R. G. Bayer

Mechanism of Wear by Ribbon and Paper

Abstract: While wear by materials such as ribbon and paper represents a significant and identifiable problem in the business machine industry, it has received little attention in the wear literature. In this paper the results of a study into the nature of the wear processes involved and the various factors which influence them are presented. A significant result of that study is the conclusion that the basic wear processes for both materials are similar, i.e., abrasion by small hard particles as compared to an adhesive mechanism for paper as proposed by some in the literature.

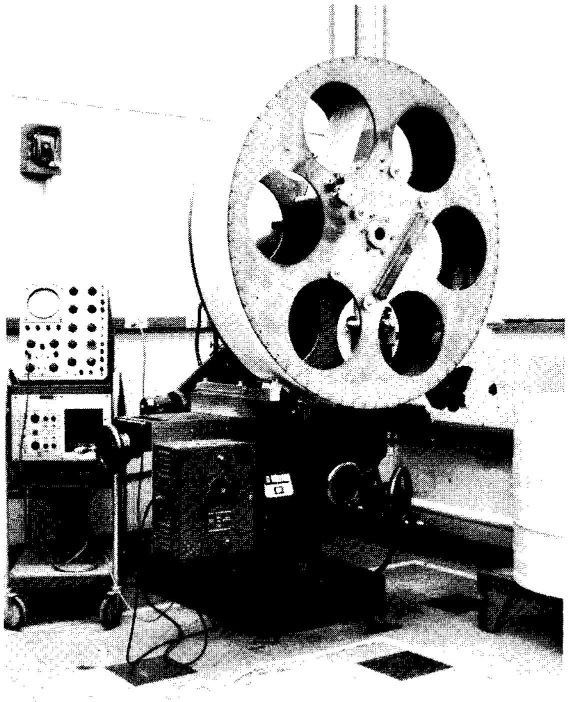
Introduction

A frequently encountered wear concern in peripheral equipment, such as punches, reader-sorters, and printers, is wear by ribbon and paper. These materials can cause significant wear not only on the softer materials which they contact, such as brass, polymers, and aluminum, but also on the harder ones such as case hardened steels, ceramics, and chromium platings. This is a result of the large amount of paper or ribbon used or processed in these machines. While ability of ribbons and papers to cause wear is frequently referred to as their "abrasiveness," the nature of their wear processes has not been completely explored and established, with only a few published articles on the subject. In the case of paper, there have been some studies [1–3] which indicate that the process is truly an abrasive one associated with hard particles contained in the paper. However, that position has been challenged in another reference [4], which argues in favor of an adhesive wear mechanism. In each of these references the same basic data reported in [1] are analyzed to show that the observed dependencies of the wear on such parameters as load, hardness, shape, etc. are consistent with either an abrasive [1–3] or adhesive [4] wear mechanism. Little or no consideration is given in these articles to the actual nature of the wear scars or the features of the papers which influence the wear. Hence, the articles are primarily analytical and result in a conflicting position as to the nature of the wear process itself. A similar situation exists with respect to ribbon wear. In published articles [5, 6] regarding wear by ribbon, the primary emphasis was on the engineering aspects of the wear process, rather than the physical mechanism itself. These articles either assumed or argued that the mechanism is an abrasive one without demonstrating significant physical evidence that this was the case. Also, as with paper, it could be argued that the analytical relationships developed could result from either an adhesive or abrasive wear model.

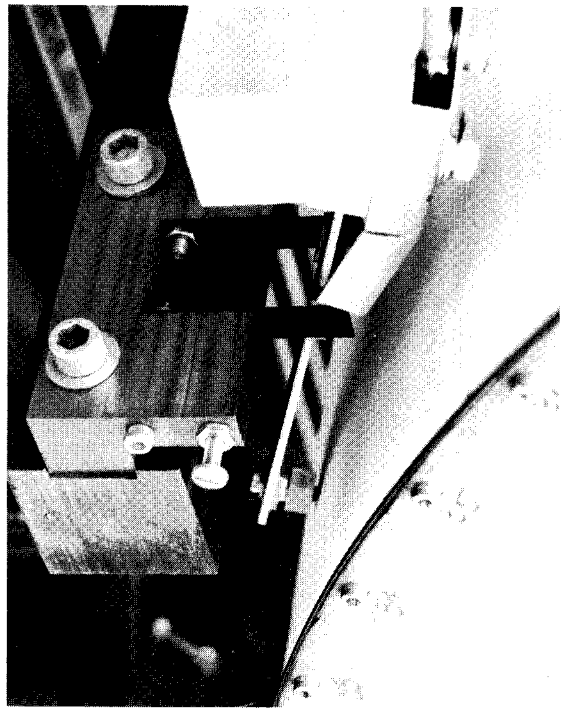
This general state of knowledge regarding the wear mechanisms for these materials made it highly desirable that further investigations, primarily regarding the nature of the wear scar and the properties of ribbons and papers which influence wear, be performed so that a clearer and more complete understanding could be achieved. As an effort in this direction, a study was performed regarding the topographical features of the wear scars produced by ribbons and papers. In the course of this study, an attempt was made to simulate the wear by an abrasive wear situation. In addition, a further effort was made to determine which aspects of the ribbon and paper were responsible for the wear. This paper presents the findings and conclusions obtained from these investigations.

Experimental procedures

A wear apparatus developed by Roshon [7] was used to produce wear on 52100 (H_m746) steel spheres (0.635 mm in diameter). This apparatus is shown in Fig. 1. Strips of either paper or ribbon were wrapped completely around the drum surface, and the wear specimen was mounted to the end of a cantilevered beam which was instrumented for load measurements. Before the start of the test, the wear specimen was pressed against the drum surface to a specified normal force. During the test, the drum rotated



(a)



(b)

Figure 1 Apparatus used for wear tests by ribbon and paper.

while the wear specimen slowly moved in a direction parallel to the axis of rotation, with the result that the wear path on the paper or ribbon was a helix. A load of 100 g was used for most of the tests.

At the conclusion of a wear test, the wear scar on the steel specimen was routinely measured and examined by several different techniques. Talysurf [8] traces were made of the worn profile, both in the direction of sliding and perpendicular to it. These were used to characterize the scar profile and roughness as well as to determine the amount of wear. The surface of the scar was also examined with optical and scanning electron microscopy.

The used surfaces of the ribbon and paper samples were also examined by similar microscopic techniques, mainly optical, but not as extensively. The examination of these surfaces was done more as a method of control rather than as a means to characterize the damage to these materials. In general, the damage to these surfaces was slight since the testing parameters of load and motion were selected to minimize this damage. This was done to simulate actual machine conditions which cause very little damage to these materials in a single engagement.

Wear scar topography

One way of investigating the nature of a wear process is to examine the type of damage produced during the process. This was done for approximately 20 different papers and six different ribbons. An extensive examination of the scars produced by two of these ribbons and two of these papers which produced wear scars that were typical of the entire groups was also done. In these selected cases, wear tests of varying lengths were conducted, up to and including the distance of sliding required to produce stable wear scar characteristics and a scar that was sufficiently large for convenient quantitative wear measurements, i.e., 10–100 μm deep. This sliding distance was in the range of 10^5–10^6 cm; an amount in this range was also the distance used in the evaluation of the complete set of samples. For the selected pairs, intermediate sliding distances of 30, 125, 250, 380, 3.8×10^4, and 3.8×10^5 cm were also used.

The predominant and consistent features of the scars produced in these tests were striations or scratches running completely across the wear scar. Occasionally a striation would end in the interior of the scar and when this would occur, an adhering inorganic particle would frequently be found, at the end of the striation, protecting the downstream side from further wear. This description applies to both ribbons and papers and is illustrated in Fig. 2. The general appearance of the laboratory-developed scars is quite similar to those found on actual components, as illustrated in Fig. 3. When the scars, either

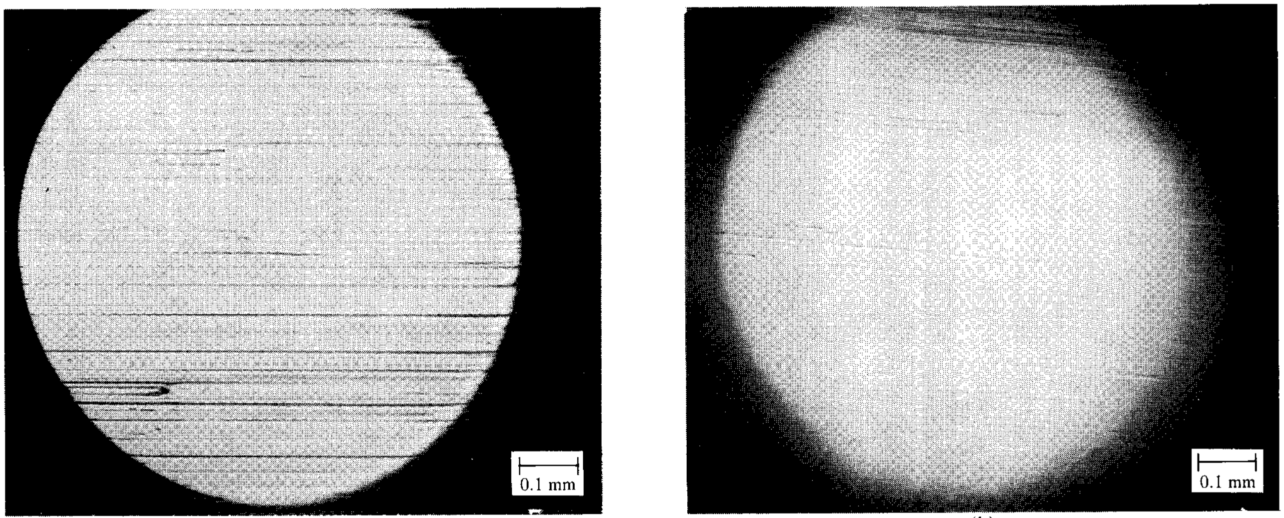


Figure 2 Typical laboratory wear scars produced on 52100 steel spheres. Wear scars by paper are shown in (a). Wear scars by ribbon are shown in (b). Note the trapped particles.

machine or laboratory generated, were cleaned of debris, e.g., ink and/or paper dust, they typically had a polished appearance under visual examination.

The same general features were evidenced at all sliding distances. However, as sliding was initiated, only occasional scratches were evident over a small area, with their density growing and the extent of the wear scars increasing with increasing sliding distance. Ultimately a flat wear scar was generated. This progression of wear scar development is illustrated in Fig. 4 for both a ribbon and a paper.

The general features of these wear scars are consistent with an abrasive wear mechanism in which hard particles are dragged across the surface. Along the path of these particles, damage would be produced as a result of either a deformation process, which would ultimately cause a loss of material from the surface through a fatigue mechanism, or a cutting action. The shape, size, and type of motion, sliding or rolling, of a particle, as well as the properties of the wearing material, would influence which deformation process occurs. While these two mechanisms would produce some differences in wear topography on the microscopic scale, they would still produce the same general appearance of a regular distribution of striations in the direction of motion. However, for paper and ribbons the well defined character of the striations, the lack of any evidence of microcracks indicating a deformation-fatigue process [9], and the characteristics of the scratches near trapped particles suggest that the predominant mode is cutting, rather than deformation.

If adhesion were the predominant mode of wear, a somewhat different scar topography would occur. In this case, material would be lost from a surface by a pull-out mechanism. Adhesion between the two surfaces would take place at randomly occurring sites over the contact area. At some of these sites, material would be pulled out from the surface as sliding progressed; at others large plastic deformation without significant loss of material might occur prior to rupture. When material was lost from a surface, it could cause further adhesion phenomena, e.g., readhesion to the original surface, or abrasion as it was carried further along the surface. Consequently, the wear scar would show some evidence of pull-outs, significant plastic deformation at individual sites, possibly readhesion events, and striations originating at random places on the wear surface. None of these features was characteristic of the wear scars examined. Also, with an adhesion wear mechanism it would be expected that some fragments of the worn steel would remain attached to the ribbon or paper. None was observed in the examinations performed on used ribbon or paper surfaces. However, it should be noted that with the wear rates obtained in these tests and the surface area of the paper and ribbon used, the likelihood of finding such particles in the examinations performed would be small.

One further point can be made regarding the relative predominance of abrasion over adhesion. Adhesion phenomena and adhesive wear are greatly modified by the use of lubricants. Consequently, if adhesion were a major factor in paper wear, it would be expected that there would be a significant difference between the topography of paper and ribbon wear scars, since the inks in the ribbon frequently use mineral oil, oleic acid, and similar materials which have lubricating properties. In fact, the two

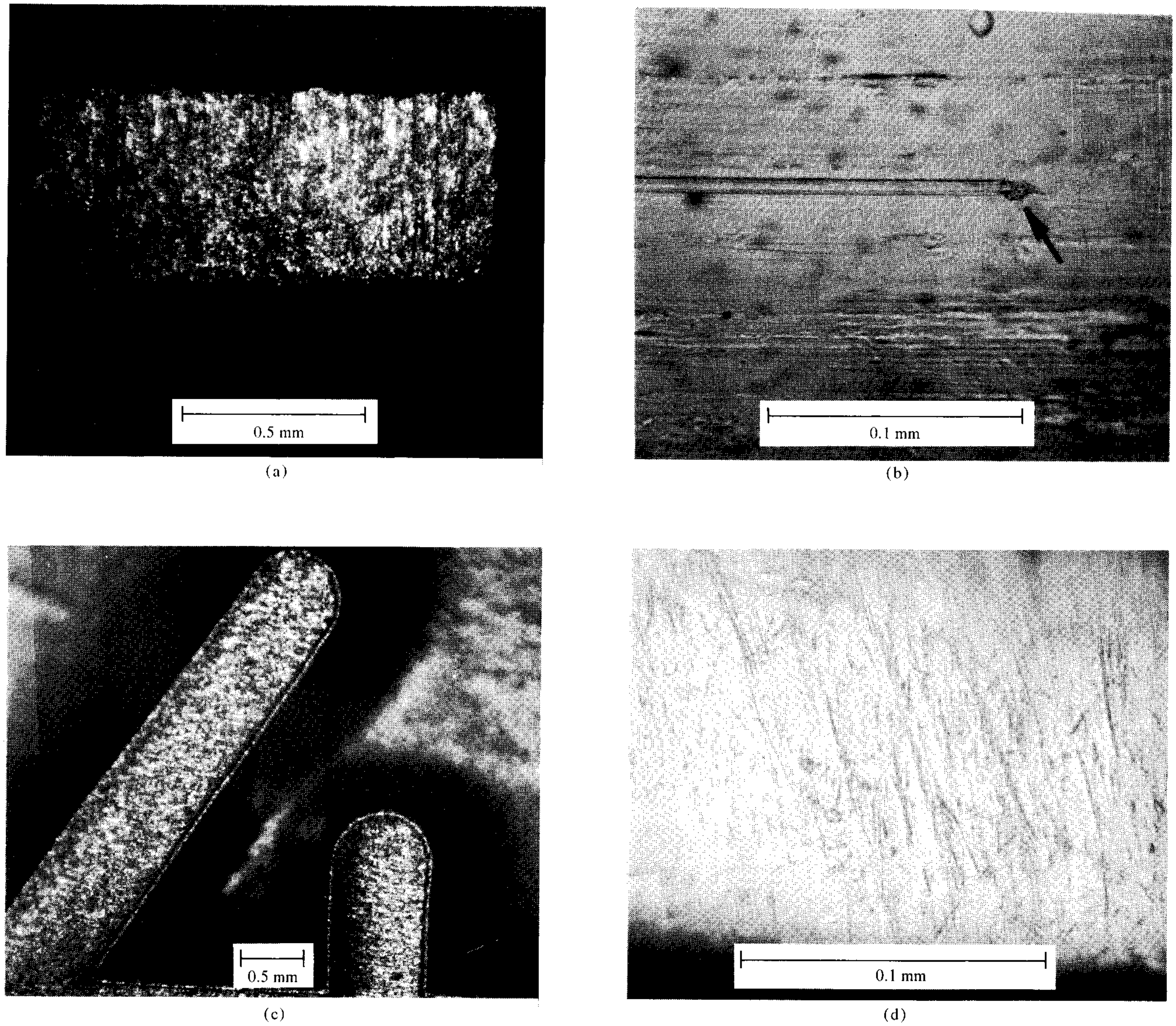


Figure 3 Worn component surfaces: (a) and (b), polymer surfaces worn by paper; note trapped particle in (b); (c), steel surface worn by paper; (d), chromium surface worn by ribbon.

types of scars have the same general features, indicating that similar abrasive wear mechanisms occur in both cases.

Simulation

As a further means of investigating the nature of the wear mechanism of paper and ribbon, a series of wear experiments were performed in which the wear was simulated by an abrasive wear situation. A woven nylon fabric, typical of the type used for ribbons, was coated with a mixture of a light petroleum oil and Al_2O_3 particles and was used as the wear medium. Wear tests were conducted for the different amounts of sliding as previously discussed and for four types of oil/particle mixtures: 1 μm particles in a 1%, 0.1%, and 0.01% by weight mixture, and a 0.05 μm particle in a 1% by weight mixture. Approximately 7.5×10^3 cm^2 of fabric surface were uniformly coated with 50 ml of these mixtures for these tests. The presence and relative size and density of the Al_2O_3 particles on the surface was confirmed by SEM and elemental x-ray examination.

Tests were performed on uncoated fabric, and it was found that the wear rates were two to three orders of magnitude smaller than with the coated samples. Hence, it was concluded that the wear obtained with the coated surfaces was primarily the result of the coating, and variations in the wear behavior could be correlated with variations in the mixtures.

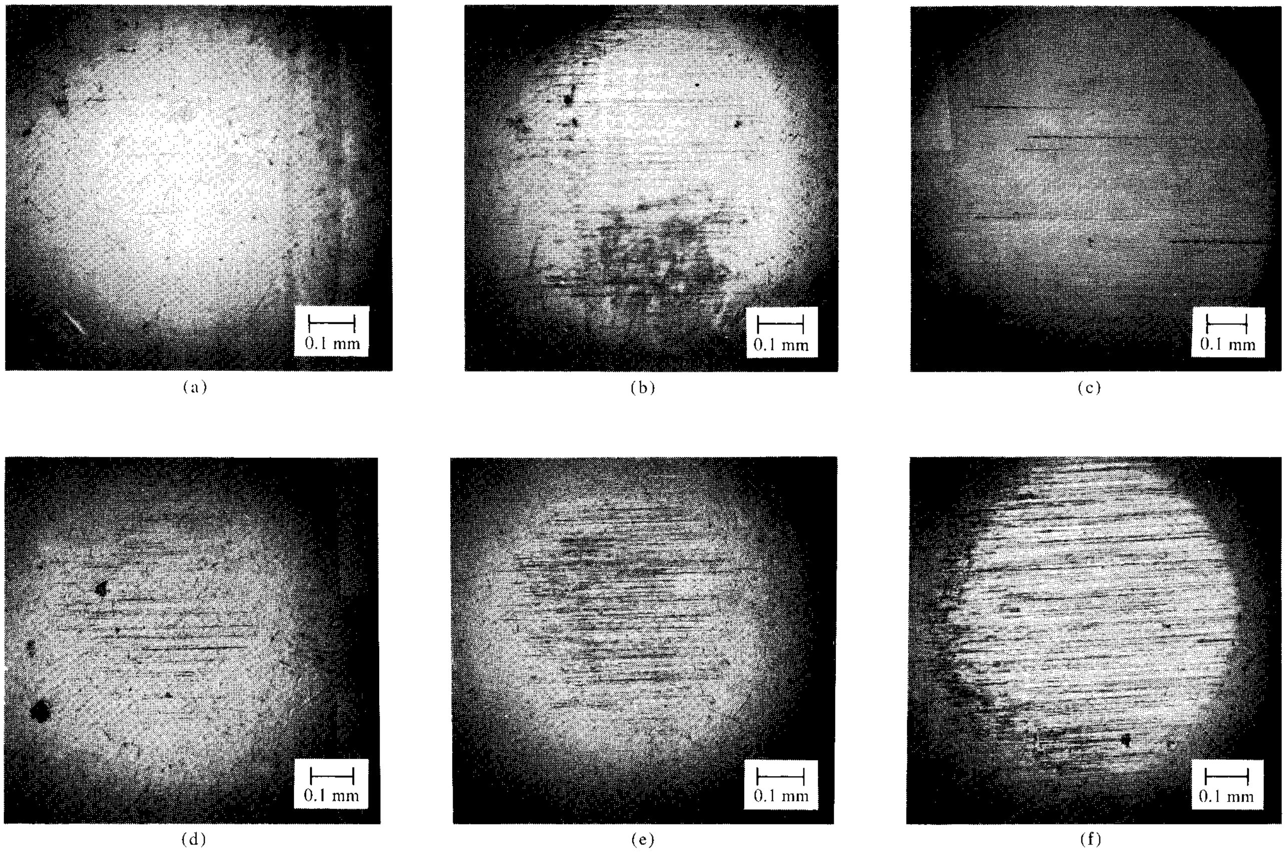


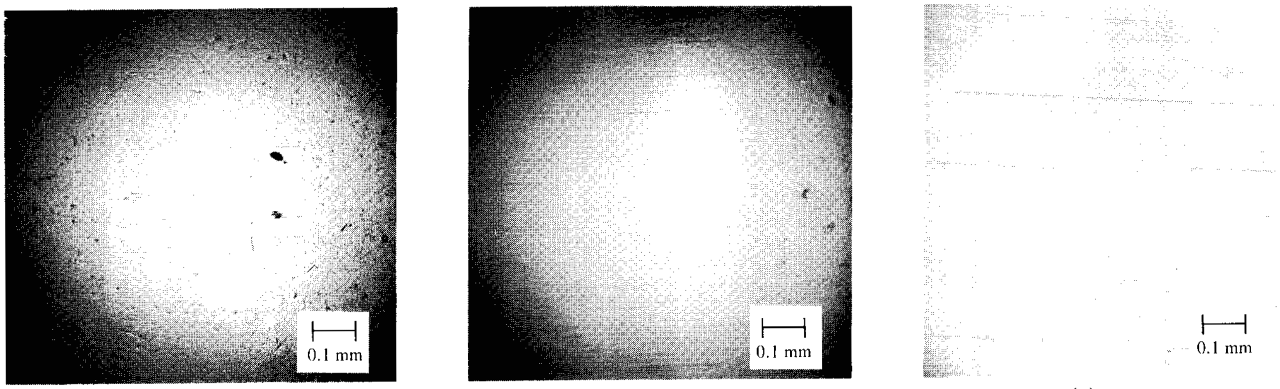
Figure 4 Wear scar topography as a function of sliding distance: (a), (b), and (c), small, intermediate and large sliding distances on paper; (d), (e), and (f), for ribbon.

The general features of the wear scar topography produced in these simulated tests were the same as those previously found with ribbons and paper, which further demonstrates the abrasive nature of their wear process. These features are illustrated in Fig. 5. The uniform size distribution of the abrasives used in the simulation is reflected in the greater uniformity of scratch widths that occur in these cases as compared to those obtained with paper and ribbons. However, the similarity of the scratch widths produced by 0.05 μm and 1 μm particles to those occurring with paper and ribbons indicates the significant abrasive size in those media to be in the range of a twentieth of a micron to several microns. This conclusion is similar to that reached in [1], which concluded that, for paper, the primary wear was the result of abrasion by a large number of submicron-size particles; an occasional larger particle produced a more pronounced scratch.

A comparison of the amount of wear produced in these tests with that obtained for ribbons and paper provides information regarding the nature of the wear process. In Table 1, data obtained from the simulated tests are presented along with data obtained for the ribbons and paper selected for extensive study. It can be seen from the data that, while wear in the simulative tests was generally higher than that for the ribbon and paper, submicron-size particles in the amounts obtained with the 0.01% and 0.1% mixtures would produce comparable wear.

The simulated test data from Table 1 indicate that the wear is proportional to abrasive size. This result is consistent with behavior observed in more conventional abrasion studies involving larger particles, e.g., ranging from 10 to 10^3 μm, which shows a linear dependency on size up to a maximum in the range of 10^2 μm [10–12]. The quantitative data in Table 1 also indicate a saturation effect in terms of amount of wear since the wear for both the 0.1% and the 1.0% mixtures is approximately the same. Hence, it appears that a linear relationship between wear and abrasive content exists up to a certain level, beyond which there is no increase in wear.

The existence of a saturation level for abrasive quantity is expected. However, the relatively low level at which it occurs is surprising and significant in terms of the level of abrasives possible in papers and ribbons. If all the particles contained in the 0.1% mixture (the level at which saturation is evident) were confined to the surface of the fabric, only a small portion of the surface would be covered



(a) (b) (c)

Figure 5 Wear scar topography as a function of sliding distance for 0.05 μm Al_2O_3 particles on fabric: (a), (b), and (c), for small, intermediate and large sliding distances.

by the particles. For a 1 μm particle, 10% coverage is estimated; for 0.05 μm, 30%. This would correspond to particle densities on the surface of from $2 \times 10^4/mm^2$ to $2 \times 10^8/mm^2$ for 1 and 0.05 μm particles, respectively, which are similar to the densities found for papers, e.g., $1 \times 10^7/mm^2$ for 0.1 μm particles [1].

This same level of coating by the 0.1% mixture increased the inorganic content of the fabric by approximately 0.07%; this is lower than the inorganic content of many papers and ribbons. Typical levels, as determined by ashing methods, are in the range of 1–20% for papers and 0.3–0.7% for ribbons. This indicates that these materials have sufficient inorganic content to provide the necessary abrasive level. Moreover, because of the large inorganic content of these materials, with respect to the apparent saturation level, it can be inferred that the significant reason for differences in abrasive levels may be more associated with size than with amount of abrasive. This is also supported by additional studies on a large number of papers and ribbons where wear rates ranged over two orders of magnitude, in which no correlation was found between ash content or elemental composition and wear rate.

Table 1 Volume of wear for 3.8×10^5 cm of sliding.

Wear specimen	52100 steel, H_m746 kg/mm
Load	100 g
Drum speed	300 cm/s
Specimen speed	0.25 mm/rev

Wear media	*Volume of wear* (cm^3)
Fabric + 0.01% Al_2O_3/oil (1 μm particles)	3.9×10^{-5}
Fabric + 0.1% Al_2O_3/oil (1 μm particles)	4.1×10^{-4}
Fabric + 1.0% Al_2O_3/oil (1 μm particles)	3.4×10^{-4}
Fabric + 1.0% Al_2O_3/oil (0.05 μm particles)	2.3×10^{-5}
Ribbon A	7.9×10^{-7}
Ribbon B	1.6×10^{-6}
Paper A	1.5×10^{-5}
Paper B	1.6×10^{-5}

Abrasive levels

Considerable variations in the abrasiveness of papers and ribbons have been observed. For a constant wear test, the volume of wear produced by paper of different types and from different sources has a range of over two orders of magnitude; ribbon, in excess of one order of magnitude. Moreover, significant variations, e.g., a factor of two, have been found in batch-to-batch variations of these materials. In an effort to identify the reasons for this variability in abrasiveness, several efforts were made to determine the nature and amount of the abrasive contained in these specimens and to correlate the abrasiveness with individual type and source of the specimens. While these efforts were not too successful, some information was obtained regarding the possible source of the abrasives.

For the papers, the highest levels of abrasion were found with samples obtained from Europe and the Orient; although a slight trend was observed for these papers to be more abrasive than U.S. papers, this was not universally true. Many U.S. papers were more abrasive than some European and Oriental papers. In general, the particle sizes and amounts of individual types of inorganics found in the papers were too small for identification by x-ray diffraction techniques. However, in one case, that of a particularly abrasive paper, this technique resulted in the identification of Muscovite, a moderately hard mineral, as one of the inorganics present.

Table 2 Abrasiveness of fabric and ink components.

	Normalized wear factor[a, b]
Fabric	2.6×10^{-9}
Fabric + vehicle	3.6×10^{-8}
Fabric + vehicle + dye	5.9×10^{-8}
Fabric + vehicle + pigment	9.1×10^{-6}
Fabric + vehicle + dye + pigment =	
Complete ribbon—batch 1	6.2×10^{-6}
Complete ribbon—batch 2	2.0×10^{-6}
Complete ribbon—batch 3	4.1×10^{-6}

[a]Wear factor = (volume × hardness of specimen) ÷ (load × distance).
[b]Measured at 20°C, 45% RH.

Correlations with ash content and physical characteristics were also attempted, but none was found. In addition, similar elemental distributions were found for most papers. In general, very little information was obtained from these studies, either about the sources of the abrasives or the reasons for the significant differences in abrasion levels. These results, along with the recognition that small amounts of submicron particles can result in significant wear, suggest that a significant source of abrasives in many cases is impurities. These impurities are either contained in the various ingredients used in the paper or introduced by the manufacturing environment.

With ribbons, as with paper, x-ray diffraction studies, elemental analysis, and ashing techniques were not useful in identifying the reasons for differences in abrasive levels. These negative results suggest that impurities are a key factor in ribbon abrasion. Further experiments were performed which resulted in the identification of the ink as the primary factor in ribbon abrasion, rather than the fabric. This was done by dividing the complete ribbon into various levels and determining the abrasiveness of each level. In Table 2 typical results are given for a ribbon which was subdivided into fabric, fabric plus ink vehicle systems, fabric plus vehicle and dye systems, fabric plus vehicle and pigment systems, and fabric plus complete ink formulation. The data in that table clearly indicate that the governing factor in ribbon abrasiveness is the ink and not the fabric. Moreover, these data show that while the vehicle and dye systems contribute to the abrasiveness, the pigment system was the major contributor in this case. This table also illustrates the variations that are obtained when different lots of the ink ingredients are used. For this particular ribbon, ash content of different lots of pigment ingredients has been found to vary by a factor of two; this again suggests the importance of impurities on the abrasive level.

Conclusion

This study has developed significant new empirical information regarding the nature of wear by ribbon and paper and the ribbon and paper characteristics which influence it. It has shown the wear processes of ribbon and paper to be similar. Moreover, while prior investigations, primarily analytical [1–6], were not able to uniquely identify the wear process as either abrasive or adhesive, this study has identified it as abrasive. It was found that only relatively small amounts of submicron or micron particles are required to produce the abrasive wear observed and that papers and ribbons frequently have inorganic contents exceeding those amounts. Further, while it has not been universally demonstrated, the data obtained indicate that in many cases variations in the impurity level of papers and ribbons are responsible for the differences in abrasive levels found.

Since little success was achieved in measuring abrasive content with analytical techniques and in correlating abrasiveness with other paper and ribbon characteristics, it is indicated that at present a wear test is the only valid manner in which relative and absolute abrasiveness can be determined for these materials. A standard wear test does not exist for both paper and ribbon. However, a standard wear test has been developed within the American Society for Testing and Materials (ASTM) to determine ribbon abrasiveness.

Acknowledgment

The author expresses his appreciation to T. Fitzgerald for the preparation of ribbon samples, to R. Wagner for the use of some micrographs of worn components, and to F. Cullen for much of the testing.

References

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. J. Larsen-Basse, "On Abrasive Wear by Paper, " *Wear* **14,** 133–136 (1969).
4. E. F. Finkin, "The Wear of Metals by Data Processing Card Stock," *Wear* **18,** 207–213 (1971).
5. P. A. Engel and R. G. Bayer, "Abrasive Impact Wear of Type," *J. Lubr. Technol.* **98,** 330 (1976).
6. P. A. Engel, J. L. Sirico, S. E. Nemier, and R. G. Bayer, "Study of Print Wire Wear," *Wear* **36,** 373–378 (1976).
7. D. A. Roshon, "Testing Machine for Evaluating Wear by Paper," *Wear* **30,** 93–103 (1974).
8. Registered trade name, Taylor-Hobson, Ltd.
9. R. G. Bayer and R. H. Schumacher, "On the Significance of Surface Fatigue in Sliding Wear," *Wear* **12,** 173–183 (1968).
10. M. A. Moore, "A Review of Two-Body Abrasive Wear," *Wear* **27,** 1–17 (1974).
11. M. M. Khruschov, "Principles of Abrasive Wear," *Wear* **28,** 69–88 (1974).
12. E. Rabinowicz, *Friction and Wear of Materials*, John Wiley & Sons, Inc., New York, 1965, pp. 167–180.

Received October 17, 1977; revised February 6, 1978.

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