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Research Paper

Effect of water desorption on the rheology and dynamic response of human hair to a non-contact impact

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ABSTRACT

Human hair is a non-homogeneous complex material made of keratin fibers oriented along the longitudinal axis which offer anisotropic mechanical properties. Nowadays, it is possible to measure the mechanical properties of hairs with the classical tests, but most often, these tests are destructive and make hard to measure the influence of some external factors or treatments on the behavior of a same hair fiber. In the current paper, vibrations induced by a non-contact impact have been utilized as a representative response of the mechanical behavior of hair. The characteristics of the vibratory response allow measuring the variation in the mechanical properties and the instantaneous effect of an external factor on the properties of a same sample. First, load relaxation tests have been performed on hair samples after moisturization and for different times of an air-drying process in order to characterize the change in the visco-elastic behavior of hair during the water desorption. Other hair samples have been tested with our non-contact impact and vibration technique in order to observe the change in the vibratory response during the water desorption. The vibratory response has then been correlated to the mechanical properties of the hair fiber.

1. Introduction

As a biological composite material, human hair has a complex multi-scale structure extremely sensitive to several external factors such as humidity, temperature, and chemical treatments. To better understand the effect of these factors, it is important to study and characterize the bio-mechanical properties of hairs. With a diameter of 60–100 μm, human hair is made of a sulfur rich protein, the keratin molecule. Its structure is composed of two concentric parts. The cuticle is the outer part and presents a multilayer organization made of flattened cells, the scales. The inner part is called the cortex and represents more than 90% of the whole hair weight (Zviak, 1988; Bouillon and Wilkinson, 2005). While the cuticle plays a protection role, the cortex is responsible for the mechanical properties of hair. Indeed, the cortex is composed

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of fibril proteins organized in helicoidal polypeptide chains, the alpha-chains. The shape of the alpha chains is maintained by hydrogen bonds located between the coils of the helices. The alpha-chains are also linked together by other types of bonds, the salt bridges and stronger covalent bonds, the disulfide bridges, in order to form the first fibril structure of hair: the intermediate filaments (IFs) (Jones et al., 1997). Then the IFs are embedded in an amorphous matrix with a high sulfur content to form the macrofibrils and the cortical cells (Leon, 1972; Wolfram, 2003). Previous studies have shown that this multi-scale organization did not differ according to the type of hair studied or the ethnic origin (Wilk et al., 1995; Franbourg et al., 2003). The fiber-matrix composite structure and the orientation of the IFs along the longitudinal axis are responsible for the anisotropic mechanical properties of hairs (Robbins, 2012). Moreover, the presence of different types of bonds and particularly of weak bonds such as the hydrogen bonds makes hair extremely sensitive to environmental factors such as temperature and humidity.

The effect of water on the structure and the mechanical properties of keratin fibers have been the subject of various previous studies. The sorption–desorption hysteresis curve shows that hair fibers are able to absorb a large quantity of water, reaching a maximum water regain of 26% for 100% of relative humidity (Chamberlain and Speakman Leeds, 1931; Barba et al., 2010). Concerning the hair structure, Popescu and Höcker (2007) have shown that water sorption resulted in swelling and emphasized an anisotropy of swelling with a radial swelling much more important than the longitudinal swelling. In another study, Feughelman (1994) built a two-phase model where the intermediate filaments are considered to be water impenetrable rods embedded in a hydrophilic matrix. This model is in accordance with the swelling behavior of hair and can represent an explanation to the dependence of the mechanical behavior of hair to relative humidity.

The variation in the mechanical behavior of hair as a function of relative humidity has also been studied in the literature. As for all the keratin fibers such as wool, the tensile properties of hair are changing with relative humidity (Hearle and Morton, 2008). When hair is wet, the Yield region starts for a lower level of stress due to the breaking of the hydrogen bonds. Kreplak et al. (2002) explain the effect of water by showing the coexistence of two deformation mechanisms in the cortex, the sliding of the alpha-chains inside the microfibrils and their stretching. The presence of water in the matrix would make the sliding of the IFs easier whereas for a dry hair under standard conditions of humidity, the macroscopic deformation would be due to the combination of both phenomena.

In this general context, one of the main tasks is to better understand the change in the mechanical behavior of hair fibers during a variation of water content. Various different techniques can be used to determine the mechanical properties of hair. The most common are the destructive techniques such as tensile tests (Velasco and Dias, 2009; Thibaut et al., 2010; Benzarti et al., 2011) and nanoindentation tests (Wei et al., 2005). Huck and Baddiel (1971) used a non-destructive method and measured the dynamic response of hair fibers using an oscillating beam method in order to characterize the elastic and loss moduli. The study presented here is experimental. It uses relaxation tests performed on several segments of a hair fiber in order to determine the global variation in the visco-elastic properties of hair during the water desorption kinetic. Then, a new mechanical approach based on the propagation of a vibration on a hair fiber has been developed. This approach uses a non-solid–solid contact impact in order to have a non-destructive solicitation and perform several tests on a same sample under different conditions. Another advantage of this method is the extremely brief solicitation time which allows measuring the instantaneous mechanical behavior of the fiber.

The present paper is organized as follows: in Section 2, the samples and the different devices used for this study are described. Section 3 presents the relaxation tests performed and the associated results. Section 4 is dedicated to the vibration study. Finally, some conclusions are drawn in Section 5.

2. Materials

2.1. *Hair samples*

For this study, virgin Caucasian hair samples of type 2 were used. Before any measurement, hair samples were washed with a clarifying shampoo, rinsed with distilled water and stored during 48 h in a room at a temperature of 22 °C and 40% RH.

2.2. *Tensile testing machine*

Relaxation tests on single hair fibers were performed with a tensile testing machine. The machine is made of the same components as the classical testing devices with a sample holder, a translation module to pull up the sample and a force sensor to compute the applied force on the fiber, as described in Fig. 1.

The translation module used is a Polytec Instruments stepper motor and can reach a maximum speed of 1.5 mm/s over a distance of 25 mm with a very high resolution lower than 1/100 μm. The speed and the displacement are controlled by a card connected to the engine control. The force sensor which can load a maximum of 3 N with a resolution of 1 mN enables the measurement of the force. The applied stress on the sensor is transmitted to a computer via a National Instrument capture card and an amplifier. Finally,

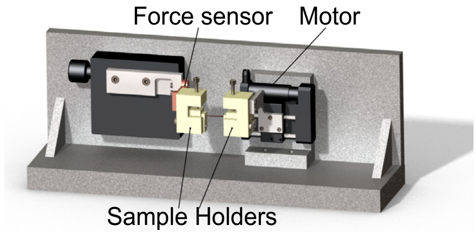

Fig. 1 – Schematic representation of the tensile testing machine.