TECHNICAL NOTE

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Distinguishing the Cause of Textile Fiber Damage Using the Scanning Electron Microscope (SEM)

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ABSTRACT: Forensic investigations have been using fiber scanning electron microscopy to identify the cause of textile damage. This study was modeled after previously documented cases with the aims to create fabric damage under a known series of conditions, to examine the fiber's fracture morphology, to photograph SEM fiber-end images, and to compare the appearance characteristics with known theory. Overlapping characteristics were observed for scissor cut, knife cut and torn fabrics. Results were not totally consistent with those previously published. In certain cases, fiber-end morphology alone may be unreliable to distinguish the source of fiber damage. A need is demonstrated for further experimentation to establish a protocol for the forensic analysis of fiber damage that would include all aspects of textile microscopy.

KEYWORDS: criminalistics, scanning electron microscopy (SEM), clothing damage, tears, cuts, fiber fractures, bites, fiber-end appearance

Textile scientists have been using the scanning electron microscope (SEM) for over 20 years to study a number of physical fiber properties, especially fiber fatigue, abrasion and deterioration caused by induced (mechanical, chemical or biological) or environmental (weathering) phenomena. Hearle, Lomas, Cooke and Duerdon [*1*] produced an atlas of over 1000 SEM micrographs depicting different sources and types of fiber damage. This atlas described a number of single fiber fracture models (for example, scissor cut as "lateral compression," knife as "clean-cut" and impact tear as a "mushroom cap") and proposed theories to explain the appearance of each model. Forensic scientists suggested that a SEM procedure could assist in differentiating sources of fiber damage: cuts from tears [*2–4*], knife from scissor cuts [*5*] and sharp instruments from canine bites [*2,3*]. Criminal investigations have allegedly identified specific sources of the fabric damage by using SEM micrographs of fiber-end appearances.

A judicial inquiry [*6*] following a murder trial established that experts had drawn incorrect conclusions about the cause of the textile damage. The textile evidence given at the trial was based in part on SEM fiber and yarn examinations. During the proceedings of the inquiry, the chief forensic investigator, Raymond, conducted a blind SEM experiment and illustrated that scientists could not distinguish the specific source of fabric damage which had created the "lateral compression" observed on the fiber ends [*7*]. The specimens for this exercise were known scissor cut fibers, known canine severed fibers and damaged fibers taken from the victim's apparel [*7*]. Justice Morling [*6*] reported that textile scientists and SEM experts could not agree on the fabric, yarn and fiber characteristics which would best illustrate the differences between cuts and tears. Whereas, textile scientists favored a stereo-macroscopic examination (5X–50X) of damaged fabric and yarn [*6*], forensic scientists suggested that a SEM examination (20X–2000X) of individual yarns and fiber ends could be used to identify the source of damage [*4–6*].

As stated by Stowell and Card [*4*], little information has been published about the SEM's ability or its possible limitations in identifying the source of fabric damage in forensic investigations. In a recently published forensic textile textbook, Carroll [*8*] devoted two short paragraphs to the identification of textile damage and mentioned that the SEM could be a useful technique. Carroll referred readers to the Hearle et al. SEM Atlas [*1*] for an in depth treatment of the subject. However, much of Hearle's research [*1*] was conducted with single fiber experiments and might not apply to forensic investigations. Textile and forensic scientists contacted in Australia, Canada, England, Japan, Sweden and the United States have indicated that no forensic protocol has been established to identify the source of textile damage by observing fiber-end morphology. Forensic scientists have been using ad hoc procedures to present SEM fiber and yarn evidence in court [*2–5*]. Chaikin [*2*], Robinson [*3*], Choudhry [*5*] and Paplauskas [*9*] presented features using a qualitative approach with very few micrographs to support their opinions; however, none of the researchers [*2,3,5,9*] commented on the range of fiber-end appearances possible from a single source of fabric damage.

Stowell and Card's paper [*4*] suggested a quantitative method which assigned a ratio to the fiber-end characteristics taken from each known source of fabric damage. Stowell and Card, however, could be criticized for inferring that scalpel characteristics would be similar to those created by knives. Hearle et al. micrographs [*1*] have suggested that very sharp surgical instruments would give a different fiber-end appearance to those severed by a knife. A lawyer, correctly briefed by a textile scientist, could challenge Stowell and Card's argument that scalpel damaged fabric produced a similar distribution of fiber-end characteristics to those found in the victim's garment [*4*]. This quantitative approach, however, has greater potential than the qualitative one and should be pursued further.

No researcher except the forensic investigator, Raymond, using the blind experimental exercise cited earlier [7], has challenged either the reliability or the validity of present SEM procedures used to identify causes of fiber damage in forensic investigations. The author first questioned the significance of SEM forensic conclusions which were based on sample sizes of 31 or fewer fibers [2–4]. Because many textile properties have very high coefficients of variation, at least 100 and as many as 600 measurements could be necessary to establish the required reliability. Forensic scientists have appeared to overlook, or to be unaware of, the intrinsic variability of textile properties. For example, one SEM paper reviewed has referred to the fiber-end appearance as being associated with the resiliency of rayon and the rigidity of nylon [9]. In fact, many apparel end-uses have utilized nylon's excellent elasticity and resiliency properties, while cellulosic fibers (rayon) have been renowned for their poor resiliency [10].

No controlled experimental study other than Stowell and Card's paper [4] has been located in support of the use of SEM micrographs as a valid approach to distinguish cuts from tears, or blade from scissor cuts. Hearle et al. [1] have not addressed validity or reliability issues and have not described any specific criteria to relate fiber-end damage to the source of fabric damage in forensic investigations.

> "*To be admitted as evidence, a forensic test should . . . satisfy three criteria: the underlying scientific theory must be considered valid by the scientific community; the technique itself must be known to be reliable; and the technique must be shown to have been properly applied in the particular case.*" [*page 48,11*]

The cited SEM procedures used to distinguish the cause of textile fabric damage have not met these three criteria.

This exploratory study has endeavored to investigate whether a SEM procedure could be a reliable tool in distinguishing between cuts and tears, and then to identify the force or instrument causing the damage by comparison to previously published reference data. The specific objectives are:

- to compare SEM micrographs of known fiber damage from the present study with those described in previously published studies;
- to provide a textile scientist's perspective on the use of the SEM micrographs to identify the source of fiber damage in a forensic investigation;
- to suggest further research to establish the SEM's validity and reliability in identifying sources of fiber damage in forensic investigations.

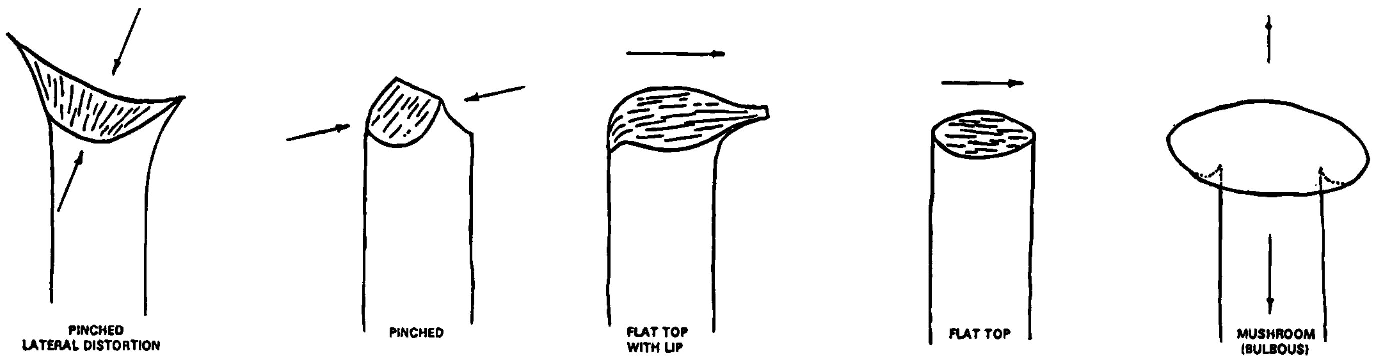
Method

An experimental approach similar to that reported by Stowell and Card [4] was followed. Nylon fiber was selected for the experiment because published forensic investigations had already referred to this generic fiber group [4–6,9]. A plain woven compact structure of untextured multifilament nylon 6.6 was selected as the test fabric. The cause of fiber damage was designated as the independent variable. Damaged specimens were produced by a pair of sharp Gingher® scissors, a sharp Wiltshire® carving knife and the Elmendorf tear tester. For both the scissor and knife cuts, one person held the fabric under minimal tension while another cut the fabric by a shearing action (scissors) or a slashing motion (knife). There was no supporting substrate under the fabric. Damaged specimens were created from only the weft direction. According to current theory [1], one would expect lateral compression for scissors, clean-cut for a sharp knife and a mushroom cap for an impact tear as illustrated in Fig. 1.

Fibers were selected at random from three different sites for each of the three methods of causing damage and then they were mounted on cello-tape under a stereo-macroscope (4X–16X). The damaged fiber specimens protruded approximately 5 mm above the edge of the tape. Each series of specimens was attached to the mounting stub (1.25 cm diameter) by conductive carbon adhesive. Two stubs, each having between 150 and 200 individual fibers, were prepared for each damage source. The fiber specimens and stub assemblies were sputter-coated with gold and then viewed on a Cambridge Stereoscan 250 at an operating voltage of 20 kV. Sections of the actual damaged fabric from each source were also mounted on studs for SEM viewing.

Fiber ends were observed on the SEM screen at 400X, 1000X and 3000X. Individual fiber images were oriented in a vertical plane. A series of approximately 100 individual fiber end micrographs for each damage source was produced at 1000X on Ilford FP4 (125 ASA) film. Micrographs were also taken for yarn clusters in the actual damaged yarn specimens at 400X and 1000X, and of a few selected individual fibers at 3000X.

The SEM micrographs were compared to Hearle et al. [1] theoretical single fiber fracture models. The author viewed the micrographs from each series one by one with the objective of designating the fiber fracture features as "lateral compression" (scissor model), "clean-cut" (knife model), or "mushroom cap"



(a) SCISSOR (SHEARING ACTION) (b) KNIFE (SLASHING ACTION) (c) IMPACT TEAR

FIG. 1—*Single fiber fracture models for scissor shearing* (a), *knife slashing* (b), *and impact (high velocity) tearing* (c).

(impact tear model). An "undefinable" category was added to the descriptor list for fiber-end appearances which did not conform to any of the three established fiber fracture models. Each micrograph from the three series was independently compared to the four defined categories. The assigned or observed features were considered to be the dependent variable in this exercise. The process then generated a distribution of "assigned" characteristics for each "actual" damaged source tested. These "assigned" features for each damaged source were compared to Stowell and Card's [4] published fiber-end appearance characteristics.

Results

Over 600 damaged fiber ends were observed either in yarn clusters or as individual fibers. Three hundred and twenty two individual fiber micrographs each with clear, distinctive fiber-end features (that is, representing 103 scissor cut, 105 knife cut and 114 impact tear fiber ends) were compared to the theoretical models portrayed in Fig. 1. Each micrograph was assigned to one of the descriptors—"lateral compression," "clean-cut," "mushroom cap," or undefinable. Table 1 presents the results of "assigned" descriptors for each "actual" source tested—scissor, knife, impact tear.

The results in Table 1 did not follow Stowell and Card's reported fiber-end characteristics [4]. Stowell and Card described *only* a "squeezed" (lateral compression) end appearance for scissor cuts, *only* a "smooth and bulbous" (mushroom cap) end appearance for tears and a variety of fiber-end appearances for scalpel cuts: "clean-cut," "bulbous," and "fractured and elongated." Their "fractured and elongated" category may be similar to the "undefinable" designation in this study. Stowell and Card's observations, based on only 67 micrographs, concluded that the SEM procedure could distinguish cuts from tears, and scissor cuts from knife cuts. Table 1, however, reports an overlapping of fiber-end characteristics in all three sources tested (i.e., scissor, knife and impact tear). The differences observed between Stowell and Card's features and those reported here could be the result of the sampling size.

Figures 2 and 3 illustrate some examples of scissor, knife and impact tear fiber-end appearances observed in this study. These micrographs, produced at 1000X (Fig. 2) and 3000X (Fig. 3), demonstrate the overlapping nature of scissor and knife cut specimens as well as illustrating examples of assigned descriptors for the observed features. The fundamental descriptors of "compression," "clean-cut," "clean-cut with striations," "globular," "mushroom cap" and "bulbous" were applied to the fiber features as defined by Hearle et al. [1]. Terms such as inverted, rivet head, clean globular, lateral distortion and lip were used by the author as further refinements for fiber-end descriptions. Striations or Choudhry's tool marks [5] are apparent on the cut surfaces of both scissor (Fig. 2*a*, 2*b* and 3*b*), and knife (Fig. 2*e*, 2*h*, 3*c* and 3*d*) specimens.

TABLE 1—*Assigning the cause of fiber damage using models based on single fiber fracture.*

	Assigned Descriptors				Number of
Actual Source	Lateral Compression	Clean-cut	Mushroom Cap	Undefinable	Specimens for each Source
Scissor	6	89	...	8	103
Knife	14	60	6	25	105
Impact					114
Tear	...	5	92	17	
Totals	20	154	98	50	322

Lateral distortion is visible in Figures 2*b* and 2*d* for scissor cut and in Figs. 2*h* and 3*c* for knife cut. Clean-cut with lip is evident in Fig. 2*c* for scissor cut and in Figs. 2*e*, 2*g* and 3*d* for knife cut. Figures 2*i*, 2*j*, 2*k*, 2*l*, 3*e* and 3*f* illustrate a variety of characteristic appearances for impact tears. Descriptors such as mushroom, inverted mushroom, rivet head and clean globular appearance could distinguish the different shapes of the impact tear specimens. Figures 2*f* and 3*e* illustrate examples of undefinable features.

Stowell and Card's Fig. 1*c* [4] for torn nylon displays some similarities to Choudhry's Fig. 8 [5] for a scissor cut man-made fiber. Choudhry's scissor cut example does not demonstrate the squeezing (that is, compression) reported for *all* of Stowell and Card's scissor cut fibers. The present study also observed scissor cut fibers (Figs. 2*a* and 3*b*) which were clean-cut with striations similar to that featured in Stowell and Card's Fig. 1*f*, a scalpel cut and Choudhry's Fig. 8, a scissor cut.

Stowell and Card [4] have given an impression to the reader that scissor cut fabric and torn fabric each produced their own unique fiber-end feature (that is, lateral compression for scissor cut fabric and bulbous for torn fabric). However, this present study illustrates that overlapping features were visible for all three sources examined. The Hearle et al. [1] micrographs for manufactured fibers (that is, man made fibers such as nylon) support the concept that cut fiber features could overlap with torn fiber features. Further, Stowell and Card's figures for cut fibers display similar features to the Hearle et al. micrographs for torn fibers in chapter 5 [1].

The present study, using 322 observations, supports the concept that the SEM procedure could distinguish tears from cuts. Eighty percent of the impact tear specimens were correctly identified. Less than 5% of the impact tear specimens fell within the clean-cut or compressed descriptors which were associated with cuts. Only 6 fibers from the 103 scissor damaged sources were identified as having "compressed" fiber ends. In fact, more knife damaged specimens than scissor cut were assigned to the "compressed" descriptor in Table 1. This study, similar to that conducted by Stowell and Card, was unable to distinguish scissor cut from knife cut fiber ends because both scissor and knife produced "compressed," "clean cut" and "undefinable" fiber-end appearances. Stowell and Card may have used too few specimens (that is, 21 scissor cut, 31 scalpel cut and 15 hand torn fiber ends) to notice overlapping features for the scissor or tear samples.

The influence of fabric structure must be pursued further. Structural variables such as fabric type (woven, weft knit or warp knit) and fabric cover (compact versus open structures) could influence what is observed from different sources of damage. It is the author's belief that fibers rupturing within a yarn (that is, a twisted bundle of fibers) or a fabric would increase the variability in fiber-end appearance. For example, fibers could be fractured by a tensile or shearing force before another severing force made contact.

Figure 4 presents a side view (4*a*, produced at 400X) and an end view (4*b*, produced at 1000X) for a typical scissor cut yarn taken from the test fabric. All the scissor cut fiber ends remained clustered in a similar plane (4*a*) and some exhibited "clean-cut" knife features (4*b*). In this test fabric, the scissor cut has created different features on the fiber ends depending on their position in the yarn or bundle of fibers. A closer examination of the fiber ends in this yarn cluster revealed the shearing action of the scissors. Three fibers in the foreground of Fig. 4*b* were cut by both blades of the scissors. This feature was noted as unique to a shearing force as applied by scissors and possibly could assist in distinguishing scissor cut from knife cut yarns. Also, the fibers on the left

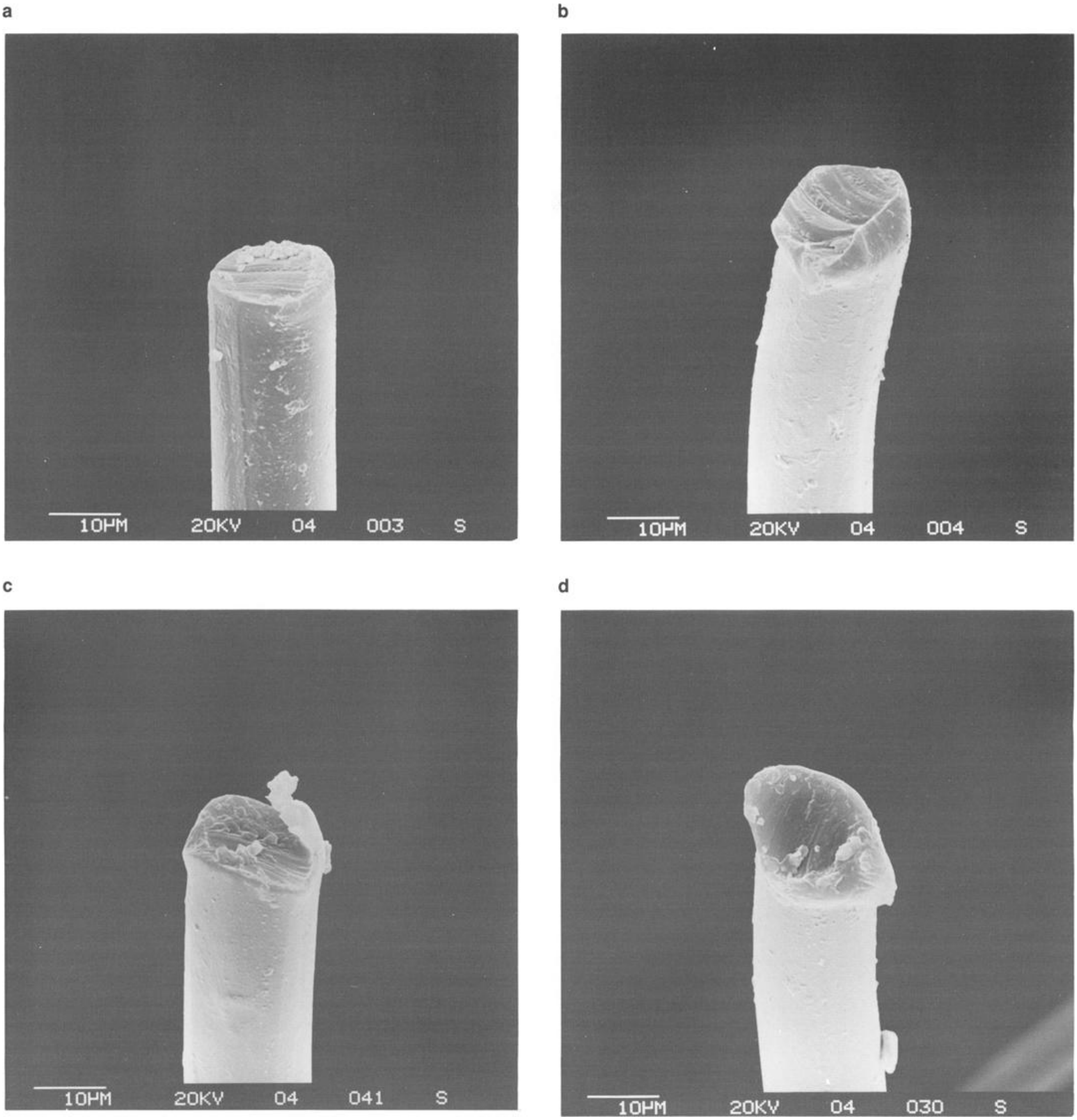


FIG. 2—*SEM micrographs (1000X) of severed fiber ends from a nylon fabric for scissor damaged fibers* (a–d), *knife damaged fibers* (e–h) *and torn fibers* (i–l). *The bar represents a length of 10 μm.*

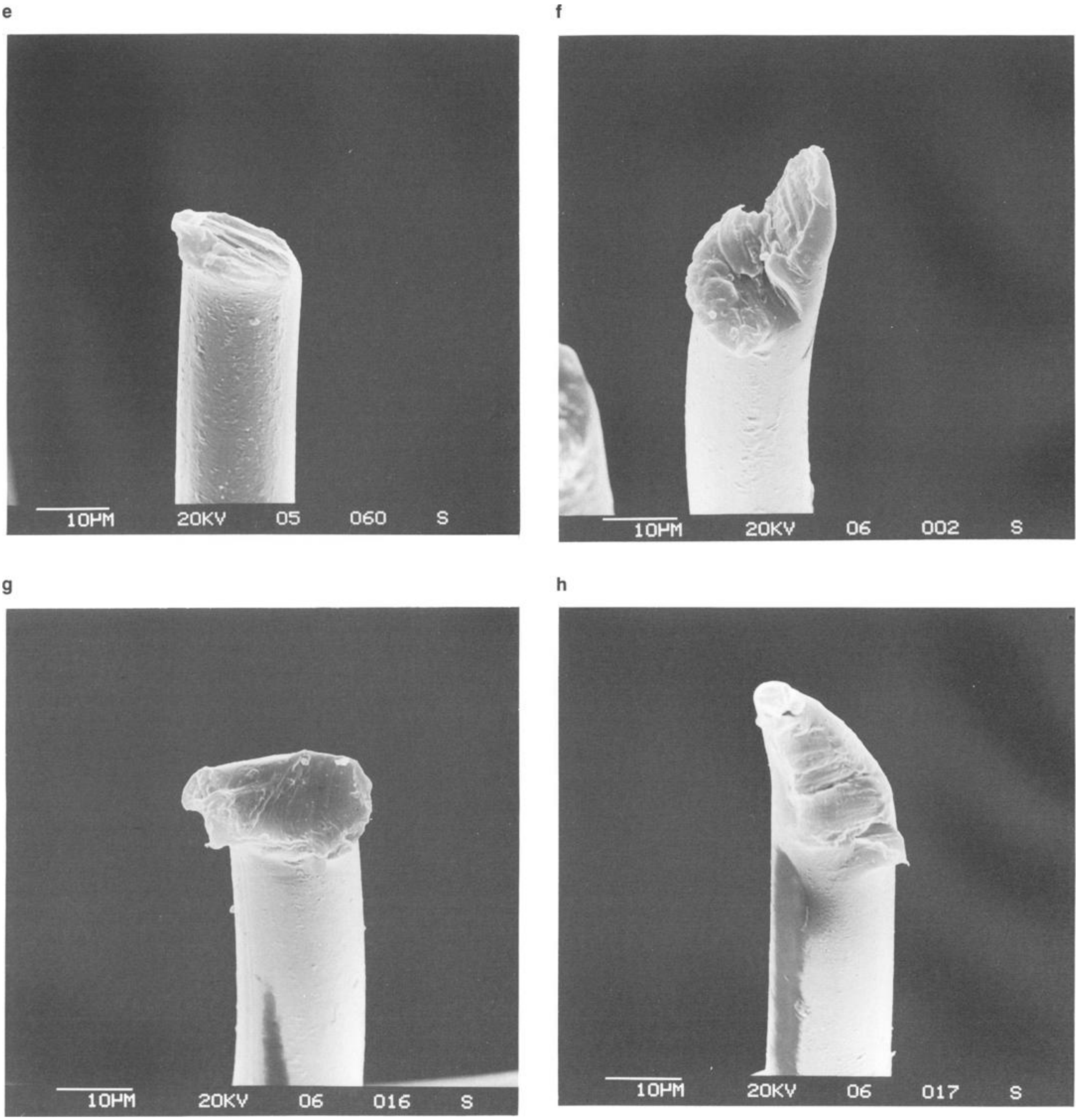


FIG. 2—*Continued*

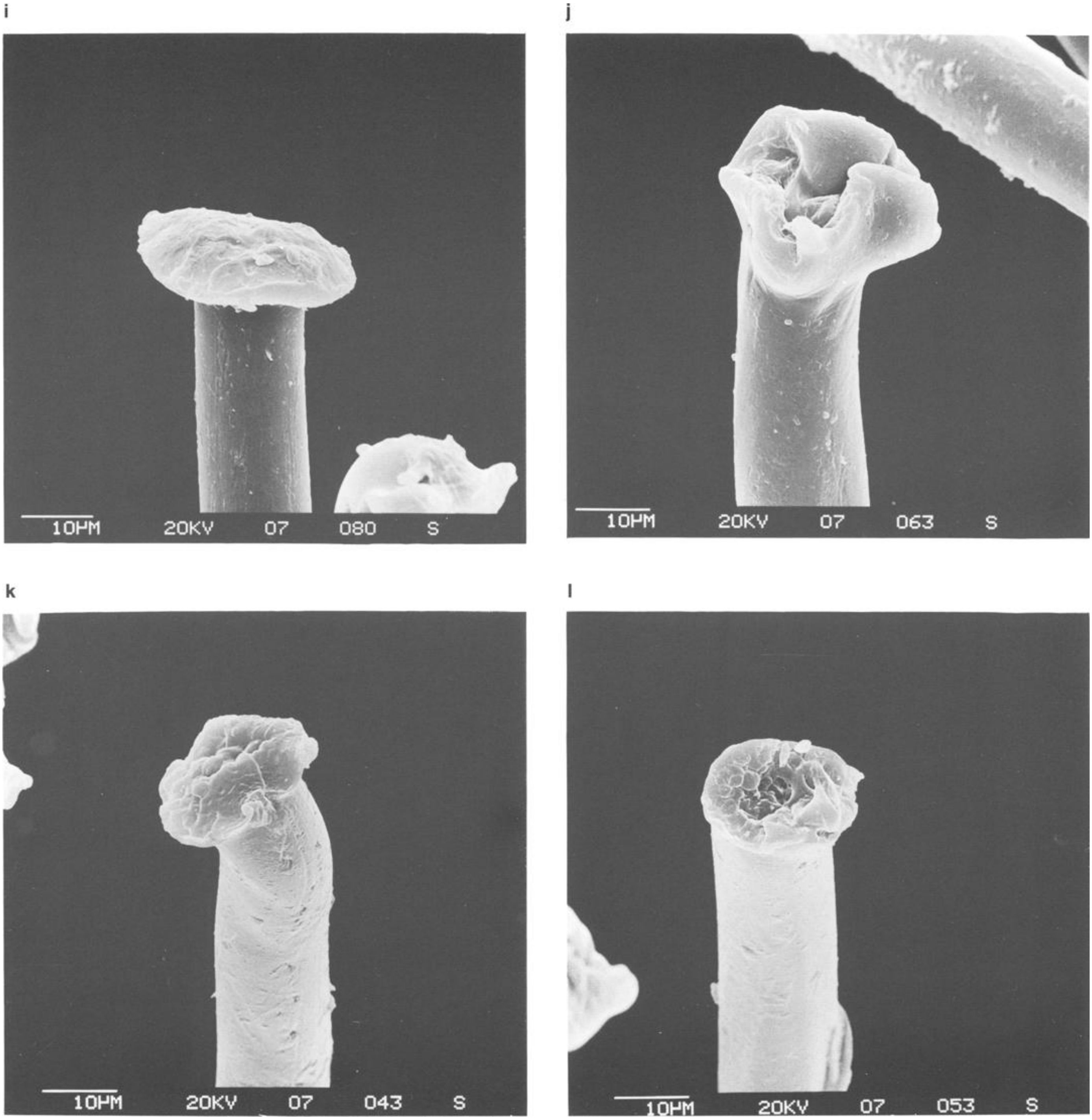


FIG. 2—*Continued*

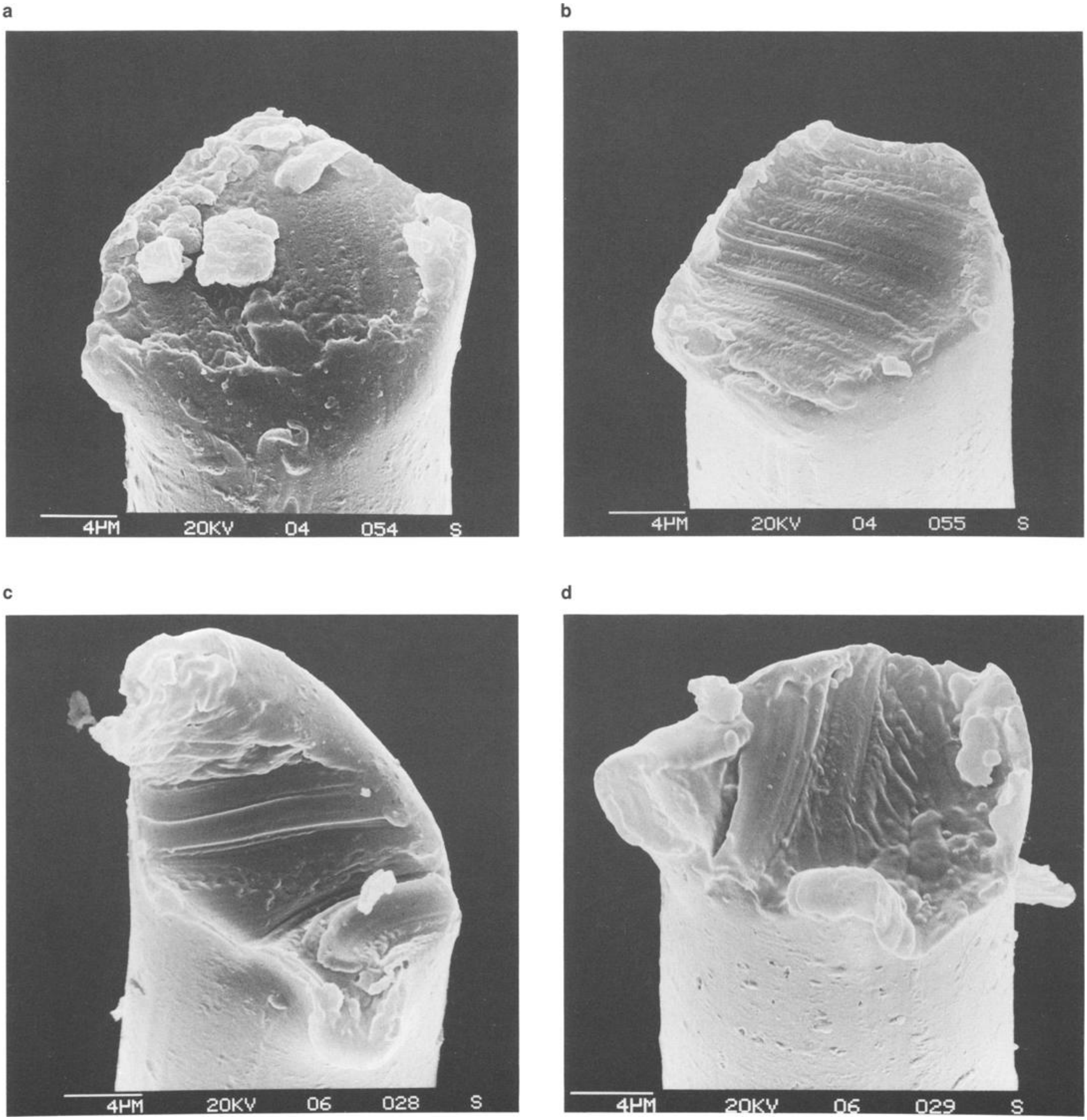


FIG. 3—*SEM micrographs (3000X) of severed fiber ends from a nylon fabric for scissor damaged fibers* (a,b), *knife damaged fibers* (c,d) *and torn fibers* (e,f). *The bar represents a length of 4* μm.

e f

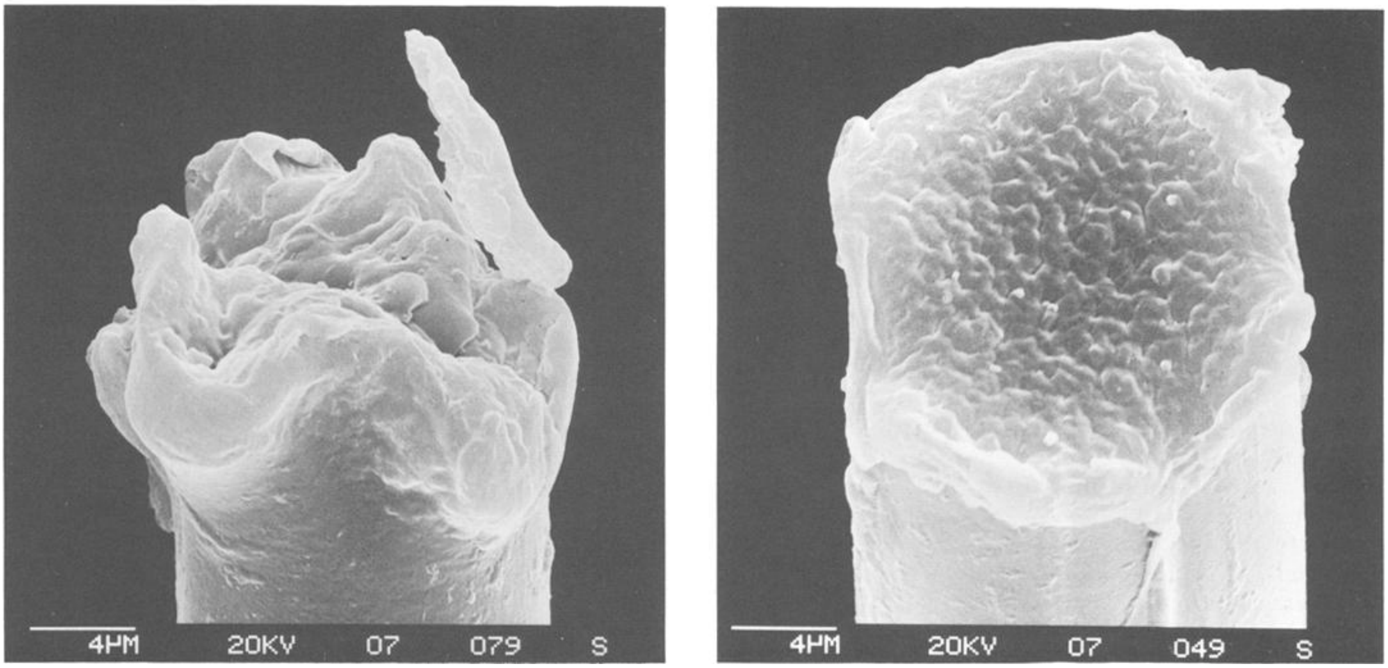


FIG. 3—*Continued*

a b

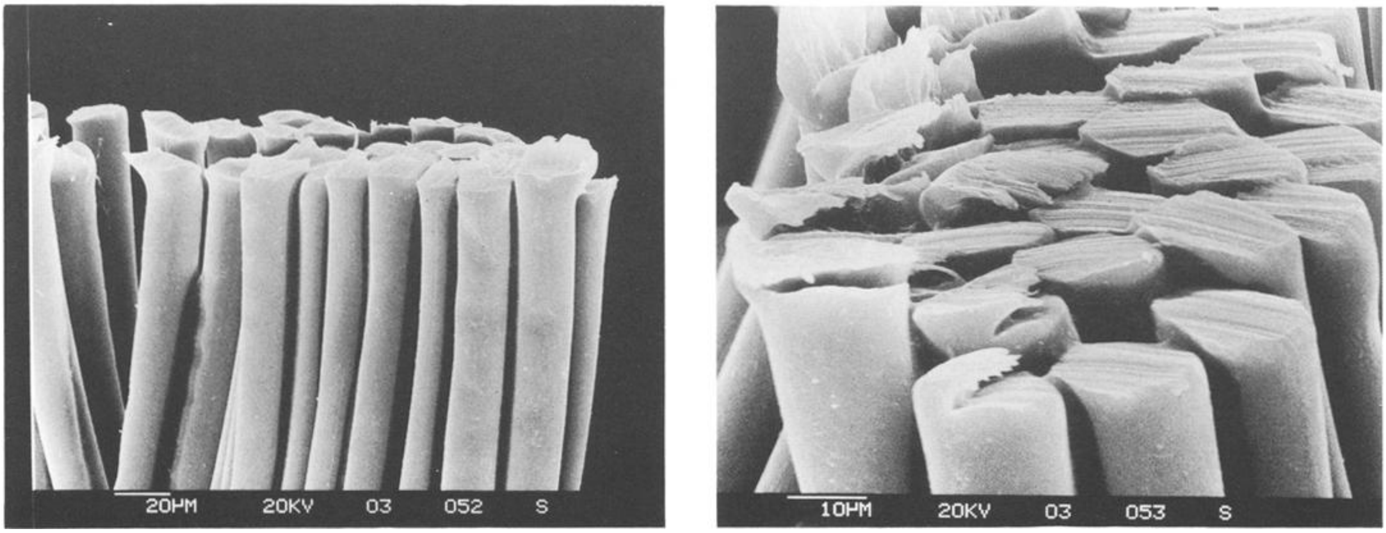


FIG. 4—*SEM micrographs of a scissor cut yarn taken from a nylon fabric (side view at 400X and end view at 1000X). The bar represents a length of 20 μm for* (a) *and 10 μm for* (b).

side of the yarn have lips pointing to the right while fibers on the right have lips pointing to the left. These observations were common when scissor cut fabric segments were scanned by the SEM in this study. Neither the knife cut nor impact tear fabric samples exhibited these fiber clustering features.

Discussion

The significance of conclusions drawn in previous forensic investigations [*2,4,5*] is questioned when only a few SEM fiber specimens are used. The rationale for making this statement is based on the observations of overlapping fiber-end morphologies and the characteristics of manufactured fibers. Some examples are presented in the following paragraphs. Hearle et al. chapters 23 and 24 [*1*] have supported the points outlined.

Nylon, or any other manufactured fibers, could be produced as a staple or a multifilament yarn. The method of tow conversion (cut or stretch-broken) determines the fiber-end appearance of the "constituent" staple fibers. Constituent fiber ends have been defined as the fiber appearances produced through the manufacturing processes of tow to staple conversion. If the fabric in question had been made from staple fiber and the damaged edge was difficult to view because of distorted or manipulated yarns [*2,4*], the fiber ends observed might represent a distribution of both constituent and damaged fiber ends instead of damaged fibers alone. This factor would be quite important if only a few individual fiber end micrographs had been observed. On the other hand, if the investigation first distinguished between the constituent and damaged fiber-end appearances, then the damaged fibers could be compared to known sources.

Not all manufactured fibers have round diameters [*10*]. Thermoplastic filament fibers such as nylon can be textured by heat setting during yarn processing, flattening one side of the fiber. This heat setting alters both the physical shape and the polymer structure of the fiber which, in turn, affects the fiber-end appearance. Aging of the textile might influence the fractured appearance [*12*]. Most woven and knitted textile fabrics have been produced from yarns with twisted fiber assemblies. Fracturing twisted fiber assemblies in a fabric structure could create different fiber appearances from the single fracture models proposed by Hearle et al. [*1*]. Micrographs of ruptured yarns [*1*] have demonstrated that yarn twist could affect the ruptured fiber-end appearance. Fiber and yarn variables, therefore, could create a range of SEM images for the same generic fiber.

Forensic scientists should be aware that the textile variables (fiber, yarn and fabric) interact with one another so that a given textile fabric structure could tear:

- in both directions (warp and weft);
- in *only* one direction (warp or weft);
- or in neither direction (only distort the yarns).

Therefore, an investigation involving alleged cuts or tears should assess the fabric's ability to tear. This procedure, along with identifying the severance direction (that is, warpwise, weftwise, or diagonally across the fabric) in the damaged garment panel, could establish that the fabric was cut irrespective of the damaged fiber-end appearances. This approach was used to demonstrate that canine carnassial and incisor teeth could cut a single jersey fabric made from multifilament nylon [*13*].

Conclusion

This paper has raised four questions or issues about the SEM protocol used to distinguish the cause of textile damage in forensic investigations. First, what would be the minimum number of observed fiber-ends needed to give a valid result? Second, should the damaged-fiber appearance features taken from fabrics be compared to those established for single fiber fractures? Third, is the distribution of appearance features more important than comparing the individual fibers to the theoretical models? Fourth, the type of fiber, yarn and fabric structure must be considered in the determination of the cause of fabric damage.

The data presented suggest that caution should be exercised when interpreting fiber-end fracture morphology to determine the cause of textile damage. The study shows a variety of fiber-end features produced by different methods of fabric damage. In addition, certain end features could be attributed to or influenced by various manufacturing processes. Finally, SEM analysis revealed overlapping fiber-end characteristics for the three sources of damage examined.

This is a limited study. Observations of one researcher on one generic fiber group are presented. As yet, no SEM experimental work has been conducted to test the hypothesis that different observers would come to the same conclusion on the cause of textile damage, given the same series of fiber micrographs. The author suggests that the SEM validity and reliability should be verified using a blind-review procedure, and that the blind review exercise should include both textile and forensic scientists at different sites. The work reported by Hearle et al. [*1*] has established an excellent foundation for the proposed experiment. Until experimentation is conducted to establish SEM validity and reliability, lawyers will continue to challenge, and be successful in discrediting, evidence based solely on SEM fiber-end appearance.

Acknowledgment

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