J. Cosmet. Sci., **58**, 269–282 (July/August 2007)

Patterns of light interference produced by damaged cuticle cells in human hair

MANUEL GAMEZ-GARCIA and YUAN LU, *Ciba Specialty Chemicals, Polymer Effect Research, 540 White Plains Road, Tarrytown, NY 10591-9005.*

Synopsis

Colorful patterns of light interference have been observed to occur in human hair cuticle cells. The light interference phenomenon has been analyzed by optical microscopy. The strong patterns of light interference appeared only in cuticle cells that had been damaged either mechanically or by thermal stresses. Cuticle cells that were not damaged did not produce this phenomenon. The zones of light interference on the hair surface were seen to extend to cuticle sheath areas whose damage was not apparent when analyzed under the Scanning Electron Microscope. The presence of oils and other hydrophobic materials in the hair had a strong effect in the appearance or disappearance of the interference patterns. Furthermore, the gradual absorption and desorption of water by the cuticle cells altered the nominal area of the colorful patterns. This paper will attempt to explain the light interference phenomenon in the cuticle cells by means of the two following mechanisms: 1) Variation in the index of refraction of cuticle cell layers due to the appearance and coalescence of micro-voids which eventually lead to the partial or total separation of cuticle cells; and 2) The interaction of white light with the micro-voids and de-cemented cuticle cells either by thin film interference or diffraction.

INTRODUCTION

The role of the cuticle sheath on the hair optical properties is paramount to its cosmetic appearance (1). For instance, shine in hair is related to the ratio of specular to diffuse light reflected from the epicuticle surface (2,4). The weak iridescence in hair contributes, on the other hand, to its natural and healthy appearance and is produced by weak colored patterns of light interference reflected by the thin film structure of virgin cuticle cells. Incidentally, it is worth mentioning that the bright color possessed by various insects and birds arises not from organic pigments but rather by a similar mechanism involving iridescence (5–8). Many beetles, butterflies, and also the feathers of various birds owe their bright colors to the phenomenon of iridescence. This phenomenon is produced by various coherent light scattering mechanisms involving light interference and diffraction as white light interacts with the ordered micro-structure present in the cell membranes of feathers and also in the skin of insects.

Color in hair is not due to a phenomenon of iridescence but rather to the interaction of white light with melanin (1). Melanin acts as a pigment and as it will be discussed later the strong iridescence patterns appearing on damaged cuticle cells may be rather del-

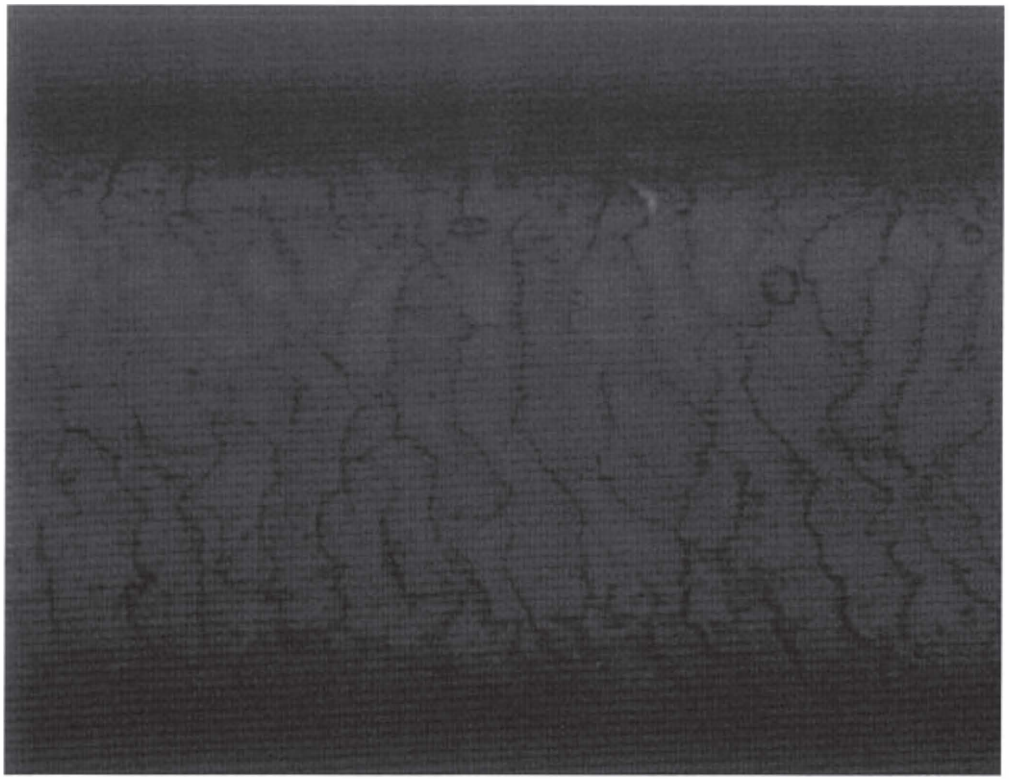

Figure 1. Optical micrograph of virgin hair (×450) showing weak colored patterns of iridescence produced by the cuticle sheath.

eterious than beneficial to the optical properties of hair. The reason is that the colored patterns are microscopic and incoherent at the macroscopic level and they may act rather as an incoherent light scattering process. Understanding the phenomenon of light scattering by the cuticle sheath is, therefore, crucial for modeling and improving the visual perception of hair (9,10). In fact, it is the cuticle sheath the part of hair that acts as a gate for the incoming and outgoing light from the hair shaft. Excessive light scattering from the cuticle cells may impair shine. It can also inhibit the amount and quality of the incoming white light penetrating into the cortex and also affect the quality of the outgoing colored light produced within the cortex by the melanin granules.

In this paper an analysis of the light interference patterns (LIPs) appearing in damaged cuticle cells will be presented. The analysis will show that the LIPs appearing in damaged cuticle cells are produced by a combination of two phenomena, namely: thin film light interference and light diffraction. Both phenomena arise from the damaging action of mechanical and swelling stresses as they induce micro-structural changes in the cuticle cell layers, in particular, in the density of the cement layer and endocuticle. The changes in density appear to be produced by the appearance of numerous micro-voids that coalesce into larger porous defects creating the conditions for cuticle cell lifting, thin film interference, and light diffraction.

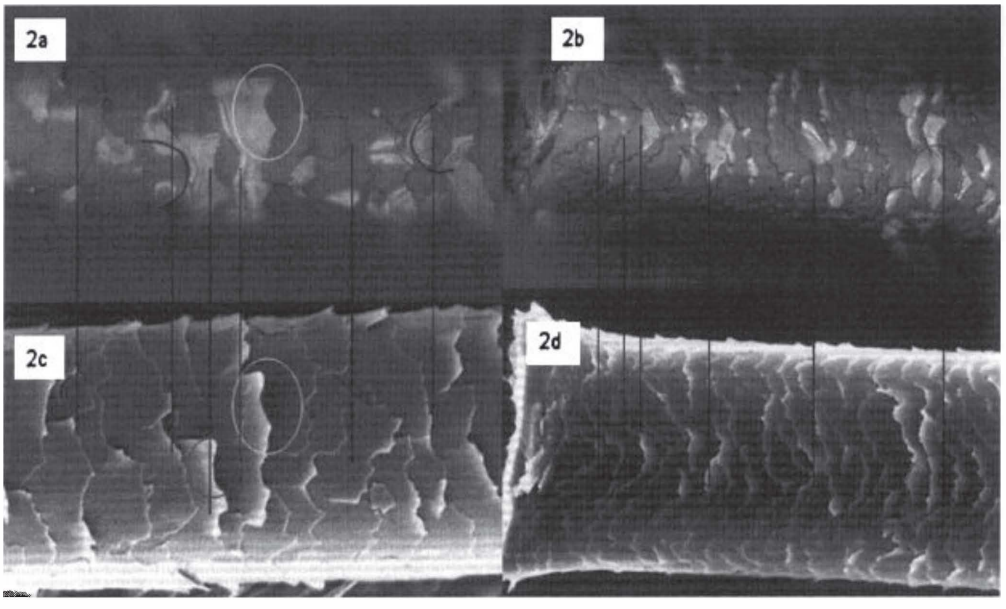

Figure 2. Optical micrographs (×350) (2a and 2b) of hair fibers with cuticle cells showing strong patterns of light interference after subjected to 20 cycles of tension and retraction. Figs. 2c and 2d are SEM micrographs (×350) showing cuticle lifting and de-cementation of areas shown in Figs. 2a and 2b, respectively. Circles and lines in captions help to identify position of same cuticle cells in both pictures.

EXPERIMENTAL

The hair used in the experiments was Premium Grade Brown Caucasian from International Hair Importers. In order to induce de-cementation and buckling of cuticle cells, single hair fibers were subjected to 20 cycles of mechanical extension and retraction at room temperature conditions. Each cycle consisted in applying a tensile deformation of 20% and allowing 1 second for deformation recovery. In all consecutive applied cycles the percentage of extension didn't exceed 20% of the original fiber length. In the past it has already been shown that this type of protocol leads to the production of a large number of de-cemented cuticle cells (12). After the fibers were damaged they were analyzed by optical microscopy using a Hi-Scope Advanced KH-3000 from Hirox LTD. When needed the hair fibers were subjected to cycles of thermal or torsion stresses using the protocols already described elsewhere (13,14). In order to asses the effect of solvent penetration on the LIPs various hair fibers, either, before or after mechanical damage were immersed in water or isopropyl alcohol. Areas of hair fibers presenting LIPs were also analyzed by SEM.

RESULTS AND DISCUSSION

MAIN CHARACTERISTICS OF LIGHT INTERFERENCE PATTERNS

Before making a detailed description of the results it should be mentioned here that the strong LIPs were only observed on hair fibers subjected to damage. Virgin undamaged hair fibers were always absent of strong LIPs and instead they showed weak colored patterns of iridescence (see Figure 1). As it will be discussed later the strong LIPs

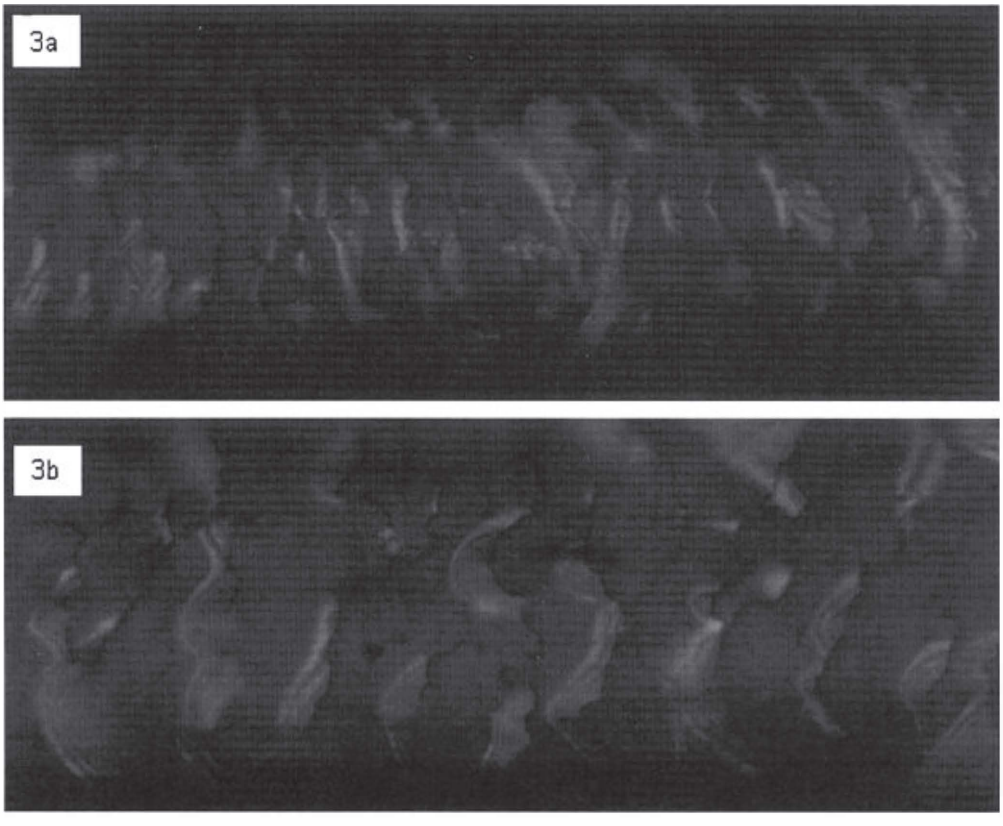

Figure 3. Optical micrographs (×370) of hair fibers showing strong patterns of light interference after the application of cyclical tension stresses.

observed in damaged cuticle cells is considered to be a distortion of the natural iridescent patterns in virgin cuticles cells. Figures 2a and 2b show typical examples of strong patterns of light interference produced by damaged cuticle cells. In Figures 2c and 2d are shown SEM micrographs of the same areas and it can be observed that the cuticle cells have undergone de-cementation and buckling after the application of cyclical extension stresses.

The most salient features in the LIPs were their colors and shapes. Commonly observed colors were blue, green, magenta, red, yellow, and white. Most frequently the colors appeared in lines, either, very thin or wide, whose shape was either hyperbolic or straight (see Figures 3a and 3b). Other colored patterns that appeared in the form of localized dots (see Figures 4a and 4b), clusters of colored dots, and as narrow and long channels were also observed (see Figure 5). Most of these punctual patterns were produced after the hair was subjected, either, to cyclical thermal stresses of wetting and blow drying or to torsion (12–13). It was observed that many of the dot-like patterns tended to disappear after the hair was soaked in water for 5 minutes, however, after the fiber was soaked in IPA for 3 minutes the colored dot patterns reappeared again. In many cases similar punctual patterns were observed in hair fibers obtained from common individuals after the fibers were immersed in IPA for 1 or 2 minutes.

In general, the color and shape of the LIPs were dependent on the form in which the

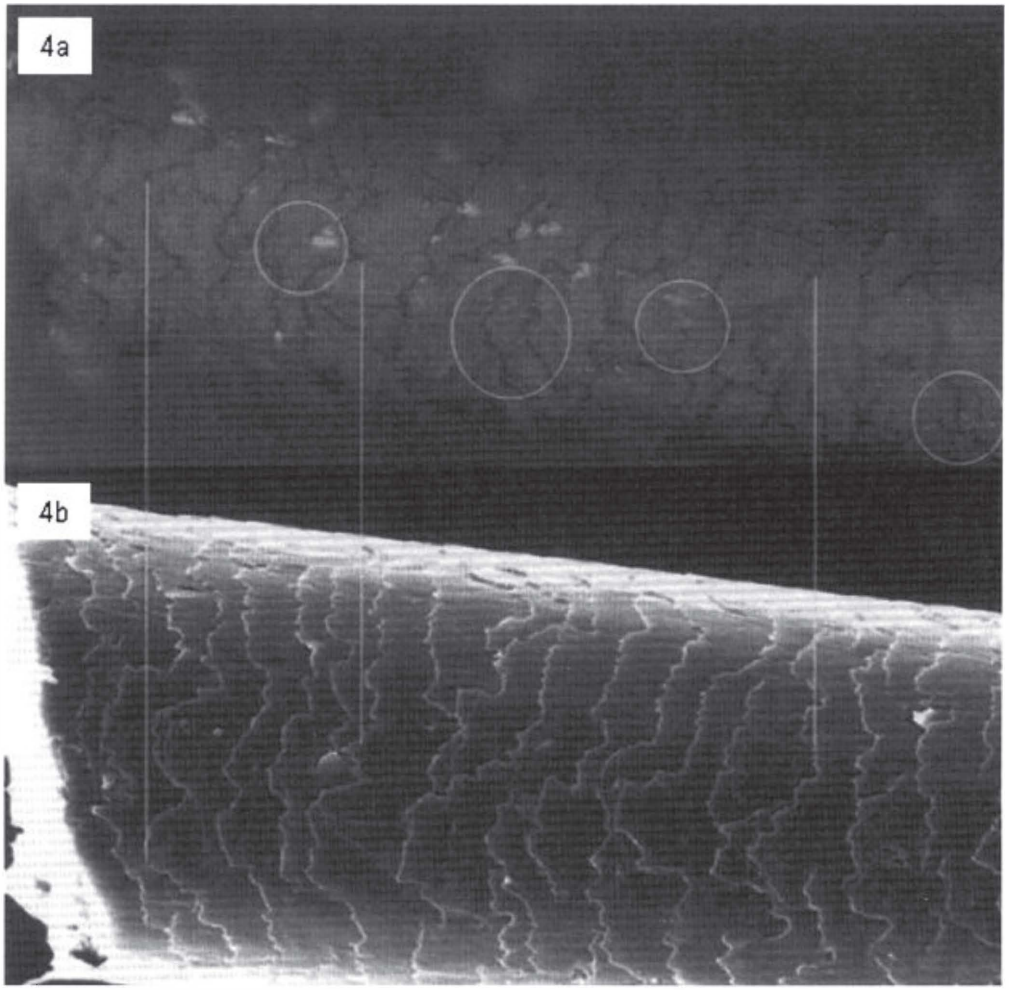

Figure 4. Optical (4a) and SEM (4b) micrographs (×370) showing details of dot like patterns appearing in cuticle cells after drying the hair fiber with a hot iron surface at T = 90 C for 5 minutes. Lines and circles in captions help to identify same cuticle sheath areas in both micrographs.

cuticle cells were damaged. For instance, the LIPs of hyperbolic shape were seen invariably associated to the folding of cuticle cells in buckles. Figures 2a, 2b, 2c, and 2d show the juxtaposition of microscopic images displaying the same area of a hair surface with de-cemented and buckled cuticle cells, one obtained by optical microscopy and the other by SEM, respectively. In these figures it can be seen that each cuticle cell that appears folded forming buckles in the SEM micrograph (see Figures 2a and 2b) has a corresponding hyperbolic pattern of light interference in the picture obtained by optical microscopy (see Figures 2c and 2d).

The hyperbolic LIPs were found to be very sensitive to the application of additional mechanical or swelling stresses to the cuticle cells. Their color and shape underwent dramatic changes when their corresponding cuticle cells were further stressed. Figures 6a and 6b show before and after pictures of a de-cemented and buckled cuticle cell that was

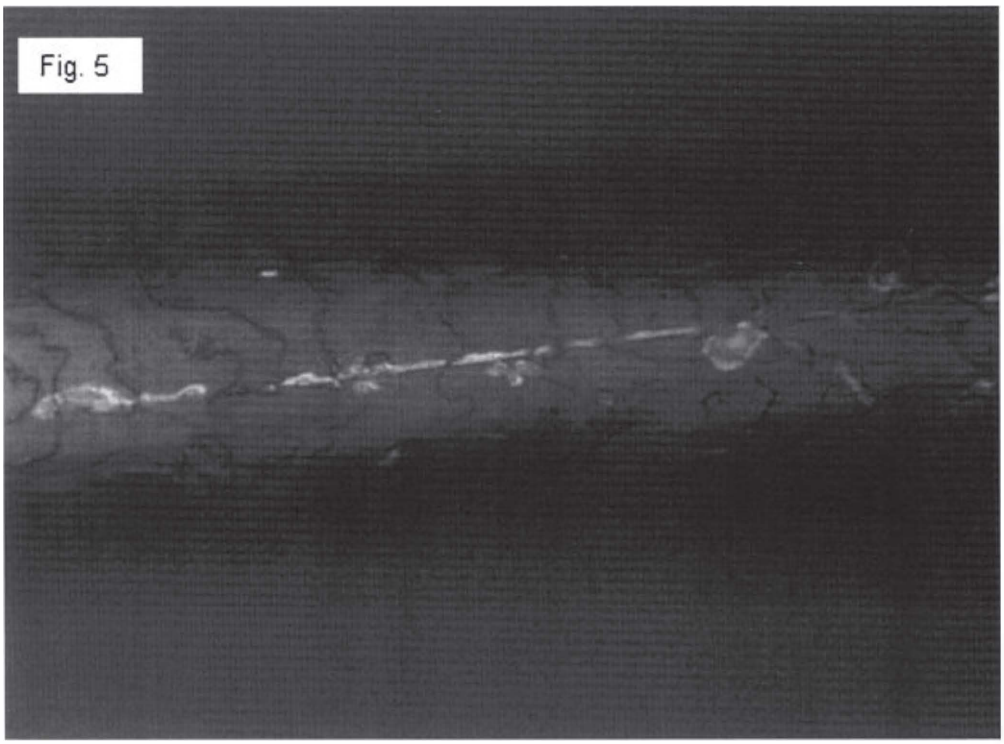

Figure 5. Optical micrograph (×250) of light interference pattern in channel form produced on hair by cyclical torsion stresses on a hair fiber using the protocol described elsewhere (13).

further stressed by applying a slight pulling force to bend the cuticle cell. The pulling force to the cuticle cells was applied by gluing a tape to the hair surface and subsequently lifting the tape. The adhesion force of the tape was such that it didn't lead to cuticle breakage. The main change observed after application of the tape was the color and shape of the cuticle cell's LIP that changed from one displaying colored bands hyperbolic in nature to one of straight colored lines or wide bands (see Figures 6a and 6b).

Figures 7a and 7b show, on the other hand, the effects of isopropyl alcohol on the LIPs of de-cemented and buckled cuticle cells. These figures show that the color and shape of the LIPs has changed after the hair fiber was immersed in isopropyl alcohol for 1 minute. It was also observed that if a de-cemented and buckled cuticle cell was allowed to recover from its deformed state by immersing it in water its LIP disappeared. It is interesting to mention here that SEM analysis of cuticle cells recovered in this manner showed them apparently re-glued again to the hair surface.

However, treatment of water re-glued cuticle cells with IPA caused them to buckle and lift again. Although, their new deformed shapes differed from those originally formed. Treatment of hair with IPA can be used, thus, to reveal breakage of cuticular cement that may have occurred previously and that has been concealed by a water recovery process. The treatment of virgin hair fibers taken from scalp close to the root with IPA never caused by itself cuticle cell de-cementation and buckling. The application of oils such as silicone and esters to de-cemented and buckled cuticle cells didn't lead to their mechanical recovery, but instead it caused the suppression of the LIPs (see Figures 8a and 8b).

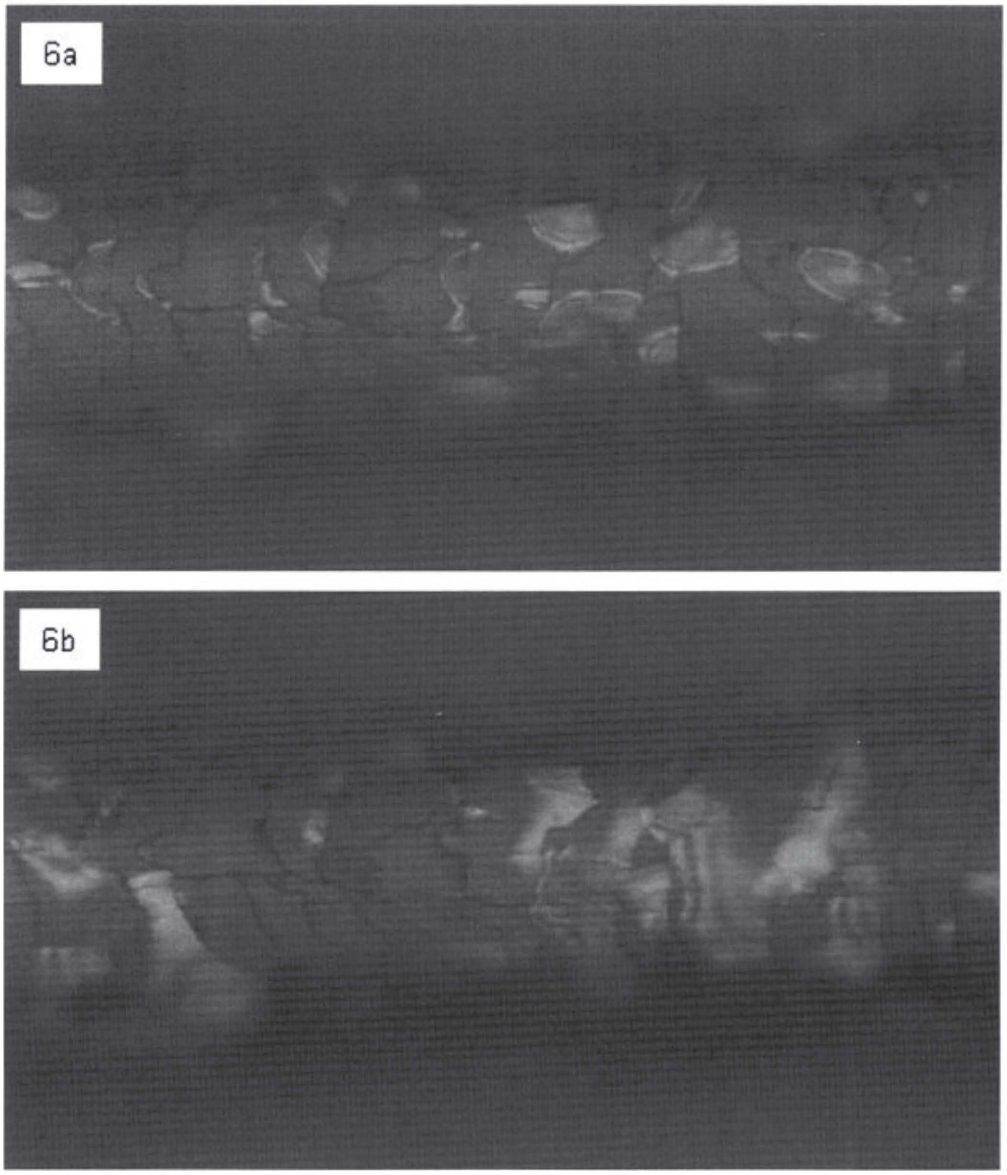

Figure 6. Optical micrographs (×250) of a hair fiber (6a) with light interference patterns produced by cyclical tension stresses, and same fiber (6b) after the cuticle cells were further stressed by gluing and stripping a tape from the surface of the hair fiber.

In some instances there were found cuticle cells that displayed LIPs but when analyzed by SEM didn't show any apparent sign of cuticle buckling and de-cementation (see Figures 9a and 9b). This observation indicates that breakage of cuticle cell cement with the inclusion of air not always leads to cuticle lifting and that it can also occur at sites far from the cuticle cell edges. Thus, when assessing the condition of the cuticle sheath by SEM, care should be exercised in the diagnosis, as the cuticle cell may appear by SEM as absent of damage. Yet when the same cuticle cells are analyzed by optical microscopy

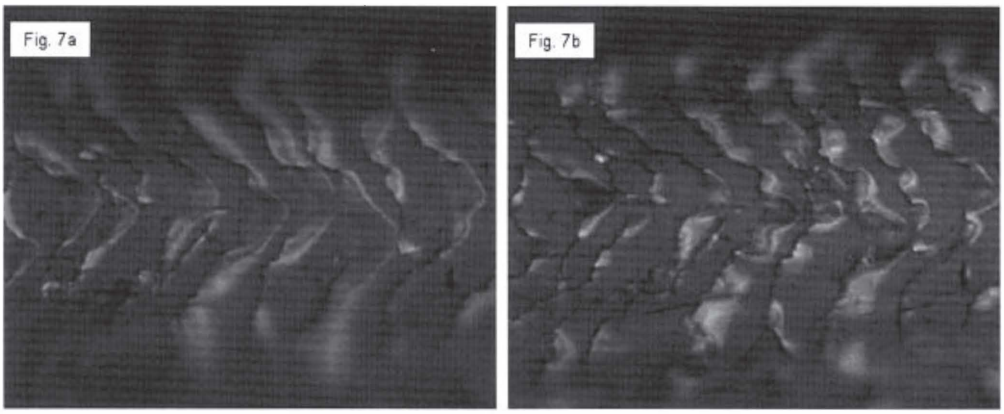

Figure 7. Optical micrographs (×300) of a hair fiber with de-cemented and lifted cuticle cells showing patterns of light interference before (7a) and after (7b) immersion in isopropyl alcohol for 1 minute.

they may show LIPs indicating internal de-cementation. The LIPs were also produced by various cuticle cells stacked together that underwent de-cementation in lumps. In many cases the extent of cuticle cell separation appeared to be shallow and superficial when analyzed by SEM, but when analyzed by optical microscopy, the associated pattern of light interference indicated that the extent of separation was deep inside the cuticle sheath.

MECHANISM FOR THE FORMATION OF LIPS OF LINEAR AND HYPERBOLIC SHAPE

The first issue that will be addressed in this section is the origin of the colored patterns displayed by the damaged cuticle cells shown in Figures 2a–2d. Incidentally, it was found that the colored patterns are not caused by stress bi-refringency (14) as they were observed to occur even without the use of polarizing filters in the microscope. Furthermore, the use of polarizing filters during the analysis didn't eliminate the colored patterns at all. Instead, the filters only caused a small attenuation in the colored pattern's intensity so the explanation for their formation should be looked elsewhere.

There are many examples of other colored patterns produced by the physical interaction of light with matter and these can be used as a starting basis for the analysis of LIPs observed on cuticle cells. For instance, the colors in soap bubbles, in Newton rings, from oil on the surface of water, from the surface of CDs, in butterfly wings, from the skin of some beetles, and from some bird feathers, all them are produced by thin film interference, light diffraction, or by the combination of both mechanisms (15,16). The cuticle cells in human hair have also the capability of producing colored patterns by thin film interference in a similar fashion to a soap bubble. This ability stems from the following facts, namely: 1) The cuticle cells are composed of various transparent layers, 2) They are flat in shape, and 3) Their thickness value is comparable to that of the wavelength of light.

In fact, the weak iridescence shown in Figure 1 is certainly due to thin film interference as the light undergoes double reflection from the cuticle cells near the surface of the hair fiber. These interference patterns are weak and incoherent at the macroscopic level, and it is probably the reason for their small effect on the overall hair color. This contrasts

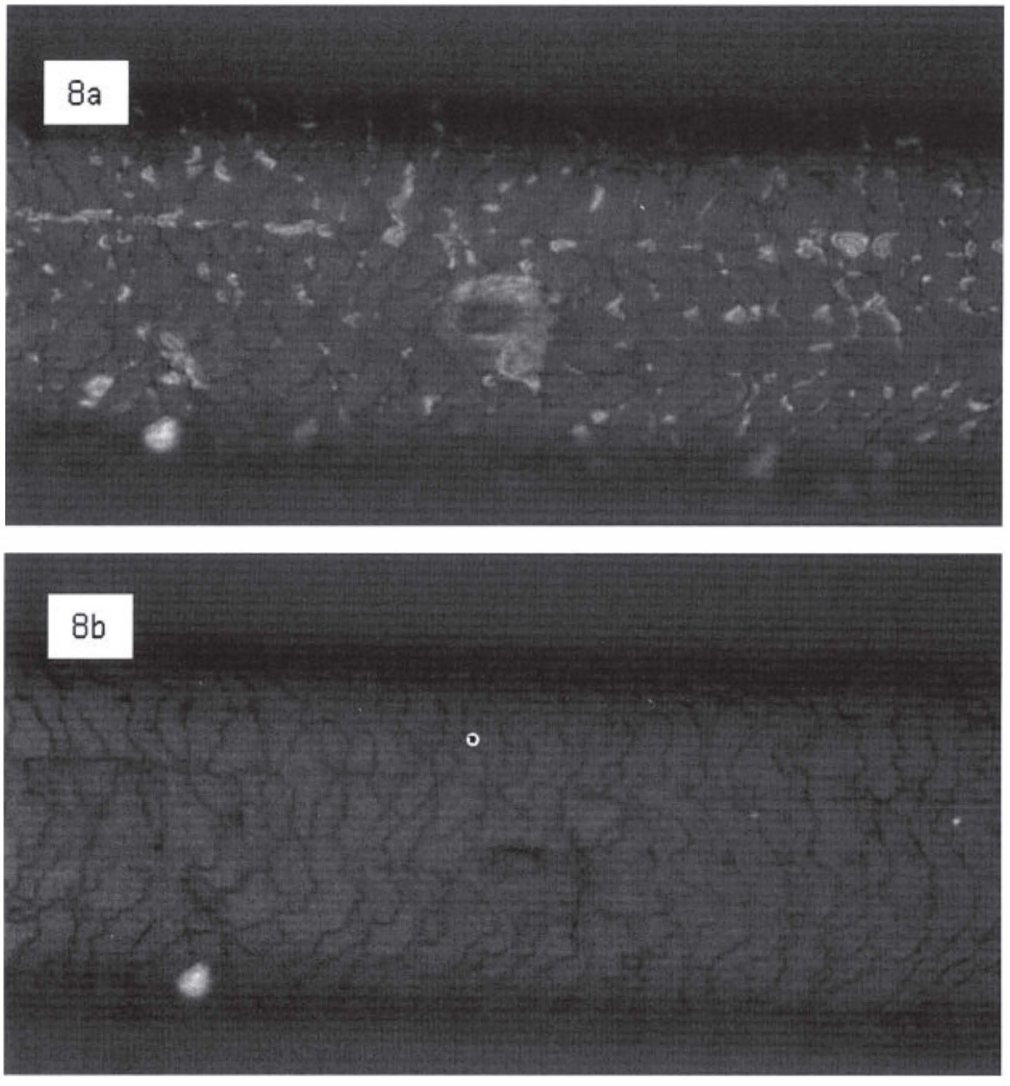

Figure 8. Optical micrographs (×250) of a hair fiber with de-cemented and lifted cuticle cells showing patterns of light interference before (8a) and after (8b) applying isopropyl myristate to the hair surface with a micro-pipette.

with the color observed in the feathers of some birds where the phenomenon of light interference is coherent at the macroscopic level and the color is exclusively due to iridescence. Yet incoherent but strong patterns of light interference can also be produced by the cuticle cells. In the following paragraph the conditions for the formation of strong patterns of light interference in human hair cuticles will be discussed.

It is a well known fact from the science of Optics (15) that strong patterns of light interference in thin films occur whenever the film meets the following three conditions, namely: 1) Its thickness is at least smaller than the wavelength of light of any particular color, 2) There are large differences in the indexes of refraction between (a): the media sustaining the incoming light and film material, and (b): between the indexes of re-

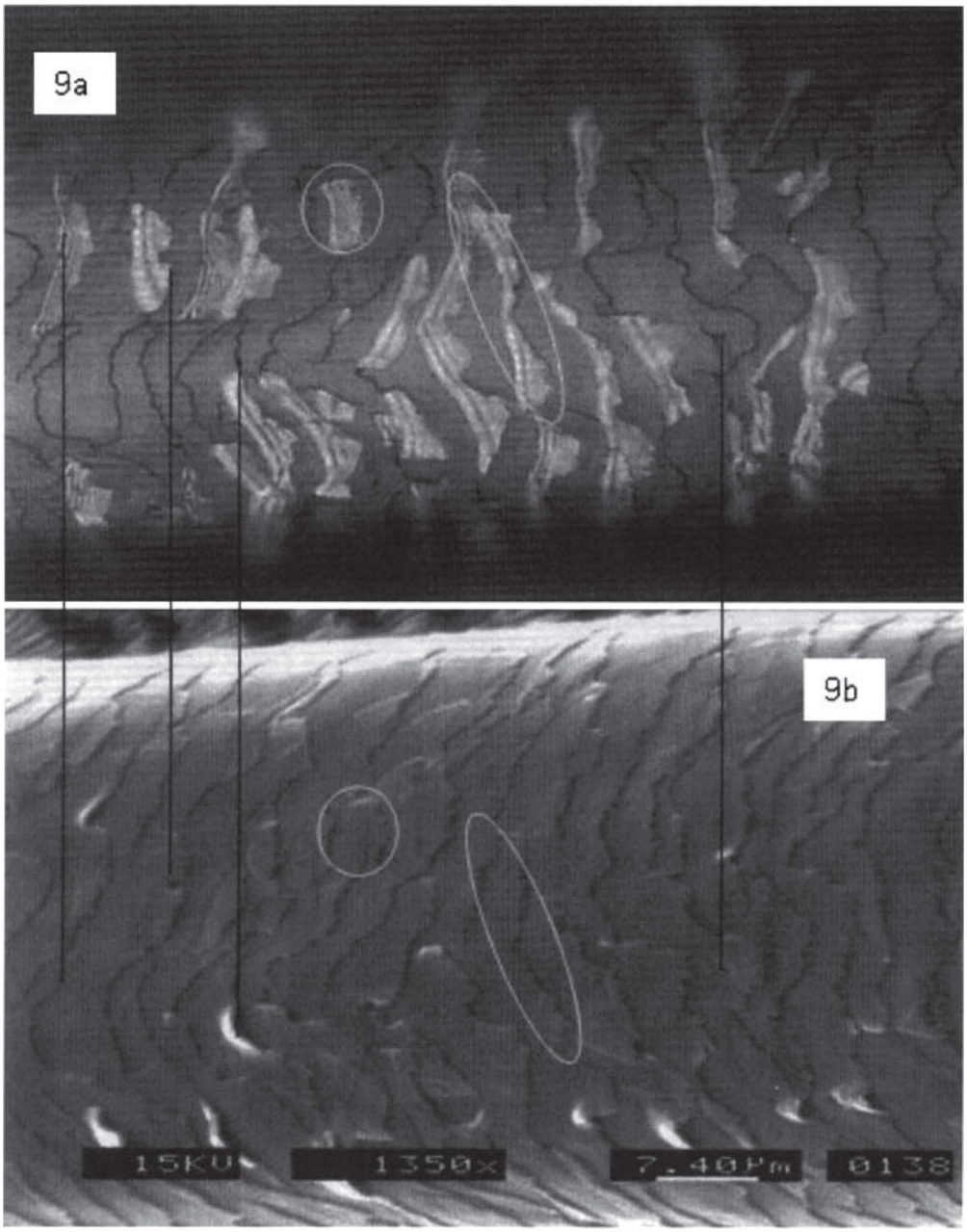

Figure 9. Optical micrograph (9a) (×270) with cuticle cells showing patterns of light interference at their edges. Fig. 9b shows an SEM micrograph of same hair fiber showing that cuticle cell edges are apparently glued to the bottom cuticle. Circles and lines help to identify same cuticle cells in both pictures.

fraction of the film material and the substrate beneath the film. If the differences in the indexes of refraction are small, weak patterns of interference will be produced such as in the case of virgin and cemented cuticle cells.

The conditions for the formation of strong patterns of light interference in the form of

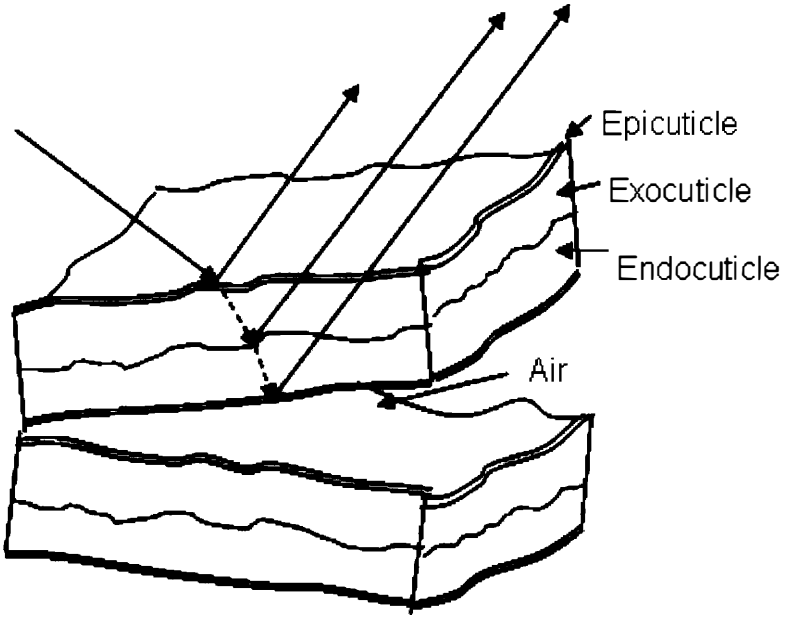

Figure 10. Schematic representation of a lifted and de-cemented cuticle cell with its corresponding layers showing possible paths of light reflection for the creation of thin film interference.

wide or thin hyperbolic bands of color are attained, therefore, when air, as a substance with a low index of refraction (n = 1), enters into the cuticle cells, either because there are micro-voids (17) or because the cuticles de-cement and buckle (see Figures 2a–2d). For instance, when the cement of a cuticle cell breaks entrapping air, the total optical path of light reflected from the top and bottom of the cuticle cell will change due to the following factors, namely: (a) changes in the cell thickness due to stress deformation, and (b) differences in the index of refraction between cuticle cell material and the new air layer created by de-cementation (see Figure 10).

A virgin cuticle cell will change, thus, the intensity of its pattern of light interference from weak to strong when its cement breaks and the cuticle cell buckles. For instance, a de-cemented cuticle cell will have at least a maximum thickness of 0.5 μ (1), a value which is smaller than the largest wavelength of light, i.e. about 0.700 μm. This fact alone will create the conditions for thin film interference. However, the LIP will become stronger as the difference in the indexes of refraction between cuticle cell material and air gap cause an additional increase in the optical path of light (16). Unfortunately, at this stage of our investigation we cannot offer an approximate value for the index of refraction of the cuticle cell as a whole or of any of its layers. However, it is believed that the cuticle cell, like some other membranes (18–19), will have an index of refraction whose value will be bigger than that of air.

Thus, according to this mechanism, the shape, size, and colors observed in the LIPs of de-cemented and buckled cuticle cells represent a contour map of the thickness in the deformed cuticle cells (see Figures 3a and 3b). The process is akin to the phenomenon of light interference produced by soap bubbles and oil on water where the bands of color represent changes in film thickness (16). This mechanism also explains why in Figures

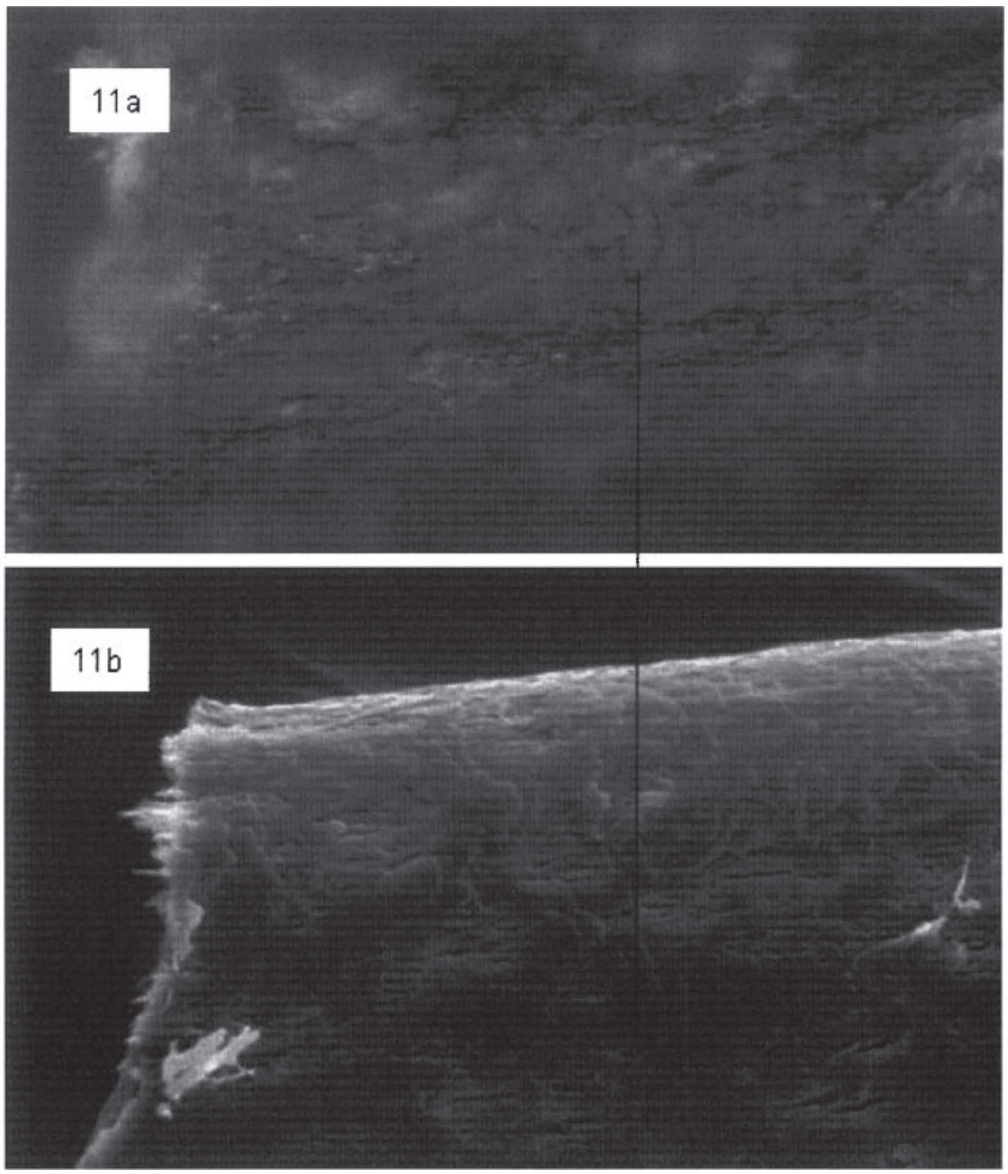

Figure 11. Optical (11a) and SEM (11b) micrographs (×370) showing details of dot like patterns appearing on portions of cortex devoid of cuticle cells after their removal by intensive wear.

5a and 5b the LIPs are sensitive to the further application of mechanical stresses as these will induce further changes in cuticle cell thickness. Changes in the shape of LIPs shown in Figures 6a and 6b obtained after the penetration of isopropyl alcohol into the cuticle cell can also be ascribed to a similar mechanism. Although, in this case one has to consider changes in the index of refraction of the cuticle cell due to the presence of the swelling solvent. Isopropyl alcohol is known to penetrate into the hair shaft and cause dehydration and contraction.

MECHANISM FOR THE FORMATION OF LIPS APPEARING AS DOTS, AGGLOMERATIONS OF DOTS, AND AS CHANNELS

The LIPs appearing in the form of microscopic isolated dots, agglomerations of colored dots, and channels shown in Figures 4a, 4b, and 5, are considered to be caused by the diffraction of white light interacting with micro-voids and holes appearing in the cuticle cells as a consequence of the action of damaging stresses. Agglomerations of colored spots were also observed in randomly tested hair fibers from the naked micro-fibrilar structure of the cortex in fibers devoid of cuticle sheath (see Figures 11a and 11b).

In most cases the presence of these colored dots in hair fibers became apparent after their treatment with IPA for 5 or 10 minutes. The colored dots never appeared in virgin hair fibers and were invariably seen in hair fibers that had undergone either mechanical or thermal stresses. This observation indicates that during the process of mechanical or thermal stressing of hair there is a damaging stage at which micro-voids and holes start to form in the cement layer before the cuticle cells crack and larger portions of cuticle cell de-cement and buckle. It is also quite possible that these holes form in the endo-cuticle or in other cuticle cell layers and are, therefore, responsible for the LIPs shown in Figures 3a and 3b. According to the ongoing arguments the formation of LIPs in the form of long lines indicates also the presence of micro-voids that coalesce into channels with high levels of mechanical stresses (see fig. 4).

CONCLUSIONS

An analysis of the patterns of light interference appearing in damaged cuticle cells has been done and indicates that they may be produced by a phenomenon related to thin film interference and light diffraction. The patterns of light interference were only observed in cuticle cells that had been subjected to damaging stresses. Therefore, their appearance indicates changes in the microscopic structure of the cuticle cell layers. Further experiments are underway to assess the effect of various actives on the phenomenon of light scattering by hair.

REFERENCES

(1) R. Robbins, *Chemical and Physical Behavior of Human Hair* 3rd ed. (Springer-Verlag, New York, 1994) pp. 211–206.
(2) R. Mcmullen and J. Jachowicz, ●ptical properties of hair-detailed examination of specular reflection patterns in various hair types, *J. Cosmet. Sci.,* **55,** 29–47, (2004).
(3) R. R. Stamm, M. L. Garcia, and J. J. Fuchs, The optical properties of human hair I. Fundamental considerations and goniophotometer curves, *J. Soc. Cosm. Chem.,* **28,** 571–600 (1977).
(4) S. Nagase, S. Shibuichi, K. Ando, E. Kariya, and N. Satoh, Influence of internal structures of hair fiber on hair appearance. I. Light scattering from the porous structure of the medulla of human hair, *J. Soc. Cosmet. Sci,* **53,** 89–100 (2002).
(5) M. F. Land, The physics and biology of animal reflectors, *Prog. Biophys. Mol. Biol.* **24,** 77–106 (1972).
(6) D. L. Fox, *Animal Biochromes and Structural Colors* (University of Calif●rnia Press, Berkeley, 1976).
(7) R. O. Prum, T. Quinn, and R. H. Torres, Anatomically diverse butterfly scales all produce structural colours by coherent scattering, *J. Exp. Biology,* **209,** 748–765 (2006).
(8) R. O. Prum, "Anatomy, Physics, and Evolution of Certain Avian Structural Colors," in *Brod Coloration,*

Vol. 1, Mechanisms and Measurements, G. E. Hill and K. J. McGraw, Eds. (Harvard University Press, Cambridge, 2006).
(9) S. R. Marschner, H. W. Jensen, M. Cammarano, S. Worley, and P. Hanrahan, Light scattering from human hair fibers, *ACM Trans. Graph.,* **22,** (2003).
(10) H. Bustard and R. Smith, Investigation into the scattering of light by human hair, *Applied Optics,* **24,** 3485–3491 (1991).
(11) M. Gamez-Garcia, Cuticle de-cementation and cuticle buckling produced by poisson contraction on the cuticular envelope of human hair, *J. Soc. Cosmet. Chem.,* **49,** 213–222 (1998).
(12) M. Gamez-Garcia, The cracking of human hair cuticles by cyclical thermal stresses, *J. Soc. Cosmet. Chem.,* **49,** 141–153 (1998).
(13) M. Gamez-Garcia, Plastic yielding in hair cuticles, *J Soc. Cosmet. Sci.,* **50,** 69–77, (1999).
(14) E. G. Coker and L. N. G. Filon, *Treatise on Photoelasticity,* (Cambridge University Press, Cambridge, December 1957).
(15) M. Born and E. Wolf, *Principles of Optics,* (Pergamon Press, Oxford), Chap. 10, pp. 554–619.
(16) D. Falk, D. Brill, and D. Stork, *Seeing the Light; Optics in Nature; Photography, Color, Vision, and Holography* (J. Wiley & Sons, New York, 1986).
(17) C. Scanavez, M. Silveira, and I. Joekes, Human hair: color changes caused by daily care damages on ultra-structure, *Coll. Surf. B.,* **28,** 39–52 (2003).
(18) J. Hirshburg, B. Choi, S. Nelson, and A. T. Yeh, Collagen solubility correlates with skin optical clearing, *J. Biom. Optics,* **11,** (2006).
(19) S. A. Prahl, *Light Transport in Tissue,* PhD Thesis, University of Austin, Texas (1988).