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Structure and mechanical behavior of human hair

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ABSTRACT

The understanding of the mechanical behavior of hair under various conditions broadens our knowledge in biological materials science and contributes to the cosmetic industry. The hierarchical organization of hair is studied from the intermediate filament to the structural levels. The effects of strain rate, relative humidity, and temperature are evaluated. Hair exhibits a high tensile strength, 150–270 MPa, which is significantly dependent on strain rate and humidity. The strain-rate sensitivity, approximately 0.06–0.1, is comparable to that of other keratinous materials and common synthetic polymers. The structures of the internal cortex and surface cuticle are affected by the large tensile extension. One distinguishing feature, the unwinding of the α-helix and the possible transformation to β-sheet structure of keratin under tension, which affects the ductility of hair, is analytically evaluated and incorporated into a constitutive equation. A good agreement with the experimental results is obtained. This model elucidates the tensile response of the α-keratin fibers. The contributions of elastic and plastic strains on reloading are evaluated and correlated to structural changes.

1. Introduction

Hair, an important part of our body, not only possesses aesthetic significance in our culture, but also offers protection. This fiber-reinforced nanocomposite plays a key role as an outer covering in many vertebrates [1]. Hair fibers have a typical hierarchical structure similar to other α-keratin materials, such as wool, nails, claws, and horns present in mammals. The keratin in reptiles and birds is primarily in the form of β-sheets [2]. Keratinous materials are categorized as α-keratin if they exhibit a helical secondary structure or as β-keratin if they are in the shape of sheets. A typical hair fiber has a diameter of 50–100 μm and is covered by an outermost layer, the cuticle. The cuticle consists of thin overlapping scales [3]. Each scale has an average length of 60 μm and a thickness of about 0.5 μm. Furthermore, 5–10 such scales overlap to create a total thickness of ~5 μm. The morphology of the cuticle edges is thought to be affected by weathering, combing, and brushing, with more severe damage seen on long hair fibers [4].

Fig. 1 shows the hierarchical structure of hair. The inner section of hair is called cortex and is composed of cortical cells that are ~100 μm long and 1–6 μm thick. These cortical cells are composed of subcomponents called macrofibrils. The macrofibrils exhibit a diameter of 0.1–0.4 μm [5]. At the nanometer scale, they are composed of intermediate filaments (IF) embedded in a matrix with high-sulfide content. One IF has a diameter of ~7.5 nm and is formed by eight protofilaments. Each protofilament is composed on its turn of four right-handed α-helix chains; therefore a total of thirty-two chains form an IF [6].

Hair fibers have 65–95 wt% of proteins depending on the humidity and up to 32% of water, with the rest as lipid pigments and other components [7]. Therefore, chemically the properties of human hair are dominated by the α-keratin [8]. It has been demonstrated that the tensile properties of hair are mostly produced by the cortex, not the cuticle. Robbins and Crawford [9] damaged the cuticle with chemicals and found no apparent difference in the tensile properties with original hair fibers. Relaxation tests by Barnes and Roberts [10] and Robinson and Rigby [11] showed that the moduli are dependent on the time as well as strain and that the thiol content affects the mechanical properties. It was also demonstrated that the tensile properties are highly dependent on the influences of various factors: a high relative humidity decreases the Young's modulus and increases the extensibility [12]; an increase in temperature leads to a decrease in Young's modulus and an increase in extensibility [13]; twisting creates damage to the hair fibers [14] and this effect leads to the decrease in the breaking stress, breaking strain and Young's modulus. Ethnicities and age also affect the properties of human hair. It has been shown that hair specimens from different ethnicities exhibit different strains at cuticle lift off [15],

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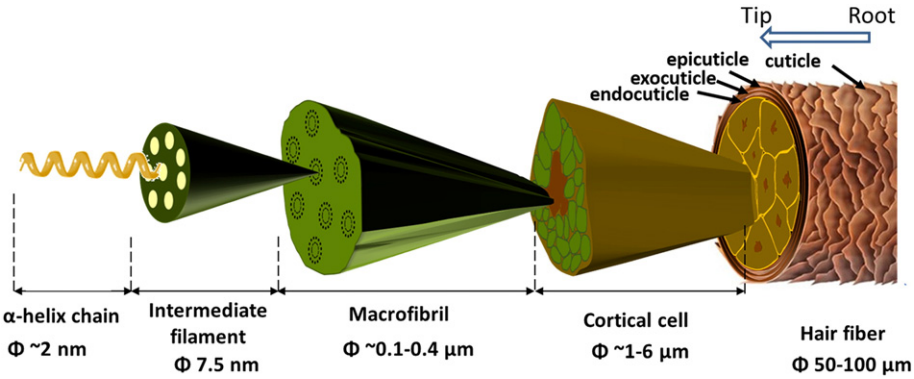

Fig. 1. Schematic representation of hierarchical structure in human hair starting at α-helix chains and progressing to the entire section.

topographies [16–18], surface roughness [16], nanomechanical properties [19], and tensile properties [17,18]. In the meantime, as hair specimens age, the relaxation time also varies significantly [20].

Being one of the most important typical α-keratin fibers, the mechanical behavior of hair was therefore studied quantitatively with respect to various contributing factors in this study. We report the sensitivities of the hair on the strain rate, relative humidity, and temperature through tensile testing. We also propose a constitutive equation for human hair and compare its predictions with experimental results.

2. Materials and methods

2.1. Specimen preparation

Hair specimens were collected from an East-Asian female in her early 30s. All the hair in the experiments was donated from only one individual to avoid the variations in mechanical properties reported between hairs from different ethnicities and the effect of aging as discussed above. No additional treatment such as straightening or dyeing except daily cleaning was conducted on the hair before collection. The average length of the collected hair was about 30 cm. Before specimen preparation, 2 cm sections were cut off at both ends from the entire hair and discarded. The remainder of the fiber was sectioned into 3 cm long pieces. For each small section, the two ends were glued into sand paper to prevent slipping between the grips during the tensile testing, leaving a 1.0–1.5 cm long hair span between sand papers to be tested. The cross-section area of each fiber was individually gauged using a 0–25 mm range micrometer with 0.001 mm accuracy. At least three measurements were made on one sample to ensure an average value in the diameter. It should also be noted that the pressing on the fiber was carefully avoided during measurements.

Specimens were tested under 20%, 50% (ambient) relative humidity (RH), and immersion in water at different strain rates. Specimens tested under water were first prepared by using the same method described above; additionally, the sand papers at the two ends were mounted into epoxy to prevent splitting in water. The hair fibers were then immersed in deionized (DI) water for 24 h to reach a full saturation before the mechanical tests. A transparent environmental chamber with a dehydrator and hydrometer was built to produce the low-humidity condition. The hair specimens were pre-treated at 20% RH for 3 days to ensure equilibrium with the environment and tested under such condition.

2.2. Mechanical testing

An Instron 3342 system with a 500 N load cell was used for tensile testing. Specimens were tested at strain rates of 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 10^{0} s^{-1} at room temperature and humidity. To determine the effect of humidity on the mechanical properties of hair, the pre-soaked specimens were tested in the DI water at 20 °C at varying strain rates. The effect of temperature on the hair was established at a strain rate of 10^{-2} s^{-1} in order to maintain a steady temperature of the hair specimen during one tensile test. Tests at higher temperatures (40°, 60° and 80 °C) were conducted in water immersion. Cyclic mechanical tests in air at different temperatures were also conducted by using hair specimens which were heated with a common hair dryer while the temperature was monitored with a thermometer. At least five to eight specimens were tested under one condition (for example, each strain rate at each relative humidity) to ensure an accurate representation of the mechanical properties.

2.3. Characterization

For structural characterization, hair specimens were fractured in liquid nitrogen and then fixed using an established method [21]. The specimens were first immersed in 2.5% glutaraldehyde solution for 3 h and further dehydrated with an ascending ethanol series (30, 50, 70, 90, 95 and 100 vol.% twice) for 20 min in each solution. The surface (cuticle) of the hair before and after testing as well as the fracture surface of the hair specimens was observed in a FEI SFEG ultrahigh-resolution scanning electron microscopy (SEM) (FEI, Hillsboro, OR, USA). The specimens were sputtered with iridium prior to observation.

The hair was also characterized by transmission electron microscopy (TEM) using osmium tetroxide (OsO_4) staining [22] with post-staining of lead. Segments of hair fibers were pre-treated by immersing in 0.5 M thioglycolic acid (pH 5.5) for 24 h at room temperature to enhance the contrast between the filaments and matrix. They were then washed with double-distilled water for 1 h and immersed in 1–2% aqueous OsO_4 for 3 days. Afterwards, the segments were washed with distilled water, dehydrated to 100% ethanol through a series of graded alcohol solutions and then transited to 100% acetone through graded mixtures of ethanol and acetone. The specimens were subsequently infiltrated using Spurr's low viscosity epoxy resin through a series of solutions with increasing amounts of resin and decreasing amounts of acetone (25% resin + 75% acetone, 50% resin + 50% acetone, 75% resin + 25% acetone, 90% resin + 10% acetone, 100% resin, 100% resin), each taking one day. Specimens were then placed in fresh resin and polymerized for 2 days at 65 °C. The embedded specimens were trimmed and sectioned on a Leica Ultracut UCT ultramicrotome using a diamond blade. Sliced sections were picked up and post-stained with lead for 60 s. A FEI Technai 12 (Spirit) (120 kV) transmission electron microscope was used for examination.

3. Results and discussion

3.1. Structural and morphological characterization

Fig. 2 shows transmission electron micrographs of transverse cross section of hair. Within cortical cells, which are separated by a cell