Light and Electron Microscopy Approaches to Sequence of Writing Problems

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Abstract: *Sequence of writing problems constitute only a small percentage of most document examiners' case loads, but solving such problems can be crucial. It is important to know the factors that make sequences capable of determination, and when possible, to know how to make such a determination or where to find further assistance. McCrone Associates, a microscopical and microanalytical consulting firm with a wide range of instrumentation and analytical techniques, is occasionally asked to supplement work performed by individual examiners in smaller laboratories. For this reason, McCrone sponsored research to ascertain which instruments, illumination methods, magnifications and techniques might provide more definitive answers to a variety of sequence of writing questions. We derived a number of insights from this research which we would like to present as a general microscopical theory of sequence determinability. It is hoped that this theory will provide the document examiner with one more practical tool with which to approach sequence of writing problems. We also invite our colleagues to test this theory and report both confirmations and discrepancies.*

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1. Introduction

The theory of sequential determinability has three elements: (1) classes of writing materials; (2) the magnifying instrument; and (3) the illumination method. Writing materials can be classified by their interaction with the paper substrate as either absorbing or coating. The decipherability of the combinations depends on the forensic document examiner's (FDE) clear understanding of the differences between each sequence combination. While the descriptions included in this paper may be useful as a starting point, the FDE should study reference samples of known sequence combinations and become fully acquainted with their unique visual characteristics.

1.1 Writing materials

Absorbing materials are inks of low-to-medium viscosity that are absorbed by the paper fibers, essentially dying them. These inks are found in ballpoint, rollerball, fountain, dip, and technical drawing pens, felt tip markers, stamp pads, typewriter cloth ribbons, and inkjet and dot matrix printers, as examples.

Coating materials rest on top of the paper fibers, forming a more or less impervious layer of material with few or no pores. Included in this class are laser printing, carbon ribbon typewriting, offset printing, serigraphy, and other materials that are not absorbed by the paper fibers.

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1.2 Instrumentation and illumination

The reflected light compound microscope with coaxial bright field illumination can provide definitive sequencing information in many cases. The scanning electron microscope (SEM), optimally configured and operated, can also provide additional information on many sequencing problems.

1.3 Class combinations

There are innumerable combinations of materials. Each case must be regarded as completely unique and analyzed using the specific evidence that is presented in the case. Three of the more common combinations are absorbing/coating, coating/coating, and absorbing/absorbing.

1.3.1 Absorbing/coating combinations have a high degree of decipherability with the reflected light microscope with coaxial bright field (CBF) illumination. The SEM is not indicated.

1.3.2 Coating/coating combinations have a very high degree of decipherability with CBF light microscopy. If the coating materials are identical, their decipherability may be lessened.

1.3.3 Absorbing/absorbing have a lower degree of decipherability with reflected light microscopy with oblique illumination (CBF is not indicated). If morphological changes to the paper substrate have occurred, more definitive results can often be achieved with the SEM.

3. Research protocol (continued with copy)

Our research protocol (much of it occurring concurrently) was as follows:

I. Review of the literature
II. Test sample construction
III. Results from survey of document examiners
IV. Instrument selection
V. Analysis of specific sequences
VI. Summary of findings

3.1. Review of the literature

We began our research by surveying the available literature. Briefly, we found references to line crossing problems as far back as 1906, where Ames may have been the first examiner to state that "To the inexperienced observer the blackest line will always appear to be on top briefly mentions pencil sequences. Godwin's 1963 paper presents a wealth of penetrating insights, and his 1982 update is the first mention of coaxial bright field illumination, which he correctly calls "specular." (In that paper he also provides an excellent description of an improvised specular illumination setup that can be easily used with any stereo microscope.) Ellen[7] devotes several pages to discussions of liquid ink, ball-point pen, wax crayon and typewriting. Most recently, Poulin[8] presents an excellent summary of the literature and a discussion of techniques. He also provides a useful table for a quick reference to analytical procedures.

Some of the articles discussed lifting techniques and other destructive methods which were not considered in our research. Other approaches such as use of the ESDA, infrared luminescence, and the video spectral scanner are reported to be useful, but were not evaluated in our research.

In the literature, the universally recommended instrument for document examination is the stereo microscope: the compound microscope is rarely mentioned as a useful tool. Earlier scanning electron microscopical studies did not discuss newer instrumentation such as the low vacuum (environmental) or field emission SEMs, but two important papers must be acknowledged. Waeschle's comprehensive 1979 paper established the foundation for all subsequent SEM studies, and Blueschke and Lacis's very recent studies of ball point ink/cloth ribbon typewriting do much to update current knowledge. Finally, the literature was found to be lacking in research of crossovers that involved laser toner applications coupled with ink, which is probably the most common sequence combination en.countered today.

3.2. Test sample construction

We constructed test samples of the following line sequence problems:

1. pencil and pencil,
2. ink and ink using the same color,
3. ink and ink using two colors,

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Quest. No.	Nature of Crossover	Number Correct (of 13)	Percent Correct	Confidence Level (Mean)
1	Pencil over pencil	7	54	1.18
2	Black ink over black ink	8	62	1.45
3	Blue ink over red ink	7	54	1.54
4	Laser print over ink	12	92	2.54
5	Ink over laser print	10	77	2.54
6	Ink over laser print	10	77	2.18
7	Cloth type over ink	12	92	2.73
8	Ink over carbon type	8	62	2.68
9	Carbon type over laser print	12	92	2.68
10	Laser print over carbon type	8	62	2.77

Table 1. Confidence levels of participating document examiners

4. ink and laser print,
5. ink and cloth typewriter ribbon,
6. ink and carbon typewriter ribbon,
7. typing and laser print.

These samples were used as subjects in evaluating various imaging methods. Towards the end of our research, we also examined rubber stamp and ink jet printing.

We limited our research to a single substrate, a good quality uncoated laser printing paper. Limited testing provided similar results with higher quality bond papers with cotton contents of 25 and 100 percent. Coated papers have a very different look under the microscope and were not included in our tests, although they may be included in future studies.

3.3. Results of survey of document examiners

We felt that it would prove valuable to compare the results of our research with those obtained from professional document examiners using the instrumentation they had on hand. We wanted to know what procedures and instrumentation they commonly used to approach these problems and whether more conclusive results could be obtained with analytical equipment not usually found in smaller laboratories.

The document examiners were asked to evaluate ten sequence problems, provide an opinion, and define the methods applied in evaluation. They were told to provide an opinion on all of the test problems, even if in an actual case their opinion would be inconclusive, or preliminary to seeking the assistance of another laboratory for further evaluation of the evidence. As background information the document examiners also completed a survey about their practice and experience, with emphasis on sequence of writing problems.

We sent out 50 questionnaires and received 13 replies for a 26% rate of return. We were pleased with this response, especially since evaluation of the samples entailed a fair amount of work. While 13 replies do not constitute a large body of data, several trends did emerge from which we can derive a limited number of conclusions.

The participating document examiners were from both private and government laboratories, and their experience ranged from thirteen to forty-seven years. Annual case loads ranged from eighty-seven to three hundred. The most frequent sequence problem encountered was ink and a mechanical impression; the second most common was ink and ink. The examiners stated that sequence problems constituted only a small percentage of their work, averaging two to twelve evaluations per year.

Table 1 lists the numbers that were correct, the percentage correct and the level of confidence in the opinions reached by the participating examiners. Confidence levels of one, two and three indicate low, moderate and high levels of confidence respectively.

The survey revealed that pencil/pencil problems are very rare (see Ellen); none of the respondents reported any of these cases.

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Ink over ink problems are frequent, but remain among the most difficult to solve with any method or instrument. The scores are consistent with that low degree of solvability.

Crossovers involving ink and mechanical impressions were the most common problems reported, and the generally higher scores reflect both the participants' greater experience and the fact that these problems are often more easily solved.

We were especially impressed with the very high scores for question 7, cloth type over ink. In our research, this proved to be one of the more difficult to sequence (an absorbing/absorbing combination).

The lower scores for questions 8 and 10 reflect problems in instrument availability. Both are most easily sequenced with the compound microscope and coaxial bright field illumination, equipment not generally available in most small private laboratories.

The levels of confidence expressed correspond to a certain degree with the difficulty of interpretation presented by the test examples. Questions 1, 2 and 3 exhibit low scores combined with low levels of confidence, whereas questions 4, 5, 6, 7 and 9 show good scores combined with high levels of confidence. These are appropriate . However, questions 8 and 10 showed only fair scores combined with inappropriately high levels of confidence.

3.4. Instrument selection

There are many ways to magnify images and each instrument, from the simplest to the most advanced, has its unique capabilities and weaknesses.

The ideal investigative instrument should be:

1. Definitive. It should give clear, definitive, verifiable answers with no ambiguity and should not present false positives.
2. Non-destructive. The ideal examination method should not alter, damage or destroy the questioned document.
3. Cost effective. It should be the least expensive method available that provides definitive answers .

We specifically evaluated the stereo microscope, which is the long standing instrument of choice for document examiners, and compared its capabilities and limitations with the compound microscope, with various illumination methods, and with the scanning electron microscope, using a variety of imaging modalities and specimen preparation techniques.

Two other magnifying instruments were briefly considered: the hand lens, and the photo macroscope or simple microscope.

3.4.1 Hand lens

This useful, inexpensive instrument is part of virtually every document examiner's tool kit. While it is especially practical for performing an initial survey of a whole document (and is easily portable) it has only limited use in sequence analysis. Its weaknesses include low magnifying power, short working distance at higher magnifications and limited accessories. It is also ill-suited for photography. Even well corrected optics such as the Hastings triplet simply don't magnify enough to be definitive in line sequence situations.

3.4.2 Photomacroscope, or simple microscope (camera, bellows and macro lens)

This is essentially a conventional camera with a bellows which increases the magnification by means of a longer lens-to-film plane distance. It differs from the compound microscope in that all the magnification comes from the objective; there is no ocular to further magnify the image. It can produce high quality photographic documentation of whatever conditions may be observed. A fairly wide variety of accessories are available including specially optimized objectives for various magnifications, half silvered mirrors for coaxial bright field illumination, Lieberkuhn mirrors and ring lights for dark field illumination and specimen stands for transillumination. Setups can be adapted to many different formats such as a 35 mm setup for slides and negatives and a 4" x 5" camera for Polaroid instant prints and negatives whenever great enlargement dictates the use of large format. There are two weaknesses in this system:

1. This setup is limited in magnification to about 20 times, and the higher the magnification, the more difficult it is to control the photography.
2. This setup is awkward to use and ill-suited for routine examination as it lacks the bright, wide fields and binocular vision users of the stereo microscope are accustomed to.

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Although this instrument might be useful in documenting observed phenomena, it is not suitable for routine examination.

3.4.3 Stereomicroscope

Document examiners consider the stereo microscope an absolutely essential piece of equipment. It permits examination of a document at a variety of magnifications and does not invert the image as does the compound microscope. Many accessories are available, including cameras and illumination devices. Available magnifications range from 5-10 X and extend to about 60X. Stereomicroscopes are true compound microscopes in that they utilize both an objective, which produces the primary image, and an ocular, which gives additional magnification. (For purposes of this paper, the term compound microscope will refer to the traditional compound microscope, not the stereo microscope.)

While many questioned sequences are decipherable with this instrument, we found the stereomicroscope less than ideal in some cases for the following reasons :

1. Inadequate magnification. This was a problem in some absorbing over coating sequences in which the definitive characteristics were seen only at high magnification on the compound light microscope.

2. Inadequate resolution. The resolution of zoom stereomicroscopes does not increase significantly with increases in magnification.

3 Inappropriate illumination methods as standard accessories. Specifically, coaxial bright field illumination [CBF] is not generally available. However, ring lights provide dark field coaxial illumination and are useful for lower magnifications. An adequate version of CBF can also be easily and inexpensively constructed (see Godown 1982).

4. Excessive depth of field. This is a result of the lower numerical aperture of the stereo microscope.

2.4.4 Compound microscope

The compound microscope provides magnification in two stages. The specimen is first magnified by the objective; the resulting primary image is then further magnified by the ocular, or eyepiece. This secondary image is focused either on the eye of the microscopist or the film plane of the camera. Typically, available magnifications start at about 40 X and extend to 1000 X or so. It is capable of considerably better resolution and higher magnifications than the stereo microscope, and the shallow depth of field at higher magnifications can actually help elucidate the sequence present in many cases. When properly configured for reflected light microscopy and photomicrography, the compound microscope can be very helpful in deciphering sequence of writing problems.

The instrument we found most useful is the reflected light microscope with coaxial bright field illumination. This configuration is most commonly used in metallurgical microscopy where it is used to examine the crystal structure of alloys and fracture surfaces.

Properly configured, a reflected light microscope consists of the following:

1. A set of objectives that are optically designed for reflected light microscopy (usually corrected for 180 mm tube length) and for use without a cover slip. For document examination, the most useful are the 5 X, 10 X, 20 X and occasionally the 40 X objectives.

2. A coaxial reflected light illumination device. This consists of a centerable lamp assembly with both field and aperture diaphragms and a half silvered mirror to reflect light down through the objective.

Contemporary microscope design incorporates "infinity corrected" optics so that there is no need for separate objectives for reflected light microscopy. These highly modular systems are also easier to use than traditional microscopes.

4. Illuminating methods for light microscopy

4.1 Reflected light

In oblique illumination, the light is directed to the specimen at an oblique angle. The resulting shadows emphasize the specimen's texture. Light directed at an extremely oblique angle is called raking light.

In reflected coaxial bright field (CBF) illumination, the light is directed to the specimen through the microscope objective itself (the microscope objective becomes the condenser) by means of a half reflecting-half transmitting mirror. No shadowing occurs (as in oblique illumination), but irregularities in surface specular reflectivity are enhanced.

In reflected dark field illumination, the light is directed to the specimen along the outer edge of the microscope objective. The condenser or mirror is just outside of the objective axis. This method is intermediate between oblique and coaxial bright field illumination and provides senuspecular reflections.

Ring light is a form of dark field illumination. It is popular in document examination because it provides many of the advantages of coaxial bright field illumination, without the disadvantages of high cost and lack of availability for many stereo microscopes. Ring light guides are available as accessories for many fiber optic illuminators.

In microscopy literature one often encounters the terms epi (Greek above) for reflected light and dia (Greek) or trans (Latin through) for transmitted light microscopy.

4.2 The scanning electron microscope (SEM)

The SEM is a very useful tool for imaging surfaces of materials. The main advantage over the light microscope is the increased depth of field which allows one to examine rough surfaces while maintaining focus on all features. This is especially useful when examining paper surfaces, which are composed of stacked and pressed fibers.

In the SEM, a beam of electrons is focused onto an electrically conductive sample by means of magnetic lenses, and rastered across the area of interest. The SEM image is produced either by the detection of electrons that are ejected from the sample material (secondary electron image or SEI) or electrons that rebound from the sample surface (backscattered electron image or BSI). Secondary electron imaging is the most commonly used mode, but backscattered electron imaging often provides critical information about chemical differences (which also affect the image characteristics). Most of our efforts concentrated on the use of secondary electron imaging for the examination of writing sequences.

For samples that are electrically non-conductive, (e.g. paper, polymer films, glass) a thin layer of a conductive material must be applied to the sample surface in order to avoid an image distorting phenomenon known as charging. Typical materials used for coating the samples include gold, carbon, gold/palladium and chromium. These procedures are commonly used for routine SEM examination, but represent serious problems when dealing with documents. To examine a sequence with the SEM, a small portion, including the crossover, is cut from the document. That specimen is adhered to a stub with electrically conductive tape; the whole specimen is then sputter coated.

In recent years the SEM suppliers have introduced two specialized types of SEMs which can be used to image non-conductive sample surfaces without the need for the application of conductive coatings. This is especially important if the document cannot be altered in any way. One SEM type is known as the environmental or low vacuum, or LV SEM. The main disadvantage of this type is that the system only uses backscattered electron imaging. The second type is known as a field emission, or FE SEM. To examine non-conductive surfaces, the electron beam is operated at low voltages (e.g. 0.5 -2 KV) to minimize the charging effects while maintaining high quality imaging capabilities. If the document examiner wants to use an SEM, we highly recommend seeking out a laboratory equipped with a field emission SEM.

The SEM should have at least three features that we consider necessary for document examination:

1. The sample stage should have tilt capability of 50 degrees or more along with 360 degree rotation.
2. The SEM should be capable of long working distances such as 35-48 mm in order to keep most of the sample in focus when working at very high tilt angles.
3. The sample chamber should be capable of holding up to 8” diameter samples in case the document can only be gently folded and not cut into smaller pieces.

As we will show later, the tilt and rotation capabilities are crucial for proper viewing of the various crossovers.

The SEM for document examination should be used as a complimentary tool to the light microscope. Although many crossover questions can be answered with the light microscope, the SEM can provide confirmatory evidence which is becoming more important in legal cases. The high resolution

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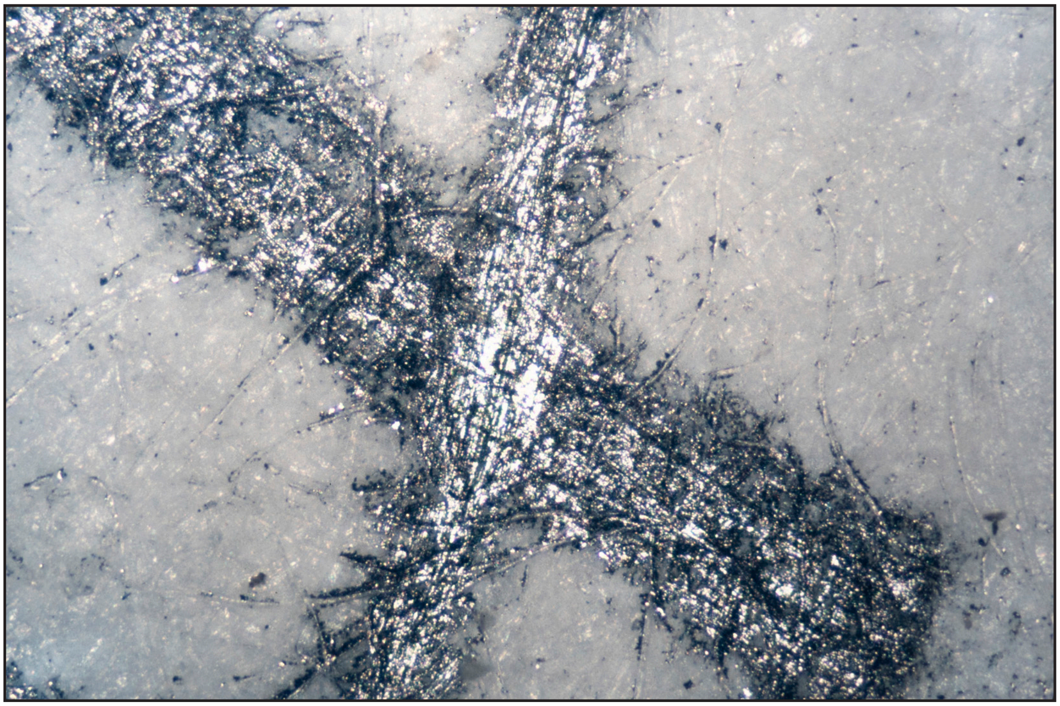

Figure 1. Pencil A over pencil B. Coaxial bright field illumination; 50X.

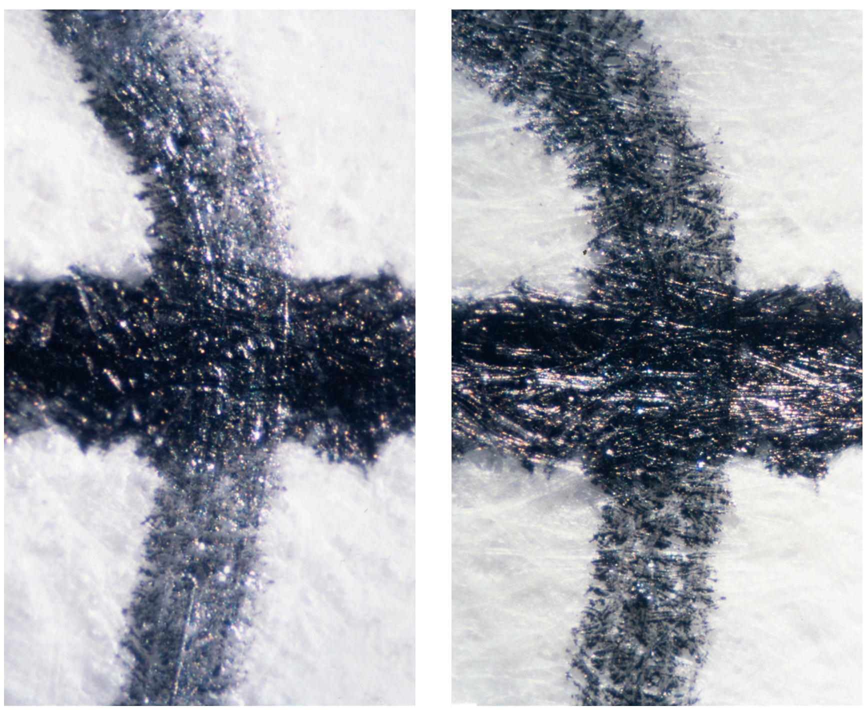

Figure 2. Pencil A over pencil B. (2a) Oblique light parallel to axis of top line. (2b) Oblique light perpendicular to axis of top line.

and depth of field capabilities are useful in some cases where light microscopy is inconclusive or for confirming preliminary results, especially if higher magnifications are required. In some situations, the SEM will be the only method capable of solving a line sequence question.

5. Analysis of specific sequences

5.1 A. Coating/coating sequences

Pencil over pencil

When a pencil is drawn across a piece of paper, a certain amount of the graphite (and other materials) are deposited as a somewhat thick, crumbly paste onto the paper fibers. Any irregularities in the pencil lead are transferred to the paper deposit as a series of scratches or striations that parallel the writing track. The direction of writing can be clearly seen as the graphite forms deposits on the leading edges of the paper fibers.

The key characteristic here is that the top pencil mark is continuous over the bottom one and that this continuity is characterized by the series of striations that the pencil leaves as it deposits its material. These can be seen with the stereo microscope at high magnification, but are best seen with the compound microscope at 50 to 100 times magnification. Coaxial bright field illumination shows the striations clearly in all orientations (Figure 1). Oblique illumination also shows the striations clearly, but the specimen striations must be oriented perpendicular to the light source, (Figure 2a); when the striations are parallel to the light source they disappear (Figure 2b), so the specimen should be rotated while viewing through the microscope. The SEM shows the sequence even more clearly (Figure 3).

When the pencil writing is light, the graphite particles are scattered among the paper fibers such that there is an insufficient base deposit of graphite for the characteristic striations to appear. In these cases the reflected light microscope will show inconclusive results.

5.1.2 Carbon typewriter ribbon over laser printing

Carbon typewritten letters are formed by a thin film of carbon paste deposited onto the paper by impact. The letters are a deep black and sharply delineated. With the reflected light microscope with CBF, the surface of the carbon type is seen as slightly mottled.

Laser printing also consists of carbon deposits, but they adhere to the paper through heat fusion. Microscopically, the character is observed as a mound of toner consisting of a series of peaks and shallow pits. The hard brittle surface has a soft sheen and in the adjacent areas one sees bits of fused carbon dust surrounding the characters. Deposits made by different laser printers and brands of toner may appear slightly different, but all consist of a low mound of fused toner.

When carbon type covers laser printing, several defining characteristics are present. The carbon type is continuous over the discontinuous laser print. That continuity is apparent both in texture (Figure 4a) and planes of focus (Figure 4b). The laser print substrate creates a disturbance for the carbon type which is shown by the slight dip where the laser print is under the carbon type. The impact of the carbon type also cracks the surface of the laser print. The crack lines usually appear between pits in the brittle surface of the laser print. These cracks can be observed with the stereo microscope at high magnification; however, they are more easily seen with the reflected light microscope with bright field coaxial illumination at higher magnifications of 100-200 X (Figure 5). Oblique illumination is less useful with this highly reflective surface, but bright field coaxial and oblique illumination can be effectively combined.

The SEM shows both the cracking and the deposits very dramatically (Figure 6). While definitive conclusions can be achieved with the light microscope, documentation with the SEM can add another level of certainty and is more dramatically demonstrable.

5.1.3 Laser print over carbon type

The principle of "continuous top over discontinuous bottom" can be evoked in deciphering laser print/carbon type sequences (Figure 7). Laser print over carbon type has a very different look under the microscope. The sequence is apparent, not because one sees the laser print as a distinct layer over the carbon type, but because one sees the effects of the laser. When the laser encounters a carbon type deposit, the intense heat of the fusing process bums into it violently, creating a turgid landscape of sharp peaks and valleys. Of course, no cracking occurs in this combination.

While this combination can be seen with the stereomicroscope, the compound light microscope

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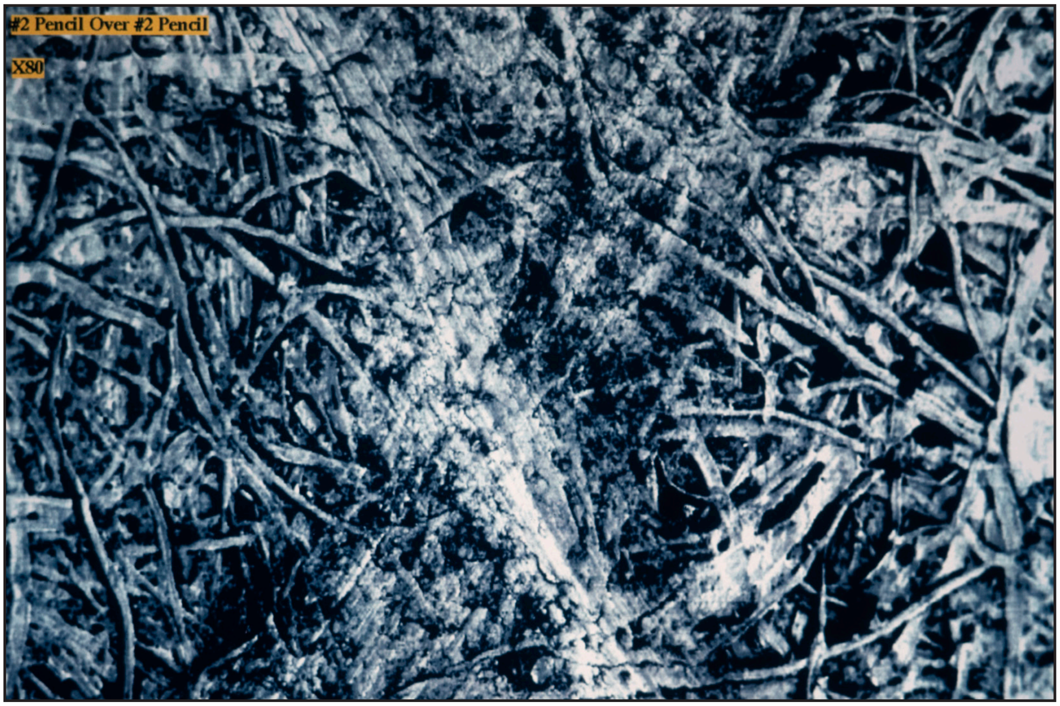

Figure 3. Pencil A over pencil B. Scanning electron microscope, 80X.

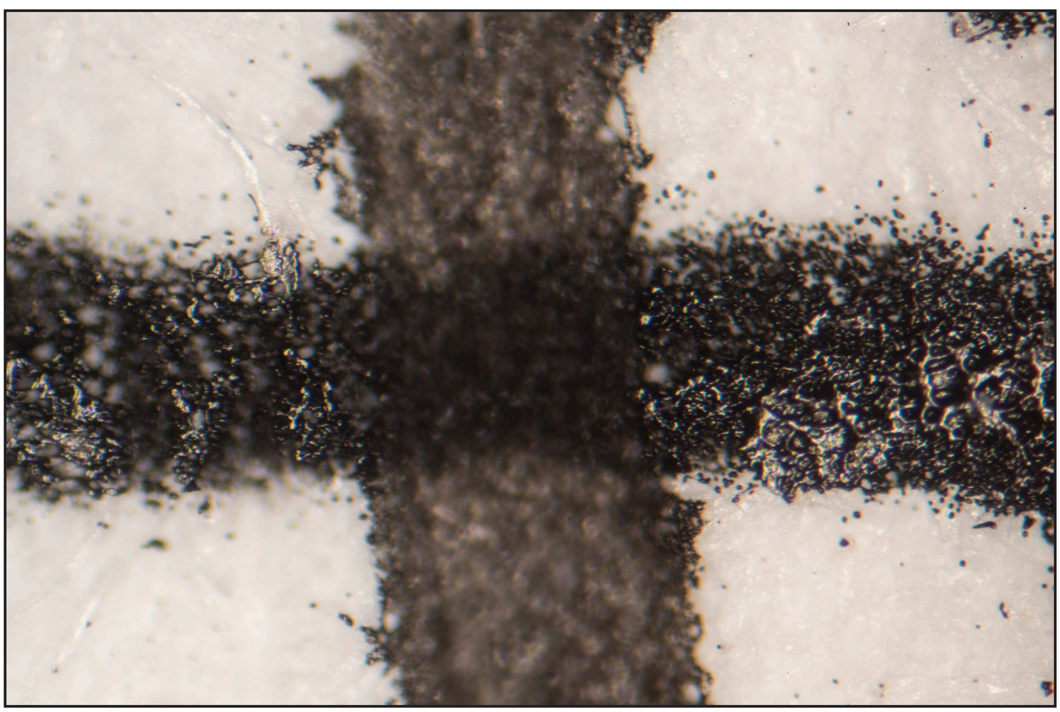

Figure 4a. Carbon typewriter over laser print. Camera focus is on laser print , which is discontinuous. 100X.

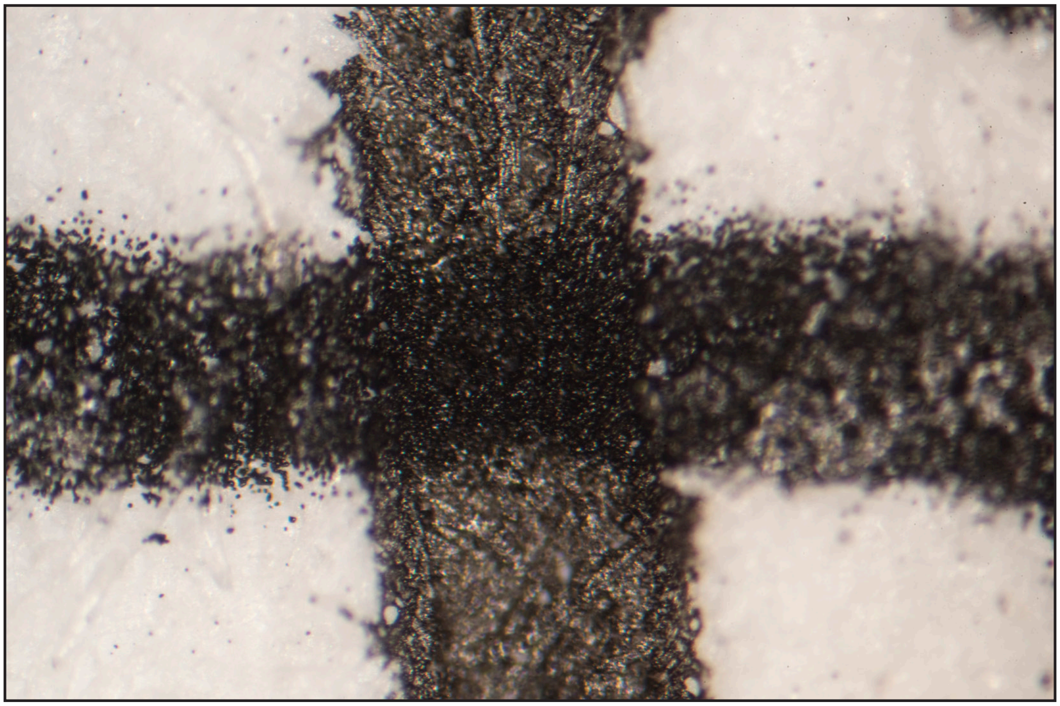

Figure 4b. Carbon typewriter over laser print. Camera focus is on carbon type, which is continuous. Note change in texture at crossover point; carbon type molds to shape of laser print as it does to paper fibers when over· paper. 100X.

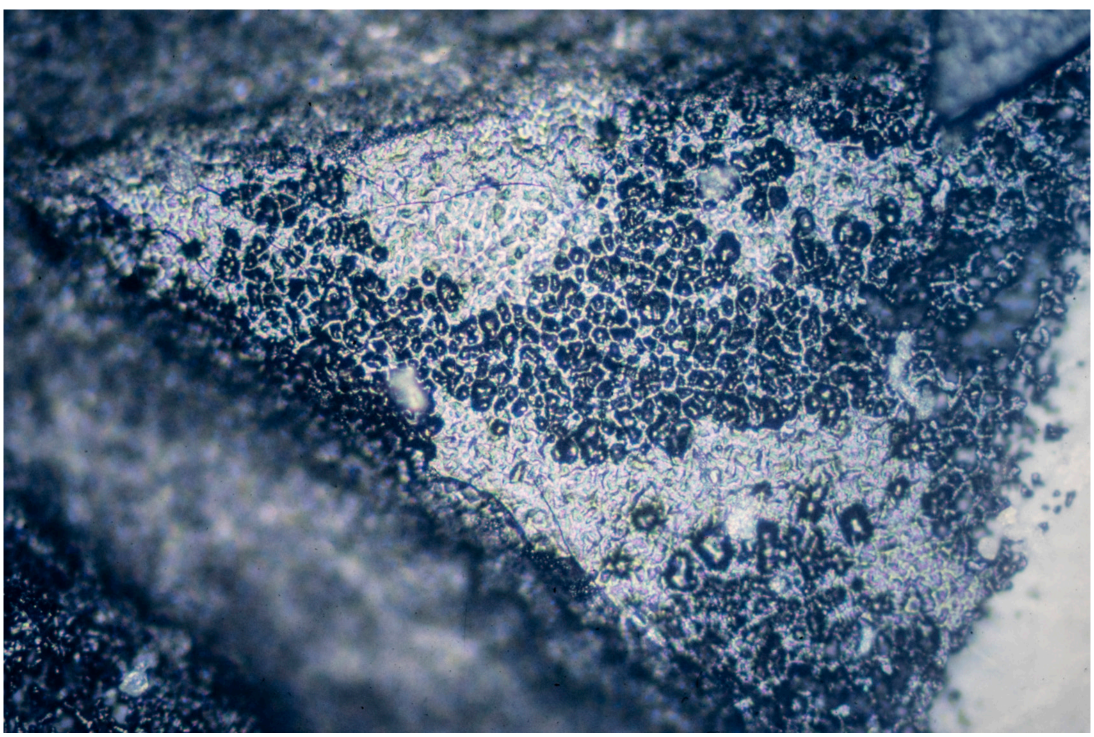

Figure 5. Carbon type over lazer print. Coaxial right field illumination 400X. Note cracking over crossover area.

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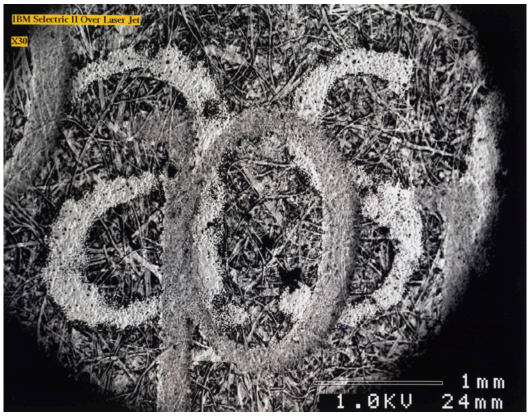

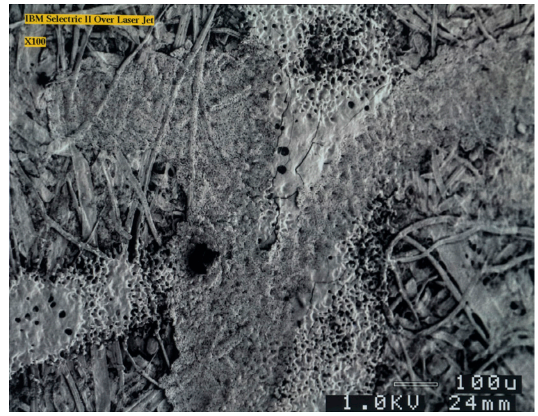

Figure 6a and 6b.. Carbon type over laser print, SEM. Note continuity of carbon type in lower magnification views; high magnification view 6c shows cracked laser print, as well as the carbon paste distinctly over the laser print.

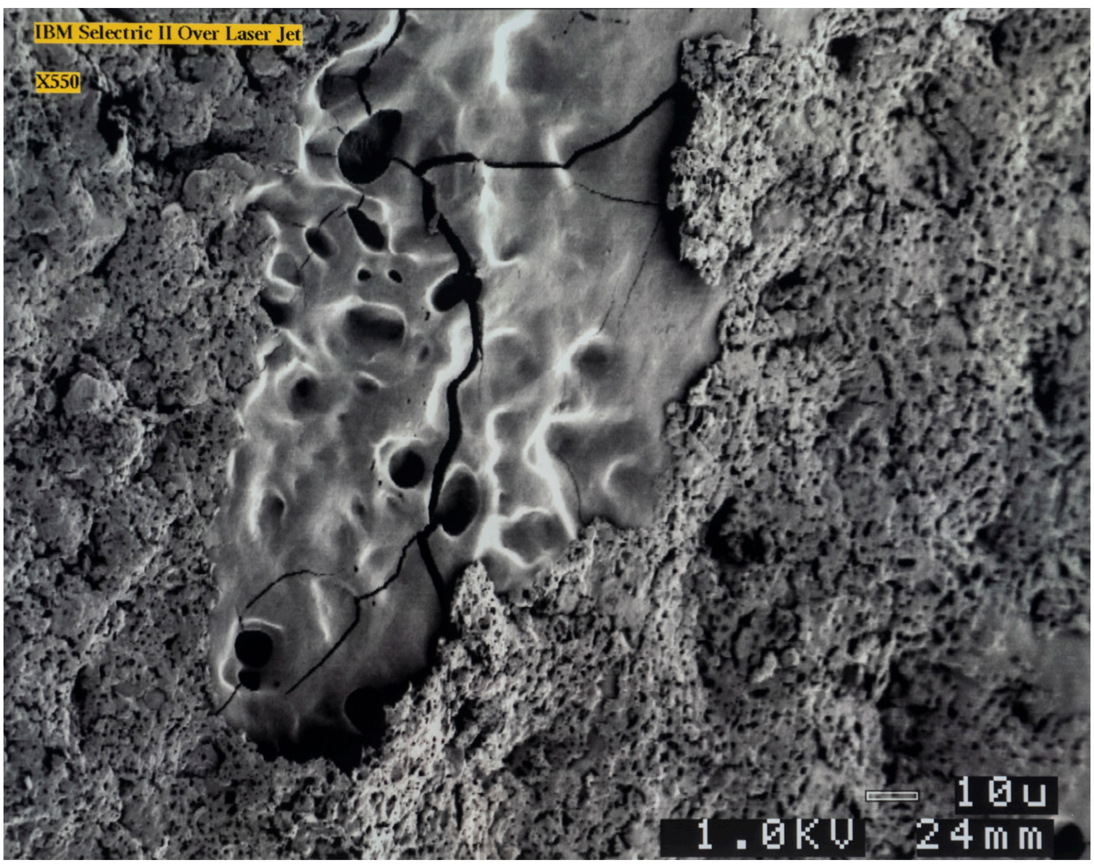

Figure 6c. Carbon type over laser print, SEM. Note continuity of carbon type in lower magnification views; high magnification view shows cracked laser print, as well as the carbon paste distinctly over the laser print.

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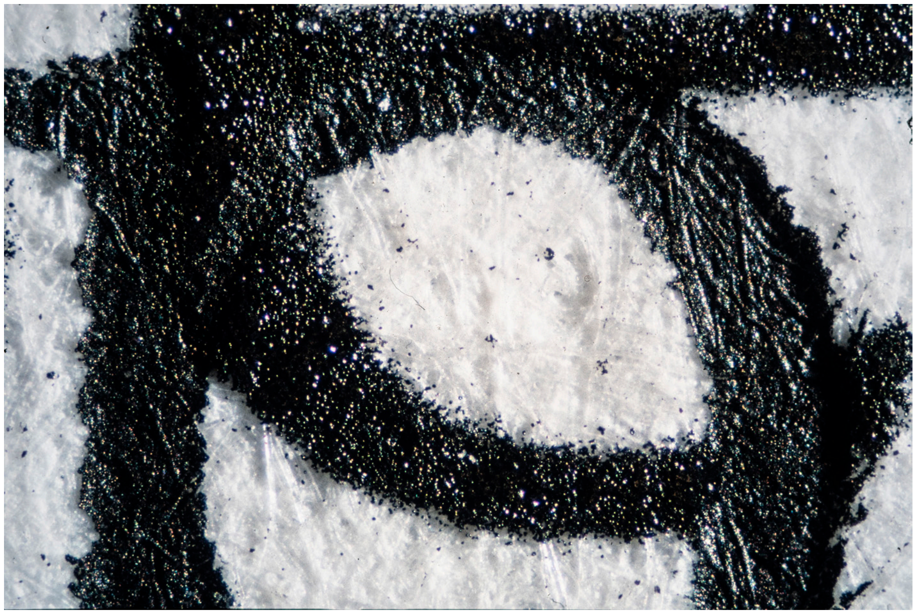

Figure 7. Carbon type over laser print. Coaxial bright field plus oblique illumination. SOX.

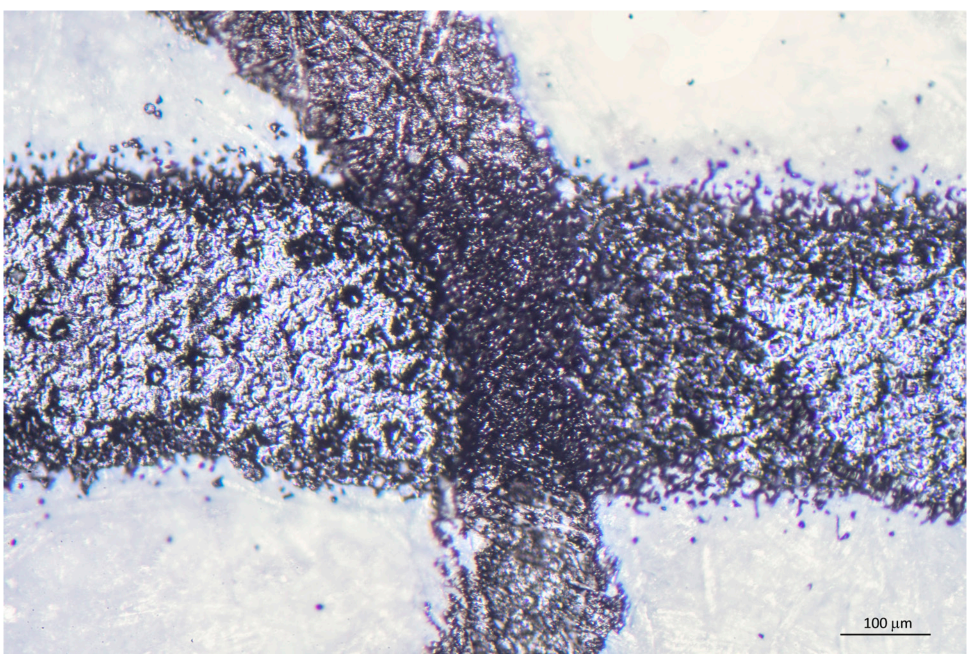

Figure 8. Laser print over carbon type. 100X. Note distinct change in texture as laser print melts carbon type. Note also slight discontinuity in focus of carbon type.

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with coaxial bright field (CBF) illumination reveals the texture in considerably greater detail (Figure 8). The process is best visualized by inspecting the SEM view (Figure 9). Note the violence of the laser bum on the soft, paste-like typewriter deposit.

5.2 Absorbing/coating sequences

5.2.1 Ink over carbon type and laser print

All inks consist of a colored pigment or dye in a liquid medium which is absorbed by the paper fibers. Ball point and other roller pens create a somewhat semi-circular trough (when used with sufficient pressure), at the bottom of which the ink covers the fibers. Fountain pens, steel nib pens and felt tip pens are usually used with less pressure, so that the trough is shallow or absent; however, the inks are much wetter (less viscous) and tend to produce a wider line as they bleed further to the sides.

When seen with the reflected light microscope under moderate magnification (about 100X), the ink is seen to soak into the fibers, dying them. Scattered blobs of the more viscous inks are sometimes seen on the leading edges of the fibers in sufficient quantity to determine the direction of the writing.

Sequences involving absorbent ink in combination with carbon type, laser print or other coating substrate are generally clearly decipherable, but false negatives are possible when the ink deposit is very light or old and dried. When ink crosses over these substrates, a very thin film of ink is deposited onto the type at the crossover point. The ink pools in the lower crevices and depressions of the substrate and is highly reflective with specular lighting. It is seen as a discrete band with a different sheen and usually a different color from the carbon or toner which has not been written over. This is best seen with the compound microscope, providing both higher magnification and resolution, but the stereo microscope can also be used. Bright field coaxial illumination is most effective, although excellent results can be obtained with ring light, a form of dark field illumination.

5.2.2 Ink over laser print

Ink over laser print is characterized by:

1. the reflective, different colored sheen,
2. pooling of ink in depressions,
3. cracking of the laser print surface in the trough, and
4. the continuous ink trough depth to a discontinuous laser letter (Figure 10).

While the SEM is inappropriate for diagnostic work, it clearly shows the effects of cracking and even pooling (Figure 11).

Not all of these characteristics are easily seen with the stereo microscope. With the higher magnifications obtainable with the compound light microscope (100 - 400X), the cracking of laser print deposits can be clearly seen if the writer used sufficient force. Continuity is better visualized with more shallow depth of field. Most importantly, the pooling of ink in the pits of the laser print are sometimes only visible at higher magnifications. This is especially important when examining older documents.

5.2.3 Laser print over ink

When carbon laser print covers a line of ink, the sequence is also readily decipherable although the evidence present is more subtle. It is precisely the absence of the colored sheen, cracking, or continuity that indicates that the laser

When we study laser print over ink exemplars, we see that the line of laser print is affected by the previous line of ink in two ways:

1. There is a slight depression in the laser print at the crossover point.
2. There is a distinct change in the surface texture of the laser print, clearly seen in both reflected light microscopy (Figure 12) and the SEM view (Figure 13).

This textural difference must be carefully distinguished from the normal variations in texture common to laser printing; one must exclude the cracking and pooling of ink before arriving at this conclusion. One must also be especially careful about false negatives. Inks that have dried for a long time

Figure 9a. Laser print over carbon type. 22X. Sequence ambiguous at this magnification, but note textural change at crossover points.

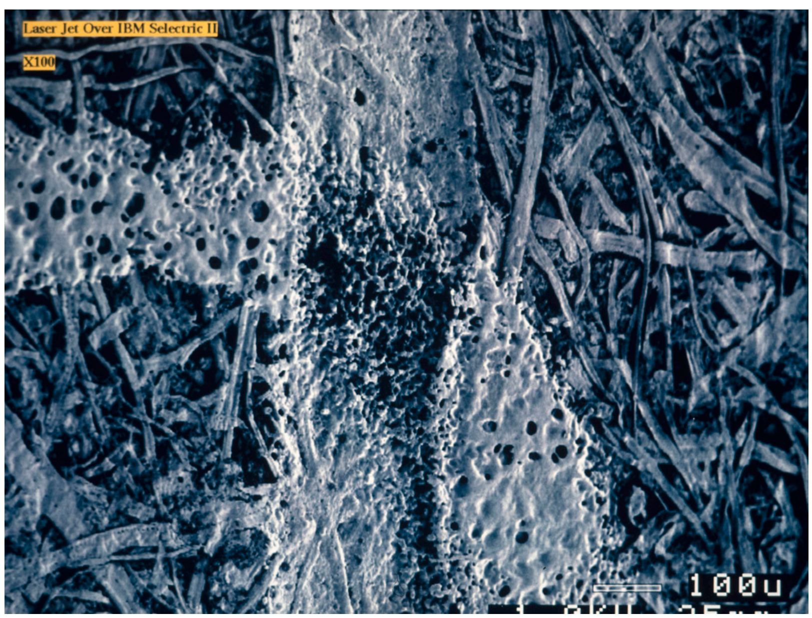

Figure 9b. Laser print over carbon type. 100X. Laser print creates distinctive turgid “Bryce Canyon” landscape as it burns into carbon type paste.

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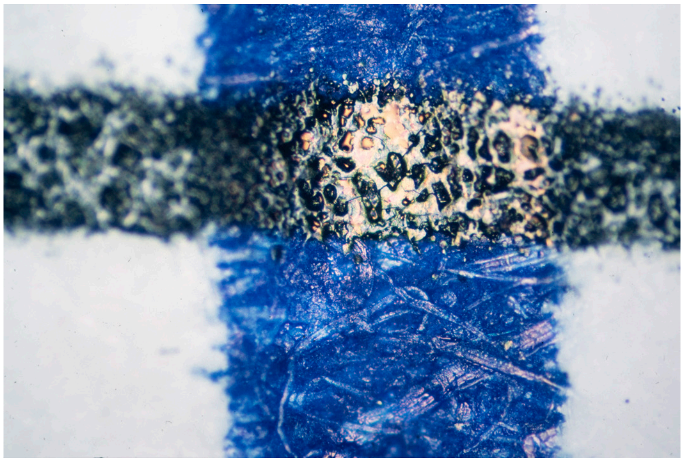

Figure 10a. Ballpoint ink over laser print. l00X. Note specular sheen with coaxial bright field illumination .

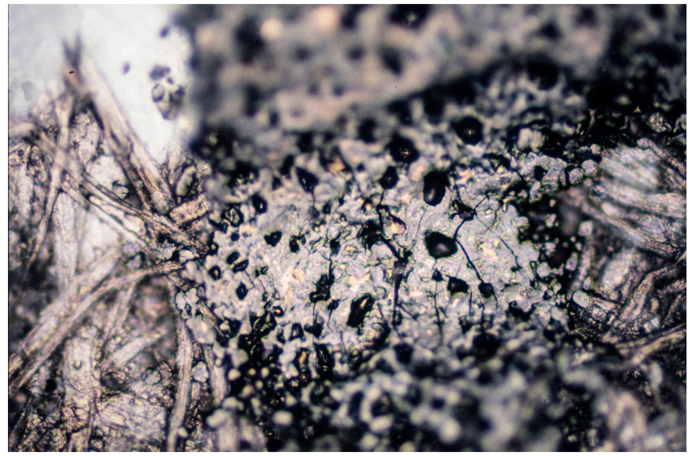

Figure 10b. Ballpoint ink over laser print. 400X. Cracks seen in laser print surface; ink pools in depressions.

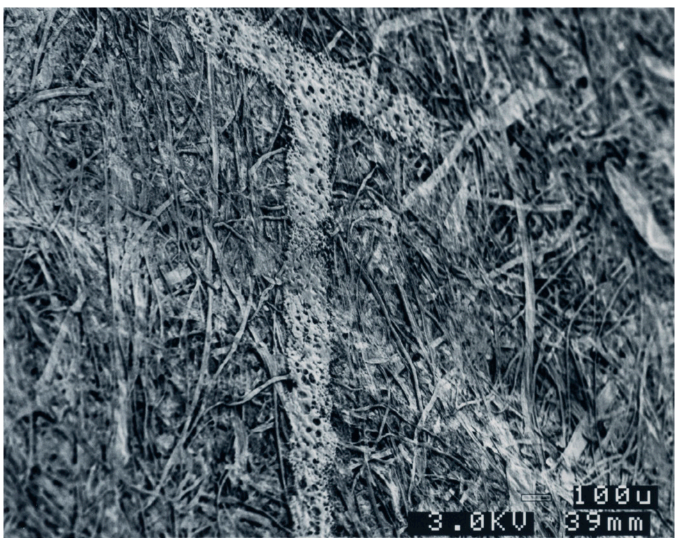

Figure lla. Ballpoint ink over laser print; SEM with 50° tilt. 23 X. Note distortion of character caused by high tilt angle. Crossover poorly seen.

Figure llb. Ballpoint ink over laser print. SEM with 50° tilt. 700X. At crossover. Note cracks and pooled ink.

on older documents sometimes require inspection at higher magnifications; only then is the pooling at the bottom of the pits observed.

There is no practical role for the SEM in ink/dry mechanical writing combinations, except as confirmation of reflected light microscopy results. The ink is visualized clearly with the reflected light microscope and less well with the SEM. For the most part, ink simply soaks into the paper fibers. Small deposits may be scattered among the fibers, but they impart little information (although they may indicate direction of writing). Furthermore, SEM is both more expensive and more destructive.

5.2.4 Ink over carbon type

Characteristics of this combination are similar to ink over laser print and are characterized by:

1. the different colored, highly reflective sheen when viewed with specular light,
2. the pooling of ink in the lower crevices,
3. the occasional flaking of the carbon type, and
4. the continuous ink trough over a discontinuous type (Figure 14).

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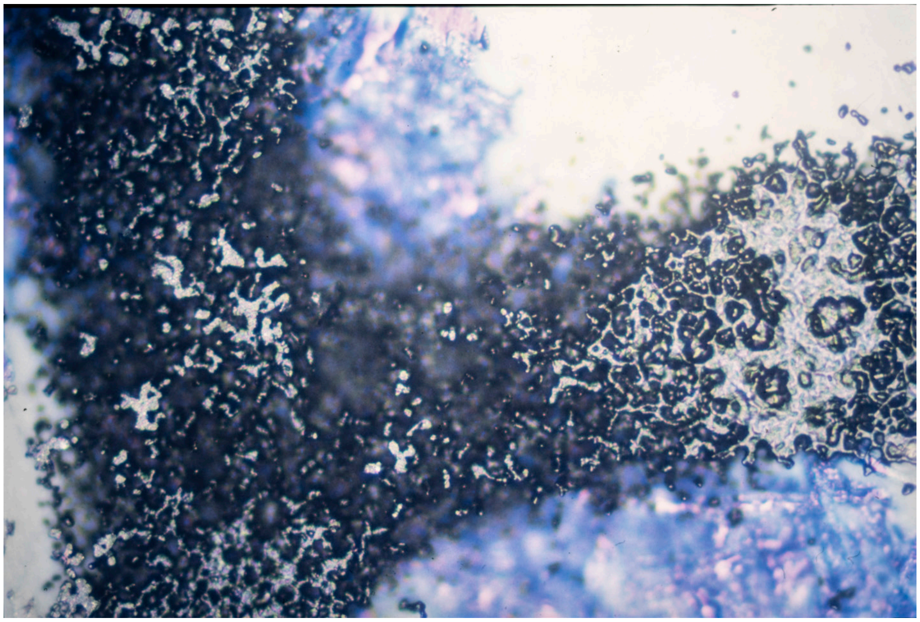

Figure 12. Laser print over ink, CBF illumination.100X. Note textural change as laser print crosses ink line .

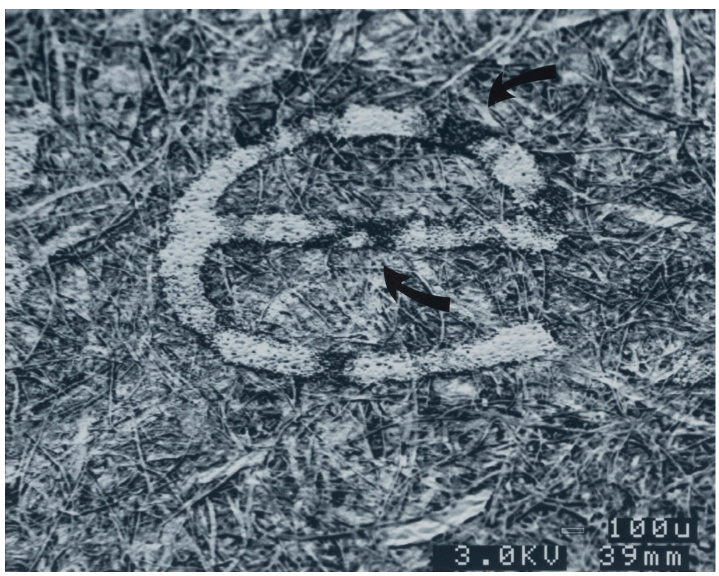

Figure 13. Laser print over ink. SEM, 50° tilt. 3 KV. Overview.

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Figure 14. Ink over carbon type. CBF illumination, 40X. Sheen was clearly seen in color view; note flaking of carbon type at crossover areas.

Carbon type deposits lack the mounds and pits of laser print, but the ink can pool in the shallow crevices present on the surface. Most pens will leave this characteristic specular sheen; in our study, positive results were achieved with a variety of ballpoint pens, rubber stamps, permanent markers, other felt tip pens and ink jet printing.

Flakes of the carbon type can also be scraped off by the tip of the pen as it crosses the typewriting, providing another indication of sequence, especially when the paper under the flaked type is devoid of ink. A word of warning, however: one should not investigate sequence by chipping off a piece of a letter with the expectation that ink under the typed letter signifies that the ink was written first. In our tests we found that the ink can seep through the type deposit, staining the fibers-whether first or last, the result looks the same. Furthermore, this is a destructive technique.

5.2.5 Carbon type over ink

The same conditions as laser print over ink apply here: the absence of ink over carbon type characteristics imply the converse sequence; there is no sheen, no flaking, and the type is continuous over a discontinuous ink line (Figure 15).

5.2.6 Pencil over carbon type or laser print

Pencil behaves like an absorbing material when interacting with coating materials. Pencil over coating materials is characterized by a brilliant sheen (Figure 16) which of course disappears when under coating materials.

5.3. Absorbing/absorbing sequences

5.3.1 Ink over/under cloth typewriter ribbon

We found this combination of two absorbing inks difficult to determine with either the light microscope or the SEM. Because the inks mix, we must rely on morphological changes to the paper caused by the impact of the type. If the type depression is sufficiently deep it may deflect the pen nib or tip slightly, creating a discontinuity (Figures 17). One would want to examine as many crossovers as possible before coming to a conclusion.

Typing over ink is also difficult to assess. The examiner must inspect the type impressions (sometimes almost non-existent) for continuities, pen skips and the like. In cases where both pen and typewriter impressions are light, altering the paper substrate only slightly, the inks are absorbed equally into the paper and leave no discernible record of their sequence of entry.

Figure 15a. Black ink over carbon type. Note sheen.

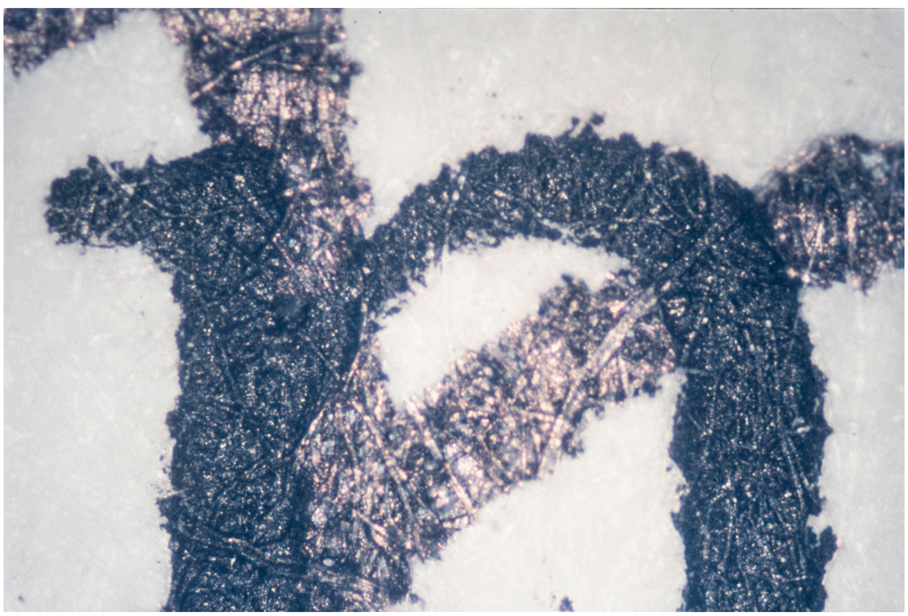

Figure 15b. Carbon type over black ink. Note principle of continuity in a and b.

The stereomicroscope and oblique illumination seem to be quite adequate for this application, although the compound microscope offers improved resolution at the cost of depth of field. Bright field coaxial illumination or ring light are not indicated here. For best contrast use oblique illumination with an intense, small diameter light source (such as a fiber optic illuminator.) Rotate the stage and/or specimen in order to view the crossovers from many angles. It is useful to make photomicrographic prints and study them carefully.

Blueschke and Lacis (1996) have reported success with the low KV SEM and stereo pairs; our own research has been less successful so far.

5.3.2 Ink over/under ink

We agree with our predecessors that absorbent ink over ink combinations are particularly difficult to decipher with any technique or instrumentation. As the inks combine and soak into the fibers they provide

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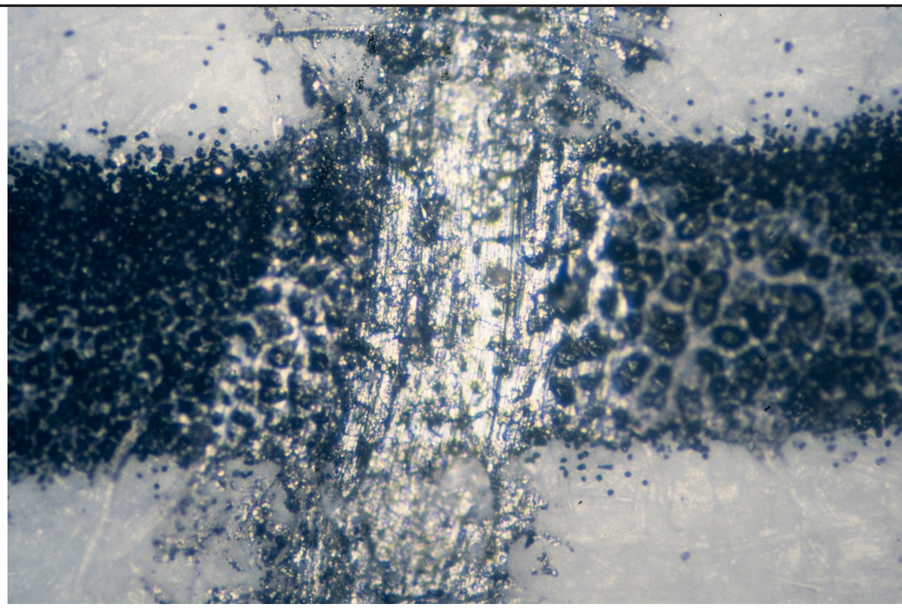

Figure 16a. Pencil over laser print. CBF illumination. 100X.

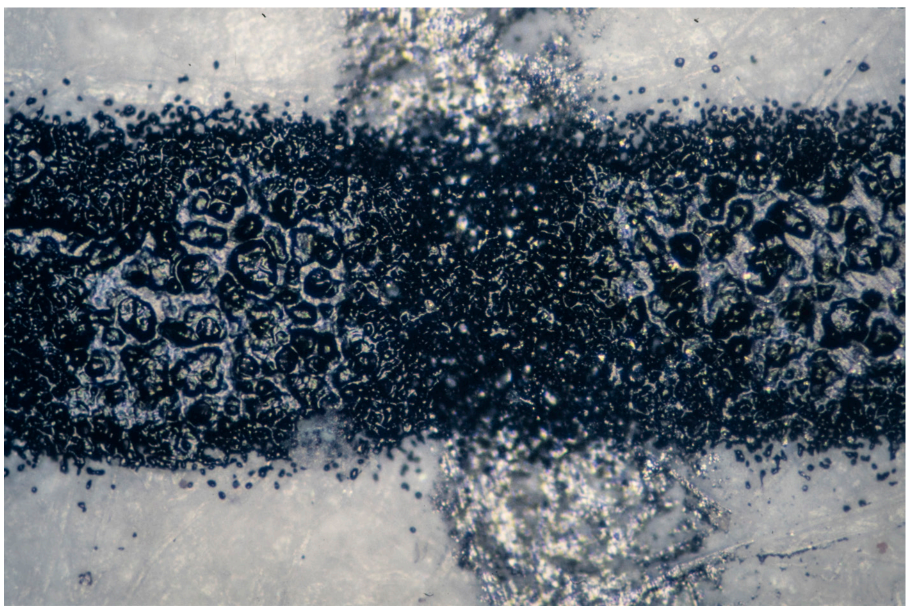

Figure 16b. Laser print over pencil. CBF illumination. I00X. Pencil behaves like an absorbing material in this combination.

very little information to the observer. Different colored inks are no more decipherable than inks of similar color. And the well-known warning bears repeating: if one ink is darker than the other, it always seems as if the darker is on top of the lighter ink; if one of the lines is more forcefully written, it seems to be over the more lightly written line. See Godown and Ellen for further suggestions.

In a few rare occasions, ink or fibers from the first line will be dragged along the axis of the second line; however, this only occurs with pencils and rigid pen tips as ball point mechanisms create much less friction and abrasion.

The most definitive conclusions occur when morphological changes to the paper substrate, the overlapping grooves, can be exploited. In the ideal case, the second line exhibits continuity over a discontinuous first line; this frequently provides an accurate conclusion using the traditional stereo microscope and oblique illumination. Many of the newer methods developed in recent years, and in particular the use of the SEM, exploit this morphological discontinuity as

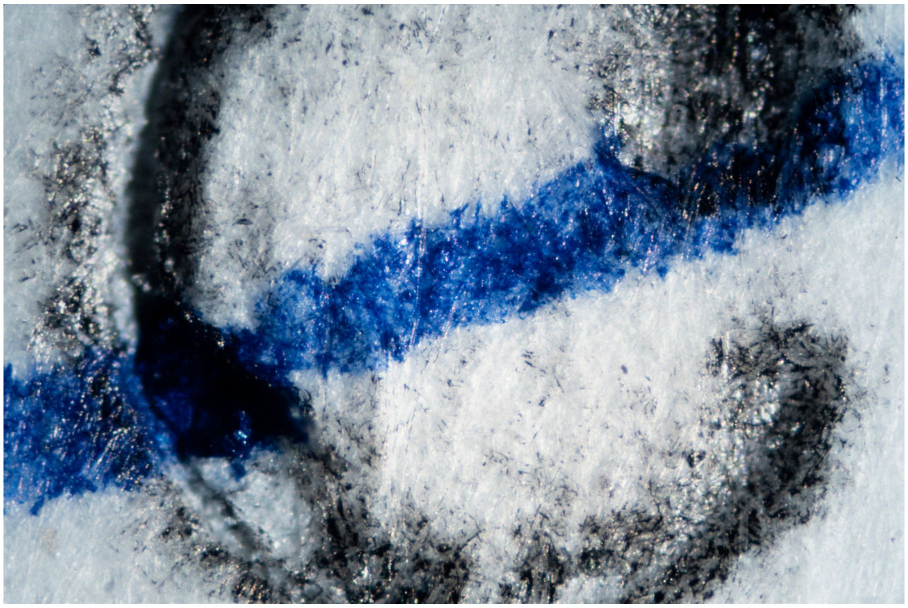

Figure 17a. Ink over cloth typewriter ribbon. 50X. Note discontinuity as tip of pen is deflected.

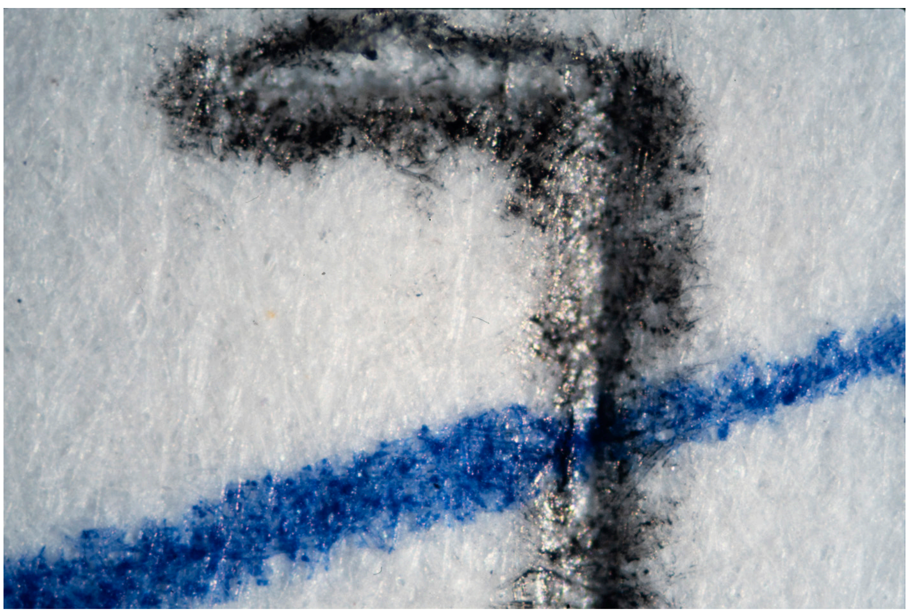

Figure 17b. Ink over cloth typewriter ribbon. 50X. Note discontinuity as tip of pen is deflected.

well. Yet again, a rather serious cautionary note is in order. It always seems as if the pen impression made with more force, the deeper trough, is secondary to the lighter, shallower impression; this ambiguous state of affairs can be clarified using the SEM.

5.3.3 Ink over ink with the SEM

SEM examination of ball point pen ink crossovers is quite difficult because the inks are absorbed by the paper fibers, rendering the ink virtually invisible for SEM imaging. Therefore, one must rely on imaging the troughs produced on the paper surface by the ball as it rolls over, or through, the paper fibers.

The pressure used by the writer will determine how deep the troughs are. Figure 18 illustrates the imaging of several troughs produced by light to heavy pressure on the pen. It is possible to identify the second in the sequence with confidence, even when the

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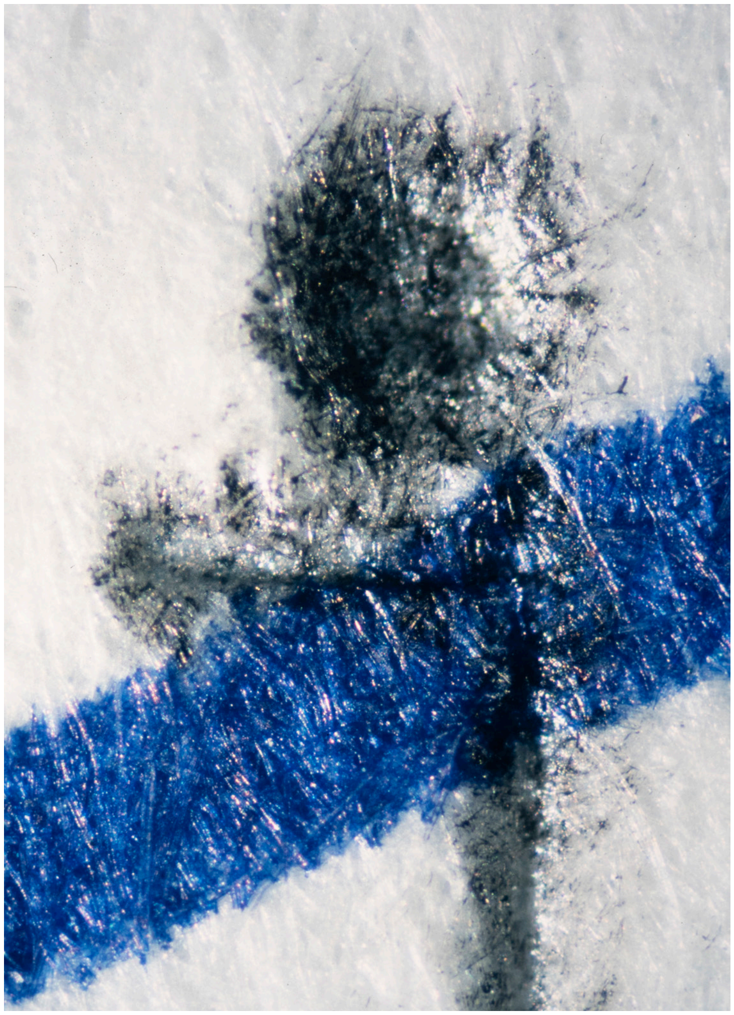

Figure 17c. Cloth typewriter over ink. Note actual continuity of ink line. In an actual case this would be judged as such, but a low level of confidence.

top writing is made with significantly less force than the bottom writing.

At high tilt angles, ideally around 50 degrees, (Figure 19) the troughs are shadowed on one side and bright on the other (analogous to low angle sunlight on a deep narrow depression). The main feature to look for is a discontinuity in the bright rim of one trough verses the other. The presence of a discontinuity in the line means that it was the first line in the sequence. The other line should have a continuously bright rim through the crossover area.

In addition to using high tilt angles, we found that there is only one rotation position that will allow for optimum observation of the trough rims. Finding the rotation position requires that the sample be observed while rotating a full 360 degrees. Figure 20 shows the effects of rotation position.

When ink lines cross at nearly 90 degree angles, the troughs can be seen rather easily. But when the crossovers are at very shallow angles, imaging the troughs becomes much more difficult. Fine adjustments must be made in tilt angles, brightness and contrast settings and rotation, in order to obtain an image which can be used with a high degree of certainty to determine the correct line sequence. Figure 21 shows various crossover angles as viewed under optimized SEM conditions.

6. Summary of findings

The following summary outlines the instruments [9], illumination methods, magnifications and techniques

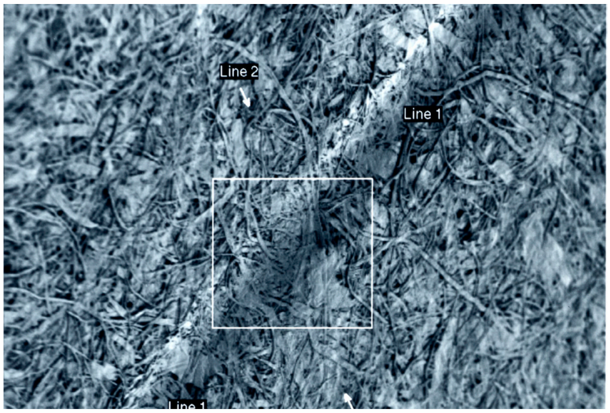

Figure 18a. Ballpoint ink over ballpoint ink. SEM. 50° tilt, 3 KV. 35X. The top line was written with light pressure.

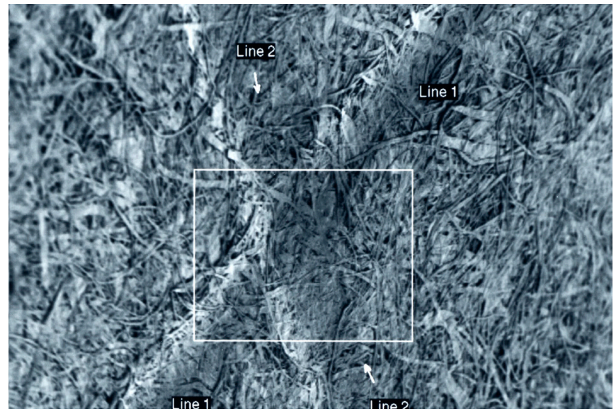

Figure 18b. Ballpoint ink over ballpoint ink. SEM. 50° tilt, 3KV. 35X. The top line was written with medium light pressure.

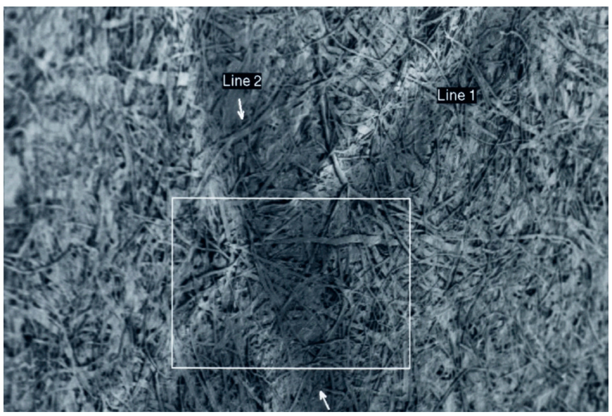

Figure 18c. Ballpoint ink over ballpoint ink. SEM. 50° tilt., 3KV. 35X. The top line was written with medium pressure.

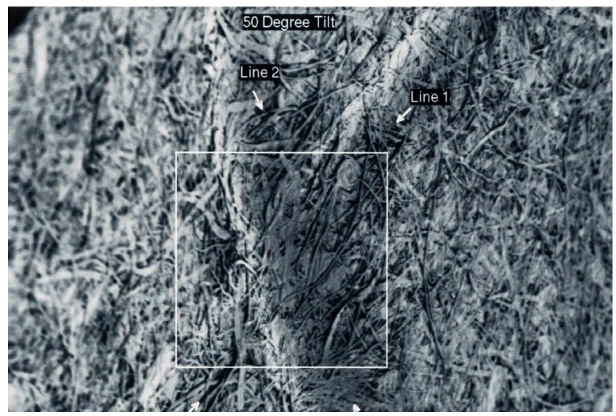

Figure 18d. Ballpoint ink over ballpoint ink. SEM. 50° tilt, 3KV. 35X. The top line was written with heavy pressure.

which provide the most definitive answers to the sequence of writing problems investigated in this study:

(1) The traditional stereo microscope with oblique lighting is useful for deciphering absorbing/absorbing sequences when morphological changes are present, but is inadequate for absorbing/ coating and coating/ coating sequence problems. Coaxial and/or ring lighting as a minimum, are necessary for evaluating these cases.

(2) The compound light microscope with low, medium and high power objectives and reflected bright field coaxial illumination can provide conclusive results in absorbing/coating and coating/coating sequences. Reflected dark field or ring light, though less ideal, are also useful.

(3) Coating/coating sequences can be dramatically demonstrated using the SEM. This instrument is superior when morphological changes have occurred. Ink/ink sequencing questions can often be resolved with the field emission SEM. Secondary electron imaging of gold coated specimens using the field emission SEM provides better contrast and topographical information than back scattered imaging using the low vacuum environmental SEM.

(4) In the absence of positive evidence of ink over a coating material when observed using lower magnification, it is prudent to evaluate the sequence further using the higher magnifications available with a compound microscope.

(5) The caveats well known to document examiners concerning optical illusions (e.g., that the heavier pressured line appears to be on top, or the darker color of ink appears to be on top) are still valid statements. Furthermore, the general statement that, in many cases, the second writing is continuous over a discontinuous first writing is usually valid. In

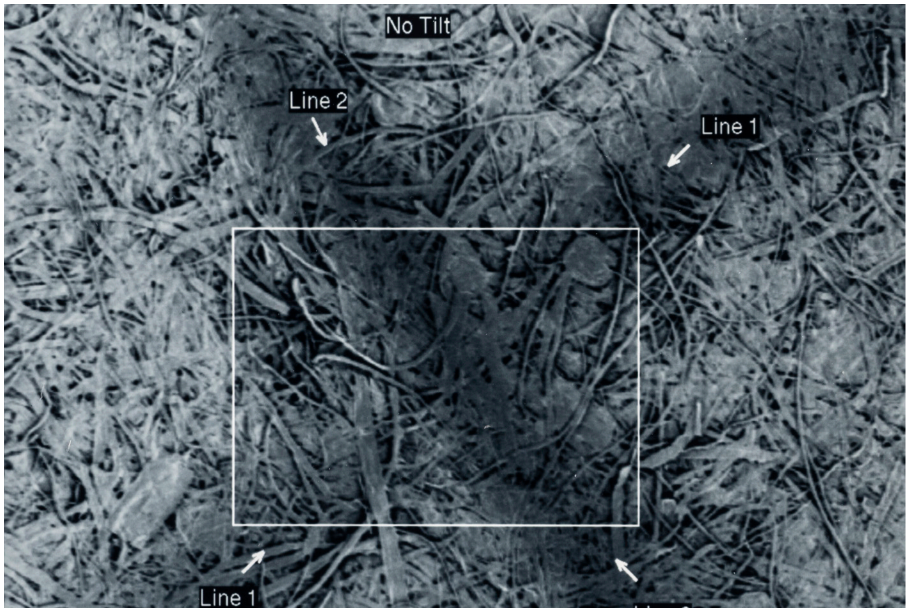

Figure 19a. Ballpoint ink over ink. SEM, 35X. 0° tilt. Note effect of tilt angle on contrast and light and shadow.

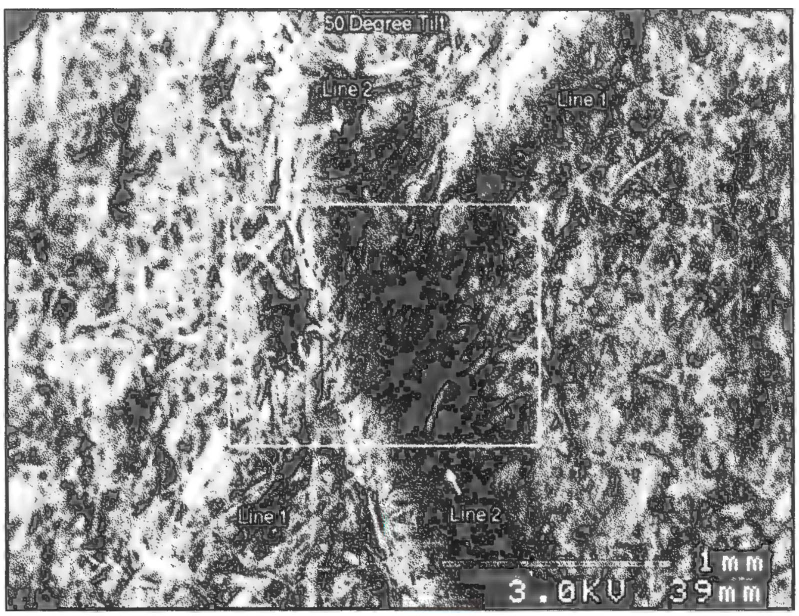

Figure 19b. Ballpoint ink over ink. SEM, 35X. 50° tilt. Note effect of tilt angle on contrast and light and shadow. (Image reprinted from 1996 paper)

actual cases, great care must be taken in establishing continuity and discontinuity.

(6) The most beneficial way to prepare oneself for case questions involving sequences is (in addition to consulting the relevant literature) to construct samples of known crossover combinations and study them with various instruments and illuminating methods, carefully noting the distinguishing characteristics.

Several sequencing problems remain problematic and deserve further study. Certainly ink/ink sequencing techniques should be further developed and refined, both with conventional light microscopy and especially the low vacuum SEM.

All researchers begin their journey at the end of the path paved by their predecessors. We hope that our efforts will enable our colleagues to go a few steps further to elucidate sequencing questions.

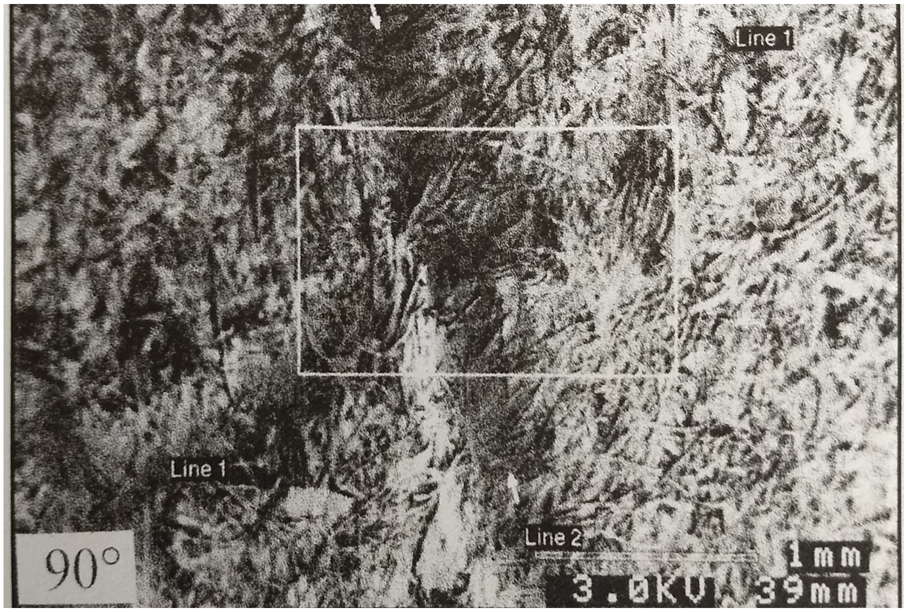

Figure 20a. Ballpoint ink over ink. SEM, 50° tilt. 35X. Effect of specimen rotation: proper rotation to see crossover. (Original Image)

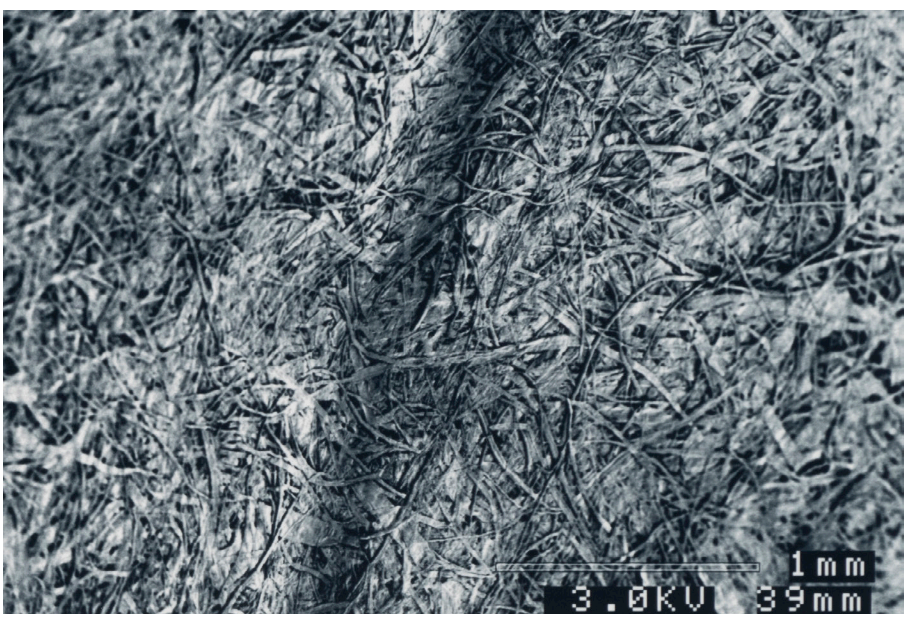

Figure 20b. Ballpoint ink over ink. SEM, 50° tilt. 35X. Effect of specimen rotation: oriented 30° vs. rotation in Fi re 20a. Crossover not definitive.

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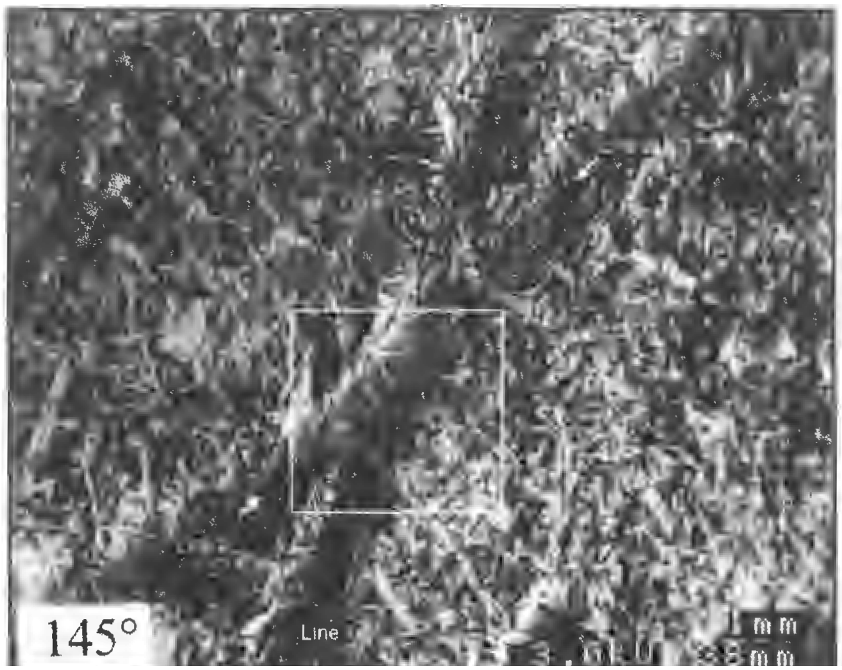

Figure 20c. Ballpoint ink over ink. SEM, 50° tilt. 35X. Effect of specimen rotation : rotated 180° vs. rotation in view a. View a shows best view of crossover. (Image reprinted from 1996 paper)

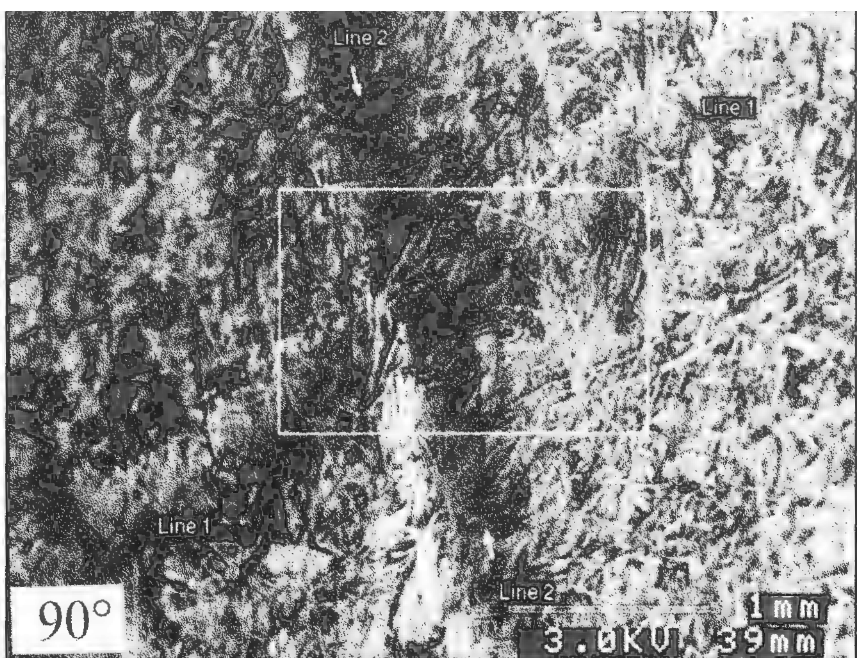

Figure 21a. Ballpoint ink over ink. SEM,50° tilt. 35X. Effect of cross.over angle: 90°. (Image reprinted from 1996 paper)

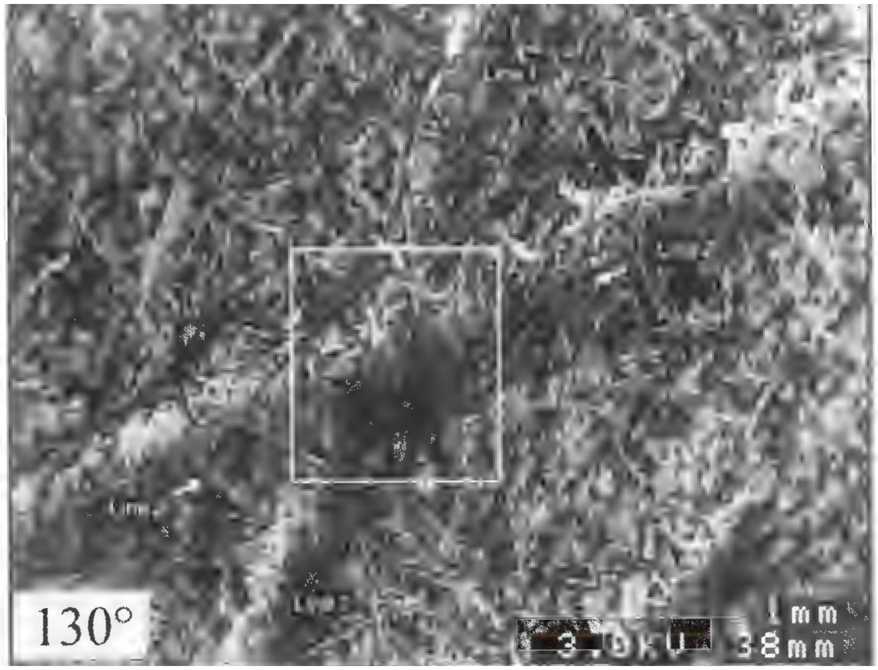

Figure 21b. Ballpoint ink over ink. SEM, 50° tilt. 35X. Effect of crossover an le: 130°.
(Image reprinted from 1996 paper)

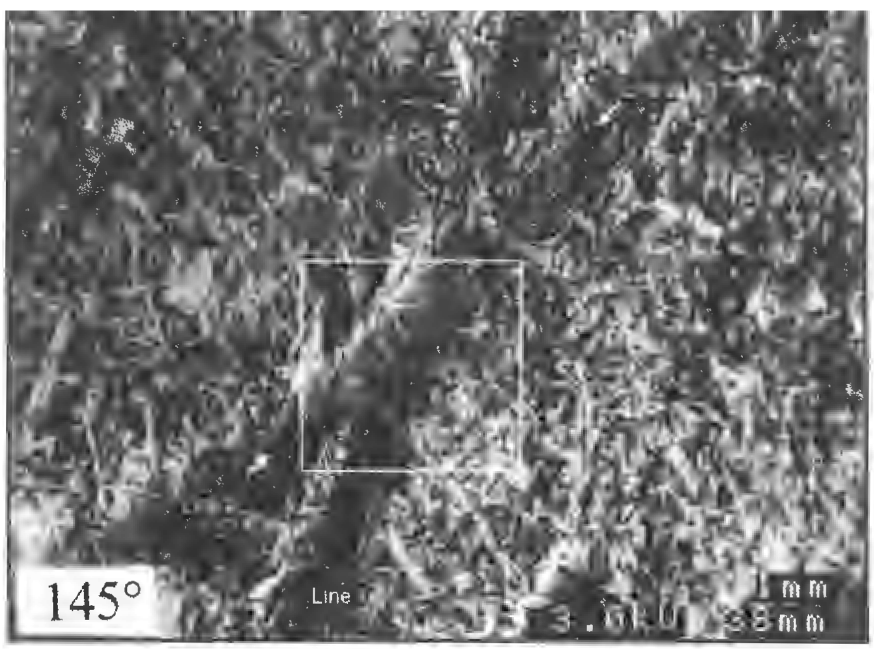

Figure 21c. Ballpoint ink over ink . SEM, 50° tilt. 35X. Effect of crossover angle : 145°.
(Image reprinted from 1996 paper)

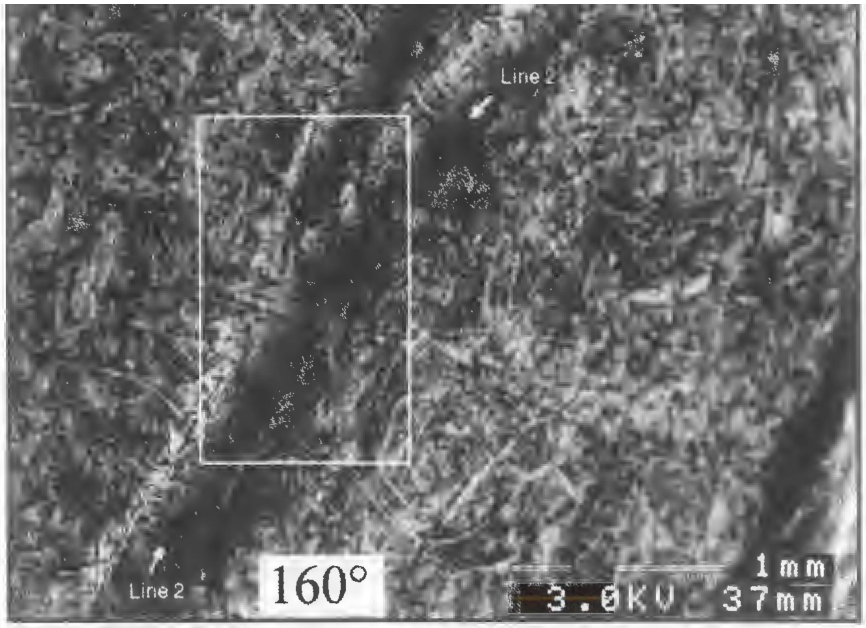

Figure 21d. Ballpoint ink over ink. SEM, 50° tilt. 35X. Effect of crossover angle: 160°.
(Image reprinted from 1996 paper)

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