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Mechanical extension of human hair and the movement of the cuticle

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Synopsis

Goniophotometry has enabled measurement of the angle that the surface of the cuticle (the scales) of a human hair fiber makes with the axis of the hair shaft. This measuring technique has been used to obtain the change of this scale angle with extension of a hair fiber under fixed conditions of temperature and relative humidity. Based on a simple model of overlapping scales of the hair cuticle, analysis shows that, for hair fibers extended to strains above 10% at 35% relative humidity and at 35°C, overlapping scales become progressively detached from each other. This scale detachment has been suggested to result from the mechanical failure of the endocuticle layer in the scale structure.

This endocuticle layer is low in disulfide cross-linking, which would result in a lowered stiffness and greater extensibility, as indicated by the higher swelling of the layer in water as against the highly cross-linked exocuticle layers. The greater extensibility of the endocuticle would also explain the greater distortion of this layer under stress, but it would not follow that endocuticular failure under stress should result.

An alternative mechanism of failure of adhesion between overlapping scales in the cuticle is suggested, based on the involvement of the hydrophobic upper-β-layer with its surface of 18-methyleicosanoic acid (18-MEA), which may provide mobility and a reduction in adhesion between scales. This potential failure of the cementing of the overlapping scale structure due to the 18-MEA is discussed, with particular reference to the standard permanent setting procedure of human hair.

INTRODUCTION

Stamm *et al.* (1) have studied by means of goniophotometry the specular reflection and the diffuse scattering of light by human hair. The data obtained provided a means of measuring the luster of hair fibers under differing conditions, such as cleanliness of the hair surface, the straightness of the hair and its alignment, and cuticle damage. Furthermore, the technique enabled the measurement of the scale angle that the surface of the cuticle (the scales) makes with the axis of the hair shaft. Guiolet *et al.* (2) have studied the effect of stretching hair on the scale angle. Two series of black and medium bleached hair were examined by them, and both types of hair were found to behave identically, from the point of view of scale angle versus the strain applied.

All these latter measurements were carried out at 35°C and 35% relative humidity. Table 2 in the paper by Guiolet *et al.* (2) shows the strain and the corresponding scale angle up to a strain of 33.9%. These results are shown here graphically in Figure 1. Each result is the mean scale angle for 20 fibers at the indicated strain. Although the individual measurements at each strain level fall within a wide range, the general trend of the change of scale angle with strain is clear. In this note the authors examine on the basis of a simple model the scale angle change expected with extension of the hair fiber and its significance in terms of the cuticular scale attachment to the hair fiber main shaft.

THE OVERLAPPING SCALE STRUCTURE

If no "decementation," mechanical failure, or slippage between overlapping scale structures occurs, the whole cuticle overlay of the fiber will act as a solid as if it were part of the hair cortex. The scale angle versus the longitudinal strain of the fiber is shown in the Appendix to follow Curve B in Figure 1. If slippage between overlapping scales occurs, then the scales will move relative to each other as the hair fiber is extended. Each scale unit is attached directly by its back edge to the hair cortex, and this attachment edge will act as a fulcrum (see Figure 3).

The scale angle versus longitudinal strain of the fiber in this latter case is shown in the Appendix to follow Curve A. It should be noted that the thickness of the scales remains unchanged in the calculation of Curve A. If the overlapping scales completely detach from each other, then the scale angle of the extended fiber would be even less affected

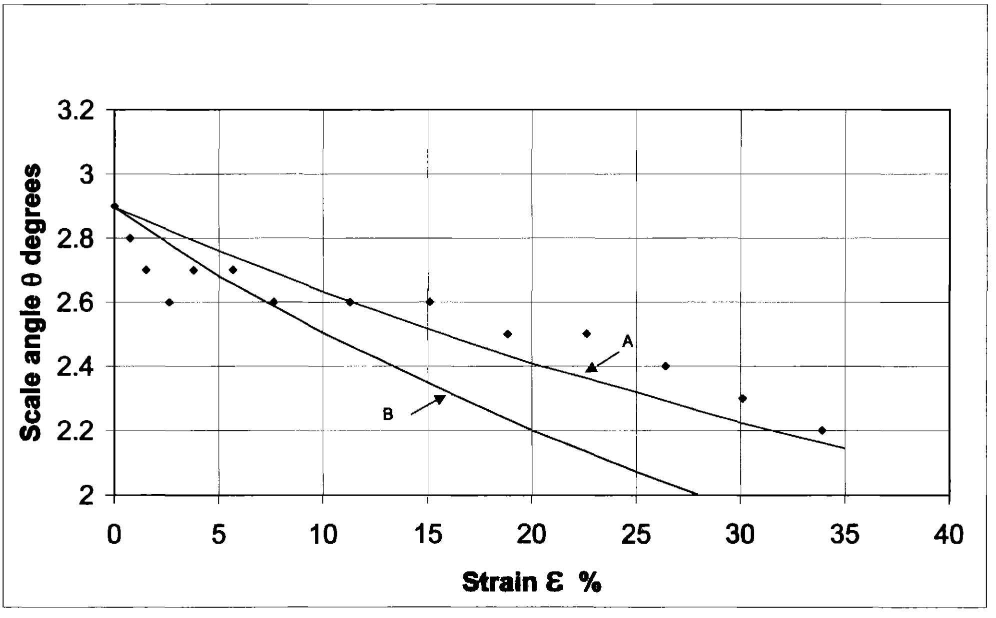

Figure 1. The plot (x axis) of the relationship between the longitudinal strain, ε, applied to a hair fiber (see text) versus the scale angle, θ (see Figure 3), shown in conjunction with the theoretical curves based on the model shown in Figure 3. Curve A corresponds to the case of free slippage between scales and Curve B to no slippage.

by extension of the main shaft. The points on Figure 1 of the measurements of scale angle versus strain obtained by Guiolet *et al.* (2) suggest that up to a strain of about 8%, with the fibers at an environmental relative humidity of 35%, there is no slippage between scales, and that above 10% slippage plus some detachment has occurred. This also concurs with the observation in Table 2 of Guiolet's paper (2) that the transparency of the hair is constant up to 7.5% strain and then drops rapidly with further extension. This change would be brought about by an air film forming between overlapping scales along the surface of detachment.

These suggestions generally concur with the observations of Gamez-Garcia (3) that the lower the moisture content of the hair fiber under test the lower the strain level at which detachment of the scale structure is initiated. The latter also noted that the lifting of the scales showed no presence of endocuticular debris at their internal surfaces. As suggested elsewhere (4), although the endocuticle has the least concentration of cystine cross-links of the layers in the cuticle cell and the highest swelling in water, it is the upper-β-layer in the cell membrane complex (CMC) that provides the possibility of specific mechanical weakness (see Figure 2). Further discussion on the nature of this β-layer will follow. Ruetsch and Weigmann (5) also have examined the damage to both human hair and wool cuticles by fiber extension to 30–35% strain. In the case of wool fibers, although

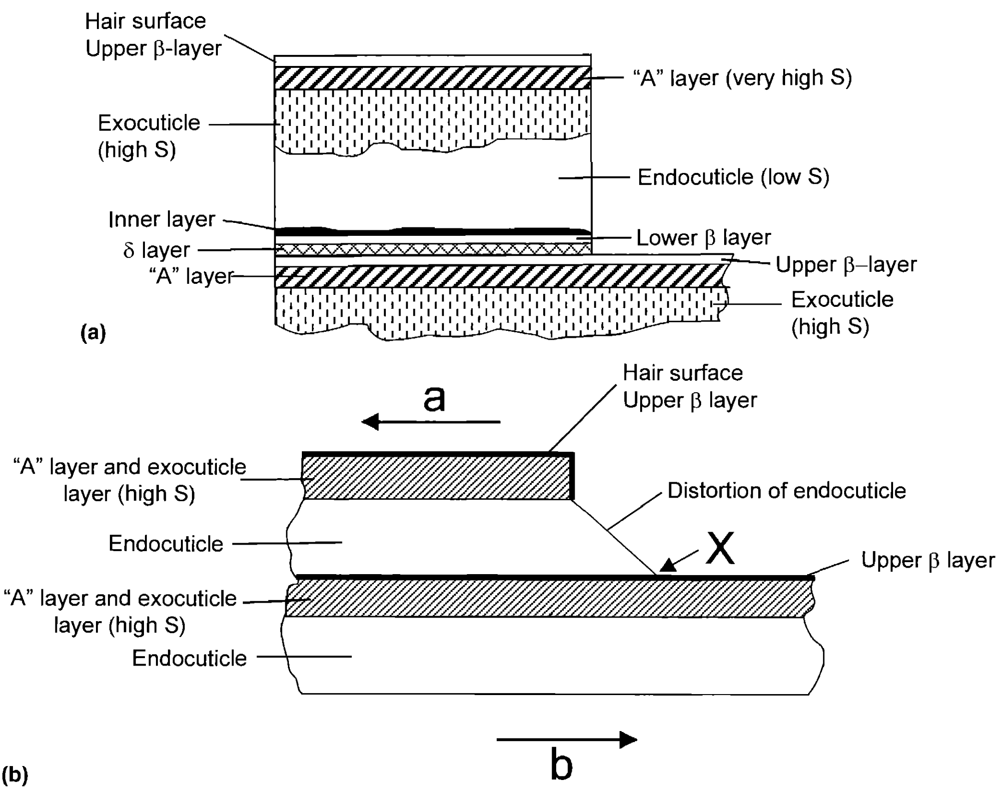

Figure 2. A sectional diagram of two overlapping scales showing in 2a details (see text) of the different layers of the scale structure. In 2b are shown the proposed distortion of the low cross-linked endocuticle when the hair fiber is extended, resulting in opposing relative stresses (a and b) in the two scales. At the endocuticle edge (X) these stresses result in shear forces, which may lead to scale lifting.

no scale lifting was observed, they still claim that failure in the intercellular cement between cuticle cells occurs, with the relative sliding of the scales, in response to the extension of the fibers.

THE CUTICLE CELL

The cuticle cell surface (4,6), as indicated in the sectional diagram (Figure 2), consists of a thin hydrophobic layer (upper-β-layer) beneath which are the two layers "A" and exocuticle. Both these latter layers contain a high degree of disulfide bonding, resulting in mechanically inextensible structures low in swelling when placed in a wet environment. The endocuticle layer beneath these rigid structures is low in disulfide cross-linking, resulting in a mechanically more extensible structure capable of a high degree of water uptake. This great difference in water uptake by the "A" and the exocuticle layers as against the endocuticle has been shown by Robinson (7) to produce the pronounced projection of scales in unextended wet wool fibers. This scale projection in the wet wool fibers is the prime cause of "felting" entanglement in wool fiber masses during washing in water.

For extension of hair fibers under ambient conditions to 30–35% strain, Ruetsch and Weigmann (5) observed from autofluorescence and scanning electron microscopic studies the cuticular damage and failure at the scale edges, which result in scale lifting. The difference in the stiffness of the "A" and exocuticle layers as against the considerably less stiff endocuticle layer results, during the longitudinal extension of a hair fiber, in a major component of the distortion occurring in the endocuticle (see Figure 2b). On the basis of this result and the observation by Swift (8) that material observed with scale lifting is associated with endocuticular debris, Ruetsch and Weigmann (5) concluded that endocuticular failure precedes scale edge lifting. This conclusion from later observation by Swift (4) and others (3) must be re-examined. Swift (4) noted the failure mechanically of the cell membrane complex (CMC) along the upper-β-layer.

As mentioned earlier, Gamez-Garcia (3) observed no endocuticular debris at internal surfaces of detached scale structure. The possible involvement of the hydrophobic upper-β-layer, together with its surface of 18-methyleicosanoic acid (18-MEA) in the failure of the cementing of overlapping scale structures and its involvement in standard permanent setting procedures of human hair in salons, is next discussed.

THE UPPER-β-LAYER OF THE CUTICULAR CMC

Jones and Rivett (6) have proposed a model for the upper-β-layer of cuticular CMC consisting of a fatty acid monolayer, approximately 3-nm thick, attached by thio-ester linkages to a proteolipid membrane of approximately the same thickness (Figure 2a). The proteolipid layer in turn is attached to the "A" layer of the exocuticle of the cuticle cell. The fatty acid is the 18-MEA, with the straight chains forming a parallel array of ordered structures terminating in a short branched chain. This parallel chain array is at right angles to the proteolipid membrane, with the branched terminating chain on the surface providing mobility to the fatty acid monolayer. The evidence (9) provided for this increased mobility is the demonstrated lowering of the melting point from 77°C for eicosanoic acid to 56°C for 18-MEA by the introduction of the methyl group. The presence of the methyl group in 18-MEA is likely to lead not only to a greater mobility of the fatty acid monolayer but also to a possible reduction of the adhesion between cells. The reduced amount of cystine crosslinks in the endocuticle certainly would result in a higher degree of swelling in water. Furthermore, the mechanical opposition to distortion would be reduced. However, the fact that the endocuticle distorts considerably more than the exocuticle when stressed does not of itself mean that the endocuticle will fracture under a lower stress than the remainder of the cuticle. The endocuticle is more extensible, as a lightly cross-linked elastomeric structure within which the molecular chains are able to flow past each other with greater ease because of the lower presence of cross-links. The 18-MEA surface in contact with the underside of a cuticle above it (see Figure 2a) can, because of its surface mobility, slide past the upper cuticle. From the above, the proposal that the surface of the upper-β-layer is the region of weakness allowing flow of cuticle past cuticle (see Figure 2a) during fiber extension must be considered as an important alternative mechanism to the breakup of the endocuticle under stress that might result in the "decementation" between cells. Near the edge of the upper endocuticle and the upper-β-layer of the lower cuticle (see "X" in Figure 2b), the distorted endocuticle will not only tend to relieve the distortion stress by allowing the lower cuticle to slide, exposing more upper-β-layer, but would also tend to lift. The lifting action would progress along the junction with the upper-β-layer, allowing a film of air to penetrate along the junction. The results of Guiolet *et al.* (2) suggest, from Figure 1 and their own data on loss of transparency, that at around 8% strain on the hair fibers under the experimental conditions of relative humidity and rate of straining, failure at the surface of fracture of the upper-β-layer commences. This failure is progressive up to the maximum extension applied.

DISCUSSION WITH REFERENCE TO PERMING AND CONDITIONING

The failure of the adhesion of cuticle cells to the hair cortex has been observed to lead to the complete breakdown of the hair at the fiber ends. This observation was obtained in experimental comparison of the action of combing of hair with and without conditioner (10). The use of hair conditioner resulted in the cuticle being present on much longer lengths of hair prior to exposure of the cortex and breakdown of the hair structure. The progressive loss of cuticle can be clearly seen in SEM pictures. Once the cortical structure is exposed, the main hair shaft fibrillates into split ends and begins to break up. As mentioned earlier in this paper, 18-MEA in the upper-β-layer not only allows for sliding of the lower cuticle relative to the upper cuticle, but plays an important role in the adhesion between cuticle cells. Failure of this adhesion would be expected to make the cuticle fragments much easier to remove, leading to exposure of the cortex. In experimental perming procedures at elevated temperatures, as described elsewhere (11), no neutralizer was used. The resultant permed hair felt smooth and was not left harsh, as is the case in the normal perming procedure. The permed hair required a minimum of conditioning, and on successive brushing and combing there was little evidence of broken pieces of hair ends, as can occur after a normal perming procedure. It appears that this perming process preserves the lubrication and adhesion of the cuticle cells better than the conventional perming process.

It should be noted that hair fibers when they first protrude from the follicles have up to ten overlapping cuticle cells. The result is that in the life of a hair fiber the action of combing and brushing will not remove the last layer of cuticle cells for some considerable time and thus for the length of hair. However, the amount of 18-MEA per unit length of hair would progressively decrease until the last cuticle layer is removed, exposing the hair cortex, leading to subsequent breakup of the fiber end. The action of cationic conditioners serves to replace the lubricating surface where 18-MEA has been depleted, helping to preserve the cuticle layer for substantially greater lengths of hair. Unlike the 18-MEA layer, conditioners are not covalently bonded to the cuticle surface and need to be replaced after the hair is washed to retain the lubricating action and protective effect.

APPENDIX

The overlapping scales, which form the cuticular outer layer of a human hair fibers, are attached by their inner edge to the hair cortex, the main shaft of the fiber. The overlapping scales form a serrated system of scale edges on the surface of the cuticle. For the purposes of this analysis the scales are considered as platelets rectangular in cross section and capable of rotation about a line fulcrum (A and B in Figure 3a,b). With the fiber unextended, the angle of the scales to the direction of the fiber is θ. If the fiber is extended by strain ϵ, the attachment of scales to the main shaft (A and B in Figure 3a, b) will move apart, and the scale angle, θ, will reduce to ($\theta - \delta\theta$). The dotted scale in Figure 3b represents the changed position of Scale 2 after extension, and

$$AB' = (1 + \epsilon)AB \tag{1}$$

In Figure 3b, BC is perpendicular to the Scale 2 surface with the fiber unextended and B′C′ with the fiber extended. Similarly, BD is perpendicular to AB, and B′D′ is perpendicular to AB′. The thickness of the scale, t, is for the unextended fiber. With low adherence between overlapping scales, extension of the fiber will result in slippage between scales, as indicated in Figure 3a. The thickness, t, of the scales will remain unchanged because of the negligible lateral forces transferred between the scales.

In the unextended state, the scale thickness, t, is given by

$$\begin{aligned} t &= BC \\ &= AB \sin\theta \end{aligned} \tag{2}$$

If slippage occurs between the scales on extension of the fiber and the thickness remains unchanged, then

$$BC = B'C' = t$$

It follows that because

$$B'C' = AB' \sin(\theta - \delta\theta)$$

then

$$AB' \sin(\theta - \delta\theta) = AB \sin\theta$$

That is, from equation 1

$$(1 + \epsilon)\sin(\theta - \delta\theta) = \sin\theta \tag{3}$$

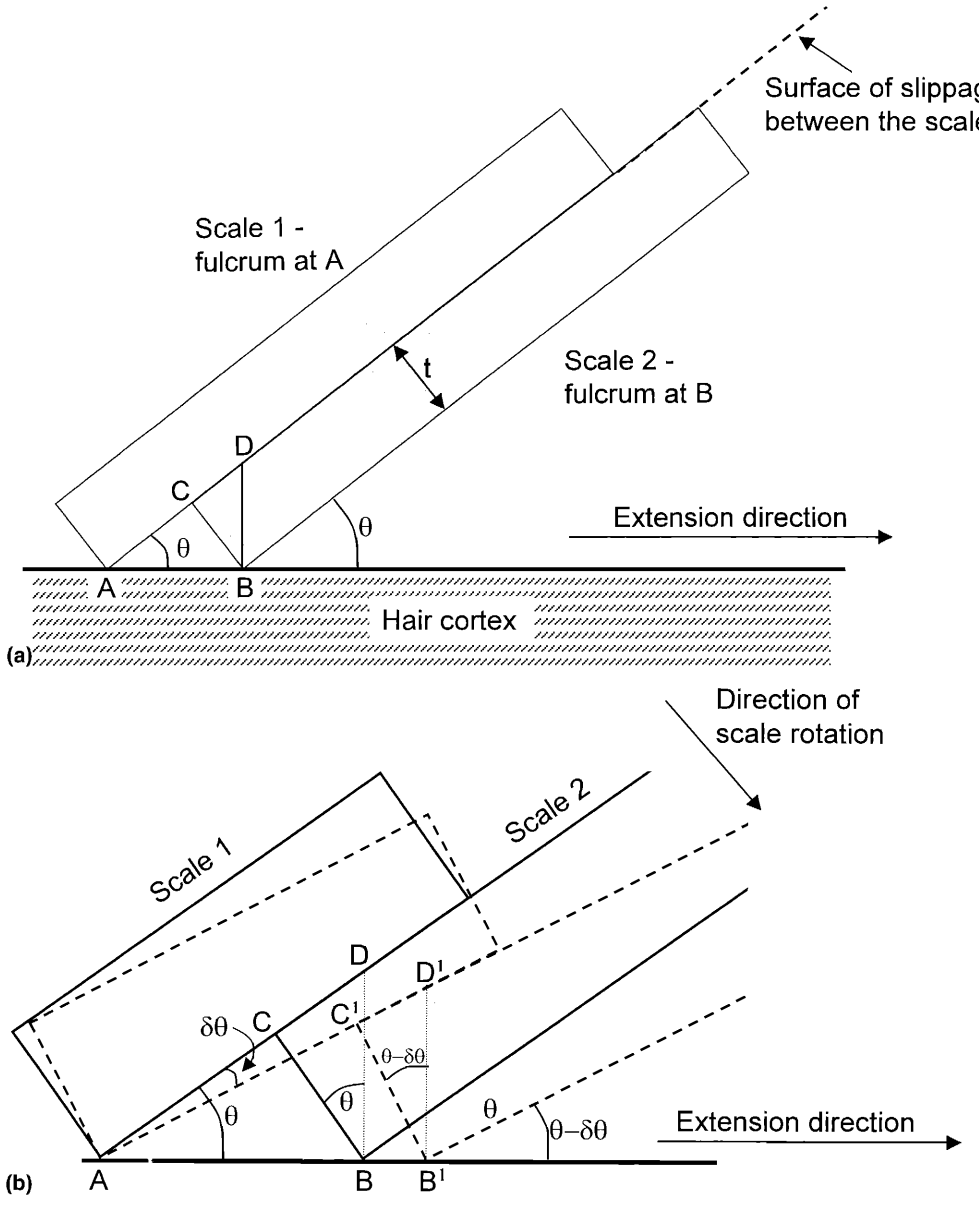

Figure 3. (a) The model adopted for the movement of two overlapping scales (1 and 2) relative to each other and the hair cortex. Each scale is assumed of rectangular section and attached to the hair cortex along a line, which acts as a fulcrum (A and B) for the whole scale (see text). (b) The geometric changes to Scale 2 in 3a with extension of the hair fiber by a strain ϵ. AB will extend to AB′ where AB′ = $(1 + \epsilon)$AB, and points C→ C′, D→D′. The angle of the scale to the fiber direction, θ, decreases to $(\theta - \delta\theta)$ with extension.

In all the results quoted in this Appendix, the trigonometric functions of any angle, ϕ (in radians), is approximated as follows:

$$\sin \phi = \tan \phi = \phi$$

and

$$\cos \phi = 1$$

because all angles quoted are less than 3° (0.5236 radians), and sin 3° = 0.5234, tan 3° = 0.5241, and cos 3° = 0.9986.

From equation 3,

$$\sin(\theta - \delta\theta) = \sin \theta \cos (\delta\theta) - \cos \theta \sin(\delta\theta)$$

which reduces, on application of the approximations indicated above, to

$$\begin{aligned} \sin(\theta - \delta\theta) &= \sin \theta - \delta\theta \\ &= \theta - \delta\theta \end{aligned} \quad (4)$$

Inserting equation 4 into equation 3 reduces to

$$(1 + \varepsilon)(\theta - \delta\theta) = \theta$$

i.e.,

$$\frac{\delta\theta}{\theta} = \frac{\varepsilon}{1 + \varepsilon} \quad (5)$$

Although θ and $\delta\theta$ were expressed in radians, because is $\delta\theta/\theta$ is a ratio, equation 5 is independent of the units of the values of θ and $\delta\theta$ and holds for the values of the angles expressed in degrees. This is the case in Figure 1 for Curve A: the relationship between the scale angle and the strain ϵ on the fiber is given by equation 5, with both θ and $\delta\theta$ expressed in degrees.

Where there is complete adherence between the scales, the whole cuticle structure acts as a solid and as a part of the underlying cortex of the fiber. The result of an extension of the hair fiber by a strain ϵ is a lateral compression strain of $\sigma\epsilon$ where σ is the Poisson ratio of the scale material. The result is that the scale angle changes with an extension strain ϵ due to the value of AB going to AB′ and DB to D′B′.

As in equation 1

$$AB' = (1 + \epsilon)AB \quad (6)$$

However, due to the lateral strain on the fiber

$$D'B' = DB(1 - \sigma\epsilon) \quad (7)$$

and with the scale thickness no long constant

$$\begin{aligned} DB &= AB \tan \theta \\ &= AB(\theta) \end{aligned} \quad (8)$$

and

$$D'B' = AB' \tan(\theta - \delta\theta)$$

which approximates with equation 6 to

$$D'B' = (1 + \epsilon) AB(\theta - \delta\theta) \quad (9)$$

Inserting equations 7 and 8 into equation 9 and approximating $\tan \theta = \theta$,

$$\theta(1 - \sigma\epsilon) = (1 + \epsilon)(\theta - \delta\theta) \quad (10)$$

which reduces to

$$\frac{\delta\theta}{\theta} = \frac{\varepsilon(1+\sigma)}{1+\varepsilon} \quad (11)$$

In amorphous solids σ approximates to 0.5, and equation 11 can be reduced to

$$\frac{\delta\theta}{\theta} = \frac{3\varepsilon}{2(1+\varepsilon)} \quad (12)$$

Equation 12 corresponds to Curve B in Figure 1, the relationship between scale angle and strain when there is complete attachment and no slippage between scales.

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