D. D. Roshon

Electroplated Diamond-Composite Coatings for Abrasive Wear Resistance

Abstract: This paper describes electroplated diamond-composite coatings which are capable of attaining wear resistance a number of orders of magnitude greater than conventional materials when subjected to abrasion by paper. The coatings consist of a single layer of diamond particles held in a matrix of electroplated metal. During the course of these studies, many parameters were found to play important roles in the wear resistance. These parameters include the diamond particle size, its size distribution, the particle density, particle shape, plating uniformity, and the properties of the matrix metal. The influence of these variables is discussed, and the results of the wear testing are presented. The plating process is also briefly described.

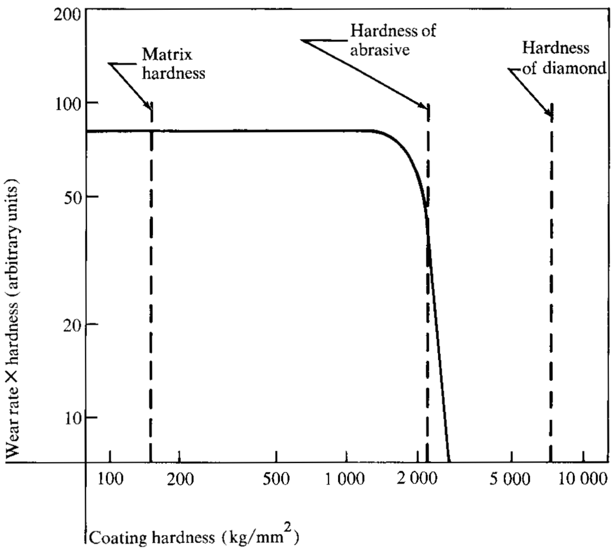
Introduction

Wear has long been a problem in machines that handle large throughputs of paper documents, since paper is a rather abrasive medium. Wear-resistant coatings, such as chromium plating and flame-sprayed tungsten carbide, have had wide application in paper handling equipment. Such coatings frequently give satisfactory service where geometry is favorable and a moderate amount of wear can be tolerated. Occasionally, however, expensive critical components can tolerate very little wear and require a long life. In this case, the conventional coatings may have grossly inadequate wear resistance, leading to the necessity of designing around the wear problem. This usually results in a costly solution. As machine speeds have increased, such problems have appeared with increasing frequency. Consequently, a study was made to determine the feasibility of developing a superior wear-resistant coating.

Studies of wear by paper [1-3] have indicated that the laws of abrasive wear are generally followed. In addition, SEM failure analysis [4] of components subjected to wear by paper has verified that the wear process is abrasive in nature. One of the most significant characteristics of abrasive wear is that the wear rate is inversely proportional to the hardness of the material being abraded. This is frequently [5] shown by plotting the product (wear rate × hardness) versus hardness, as in Fig. 1. Here it is shown (schematically only) how the product varies as coating hardness varies, when subjected to wear by an abrasive of hardness 2100 kg/mm^2 (about that of alumina). The curve remains horizontal until the coating hardness approaches that of the abrasive, when there is a dramatic decrease due to the wear rate becoming much smaller.

It can be seen that to achieve extremely small wear rates requires a coating hardness substantially greater than that of the hardest abrasive to be encountered. Paper, together with contaminant dusts from the environment, contains abrasives of hardness up to about 2100 kg/

Figure 1 Abrasive wear as a function of hardness (schematic diagram).



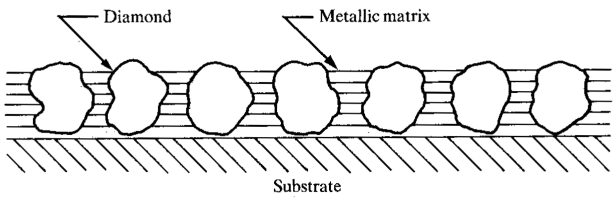


Figure 2 Single-layer diamond composite plating.

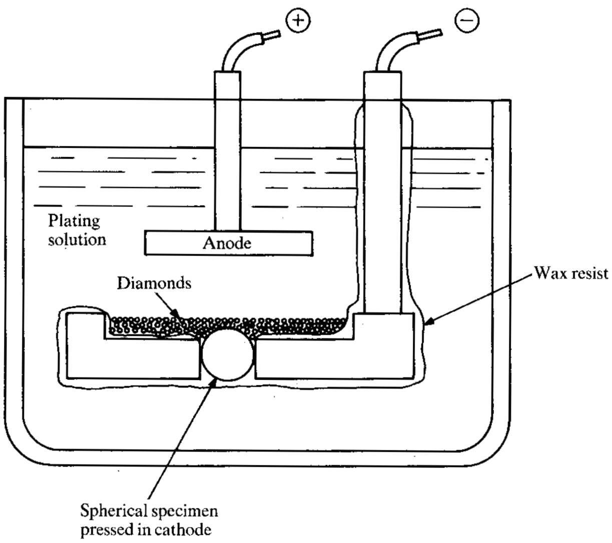


Figure 3 "Pack" method of diamond plating.

Table 1 Some hard materials.

Material	*Knoop hardness* (kg/mm^2)
Tungsten carbide	1860
Aluminum oxide	2100
Titanium carbide	2460
Silicon carbide	2500
Titanium diboride	2700
Boron carbide	2800
Cubic boron nitride (Borazon) [7]	4700
Diamond	7-10 000

mm^2 [6]. Accordingly, a coating to resist wear by paper must be considerably harder than this. The number of such materials is extremely limited. Table 1 lists some of the better known hard materials. Only Borazon [7] and diamond possess the requisite hardness for a really large increase in wear resistance. Borazon is comparable in cost to diamond. Also, some preliminary testing showed it to be substantially inferior in wear resistance. Hence, our attention was concentrated on diamond as the ultimate material. Objections to excessive cost were dispelled by some simple calculations which revealed that the cost of diamond in a 10-μm-thick coating is in the range of 2-3 cents per cm^2, with diamond powder at \$2-3 per carat.

A thin, homogeneous coating of a hard, brittle material, such as diamond, would be extremely fragile even if fabrication were feasible. However, the concept of a composite material, such as cemented tungsten carbide, allows the achieving of high effective hardness with some degree of toughness. In this case, the hard constituent provides the wear resistance, while the metallic matrix serves to bind the hard particles together and to the substrate material.

Diamond-metal composites have long been used in abrasive grinding tools, both with a sintered metal matrix and as electroplated coatings. As a result, it seemed apparent that the technology already existed for producing diamond-composite wear-resistant coatings. The electroplating process seemed most suitable and the coating development effort followed this direction.

Early in this program, it became apparent that the most efficient composite coating was the single-layer type, shown schematically in Fig. 2. The reasons for this become evident later.

Experimental procedures

Plating processes

Much of the plating development work was accomplished through commercial platers with expertise in producing plated diamond tools. Nickel is the usual matrix metal for tool purposes, and the initial work was done involving this metal. However, some potential applications for the wear-resistant coating required a nonmagnetic material. Consequently, other matrix metals were also explored. Gold, tin-nickel alloy, and rhodium were employed, in addition to nickel, as matrix materials.

The first plating effort utilized a technique similar to the composite electroplated materials (CEM) process, where diamond particles are kept suspended in the electrolyte during plating, by vigorous agitation. Some of the particles are captured as the metal is deposited. A Watts type nickel bath was used. Much useful information as to the optimum coating parameters was gained from this effort, but the maximum attainable diamond density was on the order of 30%—much less than was found necessary for long life. (Diamond densities reported here refer to the percentage of surface area covered by diamond for a single-layer coating. It is required that a substantial amount of the matrix metal be eroded away before the diamond density can be measured.)

The second process investigated, as recommended by the General Electric Co. [8], might be called a "pack" process. This method is illustrated in Fig. 3. The object to be plated is placed in a dense, stationary slurry of diamond powder and electrolyte. Current is then applied and metal deposited until the desired thickness of diamond is captured. It is important that plating conditions be such as to yield a high cathode efficiency in order to minimize hydrogen evolution. Gas bubbles can disturb the diamond particles and can also produce voids in the coating. The pack process immediately yielded diamond density above 50%. Following the initial success with nickel, an intensive development was devoted to producing a diamond-rhodium composite. The final process [9] utilized a Puragold [10] tacking layer, with a Rhodex [10] encapsulating overcoat.

The pack process was also used to produce platings with a gold matrix and with a tin-nickel alloy matrix. The latter material is hard and nonmagnetic, but rather brittle.

After some initial studies of multilayer coatings, all of the platings that were produced were of the single-layer type. These coatings are formed by plating only long enough to bond the first layer of diamond to the substrate; then it is removed from the slurry, and the additional metal is plated to complete the encapsulation.

A third process—a modification of the pack method—was developed during a limited in-house plating effort. This method, shown in Fig. 4, is a pressure cell technique in which the diamond slurry is compressed against the substrate by a piston, which also serves as anode. Electrolyte is pumped transversely through the slurry and through porous ceramic plugs which retain the diamond in place. By this means, high diamond density could be attained despite the presence of hydrogen evolution. It was found that the diamond density could be controlled by subjecting the assembled cell to vibration on a shaker table. Maximum usable diamond density was determined to be about 70%. Above this, penetration of the matrix metal was poor, apparently as a result of the phenomenon called electrostenolysis [11]. Coatings with nickel and tin-nickel alloy matrices were both successfully plated with the pressure cell technique.

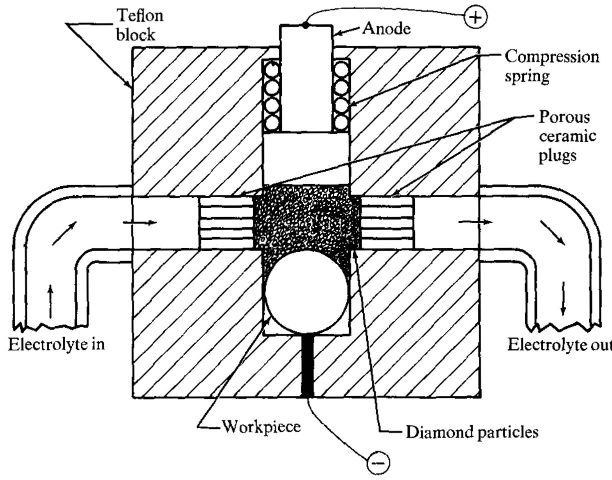


Figure 4 Pressure cell plating technique.

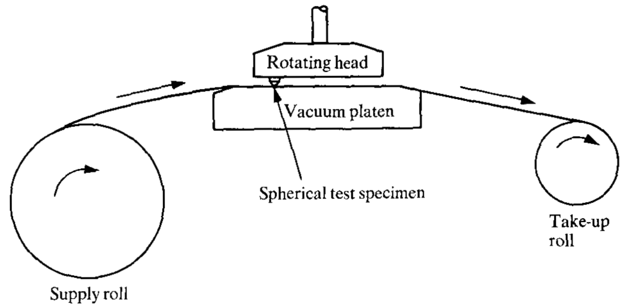


Figure 5 Continuous paper wear tester.

• *Wear testing*

Plated specimens were evaluated for wear resistance through high velocity sliding on paper. Initially, testing was accomplished by using the IBM Endicott drum tester, which has been described elsewhere [12]. However, as the coatings improved, the testing time became impossibly long. Consequently, a new tester was built which could operate continuously and unattended. This machine, shown schematically in Fig. 5, incorporated a paper drive to feed $8^1/_2$-inch-wide (21.6-cm) paper from a 10 000-foot (3048-m) roll over a vacuum platen. The specimen was mounted on a cantilever beam attached to a rotating head above the platen. The beam was equipped with a strain-gauge bridge to allow setting and monitoring the normal load on the specimen. Electrical connections to the strain gauges were brought out from the rotating head through mercury-wetted slip rings.

The wear specimen thus traveled in a circular path on the slowly moving web of paper. The paper speed was adjusted so that the specimen was exposed to mostly fresh paper at each revolution.

Wear specimens consisted of 1/4-inch (0.64-cm) diameter spheres which were plated only on one half of the sphere. Substrate materials included 52100 steel, brass, and moly-permalloy. All testing was done with a load of 20 grams at a sliding velocity of 727 inches (1845 cm) per second. The paper chosen for the testing was a moderately abrasive bond, imprinted with a dot pattern of magnetic ink character reader (MICR) ink. The ink covered 6.6% of the paper surface. The ink pattern was included to simulate the abrasiveness of documents imprinted with

Table 2 Wear test results for some common materials and for diamond composites.

Common materials

Material	*Sliding distance to reach 10-μm wear depth* (in.)	*Relative life (Chromium = 1.0)*
Solid 52100 steel—R_c 62-67	9.6×10^5	0.04
Rhodium plating	1.6×10^6	0.07
Chromium plating	2.3×10^7	1.0
Tungsten carbide—d-gun coating	5.3×10^7	2.3
Solid tungsten carbide, sintered	2.3×10^8	10

Diamond composites[a]

Matrix	*Diamond size* (μm)	*Diamond density* (%)	*Distance to failure* (in.)	*Relative life (Chromium = 1.0)*
Nickel	0–2	various	$<5 \times 10^5$	<0.02
Nickel	5	40	1×10^6	0.04
Nickel	9	10	2×10^6	0.08
Nickel	10	28	8×10^7	3.5
Nickel	9	54	5×10^8 [b]	22
Tin-nickel	9	55	1×10^9 [c]	43
Gold	15	51	3×10^8	13
Rhodium	15	50	5×19^9 [d]	217
Rhodium	30	62	2×10^{10} [e]	870

[a]All coatings were single-layer type, with thickness equal to diamond size with the exception of those containing 0–2 μm diamond, which were multilayer coatings 10 μm thick.
[b]Estimated life. Test terminated after 1×10^8 in.
[c]Estimated life. Test terminated after 2×10^8 in.
[d]Estimated life. Test terminated after 1×10^9 in.
[e]Estimated life. Test terminated after 6×10^8 in.

MICR characters, such as checks. Also, it was desired to assess the possibility of an iron-diamond reaction, such as is encountered if steel is ground with diamond tools.

Results

Selected results of the wear testing are given in Table 2, which includes some conventional materials for comparison. Materials are compared on the basis of the sliding distance required to produce a 10-μm depth of wear for the conventional materials and the distance required to produce coating wear-through in the case of the diamond composites. The comparison is somewhat unsatisfactory because the better diamond platings were not tested to a point of failure due to the long testing time and the enormous quantities of paper required. (Also, those platings containing the larger diamonds are necessarily thicker than 10 μm.) The figures given in parentheses are rough estimates of the life for these coatings based on examination of the wear scar after testing.

In order to assess the progress of wear on a specimen, a fixture was built which allowed observation of precisely the same area of the specimen each time, through a 200-μm aperture. Figure 6 is a micrograph taken through the aperture. This particular specimen consists of 15-μm du Pont diamond in a rhodium matrix. The micrograph was taken after 574 million inches of sliding. It will be noted that very little wear of the diamond particles has occurred.

It can be seen that the diamond particle size is of utmost importance. Regardless of the particle density, particles in the 0–2 μm size range impart little added wear resistance to the matrix metal. Five-μm particles provide some improvement. When the particle size is increased to 9–10 μm, a dramatic increase in wear resistance is noted. Larger particles result in additional improvement. It was also noted that the larger the particle size, the less critical was the diamond density.

Diamond density also had a dramatic effect on wear resistance. With 10-μm particles, there was little wear resistance shown at 10% diamond density, while a 28% coating lasted through 80 million inches of sliding. The life of a 54% coating was estimated to be 500 million inches. The optimum diamond density is approximately 65%, and coatings with much higher density than 65% fail early due to delamination.

As anticipated, the hardness of the matrix metal was found to influence the coating life. Harder metals slow down the rate of erosion of the matrix. Nevertheless, even very soft metals such as gold yield a long life when the diamond particles are large.

No diamond composite was observed to fail as a result of diamond wear. Instead, the failures were due to matrix metal erosion which led to loss of the diamond. Low diamond density allowed easy erosion of the matrix and therefore shortened the life. Similarly, nonuniform distribution of the diamond particles was observed to lead to localized failure at regions of low density.

Discussion

A number of parameters influence the wear performance of diamond composite coatings. All must be considered when attempting to optimize a coating for a given wear situation.

• *Particle size*

This variable is perhaps the most important coating parameter. Large particles impart much greater wear resistance than small ones. This fact appears to be related to the force required to pull a particle out of the matrix metal. A small particle is easily dislodged by an encounter with an abrasive grain in the paper, while a large particle can withstand such an encounter. In addition, partial erosion of the matrix does not weaken the particle retention as much in the case of large particles.

• *Particle density*

The diamond density is an extremely important variable because it determines the degree of matrix erosion that can occur. If the particles are widely spaced, rapid matrix erosion occurs, resulting in loss of diamonds. When the diamonds are close together, the matrix becomes inaccessible to erosion to any great depth. If the diamond particles are large enough, matrix erosion ceases after a certain depth is reached. The wear resistance of the composite can then approach that of the diamond itself. The diamond density must also not be too high, for then there is insufficient matrix to produce a strong bond to the substrate. This results in failure by spalling of diamond.

• *Coating uniformity*

Uniformity of the diamond distribution is important because of the nature of the wear process with composites. A small region of low particle density will allow rapid matrix erosion in that localized area, resulting in loss of the adjacent diamond. This loss then results in accelerated erosion and progressive failure of the entire coating—a sort of domino effect. When the particle size is large, the wear resistance is less sensitive to such local defects.

• *Diamond shape and type*

The ideal diamond shape for achieving high density and uniformity would be spherical. However, for best retention in the matrix, a rough surface is desired. Also, sharp cutting edges should be avoided to minimize the forces on the particles as well as to reduce damage to the paper. General Electric type MBG synthetic diamond met these requirements very well and had excellent wear resistance. Du Pont synthetic diamond also had a favorable shape, but proved more difficult to plate satisfactorily. In addition, it was somewhat inferior in wear resistance due to its tendency to disintegrate during abrasion. Natural diamond had excellent wear resistance and was easily plated, but tended to have many sharp cutting edges. Natural diamond powder also contained many unfavorably shaped particles which could be easily pulled from the matrix, leading to premature failure.

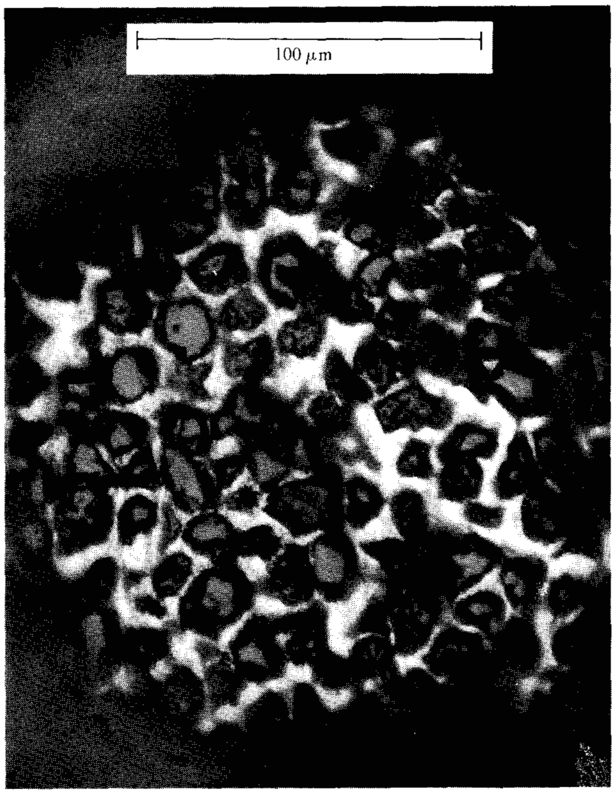


Figure 6 15-μm du Pont diamond in Rh matrix 5.74×10^8 inches of sliding.

• *Particle size distribution*

The best particle distribution is obtained when the particles are of uniform size. The presence of smaller particles in the layer tends to result in nonuniformity and increased matrix erosion.

• *Matrix metal properties*

A hard matrix metal reduces the rate of erosion, resulting in longer life. This variable becomes less important when particle size is large and the erosion depth is limited by geometry.

Ductility is a highly desirable property, especially if any impact loading is present. Tin-nickel proved unsatisfactory in this situation. Rhodium with high hardness and some ductility is an ideal matrix metal. However, rhodium matrices which contained cracks due to plating problems failed rapidly in a spalling mode. Similarly, chromium, with its inherently cracked structure, is not a suitable matrix plating.

- *Single-layer vs multilayer coatings*

There are two reasons why a single-layer coating provides the best wear resistance for a given thickness. First, the larger particle size yields a much superior coating. Second, the succeeding layers of a multilayer coating are much less uniform, resulting in inferior wear properties.

Conclusions

It has been demonstrated that electroplated diamond-composite coatings can provide wear resistance many times greater than conventional materials, especially if coating thickness is great enough to permit large (e.g., 15–50-μm) diamond particles. Various matrix metals can be used and cost is moderate in terms of the performance which can be achieved.

Acknowledgments

The author thanks F. M. Cullen for assistance in development of the pressure cell plating process and for performing much of the wear testing. R. G. Bayer and K. A. Snyder provided much encouragement and many stimulating discussions. M. Fernandez of the Amplex Corporation also is to be thanked for his untiring efforts in the development of the diamond-rhodium plating process. The original work on this project was supported by the Materials/Process (GTA) Group Technical Assignment.

References and notes

1. R. G. Bayer, D. Baker, and T. C. Ku, "Abrasive Wear by Paper," *Wear* **12,** 277–288 (1968).
2. R. C. D. Richardson, "Abrasive Wear by Paper," *Wear* **14,** 423–430 (1969).
3. G. F. Cole, The Prediction of Wear by Paper, *Wear* **21,** 141–154 (1972).
4. D. D. Roshon, unpublished results.
5. E. Rabinowicz, *Friction and Wear of Materials*, John Wiley & Sons, Inc., New York, 1965.
6. R. G. Bayer, private communication.
7. Trademark of the General Electric Co., Detroit, MI.
8. K. Gillis, "Plating with General Electric Man-made [7] Diamond," *Amer. Machinist*, May 9, 1966.
9. Process developed by the Amplex Corp., Bloomfield, CT, under the direction of Dr. Manuel Fernandez and under contract with IBM.
10. Trademark of the Selrex Co., Nutley, NJ.
11. A. Brenner, *Electrodeposition of Alloys*, Vol. 1, Academic Press, Inc., New York, 1963, p. 24.
12. D. D. Roshon, "Testing Machine for Evaluating Wear by Paper," *Wear* **30,** 93–103 (1974).

Received January 30, 1978; revised June 27, 1978

The author is with the IBM System Products Division, P.O. Box 6, Endicott, New York 13760.