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Effects of cosmetic treatments on the morphology, biotribology and sensorial properties of a single human hair fibre

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Abstract

Human hair has a complex multi-scale structure that is extremely sensitive to several external factors. Hair fiber has three compartments: cuticle (scales), cortex and medulla.

In the everyday life, hair experience important mechanical and chemical solicitations, such as smoothing, combing, drying and even washing, which can induce cracks in the cuticle. These damages diminish the mechanical properties of the cortex and contribute to a decrease in the brightness and softness of the hair.

In the present article, the effects of different cosmetic treatments: bleaching, coloring and smoothing (with different temperatures) have been explored. Firstly, the morphology of hair was measured by interferometry. A multi-scale roughness characterization was performed by applying continuous wavelet transform. This method quantified the arithmetic mean of the surface topography at each wave length and permitted observing the evolution of the cuticle morphology before and after treatment. Secondly, a patented haptic tribometer system was used to measure the friction coefficient and acoustic vibrations generated during the tribological test. Previous results have shown that vibrations are related to the softness of the hair surface.

The results show that all the treatments change the morphology and biotribology of hair by damaging the hair cuticle. These changes impact the sensorial properties of hair. In particular, the morphology of colored and bleached hair, compared to virgin one, is strongly modified: the scales are less defined, and the roughness is increased. These morphological modifications are correlated with an increase of the friction coefficient of around 50%, and acoustic vibratory level of around 2%, indicated a decrease of the sensorial properties. The hair fibre becomes rougher, dull and less soft. On the contrary, thermomechanical treatments of previously damaged hair, impact the morphology and biotribology of hair differently. The cuticle scales are flattened and the values of the friction coefficient and acoustic vibratory level decrease to reach the virgin hair values. Thus, the hair fibre seems to be smoother, brighter and softer.

In conclusion, these results are essential for understanding the impact of different solicitations on the physical and sensorial properties of hair.

1. Introduction

In our modern societies, hair plays an important role for human beings as it reflects our physical state. Indeed, women want beautiful hair that is pleasant to touch. Thus, for a long time, scientists have tried to develop cosmetic products to improve the appearance and the sensorial properties of hair such as the feel, shine, color and softness.

The human hair fiber is composed of various layers of cellular structure [1] [2] [3]. Hair fibers (about 50–100 μm in diameter) are composed of the cuticle (the outer part) and the cortex (the inner part), and in some cases the medulla in the central region. The cortex is a complex polymer structure. It is mainly composed of long keratin filaments held together by disulphide and hydrogen bonds. The cortex plays a significant role in the mechanical properties of hair [4]. However, the important component for the aesthetic properties of hair is the cuticle, the outer part that protects the cortex from the external environment. Indeed, the cuticle is important for the hair's aesthetic characteristics as it is this structure which is visible and comes into contact with other hair, skin, and cosmetic products. The cuticle consists of flat overlapping cells (scales) which are mainly filled with keratin protein [5]. Each cuticle cell is approximately 0.3-0.5 μm thick and the visible length is approximately 5-10 μm long.

Mechanical processes such as combing, smoothing and blow-drying serve to style the hair. Chemical products and processes such as chemical dye, colorant and bleach treatments improve the appearance and color of the hair. However, these treatments can also significantly damage the hair fibers, especially the cuticle. In general, hair fiber damage is due to mechanical or chemical solicitations, or a combination of both (chemo-mechanical). In particular, the mechanical and chemical solicitations such

as washing, combing, drying, smoothing, coloring or bleaching induce cracks and breaks in the cuticle [6]. This reduces the mechanical properties of the cortex [7]. The reduction of its mechanical properties considerably has a strong impact on the tribological (adhesion, friction, and wear) and morphological properties of hair (aspect of scales, surface roughness) [8].

The tribological behavior of hair has already been studied with macroscale and micro/nanoscale experimental methods. Macroscale characterization was widely used to investigate the friction between a skin replica and a hair swatch [3]. More recently, some studies focused on the frictional behavior of hair using atomic force microscopy (AFM) and friction force microscopy. In particular, AFM studies were carried out to understand damage and the effects of hair care products on hair topography [9] [10] and tribology [9] [11] [12] [13]. LaTorre *et al.* [9] used AFM and showed nanotribological changes when hair was damaged: they measured a significantly higher friction coefficient for damaged hair and attributed it to increased average surface roughness. Indeed, average roughness parameters were measured to compare changes due to damaging processes. In particular, Bhushan defined two parameters: a vertical descriptor, height standard deviation σ , and a spatial descriptor, correlation distance θ^* [14] [9]. Despite the numerous studies concerning the topographical and tribological changes of hair due to chemical or mechanical treatments, few of them have explored the correlation with the sensory perception, in particular the tactile properties of hair. Furthermore, these studies only used the friction coefficient as a marker of the tribological behavior of hair.

In this paper, we propose to explore the tribological and morphological hair changes due to chemical and thermomechanical treatments. Then, we correlate these changes with the sensorial perception of hair (brightness and soft touch). For this purpose, Caucasian hair samples were collected and evaluated using optical interferometry combined with wavelet decomposition. The wavelet decomposition allowed to access the multiscale signature of the hair fibre. Thus, it was possible to localize the damage induced by the treatments and correlate it with the tribological signature of the hair fibre. Then, friction measurements were performed with a haptic tribometer. The haptic tribometer allows simultaneously measuring the friction coefficient between the slider and the hair sample and the acoustic vibratory level generated during the friction test. This tribometer mimics the behavior of a human finger and permits to access the tactile perception of different surfaces as it was demonstrated in previous works [15] [16]. The objective of the study was to use tribological and morphological analyses to gain new insights into the effects of cosmetic treatments on the sensorial properties of hair such as its softness and its brightness.

2. Material and methods

2.1. Hair samples

Caucasian hair samples were used in this study.

We studied the effect of chemical and thermomechanical treatments (smoothing) on the morphological and topographical properties of a single hair.

To investigate the effect of chemical treatments, hair samples were selected from people who had treated their hair by bleaching or coloring with commercial products.

Then, the effect of smoothing was studied on samples of hair damaged previously. Two smoothing temperatures were chosen: 140°C (T140) and 200°C (T200). To obtain damaged hair samples, we applied 25 cycles of dipping in distilled water (10s at 25°C) and drying (10s) using a hair-dryer at 78°C [17].

Samples of 4 cm length were cut at a distance of around 5 cm away from the root area to be tested. All the measurements were performed in this region. Before any measurement, hair samples were stored in a room at a temperature of 22°C and 40% RH. 5 hair samples were tested for each type of hair in order to perform statistical analysis.

For all the measurements, the hair fibre was mounted on a sample holder and a constant preload was applied to the fibre. Thus, all the hair samples are stretched in the same way.

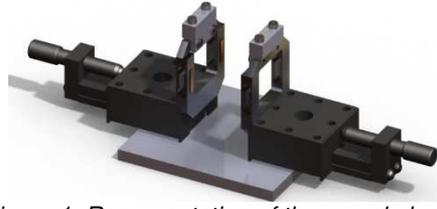


Figure 1: Representation of the sample holder

2.2. Topography measurement

2.2.1. Optical interferometry

The topography of the hair fibres were measured with an optical interferometer (Bruker Contour GT-I). A white light source is split into two different beams: one is reflected on the surface studied before touching the CCD detector and the other is reflected from the reference mirror to the CCD detector. Then, the two beams are recombined and create a series of white and dark fringes that create an interference pattern. The microscope is connected to a piezo-electric transducer to increase the measurement amplitude, with displacements controlled by a micro-calculator. The data collected by this method consists of point coordinates in the x , y and z directions, which, when reconstructed, create a three-dimensional representation of the surface.

The Vertical Scanning Interferometry (VSI) mode was used to image hair samples. A magnification of 115X was used to obtain hair images. With a vertical resolution of 3 nm, VSI mode permits to analyse rough surfaces with amplitudes ranging between 160 nm and 2 mm.

2.2.2. Wavelet decomposition

The image obtained is made up of different wavelength scales; high frequencies represent the roughness, medium the waviness and low for the form. A method based on multi scale decomposition by applying continuous wavelet transform was used [18] [19] to specifically study the modification of roughness.

The principle of wavelet analysis is based on the convolution of the topographic surface with wavelets of variable dilatations and translations of the mother wavelet $\psi(t)$. The Mexican hat was used as the mother wavelet.

This multi-scale method transforms, locates, and quantifies the amplitudes of the topographic signal from roughness to waviness over a wide band of wavelengths, without any break in the latter. Not only does this approach provide a multi-wavelength analysis tool, it is also a multiscale quantitative method. For example, it is possible to characterize a topographic component by calculating a topography parameter for each scale 'a'. The SMA or roughness spectrum is the calculation of the topography coefficient S_a (arithmetic mean) at each resolution level (scale) of the signal, where $|W_a(x, y)|$ are the absolute values of the amplitudes of the multiscale decomposition.

$$SM_a = \frac{\sum_{x=1}^{x=N} \sum_{y=1}^M |W_a(x, y)|}{MN}$$

The different steps of the wavelet decomposition are presented in Figure 2.

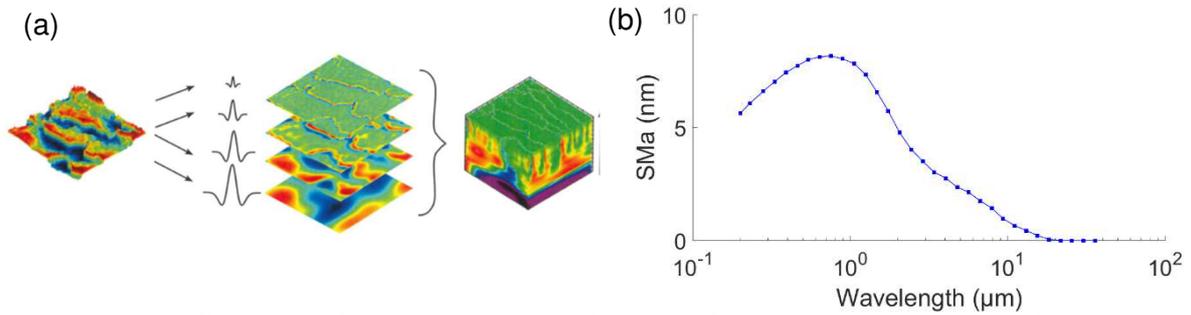


Figure 2 : (a) The different steps of wavelet decomposition: from the surface to the reconstructed cube; (b) corresponding SMA roughness spectrum

A second important advantage of this multiscale quantitative method is that it makes it possible to compare two surfaces in all the wavelength ranges in a quantitative way, without it being necessary to reposition the topographic images as in the case of inter-correlating two images. This multiscale comparison approach demonstrates the extent of its effectiveness for the problems of wear in tribology.

Figure 3(a) shows the typical topography of virgin hair. From this image, a multiscale decomposition of the surface is performed (Figure 3(b)). Four groups of wavelengths are distinguishable:

- The shape of hair for wavelengths higher than 7.2 μm
- The scale shapes for wavelengths from 1.3 to 7.2 μm
- The crest of hair scales for wavelengths from 0.5 to 1.3 μm
- Slight roughness for wavelengths from 0.1 to 0.5 μm

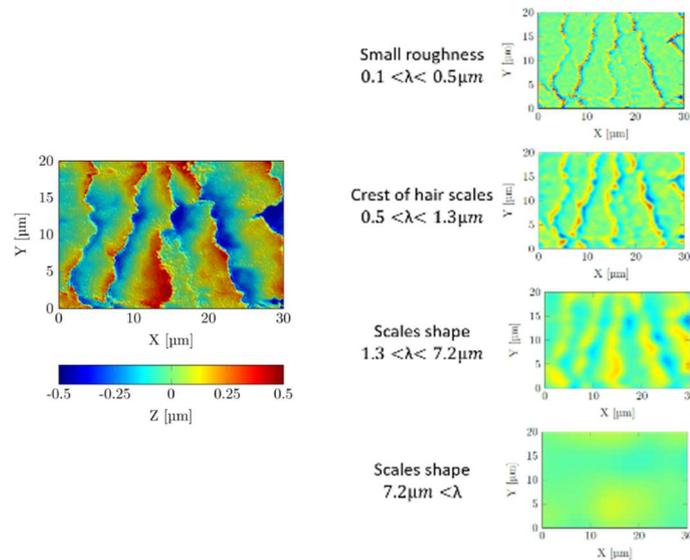


Figure 3: (a) Typical topographical image of a virgin hair fiber (b) Separation of the different surface components of virgin hair.

2.2.3. Brightness criteria

Surface roughness also has an important effect on the brightness.

For a perfectly smooth surface, a light beam which would impact the surface, would be completely reflected. On the contrary, for a rough surface, it would be dispersed.

The relationship between the roughness and brightness of a surface can be quantified using a local normal method. The image of the cuticle is decomposed into elementary areas and the slope of each area is calculated in relation with the local normal.

The local area of a summit is given by:

$$ds = \left\| \left(\frac{\partial \vec{o}\vec{z}_s}{\partial u} \right) \wedge \left(\frac{\partial \vec{o}\vec{z}_s}{\partial v} \right) dudv \right\|$$

The normal vector projected on the x, y plane is given by:

$$d\vec{s} = \left(\frac{\partial \vec{o}\vec{z}_s}{\partial x} \right) dx \wedge \left(\frac{\partial \vec{o}\vec{z}_s}{\partial y} \right) dy$$

and the standard of this projected normal vector is given by:

$$ds = \sqrt{1 + \left(\frac{\partial z_s}{\partial x} \right)^2 + \left(\frac{\partial z_s}{\partial y} \right)^2} dx dy$$

The ratio between the $dx dy$ area and the elementary area ds of the summit is equal to the cosine of the angle between the normal vector $\vec{d}s$ of the elementary area of the vertex and the vertical axis $\vec{o}\vec{z}$ (Figure 4). The local normal direction is given by the following relation:

$$\cos \gamma = \frac{1}{\sqrt{1 + \left(\frac{\partial z_s}{\partial x} \right)^2 + \left(\frac{\partial z_s}{\partial y} \right)^2}}$$

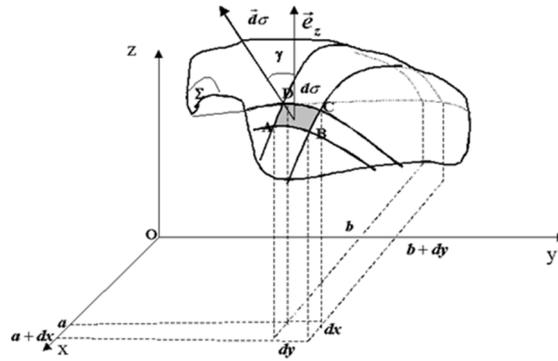


Figure 4: Definition of the local normal direction.

The normal angle deflection spectrum (NAD) is then defined as the standard deviation of the angles "γ" at the summits of the surface asperities at each analysis scale "a" and can be represented as a vector:

$$NAD(a) = \sqrt{\frac{1}{Card(S_a)} \sum_{(x,y) \in S_a} (\gamma_a - \bar{\gamma}_a)^2}$$

Where $\bar{\gamma}_a$ is the average of the angles "γ" at the peaks of the asperities of the surface at the analysis scale "a" and $Card(S_a)$ is the number of these summits at the analysis scale "a". Geometrically, this NAD spectrum characterizes the fluctuation of the angle of the normal of the summits of the surface at each scale.

A surface presenting a local normal equal to 90° is very smooth and bright. To describe this phenomenon, the normal angle deviation (NAD) is used. Thus, a decrease in value of the NAD is related to smoothness and brightness.

2.3. Friction measurement

A haptic tribometer system previously developed and patented by our team was used to perform the friction tests on hair (Figure 5) [15]. The device is inspired by the human touch process. The experimental test consists in applying a normal load F_z on the hair through a slider, which allows controlling the contact pressure, after which the hair is dragged away by a linear displacement motor in order to simultaneously measure the friction force, F_x , and the vibrations between the probe and the hair surface.

The slider is equivalent to a half spherical probe (radius $R = 10\text{mm}$), composed of an elastomer material whose mechanical properties are very close to the properties of the human finger (the Young's modulus is equal to 55kPa and its average surface roughness R_a is $2.6\ \mu\text{m}$) [20]. The normal load applied on the hair by the haptic tribometer is controlled with a normal load sensor. The maximum load during the loading can reach $3\ \text{N}$ with a resolution of $1\ \text{mN}$. During the test, the hair is fixed on a linear displacement table with a defined preload. The displacement table drags the hair away at constant speed. The friction force and the vibrations generated by the sliding between the slider and the hair are recorded by a tangential sensor (the same characteristics as the normal sensor) and a piezoelectric accelerometer, respectively, fixed on the slider.

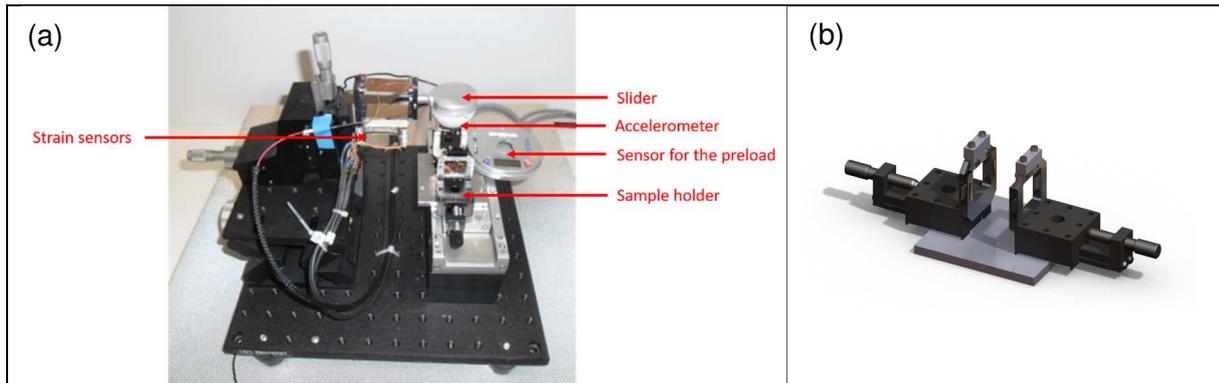


Figure 5: (a) Representation of the haptic tribometer system: the test consists in applying a normal load on the hair fibre, after which the fiber is dragged away by a linear displacement motor to simultaneously measure the friction force by the strain gauge, and the vibrations by the accelerometer. (b) Representation of the device that enables the preloading of the hair fibre.

For each test, the slider was rubbed onto the hair five times, in uniform back and forth translations. The friction length was set to $20\ \text{mm}$. In order to represent realistic frictional conditions for people, the sliding speed was set to $20\ \text{mms}^{-1}$ and the normal force applied was equal to $0.3\ \text{N}$. These conditions have been frequently observed in the literature and correspond to classical human handling conditions [21].

The average friction coefficient μ obtained from 5 cycles is calculated by the ratio between the friction force and the normal force as: $\mu = \frac{F_x}{F_z}$. In addition, to give a quantitative value to the vibrations, the average acoustic vibratory level was defined as:

$$L_a = 20 \log \left(\frac{A_{RMS}}{A_{ref}} \right)$$

Where L_a is the acoustic vibratory level, A_{RMS} the root mean square value of the acceleration in m/s^2 and $A_{ref} = 10^{-6}\ \text{m/s}^2$ the smallest acceleration that can be detected by the sensor.

During the test, back and forth translations were performed on the hair (from root-to-tip and tip-to-root) to study the dependence of friction on direction with respect to hair. Thus, the parameters along and against the cuticle were evaluated.

3. Results and discussion

For each measurement, 5 hair samples of each type were tested in view to performing statistical analysis.

3.1. Effect of chemical treatments

3.1.1. Hair topography

Figure 6 shows typical topographies obtained for virgin, colored and bleached hair. The images show that the cuticle scales are relatively intact for virgin hair. By contrast, an increase of roughness is evident for colored and bleached hair samples. The colored hair sample contains poorly defined cuticles, their edges are toothed and the surface seems to be rough. In the case of bleached hair, no well-defined cuticles can be observed, the surface is very rough with a lot of asperities. It is suggested that bleaching process has removed almost all the cuticle, leaving the underlying cortex structure. Bleaching is known to remove cuticular layers [22] [23].

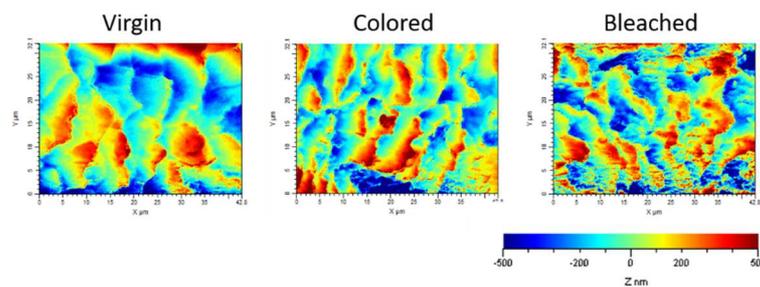


Figure 6: Representation of the topography of virgin, colored (chemically treated) and bleached (chemically treated) hair. The scale on the bottom right corresponds to the amplitudes of the topography from -500nm in blue to +500nm in red.

Figure 7 presents the SMA and NAD spectra obtained for the different types of hair samples. The spectra can be divided into several parts according to the values of the wavelengths as previously described in the Material and Methods part. It can be noticed that the value of SMA and NAD is near zero for the wavelengths higher than $10\mu\text{m}$. This is due to the fact that the cylindrical shape of the hair fiber has been removed for the topographical analysis.

The results show that the differences between the topography of the hair samples is localized at the small and medium wavelengths. Thus, the chemical treatments induce topographical modifications at the level of the hair scales (small wavelengths). Indeed, the SMA value is higher for treated hair samples, especially for bleached hair. This phenomenon is explained by the formation of surface defects due to chemical treatments, which increases the slight roughness at the hair surface.

Regarding the NAD spectrum presented in Figure 7(b), we observed that the difference between virgin and chemically treated hair samples is localized at the level of the hair scales too (from 0.5 to $7.2\mu\text{m}$). Indeed, there is an increase of the NAD for the bleached and colored hair compared to virgin one. Our hypothesis is that the chemical treatments open and lift the hair scales to allow the diffusion of colorants inside hair [24]. Thus, the hair surface becomes rougher (higher value of SMA) and less bright (higher value of NAD) because the scales are less flat than for virgin hair.

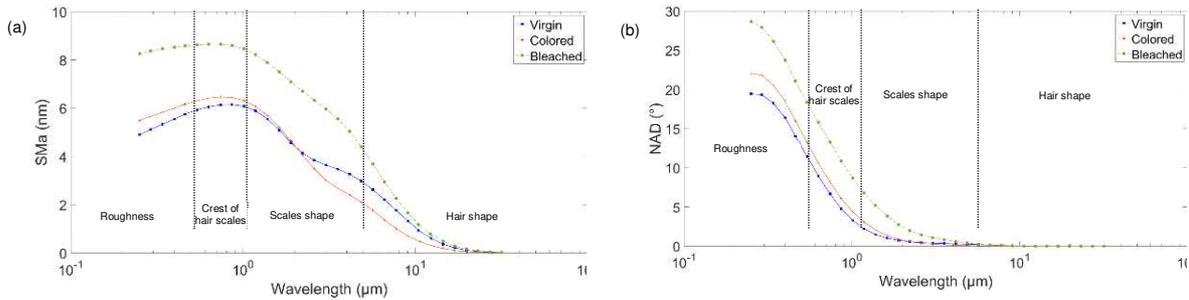


Figure 7: SMA (a) and NAD (b) spectra obtained for virgin, colored, and bleached hair samples. For clarity, the figure represents the mean spectrum of each type of hair. Four groups of wavelengths are distinguishable: the shape of hair for wavelengths higher than $7.2 \mu\text{m}$; the scale shapes for wavelengths from 1.3 to $7.2 \mu\text{m}$; the crest of hair scales for wavelengths from 0.5 to $1.3 \mu\text{m}$; slight roughness for wavelengths from 0.1 to $0.5 \mu\text{m}$

The SMA and NAD spectra corroborate the previous observations and suggest that chemical treatments have an impact on the friction and wear of hair, which may result in a decrease of its sensorial properties: decrease of soft touch and brightness.

3.1.2. Friction and wear of hair

We are interested in the effect of hair bleaching and coloring on friction and wear. The friction coefficients and acoustic vibratory levels measured are presented in Figure 8. The results revealed that the chemical treatment applied to hair has an effect in terms of friction coefficient and acoustic vibratory levels.

Figure 8(a) presents the friction coefficient measured for virgin, colored and bleached hair in two directions: root-to-tip and tip-to-root. The results show that the friction coefficient increases with a chemical treatment. Along the cuticle, the friction coefficient is about 0.28 for virgin hair, 0.44 for colored hair (increase of +57%) and 0.40 for bleached hair (increase of +42%). This increase is due to damage to the cuticle induced by the chemical treatment. Indeed, although the process is slightly different, both coloring and bleaching use hydrogen peroxide to tint hair. This process causes severe wear to the cuticle layer [14]. This phenomenon has already been mentioned in [21]. Indeed, the authors studied the effect of chemo-mechanical treatments on hair and showed that the friction coefficient was higher for damaged hair than for virgin hair and hair treated with conditioner. Generally, the friction force is divided into two components: one term due to the adhesion phenomena between the surface and the slider and one term due to the deformation of the material [25]. As the normal load applied to the fibre is low, it is reasonable to assume that this is the adhesion part which contributes the most to the friction coefficient. In the present case, the higher friction for damaged hair could be explained by the roughness developed after chemical treatments which affects friction.

The data also shows a significant friction directionality effect for virgin hair: the friction coefficient is lower in the root-to-tip direction (friction coefficient of 0.28). This result has already been reported in the literature and is due to the fact that it is easier to move a surface over hair along the cuticle [3] [26] [27] [28]. This is due to the numerous scale edges which come into contact with the slider. Indeed, these edges resist to motion as they are forced backwards and uplifted from their interface with the underlying cuticle layers. This phenomenon results in higher friction values, and a higher friction coefficient than when traveling along the cuticle.

The friction directionality effect is not observed for colored and bleached hair. This may be attributable to the damage caused to hair scales by coloring and bleaching.

Figure 8(b) presents the acoustic vibratory levels measured for the different hair samples. The acoustic vibratory level is expressed in decibels (dB). It should be noted that a difference of 3dB corresponds to a multiplication of the sound signal by two.

Along the cuticle, the data show that the acoustic vibratory level is higher for colored and bleached hair samples (respectively 97.65 dB, increase of +1.4%, and 98.26 dB, increase of +2%) than for virgin hair (96.33 dB). Previous team results have shown that vibrations are related to the softness of the surface [29]. In this work, the authors rubbed a tribo-acoustical probe on the skin surface and measured the acoustic level of vibrations induced by the friction. They showed that the level of acoustic vibrations gave a signature of skin softness. The surface is softer for a lower acoustic vibratory level. Thus, virgin hair samples are the softest: they have better tactile properties. This proves that coloring and bleaching damage hair fibers and makes them less soft.

Thus, as with the friction coefficient, we observed a directionality effect for all the hair samples. The acoustic vibratory level was always higher for the tip-to-root friction tests. This means that the hair fibers are felt less soft when touching against the direction of the cuticle scales.

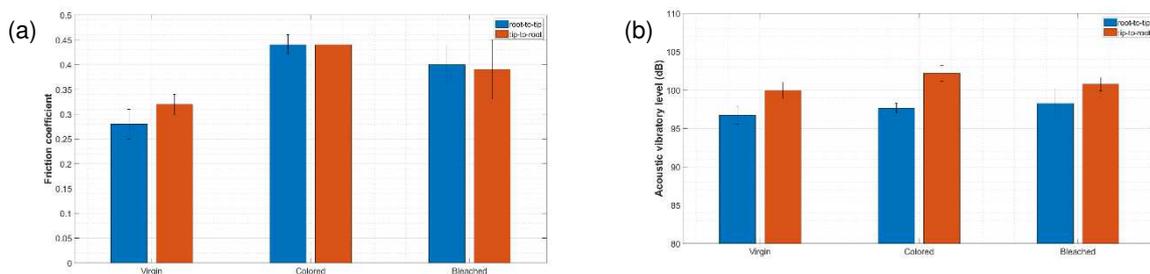


Figure 8: Effect of chemical treatments and directionality dependence of hair: (a) Friction coefficients measured for virgin, colored and bleached hair samples. (b) acoustic vibratory levels measured for virgin, colored and bleached hair samples. For (a) and (b), the blue color represents the values obtained for the friction along cuticle (root-to-tip) and the orange color for the friction against cuticle (tip-to-root). All the values correspond to the mean \pm standard deviation values.

Spectral analyses of friction induced vibration signals were carried out using Matlab R2018a to assess the frequency content and corresponding amplitude from the power spectral densities (PSD) of the signals [30] [31].

Figure 9 presents the PSD signals obtained for the different hair samples. Two main peaks can be identified in the figure for each sample. To compare the virgin and chemically treated hair, Table 1 gives the deviations of amplitude and frequency of the treated hair as a function of virgin hair values. These spectra show that the peaks are higher in amplitude for colored and bleached hair compared with virgin hair. There is also a small frequency offset. The peak height is linked to the magnitude of vibrations (due to the contact between the probe and the surface of the hair). Softness and lower friction are believed to be responsible for the lower amplitude of the signal. This was consistent with our previous observations: a higher amplitude corresponds to a higher acoustic vibratory level, thus a rougher surface. Cattaneo and Vecchi explained that smooth surfaces induce virtually no vibration, while rougher surfaces induce more vibrations [32].

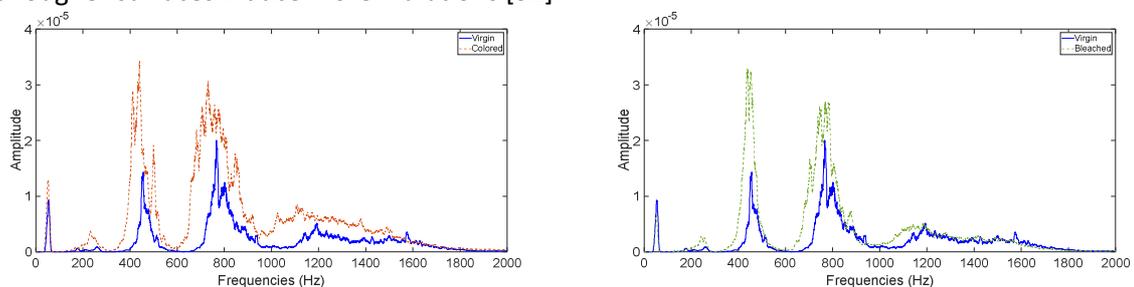


Figure 9: PSD signal (a) virgin vs colored hair; (b) virgin vs bleached hair for the root-to-tip direction.

Table 1: Deviations of amplitudes and frequencies of treated hair as a function of virgin hair values.

Sample vs Virgin	$\Delta\omega(\text{Hz})$	$\Delta\text{Amplitude} (\times 10^{-5})$
Colored	-16	2 (+142%)
	-37	1.6 (+80%)
Bleached	-6	1.8 (+128.7%)
	-2	1.3 (+65%)

To conclude this part, bleaching and coloring processes are responsible for damaging hair fiber, especially at the cuticle level. This damage impacts the sensorial properties of hair, making it rougher, dull and less soft.

3.2. Effect of thermomechanical treatments

3.2.1. Hair topography

The topography of virgin, damaged and smoothed hair is presented in Figure 10. The results show that the cuticle of the virgin hair is complete whereas the cuticles are not well defined and several scales are worn away from the damaged hair. Furthermore, the surface of the damaged hair seems to be rougher with more asperities. This result is consistent with previous works [21] [9] [11]. We assume that this damage impacts the sensorial properties of hair.

If we focus on smoothed hair, we can observe that there are fewer asperities than for the damaged hair. The morphology of smoothed hair at 140°C is similar to that of virgin hair.

The scales are well-defined whereas the edges are less marked. Thus, the hair fiber appears smoother, almost melted. The observation is amplified at a temperature of 200°C: the hair surface appears very smooth; the scales are almost gone. Our hypothesis is that the temperature could melt the cuticle which is then easily deformed by applying pressure to the hair surface via the smoothing process.

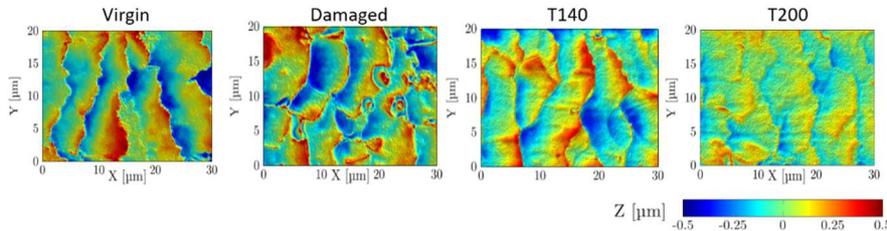


Figure 10: Representation of the topography of virgin, damaged and smoothed hair at 140°C (T140) and 200°C (T200). The scale on the bottom right corresponds to the amplitudes of the topography from -500nm in blue to +500nm in red.

Figure 11 presents the SMA and NAD spectra obtained. The differences between the topography of the hair samples is localized at the small and medium wavelengths, particularly at the level of the hair scales.

The damaged hair presents the highest values of SMA and NAD in the band of small and medium wavelengths. This is due to the appearance of asperities, markedly inclined with respect to the hair surface. Thus, the surface is rougher.

Consequently, the results show that the smoothed hair has lower SMA and NAD values than for virgin hair that increase if the temperature is high. This is consistent with the previous topographical observations: the surface becomes smoother. Furthermore, the surface is perceived as being bright due to the lower NAD.

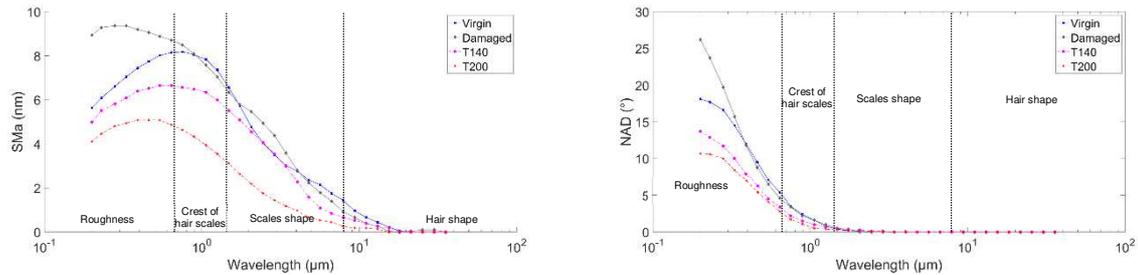


Figure 11: SMA (a) and NAD (b) spectra obtained for virgin, damaged, and smoothed hair samples at 140°C (T140) and 200°C (T200). For the sake of clarity, the figure represents the mean spectrum of each type of hair. Four groups of wavelengths are distinguishable: the shape of hair for wavelengths higher than 7.2 μm; the scale shapes for wavelengths from 1.3 to 7.2 μm; the crest of hair scales for wavelengths from 0.5 to 1.3 μm; slight roughness for wavelengths from 0.1 to 0.5 μm

Finally, we assumed that thermomechanical treatments on damaged hair could improve its sensorial properties by erasing asperities and flattening the hair surface. Nevertheless, these treatments did not permit preserving the hair’s morphology: the hair cuticles became flatter and the scales were less defined.

3.2.2. Friction and wear of hair

The friction along the cuticle is more relevant to our daily life, so we now focus on the friction tests along the cuticle.

In this part, we study the effect of smoothing at different temperatures on the morphological, topographical and sensorial properties of the hair fibers. The objective is to ensure whether thermomechanical treatments improve the sensorial quality of hair fibers damaged previously.

Figure 12 presents the friction coefficients and acoustic vibratory levels obtained. We can observe a relatively high standard deviation for damaged hair. It is due to the fact that, even if the damage is controlled, it is difficult to obtain exactly the same degree of degradation for each hair sample. The results show that damaged hair samples have the highest friction coefficient with a value of 0.45 ± 0.08 and the highest acoustic vibratory level equal to 101.87dB. As for coloring and bleaching, the results show that damaged hair is less soft and rougher than virgin hair. This is in accordance with the topographical observations.

Concerning smoothed hair, the results show that the friction coefficient (0.31 ± 0.02 and 0.3 ± 0.03 respectively for 140 and 200°C) is quite similar to that of the virgin hair (0.28 ± 0.03). Thus, smoothing damaged hair induces a decrease in acoustic vibratory level. Indeed, after smoothing treatment, the acoustic vibratory level returns to the base level. For a temperature of 200°C, it reaches a value lower than that for the virgin hair.

All these results demonstrate that the smoothing treatment improves the softness of hair fiber, making it less rough.

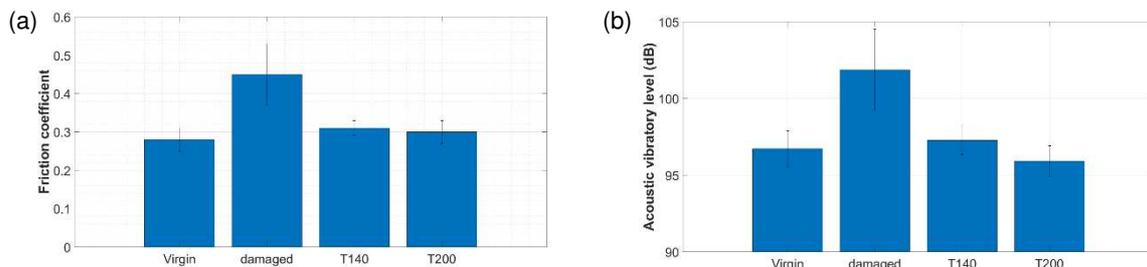


Figure 12: Effect of thermomechanical treatments of hair: (a) Friction coefficients measured for virgin, damaged and smoothed hair samples at 140°C (T140) and 200°C (T200). (b) acoustic vibratory levels measured for virgin damaged and smoothed hair samples T140 and T200. All the values correspond to the mean ± standard deviation values.

The PSD spectra of virgin and smoothed hair are presented in Figure 13. We again observe two main peaks. Table 2 gives the deviations of amplitude and frequency of smoothed hair as a function of virgin hair values. The amplitudes of the peaks are lower for smoothed hair, and there is a significant shift of the peaks towards the low frequencies. The decrease in amplitude reflects the smoother aspect of hair after the thermomechanical treatments. Indeed, a smooth surface reduces the magnitude of vibrations due to the contact between the probe and the hair surface.

Therefore, the decrease in frequency corresponds to an increase in wavelength. Thus, the period of roughness is higher for smoothed hair. This may be due to the flattening of the scales after smoothing, which erases the natural periodicity of the hair surface. This phenomenon becomes more pronounced when increasing temperature.

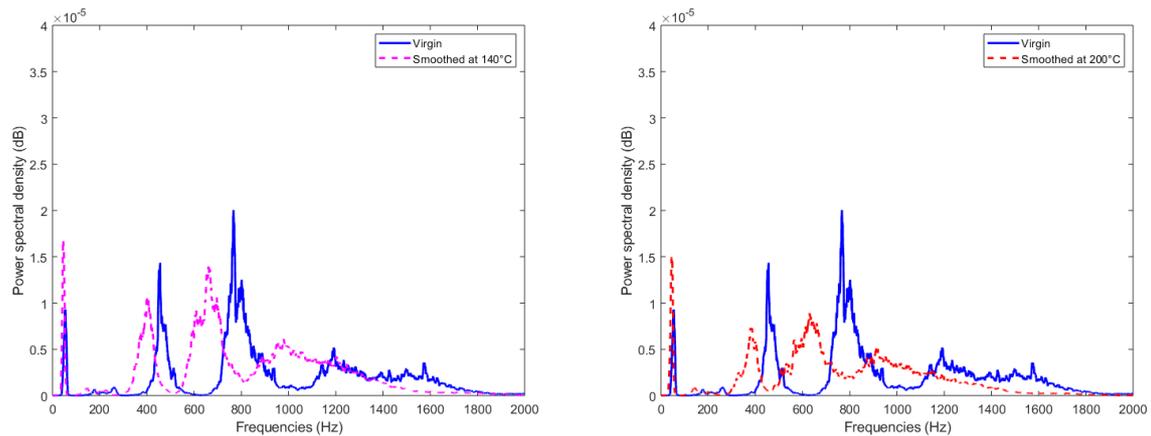


Figure 13: PSD signal (a) virgin (blue solid line) vs smoothed hair at 140°C (magenta dotted line); (b) virgin (blue solid line) vs smoothed hair at 200°C (red dotted line).

Table 2: deviations of amplitudes and frequencies of smoothed hair as a function of virgin hair values.

Sample/Virgin	$\Delta\omega(\text{Hz})$	$\Delta\text{Amplitude} (\times 10^{-5})$
T140	-56	-0.4 (-28%)
	-105	-0.6 (-70%)
T200	-71	-0.68 (-48.6%)
	-138	-1.12 (-56%)

In conclusion to this part, smoothing can improve the sensorial properties of hair, making it smooth, bright and soft.

4. Conclusion

The present study concerned the modifications of morphology and biotribology of hair due to chemical and thermomechanical treatments and the consequences on the sensory properties. The conclusions of this study are as follows:

- Chemical treatments, such as bleaching and coloring, damage the hair cuticle and have an impact on the morphological and tribological properties of hair. Indeed, after these treatments, the cuticle scales are less defined, and several asperities appear at the hair surface. This results in an increase of the SMA and NAD parameters which reflects a decrease of the sensorial properties of the hair fiber which becomes dull and rough. These treatments also affect the tribological behavior of hair. Treated hair fibers lead to higher friction coefficients and acoustic vibratory levels: the hair fiber becomes less soft.

- Applying thermomechanical treatments to damaged hair improved morphological and tribological properties of damaged hair. Indeed, after these treatments, the surface of damaged hair becomes smoother and the asperities are erased. Nevertheless, the scales are less defined. The hypothesis put forward is that the temperature melts the cuticle which is then deformed by applying pressure to the hair surface. Then, smoothed hair has friction coefficients and acoustic vibratory levels close to the one of the virgin hair. Thus, applying thermomechanical treatments to damaged hair permits to restore some of its initial properties. Finally, the hair fiber appears brighter and smoother.

Finally, these results are essential for understanding the impact of different solicitations on the physical and sensorial properties of hair. These techniques could be adapted to other cosmetic products that modify the cuticle's topography.

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