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Fatigue testing of hair—A statistical approach to hair breakage

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Synopsis

The objective of this work is to describe an alternative approach for assessing hair breakage. The methodology involves the repeated application of force, together with an evaluation of the number of cycles required before breakage—an approach often termed *fatigue testing*. The technique provides novel results, which appear to indicate more sizable differences between samples than arise from conventional constant-rate extension experiments. For example, results illustrate a substantially higher tendency for breakage in Afro hair as compared to Caucasian hair—a conclusion that appears in line with consumer experiences. Also, findings suggest a substantially larger contribution from the relative humidity of the environment to the propensity for breakage under these conditions.

The fatigue approach also lends itself to a novel means of data analysis in which breakage is treated as a statistical variable rather than as a mechanical parameter. By performing Weibull analysis of the data, a characteristic lifetime and a shape parameter are obtained to characterize the data, while survival probability plots can be generated to predict the propensity for breakage under a specific set of conditions.

INTRODUCTION

When talking to consumers about hair care needs and desires, it generally doesn't take long before the term "strength" is mentioned. Consumers appear to equate hair strength with hair health. "Strong hair" is synonymous with healthy, beautiful, and vibrant hair, while terms such as "weak," "fragile," and "brittle" are often linked to hair that is in poor condition. This is well recognized by marketers of hair care products, who frequently compose claims surrounding hair strength in an attempt to drive sales. Scientifically, the strength of individual hair fibers can easily be probed by standard mechanical testing approaches—most often the generation of stress-strain curves using constant-rate extension experiments. Figure 1 shows a schematic of a typical stress-strain curve, together with a selection of parameters that can be extracted to provide quantification.

However, while these measures provide a means for characterizing the technical strength of hair, it can be argued that such experiments are not a particularly accurate simulation of how consumers make judgments. Instead, it appears likely that consumer assessment of hair strength comes from viewing the number of broken fibers in a brush or comb after grooming, by noting the number of fibers at the bottom of the tub after showering, or by observing split ends in a mirror. In fact, in the consumer vernacular, it seems likely that "strength" represents a self-assessment involving the ease of hair

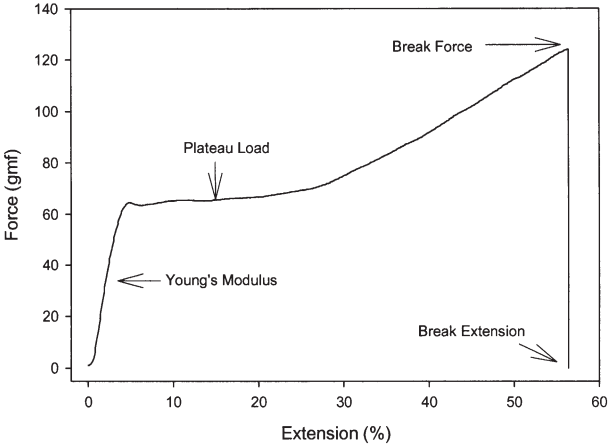

Figure 1. Typical stress-strain curve for dry hair.

breakage. While technical parameters such as stress-to-break, extension-to-break, and/or work-to-break are commonly extracted from the afore-mentioned stress-strain experiments, again it is suggested that these variables provide a scientific characterization of fiber properties rather than a simulation of consumer-relevant stimuli. The goal of this article is to describe an alternative approach for investigating hair breakage, which involves experiments that are believed to better simulate everyday wear and tear. In addition, a method of data analysis is also described that literally predicts the propensity for hair breakage.

Experimentation involves the application of a repeated force, with an evaluation of the number of cycles required for failure, a process referred to as "fatigue testing." The underlying principle behind this approach relates to repeated application of an external stimulus, leaving a sample in a weakened state where, ultimately, failure occurs upon application of a force considerably less than that required to induce breakage from a single stimulus application. As such, testing is presumed to be more akin to the external stimuli received over a lifetime of grooming. Similar experiments are commonly performed in a variety of industries as a means of evaluating resistance to repeated external force and in an attempt to predict failure rates. In such experiments, failure is taken to occur as a result of flaws that propagate and ultimately fail with repeated fatiguing. Therefore, with the distribution of flaws representing a statistical variable, the likelihood of failure (or in our case, breakage) also necessitates a statistical analysis. Thus, in this article, an experimental procedure and a means of analysis are presented for predicting the probability of hair breakage under different conditions.

BACKGROUND

In many industries it is beneficial to model the manner in which objects or materials fail. For example, in the automobile industry, knowledge of projected failure rates for bearings, shocks, brakes, electronics, and even tires forms the basis of a car's routine maintenance schedule. Thus a discipline has evolved to analyze and model failure events. Such work is often termed *reliability statistics* or *survival probability*. In this work, the objective has been to model the propensity for hair breakage under repeated fatiguing forces—a process that is proposed to better mimic the stimuli received during conventional grooming. Applications of fatigue testing are known in the textile industry and in the evaluation of other fibrous materials (1), although the approach has received only minor attention in the hair science literature. Previously, members of our Institute described microscopic analysis of fracture patterns obtained after performing such tests on a homemade device (2). Meanwhile, a parallel can be drawn between repeated application of an extensional force and the repeated application of a frictional force, as is used in flexabraison experiments (3). It is also possible to think of repeated combing experiments (4–6) as a version of a fatigue experiment. The work described here relates to experiments performed on a commercially available unit, the Dia-stron CYC800 (Dia-stron Limited, Andover, UK). This equipment has been described previously (7,8), in articles where the primary focus was to describe new commercial instrumentation. The purpose of this paper is to provide guidance in designing and performing such experiments, in addition to describing and illustrating the novel nature of the data analysis.

In similar applications of fatigue testing involving other fibrous materials, it is taken that breakage occurs as a result of propagating flaws that ultimately result in failure of the fiber. Such flaws are generally thought to be at the surface—that is, in a homogeneous fibrous material, the surface represents a greater area than the bulk, and consequently there is a higher likelihood of these flaws being present at the surface. As such, failure is taken to be virtually independent of fiber thickness and, instead, the fiber length is considered more important. That is, there is a higher likelihood for such flaws to exist in a long fiber compared to a shorter one. Some issues arise in thinking about hair in the same manner. First, unlike many synthetic fibers, hair does not have a homogeneous structure. It is well recognized that the surface of hair consists of a hard, resistant cuticle layer that protects the inner portions but has no significant contribution to the tensile strength (9). Instead, the inner cortex structure is responsible for the bulk of the strength. Therefore, propagating surface cracks would not be expected to result in fiber breakage and, consequently, failure must be considered a result of bulk flaws. Microscopic analysis of fibers that have been subjected to this repeated stimulus do frequently show the presence of propagating surface cracks (for example, see Figure 2), but these are not thought to be points that ultimately result in breakage.

Hair also differs from many synthetic fibers in that there is considerable variability in dimensions. Synthetic fibers are often manufactured to high dimensional tolerance, which does not occur in natural fibers. Therefore, use of a common fatiguing force on fibers of varying dimension will result in a range in the applied stress (force per unit area). Furthermore, with differences in applied stress comes an influence on the number of cycles to break. That is, a fiber is likely to fail earlier when exposed to repeated application of a higher stress. This occurrence is well recognized in fatigue testing, as will be discussed at some length.

Ideally, there is the desire to apply a repeating force (or, more specifically, a repeating stress) that is representative of actual grooming conditions. However, this information is not readily available. As such, while these experiments appear to better simulate real-life conditions, it is not yet possible to replicate them. Nevertheless, it is possible to use the approach to compare the likelihood of breakage in hair of varying quality, or after specific

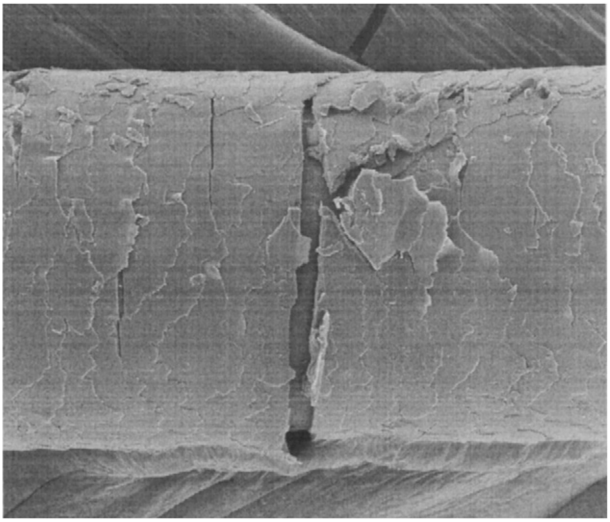

Figure 2. Propagating cracks in the cuticle as a result of fatiguing.

treatments. Alternatively, by altering the applied stress, it becomes possible to model the impact of increasing or decreasing grooming forces on the propensity for breakage. Both of these areas will be addressed in this report.

In designing and performing such experiments, the magnitude of the fatiguing force is by far the most significant variable, and it requires consideration for a number of reasons. The first involves timeliness, in that fatigue experiments can be very lengthy if relatively low repeating stresses are employed. Thus, when comparing samples under a common set of conditions, it may be prudent to select forces that do not make experiments too lengthy. However, while application of higher stresses leads to faster data generation, conditions may stray further from those presumed to accompany everyday grooming. Especially useful information may arise from performing experiments across a range of fatiguing forces, as this provides insight into the relationship between the magnitude of the external stimulus and the propensity for breakage. This may be useful to the manufacturers of conditioning products, where functionality lies primarily with the ability to provide surface lubrication and therefore lower grooming forces.

There are other experimental variables that are worth noting from a fundamental viewpoint. In theory, the speed at which the fatiguing force is applied would be expected to have an effect. It is well recognized that hair is a viscoelastic material, and consequently dynamic mechanical properties will have frequency dependence; that is, at higher frequencies hair appears more elastic (solid-like), while at lower frequencies there is more time for molecular relaxations that result in a higher viscous (liquid-like) component. In this work, a constant fatiguing rate was used, with no attempt being made to study this variable.

As will be becoming clear, the distribution of such flaws in a sample represents a statistical consideration, and consequently necessitates a statistical analysis of the results. This is believed to be another uniqueness of the approach, in that testing produces predictions of the probability of breakage.

EXPERIMENTAL

All experiments were performed on a commercially available unit, the Dia-stron CYC800 (Dia-stron Limited, Andover, UK). While details of this equipment have been reported (7,8), a brief overview is presented here. Single hair samples (28-mm-long) were prepared using the standard crimping block and press supplied by Dia-stron for use with all their tensile analyzers. These fibers were then placed onto a carousel, from where, one-by-one, they were automatically loaded into the fatigue-testing portion of the equipment (see Figure 3). The instrument repeatedly applied a user-defined cycling force, which was repeated until the fiber broke. The broken fiber was automatically removed from the tester and returned to the carousel so that the next fiber could be loaded and tested. All experiments were at a fatiguing speed of 40 mm/sec.

All experiments were performed with the equipment in a bench-top humidity chamber obtained from Electro-Tech Systems (Electro-Tech Systems Inc., Glenside, PA). Experiments were performed at 20%, 60%, and 90% relative humidity (RH). The work describe herein involved two different hair types. Initial experiments were performed on blended European medium brown hair. Additional experiments were performed on single-source, virgin Afro hair obtained from a male of Caribbean ethnicity. All hair was procured from International Hair Importers (Glendale, NY).

As mentioned above, variability in fiber thickness results in application of a common force leading to a range of stresses; therefore, there is a need to measure dimensions of all fibers. This was performed using the laser micrometer portion of an automated Dia-stron MTT675 tensile tester. This same instrument was used to perform conventional constant-rate extension experiments, the results of which will be compared to the fatigue data.

Depending on the magnitude of the stress, it is possible for fibers to survive a great number of fatiguing cycles. Therefore, to aid with the time required to perform such experiments, it is useful to set an upper limit, above which the fiber is considered to have survived and the equipment moves on to the next sample. Initially the factory setting of 300,000 cycles was used as an upper limit; however, in later work, this value was increased to 500,000. As will be described, it is still possible for the survivors to be included in the analysis by invoking the concept of censored data.

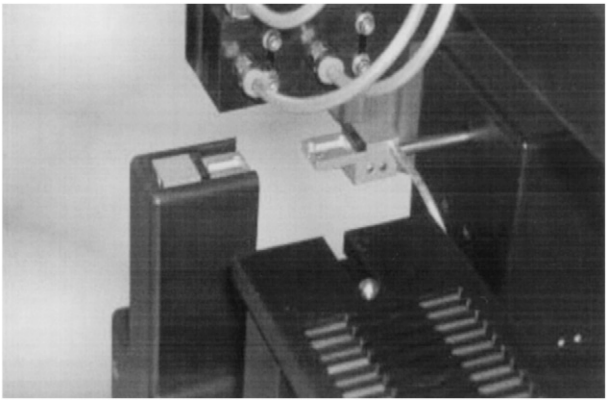

Figure 3. Close-up of the fatigue testing head on the Dia-stron CYC800.

INFLUENCE OF FATIGUING STRESS MAGNITUDE ON THE NUMBER OF CYCLES-TO-FAIL—THE S-N CURVE

Instinctively, the magnitude of the fatiguing stress would be expected to have an influence on the number of cycles-to-fail. That is, samples that receive a higher fatiguing stress will have a tendency to fail faster. In fatigue testing this relationship is commonly represented by what is termed an S-N curve, where the stress is plotted against the logarithm of the number of cycles to failure. Figure 4 shows such a plot for Caucasian hair equilibrated at 60% RH.

From the regression line it becomes possible to evaluate an average number of cycles-to-break as a result of the applied stress. Table I shows this information and also, for easier reading, converts the stress back into a force based on an average-sized 70-um fiber. From conventional constant-rate extension testing, it can be determined that, on average, a healthy 70-um hair fiber typically breaks upon application of an approximate 80 g force at 60% RH. However, from Table I, it can be seen that repeated application of a 55 g force on a 70-um hair fiber would be expected to induce breakage after around 400 cycles. In fact, results suggest that a repeating force that is only half that of the break force would still be expected to induce breakage after approximately 14,000 cycles. This illustrates the point made previously regarding the relevance of results obtained from conventional stress-strain experiments with regard to actual consumer practices.

While the regression line allows for an estimation of the number of cycles-to-fail under a given repeated stress, from Figure 4 it is clear that there is considerable spread in the data. A repeating 40 g force on a 70-um fiber may result in an average of 14,000 cycles-to-break, but breakage occurred as early as 1000 cycles, and some samples survived all 300,000 cycles. As will be shown later, this distribution is used in the analysis and modeling of the likelihood of breakage.

From these results, it is possible to observe an exponential relationship between the stress and the number of cycles-to-break (Figure 5). Thus, we begin to visualize how a reduction in grooming force (as provide by conventional conditioning products) has a dramatic influence on the propensity for hair breakage. This is an area that will be discussed more fully after outlining the data analysis method.

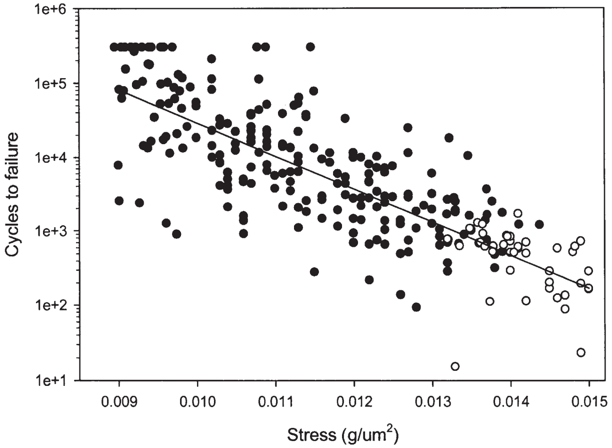

Figure 4. S-N curve for Caucasian hair at 60% RH.

Table I

Average Number of Cycles-to-Break as a Function of Fatiguing Stress as Obtained from an S-N Curve Created at 60% RH

Stress range	Force on 70-μm fiber	Average no. of breakage cycles
0.0145 g/μm^2	55.8 g	370
0.0135 g/μm^2	52.0 g	920
0.0125 g/μm^2	48.1 g	2,300
0.0115 g/μm^2	44.3 g	5,700
0.0105 g/μm^2	40.4 g	14,100
0.0095 g/μm^2	36.6 g	35,100
0.0085 g/μm^2	32.7 g	87,300

While the underlying idea behind the work described herein involves a statistical approach to hair breakage, there is still a need to keep in mind some basic mechanical testing principles. Specifically, this involves an awareness of the magnitude of the applied force relative to the "Hookean" or "elastic" region of the stress-strain curve. Figure 1 shows a schematic of a stress-strain curve for hair, and shows the pseudolinear region that occurs at low strains. Within this region, hair is often taken to have spring-like properties, wherein the application and removal of an applied deformation leaves fibers in a recovered state. However, if an applied force exceeds that of the linear-like region, the fiber yields, becomes permanently deformed, and retains a residual strain upon removal of the applied force. With each fatigue cycle this residual strain progressively increases and the experiment essentially becomes a complex extension experiment.

As such, without appropriate scrutiny, results from two distinctly different experiments can be mixed—a cyclic fatiguing experiment carried out in the linear-like region of the stress-strain curve, and a complex extension experiment resulting from the application of forces outside of this region. An attractive feature of the Dia-stron equipment is that it allows for stress-strain curves to be collected throughout the experiment, and therefore proves knowledge of whether experiments are being performed in the "linear" region (Figure 6). From a modeling viewpoint, this is an academic point, with consumers having

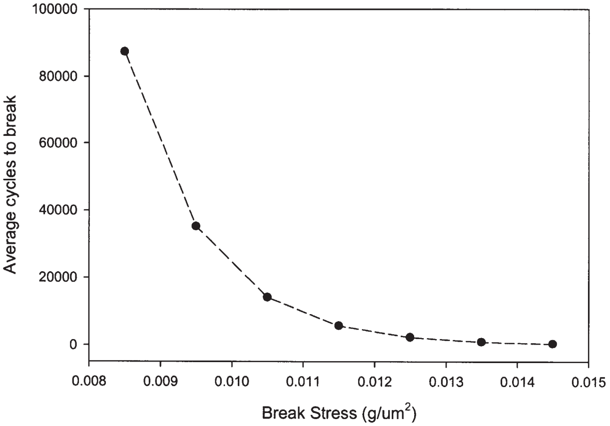

Figure 5. Average number of cycles-to-fail versus break stress as a function of applied stress as obtained from the S-N plot for Caucasian hair at 60% RH.

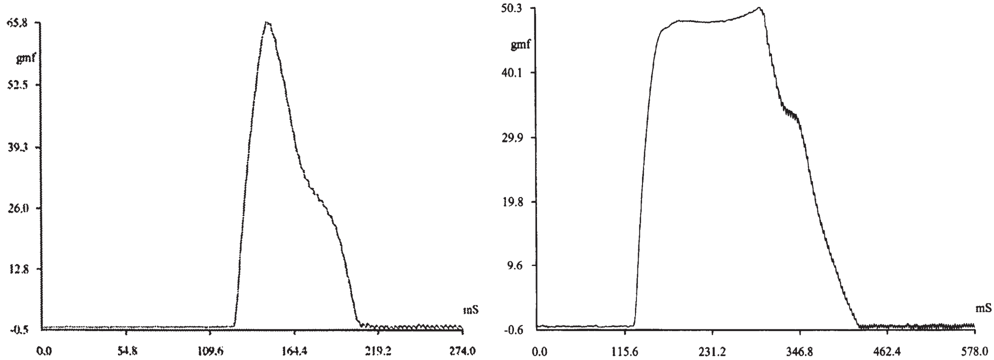

Figure 6. Stress-strain curves for initial fatiguing cycle, illustrating the shapes seen for fibers inside (left) and outside (right) the linear-like region.

no awareness of this occurrence. Thus, in attempting to simulate real-life events, it is necessary to perform experiments involving stress that can span both conditions. Figure 4 is coded in such a way as to show data from all occurrences. The solid data points represent experiments where the applied stress was within the "linear" region, while the hollow points represent experiments where the stress was above the yield point. This convention will be used throughout this document.

It should be noted that "linear region" experiments can be performed at stresses that would appear to be above the yield point as obtained from conventional stress-strain experiments. This again relates to the viscoelastic properties of hair and is a consequence of the considerably higher strain rate used in these fatiguing experiments. The higher elasticity of fibers under such conditions also hinders the potential for creep (i.e., viscous relaxation), which is another potential occurrence that could complicate matters from a mechanical viewpoint.

As mentioned above, there are two potentially useful applications for the S-N curve. First, it becomes possible to observe and model how a reduction in the fatiguing force (lubrication) reduces the propensity for breakage. Second, in comparing the effects of different treatments, it becomes possible to identify an appropriate range for the applied stress in order to expedite testing.

MATHEMATICAL TREATMENT OF THE DATA

Figure 7 shows a histogram consisting of fatigue data for 50 virgin Caucasian hair samples obtained from the repeated application of a 0.010–0.011 g/um^2 stress at 60% RH. When performing any measurement, it is prudent to examine the statistical distribution of data points. Most commonly, we are familiar with a normal distribution, where data points form a symmetrical bell-shaped distribution about the mean. However, other distributions exist, and visual inspection of Figure 7 suggests that the data may be better described by an exponential distribution function.

When performing survival probability it is common to fit a Weibull distribution to the data. Named after its inventor (10), the Weibull distribution is a highly flexible distribution

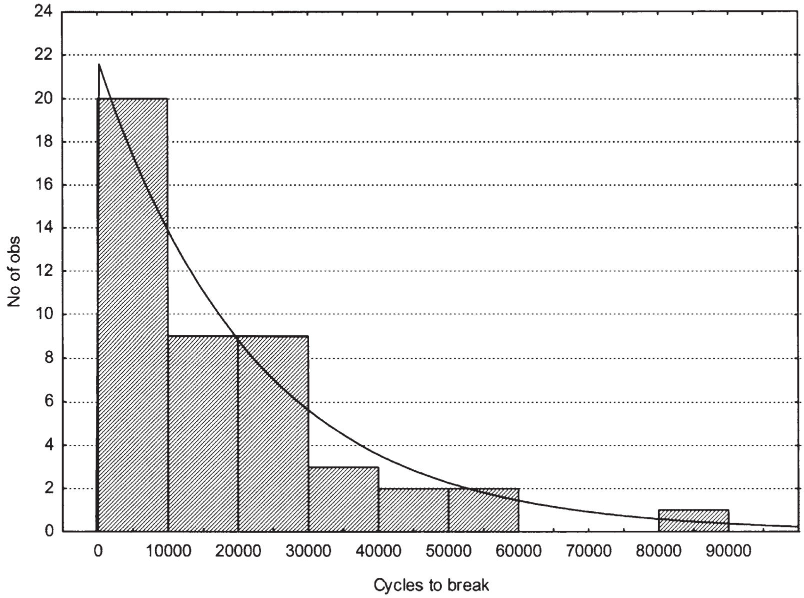

Figure 7. Histogram showing the number of cycles-to-fail for 50 Caucasian hair fibers exposed to a repeated 0.010–0.011 g/um^2 stress at 60% RH.

that can be used to fit a wide variety of different data sets. The cumulative form of the Weibull function is shown in equation 1:

$$F(x) = 1 - e^{-(x/\alpha)^{\beta}} \tag{1}$$

where F(x) is the probability of the fiber breaking in x cycles, α is the characteristic lifetime at which 63.5% of the fibers have broken, and β is the shape factor.

The flexibility of the expression is provided by the Weibull shape factor, β: when $\beta = 3.6$, the Weibull function approximates the normal distribution; when $\beta = 1$, the distribution is equivalent to the exponential distribution. As such, it can be seen how the above expression can be used to describe a wide variety of data—thus part of the analysis involves determining the value of the shape factor. Moreover, the magnitude of this parameter is also indicative of failure distribution. A shape parameter greater than 1 represents a progressively increasing failure rate, which is characteristic of a wearing-out mechanism; that is, relatively few failures occur initially, but the number gradually increases with further fatigue cycles. Conversely, a shape factor less than 1 indicates a higher tendency for early failures, with a decreasing failure rate as a function of additional fatiguing. A shape factor equal to unity is indicative of a constant rate of failure. The other parameter evaluated from such an analysis is the characteristic lifetime, α, which represents the number of repeated cycles to reach 63.2% failure.

The evaluation of these parameters is achieved through rearranging the Weibull equation into a linear form as shown below:

$$\ln(1 - F(x)) = -(x/\alpha)^{\beta} \tag{2}$$

$$\ln\left[\ln(1-F(x))\right] = -\beta(\ln x) - \beta(\ln\alpha) \tag{3}$$

where 1–F(x) is the probability of surviving x cycles.

Thus, a plot of the double natural logarithm of the cumulative function versus the logarithm of the cycles-to-fail gives a straight line from which the shape factor is obtained from the slope, and the characteristic lifetime is obtained from the intercept.

At this point, there is the need to briefly describe how the collected data is used to produce the cumulative distribution function (F(x)). The most common approach to producing an estimate involves the median rank method. The approach first involves ordering cycles-to-fail results for all fibers from lowest to highest. At this point, fibers that survived the fatiguing process—that is, those that did not break upon application of the threshold number of cycles—can also be added to the list. The median rank equation is given below:

$$\text{Median rank (Xi)} = \frac{i-0.3}{n+0.4} \tag{4}$$

where i is the sample number and n is the total number of samples. For more information on this process, the reader is directed to the substantial literature on this subject.

Table II shows characteristic lifetimes and shape factors as a function of stress for virgin Caucasian hair tested at 60% RH, that is, the data shown in Figure 4. The results for each stress represent an analysis of 50 fibers. The characteristic lifetimes again reflect the exponential relationship between the number of cycles-to-fail and the applied stress. Meanwhile, a shape parameter approximating unity suggests that the results for each set of data generally abide by an exponential distribution function.

With the evaluation of the two Weibull parameters, it becomes possible to reconstruct the distribution from which they were derived, and in doing so, predict the likelihood for survival (or failure) as a function of the number of cycles. Figure 8 shows the survival probability plot resulting from analysis of the data generated for stresses in the range of 0.010–0.011 g/μm^2. Considering this graph, it is seen that the survival probability is 100% when zero cycles have been applied, with this value dropping as the number of cycles increases. The inverse of this graph would be a failure probability plot. From these results it becomes possible to model the likelihood of breakage under a range of different conditions.

Table II

Weibull Parameters for Caucasian Hair at 60% RH as a Function of Applied Stress

Stress range	Characteristic lifetime, α	Shape factor, β
0.013–0.014 g/μm^2	1,640	1.07
0.012–0.013 g/μm^2	3,760	1.01
0.011–0.012 g/μm^2	11,100	0.90
0.010–0.011 g/μm^2	23,200	1.01
0.009–0.010 g/μm^2	114,000	0.77

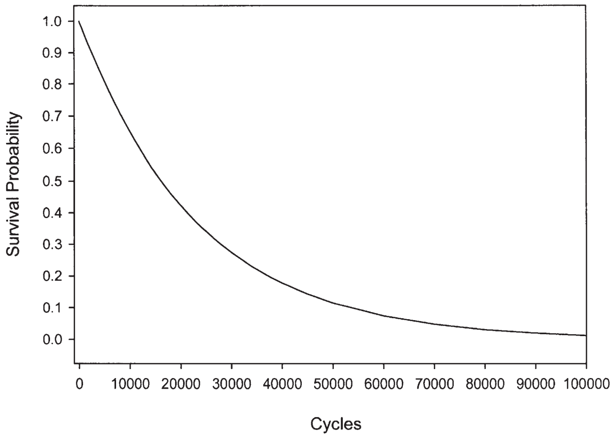

Figure 8. Survival probability plot for virgin Caucasian hair fibers when exposed to a repeated 0.010–0.011 g/um^2 stress at 60% RH.

EXPERIMENTAL RESULTS

Figure 9 shows survival probability plots as a function of the applied stress, which were calculated from the data in Table II. The results appear logical, and reflect how application of higher stresses decreases the survival probability. However, the usefulness of these plots becomes clear in attempting to model the influence of different experimental variables. For example, Figure 5 convincingly reminds us that a reduction in the fatiguing force can dramatically increase the number of cycles before breakage occurs. Now it becomes possible to express this occurrence in terms of the probability of fiber breakage. An example is shown in Table III, in which differences in the applied stress are accounted for in terms of a decreasing fatiguing force applied to fibers of common dimension. Thus, it is predicted that decreasing the fatiguing force on a 70-μm fiber from 52.0 g to 36.6 g results in the probability of fibers surviving 5,000 cycles, increasing from virtually zero to almost 100%. This very clearly illustrates the benefits of lubricating hair treatments

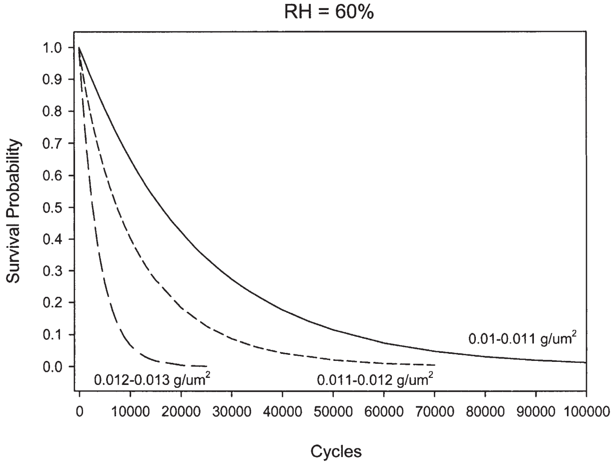

Figure 9. Survival probability plots for virgin Caucasian hair fibers at 60% RH as a function of repeated applied stress.

Table III

Probability Results Obtained from Weibull Parameters for Caucasian Hair at 60% RH as a Function of Applied Stress, Illustrating the Extent to Which the Likelihood of Survival Depends on the Magnitude of the Applied Force

Conditions	Stress	Probability of surviving 1,000 cycles	Probability of surviving 5,000 cycles	Probability of surviving 10,000 cycles
52.0 g force on a 70-μm fiber	0.0135 g/μm^2	55%	4%	0%
48.1 g force on a 70-μm fiber	0.0125 g/μm^2	77%	26%	7%
44.3 g force on a 70-μm fiber	0.0115 g/μm^2	89%	62%	40%
40.4 g force on a 70-μm fiber	0.0105 g/μm^2	96%	81%	65%
36.6 g force on a 70-μm fiber	0.0095 g/μm^2	97%	91%	86%

Table IV

Probability Results Obtained from Weibull Parameters for Caucasian Hair at 60% RH as a Function of Applied Stress, Illustrating the Extent to Which the Likelihood of Survival Depends on the Dimensions of the Fiber

Conditions	Stress	Probability of surviving 1,000 cycles	Probability of surviving 5,000 cycles	Probability of surviving 10,000 cycles
30 g force on a 63.4-μm fiber	0.0095 g/μm^2	97%	91%	86%
30 g force on a 60.3-μm fiber	0.0105 g/μm^2	96%	81%	65%
30 g force on a 57.6-μm fiber	0.0115 g/μm^2	89%	62%	40%
30 g force on a 55.3-μm fiber	0.0125 g/μm^2	77%	26%	7%
30 g force on a 53.1-μm fiber	0.0135 g/μm^2	55%	4%	0%

that reduce grooming forces. In short, the exponential relationship between cycles-to-break and the applied stress works to our favor.

The magnitude of the average repeated force encountered by individual fibers during grooming is not readily obtainable, yet it could be argued that the forces described here are probably excessively high. This is not disputed and, for now, it is emphasized that results and calculations illustrate relative trends rather than modeling real-life conditions. However, as will be shown, there are a number of variables that alter circumstances such that these conditions do not appear unreasonable. The first involves the dimensions of the fibers, where calculations readily show how the squared relationship between stress and the radius of a fiber (i.e., stress = $f/\pi r^2$) can quickly result in the potential for more-reasonable forces. To illustrate this point, Table IV shows a different way of looking at this same data. Here differences in the applied stress are accounted for in terms of fibers with decreasing dimensions under application of a common load. These results quite dramatically illustrate a problem for individuals with fine hair, in that this same exponential relationship works against them. Thus, there appears to be a steep drop-off in survival probability with relatively small decreases in fiber dimensions.

AFRO HAIR VERSUS CAUCASIAN HAIR

It is widely regarded that Afro hair is considerably more prone to breakage than Caucasian hair. This is often hypothesized to be a consequence of the highly kinky conformation leading to points of high stress in the structure. Table V shows break stress and break extension results from conventional constant-rate extension curves for both virgin Caucasian and single-source Afro hair that back up this supposition. Figure 10 shows fatigue results for single-source Afro hair fibers plotted in the form of an S-N curve, compared to results for Caucasian hair. Again, all measurements were performed at 60% RH.

Two observations arise from these results. First, the regression line for the Afro hair falls below that of the Caucasian hair. But, in addition, there appears to be considerably more variability in the Afro data. That is, while some Afro fibers survive for an equal or longer duration than the Caucasian hair, a significant number fail after very few fatiguing cycles.

Table VI shows Weibull parameters for Afro and Caucasian fibers that received a 0.010–0.011 g/μm^2 repeated stress. It is seen that the characteristic lifetime for Afro hair is only about half that of Caucasian hair, while a much lower shape factor is obtained. Another function served by the shape factor is to provide an indication of scatter in the experimental data. The smaller the shape factor, the higher the variability. Figure 11 shows survival probability plots produced from these results and illustrates the influence of the shape factor. The plots demonstrate a relatively high probability for Afro fibers to break after application of comparatively few fatiguing cycles. However, if fibers survive this initial period, their likelihood of surviving higher numbers of cycles dramatically improves.

The information obtained from this kind of testing yields more insight into the nature of hair breakage as compared to conventional constant-rate stress-strain testing. Expanding on an earlier point, the highly fragile nature of Afro hair is such an issue that it demands very different habits and practices, a point that would not seem to be reflected in a relatively meager 13% reduction in break stress and break extension. Such anticipated differences

Table V

Comparing Conventional Tensile Properties for Caucasian and Afro Hair at 60% RH

Hair type	Break stress	Break extension
Caucasian	2.07 g/μm^2	45.1%
Afro	1.80 g/μm^2	39.3%

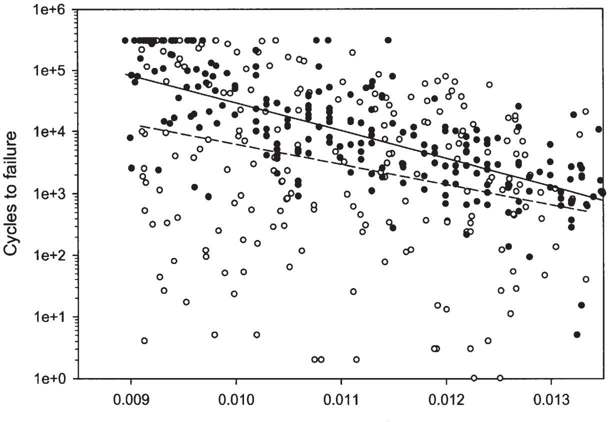

Figure 10. S-N curves for Caucasian and Afro hair at 60% RH. Filled circles represent data for Caucasian hair; hollow circles are Afro hair.

Table VI
Comparison of Weibull Parameters for Caucasian and Afro Hair after Repeated Fatiguing with a 0.010–0.011 g/μm^2 Stress at 60% RH

Hair type	Characteristic lifetime, α	Shape factor, β
Caucasian	23,200	1.01
Afro	12,600	0.39

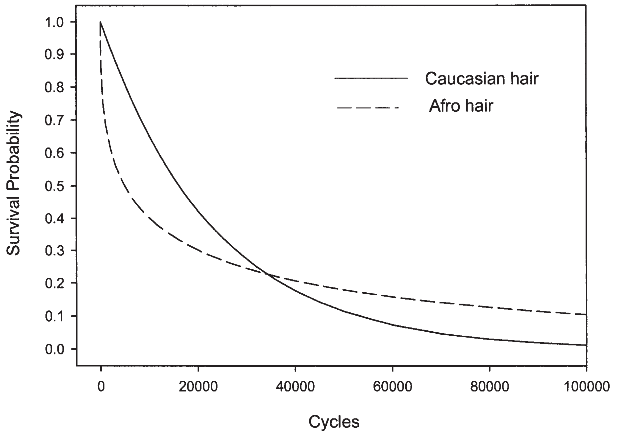

Figure 11. Survival probability plots (from Weibull analysis) for Caucasian and Afro hair upon exposure to a repeating 0.010–0.011 g/um^2 stress at 60% RH.

are perhaps better reflected in fatigue results, which suggest considerable differences in propensity for breakage for the two hair types.

THE EFFECT OF PLASTICIZATION ON THE PROBABILITY OF HAIR BREAKAGE

While lubrication reduces the fatiguing force during grooming, there is also a desire to understand whether cosmetic ingredients penetrate into hair to provide any influence on the propensity for breakage. In the absence of any chemical reactions, the influence of such materials may be expected to involve some degree of plasticization as a result of their incorporation in the hair structure. While well-characterized effects from ingredients may not be available, the plasticizing influence of water is extremely well documented. Consequently, changes in relative humidity are used to modify the plasticization of hair fibers. Conventional stress-strain testing results can be generated that show how raising the humidity from 60% to 90% results in an approximate 15% decrease in break stress, while decreasing the humidity from 60% to 20% results in an approximate 10% increase in break stress. Figure 12 shows fatigue data for Caucasian hair at 20%, 60%, and 90% RH in the form of S-N plots. Results show that altering the humidity induces changes in line with predictions, but the magnitude of these effects is considerably larger than anticipated.

From the S-N plots, these alterations in relative humidity have produced better than a 10-fold influence in the number of cycles-to-fail. From the regression lines, it can be calculated that the application of a repeated 0.0125 g/um^2 stress at 60% RH results in an average of approximately 2,000 cycles-to-fail, while at 20% RH this value increases to approximately 45,000 cycles. Similarly, the application of a repeated 0.0095 g/um^2 stress

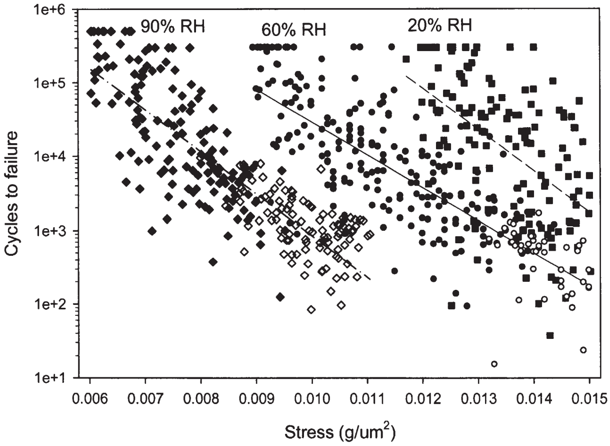

Figure 12. S-N curves for Caucasian hair as a function of relative humidity.

at 60% RH results in an average of approximately 45,000 cycles-to-fail, while at 90% RH this value decreases to only about 900 cycles.

Figure 12 also shows how plasticization due to higher relative humidity causes a reduction in the yield point of fibers. As will be recalled, hollow data points in these S-N plots reflect results from experiments that fall outside the pseudo-Hookean region. For example, application of a repeated 0.0095 g/um^2 stress leads to experiments being performed in the linear-like region at 60%, but at 90% RH this same stress now exceeds this limit. Thus, from a mechanical testing viewpoint, we are comparing results from two different experiments, but in terms of modeling, results from both types of experiments appear to fit on single linear S-N curves.

It was noted that the magnitude of the stresses being used may well be higher than those encountered during actual grooming. However, it was demonstrated how the presence of fibers with smaller dimensions allowed for the generation of stresses that may be more in line with actual practices. These results show how increased humidity also contributes to the potential of breakage at significantly lower stresses.

Table VII lists Weibull parameters calculated from these data sets that further illustrate the substantial influence of relative humidity on the propensity for fibers to break under

Table VII

Weibull Parameters Obtained for Caucasian Hair as a Function of Both Repeated Stress and Relative Humidity

Stress range	20%	RH	60%	RH	90%	RH
	α	β	α	β	α	β
0.006–0.007 g/μm^2	—	—	—	—	213,000	0.86
0.007–0.008 g/μm^2	—	—	—	—	53,300	0.67
0.008–0.009 g/μm^2	—	—	—	—	8,700	1.21
0.009–0.010 g/μm^2	—	—	114,000	0.77	2,040	1.26
0.010–0.011 g/μm^2	—	—	23,200	1.01	1,080	1.42
0.011–0.012 g/μm^2	—	—	11,200	0.90	—	—
0.012–0.013 g/μm^2	100,000	0.62	3,760	1.01	—	—
0.013–0.014 g/μm^2	27,700	0.65	1,640	1.07	—	—
0.014–0.015 g/μm^2	8,750	0.60	—	—	—	—

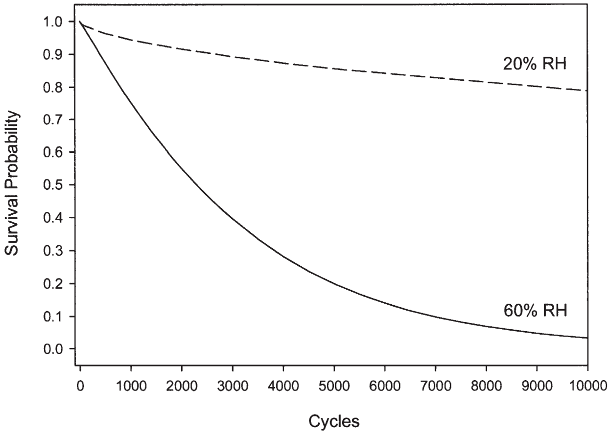

Figure 13. Survival probability curves (from Weibull analysis) for Caucasian hair as a function of relative humidity (20% and 65%) when receiving a 0.012–0.013 g/um^2 repeated stress.

Table VIII
Survival Probability Results for Caucasian Hair upon Application of a Repeating 0.009–0.010 g/μm^2 Stress at 60% and 90% RH

Conditions	Probability of surviving 1,000 cycles	Probability of surviving 5,000 cycles	Probability of surviving 10,000 cycles
60% RH	97%	91%	86%
90% RH	66%	5%	0%

these conditions. Further, the use of survival probability plots again demonstrates these dramatic effects. Figure 13 shows such plots for Caucasian hair under a repeating 0.012–0.013 g/um^2 stress at both 20% and 60% RH. Meanwhile, Table VIII shows in numerical form the significant increase in the likelihood of breakage that arises when applying a 0.009–0.010 g/um^2 stress at 90% versus 60% RH. The effects of humidity are well recognized in conventional mechanical testing experiments, but the magnitude of the influence seen here is dramatically higher and suggests that grooming in humid environments results in more trauma than previously predicted.

To this end, it is noted that the phenomenon "hair fall" is especially troublesome in humid Southeast Asian countries. This consumer term is used to describe the general observation of hair fibers that are lost from the head as a result of grooming, washing, and everyday wear and tear. The occurrence is generally associated with shedding of the hair, although these results suggest a considerably higher propensity for breakage under such conditions.

SUMMARY

A commonly heard complaint about the use of conventional, constant-strain-rate mechanical experiments is that, while results may show typical break forces in the range of 70–100 grams, under *in vivo* conditions the application of such forces would presumably result in hair fibers being plucked from the scalp before breakage conditions arise (11). Fatigue experiments demonstrate that repeated application of forces considerably lower than the break force can still give rise to breakage, with the failure rate being proportional to the magnitude of the applied stress. Results suggest that the relationship between these parameters is exponential in nature, sometimes allowing seemingly small changes to have large effects.

The automated nature of the Dia-stron equipment ensures that experiments are not labor intensive, but depending on the force selected, a full carousel of 50 fibers can take weeks to run. As such, the data in Figure 12, showing breakage data across three humidities and a range of stresses, represents approximately six months of instrument time. However, with patience, this approach appears to yield novel data that provide unique insight into the breakage of hair fibers.

At the simplest level, results can be expressed as an S-N curve showing the relationship between the number of cycles-to-fail and the magnitude of the repeating stress. However, by performing Weibull analysis of the data, a characteristic lifetime and a shape parameter are obtained that serve to describe the data, and from these two parameters, one is able to generate probability survival plots that predict the propensity for breakage under a specific set of conditions. As such, by this analysis, breakage is treated as a statistical parameter rather than as a mechanical one.

Systematic experiments allow for modeling the effect of a variety of variables. By keeping the fatiguing conditions constant, it is possible to investigate the effect of hair type—where differences between Afro and Caucasian hair appear in line with well known consumer experiences. Meanwhile, dramatic differences as a function of relative humidity are new and noteworthy. By keeping the hair and the environmental conditions constant, it becomes possible to model how increasing or decreasing fatigue forces influence the likelihood for breakage. Moreover, the presence of an exponential relationship between the applied stress and cycles-to-break indicates how even relatively small changes can have large benefits. On the reverse side, this exponential relationship suggests problems for individuals with fine hair, as normal grooming forces lead to higher stresses as a consequence of smaller fiber diameters, with a commensurate increase in the likelihood of breakage.

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