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The cracking of human hair cuticles by cyclical thermal stresses

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Synopsis

Cycles of wetting and blow-drying were applied to hair fibers and resulted in the formation of multiple cracks on the hair cuticles. The peculiarity of these cracks was that they always appeared aligned parallel to the longitudinal axis of the hair fiber. The cracks appeared to be initiated at the end of the cuticles close to the cortex and propagated invariably towards the outer cuticle edges. The maximum growth length of each crack was seen to be limited to the size of one cuticle. Crack formation did not only occur at the outer edges of the cuticles but also took place in the second and third overlaid hidden cuticle sections. The results show that these cracks form when the external portions of the cuticles undergo drastic reduction in their hydration water. Under these conditions the outer cuticle portions become rigid and brittle and crack by the action of circumferential tension stresses arising from the swelling pressure of both the cuticle layers underneath and the cortex itself. Hair cuticle analysis from a panel of 100 individuals showed that these cracks are present in the hair of people who commonly blow-dry their hair and appear to a much lesser extent in the hair of subjects who do not practice this type of grooming process. The combing of hair fibers presenting this type of cracking was seen to result in the breakage of large portions of cuticle. The effect of some cosmetic actives on the formation of these cracks is also discussed.

INTRODUCTION

Hair cuticles represent the hair structure components most exposed to various grooming and environmental stresses during the life of a hair fiber. The outer cuticles at the hair surface are frequently subjected to harsh stresses such as abrasion, UV light, bleaching, and blow-drying (1–4). It is well known that once the cuticles are one or two centimeters away from the hair root, patterns of breakage and abrasion start to appear at the cuticle edges (5). By the time the hair is about 14 or 20 cm long, if not enough care is taken, the cuticles might be totally absent at the tips, giving rise to the earlier formation of split ends (6). It is mostly because of these reasons that the effects of combing abrasion on hair cuticles have been thoroughly studied in the past. There are, however, other grooming practices, such as hair blow-drying, whose effects on the cuticle degradation process are still poorly understood.

As it is well known, hair blow-drying is nowadays a common practice by many people. When keratin fibers are heated, not only water adsorbed to hair by capilarity is rapidly evaporated but there is also a rapid loss in the free and bound water of the hair (7,8). The rapid loss of hydration water may cause morphological changes within the cortex due to destabilization of the keratin crystalline regions (9). The consequences of this type of process in hair cuticles after cyclical thermal stresses have not yet been analyzed. This paper represents part of a study whose aim is to reproduce patterns of cuticle damage found in a panel of 100 individuals (10). This article reports the production of small longitudinal cracks by cyclical thermal stresses. The cracks were mainly found in the hair cuticles of subjects who frequently blow-dry their hair.

EXPERIMENTAL METHODOLOGY

The panel of 100 individuals participating in this study was mainly composed of women with Caucasian brown hair never treated chemically. A total of ten fibers per each individual was analyzed. The different patterns of cuticle damage found in these individuals such as cuticle decementation, abrasion, craters, and cracks were classified and quantified. Cycles of mechanical tension, torsion, bending, and thermal stresses were then applied to single hair fibers in order to reproduce such patterns (10). Only the cyclical thermal stresses were seen to reproduce the types of cracks mentioned above, and therefore, only the experimental conditions related to this type of stress will be described here. The other types of damage and experimental conditions are described elsewhere (10–12). Each thermal cycle consisted of immersing single hair fibers for a period of ten seconds into de-ionized water followed by ten seconds of blow-drying. The temperatures used during blow-drying and measured at the level of the wet hair surface varied between 30° and 120°C. The number of applied wetting/blow-drying cycles varied between five and 100 as required. A total of ten fibers per each set of thermal cycles was analyzed for short longitudinal cuticle cracks. The number of these cracks per millimeter of hair was then counted. From this data, means and standard deviations were calculated. Prior to the thermal cycles the fibers were thoroughly washed with SLS and rinsed with tap water.

The hair used in the single-fiber experiments was from a subject whose hair was washed only with a 10% SLS aqueous solution for a period of one year. Sections of hair fibers three inches long and cut close to the root were used in the experiments. The hair fibers were subsequently cut into two snippets 1.5 inches long each; one snippet was used as a control while the other one was subjected to thermal cycling. All selected hair fibers presented an average diameter of 82 + 11 μm. Caucasian virgin brown hair from International Hair Importers in the form of tresses was also used to study effects of combing abrasion on wet/blow-dry cycled hair. Aqueous solutions of glycerin, propylene glycol, polyquaternium 11, cetrimonium chloride, steralkonium chloride, and hydrolyzed wheat protein polysiloxane copolymer (13) at a 2% w/w were also used as wetting solutions during thermal cycling. These solutions were prepared in order to test the effect of some cosmetic actives on cuticle cracking. After thermal cycling, the fibers were prepared for SEM analysis.

RESULTS AND DISCUSSION

SHORT LONGITUDINAL CUTICLE CRACKS FOUND IN A HAIR ANALYSIS FROM A PANEL OF 100 INDIVIDUALS

SEM analysis of hair fibers pertaining to subjects in the panel showed that most of them presented different numbers of short longitudinal cracks in their cuticles. The population of these individuals could, however, be divided into two main groups, namely one with a high number of cuticle cracks and the other with a very low number. The first group, representing about 40% of the panel, showed an average of 184 ± 15.5 cracks per mm of hair (cpmh), while the other 60% showed an average of about 7 ± 1.3 cpmh. Figures 1a and 1b show typical images of these cracks as found in the panel analysis. Incidentally, the higher number of cuticle cracks corresponds to the hair of people who manifested to blow-dry their hair on a daily basis. It was precisely this observation that suggested the possibility of reproducing the cracks in the laboratory by cycles of wetting and blow-drying. In Figure 1 it can be seen that the particularity of these cracks is their position on the cuticles, i.e., they always appear aligned parallel to the longitudinal axis of the hair fiber, and their length is no longer than a single cuticle size. The cracks were found to occur more frequently at the discontinuities formed by the cuticle edges. They seemed to be initiated near the middle section of the cuticle at that end close to the cortex. Their direction of propagation also seemed to be towards the outer edges of the cuticles. Figure 1b shows, for instance, a long crack whose width is larger at the cuticle end close to the cortex and very sharp at its tip towards the outer edge of the cuticle; this crack has not yet been able to propagate all the way throughout the outer cuticle edge.

CRACK REPRODUCTION IN THE LABORATORY

After observing that the short longitudinal cracks were consistently found in a large portion of people from the panel, a way to reproduce them in the laboratory was researched. First, single hair fibers were subjected systematically to cyclical tension, torsion, and bending stresses, and it was found that none of these conditions could reproduce the cracks. The cuticle patterns of damage resulting from these stresses have been reported elsewhere (10–12). The next step was to take fibers three inches long and

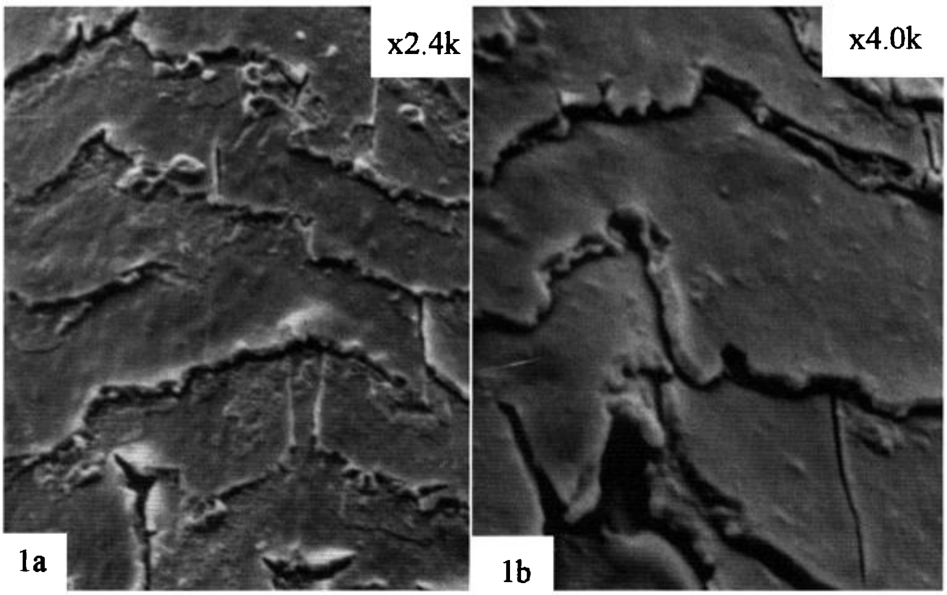


Figure 1. Typical cuticle cracks found in hair from individuals who blow-dry their hair. 1a, ×2.4k; 1b, ×4.0k.

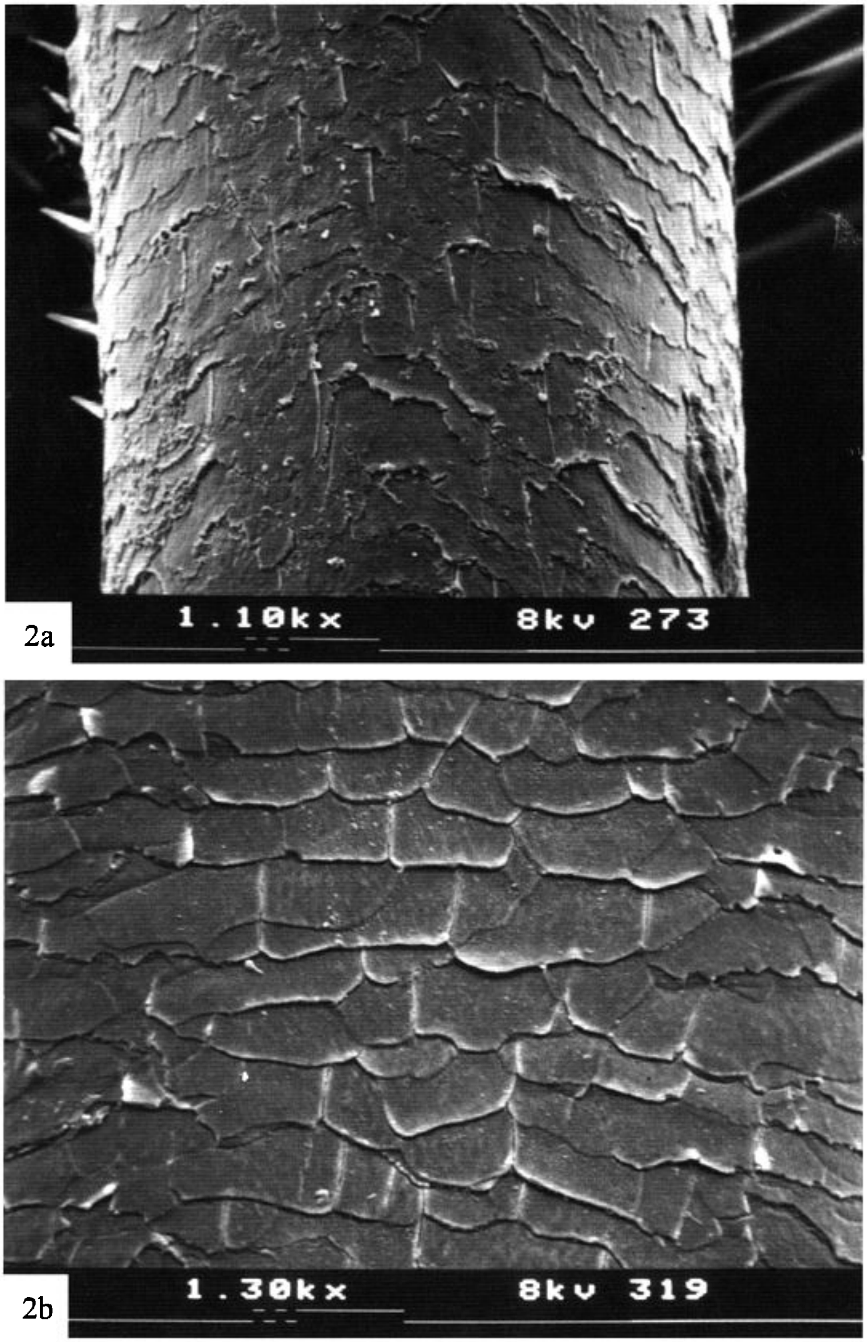
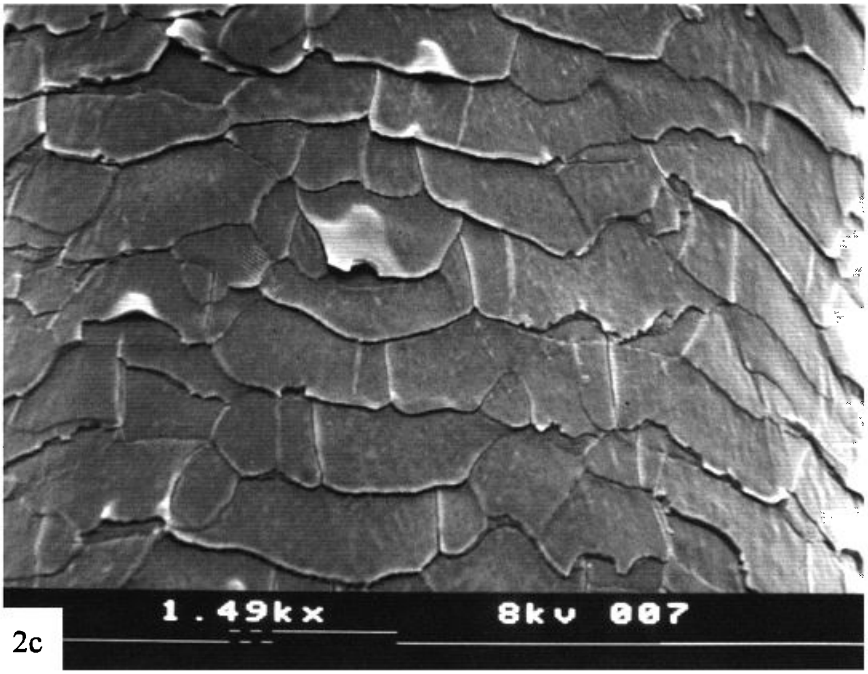


Figure 2. Cuticle cracks reproduced in the laboratory as follows: 2a and 2b after 20 thermal cycles; 2c after 60 thermal cycles.



2c

Figure 2. Continued.

cut them in half. One half was used as a control, and the other half was subjected to cycles of blow-drying and wetting at different temperatures and for different intervals of time. The number of cracks already present in the control were counted and compared with those appearing in the thermally cycled fibers. A total of ten fibers per each trial were analyzed. The average number of cracks per millimeter found in the control samples was 6 ± 2.1.

After several trials it was found that short thermal cycles of ten seconds of blow-drying at 75°C combined with ten seconds of wetting at 25°C were able to reproduce and increase dramatically the number of short longitudinal cuticle cracks. In Figures 2a, 2b, and 2c are shown typical images of hair fibers subjected to 20 and 60 of these cycles. A total of 21 cracks can be counted in the 76 × 52 micrometer section of hair represented in Figure 2b. In Figure 2c it can be seen that the total number of visible cracks reaches a value of 26; the surface hair dimensions captured by this micrograph are approximately 67 × 42 microns. The number of cracks shown in Figures 2b and 2c correspond to an average of 472 and 562 cracks per millimeter of hair, respectively. Such high concentrations of cuticle cracks are rarely found in people's hair and can only be produced in the laboratory. Figures 3a, 3b, and 3c show higher magnifications of these cracks, while Figure 4 shows the average number of cuticle cracks found in hair samples as a function of thermal cycles in relation to the control. In this last figure it can be seen that the number of cracks per unit area on the hair surface increases up to a limit and then levels off with the number of thermal cycles.

A close examination of Figures 1, 2, and 3 reveals that, in all cases, the applied thermal cycles resulted in the production of cracks similar to those already observed in the panel

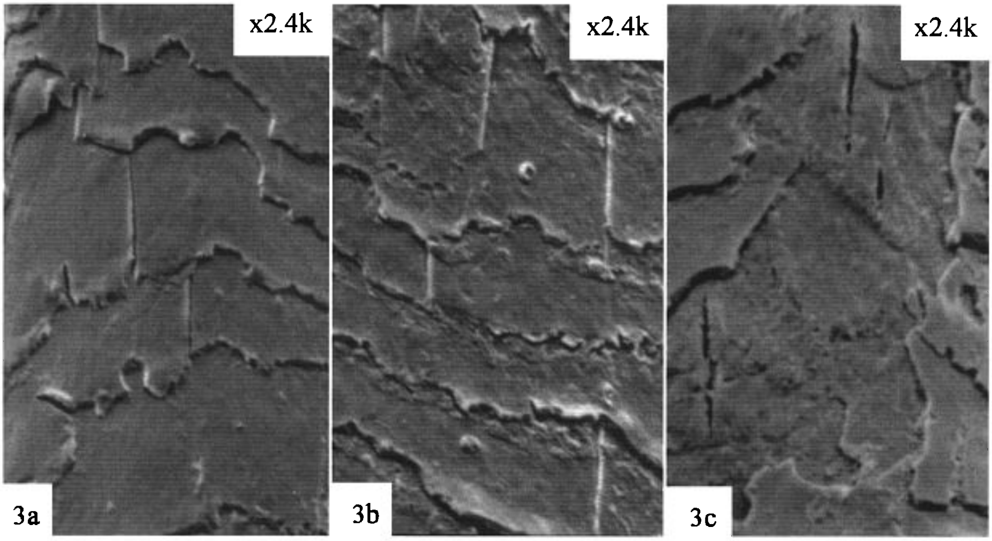


Figure 3. Magnified views of cracks shown in Figure 2 as follows: 3a after 20 thermal cycles; 3b and 3c after 60 thermal cycles. Each cycle consisted of ten seconds of blow-drying at 75°C followed by ten seconds of wetting at 25°C.

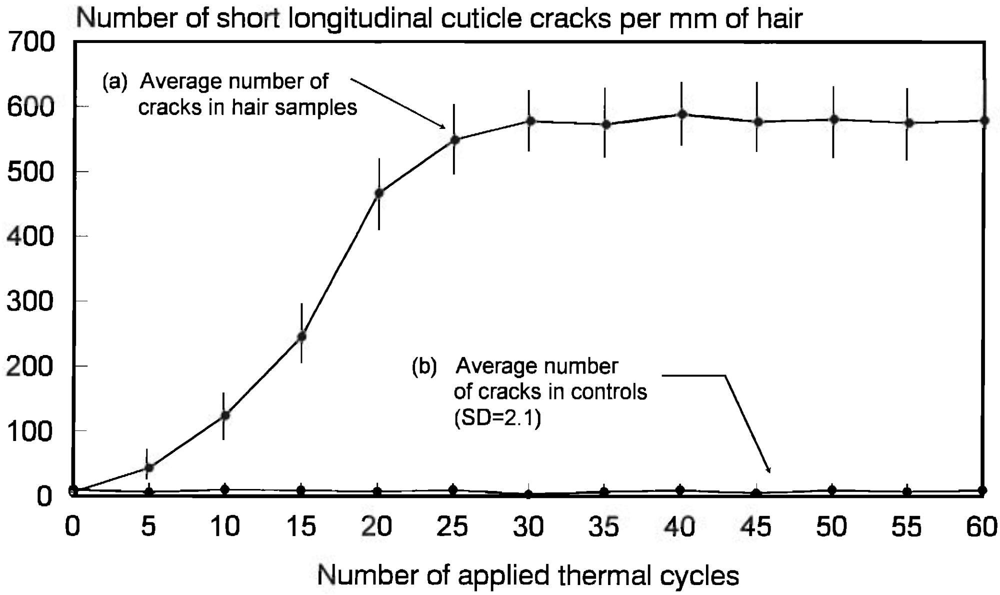


Figure 4. Variations in the average number of cuticle cracks found in the laboratory as follows: (a) in thermally cycled fibers as the number of thermal cycles increases, and (b) in their corresponding half snippet used as a control (non-exposed to thermal cycles). Each point represents average of cracks found in ten hair samples. Each cycle consisted of ten seconds of blow-drying at 75°C followed by ten seconds of water immersion at 25°C. Error bars represent one standard deviation about the mean.

analysis. This observation clearly shows that the cuticle cracks found in hair subjects from the panel arise mainly as a consequence of subjecting hair to thermal stresses during blow-drying. An analysis of the cracks shown in Figures 1, 2, and 3 indicates that their formation is mainly limited to the outer part of the cuticles. This observation suggests that the stresses involved in crack formation are more intense at those cuticle portions near the outer hair surface. Since blow-drying and wetting involves swelling and deswelling of the hair fiber, the following experiment was carried out in order to test whether the phenomenon of swelling *per se* plays a role in crack formation. Several solvents with limited swelling capacity were used in the thermal cycling experiments instead of water. The solvents were ethanol, iso-propanol, and methanol; these solvents have already been reported in the literature as poor keratin swelling solvents (14–16). The results showed that thermal cycling experiments with these solvents do not lead to crack production at all, indicating that cuticle swelling is a necessary phenomenon for cracks to occur.

Increasing both the water-swelling and blow-drying times to periods longer than ten seconds did not have any effect on the number of produced cracks. Also, it was observed that non-swollen hair fibers, which were thermally cycled with water immersion time periods as short as five seconds, underwent cuticle cracking. In such short time periods of water immersion, only the cuticular system and a small portion of the cortex can be expected to swell. These observations indicate that cuticle cracking is not due to a thermal shock arising from rapid changes in cuticle temperature. It seems rather that cuticle cracking occurs because those outer cuticles sections lack elasticity to comply with the dimensional changes either of the swelling cuticle layers underneath or of the swelling cortex.

In the case of blow-drying, the lack of elasticity in the outer cuticle sections will originate from rapid cuticle dehydration at high temperatures. Thus, it would appear that when hair is wet or dried at room temperature, all cuticle portions and the cortex contract in a synchronous manner. However, if during a water evaporation process only the outer cuticle sections contract more rapidly than those cuticle layers underneath or than the cortex itself, cracking will occur. Cracking during blow-drying takes place, thus, as a consequence of circumferential extension stresses set up on dry portions of cuticle by the swollen pressure of both the cuticle layers underneath and the cortex itself. It should be mentioned here that circumferential or "hoop" stresses are known to occur in cyclindrical pipes subjected to internal positive high pressures (17). Cracks at lower hair-swelling pressures may also occur if the cuticles lose their natural elasticity due to weathering. This might explain why cuticle vertical cracks are found at lower hair-surface concentrations in people who do not blow-dry their hair.

The repetitive action of cuticle "rigidization" and water swelling set up on the outer cuticle sections by the absorption and desorption of water during thermal cycling did not lead immediately to crack formation. For instance, it was found that before the cracks became fully developed, they appeared first as sharp white lines on the cuticle surfaces (see Figure 5a); then, upon further thermal cycling, the white lines turned into full cracks. The appearance of these white lines indicates that before the cuticles crack, the mechanical energy accumulated by the circumferential tension stresses or "hoop stresses," is first dissipated by the formation of localized shear yield regions. This form of mechanical energy dissipation is a very common phenomenon that takes place in polymeric materials before they fracture (18).

Increasing the water temperature during thermal cycling to about 50°C resulted in more diffuse and wider shear yield regions that did not turn into cracks even after the

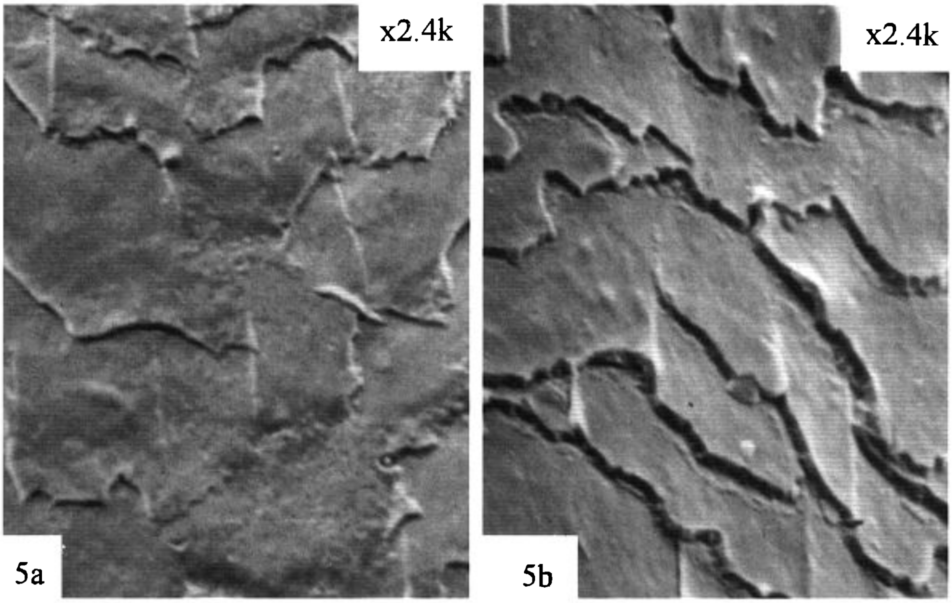


Figure 5. Cuticles with shear yield regions formed before cracking takes place (5a) and with shear yield regions produced during thermal cycling with water at 50°C (5b).

application of a high number of thermal cycles (see Figure 5b). Below this temperature, shear yield regions and cracks were always produced. Thus, increasing the water-swelling temperature during thermal cycling softens the cuticle proteins, preventing the shear yield regions from becoming full cracks. It should be mentioned here that those cuticles cracked thermally were seen to be easily broken during hair combing. For instance, Figure 6 shows a hair fiber from a tress that has been subjected to thermal cycles followed by combing. This micrograph shows that the removal of cuticles by abrasion occurs mainly at the cracked sites.

EFFECTS OF BLOW-DRYING AND WATER TEMPERATURE

The temperature at which air from the blow-dryer reaches the hair surface seemed to be crucial in the incubation and propagation of thermal cracks. In the trial experiments it was observed that the average number of cracks produced for a particular number of cycles was maximum when the hair surface temperature was maintained for about ten seconds between 75° and 95°C. In Figure 7 is shown the average number of cracks as a function of air temperature at the wet hair surface. In this figure it can be seen that temperatures lower than 50°C do not increase the average number of cracks already present in unexposed hair, while temperatures higher than 95°C lead rather to hair surface and bulk distortion. It is quite plausible, thus, that temperatures lower than 65°C do not produce the critical rate of water evaporation needed for the top part of the cuticles to contract and become rigid, while temperatures higher than 85°C might soften the cuticle proteins, releasing, thereby, the mechanical stresses by viscous flow.

The temperature rate used during thermal cycling was found also to be an important parameter. For instance, if the hair surface temperature was increased at a very slow rate,

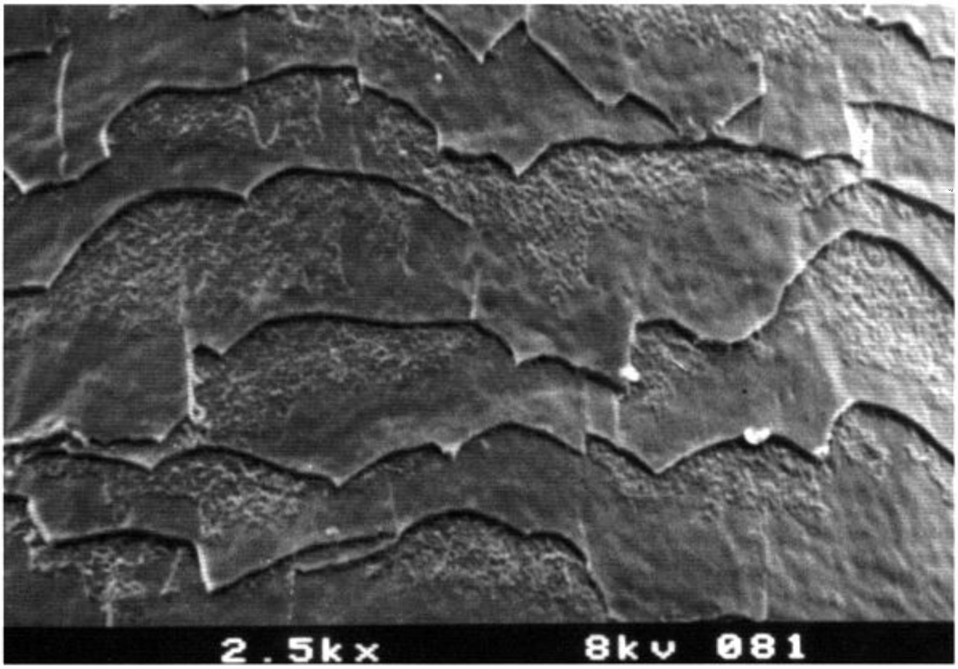


Figure 6. Typical combing abrasion pattern of hair with cracked cuticles.

i.e., 10°C per minute up to 75°C, crack formation was almost nil. In contrast, if hair samples at 25°C were suddenly exposed to a temperature of 75°C, they immediately showed an increase in the number of new thermal cracks. Thus, high temperature rates cause cracks because they produce a rapid contraction of the top part of the cuticles while maintaining in a swollen state both the cuticle layers underneath and the cortex itself. Conversely, low temperature rates do not cause cracking because cuticles and cortex contract in a more synchronous manner.

It is worth mentioning here that cracks similar to those produced thermally were also formed in fibers swollen with mixtures of strong swelling solvents and strong dehydrating solutions. As is well known, formic acid is a strong swelling solvent because it is able to break hydrogen bonds and salt bridges not accessible to water and to cause higher levels of swelling in keratin fibers (19,20). In contrast, solutions of saturated NaCl are known to dehydrate the fibers (21). Experiments with mixtures of formic acid and saturated solutions of NaCl (50/50%), or mixtures of formic acid and glycerin (20/80%), were seen to produce similar cracks on the cuticles (see Figure 8). The cuticle cracks were observed to appear after ten hours of fiber immersion in these solutions. Also, it was observed that if a thin film of gold is deposited onto a clean hair fiber and then allowed to swell in water, that part of the cuticle covered with gold shows also vertical cracks somewhat similar to those produced thermally (see Figure 9). The explanation to these phenomena is straightforward, i.e., in both cases, with the swelling experiment and with the gold film, only a portion of the cuticle is restrained to expand during the swelling process of both the cuticle layers underneath and the cortex, and cracking occurs by the already advanced mechanism.

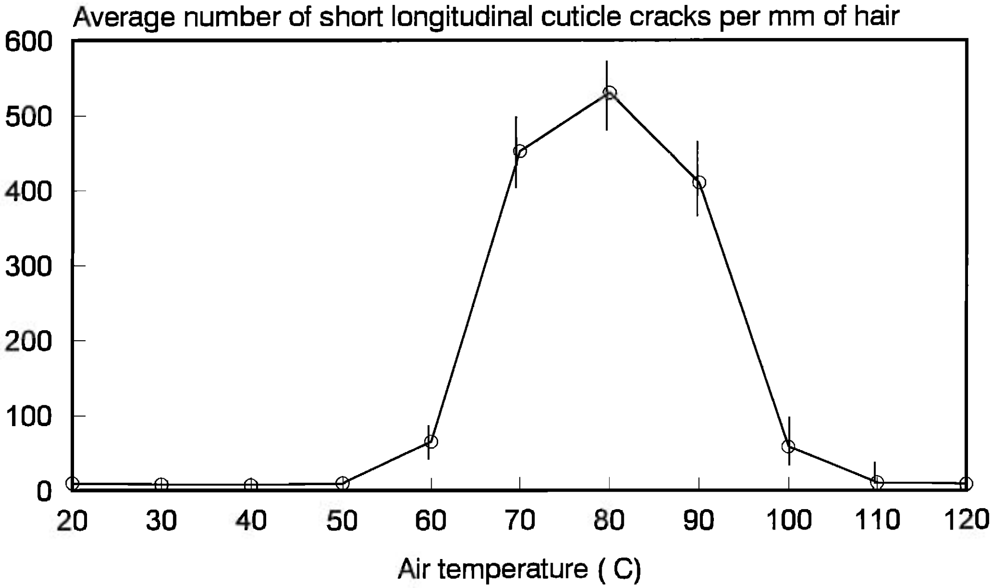


Figure 7. Plot of average number of cuticle cracks reproduced in the laboratory vs blow-drying temperature. The number of applied thermal cycles was kept constant at 20 cycles, and the air temperature was measured at the level of the hair surface. Error bars represent one standard deviation about the mean.

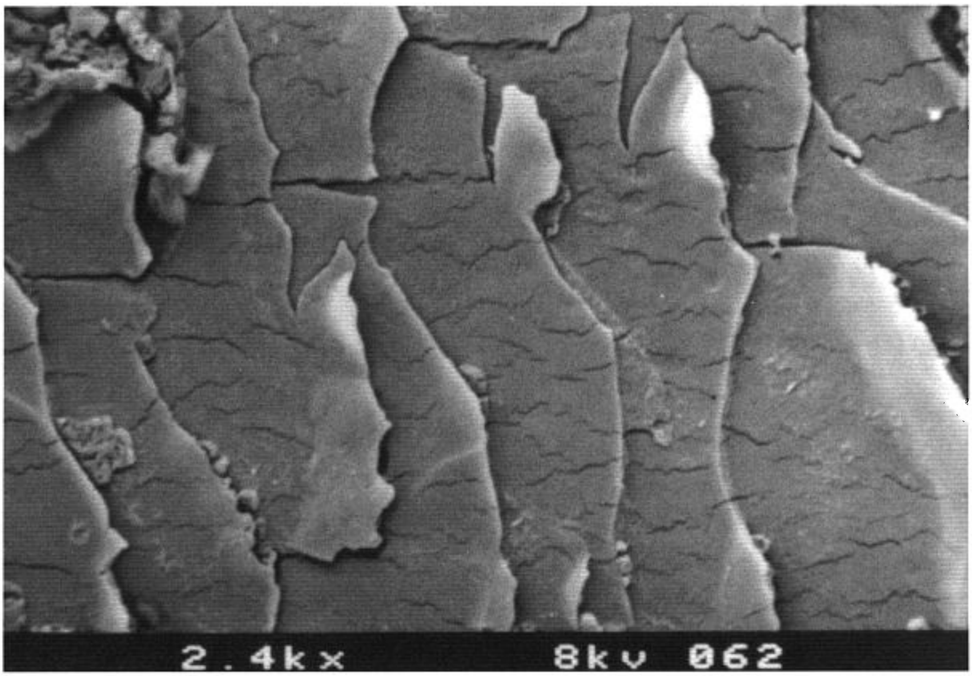


Figure 8. Cuticle cracks produced after immersing a hair fiber in a 50/50% solution of saturated NaCl and formic acid for ten hours.

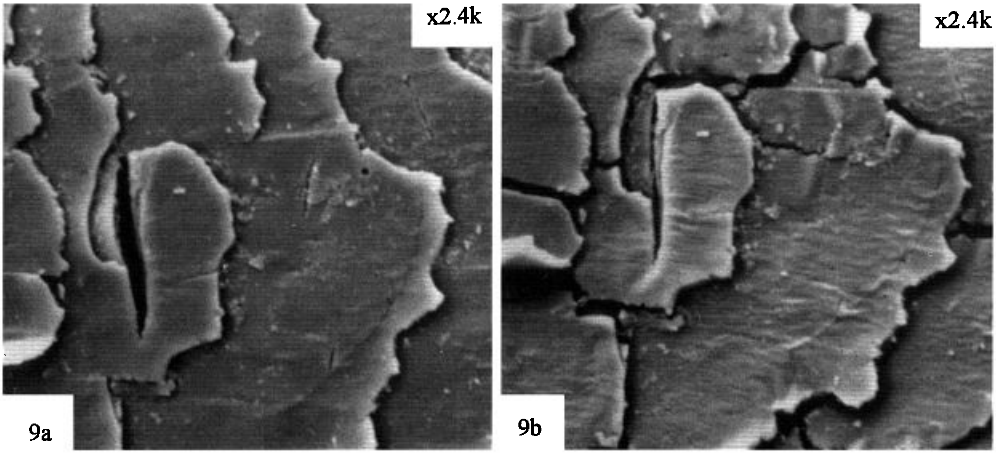


Figure 9. Fiber with a thin gold film deposited on its surface before water immersion (9a) and after water immersion (9b).

EFFECT OF SOME COSMETIC ACTIVES

When 2% w/w aqueous solutions of glycerin and propylene glycol were used during thermal cycling instead of water, the hair cuticles did not show any increase in the average number of cracks characteristic of virgin hair fibers. This observation suggests that during thermal cycling these actives retard water evaporation and also are able to plasticize the cuticles, thereby preventing crack formation. Glycerin and propylene glycol could, however, be easily removed from the hair fiber by simple water rinsing, and under these conditions the cuticles cracked again. The use of 2% aqueous solutions of various quarternaries instead of water during thermal cycling did not indicate any cuticle crack prevention at all. The quaternaries analyzed were as follows: polyquaternium 11, cetrimonium chloride, and steralkonium chloride.

The deposition of four alternating layers of a positive polymer (polyethylenimine) and a negative polymer (polyacrylate) on the hair surface was not capable of preventing crack formation. For instance, in Figure 10 it can be seen that cracks still formed, both on the hair cuticles and also on the deposited polymer layers. Other substances that did not prevent crack formation when deposited onto the hair surface were oils such as triglycerides, silicon oils, mineral oil, and petrolatum. In contrast, an aqueous solution of hydrolyzed wheat protein polysiloxane copolymer at 2%, used instead of water during thermal cycling, prevented cuticle cracking. The crack prevention effect was seen to take place even after the hair was water rinsed. This protein copolymer, which crosslinks upon heat application, is believed to retard water evaporation and also to give a strong cohesiveness to the cuticles, thereby preventing thermal crack formation.

CONCLUSIONS

Hair blow-drying produces cuticle cracks that can be reproduced in the laboratory by the application of alternating cycles of hair wetting and blow-drying. The cracks were seen to result as a consequence of circumferential tension stresses imposed on the dried portion of the cuticles at the top by the swollen cortex. The temperature range at which

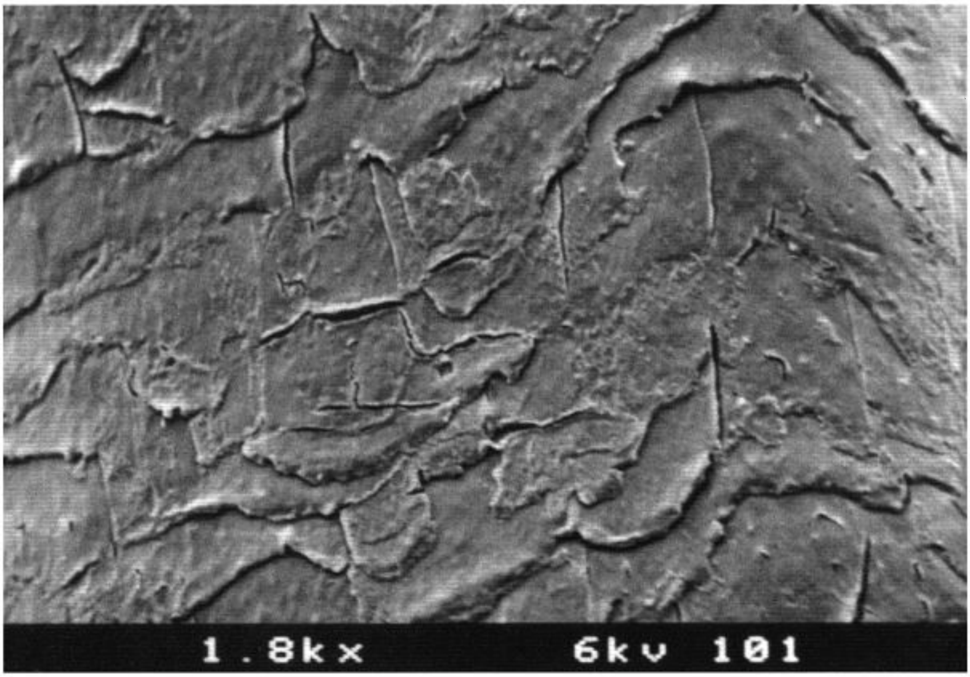


Figure 10. Cracks formed on cuticles of hair treated with four alternating layers of polyethylenimine and polyacrylate.

these cracks seem to take place is between 75° and 95°C. It was also shown that the combing of hair with cracked cuticles results in the removal of big portions of cuticle. The prevention of crack formation by the use of some cosmetic actives was shown to be possible.

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