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A statistical analysis of hair breakage. II. Repeated grooming experiments

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Synopsis

The objective of this work was to introduce the idea of analyzing data from repeated brushing and combing experiments on hair in accordance with standard fatigue testing approaches. In mechanical testing terms, the brushing and combing of hair represents a fatiguing process wherein individual strands experience repeated exposure to an external stimulus. Therefore, in accordance with fatiguing principles, one expects a gradual propagation of flaws within individual fibers until, ultimately, catastrophic failure (breakage) results. A previous paper in this series described the modeling of single-fiber fatigue data using the Weibull approach, and, in so doing, introduced the idea of treating fiber breakage as a statistical variable. Here, a grouped Weibull methodology was used to analyze breakage data from repeated brushing and combing experiments.

At a top level, the generation of the two Weibull parameters provides a means of characterizing these experiments. However, the real strength of the approach involves the ability to generate survival probability plots that provide predictions as to the likelihood of fiber breakage under different conditions. Therefore, assuming laboratory experiments are a reasonable representation of real-life conditions, it becomes possible to predict breakage rates on actual heads as a function of different habits and practices. It is also shown how the two Weibull parameters, together with information about the number of fibers in the test tresses, allow for the modeling of repeated brushing and combing tests and allow anyone to re-create the experimental outcome for comparison to their own experiences.

These principles have been demonstrated using experiments that compare breakage in virgin and chemically damaged hair, while also showing how conditioning treatments provide considerable retardation.

INTRODUCTION

The generation of stress-strain curves is often used as a means of quantifying the strength of single hair fibers. It is well-known that the tensile properties of hair can decrease significantly as a result of exposure to the sun’s UV rays or certain deleterious cosmetic treatments (1) (e.g., bleaching, coloring, perming, or relaxing), and extracting various parameters from such experiments can convincingly quantify these effects. However, for some time there has been concern that the break force for a typical fiber, as measured by such experiments, is higher than that required to pluck hair from a follicle (2). Therefore, while this approach provides a means of characterization, there may be questions regarding the relevance of experimental results to real-life occurrences. The presence of split ends is evidence enough that fiber breakage does indeed occur on the head—and so another mechanism must explain their formation. It has been suggested that grooming gives rise to a combination of bending, torsion, and interfiber friction that can result in localized stresses sufficient to cause breakage (3–7) or lead to the weakening of fibers such that breakage occurs more readily. Accordingly, some have suggested that repeated grooming experiments may represent a better simulation of how consumers assess the strength of their hair. In these experiments, hair tresses are repeatedly brushed or combed a given number of times, with subsequent counting of the number of broken fibers that result. This type of testing dramatically demonstrates benefits associated with conventional conditioning products, in that surface lubrication reduces grooming forces, snagging, and tangling—thus leading to considerably less breakage. Indeed, antibreakage claims on commercial conditioning products are generally substantiated by this method.

In the first paper of this series (8), single-fiber fatigue experiments were studied, and it was demonstrated how fibers will break in a predictable manner under repeated application of forces considerably lower than those required to cause failure from a one-time application. The conventional explanation for this occurrence involves repeated external stimuli causing propagation of flaws within a fiber, which ultimately results in catastrophic failure. Results were able to demonstrate the influence of a number of experimental variables on the tendency for breakage. In particular, the likelihood of breakage depends strongly on the extent of the repeating stress (i.e., stress = force/unit area), with changes in the magnitude of the applied force and/or fiber dimensions yielding predictable outcomes. Results showed an exponential relationship between the repeated stress and the number of cycles required to induce breakage, a finding that helps explain the beneficial effect of conditioner treatments in the afore-mentioned repeated grooming experiments. Specifically, surface lubrication reduces grooming stresses, which subsequently leads to a considerably higher number of the repeated stimuli (grooming strokes) required to induce breakage. Results from these single-fiber fatigue experiments also suggested substantially larger differences as a function of hair type and various external factors compared to those obtained from conventional stress-strain testing.

As already suggested, repeated grooming experiments represent a version of a fatigue test, as individual fibers experience a repeated external stimulus as a consequence of the comb or brush passing through the hair. Thus, one may envisage treating results from these experiments according to mathematical approaches commonly utilized in the field of fatigue testing. As shown previously (8), applying Weibull statistics to single-fiber fatigue experiments allows breakage to be treated as a statistical variable and produces predictions for the likelihood of hair breakage under specific conditions. In this work, we describe such an approach for performing comparable analyses in repeated grooming experiments and show how it can be used to model failure rates.

BACKGROUND

In general, fatigue testing involves the repeated application of an external stimulus, with subsequent evaluation of the cycles before failure. In the first paper in this series, single-fiber fatigue experiments were performed using commercially available equipment

(Dia-stron CYC800, Dia-stron, UK), where experiments involve repeated application of a user-defined force until breakage. The propensity for breakage was found to depend strongly on the magnitude of the repeating stress (i.e., stress = force/unit area), meaning that the magnitude of the repeating force and the fiber dimensions are major influences. This relationship is shown in Figure 1, in what is often termed an S-N curve.

From Figure 1, one observes that an exponential relationship exists between the magnitude of the repeating stress and the number of cycles to fail. Extrapolating these findings into the world of hair care, one observes how lowering the stresses associated with grooming will significantly reduce the likelihood of fiber breakage, and it explains why many conditioning products produce dramatic effects in repeated grooming experiments.

These single-fiber experiments provide fundamental understanding, but the magnitude of the stresses experienced by individual fibers during everyday grooming is not readily available. As such, while it is possible to model the propensity for breakage as a function of the applied stress, it is unknown where real-life conditions lie. Repeated grooming experiments represent the opposite scenario—in that real-life stresses and strains are presumably replicated relatively well but the magnitude of these stimuli is unknown. Nevertheless, this comparision does introduce the idea of treating repeated grooming results by fatigue testing approaches.

WEIBULL ANALYSIS OF FAILURE DATA

In a fatigue test, failure is commonly attributed to the propagation of pre-existing flaws within a material. Accordingly, with the distribution of such flaws on a hair fiber being statistical in nature, breakage also needs to be treated as a statistical variable. Therefore, modeling and characterization of breakage involves fitting a statistical distribution to the data. A convenient approach involves utilization of the highly flexible Weibull distribution (9). The flexibility of this expression arises from the presence of the Weibull shape factor, β. By means of illustration, when $\beta = 3.6$,

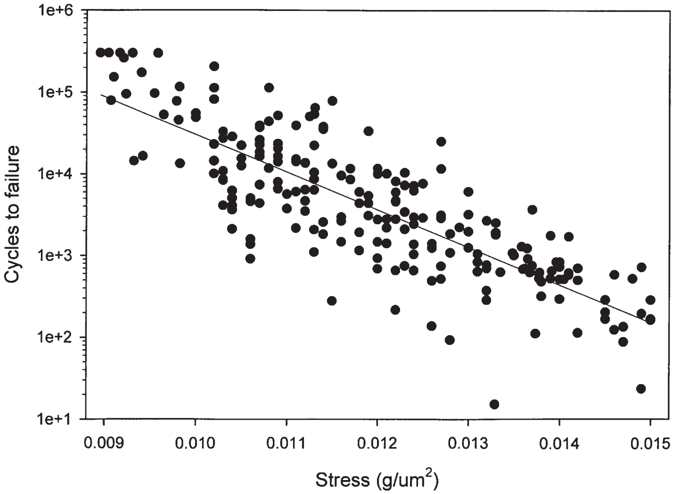

Figure 1. S-N curve showing failure data for virgin Caucasian hair at 60% relative humidity.

the Weibull function approximates the normal distribution, whereas, when $\beta = 1$, the distribution is equivalent to the exponential distribution. Therefore, this approach can be used to model a wide range of data that is subsequently characterized by evaluation of the two Weibull parameters—the shape factor and the characteristic lifetime.

The linear form of the Weibull equation is shown below:

$$\ln[\ln(1/1 - F(x))] = -\beta(\ln x) - \beta(\ln \alpha)$$

where F(x) is the probability of the fiber breaking in x cycles, 1-F(x) is the probability of surviving x cycles, α is the characteristic lifetime at which 63.2% of the fibers have broken, and β is the shape factor.

Thus, a plot of the double logarithm of the reciprocal of the survival probability function versus the logarithm of the number of cycles-to-fail yields the shape parameter from the slope and the characteristic lifetime from the intercept.

Estimation of the cumulative distribution function, F(x), involved the commonly used *median rank* method. As outlined in the earlier publication, this approach first involves ordering cycles-to-fail results for all fibers from lowest to highest and then applying the median rank equation given below:

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

where *i* is the sample number and *n* is the total number of samples.

After evaluation of the two Weibull parameters, it becomes possible to reconstruct the best-fitting distribution from which they were derived, and, in doing so, generate predictions for the likelihood for survival (or failure) as a function of the number of cycles. The result is termed a survival probability plot, and this process has been described for single-fiber experiments in previous papers (8,10,11). By means of illustration, Figure 2 shows a survival probability plot obtained for virgin Caucasian hair fibers exposed to a repeating 0.010-0.011 g/um^2 stress at 60% relative humidity. For reference purposes, this magnitude is approximately half of the break stress for hair in a conventional stress-strain experiment under the same conditions.

Therefore, from Figure 2 one observes a 100% likelihood of survival when zero stress cycles are applied, with the survival probability progressively decreasing as a function of additional cycles. Thus, from performing comparable experiments under differing conditions, it becomes possible to generate similar plots that allow for breakage predictions as a function of specific variables (e.g., the magnitude of the applied stress, the nature of the hair, the environmental conditions, etc.).

As will be shown in this report, repeated grooming experiments can be modeled using what is termed a grouped Weibull analysis (12). Such experiments involve generating a cumulative distribution function by obtaining a running total of broken fibers over regularly repeating time intervals (for example, after 1000, 2000, or 3000 grooming strokes).

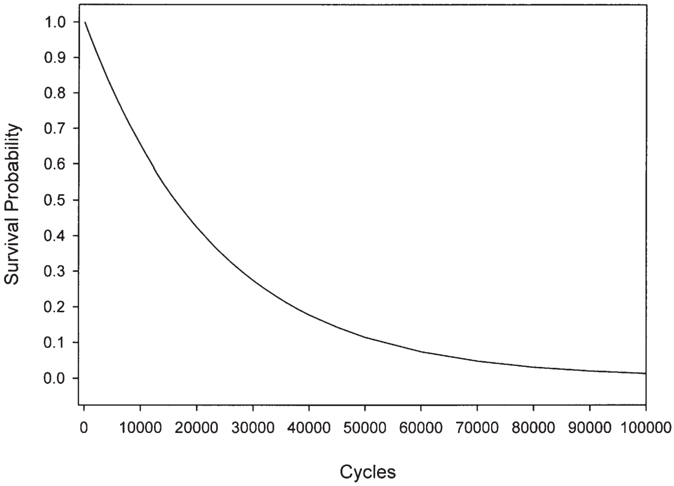

Figure 2. Survival probability curve for virgin Caucasian hair fibers exposed to a repeated 0.010–0.011 g/μm^2 stress at 60% relative humidity.

EXPERIMENTAL

Repeated brushing experiments were performed on a custom-built unit shown in Figure 3. The device consists of a hollow rotating drum-like assembly, where four outer crossbars contain holders for mounting combs or brushes. These outer arms are detachable to allow for different holders to be mounted and experiments to be performed using a variety of combs or brushes. The four combs or brushes are mounted at 90° angles, allowing one complete drum revolution to comb (or brush) a tress four times. This entire setup is duplicated three times in the horizontal direction, allowing four tresses to be combed simultaneously. Collection plates are located under each tress to save broken fiber fragments, while spacer plates on the rotating drum prevent cross contamination. The device contains a variable-speed motor, although experiments generally are performed at 50 strokes/minute.

All testing was performed using standard 8-inch, 3-g Caucasian hair tresses obtained from International Hair Importers, while grooming was performed using the head portion of Goody Purse Style brushes. All experiments were performed under controlled humidity conditions via the use of a climate-controlled room or a bench-top chamber.

On the surface, the performing of such tests would seem rather straightforward, but, in actuality, there are many experimental factors that can contribute to variability and influence the outcome. Therefore, when reporting results, it is important to describe conditions as fully as possible. For convenience, these can be categorized into four groups: hair factors, brush/comb factors, environmental factors, and product-usage factors.

(I) HAIR FACTORS

The propensity for hair breakage increases significantly with hair damage. Therefore, the more damaged the hair, the higher the number of broken fibers. While there may

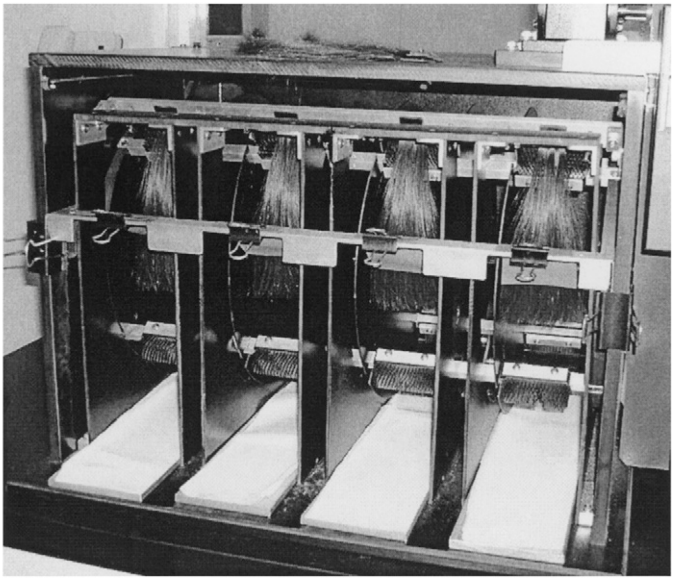

Figure 3. TRI's custom-built repeat-combing/brushing apparatus.

be multiple sources of hair damage, the easiest way to generate reproducibly in the lab involves the use of chemical treatments. It is recognized that a high proportion of US women utilize some form of chemical treatment on their hair, and so employing such conditions can be considered to represent the norm rather than the exception. The shape and size of tresses would also be expected to have an influence, with higher grooming forces being encountered when combing or brushing a thicker mass of hair. In addition, fiber dimensions and the degree of curvature may also be expected to alter the grooming forces.

(II) BRUSH/COMBING FACTORS

Grooming forces will be also be dependent on the nature of the comb or brush, with, most obviously, the spacing between teeth or bristles having an influence. However, in principle, different comb or bristle materials may also have a different tendency for abrasion. There is also the need to consider the quality of the combs and brushes—broken or bent teeth and bristles may lead to increased snagging.

(III) ENVIRONMENTAL FACTORS

Single-fiber fatigue results suggested substantial differences in breakage as a function of the relative humidity (8). This would seem to stem from changes in the plasticity of the fibers and the subsequent influence on flaw propagation. However, when dealing with hair arrays in grooming experiments, there is the need to consider additional factors, such as static flyaway at low humidity and potentially increased friction and snagging at elevated humidity due to fiber swelling.

(IV) PRODUCT USAGE FACTORS

The purpose of performing these experiments is generally to demonstrate the ability of lubricating conditioner treatments to reduce breakage. Therefore, the effectiveness of such products relates to their ability to provide dry-state lubrication. While different products will vary in their deposition efficiency, their effectiveness is also related to the manner in which a product is used. For example, changes in the product:hair dosage ratio, the residence time of the product on the hair, and/or the rigor with which rinsing is performed will all influence the deposition of conditioning ingredients.

METHODOLOGY

Hair tresses were treated according to our standard procedure, then allowed to air dry and equilibrate under controlled humidity conditions. In all experiments this involved applying a leading commercially available conditioner product at a 15% v/w dosage, followed by massaging through the hair for one minute and rinsing for 30 seconds with 38°C water at a flow rate of 1 gallon/minute. Chemical damage was induced by bleaching tresses with a 6% hydrogen peroxide solution (pH 10) for 40 minutes.

Unconditioned tresses, particularly those that had been chemically damaged, required carefully detangling with a wide-toothed comb prior to testing. Four tresses can be mounted on our device at the same time. The tresses are then automatically groomed in 1,000-stroke blocks, with subsequent counting of broken fibers in the collection trays under each tress. These values are recorded, the trays are cleaned, and the tresses are cycled through another 1,000 strokes. This process is repeated until a total of 10,000 grooming strokes have been carried out.

RESULTS

Table I shows typical data obtained from this protocol for virgin Caucasian tresses brushed at 60% relative humidity. The most simple, and often a perfectly adequate, means of analysis involves comparing means for different treatments after a given number of grooming strokes. Figure 4 shows box and whisker plots representing breakage data for unconditioned virgin hair tresses and hair treated with a commercially available shampoo and conditioner regimen after 10,000 brushing strokes. Results convincingly illustrate the benefit provided by such products, in that the extent of breakage in this particular instance has been reduced by approximately 60%. However, additional information can be obtained upon analyzing results in accordance with the fatigue testing principles described earlier.

GROUPED WEIBULL ANALYSIS

Table II illustrates how this data is treated by the grouped Weibull approach. Column 2 contains the total number of broken fibers for all eight tresses as a function of the

Table I

Number of Broken Fibers Generated during Repeated Brushing Experiments on Virgin Caucasian Hair at 60% RH

No. of brush strokes	Tress 1	Tress 2	Tress 3	Tress 4	Tress 5	Tress 6	Tress 7	Tress 8	Total
1,000	17	9	11	5	14	19	17	18	110
2,000	5	5	5	2	5	4	4	8	38
3,000	4	2	3	1	3	4	5	4	26
4,000	2	2	0	6	3	2	3	1	19
5,000	4	4	2	5	2	4	3	4	28
6,000	2	1	4	2	4	4	6	2	25
7,000	3	2	2	4	5	3	3	3	25
8,000	2	3	1	3	2	2	3	0	16
9,000	3	3	0	4	2	5	2	5	24
10,000	1	2	4	1	3	3	0	1	15
Total	41	33	32	33	43	50	46	46	326

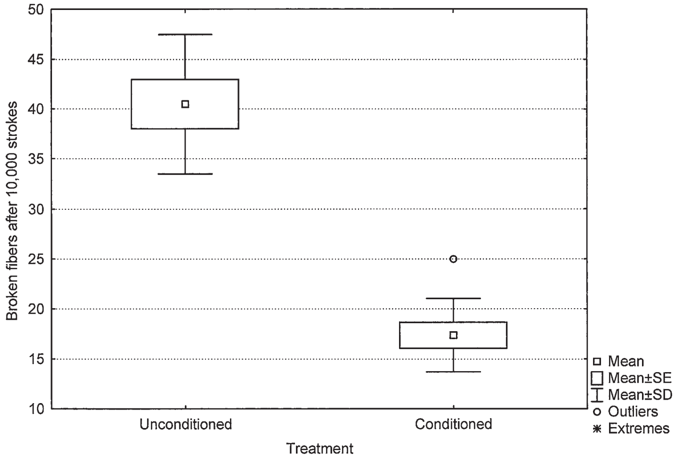

Figure 4. Mean values for the number of broken fibers after brushing hair tresses 10,000 times.

number of combing cycles. Column 3 then shows a running total of the number of broken fibers, or, in other words, the cumulative breakage frequency. Column 4 shows the previously described median rank approach for estimating the cumulative distribution function. On average, we have found each tress to contain approximately 2,500 fibers; therefore, the total number of fibers across the whole experiment (i.e., N in the median rank equation) is 20,000. Columns 5 and 6 show the creation of the double log expression that forms the y axis in the Weibull plot. Meanwhile, column 7 represents the x axis. It is especially convenient to set up these calculations (together with the later creation of the survival probability plot) using an Excel spreadsheet. The resulting Weibull plot, together with the resulting values for the characteristic lifetime and the shape factor, is shown in Figure 5.

Table II
Grouped Weibull Analysis of Repeated Brushing Data for Virgin Caucasian Hair at 60% RH

Grooming cycles	No. of failures	Cumulative frequency	Median rank	1/(1−Median rank)	ln(ln(1/(1−Median rank)	Ln (grooming cycles)
1000	110	110	0.00439	1.004407	−5.4267	6.907755
2000	38	148	0.00591	1.005943	−5.1285	7.600902
3000	26	174	0.00695	1.006996	−4.96583	8.006368
4000	19	193	0.00771	1.007768	−4.86165	8.29405
5000	28	221	0.00883	1.008906	−4.72541	8.517193
6000	25	246	0.00983	1.009925	−4.6176	8.699515
7000	25	271	0.0108	1.010946	−4.5202	8.853665
8000	16	287	0.0115	1.011601	−4.46245	8.987197
9000	24	311	0.0124	1.012584	−4.38157	9.10498
10000	15	326	0.0130	1.0132	−4.33412	9.21034

In this instance, we obtain a characteristic lifetime (α) of 55.2 million grooming strokes and a shape parameter (β) of 0.48. That is, one may predict that 55.2 million grooming strokes would be required in order to break 63.2% of the fibers. Meanwhile, a shape parameter less than 1 is indicative of a process wherein the highest rate of breakage occurs early in the experiment. Of course, there is danger in ascribing too much significance to the long-range extrapolation that yields the magnitude of the characteristic lifetime. Specifically, a prediction involving the outcome after tens of millions of cycles, based on an experiment involving a few thousand cycles, is obviously dubious. Instead, it is emphasized that together these two Weibull parameters describe the collected data, and, as outlined earlier, can be used to generate a survival probability plot that predicts the

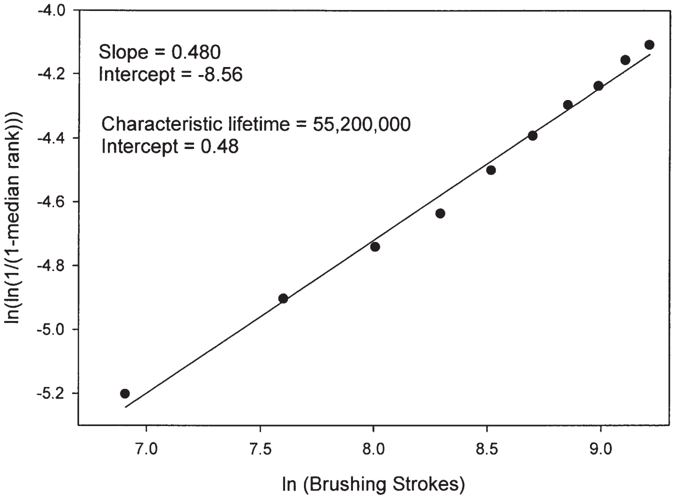

Figure 5. Weibull plot for repeated brushing data of virgin Caucasian hair at 60% RH.

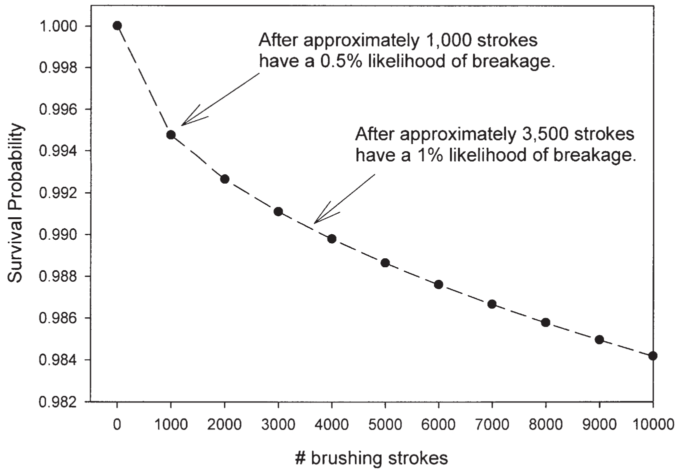

Figure 6. Survival probability plot for brushing virgin Caucasian hair at 60% RH.

likelihood of fiber breakage as a function of brushing strokes over the range of the experiment (see Figure 6).

These results lead us to predict that, under these conditions, it is necessary to brush hair approximately 1,000 times to produce a 0.5% likelihood of fiber breakage and around 3,500 times to produce a 1% likelihood of breakage. These probabilities sound low, at least until projecting the results onto actual heads, where it is generally accepted that around 100,000–150,000 fibers are typically present. As such, using 100,000 fibers as a round number, we obtain the prediction that 500 broken fibers would be expected after 1,000 grooming strokes and 1,000 broken fibers after 3,500 strokes. These numbers no longer sound so trivial, which is one reason why it is prudent to use conditioning products.

As depicted in Figure 4, use of the exact same testing procedure to generate data for conditioned hair gives rise to considerably less breakage—and applying the same Weibull analysis yields a characteristic lifetime of 1.04 billion grooming cycles and a shape parameter of 0.43. Again we highlight the caveat regarding long-range extrapolation and the magnitude of the characteristic lifetime. Thus, one should not directly compare the enormousness of this parameter for the treated and untreated hair and conclude a 20-times improvement in fatigue resistance. Instead, Figure 7 compares survival probability plots for conditioned and unconditioned hair, and demonstrates the benefits associated with such products in statistical terms. These results predict that around 5,000 grooming strokes (i.e., five times as many) are now required to produce a 0.5% likelihood of breakage in conditioned hair, while approximately 25,000 strokes are necessary to include a 1% chance of breakage.

It is worth spending a moment to consider typical grooming habits and practices and their relationship to the number of grooming cycles used in these experiments. If we assume that ten grooming strokes are employed each time a consumer brushes her hair—and that three such grooming experiences are performed each day—then 1,000 grooming strokes are attained in slightly over a month. Obviously, widely different habits and practices exist, but 10,000 grooming strokes by no means sounds excessive over the lifetime of a hair fiber, with long hair potentially seeing significantly higher repetitions.

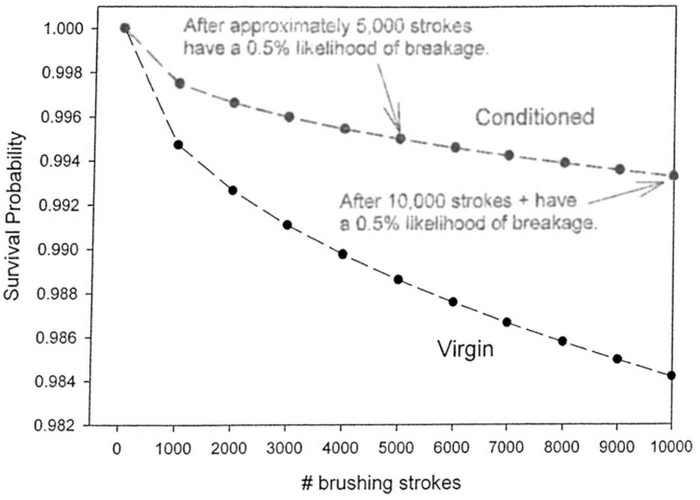

Figure 7. Survival probability plot for brushing virgin and conditioned Caucasian hair at 60% RH.

WEIBULL ANALYSIS IN THE MODELING OF REPEATED GROOMING EXPERIMENTS

The inverse of a survival probability curve is a failure probability curve. That is, a 99% likelihood of survival equates to a 1% chance of failure. As such, by calculating a failure probability and multiplying results by the number of fibers in our test tresses (approximately 2,500 in this instance), we obtain a model that is able to describe the whole experiment. Figure 8 shows such models, together with actual experimental results, for our virgin hair and conditioned hair experiments. This also illustrates how the reporting of the Weibull parameters (together with the number of fibers in the tresses) provides an extremely useful means of documentation, as it allows anyone to recreate the whole experiment for comparison and contrasting purposes.

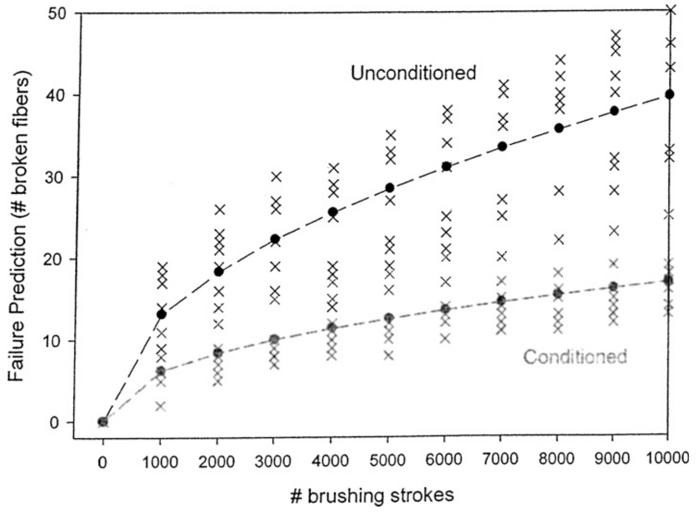

Figure 8. Models and experimental data for repeated grooming experiments on virgin and conditioned Caucasian hair at 60% RH.

By means of illustration, Table III shows Weibull parameters obtained from a series of experiments that were intended to investigate the influence of different experimental variables, while Figure 8–11 show the models generated by these values in comparison to the experimental data.

Figure 9 shows models, plus experimental data, for virgin and bleached hair, and illustrates the higher incidence of breakage that occurs as the result of chemical damage. Figure 10 shows the effect of conditioning on bleached hair and illustrates the still-greater benefit of these treatments on damaged hair. Meanwhile, Figure 11 shows how breakage greatly increases upon repeated chemical treatment of hair.

An unexpected finding from our single-fiber fatigue work involved an especially dramatic effect relating to the relative humidity of the environment. While it is well recognized that the mechanical properties of hair change as a result of the relative humidity dictating the moisture content of hair, it was found that a massively larger influence was obtained on fatigue testing results as compared to conventional stress-strain experiments. Figure 12 shows models and experimental data resulting from repeated grooming of virgin Caucasian hair as a function of the relative humidity. Findings from these experiments are in line with predictions from the single-fiber work.

Table III

Weibull Parameters for Repeated Brushing Experiments on Caucasian Hair after Different Treatments

Treatment	Characteristic lifetime	Shape factor
Virgin hair	55,200,000	0.48
Conditioned hair	1,040,000,000	0.43
1× Bleached hair	3,480,000	0.64
Conditioned bleached hair	1,510,000,000	0.54
3× Bleached hair	538,000	0.61

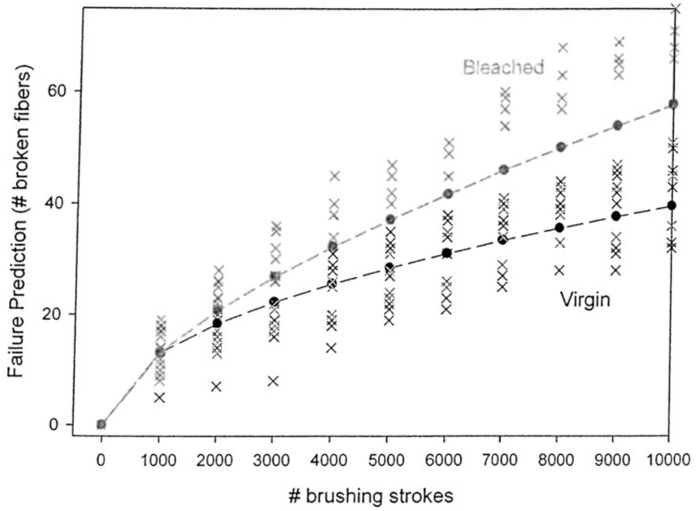

Figure 9. Models and experimental data for repeated grooming experiments on virgin and bleached Caucasian hair at 60% RH.

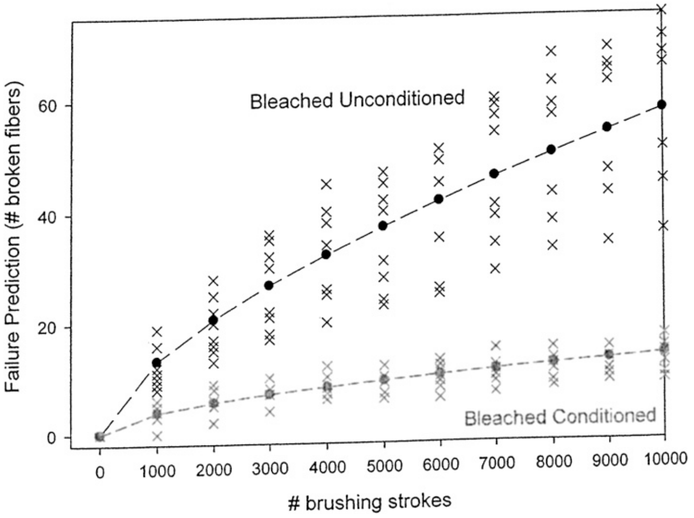

Figure 10. Models and experimental data for repeated grooming experiments on bleached hair both with and without conditioner at 60% RH.

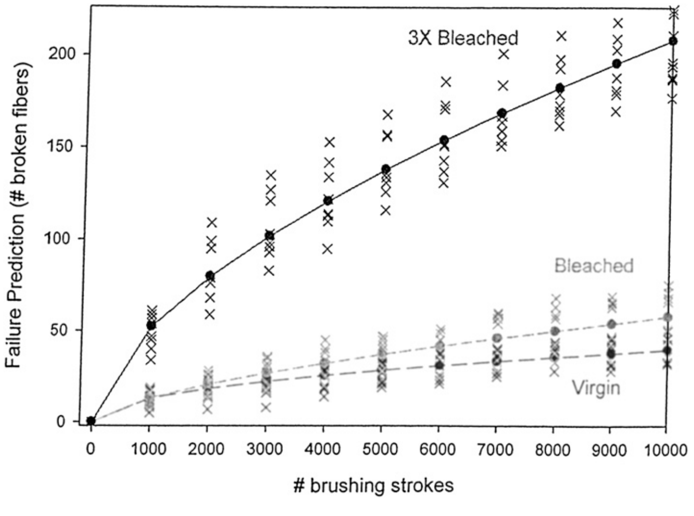

Figure 11. Models and experimental data for repeated grooming experiments on virgin, 1× bleached, and 3× bleached Caucasian hair at 60% RH.

SOME COMMENTS ON THE NATURE OF BROKEN FIBER FRAGMENTS

In their studies, Robbins and Kamath (6,7) focused heavily on the size of broken hair fibers in repeated grooming experiments, distinguishing between short (< 2.54 cm) and long (> 2.43 cm) fragments while also proposing mechanisms for their occurrence. So-called "short segment breakage" was hypothesized to occur by the "end wrapping" of fibers during grooming, while "long segment breakage" was proposed to occur by "impact

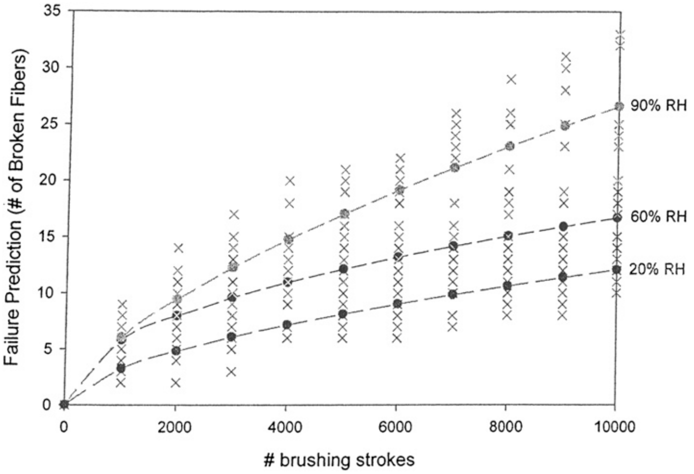

Figure 12. Models and experimental data for repeated grooming experiments on virgin medium brown Caucasian hair at 20%, 60%, and 90% RH.

loading" on looped fibers and entanglements. In short, the two mechanisms represent different ways by which sufficiently-high localized stress could be generated to induce breakage. It is not disputed that snags and tangles can lead to direct breakage; however, we argue that fatigue theory dictates hair fibers can (and will) break upon repeated application of forces considerably less than "the break force." In short, there is another breakage mechanism that involves progressive propagation of flaws within the fiber, and it does not require the presence and occurrence of tangles.

While we did not specifically focus on the size of the broken fibers, top-line observations from our experiments suggested the highest proportion occurring as extremely short fragments (≤ 1-2 mm in length). In fact, the shortest of these appear as dark, dust-like specks, although microscopic investigation confirms them to be hair pieces. Obviously, such short fragments would not be noticed by the wearer, although the other sides of the break (that on the hair which remains attached to the head) would presumably propagate equally well to form a split end.

These short breaks must represent fractures at the very tips of fibers. This observation appears instinctive, as fiber ends are oldest, have sustained more wear and tear, have become most damaged, and will have increased friction with a comb or brush. Therefore, in terms of the fatiguing principles discussed here, one would expect the highest density of potentially catastrophic flaws to be in this region. Moreover, the density of these flaws may be expected to progressively decrease upon moving towards the root end, where the hair is younger and has received less wear and tear. Therefore, one may expect a distribution in the length of broken fibers that is commensurate with the likelihood of flaws. Specifically, we may anticipate a high population of short fragments due to more flaws being present near the tips, with progressively lower populations of longer fibers as the result of fewer flaws being present nearer the root.

To test this theory, we performed additional experiments on 20 virgin Caucasian hair tresses at 60% relative humidity. This time both the number and the size of the broken fibers were recorded. Weibull parameters that describe the formation of differently sized fragments are shown in Table IV, while the models obtained from these results are shown in Figure 13.

Findings suggest significant systematic trends. The formation of longer fibers is modeled with a low shape parameter, indicating that the highest incidence of formation takes place early in the combing process. Conversely, formation of the shortest fragments is described by a higher shape factor, showing a greater formation rate with increased grooming cycles. In short, the smallest fiber fragments are generated in a "wear-out" mechanism, while the longer fragments form by a "premature failure" mechanism. Moreover, fiber sizes between these extremes show intermediate behaviors.

To summarize: as anticipated, an increased number of sort fiber fragments are formed with repeated grooming, presumably due to flaw propagation in the most-damaged tip area. However, contrary to our thesis, the formation of longer fragments is more abundant earlier in the grooming process. A premature failure mechanism (i.e., a shape parameter less than 1) results from the relatively rapid failure of pre-existing defects, without appreciable generation and propagation of new ones. Therefore, one explanation for the long-fiber results involves a "weeding out" of already damaged fibers early in the process. An alternative explanation is the hypothesis of Robbins and Kamath, which proposes that longer fragments are the result of tangles that occur during the grooming process, that is,

Table IV

Weibull Parameters Describing the Formation of Differently Sized Breakage Fragments

Fragment size	Characteristic lifetime	Shape factor
≤ 2 mm	252,000	1.80
2 mm–1 cm	1,940,000	1.13
1 cm–3 cm	34,000,000	0.76
≥ 3 cm	627,000,000	0.53

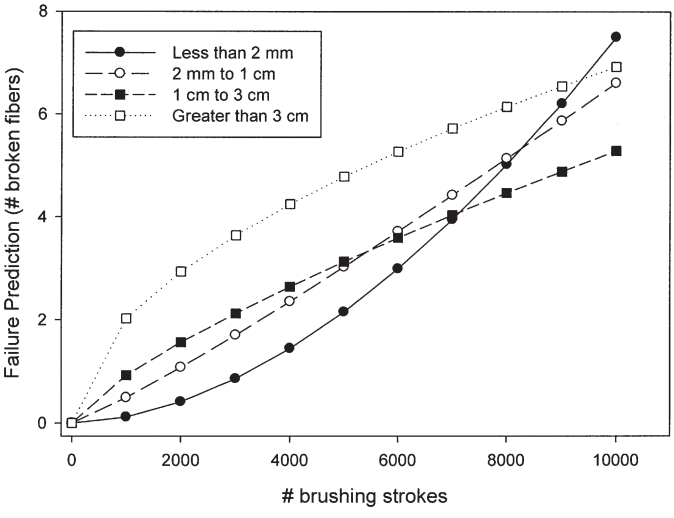

Figure 13. Failure prediction curves for different-sized fragments as a function of brushing strokes at 60% RH.

a higher incidence of tangles occurs earlier in the grooming process, which are gradually "brushed out" with time.

In addition to the size of the broken fibers, there is also a need to mention the thickness. As has been shown, there is a squared relationship between the radius of a fiber and the applied stress, and an exponential relationship between the stress and the propensity for breakage. Therefore, theory suggests a considerably higher tendency for breakage of fine fibers within a tress during the performing of such experiments. While we did not specifically generate data to test this presumption, general experimental observations do appear to be in agreement.

CONCLUSIONS

In mechanical testing terms, the grooming of hair represents a fatiguing process wherein individual strands experience repeated exposure to an external stimulus. Therefore, in accordance with fatiguing principles, there is a gradual propagation of flaws within individual fibers until ultimately catastrophic failure (breakage) results. As such, hair fibers will break upon repeated application of forces considerably lower than those required to induce breakage from a single-force application. Moreover, this process occurs in a predictable manner that can be modeled to provide an understanding of the contributions associated with different variables in hair breakage.

The first paper in this series utilized single-fiber fatigue experiments to generate fundamental learning on the effects of such variables. Particularly noteworthy was that considerably larger differences were observed as a function of hair type and environmental conditions in fatigue experiments as compared to conventional stress-strain testing. Results also showed a strong dependence of breakage on the magnitude of the applied stress, thus demonstrating how lubrication provided by conditioner products lowers grooming stresses and provides considerable protection against breakage. As such, this introduced the idea of using standard fatigue testing approaches to describe and model the data obtained from repeated grooming experiments.

Failure analysis is often modeled using Weibull statistics, an approach that introduces the novel idea of treating hair breakage as a statistical variable. Therefore, the output from this approach yields predictions as to the likelihood of hair breakage under differing conditions. In this instance, a grouped Weibull analysis was used to analyze breakage data from repeated grooming experiments. Perhaps contrary to first impressions, these tests are not as straightforward to perform as may be imagined. Therefore, some time was spent describing the equipment and the importance of certain experimental variables. The Weibull analysis technique is described, and it is shown how generation of the two Weibull parameters (the characteristic lifetime and the shape parameter) provide a means of quantifying these experiments. However, the real strength of the approach involves the ability to generate survival probability plots that provide predictions as to the likelihood of fiber breakage under different conditions. Therefore, assuming these laboratory experiments are a reasonable representation of real-life conditions, it becomes possible to predict breakage rates on actual heads as a function of different habits and practices. Of course, such experiments frequently represent accelerated wear and tear and consequently stray somewhat from real-life practices. However, more accurate predictions may be obtained by performing more lengthy experiments involving more intricate and realistic application conditions. Nevertheless, experiments herein illustrate the considerable effects of conditioning, chemical damage, and the relative humidity of the environment on the propensity for fiber breakage. It is also shown how the two Weibull parameters, together with information about the number of fibers in the test tresses, allow for the modeling of repeated grooming testing and allow investigators to re-create the experimental outcome for comparison to their own experiences.

Preliminary experiments also examined the nature of the generated fiber fragments. The appearance of small fragments (resulting from breakage near the hair tips) occurs according to a "wear out" mechanism, by which an increased number of grooming strokes leads to an increased rate of formation. However, the diminished occurrence of longer fragments with increased grooming indicates a "premature failure" mechanism, which may be explained in terms of the gradual brushing out of snags and tangles.

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REFERENCES

(1) C. R. Robbins, *The Chemical and Physical Behavior of Human Hair, 4th ed.* (Springer-Verlag, New York, Heidelberg, 1988), Ch. 8.
(2) W. Hamburger, H. M. Morgan, and M. M. Platt, Some aspects of the mechanical behavior of hair, *Proc. Sci. Sect.,* **14,** 10–16 (1950).
(3) A. C. Brown and J. A. Swift, Hair breakage: The scanning electron microscope as a diagnostic tool, *J. Soc. Cosmet. Chem.,* **26,** 289–297 (1975).
(4) C. Robbins, Hair breakage during combing. I. Pathways to breakage, *J. Cosmet. Sci.,* **57,** 233–243 (2006).
(5) C. Robbins, Hair breakage during combing. II. Impact loading and hair breakage, *J. Cosmet. Sci.,* **57,** 245–257 (2006).
(6) C. Robbins and Y. Kamath, Hair breakage during combing. III. The effects of bleaching and conditioning on short and long segment breakage by wet and dry combing of tresses, *J. Cosmet. Sci.,* **58,** 477–484 (2007).
(7) C. Robbins and Y. Kamath, Hair breakage during combing. IV. Brushing and combing hair, *J. Cosmet. Sci.,* **58,** 629–636 (2007).
(8) T. A. Evans, A statistical analysis of hair breakage, *J. Cosmet. Sci.,* **60,** 599–616 (2009).
(9) W. Weibull, A statistical distribution function of wide applicability, *J. Appl. Mech,* **9,** 293–297 (1951).
(10) S. B. Hornby, Cyclic testing: Demonstrating conditioner benefits on damaged hair, *Cosmet. Toiletr.*, **116,** 35–39 (2001).
(11) S. B. Hornby, N. J. P. Winsey, and S. P. Bucknell, New techniques to capture viscoelastic changes in hair induced by mechanical stress, *IFSCC Magazine,* **5**(2), 93–97 (2002).
(12) B. Dodson, *The Weibull Analysis Handbook, 2nd ed.* (American Society for Quality Press, Milwaukee, 2006), Ch 1.