtained by calculating the difference between the worn surface defined by these traces and the original flat surface.

Results: The results of a series of tests using SICPA S10 green ink (#2-003-2929) are shown in Fig. 36. The wear volume on the flat is plotted against the sliding distance as measured by the number of revolutions. The flats for these experiments were cut from a currency plate end. Each point on the graph represents a separate test run for the indicated number of revolutions. The curve is a linear least squares fit to the plotted data.

A dimensionless wear coefficient, K, was calculated from Fig. 36 using the equation, $K = VH/LD$, where V is the wear volume, H is the hardness, L is the load and D the sliding distance. The K found was $6.2\text{X}10^{-4}$. This represents a relatively high rate of material removal and is indicative of significant abrasive wear.

An example of a wear scar obtained in the flat-on-ring test is shown in Fig. 37. This is a topographic plot generated from profilometry data. Photographs of the scar and the surface of the PVC ring are shown in Fig. 38 and 39, respectively. The worn flat is characterized by grooves in the direction of sliding having a maximum depth of about 3.0 µm. This is approximately the size of the largest particles in the ink used in this test. For example, see Fig. 40.

It should be noted that there are indications of damage in the area just ahead of the slider (see Fig. 38). This area is shown at higher magnification in Fig. 41. Here the surface appears to be pitted or indented by sharp particles; however, at higher magnification the edges of the pits are not sharp but rounded as if erosion had taken place. This has the appearance of soft abrasive wear where the particles are of essentially the same hardness as the chromium plating. Under these circumstances the pits would be formed by abrading away the softer areas in the chromium plating.

The high wear rate in this test deserves comment. The test emphasizes abrasive wear based on the rough PVC surface and the fact that particles can easily be trapped in front of the slider. In the rotating pin-on-flat test it is more difficult to trap particles since the rotating ball continuously brings in new surface void of particles, and there is a flow of the ink-particle mixture laterally out of the contact line.

D. GTA Test

Test Method: The Gravure Technical Association (GTA) markets a relatively inexpensive test system for the evaluation of the abrasiveness of printing inks. The test system includes a test machine, referred as the GTA Ink Abrasion Tester, necessary supplies, and instructions for conducting tests. A test machine together with necessary supplies was provided to NBS by BEP for evaluation. In this test method the ink to be evaluated is rubbed against a chromium coated glass slide by means of a felt covered rider. The amount of chromium coating worn away is taken as a measure of the abrasivity of the ink. This result is then compared with results obtained for other inks or perhaps a standard ink. In this way a relative ranking is obtained. That is, the test is intended to give relative abrasivity compared to other inks and not a wear rate for chromium. Our analysis which is summarized below indicated that the chromium coating on the glass slides was significantly different in tribological behavior than electrodeposited chromium. Therefore, the GTA test can not be expected to give the desired determination of ink abrasivity.

A schematic drawing of the GTA Tester is shown in Fig. 42. The chromium coated slide is held in the bottom of a rectangular reservoir which contains the ink. The rider to which the felt is attached is rubbed against the glass slide in a reciprocating motion. The number of cycles of sliding is indicated by a mechanical counter which can be set to turn off the machine after a predetermined number. The applied load and stroke rate are all fixed, i.e. there are no provisions for varying these quantities. Values measured for machine provided by BEP are listed below.

Load ---- 9.3 N
Frequency ---- 80 strokes/s
Stroke Length ---- 5.65 cm
Rider Width ---- 1.7 cm

The vacuum deposited chromium coating on the glass slides is extremely thin and transmits light. It is specified to have 40% transmittance at 550 nm which indicates that the coating is no more than a few tens of nanometers thick. Wear of the coating will result in an increase in light transmittance which can be measured by means of a photometer.

Conceptually this test method is very attractive. Wear of chromium plating by printing inks, although a serious problem in the printing industry, normally occurs at very low rates. Thus to obtain an easily measurable amount of wear by many methods will require a rather long test. Not only is this undesirable because of the time factor, but with a long test the problem of maintaining constant test conditions is also greatly increased. Without good control over test conditions, indicated differences among inks is subject to substantial uncertainty. Because transmittance is very sensitive to coating thickness, wear can be measured even when wear rates are very low with the advantage that a relatively short test is required.

Ordinarily, the transmittance measurement would be made by a simple photometer and light source. This equipment is not provided with the GTA system. Since it was noted in preliminary tests that there was a tendency for the chromium to be removed in streaks, it was decided to employ a scanning microdensitometer so that information on the variations in wear across the contact region as well as the total loss could be obtained. A scanning microdensitometer was assembled by replacing the stylus and pick-up head of an automated profilometer system with a light source and photodetector. With this device light intensity as a function of position on the chromium coated glass slide could be recorded. Variations in transmitted intensity as well as the integrated intensity was available from these measurements.

Based on experience with other tests being conducted at NBS it was known that wear of chromium plating by printing inks can be quite sensitive to the substrate employed. In particular it was considered important to simulate the contact conditions in cylinder wipe presses as closely as possible. Thus, the majority of the evaluation was carried out using PVC wiper roll cover material obtained from BEP rather than the felt material that was provided. In operation, a thin, 1.0 cm wide strip, of the PVC material was cemented to the slider.

Currency printing inks have the consistency of pastes at room temperature and furthermore dry out with exposure to air. The rate of drying is increased by the mixing action associated with sliding. The GTA test can not operate under these conditions and it is necessary to dilute the ink with a solvent to make it less viscous. Literature with the GTA tester recommends a specific viscosity determined by the Zahn Cup method. It is suggested that two or three parts solvent to ten parts ink will be required. Measurements of viscosity were not made in our evaluation, however, tests were conducted with a series of different ink dilutions to cover a wide range of viscosities. As will become apparent, ink viscosity is a very important quantity in this test.

Test Results: Figure 43 shows chromium coating wear as a function of the number of cycles sliding for a green currency ink diluted with mineral spirits (three parts ink to one part mineral spirits). For comparison the results are shown for similar tests conducted with paraffinic mineral oil (125-135 SUS) also diluted with the same concentration of mineral spirits. The amount of wear observed in both cases is about the same. The mineral oil-mineral spirits solution does not contain abrasive particles while the ink does. In seeking an explanation for this behavior it was considered that the wear might have been produced by hard particles in the PVC wiper roll material. The particles could be there either inherently as part of the PVC formulation or due to embedment from the previously used printing ink, despite carefully cleaning between tests. Thus tests were conducted using the felt material supplied for the GTA tester. In this case wear with the mineral spirits-mineral oil mixture was even greater. Photographic prints prepared by using the glass slides as negatives are shown in Fig. 44. With a 3:1 mixture of mineral spirits and mineral oil most of the chromium in the contact area was worn away with the GTA felt material while there was relatively little wear when PVC was used. Each test consisted of 300 cycles. Several other cloth materials commonly used in metallographic polishing procedures were tried. It was considered that such materials would not contain abrasives due to the requirement that they should not scratch surfaces which in many cases would be much softer than chromium plating. The materials included Buehler Microcloth, silk, velveteen, and nylon. All produced wear similar to GTA felt except nylon which gave a result similar to PVC. When mineral oil without dilution was employed, the GTA felt produced very little wear after 300 cycles.

The above results indicate that the chromium coating is quite easily removed from the glass slides, even by very soft materials. This kind of behavior is certainly not expected to be representative of electrodeposited chromium on printing plates. One would not expect a detectable amount of electrodeposited chromium to be removed from a printing plate after rubbing for a few thousand centimeters with organic fibers. An observation made during experiments with the chromium coated glass slides suggested a direct means of comparing the behavior of glass slides with electroplated printing plates. It was noted that in tests with mineral oil and mineral spirits that a dark discoloration developed on the contact area of the white GTA felt due an accumulation of chromium debris particles rubbed off the glass slide. When an electroplated chromium specimen was used in place of the GTA glass slide, there was no discoloration of the felt indicating that there was no observable wear. The chromium plated specimen was obtained by cutting a section from a currency printing plate end that had been provided by BEP for other studies. We therefore must conclude that the chromium coating on the GTA glass slides has very different properties than electroplated chromium on printing plates.

On the basis of our experiments it appears that the main factor determining the amount of wear with the GTA slides is the viscosity of the ink or other fluid. As long as a fluid film prevents solid contact with the chromium coating wear will not occur. Given two inks with the same viscosity but with one ink having particles larger than the fluid film thickness, the ink with large particles will cause wear of the coated slide whether they are hard or quite soft particles. Are there conditions where the GTA test could give good correlation with service? It may happen that the fluid film conditions in some printing operations are similar to those in the GTA test. For example, gravure cylinder and doctor blade wear are known to be influenced by the lubricating properties of gravure inks. An ink with large particles, which happen to be hard enough to cause wear in the press, may be shown to be relatively abrasive by the GTA test, leading to a fortuitous example where good correlation exists between the GTA test and service experience. Unfortunately an ink with large soft particles would also appear abrasive in the GTA test but might not cause wear in service.

Although the GTA test, as it is presently constituted, does not appear to be suitable for measuring the abrasivity of printing inks, the concept of a simple and rapid test of this type is still attractive. By developing a chromium coating for glass slides, perhaps an electrodeposited coating, that better simulates the chromium plating on printing plates, it may be possible to remedy the most serious deficiency of the GTA test. In fact, it is our recommendation that an effort be undertaken to improve the GTA test in this way.

E. Transfer of Wear Test Method to BEP

The method developed during the past year employing the rotating pin on disc wear tester could be transferred for use by BEP staff. This would require purchase and modification of a commercial Schiefer Tester into the configuration now used at NBS. The purchase cost would be approximately $6350; the modification cost would depend on the place of modification (NBS or outside private shop). The test method developed at NBS would be documented and instruction in its use would be provided. Methods for preparing the PVC counterface surface, and the chromium-coated steel balls would be explained. With this recommended approach both NBS and BEP would have an identical wear test system so that joint comparative measurements could be carried out. In this way the transfer of wear test methodology to BEP staff would be most feasible. There are also possible additional modifications to the tester to be considered; the first one recommended would be to enclose the specimen area so that an inert gas environment could be established during the test.

The rotating pin-on-disk test method could be used to measure (1) the abrasivity of different inks currently in use, (2) the consistency in wear properties of the "same" ink formulation over a period of time, (3) the consistency of chromium plating over a period of time, (4) the wear characteristics of new ink formulation.

The second wear test method developed in the program, the flat-on-ring method, is not proposed for transfer to BEP at this time; the method still needs further development before it could be used in a routine manner. The advantages of this method have been discussed already, and are significant.

IV. Summary and Conclusions

Studies have been conducted of wear processes occurring in BEP currency and stamp printing. From this work the following conclusions have been drawn.

1. In the water wipe press, wear of chromium plated currency printing plates occurs primarily at the wiper roll contact. Particles in the ink are trapped at the contact between the PVC covered wiping roll and the printing plate surface. Sliding under pressure of these particles at the speed existing in the

contact causes abrasive scratching and polishing of the printing plate surface.

2. According to the results of our laboratory tests which simulate the conditions at the wiper roll and printing plate contact, factors which have a significant influence on wear rate are particle size, hardness and concentration, and the roughness of the PVC surface. An increase in any of these factors can result in a substantial increase in wear rate.

3. Other factors which were not studied in detail but which were indicated to have a strong effect on wear were fluid film thickness at the wiper roll-printing plate contact (this is determined by contact pressure, ink rheology, and sliding speed) and the ability of the ink to form a protective solid film on the plate surface. Some ink constituents were found to form a transfer film on chromium in laboratory experiments. Films were observed on printing plate-ends which had sustained extremely long service lives without appreciable wear.

4. Particles contained in the PVC wiper roll cover material do not, in general, cause significant wear of the printing plates. Large, hard, foreign particles which are occasionally embedded in the PVC material may cause severe scratching damage.

5. Among the inks received from BEP for study in this program, the wear rate of the highest wearing rate ink was 25 times greater than that of the lowest in laboratory wear tests. Since only a few different types of inks and different lots among these types were studied, this result indicates that there is a potentially large difference in wear rates among printing inks.

6. Currency inks that produced high wear rates were:
SICPA S4 black lot # 2-003-4740
SICPA S10 green lot # 2-003-4532

7. Currency inks that produced low wear rates were:
BEP Bk 3270-373 w/o dryer
BEP G-4716-MRE w/o dryer
SICPA S4 black lot # 2-003-3163

8. For stamp inks a correlation was established between service behavior and laboratory results. An ink that caused severe scratching in service was also found in laboratory tests to produce severe scratching of chromium plating. Similarly, inks that did not cause scratching in service did not do so in the laboratory. It was also interesting to note that severe scratching did not necessarily correlate with a high wear rate. The concentration of abrading particles is clearly an important factor here.

9. Three laboratory tests were evaluated for use in the study of wear in the printing process. They were the rotating pin-on-disk test, the flat-on-ring test, and the GTA test. The rotating pin-on-disk test was found to be suitable both for the evaluation of the wear behavior of different printing inks and of different chromium platings. Appropriate test procedures were developed for both of these tasks. Preliminary experiments indicated that the flat-on-ring test could also be used for these tasks but further development is necessary. The GTA test was found to be unsuitable for determining ink abrasivity. The chromium coating on the glass slides used to measure abrasivity was easily scratched by soft materials that caused no detectable damage to the chromium plating used on printing plates.

10. Using the rotating pin-on-disk test, it was demonstrated that with various printing inks the wear rate of soft chromium plating was substantially greater than hard BEP type chromium plating. No appreciable difference was found between a transition type chromium plating and BEP type plating.

V. Recommended Future Work

A. Scratching Test Development

Scratching of engraved printing plates during use is a serious problem and arises from particles in the ink, present either through intentional or accidental inclusion. One test method for evaluating inks for scratching tendencies, the GTA method, has already been evaluated in the first part of this program, and was found to be inadequate. A new test that overcomes those noted deficiencies is needed. The new test would examine chromium plating on metal substrates so that the relationship to actual printing plates will be close. One possible method would use a single stroke of a slider in the presence of ink on a very thin plating. The depth and number of scratches would be determined using chemical etching to penetrate to the underlying metal and microscopy methods of measurement. It is thought that the method could later be automated for rapid, routine use.

B. Additional Wear Test Methods

One possible test, the button test, would involve a chromium plated cylinder or sphere loaded against a rotating PVC specimen. To ensure a rapid wear rate a high stress test should be run with provisions being made to get an adequate amount of abradant into the contact area. There are several ways to accomplish this: (1) a cylinder-shaped specimen would collect more abrasives at the entrance zone than a sphere, (2) roughened surfaces will contain polishing abrasives (roughening could be accomplished by a light grit blast of both surfaces), (3) the PVC surface might be made porous.

The button test could be used on an operating press and in a bench test rig by making the arm detachable. In this way a correlation could be established between the test rig and the press. Further, with the arm attached to the press a correlation could be established between the wear measurements and changes observed in the currency bills.

C. Additional Wear Measurement Methods

It would be very important to obtain a value for the wear rate of printing plates in actual service, and for a range of conditions. This information would provide a baseline for use in deciding whether subsequent wear experience is reasonable, or whether perhaps some part of the printing process is not under usual control. Such information would also permit a comparison between laboratory wear data and printing operation wear data; that would indicate the degree to which the laboratory wear test simulates the actual use. Several possibilities exist that might permit obtaining service wear data. Direct measurement of wear on the chromium printing plates would be best; however, security precautions make that difficult. Another approach recognizes that the steel wiper blades that bear on the wiping roll experience very similar sliding conditions to the printing plates. Chromium plating of the wiper blades would permit an even closer comparison to be made, once the loads involved were determined. The blades could also serve to study other new materials for possible printing plate use.

As another approach, a simple specimen holder could be added to the press that would hold a small test specimen against the PVC wiping roll during operation of the press. It would not interfere with the usual operation. A possible design has been developed (Fig. 45). Since it is not necessary to measure friction such a device could be relatively simple consisting of a magnetic base and a loaded lever arm. Such a device could be constructed using a conventional dial indicator, suitable attachments, and a magnetic base. An advantage of this approach is that replaceable tips are available which could be chromium plated for use as specimens. This device would provide accurate wear data in a short period of time and it would not interfere with the printing operation. Secondly, it could be used as a separate wear test by loading it against an external PVC rotating rod. It would improve the simulation to have the same device used in service and in a bench wear test.

D. Fundamental Research Studies

Based on the laboratory test results and the understanding of printing plate wear mechanisms obtained in the past two years, a program of fundamental research is recommended. It would provide quantitative relationships between a number of important parameters that influence wear in printing processes. The results obtained from experiments using appropriate laboratory wear test devices would provide the basis for determining the cause of wear problems when they do arise and also for reducing wear under normal conditions. The test matrix would be constructed from the following elements:

Particles:	type size concentration
Fluid:	viscosity pH film thickness
Test variables:	load speed temperature
Counterface material:	roughness hardness

In these tests BEP type chromium plating would be used throughout. Because of the size of the test matrix it might not be possible to study all the different combinations of elements. Each of the above elements should be studied under at least one set of constant conditions.

ACKNOWLEDGMENTS

The authors are pleased to recognize the very valuable assistance provided in this project by NBS staff: David Lashmore and Cris Johnson in preparing various plated test materials, Eric Whitenton in conducting optical measurements, and BEP staff: Robert Hall and William Newitt in providing information on printing technologies and specimens of inks, plate-ends, and wiping blades.

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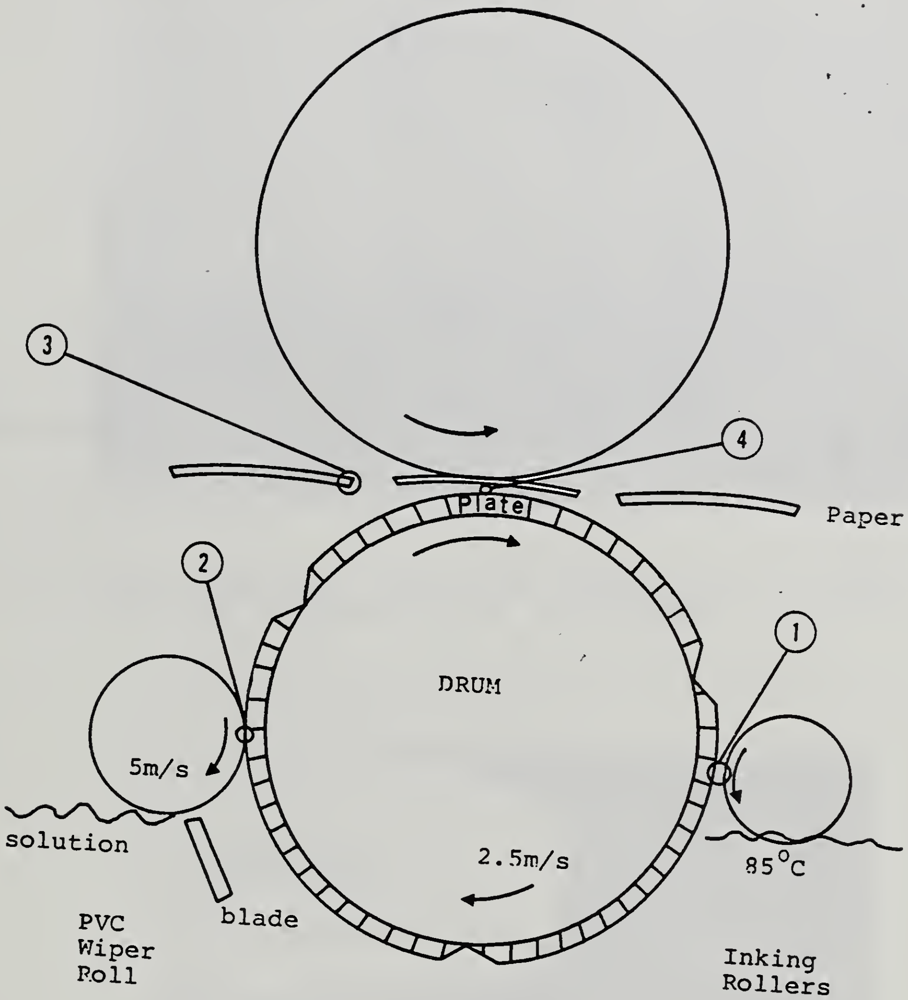

Figure 1. Schematic drawing of the currency printing process showing the wearing contacts.

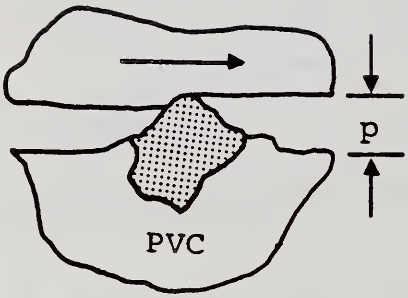

Figure 2. Schematic drawing of the two-body abrasive wear process.

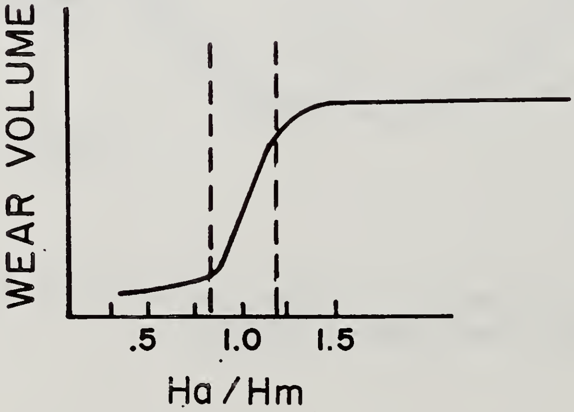

Figure 3. Effect of hardness on abrasive wear volume [2]. H_A is the hardness of the abrasive; H_M is the hardness of the wearing body.

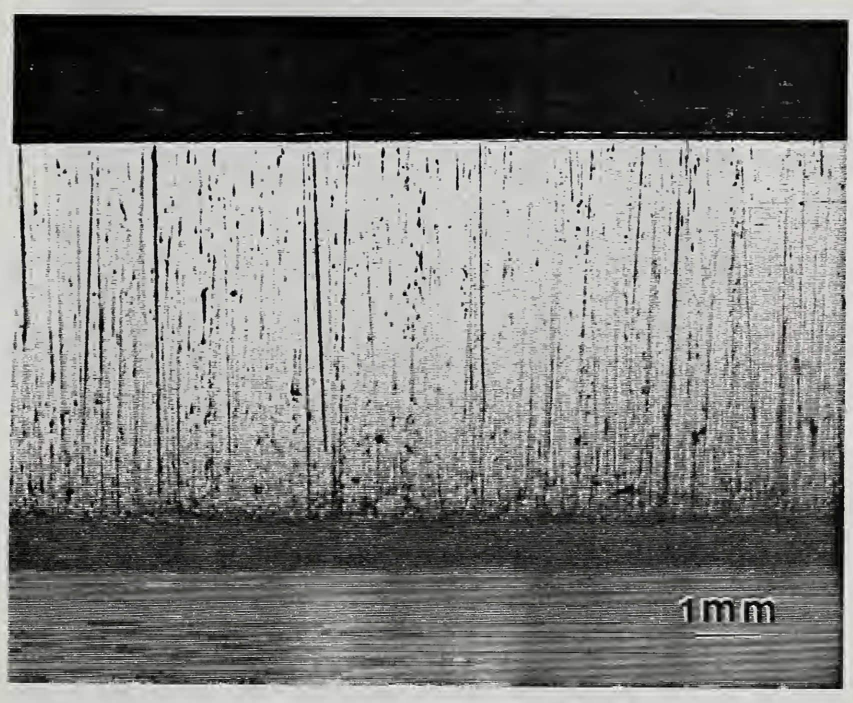

Figure 4. Photograph of the worn surface of a wiper blades showing abrasive wear scratches.

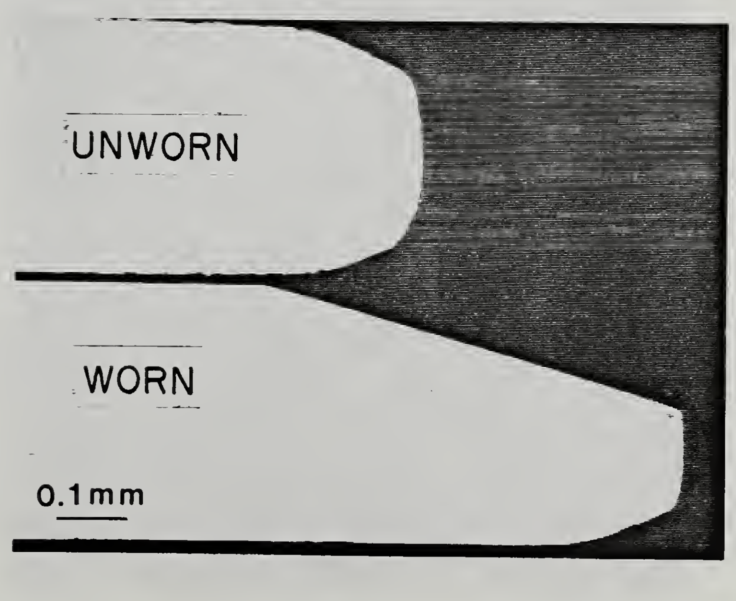

Figure 5. Photographs of the cross sections of worn and unworn wiper blades.

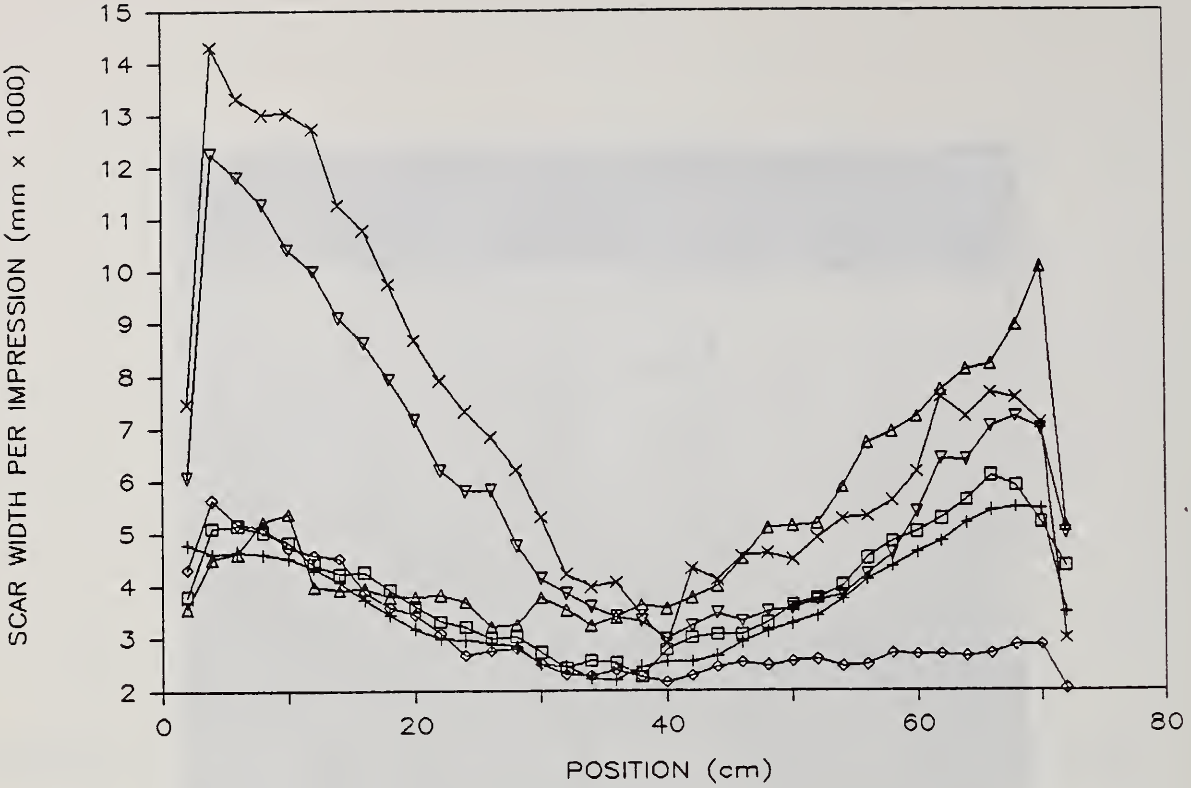

Figure 6. Wear scar widths on the seven wiper blades as a function of position along the blade.

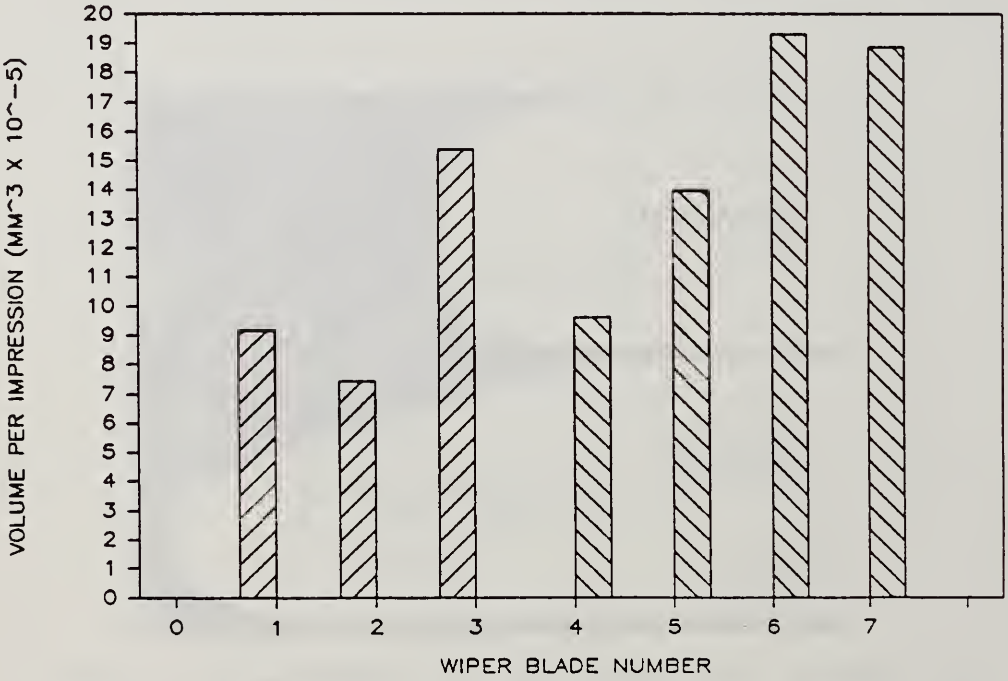

Figure 7. Wear volume as a function of number of impressions for seven different wiper blades.

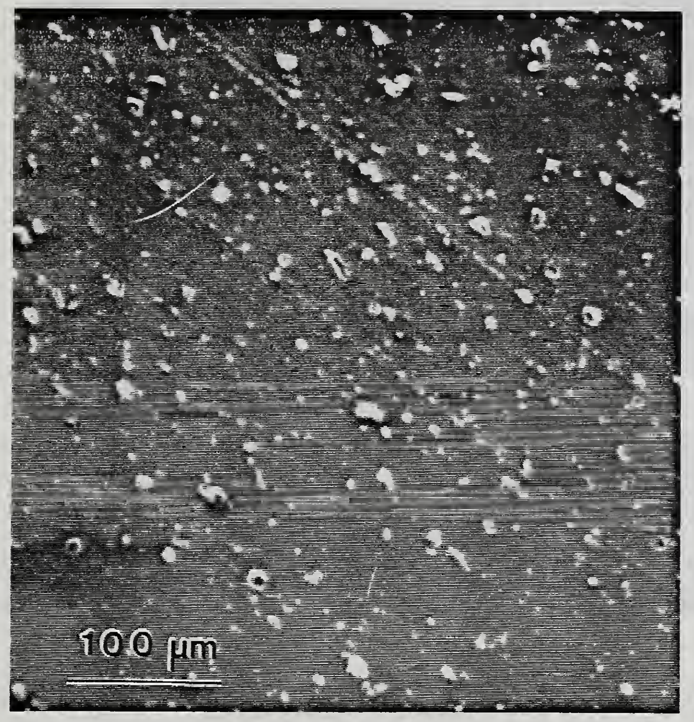

Figure 8. Photograph of unused PVC wiping roll cover surface material.

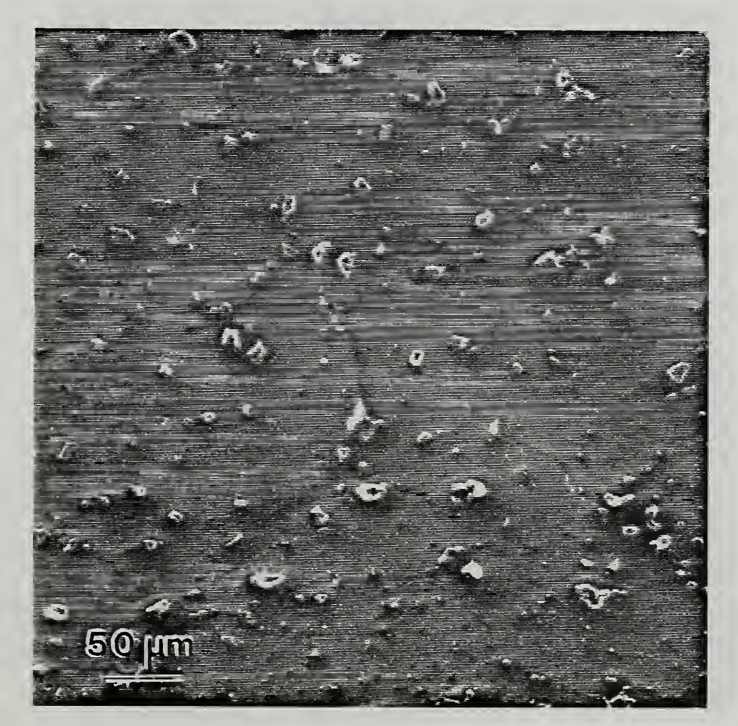

Figure 9. Photograph of a worn PVC wiping roll surface after use in service.

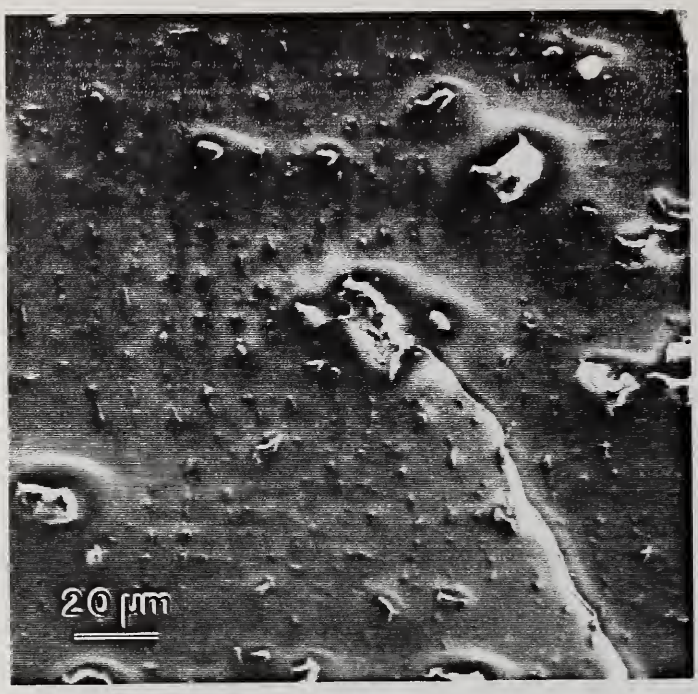

Figure 10. Photograph of a worn PVC surface showing cracks and particles.

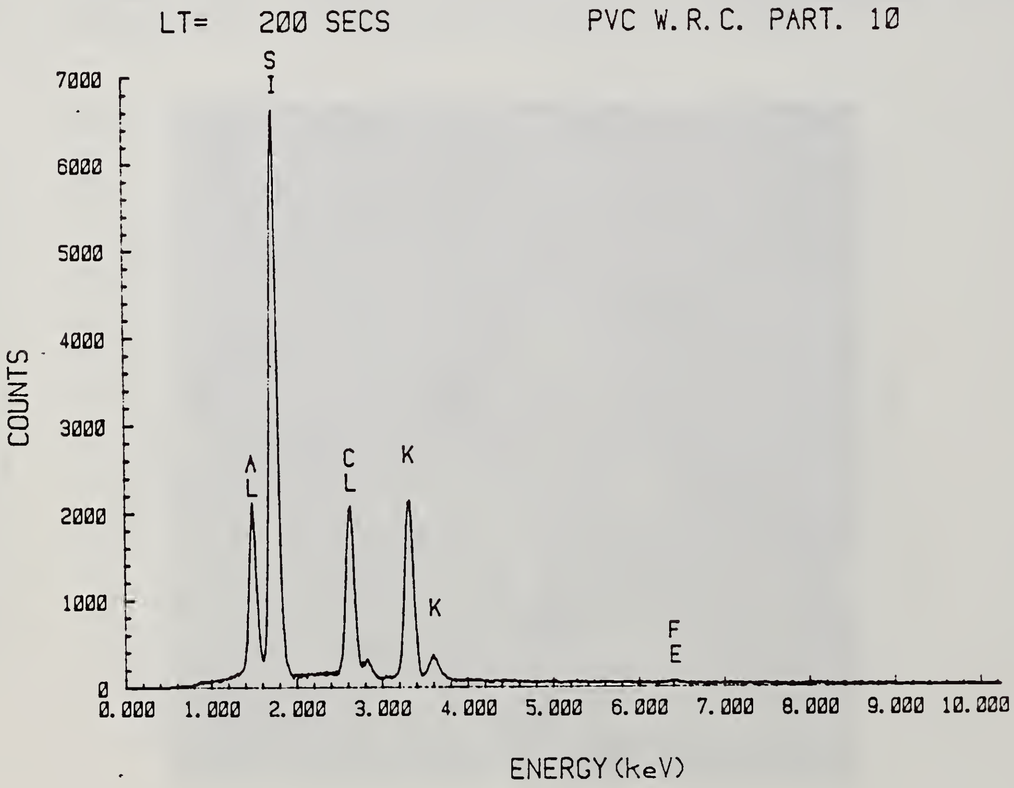

Figure 11. Energy dispersive x-ray analysis of particle in PVC wiping roll cover showing aluminum, potassium, and silicon.

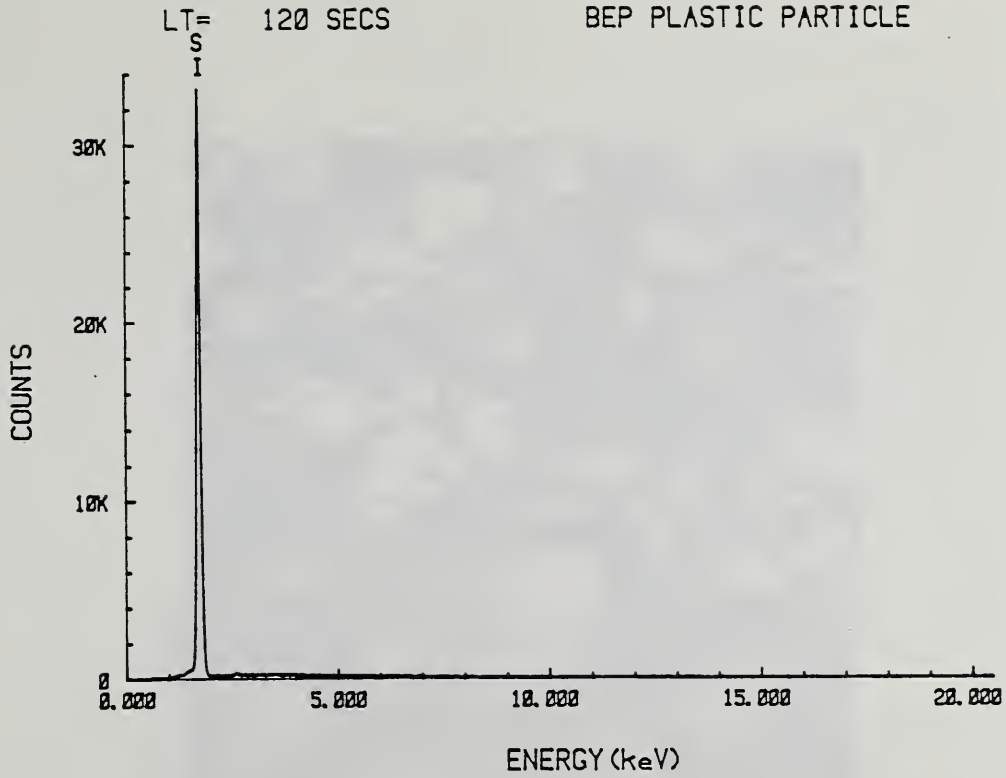

Figure 12. Energy dispersive x-ray analysis of particle in PVC wiping roll cover showing only silicon.

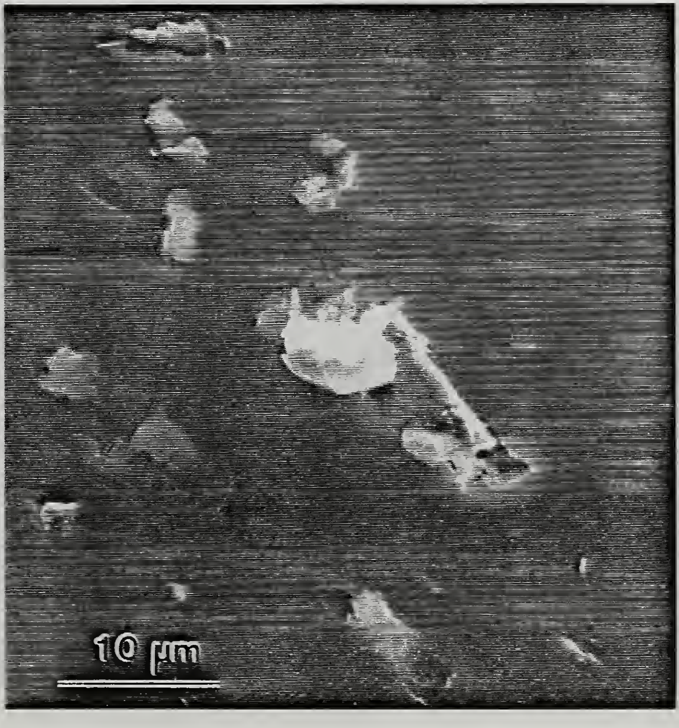

Figure 13. Photograph of the silicon containing particle from Fig. 12.

Figure 14. Photograph of amorphous silica particles used in BEP formulated ink.

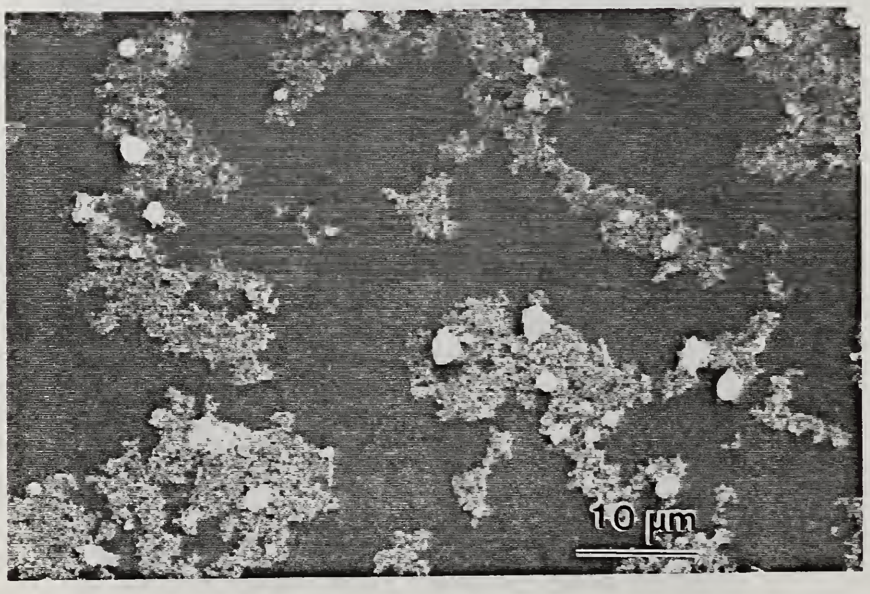

Figure 15. Photograph of particles from synthaline green used in BEP formulated ink.

Figure 16. Photograph of chromium plated surface showing transfer of amorphous silica particles.

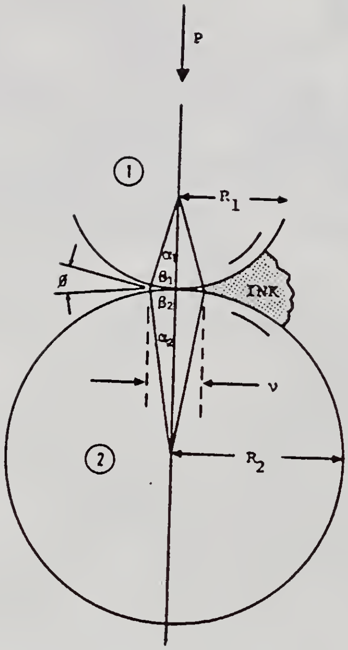

Figure 17. Schematic drawing showing variables in the ink wiping process.

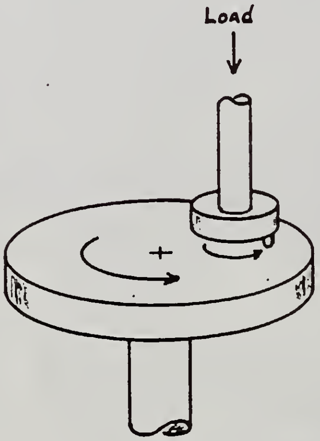

Figure 18. Schematic drawing of the rotating pin-on-disk specimen configuration.

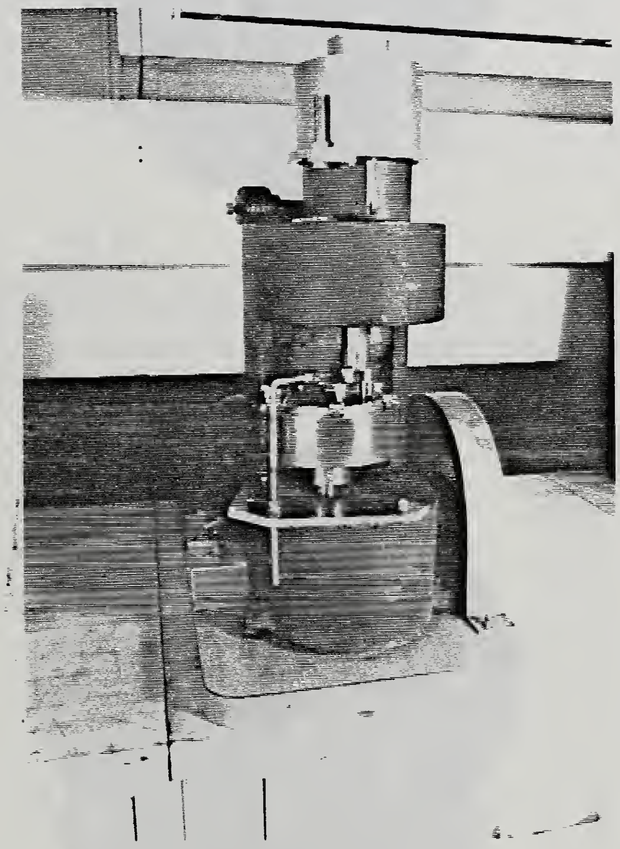

Figure 19. Photograph of the rotating pin-on-disk (Schiefer) test machine modified to determine wear of chromium plating by printing inks.

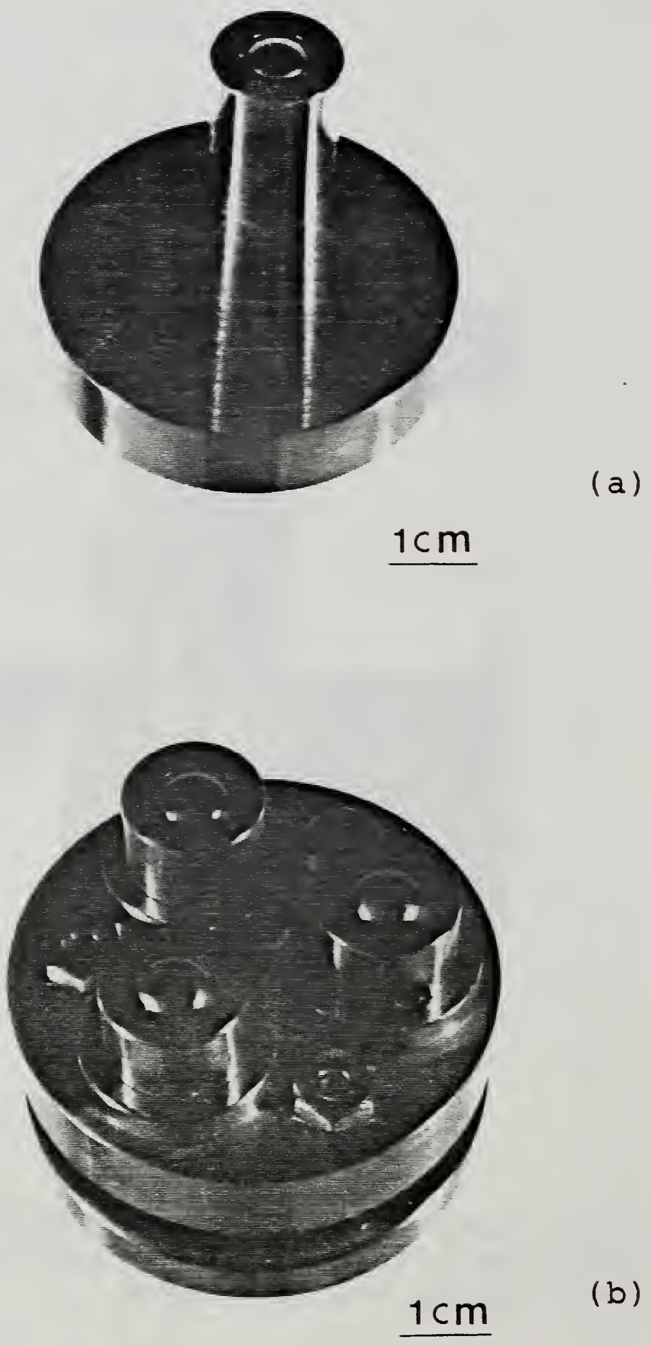

Figure 20. Photographs of the single pin holder (a) and three pin holder (b) used in the rotating pin-on-disk test machine.

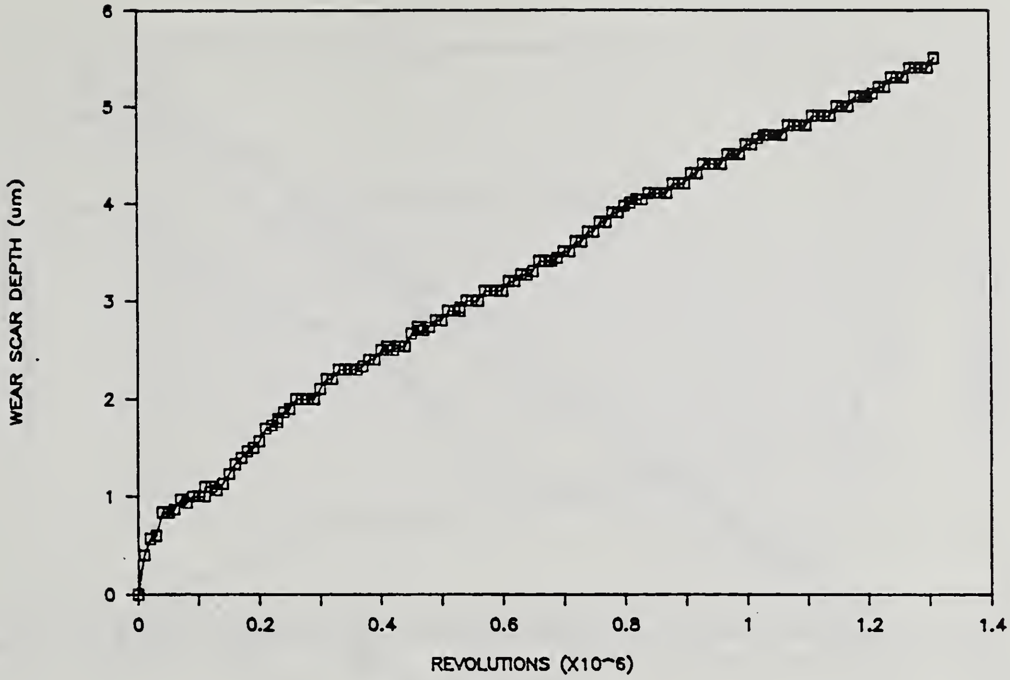

Figure 21. Rotating pin-on-ring wear test results illustrating measurement precision. Depth of wear of chromium plating caused by a currency ink is plotted as a function of sliding distance measured in revolutions.

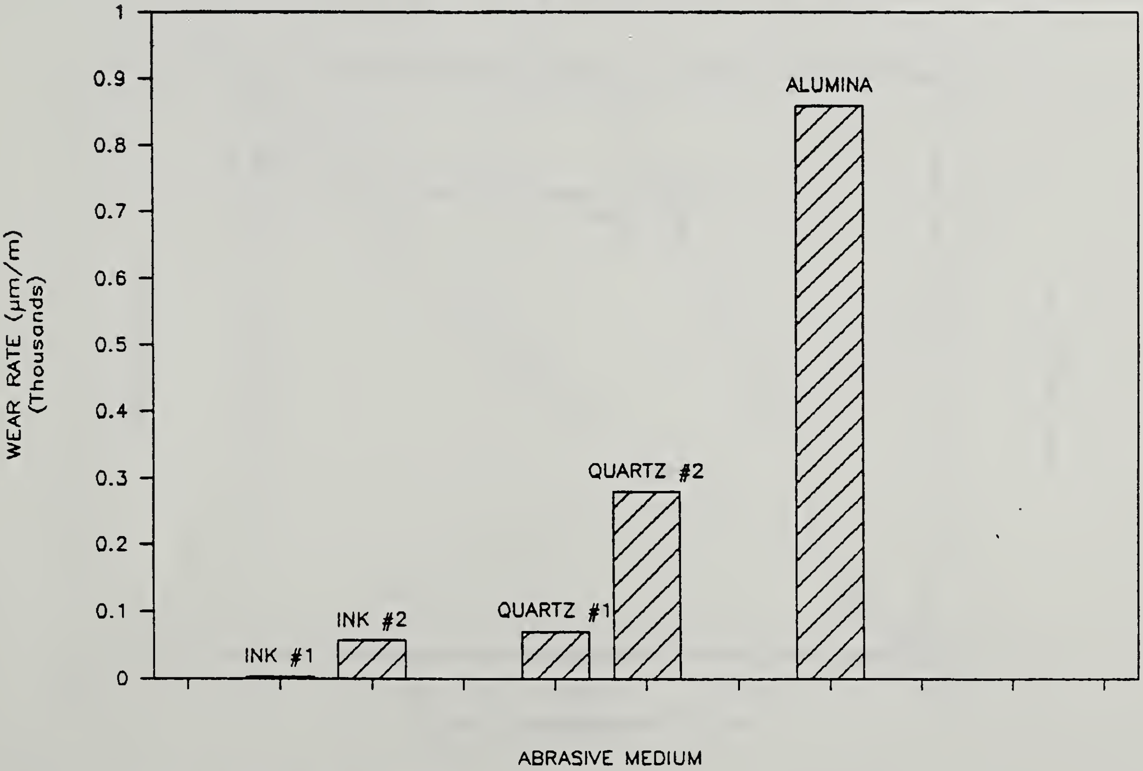

Figure 22. Wear of chromium plating by printing inks compared to wear by other abrasives. Minimum and maximum values are shown for the ink and quartz media studied.

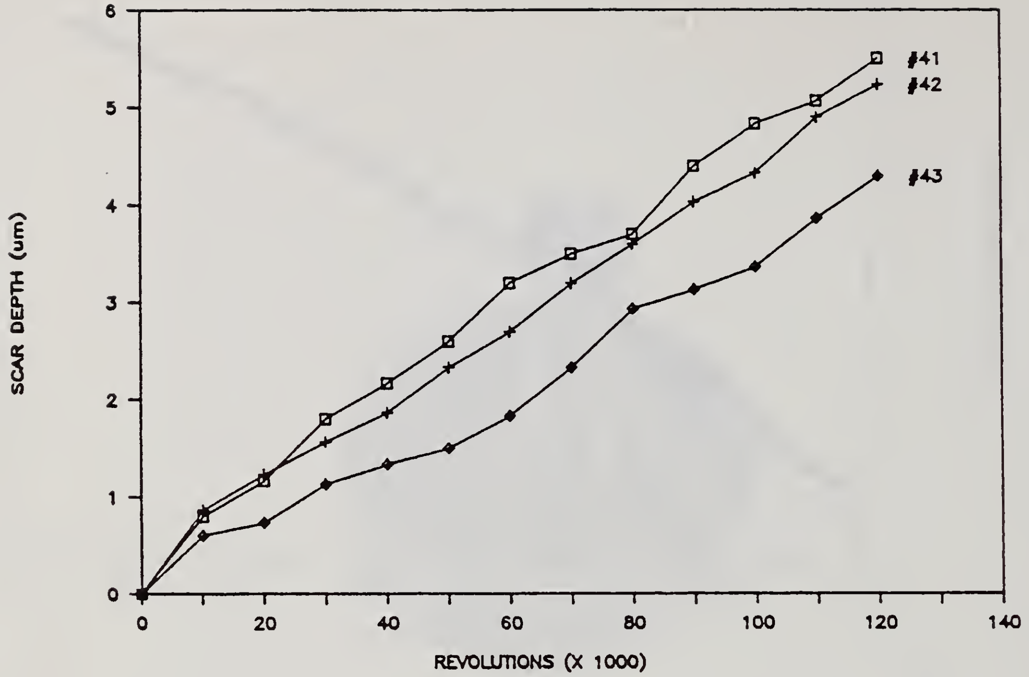

Figure 23. Results of three separate tests conducted under the same conditions with the same materials are shown to illustrate good repeatability.

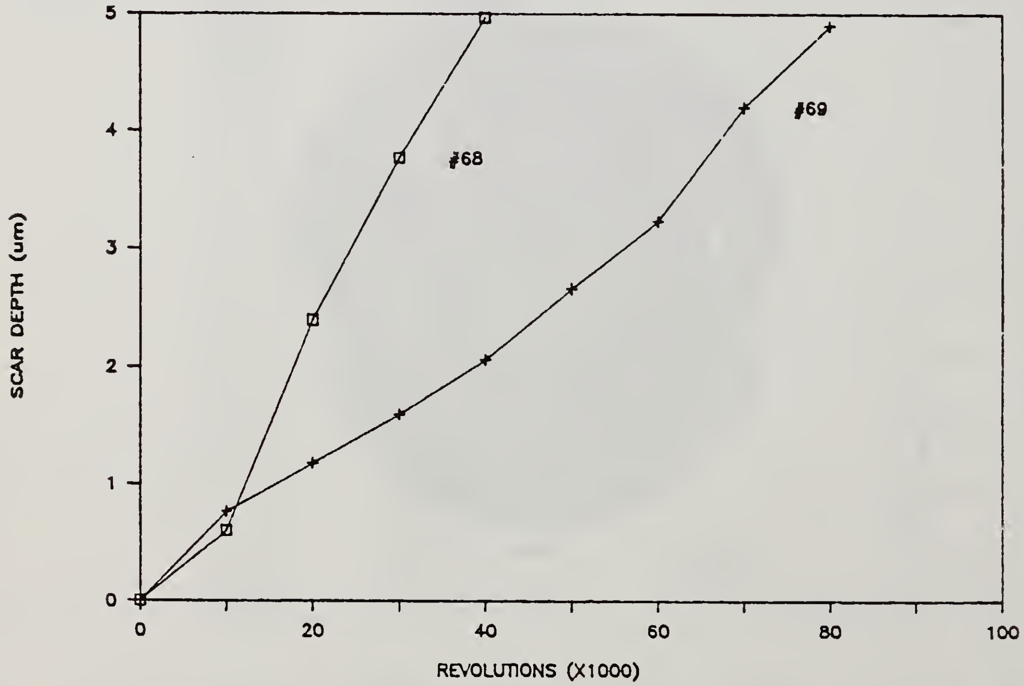

Figure 24. Results of two tests, run under the same conditions, where repeatability was poor.

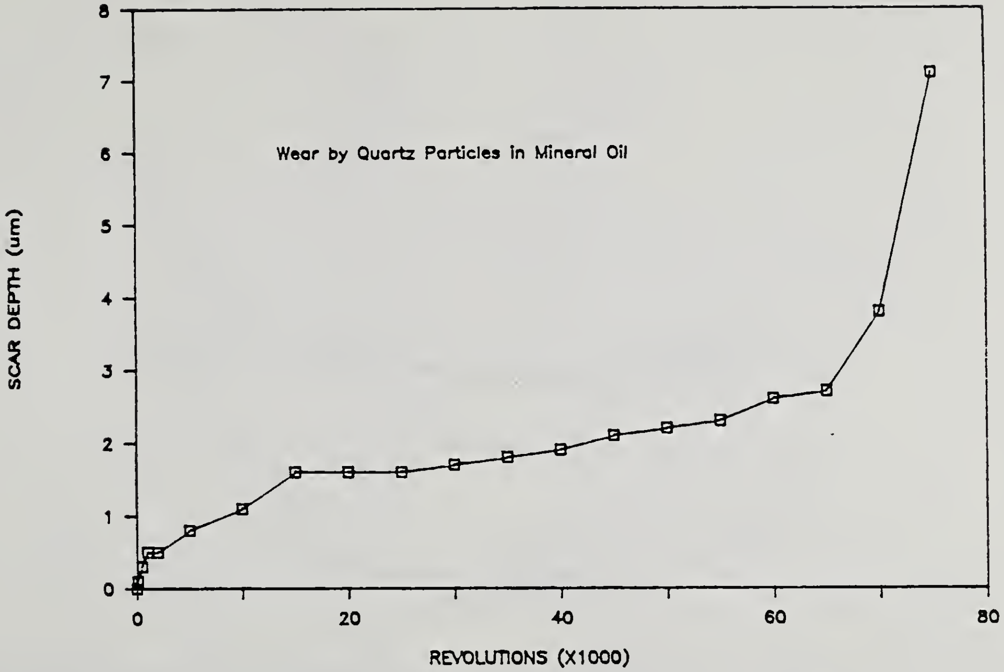

Figure 25. Wear of chromium plating by quartz particles in mineral oil showing rapid increase in scar depth that occurred in the latter half of the test.

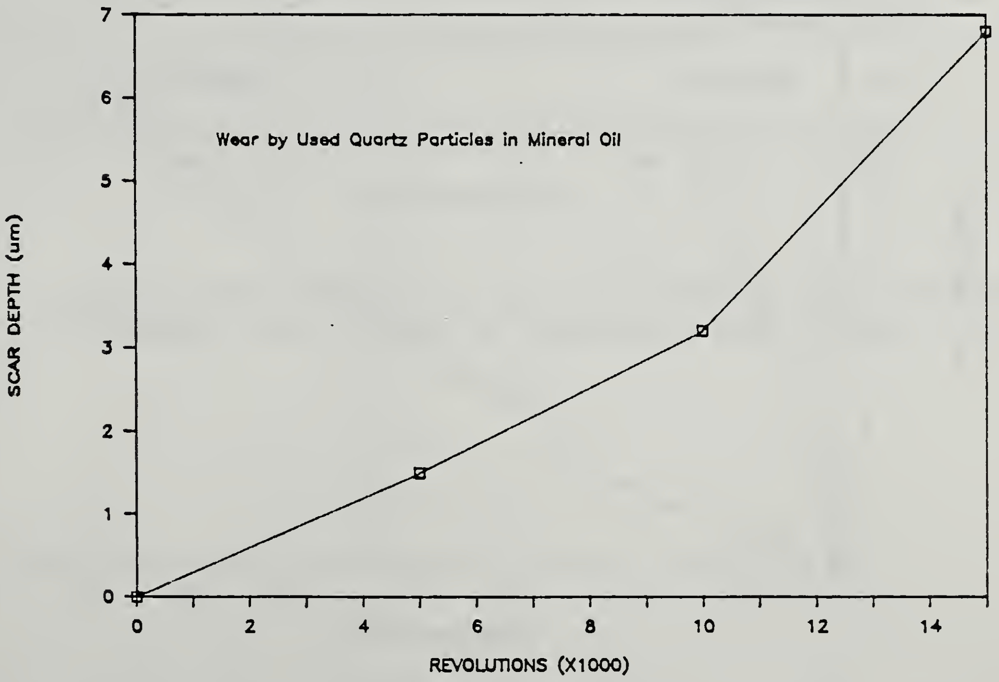

Figure 26. Wear by used quartz slurry. In contrast to Fig. 9, wear rate was rapid throughout test.

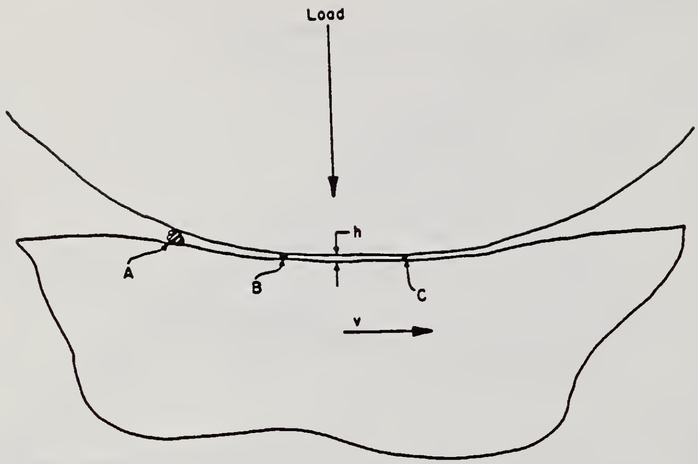

Figure 27. Drawing illustrating the effect of wear particles in a fluid film.

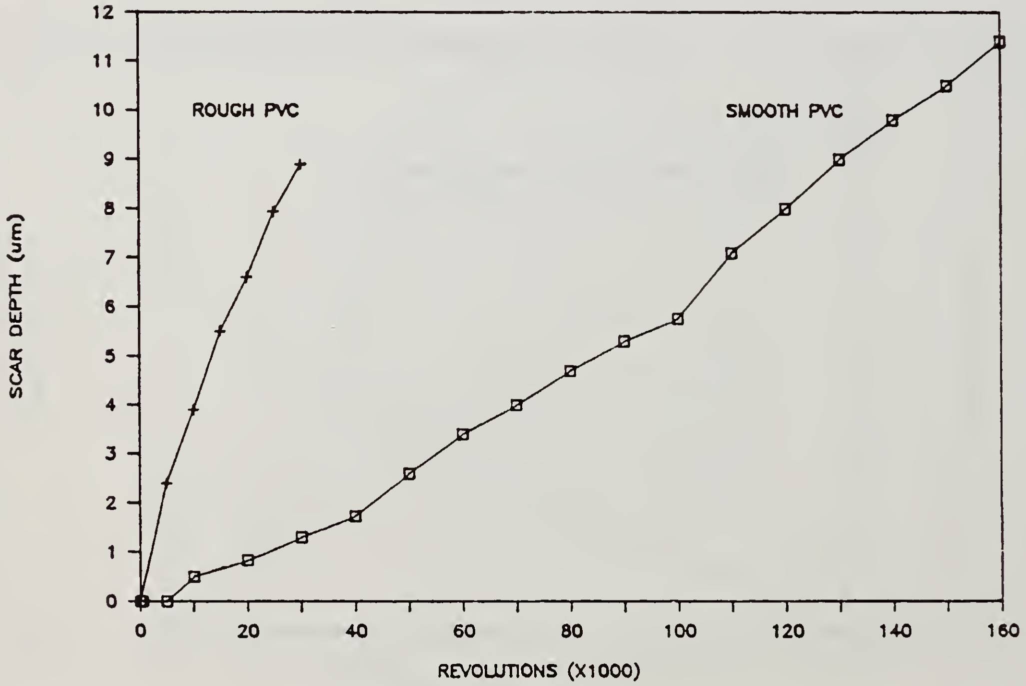

Figure 28. Rotating pin-on-disk test results showing effect of PVC counterface roughness on wear rate.

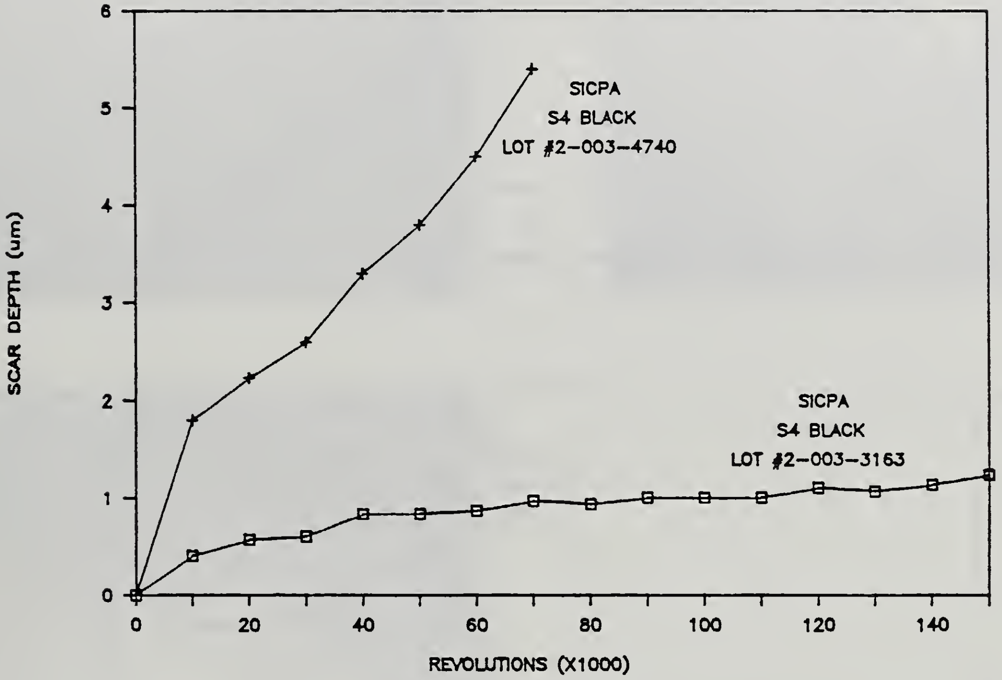

Figure 29. Results are shown for two inks exhibiting markedly different wear rates in separate test runs.

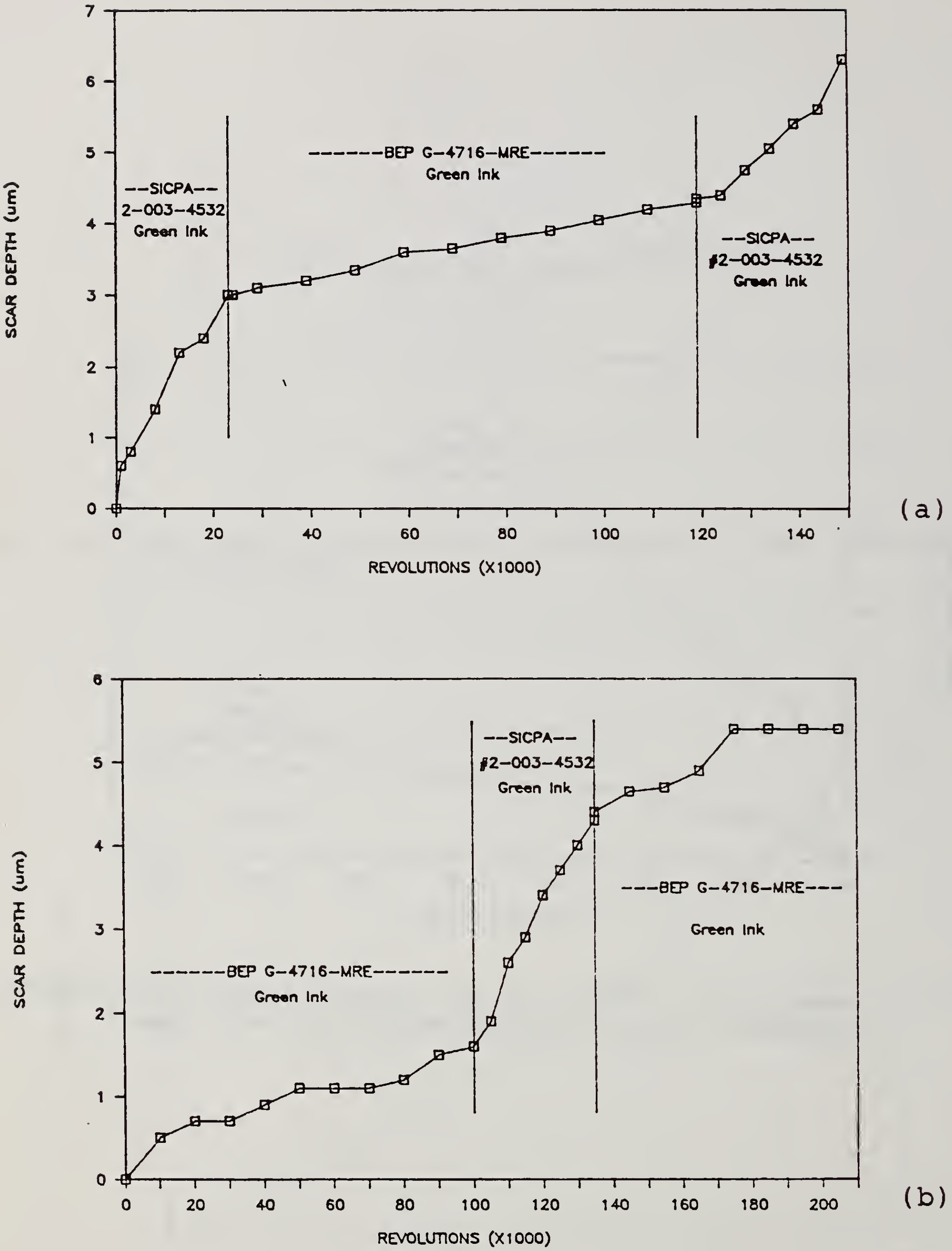

Figure 30. Wear of chromium plating by two different inks is compared by alternating the inks in the same test run. In (a) the test was initiated with a fast wearing ink. In (b) the slow wearing ink was used first.

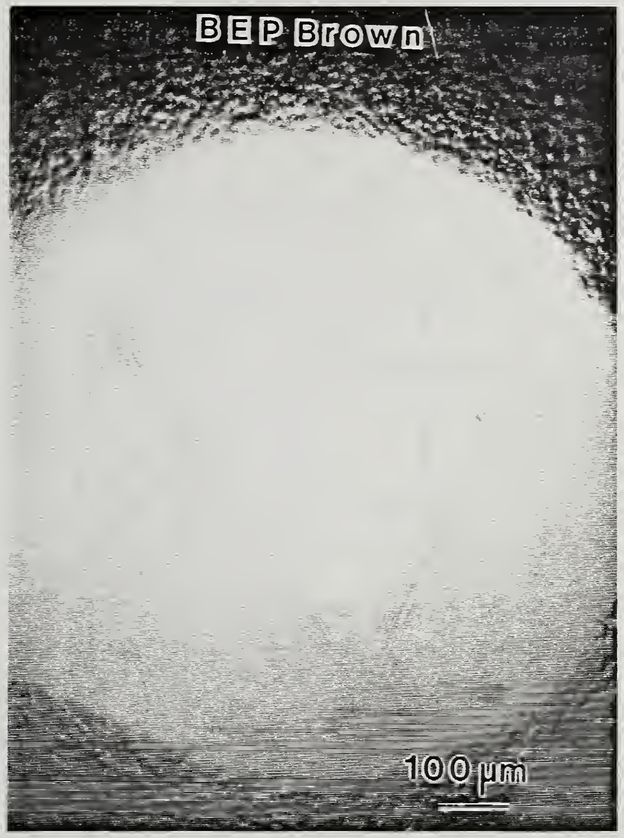

Figure 31. Photographs of wear scars on chromium plated pins after test runs with three intaglio stamp inks. Note differences in scratching produced by each ink.

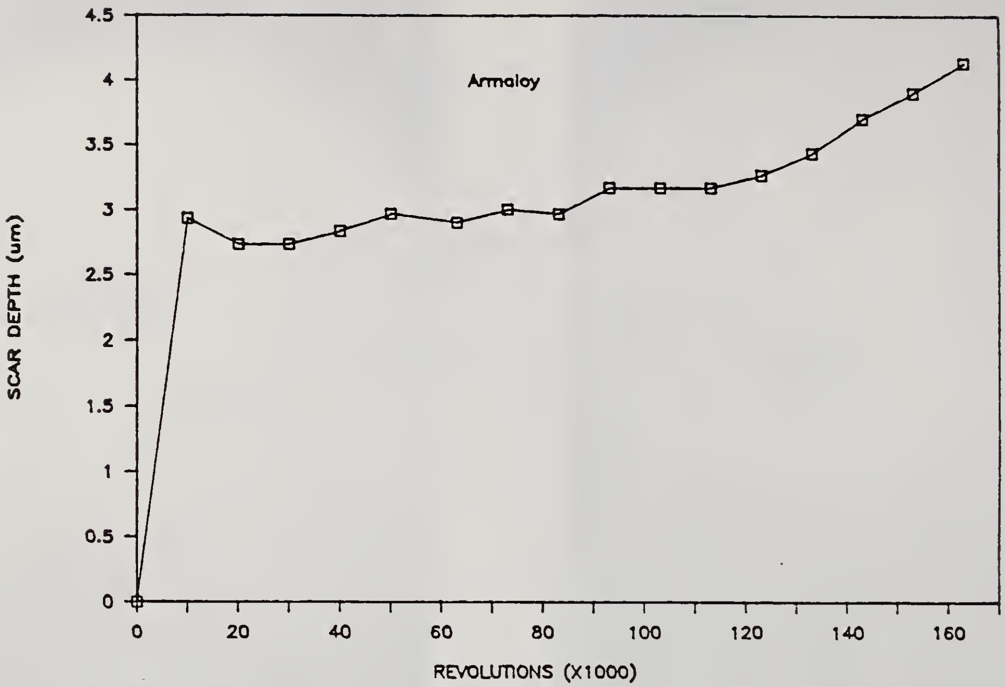

Figure 32. Wear behavior of Armaloy chromium plating is shown as a function of sliding distance. Porous chromium outer layer results in rapid initial wear rate.

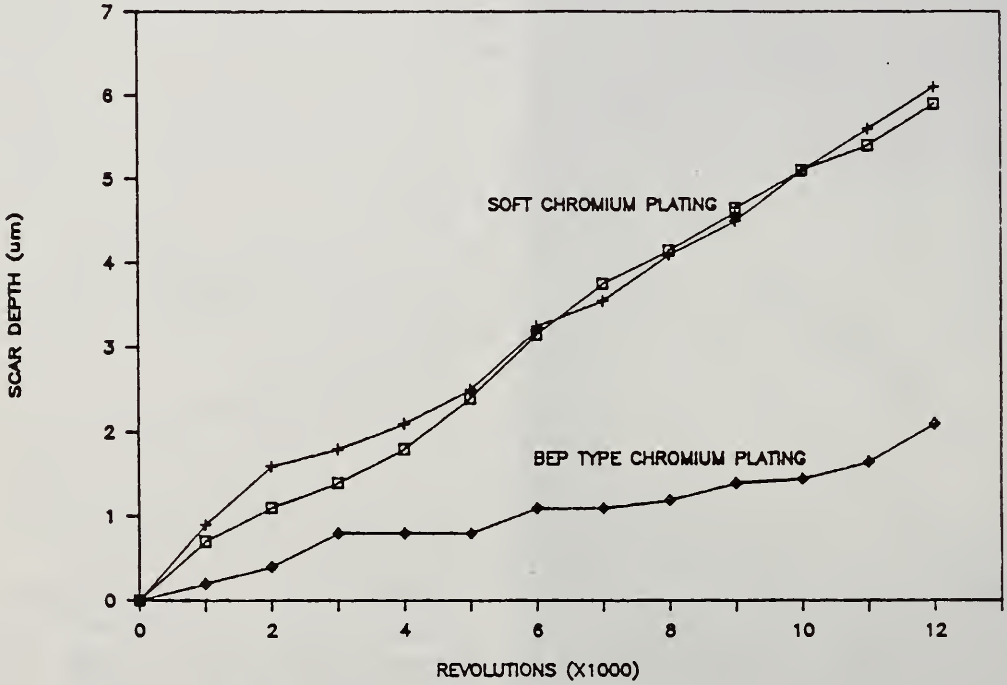

Figure 33. Wear behavior of soft chromium plating is compared to BEP type chromium plating. The three pin holder was employed for this test.

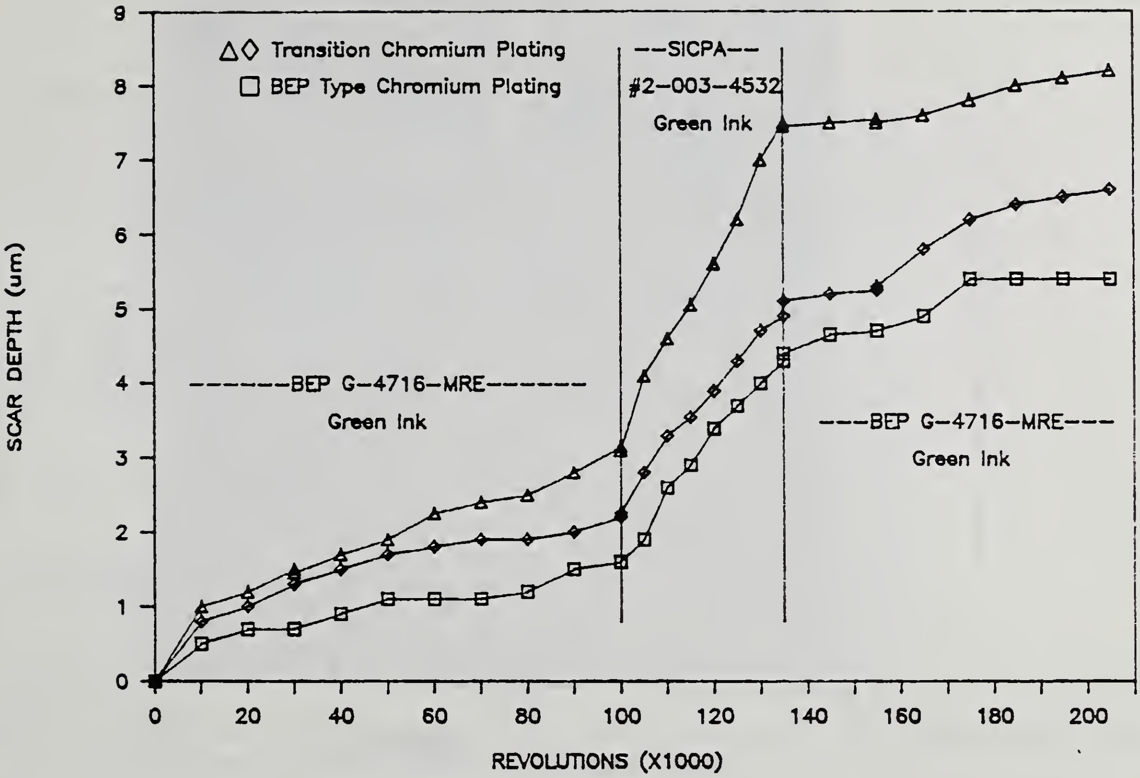

Figure 34. Wear behavior of transition type chromium plating is compared to BEP type chromium plating. The three pin holder was used for this test.

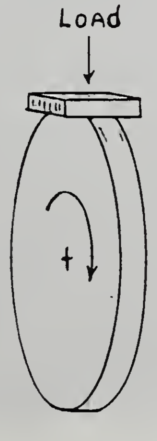

Figure 35. Schematic drawing of flat-on-ring specimen configuration.

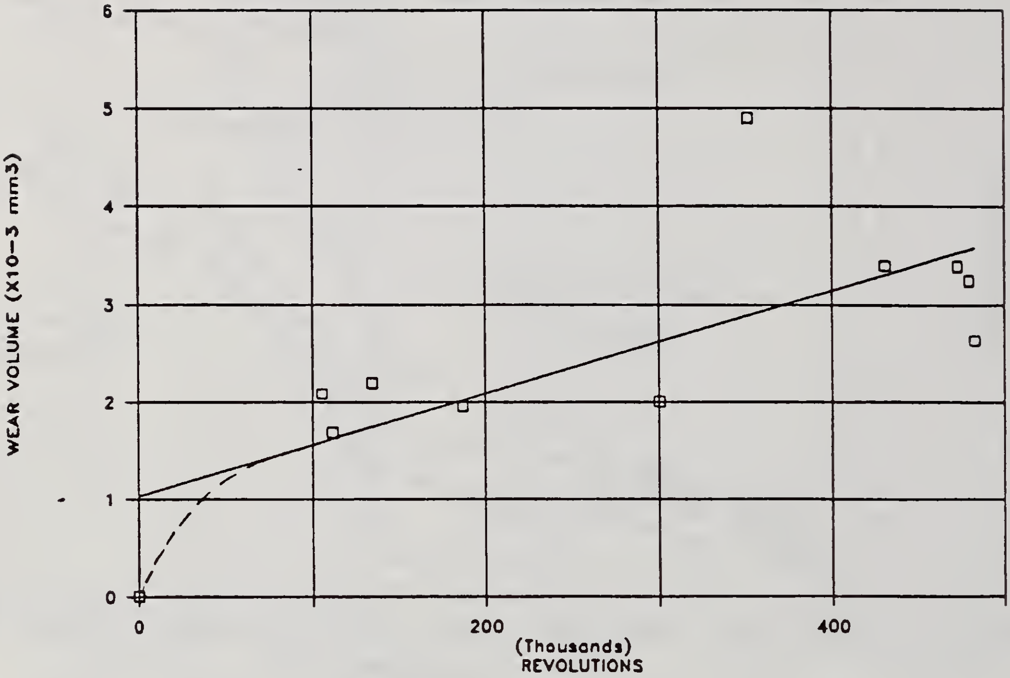

Figure 36. Wear of BEP chromium by SICPA S10 green ink with the flat-on-ring test. Each point is the result of a separate test. Curve is least squares fit to data.

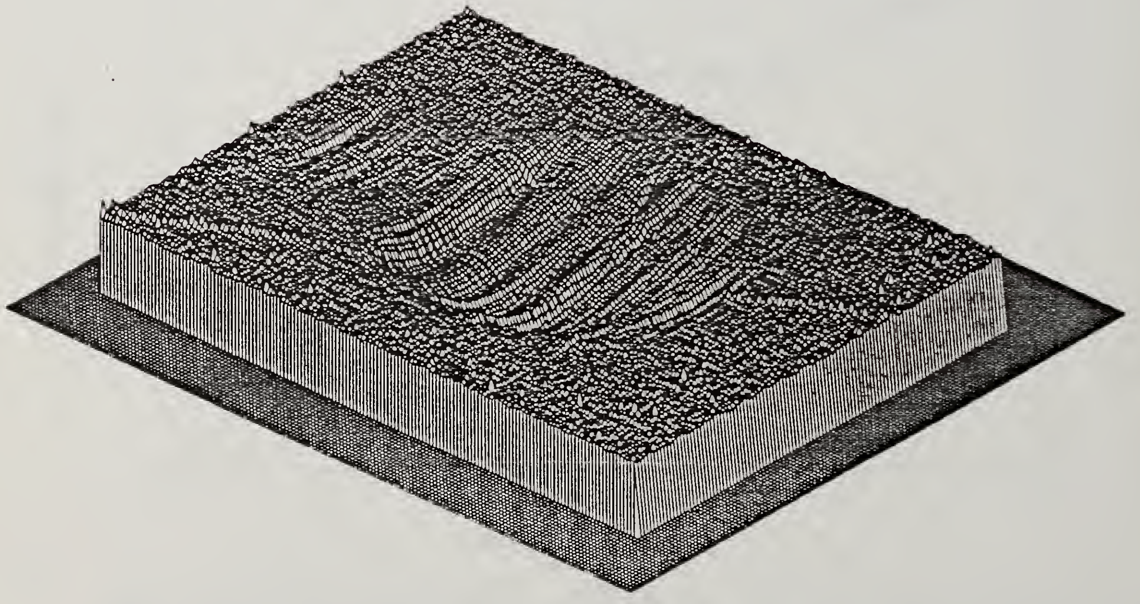

Figure 37. Topography of wear scar on specimen from flat-on-ring test obtained by surface profilometry.

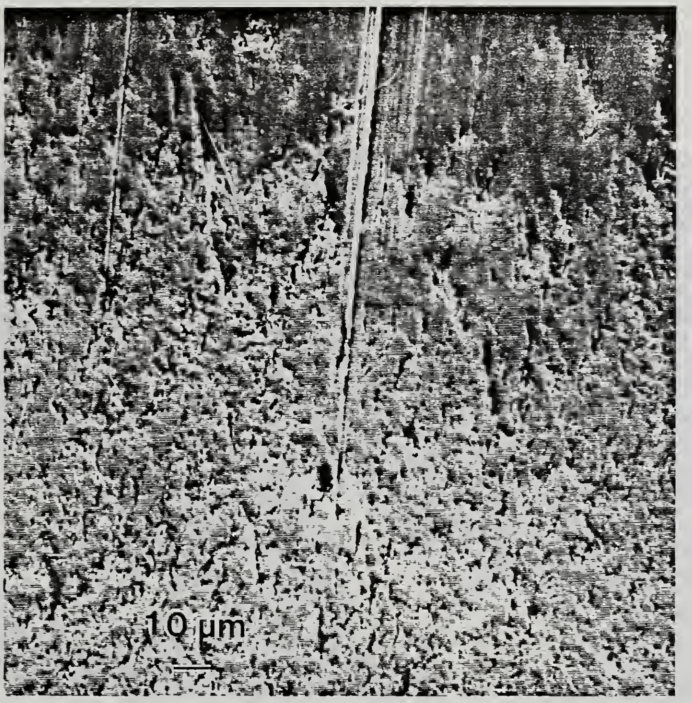

Figure 38. Optical photograph of entrance zone of wear scar on specimen from flat-on-ring test.

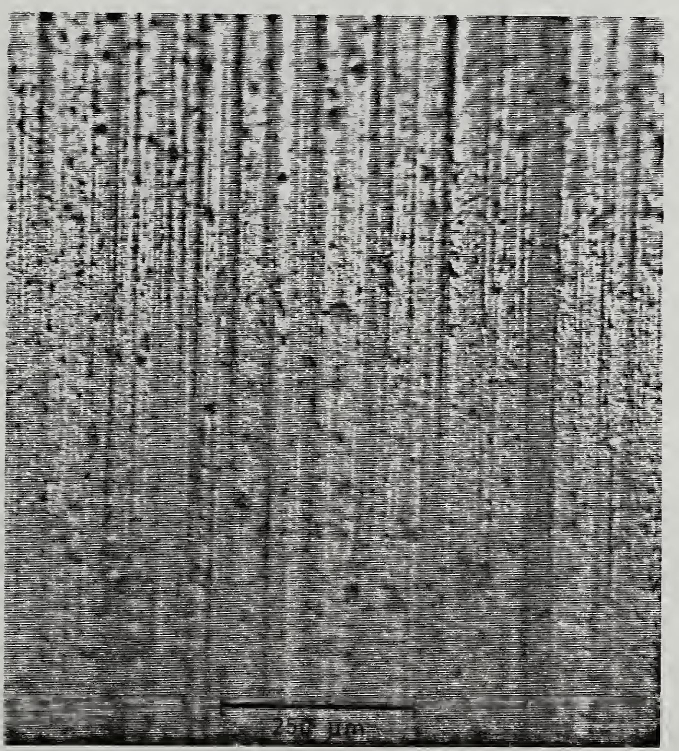

Figure 39. Optical photograph of surface of PVC ring from flat-on-ring test.

Figure 40. Scanning electron micrograph of a large particle from SICPA S10 green ink used in flat-on-ring test.

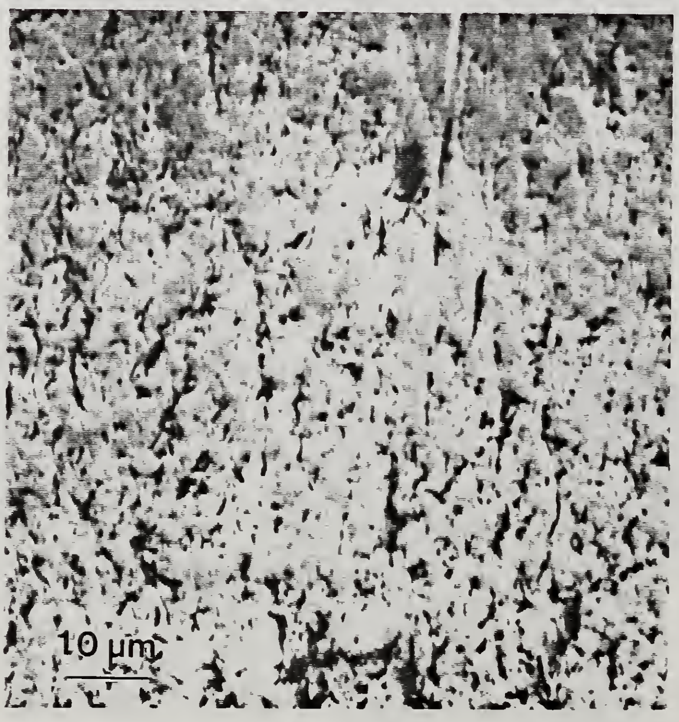

Figure 41. Scanning electron micrograph of entrance zone of wear scar from flat-on-ring test showing indentation damage produced by hard particles.

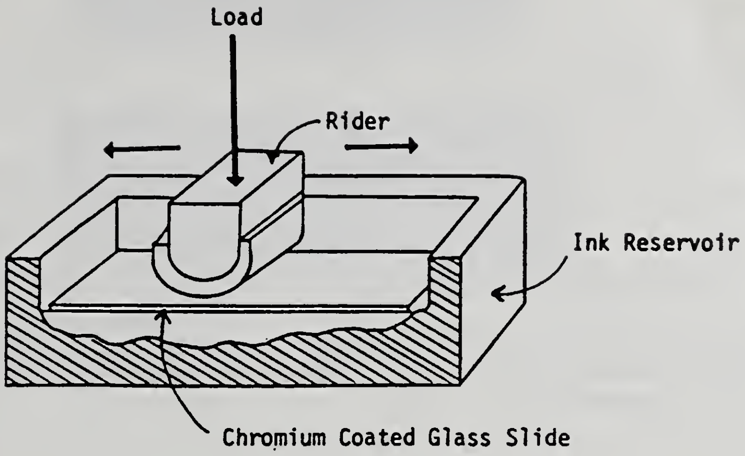

Figure 42. Schematic diagram of the GTA test configuration.

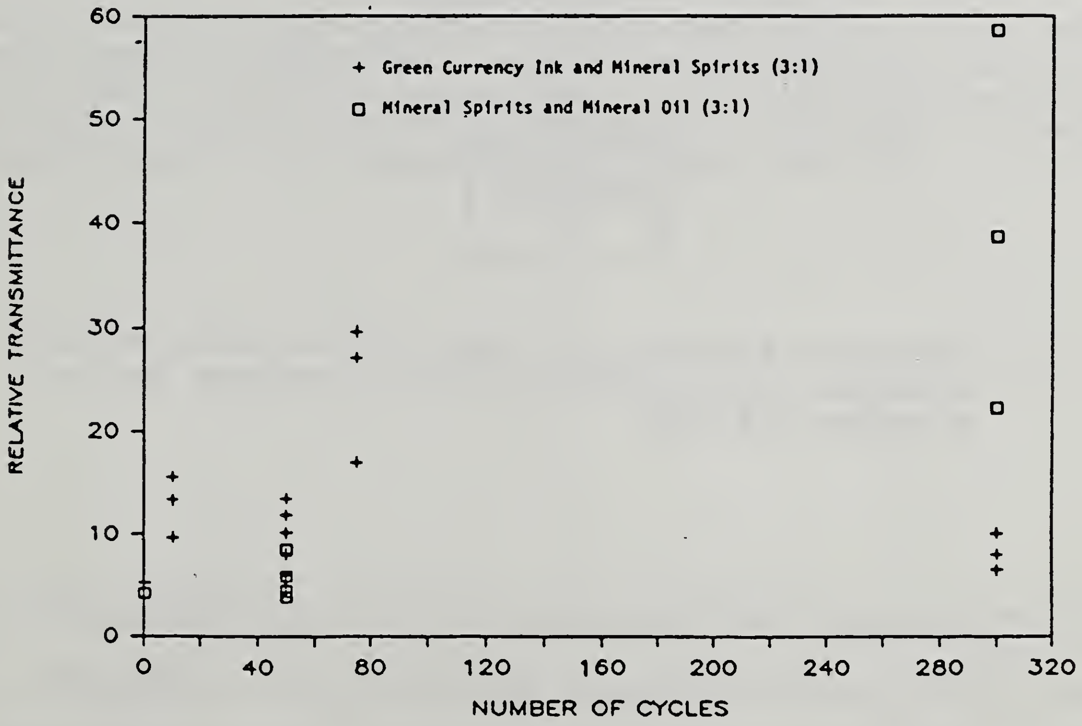

Figure 43. Wear (indicated by relative transmittance) of chromium coating on glass slide as a function of number of cycles for two different fluids.

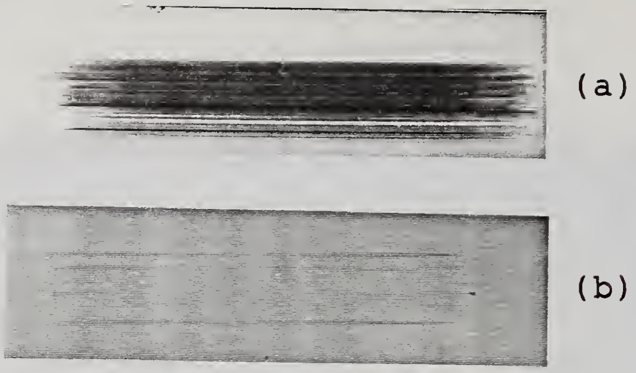

Figure 44. Photographs of worn areas on chromium coated slide after test using (a) GTA felt and (b) PVC wiper roll cover material.

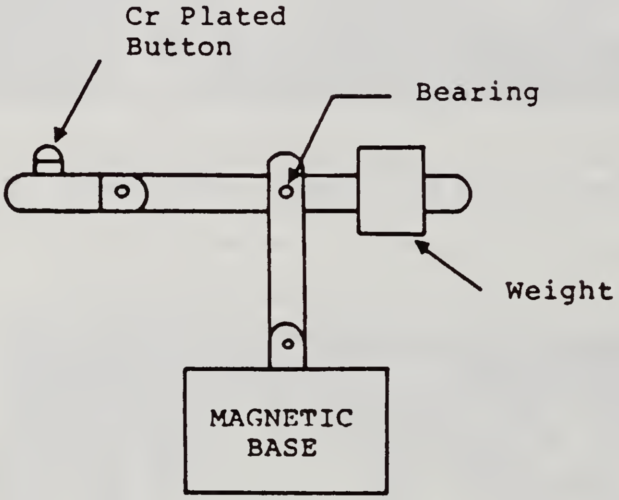

Figure 45. Schematic diagram of a test device which would be attached to a printing press to measure wear of chromium plating.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The principal modes of wear during currency and stamp printing by the intaglio method were identified. Three laboratory test methods were developed and applied to a study of different ink materials and different chromium platings. The importance of abrasive particles in the inks was established. Recommendations for continued research, both fundamental and applied, were made.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

abrasive; electroplating; inks; polishing; polyvinylchloride; printing; wear

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