J. Cosmet. Sci., 49, 213–222 (July/August 1998)

Cuticle decementation and cuticle buckling produced by Poisson contraction on the cuticular envelope of human hair

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Accepted for publication July 15, 1998.

Synopsis

Cyclical extension stresses in dry hair at strain levels between 7% and 15% were seen to produce localized cuticle decementation and buckle formation at the cuticle edges. The experiments show that this type of damage results from circumferential compression stresses on the dry cuticular envelope that acts as a rigid thin-wall pipe during the process of Poisson contraction as the fiber is being elongated. Higher cyclical extensions (>25%) were seen to result instead in cuticle lifting with no buckle formation. This latter type of cuticle damage is similar to the one observed by Reutsch *et al.* and was already ascribed to the action of longitudinal shear stresses. When the hair was moistened or solvent-swollen, no damage was observed at each individual cuticle; instead, long deep transversal cracks and decementation of the whole cuticular envelope from the cortex were observed. The experiments indicate that the lack of individual cuticle damage under swollen conditions results from a strengthened hydrogen-bonding crosslinked endocuticle and from a lesser fiber Poisson contraction when the fiber is swollen. Cuticle buckling and decementation at the cuticle edges like those described above were also frequently found in the hair of a panel of 100 individuals. The prevention and repair of this type of damage is also discussed.

INTRODUCTION

The cuticular envelope of human hair is constituted by six to ten cuticle cells cemented and overlapping each other like shingles on a roof. The role of the cuticle in maintaining the integrity of the whole hair fiber is of paramount importance and has already been discussed elsewhere (1–4). Damage to the cuticle can be produced by a variety of factors such as combing abrasion, UVB light, and chemical treatment (5–9). Therefore, protection of the cuticle from any of these damaging factors is one of the main goals of a hair care formulator. A great variety of conditioners and shampoos have already been formulated with actives that can help to prevent or reduce overall hair damage. Success in fully protecting the cuticle from deterioration depends, however, on understanding the mechanisms involved in the damaging process.

A great deal of progress in this direction has already been made. For instance, changes in cuticle morphology due to combing abrasion have been studied by Swift (1) and by Swift and Brown (2), while several other researchers have analyzed the effects of chemical treatments on the cuticle (5,6). Cuticle lifting and decementation resulting from the imposition of high extension strains (>30%) to hair have also been reported by Reutsch *et al.* (10). These workers have shown that depending on the hair conditions, cuticle lifting may occur by two main mechanisms: 1) cuticle decementation or failure of the cement layer at the cell membrane complex and 2) mechanical failure of the endocuticle. Since an analysis of hair cuticles from a panel of 100 individuals showed that cuticle lifting and buckling at the cuticle edges is a common phenomenon, we decided to investigate the conditions under which this type of damage occurs. In this paper it is shown that localized cuticle decementation leading to lifting and buckling of the cuticles starts to take place when dry hair fibers are cyclically extended at strains higher than 7%. It is also shown that this type of damage can be prevented and even repaired with the use of adequate cosmetic actives.

EXPERIMENTAL METHODOLOGY

Cyclical extensions ranging from 7% to 30% were applied to hair with a Diastron tensile tester in the automatic mode. The number of cycles applied varied between 50 and 200. The extension speed was 120 mm/min, and there was an interval of about two seconds between each cycle. The hair used for all these experiments was from a subject whose hair was washed only with a 10% aqueous SLS solution for a period of one year. The hair fibers used were snippets 2.5 inches long, cut close to the root. Hair from International Hair Importers was also used when needed. Some hair fibers were also allowed to swell for 36 hours in DMSO, IPA, and ethanol, and were then stress-cycled to investigate the effect of swelling on cuticle damage. Hair from a panel of 100 individuals was also analyzed by SEM for cuticle lifting; at least ten fibers per each individual were tested.

Also, in order to test the effect of some cosmetic chemicals on cuticle damage, a different set of fibers was treated with each one of the following aqueous solutions: glycerin, propylene glycol, a cationically modified gluconamide compound (11), hydrolyzed wheat protein polysiloxane copolymer (12), cystine polysiloxane (13), polyacrylate polymer, and polyethylenimide, each of these at a level of 3% w/w. After treatment the fibers were dried at 65% relative humidity (RH) and stressed cyclically. The experiments were carried out in a controlled humidity chamber at 10, 65, 80, or 100% RH. After stressing, the hair fibers were immediately prepared for SEM analysis.

RESULTS AND DISCUSSION

Figures 1a and 1b show typical patterns of cuticle lifting found in the hair of people from the panel. The analysis showed that this type of cuticle damage is present, although to different extents in about 80% of the hair population from the panel. In an attempt to reproduce these patterns of cuticle lifting in the laboratory, first a set of 2.5-inch hair snippets was subjected systematically to tension, torsion, and thermal cyclical stresses. The experiments showed that only the tensile cyclical stresses lead to such patterns of cuticle lifting. The other stresses produced very distinct forms of cuticle damage, and they will be described elsewhere (14). Most of the patterns of cuticle lifting found in this investigation were seen to occur by cuticle decementation or failure of the cuticular cement. For instance, in Figures 1–3 it can be seen that the sections of lifted cuticles do

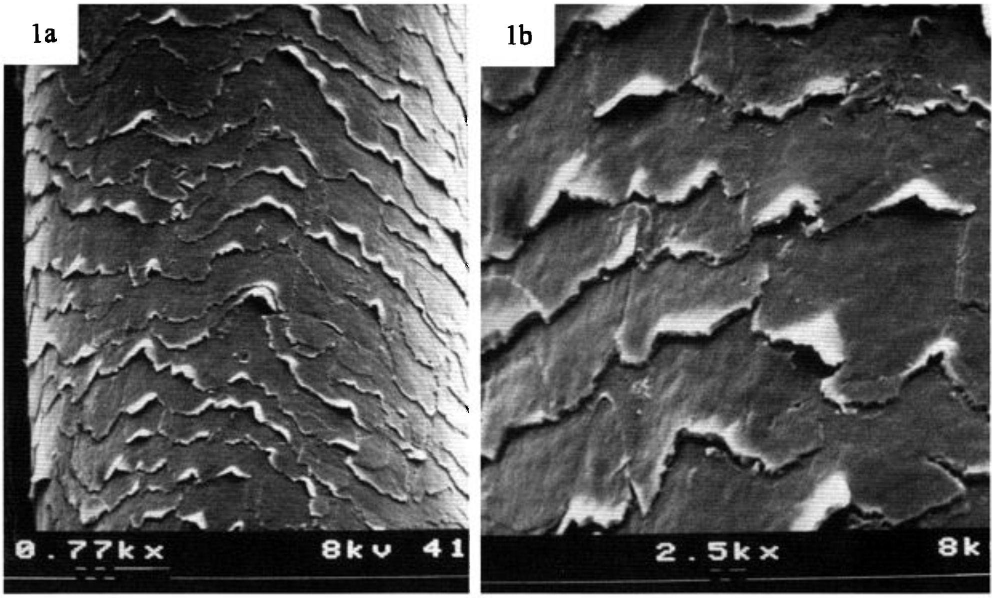

Figure 1. Typical patterns (1a and 1b) of cuticle lifting and buckling found in hair from a panel of 100 individuals.

not show the presence of endocuticular debris at their internal surfaces, indicating, thus, the absence of endocuticular rupture. In these micrographs it can be seen that the damaging stresses not only produce failure of the cuticular cement but also force the cuticle cells to bend and distort, forming a buckling effect. As will be discussed in the following paragraphs, this type of cuticle lifting was found to increase with the number of applied tensile cycles and was observed to be very sensitive to moisture.

EFFECTS OF RELATIVE HUMIDITY AND NUMBER OF STRAIN CYCLES

In general, it was observed that the lower the moisture content in the testing chamber the lower was the inception strain level needed to produce cuticle lifting and buckling. Furthermore, at constant moisture the number of lifted and buckled cuticle cells increased with the number of strain cycles and also with the strain level. For instance, in Figures 2a, 2b, and 2c are shown surfaces of hair fibers subjected to 50, 100, and 200 strain cycles, respectively, under a constant strain level at 10% extension and a relative humidity of 10%. In this figure it can be seen that the number of cuticle edges lifted and buckled increases with the number of stressing cycles. It should be mentioned here that although the number of decemented and lifted cuticle edges was seen to increase with the number of strain cycles, the size of the cuticle decemented area was observed to increase only with the strain level. In Figure 3 is shown the surface of a hair fiber subjected to 200 cycles but at a higher extension (25%) and at 10% RH.

As the moisture content in the chamber housing the tensile tester increased, the cuticle decemented area decreased and the number of lifted and buckled cuticle cells decreased considerably. This was also true even when the fiber was strained beyond 30%. For instance, in Figures 4a and 4b are shown the surfaces of hair fibers subjected to 200

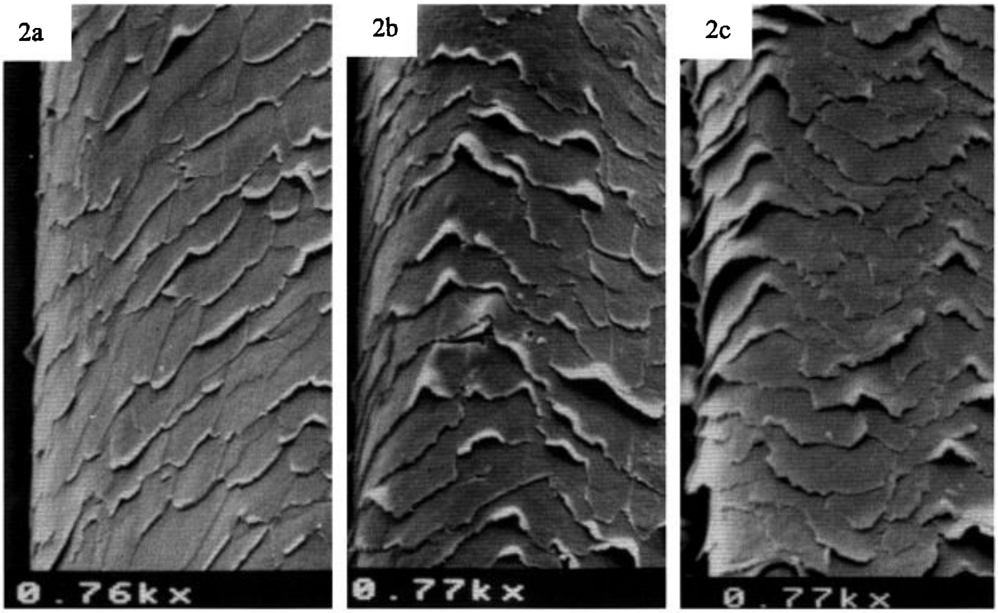

Figure 2. Surfaces of hair fibers after cyclical extension of 10% at 10% RH with different numbers of strain cycles as follows: 1a, 50 cycles; 1b, 100 cycles; 1c, 200 cycles.

strain cycles under a constant extension value of 15% but at two different moisture contents, namely 65% and 80% RH, while in Figure 4c is presented the surface of a hair fiber subjected to 200 strain cycles at an extension of 30% and 100% RH. In these figures it can be clearly seen that when a higher amount of moisture is absorbed by the hair, little to no damage is observed on any of the individual cuticle cells; instead, the damage takes place on the whole cuticular envelope. In Figures 5a and 5b it can be seen in more detail that after stressing a hair fiber at 100% RH and 30% extension, the cuticle envelope has been detached from the cortex and cut transversally by deep cracks.

EFFECTS OF SOLVENT SWELLING

In order to investigate whether the absorption of other solvents had an effect similar to that of water and to determine whether swelling is a phenomenon related to the disappearance of cuticle lifting and buckling, several hair samples were strain-cycled during immersion while swelling in the following solvents: DMSO, ethanol, and isopropanol. The experiments showed that when hair fibers are strain-cycled at 15% extensions, 10 or 15 minutes after their immersion in any of these solvents, the cuticle still decements and buckles in a manner similar to that of fibers tested under the most extremely dry conditions. However, if longer swelling time periods are allowed to elapse, the degree of cuticle lifting and buckling decreases considerably, until it disappears totally after 36 hours of hair swelling. The fibers that were tested fully swollen presented deep transversal cracks identical to those produced at high moisture contents.

The fact that the cuticle is seen to be lifted soon after solvent immersion indicates that plasticization of the cuticle cement by the solvent plays only a limited role in eliminating cuticle lifting and buckling. It seems, rather, that when a non-swollen or dehy-

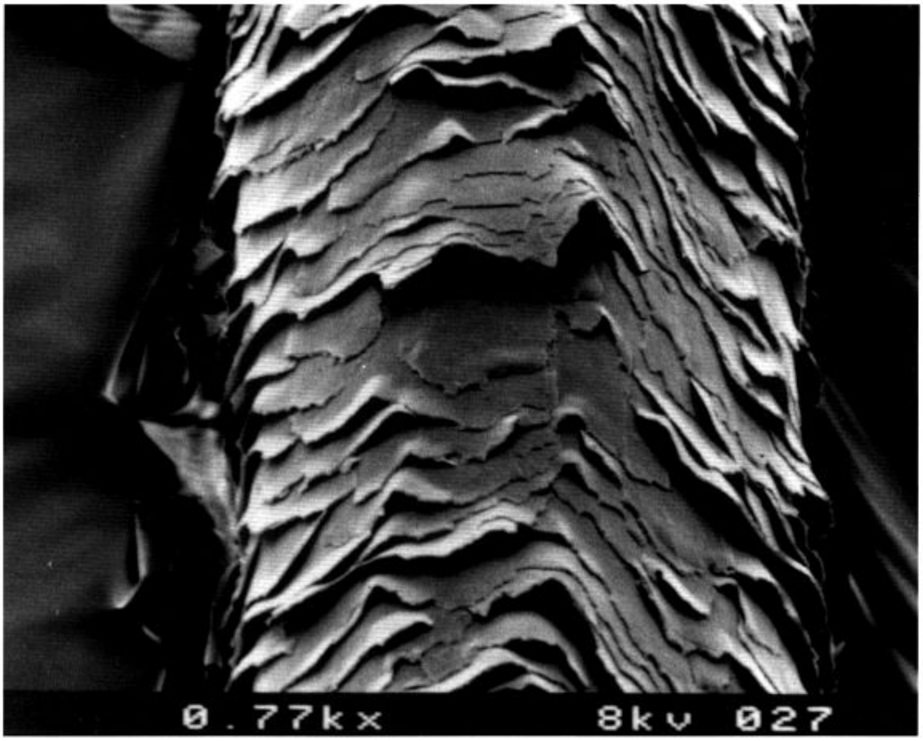

Figure 3. Surface of a hair fiber after 200 strain cycles at 25% extension and 10% RH.

drated fiber is being elongated, its cuticular envelope acts as a laminar rigid thin-wall pipe under a process of radial compression. Such a compression process is the result of the fiber's Poisson contraction as the fiber is elongated; the term "Poisson contraction" is used in mechanics of solids to describe the lateral contraction experienced by a slab of material when subjected to tensile deformations. The compression stresses can usually be calculated from the Poisson's ratio, which is the ratio of the strain in the lateral direction to that in the axial direction (15). In the case of hair, calculations reveal that when 7%, 15%, or 30% tensile strains are imposed on the hair fiber, its cortex radius decreases by 4.6%, 7.1%, and 12.0%, respectively. Such radial contractions acting on the dry and rigid cuticular envelope will, certainly, generate circumferential compression stresses capable of decementing and buckling the cuticle. As is well known, a typical form of failure in thin-wall pipes under compression is wall buckling, a phenomenon that takes place after the circumferential compression stress reaches a certain limit (15,16).

Since cuticle lifting and buckling are mostly observed at low extensions (see Figures 2a, 2b, and 2c), it can be inferred that compression and shear stresses in the fiber circumferential direction cause more cuticle damage at low elongations (7–15%), while at higher extensions (25–40%) the predominant longitudinal shear stresses with a small component of circumferential compression stresses will produce the massive cuticle lifting observed in Figure 3. Thus, when a dry fiber starts to be elongated, its cuticle will first experience strong circumferential compression stresses and later at higher extensions will be subjected mostly to the type of longitudinal shear stresses discussed by Reutsch *et al.* (10).

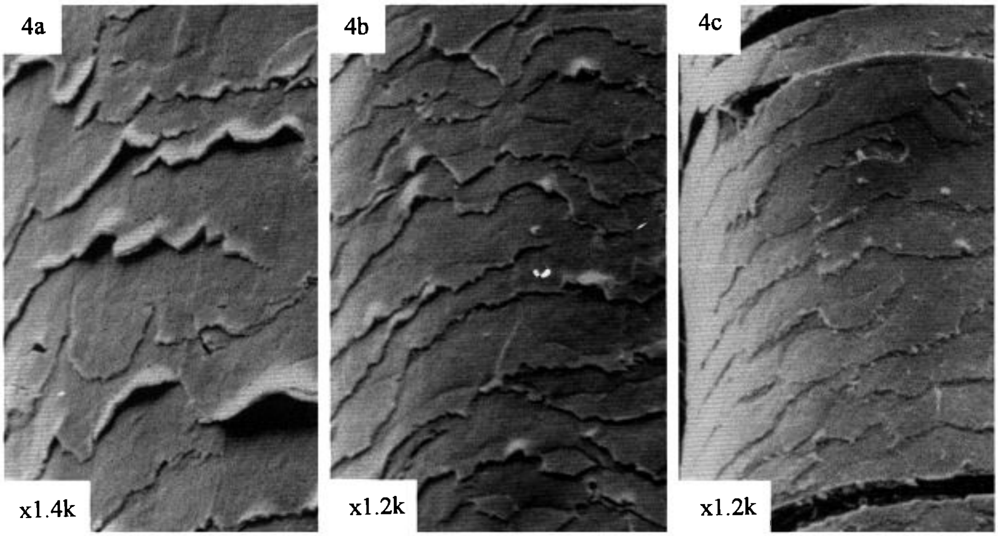

Figure 4. Surfaces of hair fibers after 200 strain cycles at different relative humidities and different extensions as follows: 4a, 65% RH and 15% extension; 4b, 80% RH and 15% extension; 4c, 100% RH and 30% extension.

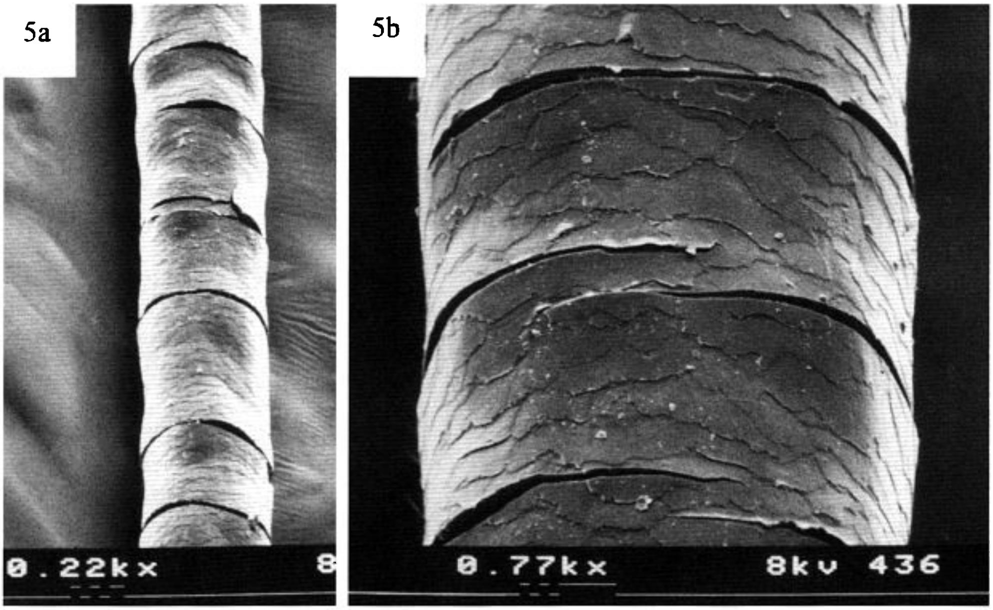

Figure 5. Surface of a hair fiber after 200 strain cycles at 30% extension at 100% RH showing deep transversal cracks and cuticular envelope detachment from the cortex. 5a ×220; 5b ×770.

In contrast, when the volume of a hair fiber is increased by solvent or water swelling, the cortex and cuticular envelope expand radially. Under these conditions, two main phenomena will occur: first, the endocuticular regions of the fiber will act as a soft swollen gel highly crosslinked by hydrogen bonding, and second, the Poisson contraction will be considerably less than when the fiber is not swollen. The first phenomenon will

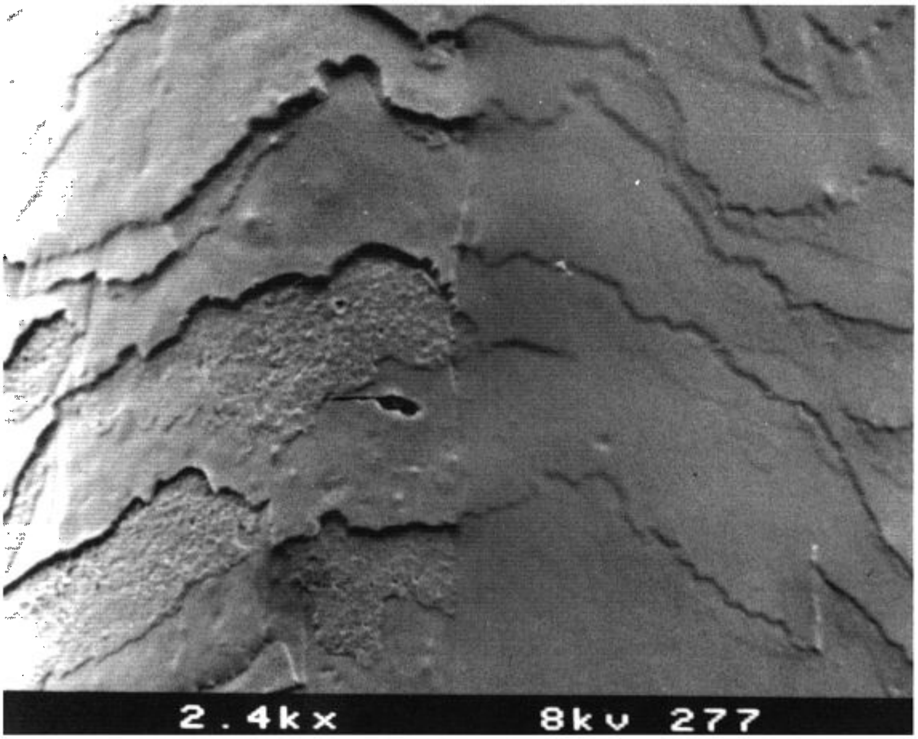

Figure 6. Surface of a hair fiber half of which was treated by capillarity with a 3% aqueous solution of hydrolyzed wheat protein polysiloxane copolymer.

strengthen and give more elasticity to the endocuticular regions, while the second one will substantially reduce the circumferential shear and compression stresses. The occurrence of these two phenomena will, certainly, account for the observed lack of individual cuticle damage when the fibers are subjected to low and high extensions (7–40%) under swollen conditions (see Figures 5a and 5b). The results also suggest that after the endocuticular regions have been strengthened and expanded by swelling, the cementing junction between the cortex and cuticular envelope becomes the weakest link, which breaks by the shear stresses set up at high extensions. Once the cuticular envelope and cortex are separated along the fiber, extension stresses act alone on the swollen cuticular envelope, producing the long, deep transversal cracks observed in Figures 5a and 5b.

EFFECTS OF FIBER PRETREATMENT

Hair fibers that were pretreated with 3% aqueous solutions of glycerin or propylene glycol without rinsing, followed by a drying period of six hours, did not present severe patterns of cuticle lifting and buckling when strain-cycled. However, if the hair fibers were rinsed before cycling, cuticle decementation took place. These experiments indicate that the presence of small amounts of low-vapor-pressure swelling solvents in the hair fibers helps to swell and plasticize the cuticle, preventing lifting and buckling. Treatment of hair fibers with a 3% w/w aqueous solution of a cationically modified gluconamide compound (11) was also effective in preventing cuticle lifting and buckling, even when the fiber was rinsed after treatment. The preventive effect of some cosmetic actives like these probably arises as a consequence of the presence of moisture or swelling solvents in the hair, which were already seen to inhibit cuticle lifting and buckling.

It was also observed that lifted and buckled cuticles returned to their normal appearance after immersion in water; a similar observation was also made by Reutsch *et al.* (10). Decementation of the cuticles could, however, be easily brought back with a lower number of strain cycles at very low strain levels. This was not the case when the lifted cuticle cells were treated with a hydrolyzed wheat protein polysiloxane copolymer (12). This cosmetic active, which crosslinks upon drying, was seen to form a flexible thin film capable of recementing the lifted cuticles, increasing the decementing strain threshold. The thin film was also seen to be very smooth, i.e., in Figure 6 it is shown that the half portion of a hair fiber treated with this protein/copolymer is smoother than the other half, which was untreated. It is interesting to note that polymeric materials have been used in the past to stabilize the intercellular cement of wool (17).

An even stronger cuticle-cementing polymer was cystine polysiloxane (13); this protein-silicone copolymer when used at 2% or 3% w/w levels was capable of rendering lifted cuticles very resistant to redecementation. For instance, it was observed that lifted and buckled cuticles returned to their natural position upon water immersion; however, when the hair fibers were tightly knotted, the cuticles lifted again. This was not the case when the cuticles were treated with a 3% aqueous solution of cystine polysiloxane prior to knotting (see Figures 7a and 7b).

Other polymers tested at 3% w/w in an aqueous solution were polyacrylate polymer and polyethylenimine (PEI). These polymers were seen to penetrate between the spaces left by the decemented cuticles and to cause swelling of the cuticle even when the hair was dry. Both polymers seemed to reduce cuticle lifting in virgin fibers but failed to reglue the already decemented ones. Also, after blow-drying of the hair, both polymers seemed

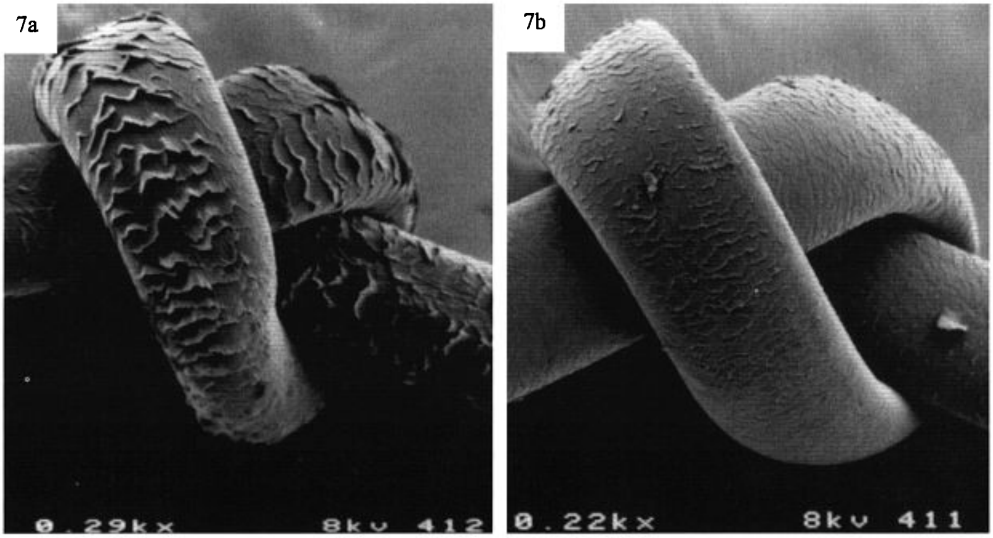

Figure 7. Surfaces of two hair fibers treated as follows: 7a treated with 200 extension cycles, 20% extension, at 10% RH, then water immersed and knotted; 7b treated with the same process as the fiber in 7a but with a 3% aqueous solution of cystine polysiloxane before knotting.

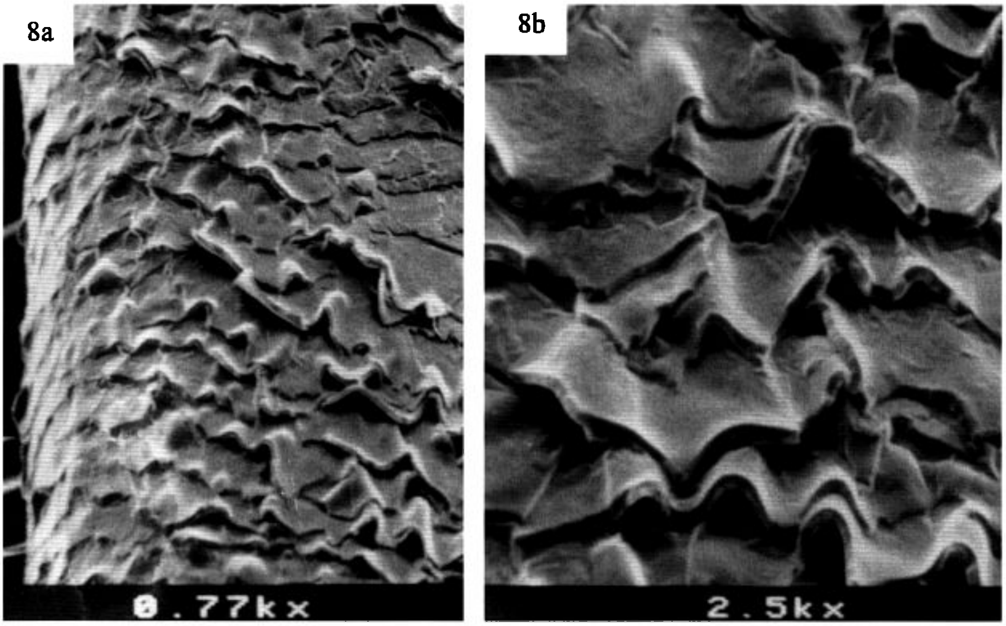

Figure 8. Surfaces of decemented cuticles treated with a 3% aqueous solution of polyethylenimide (PEI) after three cycles of wetting/blow drying. 8a ×770; 8b ×2500.

to cause severe cuticle shape distortion. In Figures 8a and 8b are shown decemented cuticles treated with PEI after three cycles of wetting/blow drying. In these figures it can be clearly seen that after blow/drying the decemented cuticles appear severely distorted. From these observations it can be inferred that decemented cuticles can be distorted or reglued depending on the mechanical properties of the dry polymer.

CONCLUSIONS

The experiments show that strain cycles at low extensions in dry hair fibers produce lifting and buckling at the cuticle edges. Strain-cycling experiments with swollen fibers indicate that decementation and buckling of the cuticles is caused by circular compression stresses on the cuticular envelope. It is also shown that this type of damage can be prevented and repaired by using appropriate hair swelling actives or by pretreating the fibers with appropriate polymeric substances capable of recementing the cuticles.

ACKNOWLEDGMENTS

The author wishes to thank Ann Harder for her valuable technical assistance and Herb Eldestein for his helpful discussions.

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