Abrasion Phenomena in Twill Tencel Fabric

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ABSTRACT: The abrasion characteristics of Tencel fabrics were evaluated by Martindale abrasion and laundering, and the breakdown mechanism of fibers was surveyed by scanning electron microscopy. The fabric was subjected to pad-dry-cure treatment with two different types of modified dimethyloldihydroxyethylene urea resins (*Reaktant DH* and *Reaktant FC*). Although the degree of dry abrasion varied with different resins, the damage exhibited by individual fibers differed little from untreated to resin-treated; the major mechanism of abrasion was through friction, and the mechanism of fiber failure was multiple splitting and transverse cracking. In untreated Tencel, the characteristic feature of wet abrasion was massive fibrillation, and in crosslinked fabrics, the wet abrasion mechanism was through fiber slippage and slicing action, although in the *Reaktant FC*-treated fabric, the wet abrasion mechanism was more through slicing than through fiber splitting. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 102: 1391–1398, 2006

Key words: crosslinking; fibers; degradation; electron microscopy; failure

INTRODUCTION

One of the characteristics of Tencel that contributes to its significant application in the fashion industry is its ability to fibrillate. Various enzyme finishing techniques[1,2] are used to produce "soft-touch" fabrics with a microfibrillar surface, which gives the fabric surface a special appearance and feel, known as the "peach-skin " effect. The fibrillar surface causes greater light scattering, and dyed fabrics appear lighter in color to their unfibrillated counterparts. The advent of peach-skin Tencel fabrics resulted in high returns for the designer apparel market, and developments for industrial applications for Tencel became, understandably, a low-key second priority activity. Over the past few years, peach-skin Tencel fabrics have been available for both casual and designer wear, but the market now desires a more formal look and, with the different finishing treatments available, a wide range of fabric handle and surface effects are possible. However, introduction of easy-care Tencel textiles has placed new emphasis on resin treatment, since abrasion damage occurs much more readily in chemically treated Tencel fabrics. Many studies have been conducted to reduce the fibrillation tendency of Tencel fibers and fabrics, but little attention has been given to the changes brought about in the fibers due to resin treatment, which led to the eventual breakdown of the fabric.

Generally, abrasion is the physical destruction of fibers, yarns, and fabrics, resulting from the relative motion of a textile surface over another surface, quite often another textile. Fabric failure occurs by the gradual breakdown of the internal cohesion of the individual fibers or by a gradual breakdown of the forces of structural cohesion between the fibers.[3] The relative occurrence of these two phenomena depends to a great extent upon the fabric geometry, but there are limitless factors involved (e.g., combination of weaves, construction of yarn, size, and twist of yarns) according to the individual behavior of different fibers. All these variables have made it impractical to establish general conclusions, which could apply to a large range of fabrics. Valuable information concerning the effect of construction on certain properties, such as tear strength, abrasion resistance, and crease recovery, has been made available, but most of the information relates to fabrics made by cotton-spun yarns.[4–7] Detailed electron microscopy work on fiber fracture, published by Hearle et al.[8] and Clegg,[9] has made an extensive and informative microscopial examination on cotton worn textile articles, such as cotton shirts, overalls, pyjamas, pillow slips, etc.

Importantly, most abrasion tests depend on applying energy to the fabrics and measuring their response to it. The manner of transferring the energy from machine to the fabric is different for different ma-

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chines, but the basic principles are the same.[10–13] Therefore, according to Hamburger,[14] good abrasion resistance depends more on a high energy of rupture than on high tenacity at break. Furthermore, abrasion is not influenced so much by the energy absorbed in the first deforming process (total energy of rupture), as by the work absorbed during repeated deformation.[15,16] This work is manifested in the elastic energy or the recoverable portion of the total energy. Thus, to prevent abrasion damage, the material must be capable of absorbing energy and releasing that energy upon the removal of load. Energies in tension, shear, compression, and bending are all important for the evaluation of surface abrasion; however, these energies are unknown, and therefore elastic energies in tension permit at least a quantitative interpretation of abrasive damage in fibers and fabrics.

Considering the molecular structure of Tencel fibers, it has been well reported that the ratio of crystallites to amorphous regions is 9:1, and they are oriented along the fiber axis.[17–19] Orientation of crystallites and amorphous regions increases the fiber strength by reinforcing interchain attraction.[20–23] However, to the extent that the molecules are oriented parallel to the fiber axis, there is a lower proportion remaining for subsequent deformation in extension, which suggests that the deformation mechanism in lyocell is very stiff and operates by the stretching of interatomic bonds in the chain or by opening up of valence angles.[24] Generally, when a fiber is stretched to some fixed extension, crystallites are first to respond and are fast enough to deform along with fiber by absorbing the input energy; as time passes, the amorphous regions deform along the fiber and absorb some of the stretching energy from the crystallites, allowing them to relax; more time allows more amorphous regions to share this energy, causing greater relaxation of crystallites. If force is applied at a constant rate, crystallites will respond more or less, in phase with application of load, while amorphous regions will lag behind, and slower amorphous regions will lag behind even further. The result of this is that certain mechanisms strive to respond to the first increments when subsequent increments are being added. If this process is reversed by removing load or extension, the deformation mechanism reverses itself to allow recovery to the fiber; crystallites are again the fastest to respond to the removal of the load, and amorphous regions are again delayed as they lag behind to the application of load. This repetition of a simultaneous sequence of response in recovery and deformation results in cumulative behavior of fiber, and is very important in depicting the mechanical behavior of the fiber.[15,16,25,26] In a previous paper by the authors,[24] we have observed the elastic and cumulative behavior of Tencel filament, and the slower response of amorphous regions was highlighted. As amorphous regions are highly aligned along the fiber axis, there are fewer kinks and bends; therefore, less time and energy is required for deformation. Hence, most of the energy absorbed by the crystallites during repeated loading cycles was returned to the surroundings, causing finite deformation in the fiber system.

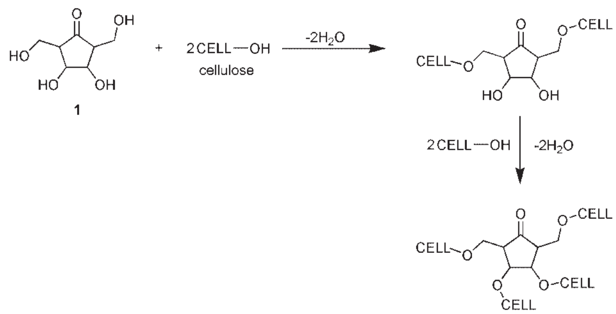
It is well documented[27,28] that resin treatment brings morphological changes in cellulosic fiber structure by increasing elastic recovery and reducing extensibility. Consequently, the work absorption capacity of resin-treated fibers is less than their untreated counterparts. Cotton shows considerable loss in abrasion resistance, even greater losses are observed in resin-treated viscose rayon[29] (although resistance to higher strains is less, ability to recover from low strain is increased). At high loads used in the laboratory tests, abrasion resistance of resin-treated fabrics was considerably lower than untreated fabrics, but under mild test conditions abrasion resistance of resin-treated fabrics actually exceeded that of untreated fabrics. This shows that under severe abrasion conditions, high work absorption is necessary, and elasticity is more important under mild conditions, more likely to be encountered during the life of a garment. Similar studies concerning other cellulosic fibers have not been reported.

Morphological changes in Tencel fibers due to resin finishing prevent the fiber from fibrillating, but cause more than 50% reduction in abrasion resistance.[1,30] Through the research described herein, a microscopy investigation was made of the mechanism of abrasion in resin-treated and untreated Tencel fabric, to determine whether a correlation exists between Martindale damage with dry abrasion and washing damage with wet abrasion.

EXPERIMENTAL

Materials

Dyed 100% Tencel 3/1 twill fabric of $30 \times 30/44 \times 35$ quality composed of staple fibers, obtained from Lenzing, was used throughout this study; the fabrics had been singed on an Osthoff singeing machine, jig-desized, and scoured, and jig-dyed using a 2% omf *Procion H-EXL* mixture dye recipe at 80°C over 30 min, and neutralized in a pilot plant. Dyed fabric was used to make visual assessment easier, with respect to fibrillation behavior; the dye and its application have no significant effect on fibrillation behavior of fiber. Hence a comparison with undyed fabric was unnecessary for this study. *Reaktant DH* and *Reaktant FC*, the crosslinking agents, were obtained from TextilColor AG. Both *Reaktant DH* and *Reaktant FC* are modified dimethyloldihydroxyethylene urea (DMDHEU; **1**) derivatives; in *Reaktant DH*, its methylol group modified with a urea derivative, and the dissolved solid content



Scheme 1 Catalytic condensation reaction of DMDHEU with cellulose.

was 41%; *Reaktant FC* is modified to reduce formaldehyde evolution in processing (classified as a "low formaldehyde" resin), and the dissolved solid content was 58%. DMDHEU resins afford easy-care properties (dimensional stability) to cellulose by crosslinking separate cellulose chains through a catalyzed condensation reaction between primary hydroxyl groups in the cellulose and the hydroxyl moieties in the resin; although the absolute reaction is not understood, particularly with DMDHEU derivatives, the mechanism of crosslinking is based on the reaction in Scheme 1. All other chemicals were of general laboratory grade supplied by Aldrich.

Fabric treatment

The fabric samples (30×42 cm^2) were impregnated in a pad bath containing 50 g dm^{-3} resin and 10 g dm^{-3} catalyst for 10 min. The samples were padded through the squeeze rollers at a pressure of 15 kg cm^{-2}, to obtain 80–85% pick-up, and then dried in a Werner Mathis stenter for 3 min at 130°C, and finally cured for 3 min at 160°C.

Fabric testing

The dry abrasion resistance mechanism was observed using a Martindale abrasion machine, according to the standard testing procedure BS EN ISO 12947–2. Fabric samples were abraded against standard worsted wool abradant fabric at a constant pressure of 9 kPa. The treated samples were also washed five times using the standard procedure BS EN ISO 15487 at 40°C for 100 min, with an additional make-up load of 1 kg. After washing, the fabric samples were tumble-dried for 15–20 min, to achieve a reduction in moisture level to 15–20% and then air-dried.

In general, the number of abrasion cycles withstood by resin-treated fabric samples before the appearance of the first hole was less than that of the untreated sample, and therefore abrasion was restricted to the breakdown of the first one or two yarns. The damage to the individual unbroken fibers at the fabric surface was also determined in regions where abrasion was apparent, but no hole had yet formed.

The number of wash trials employed in this study is not a measure of the life of fabric, but is only to determine the nature of fiber damage imparted during the course of actual wear and laundering operations.

Scanning electron microscopy

Small pieces of fabrics selected from areas of abrasion damage were mounted on the aluminum stubs for examination in the microscope. After mounting, these specimens were coated with gold, ~20 nm thickness, by thermal evaporation and were examined with a Cambridge Stereoscan, Model S-360 scanning electron microscope (SEM). SEM was preformed at 10 kV accelerating potential, and pictures of abraded surfaces were taken at 500× magnification.

RESULTS AND DISCUSSION

Abrasion mechanism of Tencel fabric

Abrasion of fibers is a complicated mechanism because of the anisotropic nature of woven fabrics, which represent a two-phase system of fibers, but it can be made easier by considering the structure of the fabric. The face of the fabric warp yarns, which are the stress-bearing yarns in this fabric system, occupy a raised position on the face of the fabric; the filling yarn (weft) is pushed down by the higher density of the warp yarn. During the course of Martindale abrasion, the warp yarns were broken and periodically removed from the field of abradant action. Through the first few 1000 cycles, the fabric hairiness was removed, as the abrasion continued disintegration of warp yarn structure proceeds by successive elimination of individual fibers as effective components of the fabric. The end point was determined by the rupture of the first one or two yarns in the fabric system. It was observed that, as the rupture of a warp yarn occurs in a particular area, the filling yarn still remains undamaged. This shows that abrasion resistance on the face side of the fabric is contributed to only by the warp yarns themselves due to the structural arrangement in the fabric system. On rupture of fewer warp yarns, the filling yarn will come into play, but because it is not the stress bearing yarn, the rupture of these yarns will occur in a much lower number of cycles.

The advantage of the Martindale abrasion test is that the fabric sample gets abrasion in all directions. Stress develops along the fiber from the force acting transverse to the fiber axis as a result of surface friction; the magnitude of surface friction developed is directly related to the harshness of standard worsted fabric abradant.[4,31] The surface protuberances of the

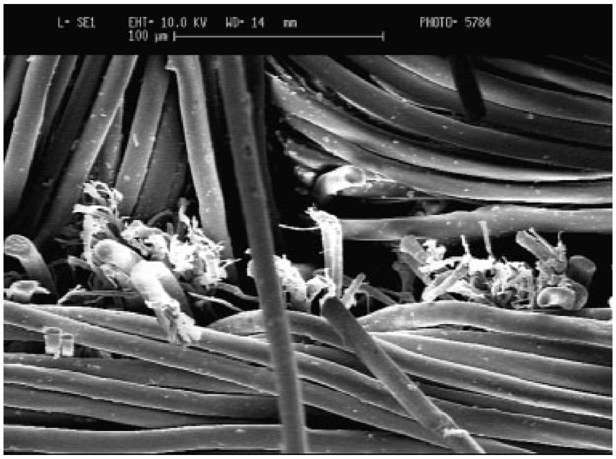


Figure 1 Detail of Tencel fabric abraded against standard worsted fabric.

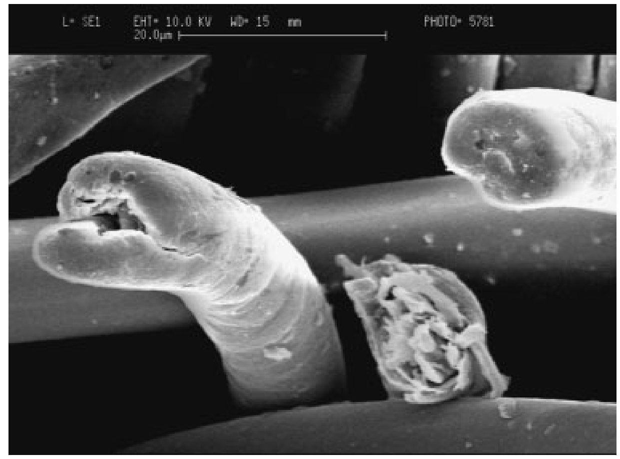


Figure 2 Multiple splitted, rounded, and axially split rounded fiber ends (untreated Tencel fabric).

worsted wool fabric abradant have a greater length, in comparison with the Tencel fiber diameter; therefore, the abrasion mechanism occurred by friction due to deep penetration of worsted protuberances into the Tencel fabric structure. During the course of abrasion, fiber to fiber cohesion plays an important role, usually influenced by yarn twist or close fiber packing.[31] Tencel abrasion behavior indicates that fiber cohesion is strong in the fabric system, and it causes the shear of the fibers themselves. Frictional forces developed in the yarn due to the Lissajous motion of the abrasion test were dissipated largely in the fibers by the development of tensile and shear stresses; repetition of such stresses resulted in fiber fatigue, which caused the loss of fiber mechanical properties, leading to rupture. Fibers in the crowns broke down in succession, and this caused a reduction in fiber cohesion and yarn strength. In lateral abrasion cycles, it appeared that frictional forces were able to displace fiber from their normal position, and these fibers ruptured through bending and flexing.

The abrasion performance of Tencel fabric observed was better than expected from its work absorption capacity, as judged from stress–strain data.[24] Possible contributing factors might be yarn crimp, which is a function of the fabric structure, yarn twist, which is determined in yarn production, and fiber spacing and longer floats, which is a function of the weave. In the first course of cycles, straightening of yarn crimp occurs, the optimum yarn twist and fiber spacing allowed the fibers to slip from the abrasive asperity, and longer floats reduced the magnitude of stress at the surface fibers. Since the yarns were held firmly between two interlacing points, fiber rupture occurred at the crevices of the weaves, as shown in Figure 1, which shows that rupture was by multiple splitting of the fiber, revealing the internal fibrillar structure of Tencel fibers, also shown in Figure 2. It has also been observed in other cellulosic fibers that this multiple splitting results from the tensile stress due to frictional forces.[8,32]

The particular length of fibers that rise on the surface of the fabric after breakage of individual fibers is no longer an effective component of fabric. In addition, these are much more vulnerable to further attack by repeated abrasion action. Evidence of multiple cracks along raised fibers indicates the repeated bending and flexing of fibers; propagation of transverse cracks is shown in Figure 3. It is also possible that some cracking was initiated by abrasion and then propagated by bending action. There was also some evidence of step breakage, as shown in Figure 4, which indicates the occurrence of transverse cracking, later joined by axial splitting; fiber ends were also rounded off and axially split due to repeated abrasion action, as shown in Figure 2.

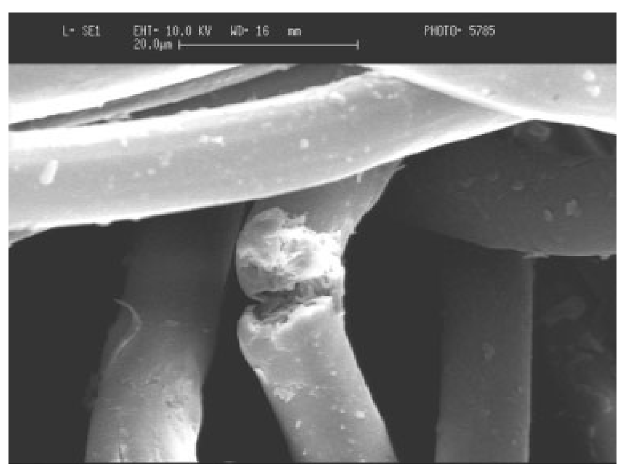


Figure 3 Propagation of transverse cracking during Martindale abrasion test (untreated Tencel fabric).

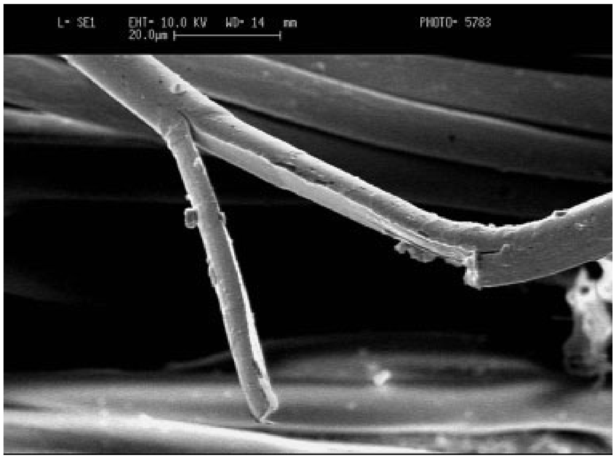


Figure 4 Step breakage of Tencel fiber during Martindale abrasion test (untreated Tencel fabric).

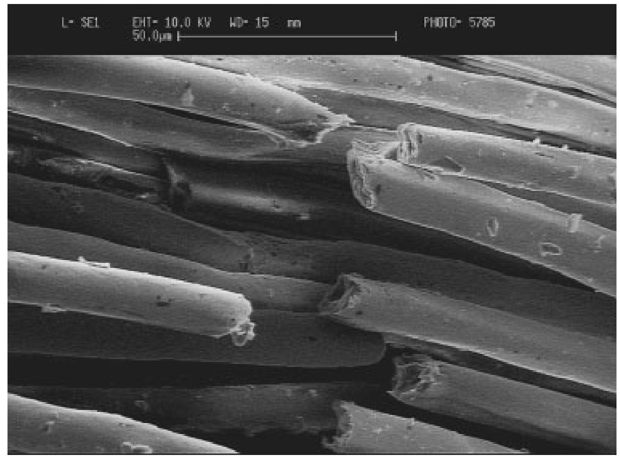


Figure 5 Brittle fiber failure in *Reaktant FC* treated fabric.

Abrasion mechanism of resin-treated Tencel fabric

Easy-care properties of fabric samples treated with *Reaktant DH* and *Reaktant FC* resins are shown in Table I. It should be noted that different resins that can produce almost same improvement in crease recovery may not give the same values for fabric abrasion resistance, as a result of differences in fiber extensibility; the extent to which extensibility is reduced depends on the resin structure and length and extent of crosslinks formed.

Reaktant DH is a commercial product of DMDHEU; its abrasion resistance value indicates that it causes less reduction in fiber extensibility compared to *Reaktant FC*. SEM study on *Reaktant DH* treated samples indicates that the derivatisation on its methylol groups may be with relatively large moieties, which reduce the penetration of the resin into the fiber interior and, therefore, much of the crosslinking takes place at the periphery of the fiber. As a result of the high portion of intramolecular crosslinks and resin deposition, the abrasion mechanism of *Reaktant DH* treated samples was not distinctly different from the untreated fabric. Fiber to fiber cohesion increased, which caused higher frictional forces to develop, and breakdown of the fabric structure occurred in a lower number of cycles compared to untreated Tencel. The main mode of fracture is multiple splitting (due to tensile fatigue) and transverse cracking (due to repeated bending and flexing). Further abrasion also rounded-off the fiber ends and caused axial splitting.

SEM study on *Reaktant FC* treated fabric samples indicates that it forms a high proportion of intermolecular crosslinks with respect to intramolecular crosslinks and polymer deposition, which reduced fiber extensibility to such an extent that the friction force was high enough to break fibers after 2000 cycles and causes almost 74% reduction in abrasion resistance. The main mode of fracture observed is granular rupture of fibers, which appears as brittle fractures, as shown in Figure 5. Internal cohesion between fibril elements causes the excess stress to transfer to neighboring fibril elements and, thus, fibrils break at the adjacent position giving a brittle fracture. There was also evidence of fiber splitting, fiber ends being rounded-off, and axial splitting.

Wet abrasion phenomenon of Tencel fabric

Visually, the main abrasive damage in untreated fabric during laundering is progressive fibrillation; when wet, fiber swelling stiffens the fabric, and the flexibility required to prevent the development of high abrasive stresses is reduced. The complex and repeated

TABLE I
Easy-Care Properties of Tencel Fabric Treated with *Reaktant DH* and *Reaktant FC*

Resin	Resin solids add-on (%)	DCRA[a] (degrees)	% Increase in DCRA[a]	Abrasion resistance (no of cycles)	% Decrease in abrasion resistance
Untreated	–	190.7 ± 4.2	–	10,250	–
Reaktant DH	1.54	221.0 ± 5.1	15.9	5,480	46.5
Reaktant FC	1.64	211.3 ± 5.5	10.6	2,700	73.6

[a] Dry crease recovery angle.

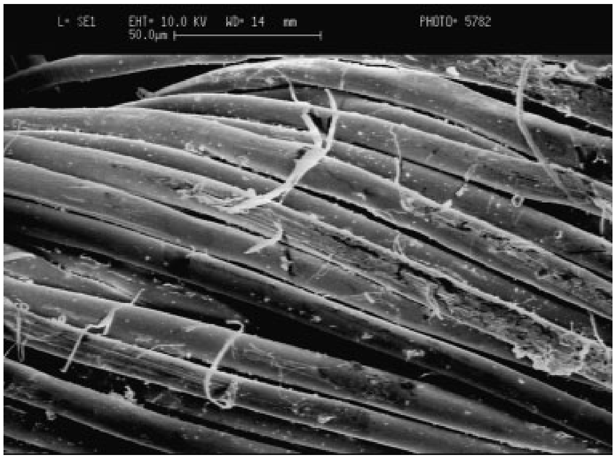


Figure 6 Beginning of fibrillation after first wash of Tencel fabric.

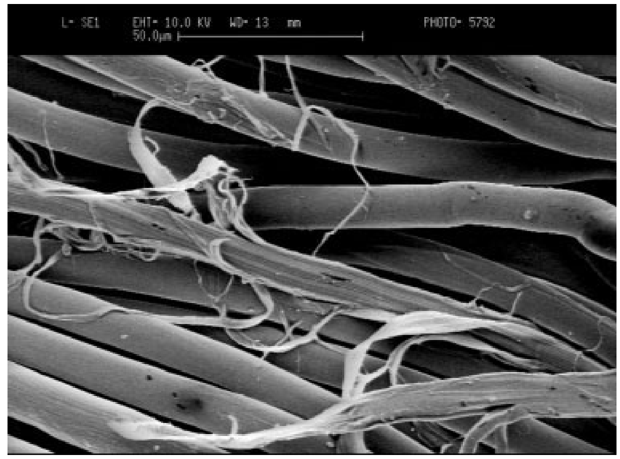


Figure 8 Mild fibrillation observed in *Reaktant DH* treated sample after five washes.

contact abrasion mechanism during laundering causes fibrillation of fibers. It was observed that fibrillation starts from minor cracks (Fig. 6), which with further abrasion causes the complete disintegration of fiber structure, as shown in Figure 7. Macrofibrils were liberated individually or in groups (some crisscross the fiber direction) due to such fibrils being held in fiber structure by relatively weak hydrogen bonding and van der Waals forces. Considerable damage to the fabric also resulted from creasing. In the creases, stresses acting on the fabric vary from maximum tensile effects on the outer curvature of the crease to compressive stresses on the inside. Maximum stresses developed at the outer curvature, which rub against the makeweight fabric (used as 1 kg load) and surface of washing drum, caused successive localized fibrillation. Finally, the lubricating effect of water and detergent also tends to increase abrasion damage due to fiber displacement, fibers displaced from their original position were more vulnerable to abrasion damage, and massive fibrillation was observed.

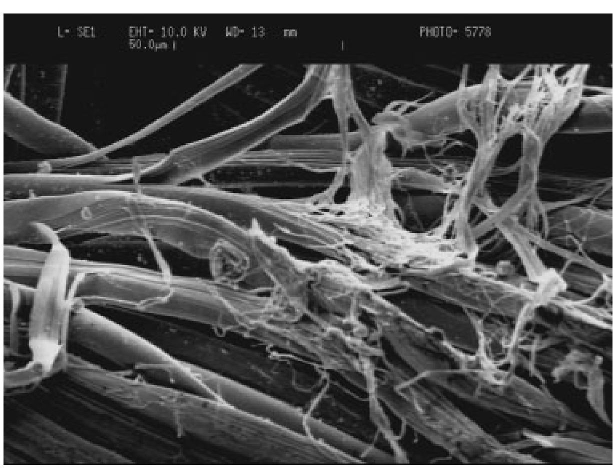


Figure 7 Complete disintegration of fiber through massive fibrillation.

The main advantage of resin finishing is that it prevents the fibrillation tendency of fabric by reducing yarn swelling and by improving lateral cohesion between fibrils. After the first wash, fabric hairiness increased, but in subsequent washes the stiffness caused by resin treatment causes dehairing of the fabric surface. Fiber slippage was reduced, and the spacing between the yarns also helped fibers to release bending stresses by moving toward the neutral plane, resulting in no creasing through the course of five launderings.

The wet abrasion mechanism in *Reaktant DH* samples was different from *Reaktant FC* treated samples. As expected, the intramolecular linkages formed by *Reaktant DH* at the outer periphery were broken by the cumulative effect of laundering; there was little evidence of fibrillation after five laundering cycles, as shown in Figure 8. Small wedges or notches at the surface of the fibers (marked by an arrow in Figure 9) indicate the slicing action by the drum liner; it appeared that the abrasion mechanism in *Reaktant DH* samples is a combination of fiber slippage, bending, and slicing.

In *Reaktant FC* treated fabric, the slicing action is progressive and causes removal of small fragments from the surface of the fibers, and propagation of fiber rupture by slicing action is also evident in Figure 10. In some instances, large segments were peeled from the fibers revealing the inner fibril structure, as shown in Figure 11, which shows that crosslinking between the fibrils had been greatly increased by the *Reaktant FC* resin. Embrittlement of fibers caused by reduced interfibril slippage resulted in transverse cracking and frayed broken ends (Fig. 12), which gives the appearance of fibers being pulled apart.

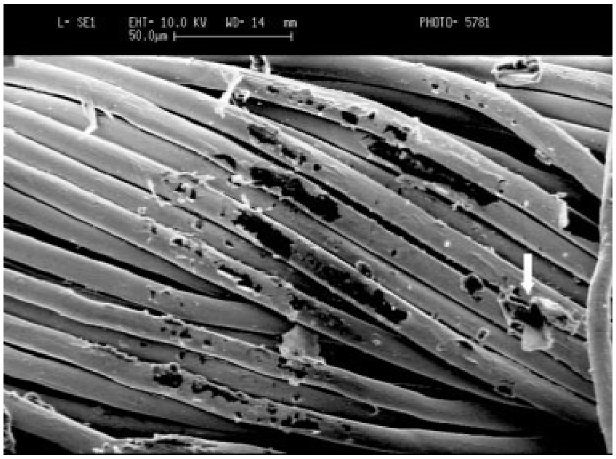


Figure 9 Longitudinal slicing of fiber (white arrow) in *Reaktant DH* treated sample during laundering.

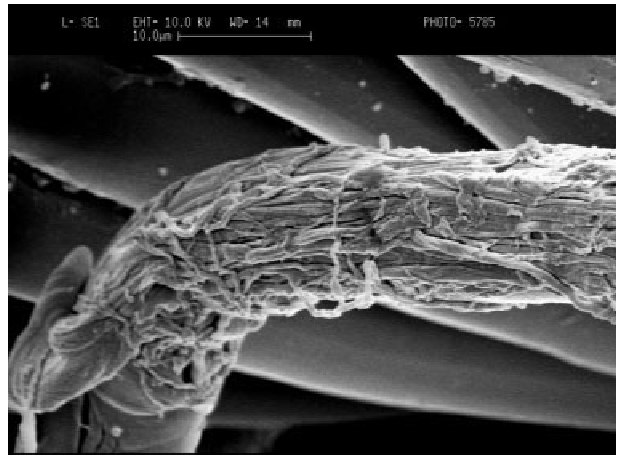


Figure 11 Inner fibril structure of *Reaktant FC* treated fiber.

CONCLUSIONS

Abrasion resistance of woven fabric depends on two factors: the inherent properties of constituent fibers; and the geometric arrangement of fibers in the yarn and arrangement of yarns in the fabric. The geometrical arrangement of spun yarns is particularly important in view of the fact that fiber–fiber interaction plays a major role in fabric behavior; during dry abrasion resistance of Tencel fabric, fiber–fiber interactions contributed significantly to the abrasion behavior of fabric.

When Tencel fabric was treated with *Reaktant DH* and *Reaktant FC* resins, the reduction in abrasion resistance reflected the modified fiber mechanical properties, and reduction in abrasion resistance depended upon the extent of reduction in fiber extensibility caused by different resins. Fiber slippage was reduced due to inter- and intramolecular crosslinking and resin deposition on the fabric surface, which caused higher frictional stresses during Martindale abrasion testing, leading to rupture in a lower number of cycles. The mechanism of fiber failure in untreated and resin-treated fabrics was same, i.e., multiple splitting and transverse cracking of fibers.

When untreated and resin-treated fabrics were repeatedly abraded in a washing machine and tumble dryer, two distinctly different types of damage occurred: in untreated fabric, wet abrasion is the result of swelling of fibers in water and mechanical action of the machine, tearing the fibrils apart; in crosslinked fabrics, lateral bonding between the fibrils markedly reduced the fibrillation tendency of fabric because of reduction in fiber swelling. In *Reaktant DH* treated fabric samples, the intramolecular crosslinks were broken by the mechanical action and, thus, mild fibrillation was observed after five washes, the mechanism being through fiber slippage and slicing action. How-

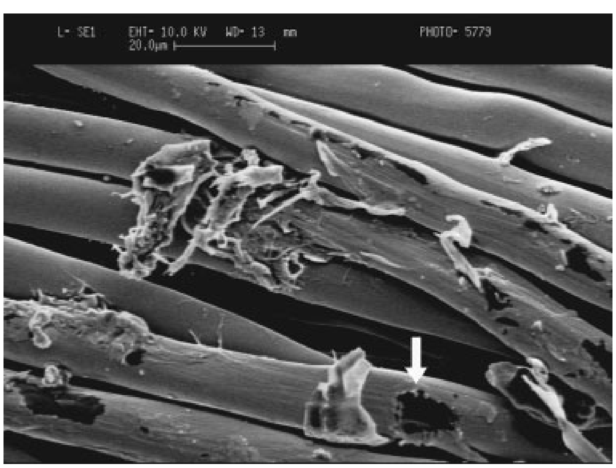


Figure 10 Longitudinal slicing of fiber (white arrow) in *Reaktant FC* treated fabric during laundering and propagation of transverse cracking.

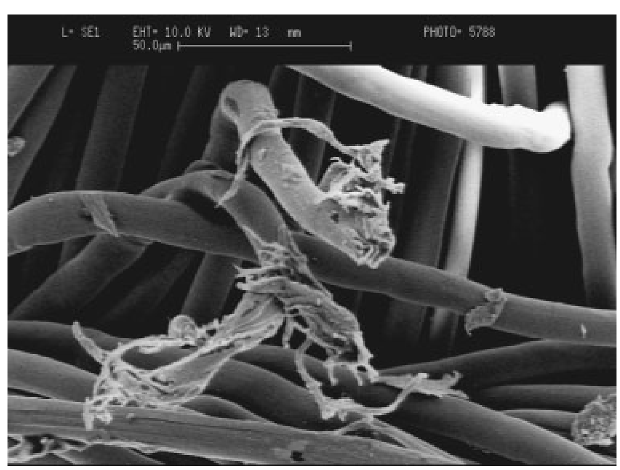


Figure 12 Frayed broken fiber ends observed in *Reaktant FC* treated fabric after machine wash abrasion.

ever, in *Reaktant FC* treated fabrics, the slicing action was more progressive.

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