

METHOD FOR EVALUATING TONER ADHESION ON COPIER PAPER

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ABSTRACT

A new instrument and technique developed at the USDA Forest Service, Forest Products Laboratory to evaluate the adhesion of inks on paper was used to study toner loss on copier papers. This instrument creates a fold with a very small radius in the printed region of a paper specimen. This fold is repeatedly rolled through the specimen until the desired degree of wear is induced. If the radius of the fold is small enough, a critical strain is reached where the toner layer fractures cohesively. Subsequent cycling will cause adhesive failure of the toner as fragments are peeled from the paper surface. Image analysis techniques were developed to quantify toner loss. The extent of toner loss is a function of several factors including instrument parameters (smaller gaps and more cycles increase toner loss), copier parameters (lightest and darkest settings are least durable), and paper properties (toner is more durable on 20% recycled content copier paper than on virgin copier paper).

INTRODUCTION

A new instrument and technique have been developed to evaluate the fold endurance and surface adhesion of sheet materials (Figure 1). Patented in 1996 [1], the instrument was developed primarily as a means to evaluate the surface adhesion of paper coatings, inks, and toners. The function of the Rolling-Fold Durability Tester (RFDT) is to cycle a small radius fold through a printed (dark) region of a paper specimen. The sharp 180° fold can be made small enough to fracture the coating material on the surface. A similar mechanism is used in ASTM Standard F 1351-96 [2]. As the fold "rolls" through the printed region, fragments of toner are peeled from the surface exposing the paper substrate. Adjusting the fold radius (gap) and number of cycles can strongly influence the extent of wear. Image analysis techniques were used to quantify toner loss. In this study, several factors were evaluated that affect the adhesion of toner to copier paper. We will show that loss of toner is a function of instrument parameters, paper properties, and copier system.

EXPERIMENTAL

Functionality of RFDT

Figure 2 is a schematic representation of the RFDT functional mechanism. A printed paper specimen with a solid black image is inserted between two parallel vacuum plates that are separated by a fixed gap. The bottom plate is displaced in a parallel plane to cause the fold to traverse through a predetermined region of the specimen. With each cycle, toner is removed exposing the paper substrate. In the first few cycles, the toner fractures cohesively in a pattern influenced by fold radius, toner thickness (deposition), and paper directionality (machine vs. cross-machine). Subsequent cycles cause the fractured toner to peel from the paper surface (adhesive failure) thereby continually removing toner as the test progresses (Figure 3). Plate speed, gap, and number of cycles can be adjusted to induce various levels of wear.

Quantifying Toner Loss

Two image analysis systems were developed to quantify toner loss. The first system incorporates a machine vision video camera mounted on the RFDT (Figure 1). The camera views a small portion of the test specimen at high resolution (approximately 30 mm² at 10,250 pixels/mm²). The camera is interfaced to a frame-grabber board to capture an image of the test specimen before and after each test. The images are then reduced to their characteristic

grey-level histograms (Figure 4). To determine toner loss, an increase in the number of pixels in the white region (140 to 255 pixels) is considered to be a relative measure of paper exposed after the toner is removed. Toner loss is defined as an increase in the number of pixels above the 140 grey-level between the “unexercised” and “exercised” specimens (expressed as a percentage of total). A similar technique has been used to characterize print quality [3].

The second system incorporates scanner-based imaging. Each specimen was scanned at 300 dpi before and after testing. A larger region of the specimen (Figure 3) was selected and scanned at a much lower resolution (about $2,500 \text{ mm}^2 @ 140 \text{ pixels/mm}^2$) than the camera. To simplify analysis, the scanned image was brought to a threshold at a grey-level of 128. This divided the histogram into distinctly black and white regions. Similar to the camera-based system, toner loss is defined as the percentage of pixels above the 128 grey-level exposed in the “exercised” specimens. Scanner-based imaging was used for most of the tests reported in this paper.

RESULTS and DISCUSSION

Instrument Parameters

The RFDT was designed to produce an intense strain at the surface of a sheet material to fracture or otherwise fail the surface treatment. By controlling the gap, speed, and number of exercise cycles, it was presumed this could be done with a high degree of precision and repeatability. Although a broad range of speeds did not seem to effect toner loss, the gap and number of cycles had a significant effect (Figure 5). As the gap was reduced from 1 to 0.64 mm, the loss of toner increased by about a factor of 4, reflecting the increased severity of the strain caused by reducing the radius of the fold. Figure 5 also shows that as the test proceeds (more cycles), toner is continually removed.

In addition to utilizing the image analysis techniques described in the previous section, the amount (weight) of toner lost from each sample was also determined. Samples were weighed before and after testing; the difference in weight was attributed to toner loss. Figure 6 shows the relationship between the percentage of toner loss as calculated by scanner-based imaging and the actual weight loss of the specimen. This relationship validates the image analysis techniques used to quantify toner loss.

The orientation of the printed surface as inserted into the gap has a significant effect on toner loss. Several specimens were tested with the toner facing either inside or outside the fold at a gap of 0.9 mm (fold radius of 0.45 mm). The amount of toner lost when the toner faced inward was five times that lost when the toner faced outward. This can be explained by considering that the paper thickness (0.13 mm) will reduce the radius of curvature to 0.32 mm on the inside of the fold, resulting in a corresponding increase in the magnitude of strain levels in the toner. The fracture and peel mechanisms are also different, with tension strains on the outside and compression strains on the inside. No attempt was made to analyze fold mechanics. However, based on extensive preliminary tests, it was determined that placing the printed surface on the outside of the fold was adequate for tests on toners.

Copier Parameters

Copy quality depends on several copier parameters, including machine manufacturer and model, age, and usage [4]. Although similar mechanically, copy machines from different manufacturers utilize different toner chemistries [5-7]. Therefore, toner surface adhesion and durability can vary widely. For this study, we investigated the durability of reproduced images from three different copy machines (Figure 7). Under fairly mild test conditions, there was a rather large disparity among the three machines. No attempt was made to evaluate all types of machines since much of the relevant information about machine functionality and toner composition is proprietary.

One copier parameter, the toner deposition level, is easy to control. Five toner deposition levels were investigated using a range of darkness settings for one specific copier (Figure 8). The highest deposition level was found to be the least durable. Furthermore, the lightest deposition level appeared to be less durable than the intermediate levels

Paper Parameters

Two paper parameters were evaluated in this study: paper type and sheet orientation relative to fold travel. Two 75-g copier papers, one 100% virgin paper, and one 20% recycled content paper were tested in both the machine- and cross-machine directions (Figure 9). Images on the recycled content paper were very durable relative to the virgin paper. Representative images of the machine-direction papers are shown in Figure 3, and corresponding histograms for the virgin paper are shown in Figure 4. Micrographs of the surfaces of these specimens (Figs. 10 and 11) show fold lines where toner had fractured and peeled from the surface. Much larger regions of paper substrate were exposed in the virgin specimen. Micrographs of unprinted paper surfaces provide an explanation for this difference.

The recycled content paper appeared to have a more open structure, providing a more porous substrate for enhanced mechanical binding of the toner. Mechanical interlocking has been shown to improve the adhesion of coatings to paper [8,9]. Air permeability measurements support this observation. The permeability of the virgin paper was 6.8 mL/s compared to 8.7 mL/s for the recycled content paper. In addition, the virgin paper appeared to have more filler on the surface, which may have reduced adhesion of the toner. These combined characteristics may explain why the recycled content papers were more durable.

Specimens tested with the machine direction of the paper perpendicular to the fold line were less durable than those tested in the cross-machine direction (Figure 9). This was due to a difference in the flexibility of the sheet as it was forced to encounter the tight 180° fold. We observed an interesting difference in the fracture pattern. For the machine-direction specimens (Figures 3, 10, and 11), the pattern was equally spaced fractures parallel to the fold. This pattern was not the product of a smooth fold radius, but rather of sharp creases that were evenly spaced in segments roughly equivalent to the width of the gap (like links in a chain). The cross-machine direction specimens bent more easily, so creasing was less severe and less toner was lost. Again, air permeability measurements seem to support this observation. After just 10 cycles, the permeability of the virgin copier paper increased to 12.9 mL/s in the machine direction and 8.3 mL/s in the cross-machine direction; permeability of the recycled content copier paper increased to 13.1 mL/s in the machine direction and 9.9 mL/s in the cross-machine direction. Several investigators have attempted to relate toner fracture properties to deinking efficiencies [4-7,10]. Aside from visual observation, the mechanics of folding and fracturing has yet to be studied.

Paper moisture content (when tested) also seems to affect the durability of toner. Figure 12 shows the difference in durability between two relative humidity levels, 20% and 50%, at two toner deposition levels. The differences in durability may be attributed to an increase in the stiffness of the paper at the lower humidity level, an increase in the brittleness of the toner, or a combination of these characteristics. Swelling of paper has been shown to have a significant impact on toner fracture [10].

Problems Encountered

Several factors that were difficult to control had a significant impact on durability measurements. Of these, non-uniform toner deposition at the lightest levels introduced the most variability. The right side of the test section yielded a toner loss value of only 13.1%, whereas the toner loss value of the left side was calculated to be 29.4% (Fig. 13). This disparity introduced a significant degree of uncertainty with the camera-based imaging system since only a very small portion of the exercised area was viewed. However, this uncertainty could be minimized with scanner-based imaging, accounting for an average distribution for the whole image.

Another factor that complicated the tests was the occurrence of paper “pickling.” For the very tight gaps, several of the recycled content specimens “pickled” or de-bonded in the initial cycles. This was thought to be due to shear failure of the inner layers of the paper (internal delamination). By increasing the gap, pickling was no longer observed (except at very high cycle levels, not reported here).

CONCLUSIONS

The focus of this study was to determine the utility of the Rolling-Fold Durability Tester (RFDT) for characterizing toner durability on copier papers. Functionally, the RFDT can be configured to impose strains severe enough to fracture or otherwise fail the toner after repeated cycling. By controlling the gap width and number of cycles, it is possible to influence the degree of toner loss. However, there are practical limitations to these parameters where the substrate itself may begin to fail. The mechanism of toner failure in these tests seems to be cohesive fracture in the first couple of cycles, followed by adhesive failure (peeling) in subsequent cycles.

Toner loss depends on several factors, including both copier and paper parameters, and can vary greatly. Manufacturers of copy machines employ very different toner chemistries. These differences can have a profound effect on the durability of toner on different paper surfaces. It is suspected that the more “durable” toner systems are either more ductile (resistant to fracturing) or more brittle (fracture extensively, with smaller toner fragments less likely to peel from the paper). Toner deposition levels (darkness) affect durability and can be controlled to some extent. However, toner deposition is often not uniform and can introduce variability in test results. Paper parameters such as orientation, recycled content, and moisture content also affect toner adhesion. Toner is less durable on papers tested in the machine direction than those tested in the cross-machine direction probably as a result of the stiffness differential between the orientations. Toner was found to be more durable on a recycled content paper because of a combination of sheet characteristics, including increased porosity for better mechanical binding, lower bending stiffness for less severe creasing, and an undetermined surface interaction (coating) for improved toner

adhesion. However, these sheet characteristics are not unique to recycled content papers and are likely influenced by papermaking processes.

Although limited in scope, this study was effective in determining the utility of the RFDT for characterizing toner durability. Based on these results, the RFDT would be quite useful in an extensive study on toner adhesion, possibly considering the influence of subtle changes in toner chemistry, toner curing mechanisms, and paper surface interactions (sizing).

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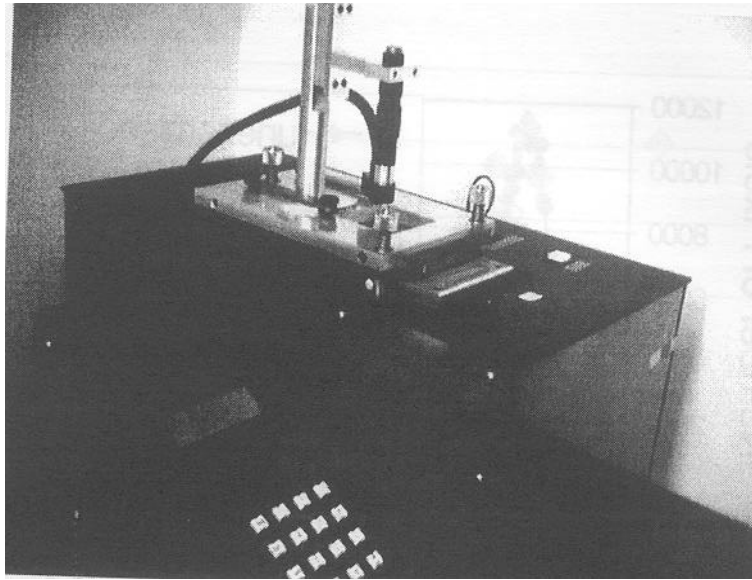


Figure 1. Rolling-Fold Durability Tester (RFDT) used to test fold endurance of sheet materials. Note the cigar-sized video camera mounted above the unit to monitor toner loss.

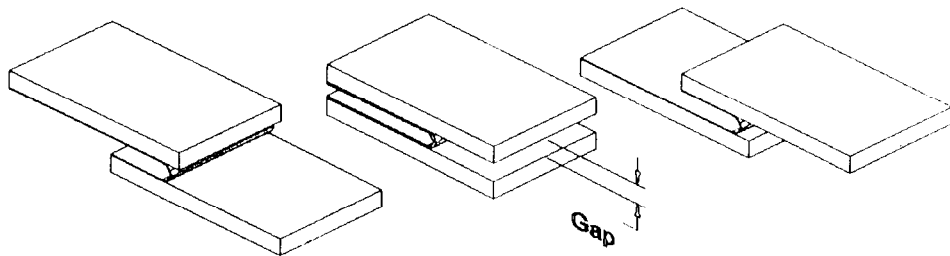


Figure 2. Schematic representation of three stages in the rolling action on an inserted specimen. Top plate is fixed while bottom plate slides backwards in a half-cycle (left to right). Fold radius is equal to the gap/2.

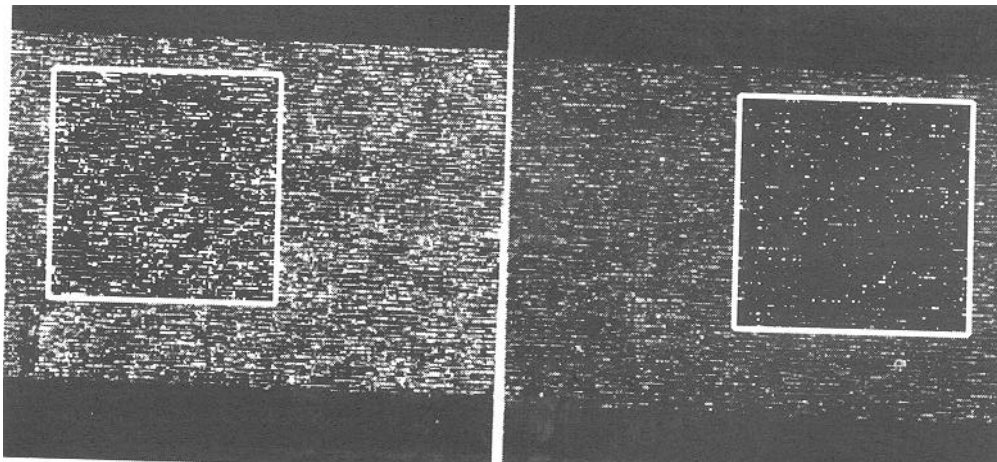


Figure 3. Scanned image of two worn machine-direction specimens. The fold "rolls" through the specimen (as shown from top to bottom) causing the toner to fracture in a striated pattern. The boxed regions are scanned for image analysis to quantify toner loss. The specimen on the left is from virgin copier paper and the specimen on the right is from 20% recycled content copier paper. Gap=0.762mm, 20 cycles.

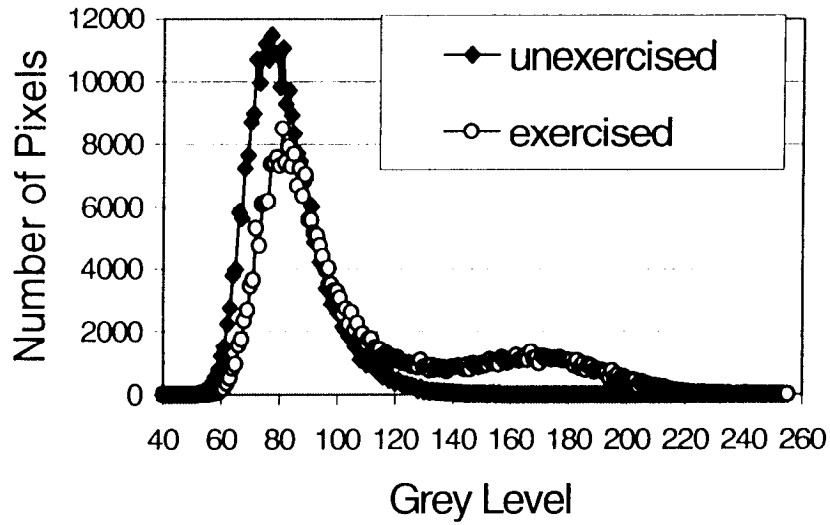


Figure 4. Image histograms of unexercised and exercised specimens for 100% virgin copier paper. As toner is lost, the dark peak (grey-level = 80) diminishes, exposing the lighter paper substrate (grey-level > 140).

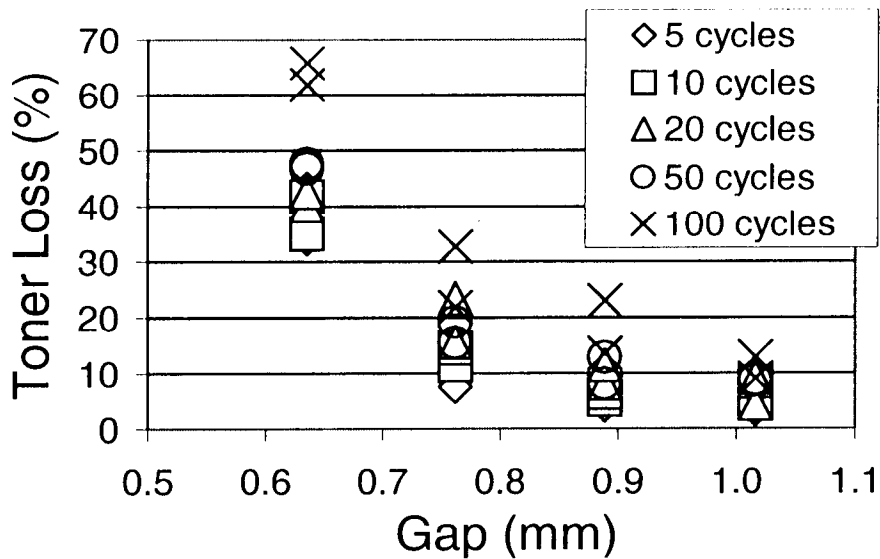


Figure 5. Toner loss as a function of plate gap and number of cycles.

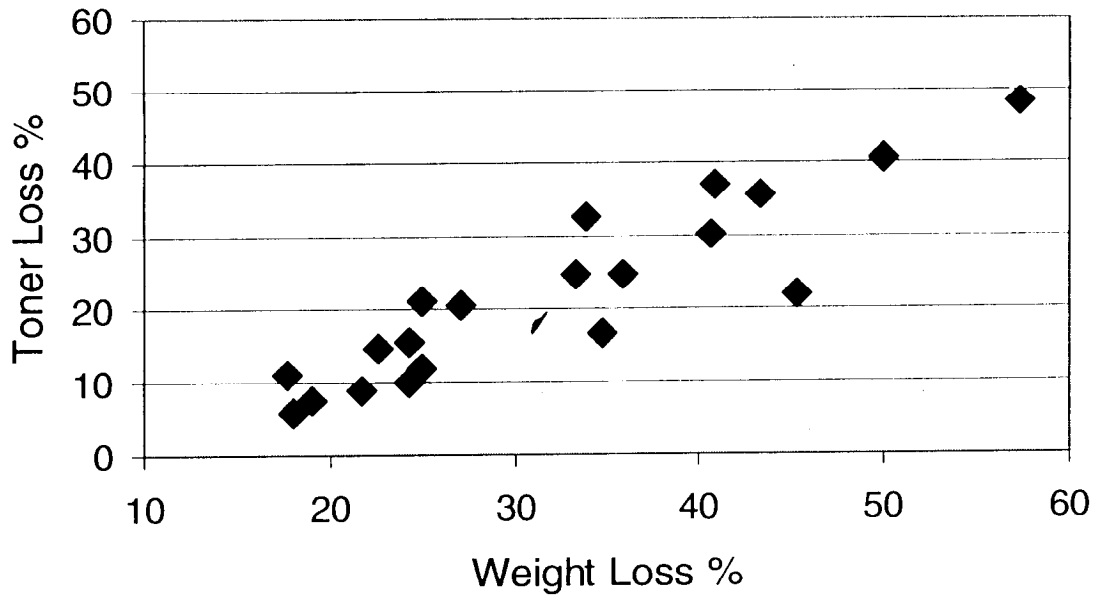


Figure 6. Calculated toner loss by scanner-based imaging and corresponding measured weight loss for various gaps and cycles.

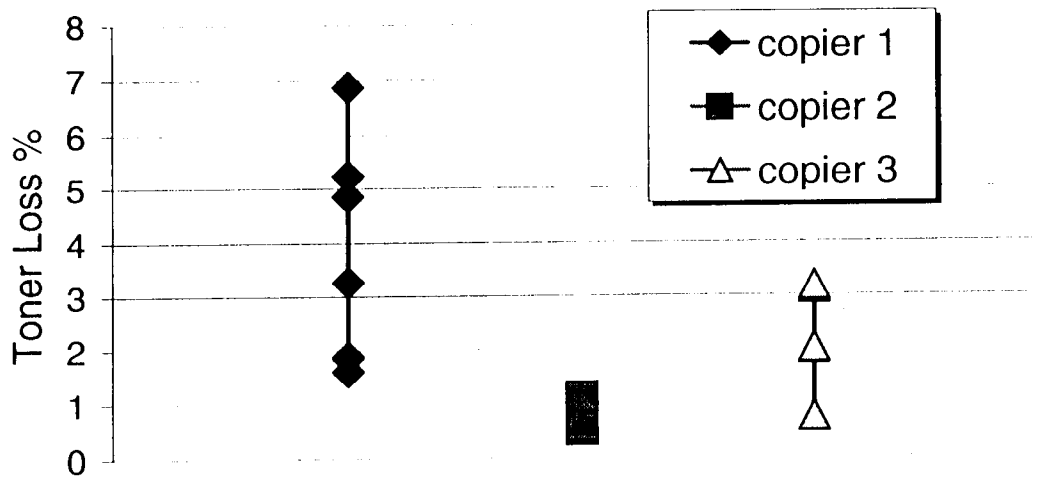


Figure 7. Toner loss as a function of copier type for three different copiers. Paper was photocopied at default darkness levels. Gap=0.762mm, 20 cycles.

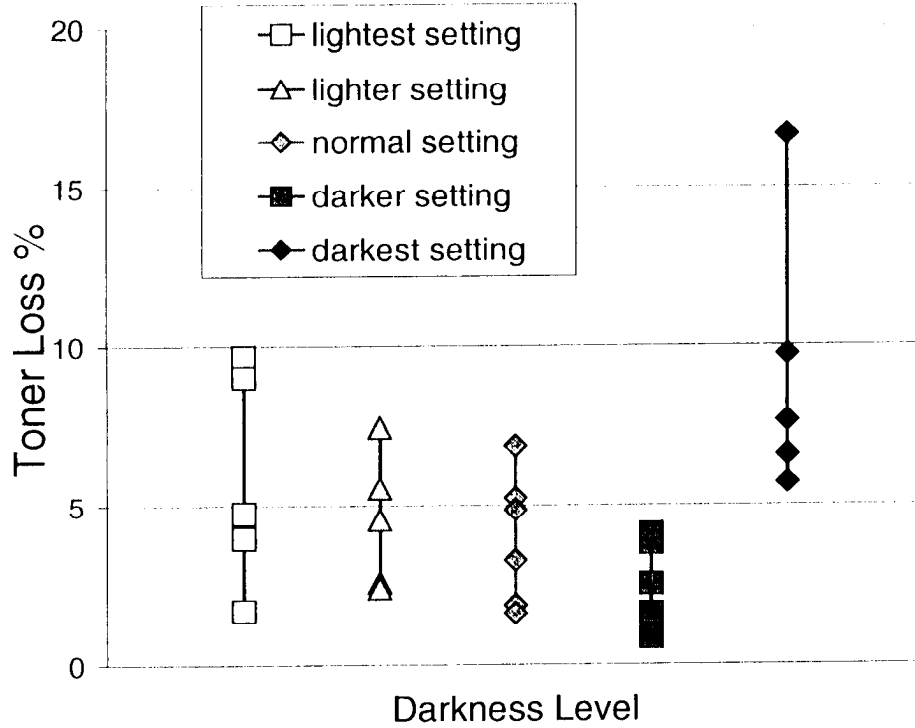


Figure 8. Toner loss as a function of darkness (deposition) levels for copier 1. Gap=0.762mm, 20 cycles.

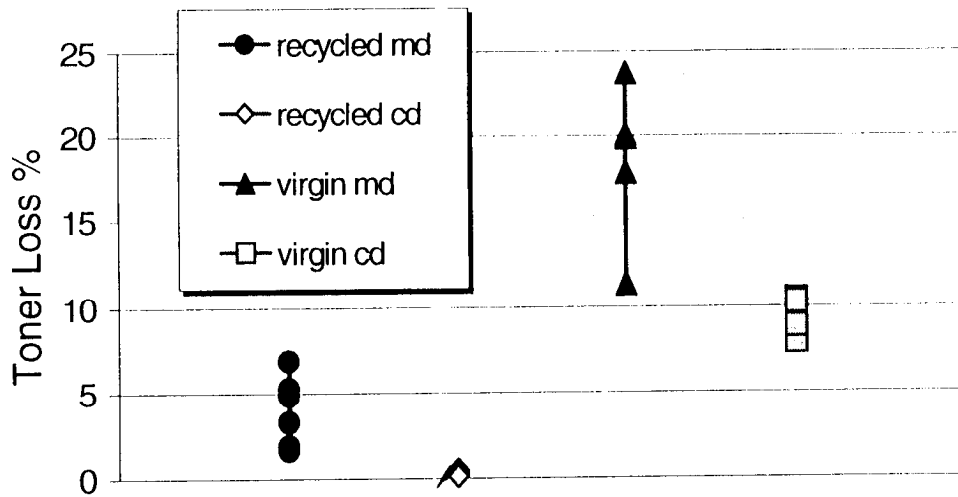


Figure 9. Toner loss as a function of paper type and orientation. Gap=0.762mm, 20 cycles.

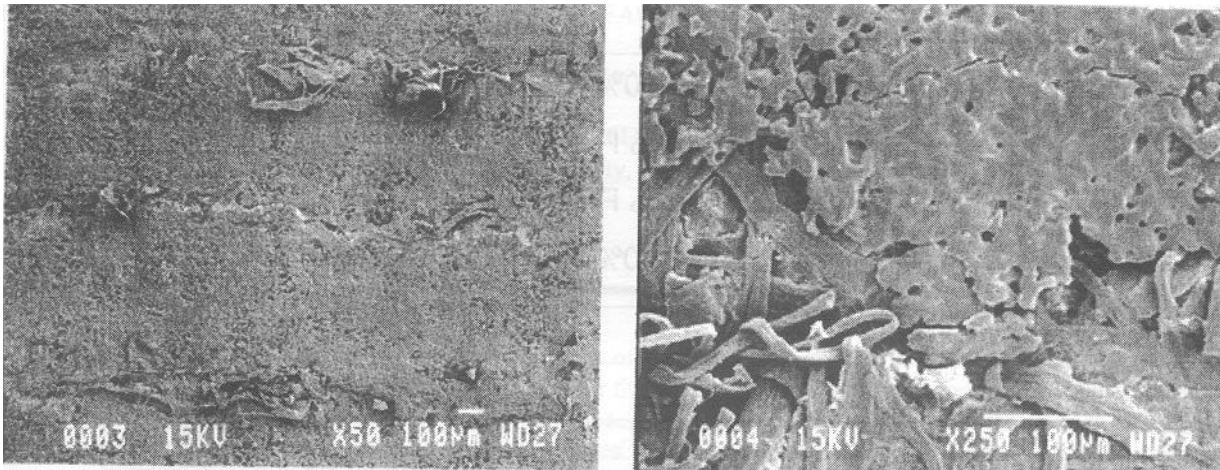


Figure 10. Micrographs of folds created in 100% virgin specimen by RFDT. At 50x, large areas of paper substrate were exposed where toner was removed. At 250x, fractures in remaining toner were apparent. Gap=0.762mm, 20 cycles.

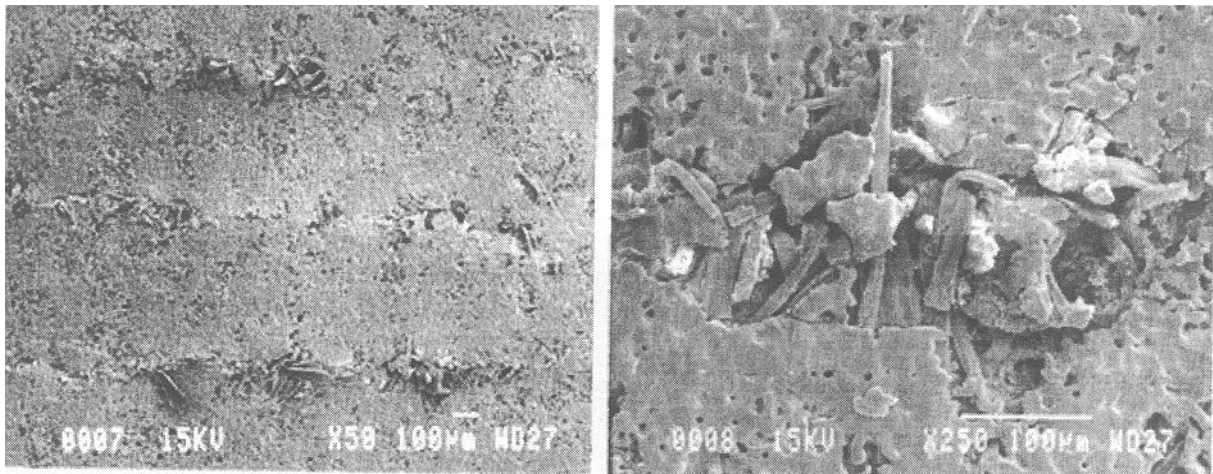


Figure 11. Micrographs of folds created in 20% recycled content specimen. At 50x, small areas of paper specimen are exposed where toner was removed. At 250x, fractures in remaining toner were observed. Gap=0.762mm, 20 cycles.

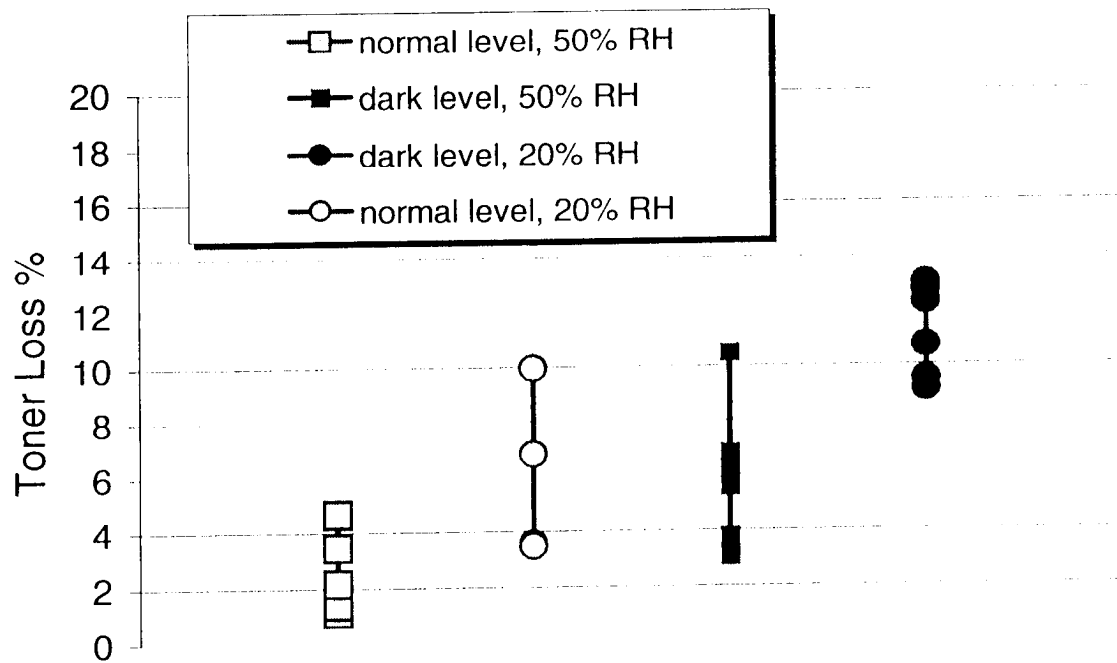


Figure 12) Toner Loss as a function of two relative humidity (RH) levels and two darkness levels. Gap=0.89mm, 20 cycles

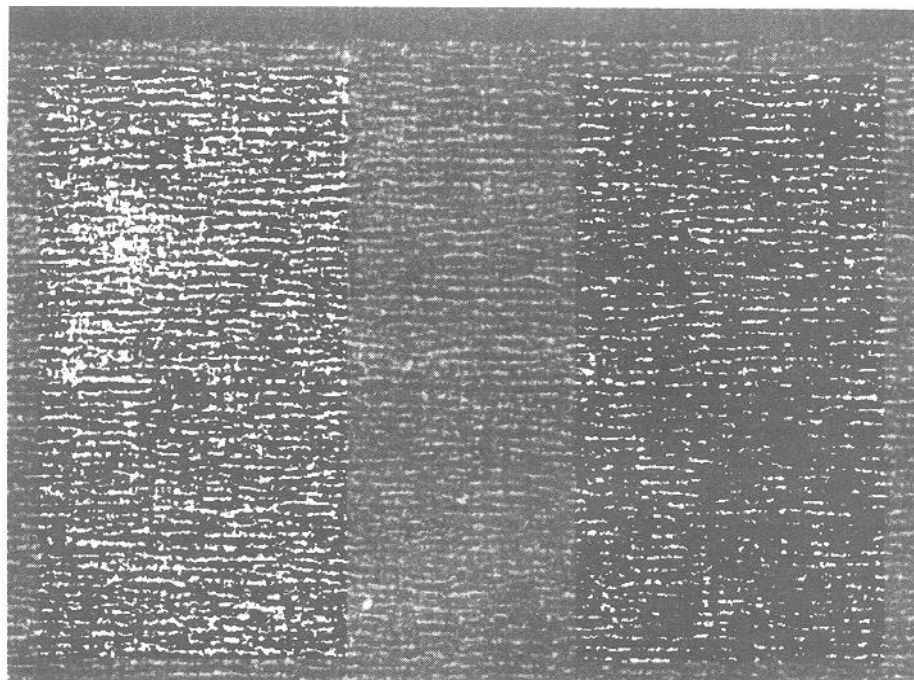


Figure 13) A single test specimen showing a significant difference in appearance of two thresholded regions on either side of the specimen. Gap = 0.762mm, 20 cycles

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