An Examination of Fatigue Striations in Human Dentin:  
*In Vitro* and *In Vivo*

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Abstract: Although striations are often used in evaluating fatigue crack growth in engineering materials, they have not been used in studying the mechanics of fracture in hard tissues. The primary objective of this study was to evaluate the striations resulting from fatigue crack growth in the dentin of human teeth. Compact tension (CT) specimens obtained from the coronal dentin of molars from young (17 ≤ age ≤ 37 years) and senior (age ≥ 50 years) patients were subjected to cyclic Mode I loads. Striations evident on the fracture surfaces were examined using a scanning electron microscope (SEM) and contact profilometer. Fatigue crack growth striations that developed in vivo were also examined on fracture surfaces of restored molars. A power spectrum analysis of surface profiles from the CT specimens showed that the striation spacing ranged from 50 to 170 μm. The average spacing in the dentin of seniors (130 ± 23 μm) was significantly larger (p < 0.001) than that in young dentin (88 ± 13 μm). Fatigue striations in the restored teeth exhibited features that were consistent with those that developed in vitro and a spacing ranging from 59 to 95 μm. Unlike metals, the striations in dentin developed after a period of cyclic loading that ranged from $1 \times 10^3$ to $1 \times 10^5$ cycles. A quantitative evaluation of the striation spacing using the Bates-Clark equation suggested that cyclic crack growth within the restored teeth occurred at a stress intensity range near 0.7 MPa m$^{1/2}$, and a stress range of ~12 MPa. © 2007 Wiley Periodicals, Inc. J Biomed Mater Res Part B: Appl Biomater 85B: 149–159, 2008

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INTRODUCTION

Fatigue failures are a common problem and have been a topic of extensive research for more than a century.¹⁻³ In engineering materials, fatigue failures are often facilitated by cyclic crack extension, which is identified by a series of self-similar inflections on the fracture surface regarded as “striations”. The striations represent the position of the crack after each cycle and are a result of incremental changes in the crack tip root radius.⁴ Based on this topographical map of crack extension, the striations and their spacing disclose important information about the mechanistic aspects of crack growth and resistance.

In many cases the striation geometry can be used to interpret characteristics of the material and the nature of cyclic loading. The striation morphology (height/amplitude, length, and orientation) typically depends on the ductility of the material, magnitude of stress and stress ratio.⁵ In metals, striations arise via two primary mechanisms, i.e., alternating slip and crack tip blunting and resharpening. In general, one striation spacing is equivalent to the crack length extension in one cycle. The number of striations evident on the fracture surface may range from a few hundred to thousands in number, depending on the magnitude of driving force.⁴⁻⁶ As such, striations can enable a fractographic determination of the crack growth rate and a validation of macroscopic measurements obtained from experimental examination. However, not all materials exhibit fatigue striations. For instance, the fracture surface morphology that results from fatigue and quasi-static loading are not unique in engineering ceramics.⁷

Concerns of fatigue crack growth and fracture are not limited to engineering materials and structures. For example, restored teeth are more likely to experience fracture over time as a result of damage induced by the restorative process and continuous cyclic loading.⁸⁻¹¹ Tooth fracture is poten-
Dentin is traversed by tubules that extend from the pulp towards the dentin enamel junction (DEJ). The tubule lumens are surrounded by a hypermineralized cuff of peritubular dentin and the material located between the tubules is known as the intertubular dentin. By virtue of the complexity of this structure, an examination of fatigue in dentin and biological tissues as a whole (e.g., bone, tissues of the tooth, cartilage, etc.) presents an interesting challenge.

Within the last decade there has been growing interest in the fatigue behavior of hard tissues such as bone and tissues of the tooth (enamel and dentin). In vitro studies have analyzed fatigue and cyclic crack growth in dentin of bovine teeth, elephant tusks, and human teeth. The rate of crack growth in dentin is reportedly a function of tubule orientation, the frequency of loading and stress ratio. Furthermore, the crack growth rate is maximum and fracture toughness is minimum for crack extension perpendicular to the tubules. Also, the fatigue crack growth resistance and fracture toughness of dentin decreases with patient age.

There are a host of complex mechanisms contributing to crack extension in dentin. Toughening mechanisms such as bridging of the crack and microcracking have been identified in the fracture of bovine and elephant dentin. Evaluations on the mechanisms of fatigue crack growth have suggested that cyclic extension is comprised of crack-tip blunting and resharpening and that there is a combination of cyclic microfractures and near-tip viscoplastic deformation that are enrolled as a function of the cyclic stress ratio. Despite these aforementioned efforts, the mechanisms of cyclic crack extension in human dentin are not completely understood. Prior efforts have been limited to in vitro experiments and have not identified fatigue striations or examined their potential for exploring the cyclic extension process that occurs in vivo. Therefore, the primary objectives of this study were to identify if striations are generated as a result of fatigue crack growth in dentin and to examine how their characteristics are influenced by the driving force and patient age. The investigation was also aimed at comparing fracture surfaces from in vitro experiments with those that develop within restored teeth in vivo.

**MATERIALS AND METHODS**

Restored and unrestored human molars were obtained from participating clinics within the state of Maryland. All methods of acquisition and storage were in compliance with an approved protocol issued by the Institutional Review Board (IRB) of the University of Maryland. Immediately after extraction the teeth were stored in Hanks’ Balanced Salt Solution (HBSS) with record of age and gender of the patient. The extracted molars were molded in a polymer resin and sectioned using a computer controlled slicer/grinder with water based coolant and diamond abrasive slicing wheels. The restored molars (n = 6) were sectioned longitudinally along the bucco-lingual plane approximately midway between the mesial and distal surfaces. A total of six restored teeth were examined for patients of 32 ≤ age ≤ 75 years. For the unrestored molars (n = 15), a series of primary sections were introduced in the bucco-lingual direction to develop slices of 2 mm thickness. Secondary sections were then introduced to obtain compact tension (CT) specimens patterned after ASTM standard E647 with the tubules oriented perpendicular to the expected plane of crack growth. The geometry of the specimen was in compliance with the ASTM standard E399, *B*/*a* ≥ 2.5(K/I)^2 where *B*/*a* and *a* are the channel thickness and crack length and *K* and *I* are the fracture toughness (≥1.6 MPa m^0.5_) and yield strength (≥80 MPa) of the material, respectively.

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* Figure 1. An illustration of a restored tooth and the primary tissues.
CT specimen was stained with an indelible marker to aid in crack length measurements. Of the 15 CT specimens prepared, six were regarded as “young” (17 ≤ age ≤ 33) and nine were regarded as “old” (50 ≤ age ≤ 77). These age groups were defined according to results of previous studies.\textsuperscript{19,27} According to a post-hoc analysis of the striation spacing measurements, the power for each group exceeded 0.8.

Fatigue testing of the CT specimens was conducted using a universal testing system (EnduraTEC ELF 3200, BOSE Cooperation, Eden Prairie, MN) with a maximum load capacity of 225 N and resolution of ±0.01 N. Cyclic (Mode I) loading was achieved with the specimens submerged in a hydration bath of HBSS at room temperature (22°C). To initiate a crack from the notch, a sinusoidal load was applied under load control at 5 Hz with peak loads between 8 N and 16 N and stress ratio (R) of 0.5.

Crack length measurements were conducted visually using a back lighting technique in which the back surface (with channel) was illuminated with white light and inspection of the crack length occurred on the stained face using an optical microscope (100×) with scaled reticule.

Following crack initiation, cyclic loading was resumed using \( R = 0.1 \) for crack propagation. Measurements of the change in crack length (\( \Delta a \)) were made over specific intervals of fatigue loading until complete specimen fracture. The number of cycles between measurements (\( \Delta N \)) was chosen according to the observed crack growth rate and typically ranged between 1 and 50 kcycles. Details of the experimental loading process and crack length measurements are described elsewhere.\textsuperscript{19} Using the incremental crack length measurements, the steady-state region of fatigue crack growth (\( da/dN \)) was identified and then modeled using the Paris Law\textsuperscript{28} according to

\[
\frac{da}{dN} = C(\Delta K)^m
\]

where \( \Delta K \) is the stress intensity range, and \( da \) and \( dN \) represent the incremental crack extension (\( \Delta a \)) and number of cycles (\( \Delta N \)), respectively. The quantities \( C \) and \( m \) are the fatigue crack growth coefficient and exponent, respectively, and \( \Delta K \) was determined according to\textsuperscript{19}

\[
\Delta K = \frac{\Delta P}{B^* \sqrt{W}} \left( \frac{B^* + 1}{B + 1} \right) \left(0.131 + 0.320 \alpha + 0.211 \alpha^2\right)
\]

where \( \Delta P \) is the load range (\( P_{\text{max}} - P_{\text{min}} \)), \( B \) and \( B^* \) are the full specimen thickness and reduced thickness about the channel, respectively, and \( \alpha = a/W \) [Figure 2(a)]. A representative fatigue response for a dentin CT specimen with three distinct regions of crack growth is shown in Figure 2(b); of particular interest here is the region of “steady state” fatigue crack growth or “Paris Region” (i.e., Region II). The Paris Law parameters from these experiments have been reported earlier\textsuperscript{19} and are listed in Table I for reference. An evaluation of fatigue crack growth and quantitative analysis of the fracture surfaces was completed for all 15 specimens.

Each of the fractured CT specimens was removed from the hydration bath, dehydrated in air for at least 72 h, and then coated with gold palladium using a cold sputter machine (Model LLC Desk II, Denton vacuum, Moores- town, NJ). The fracture surfaces were examined using a scanning electron microscope (Model JSM-5600, JEOL, Peabody, MA) (SEM) in the secondary electron imaging mode (SEI). The restored teeth were also examined using an optical microscope and the SEM to identify cracks and quantify the striation characteristics. For those sections with prominent cracks (\( a \geq 1 \text{ mm} \)) the crack was extended to fracture through application of a bending moment applied out of plane to the sectioned surfaces. The exposed fracture surface of the pre-existing crack that developed \textit{in vivo} was examined using the SEM.
Table I. Paris Law Parameters for the Human Dentin Specimens

<table>
<thead>
<tr>
<th>Age group</th>
<th>Tubule Orientation</th>
<th>Paris Law Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young n=6</td>
<td>90°</td>
<td>( m )</td>
</tr>
<tr>
<td>Senior n=9</td>
<td>90°</td>
<td>( m )</td>
</tr>
</tbody>
</table>

* Significant difference indicated by \( p \)-value.

Surface profiles were obtained from the fractured CT specimens using a profilometer (Model T8000, Hommelwerke, Rochester Hills, MI) with 10-μm probe diameter. For the CT specimens, the measured traverse length ranged from 1 mm to 2 mm depending upon the length of steady state (Region II) crack growth. Three profiles of the fracture surface were obtained at different locations within Region II. Each profile consisted of 8000 data points and the average surface roughness \( (R_a) \) and 10 point roughness \( (R_z) \) were calculated using a cutoff length of one fifth the traverse length. Because of the relatively small fracture surfaces of the restored teeth, grayscale profiles of the fracture surfaces were obtained from SEM micrographs and then analyzed using commercial imaging software (NIH Image J, USA). The grayscale value was plotted as a function of length along the evaluated surface, which represented the difference in intensity of secondary electrons attributed to the variations in surface height.

An estimation of striation spacing was achieved using a power spectrum analysis from the frequency content of surface profiles and SEM images obtained from the fracture surfaces. Briefly, a fast Fourier transform (FFT) was used to evaluate the power of spatial variation in surface height distribution as a function of frequency. For a function of space, the Fourier equation can be described by

\[
\hat{f}(x) = \sum_{k=\text{lowest}}^{\text{highest}} a_k \sin(2\pi k x - \nu_k)
\]

where \( k \) corresponds to frequency and \( x \) represents the physical distance on the surface profile. The coefficient \( a_k \) gives the magnitude of the \( k \)th frequency and \( \nu_k \) gives the relative phase difference. The profile data sets obtained from the \textit{in vitro} and \textit{in vivo} fracture surfaces were processed to obtain the power spectrum using commercial software (Version 7.0.1, MATLAB, Natick, MA). From these distributions the primary wavelength of the profile data was obtained and represented the apparent periodicity in the fracture surfaces (i.e., the striation spacing).

Striations evident on fracture surfaces of the CT specimens that developed \textit{in vitro} were similar to those on fracture surfaces of the restored teeth in geometry and distribution. Consequently, the known conditions responsible for development of the striations \textit{in vitro} were used to infer the conditions responsible for their development \textit{in vivo}. Empirical relationships have been proposed for modeling fatigue striations such as that proposed by Bates and Clark,\(^{30,31}\) which is described as

\[
\text{Striation Spacing} \approx A \left( \frac{\Delta K}{E} \right)^2
\]

where \( A \) is the Bates-Clark Number, \( \Delta K \) is the stress intensity range and \( E \) is the elastic tensile modulus. For a known crack length, the relationship between \( \Delta K \) and stress range \( (\Delta \sigma) \) is defined by linear elastic fracture mechanics (LEFM) according to\(^{32}\)

\[
\Delta K = F \Delta \sigma \sqrt{\pi a}
\]

where \( F \) is a geometry factor and \( a \) is the crack length. Thus, the Bates-Clark number was determined for striations on fracture surfaces of the dentin CT specimens and then used with measurements of striations generated \textit{in vivo} to estimate the apparent driving force (\( \Delta K \)) and cyclic stress range (\( \Delta \sigma \)) contributing to their development.

RESULTS

Fracture surfaces resulting from fatigue crack growth in the dentin CT specimens were examined for presence of visible striations. All of the surfaces exhibited striations. A representative fracture surface from a CT specimen is shown in Figure 3(a). The image shows two distinct regions of crack growth corresponding to fatigue and fracture. The three regions of cyclic extension are highlighted in this figure as well, and were identified using the crack length measurements and growth rate history. Fatigue striations are clearly visible in Region II. Note that the striation spacing is location dependent and increases with crack length and corresponding \( \Delta K \), particularly near the transition of Region II and Region III. Magnified views of striations evident on the surfaces of specimens obtained from molars of a young (17-year-old male) and senior (50-year-old female) patient are shown in Figure 3(b,c), respectively.

A representative surface profile from the fracture surface of the CT specimen in Figure 3(c) is shown in Figure 4(a). The profile was obtained parallel to the direction of crack growth. The average surface roughness \( (R_a) \) and 10 point roughness \( (R_z) \) obtained from all specimens are listed in

\( m \) is the Bates-Clark Number,

\( K \) is the stress intensity

\( C \) is the Paris Law Parameter,

\( m \) is the elastic tensile modulus.
Table II. Both the $R_a$ ($p < 0.03$) and $R_z$ ($p < 0.002$) of fracture surfaces from the young dentin were significantly greater than those specimens obtained from the teeth of senior patients. The power spectrum for the fracture surface in Figure 4(a) is shown in Figure 4(b). Two peaks are evident at 120 $\mu$m and 155 $\mu$m. To identify the primary cyclic wavelength, an integration of power was performed as a function of wavelength and the maximum change in slope (inflection) of this curve was used in defining the dominant wavelength (i.e., striation spacing). The integral curve for the spectrum in Figure 4(b) is shown in Figure 4(c), and exhibited the maximum change in slope at 155 $\mu$m. These measures were confirmed by the striations evident from the SEM evaluation. Results from the striation spacing measurements for all specimens of the two age groups are listed in Table III. The average striation spacing for fatigue crack growth in the young and old dentin specimens was 88 $\pm$ 13 $\mu$m and 130 $\pm$ 23 $\mu$m, respectively. According to the student’s $T$-test, the striation spacing in the old dentin was significantly higher ($p < 0.001$) than that obtained for young dentin.

Cracks were also identified in the dentin of restored teeth that underwent extension in vivo. The cracks were most frequently identified at the line angles (within a region of apparent stress concentration) and extended from the margins with orientation perpendicular to the dentin.

Figure 3. Fracture surfaces of CT specimens with 90° tubule orientation and evidence of fatigue striations. In all figures the arrow indicates the direction of crack growth. (a) fracture surface of a dentin CT specimen with distinction of the three regions of cyclic crack growth (I, II, and III); (b) striations in Region II of crack growth in a young CT specimen (male, 17-years-old). A striation spacing of $\sim$50 $\mu$m is evident; (c) striations in Region II of crack growth in an old CT specimen (female, 50-years-old). A striation spacing of $\sim$150 $\mu$m is evident. The images in (b) and (c) were taken at a stress intensity range $\sim$0.9 MPa-m$^{0.5}$. 

Figure 4. Fracture surface profiles obtained for the CT specimens and results from power spectrum analysis. (a) fracture surface profile of a CT specimen obtained from old dentin in Figure 3(c); (b) power spectrum for surface profile in Figure 4(a). $W$ and $P$ are the wavelength and power, respectively; (c) power summation for spectrum in Fig 4(b). The largest inflection was obtained for 155 $\mu$m. All profiles were obtained in Region II of crack growth.
tubules [Figure 5(a)]. Fatigue striations were identified on fracture surfaces of the restored teeth. An example is shown in Figure 5(b). According to a power spectrum analysis of the grayscale content, the striation spacing on fracture surfaces of the restored teeth ranged from 59 to 95 \( \mu \text{m} \). The power spectrum for the surface in Figure 5(b) is shown in Figure 5(c). A single peak is evident at a wavelength of 93 \( \mu \text{m} \). The dominant striation spacing for all specimens of the two age groups is listed in Table IV. Note that two specimens included in Table IV do not fall within the age definitions used in the \textit{in vitro} analysis for the young and old groups. Consequently, results for the “young” restored group should be considered to represent young and middle ages. The average striation spacing for the fractures surfaces of teeth from the young/middle and senior patients was 67 \( \pm 6 \) \( \mu \text{m} \) and 89 \( \pm 10 \) \( \mu \text{m} \), respectively, and were found to be significantly different \( (p < 0.05) \).

**DISCUSSION**

Striations were evident on fracture surfaces of both the dentin CT specimens and restored teeth. In metals, striations develop as a result of crack tip blunting and resharp-ening through a process comprised of dislocation movement and slip (i.e., plastic deformation).\(^{32}\) Consequently, their presence in dentin suggests that crack exten-sion is comprised of a process that is assisted by the material’s capacity to undergo “plastic-like” deformation.

Results from the power spectrum analysis showed that the average striation spacing on fracture surfaces of CT specimens from the senior patients (130 \( \pm 23 \) \( \mu \text{m} \)) was significantly higher \( (p < 0.001) \) than that for young dentin (88 \( \pm 13 \) \( \mu \text{m} \)). The difference in striation spacing between these two groups implies that crack tip blunting is less active in old dentin. While the exact mechanism responsible for their development is yet to be identified, the increase in spacing with patient age is consistent with expectations. Occlusion of the tubule lumens and consequent increase in mineral content of dentin with aging would be expected to reduce the capacity for inelastic deformation and crack-tip blunting.

Striations on fracture surfaces of the young CT specimens were not only more closely spaced than those in old dentin, they were also more pronounced. Undoubtedly, the magnitude of surface roughness increases with the extent of blunting as a result of geometric inflections in the frac-ture surface. In fact, fracture surfaces of CT specimens from patients of the oldest age (and largest extent of tubule occlusion) exhibited significantly lower roughness \( (p < 0.03) \) and striation patterns with lower height amplitude. Energy absorption in fracture increases with surface roughness through the extent of new surface generated.\(^{33}\) Thus, the lower surface roughness of specimens obtained from senior patients implies that there is a decrease in energy absorption per unit crack extension and that this occurs as a result of a decrease in ability to undergo inelastic deformation. These observations indicate that dentin becomes

**TABLE II. A Comparison of Surface Roughness in Region II Fatigue Crack Growth in Dentin**

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Tubule Orientation</th>
<th>Roughness ( (\mu \text{m}) )</th>
<th>Roughness ( (\mu \text{m}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( R_a )</td>
<td>( R_z )</td>
</tr>
<tr>
<td>Young</td>
<td>90°</td>
<td>1.7 ± 0.3</td>
<td>*</td>
</tr>
<tr>
<td>Old</td>
<td>90°</td>
<td>1.4 ± 0.3</td>
<td>( p &lt; 0.03 )</td>
</tr>
</tbody>
</table>

\* Significant difference indicated by \( p \)-value.

**TABLE III. Striation Spacing (Dominant Wavelength) on the Fracture Surfaces of Young and Old Dentin CT Specimens**

<table>
<thead>
<tr>
<th>Age/gender (years)</th>
<th>Dominant Wavelength (( \mu \text{m} ))</th>
<th>Bates-Clark No. (A) ( \times 10^4 )</th>
<th>Age/gender (years)</th>
<th>Dominant Wavelength (( \mu \text{m} ))</th>
<th>Bates-Clark No. (A) ( \times 10^4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>17/M</td>
<td>88</td>
<td>5.47</td>
<td>50/F</td>
<td>102</td>
<td>9.27</td>
</tr>
<tr>
<td>17/F</td>
<td>91</td>
<td>5.71</td>
<td>50/M</td>
<td>100</td>
<td>6.25</td>
</tr>
<tr>
<td>17/M</td>
<td>90</td>
<td>5.59</td>
<td>50/F</td>
<td>148</td>
<td>6.38</td>
</tr>
<tr>
<td>20/F</td>
<td>85</td>
<td>5.31</td>
<td>52/M</td>
<td>129</td>
<td>8.06</td>
</tr>
<tr>
<td>28/M</td>
<td>69</td>
<td>4.31</td>
<td>53/M</td>
<td>170</td>
<td>10.60</td>
</tr>
<tr>
<td>33/M</td>
<td>108</td>
<td>6.77</td>
<td>59/M</td>
<td>135</td>
<td>8.44</td>
</tr>
<tr>
<td>77/M</td>
<td>131</td>
<td>8.19</td>
<td>77/M</td>
<td>113</td>
<td>7.06</td>
</tr>
<tr>
<td>77/M</td>
<td>146</td>
<td>9.13</td>
<td>77/M</td>
<td>146</td>
<td>9.13</td>
</tr>
</tbody>
</table>

Avg = 22 \( \pm 7 \) \( 88 \pm 13 \) \( 5.53 \pm 0.79 \) \( 61 \pm 13 \) \( 130 \pm 23 \) \( 8.16 \pm 1.43 \)
more brittle with age. Indeed, previous studies of old dentin have shown that there is an increase in “brittleness” with patient age and a reduction in fracture toughness. A first order estimate of the apparent “plastic” zone about the crack tip in the dentin specimens can be obtained from

\[
 r_y \approx \frac{1}{6\pi} \left( \frac{K_c}{\sigma_y} \right)^2
\]

where \( r_y \) is the radius of the plastic zone, \( K_c \) is the fracture toughness and \( \sigma_y \) is the yield strength. For dentin, it appears most appropriate to describe this region as the inelastic zone (rather than the plastic zone) due to the erroneous mechanistic implications associated with plastic deformation. Assuming a fracture toughness of 1.65 to 1.8 MPa-m and a yield strength of \( \sim 80 \) MPa, the inelastic zone size in young dentin is \( 23 \leq r_y \leq 28 \) µm. The average striation spacing for the young dentin is nearly three times this distance. As the dentin of senior patients does not exhibit yielding behavior, the inelastic zone is very small. Hence, the development of striations in dentin does not appear to be solely dependent on a near tip inelastic zone. An earlier estimate of near-tip deformation in the

**TABLE IV. Striation Spacing (Dominant Wavelength) on the Fracture Surfaces of Young/Middle and Old Restored Dentin (crack growth in vivo)**

<table>
<thead>
<tr>
<th>Age/gender (years)</th>
<th>Dominant Wavelength (µm)</th>
<th>Age/Gender (years)</th>
<th>Dominant Wavelength (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32/M</td>
<td>59</td>
<td>60/F</td>
<td>93</td>
</tr>
<tr>
<td>42/F</td>
<td>77</td>
<td>61/F</td>
<td>95</td>
</tr>
<tr>
<td>43/M</td>
<td>65</td>
<td>75/M</td>
<td>78</td>
</tr>
<tr>
<td>Avg = 39 ± 6</td>
<td>67 ± 9</td>
<td>Avg = 65 ± 8</td>
<td>89 ± 10</td>
</tr>
</tbody>
</table>
fracture of dentin using moire interferometry estimated that the region of nonlinear deformation extended \( \sim 250 \, \mu m \) from the crack tip.\(^{12}\) The estimate for \( r_y \) does not describe the secondary zone of nonlinear elastic deformation about the crack, which is undoubtedly much larger due to the viscoelastic behavior of dentin.\(^{35}\) Therefore, it appears that the development of fatigue striations in both young and old dentin may be assisted by viscoelastic deformation.

In most materials the fatigue crack growth rate estimated from macroscopic crack length measurements is in agreement with the growth rate estimated from microscopic (striation spacing) measurements,\(^{30}\) assuming that each cycle resulted in a new striation. A comparison of the fatigue crack growth rate in the CT specimens obtained using both approaches is shown in Figure 6. The difference between these two estimates indicates that the striations are not formed every fatigue cycle, but rather are associated with a period of cyclic loading. To further understand this process, an estimate of the number of fatigue cycles responsible for each striation was performed using previously reported results for average crack growth rates (Table I) and the striation spacing (Table III). Briefly, the striation spacing \((\Delta \alpha)\) was used with Eq. (1) to estimate the period of cyclic loading \((\Delta N)\) responsible, over the permissible range of driving force \((\Delta K)\). The range in fatigue cycles required for crack extension equivalent to the average striation spacing is shown in Figure 7 for both young and old dentin. For a \( \Delta K \) of \( 0.80 \, MPa \cdot m^{0.5} \), \( \sim 100 \) kcycles were required to extend the crack a distance of one striation in young dentin. At the same \( \Delta K \), an extension of one striation in the old dentin required only 4 kcycles. The larger

Figure 6. Estimates for the fatigue crack growth rate from macroscopic measurements (during loading) and from striation spacing assuming that each striation developed as a result of a single cycle. Growth response is for a CT specimen of young (male, 17-years-old) dentin.

Figure 7. The number of cycles required for a crack to extend a length equivalent to the dominant striation spacing.

Figure 8. Striations and evidence of microcracking along adjacent peritubular cuffs. Arrows in (b) indicate a ridge/step (bifurcation of crack) formed because of microcracking (crack growth is from left to right).
number of cycles required for subsequent striations in young dentin must be attributed to differences in the relative potency of the participating toughening mechanisms, particularly those contributing to the blunting behavior.

High magnification SEM images of the fracture surfaces showed evidence of distinct ridges (steps) at the striation boundary [Fig. 8(a)] with a comparatively high concentration of microcracks extending between the peritubular cuffs [Fig. 8(b)] at these locations. The microcracks on the fracture surface followed the striation root and appeared a short distance (1–5 µm) in front of the striation marks. They serve as a potential source for bifurcation and/or an alternate path of crack extension. Both the generation and presence of these microcracks results in energy dissipation near the crack tip (i.e., toughening) and hence retardation of the crack growth rate. Within the blunting zone, bridging of the crack by collagen fibrils and/or hydraulic processes likely facilitate crack growth retardation and promote extension along alternate paths. Crack growth appears to proceed at an oblique orientation consistent with the plane of maximum shear stress in the fracture surface shown in Figure 8(b). Further cyclic loading enables the crack to extend outside of this region and develop adequate energy for another increment or “burst” of extension in a direction perpendicular to the tubule orientation, i.e., the orientation with lowest fracture toughness.21

At first glance the striations may seem to develop from unbroken ligaments spanning the crack. However, previous work on ligaments in the fracture of dentin and bone has shown that they are not continuous throughout the sample thickness.22,36 Also, microscopic analysis of the CT specimens [e.g. Figure 3(a)] showed that in most cases striations extended across the entire specimen thickness. A crack extending in a young dentin CT specimen is shown in Figure 9(a) with magnified views of ligaments of dentin [Figure 9(b)] and collagen fibrils [Figure 9(c)] spanning the crack. As evident in Figure 9(b), there are ligaments of dentin spanning the primary crack with spacing that is not consistent with the striation periodicity. Thus, the striations are not a direct result of fractured ligaments.

One of the primary objectives of the investigation was to compare striations on fracture surfaces resulting from crack extension in vitro and in vivo. The comparison showed that the striations resulted from crack growth in both environments, that their features were similar and that there was an increase in the striation spacing with patient age. Although the driving force responsible for crack extension in vivo was not known, the “apparent” stress intensity range responsible for crack extension in vivo can be estimated according to results of the in vitro experiments using the striations for registration. At a stress intensity range of 0.80 MPa m^{0.5}, the average Bates-Clark number for fatigue crack growth in the young and old CT specimens was 5.53E04 ± 0.79E04 and 8.16E04 ± 1.43E04, respectively (Table III). Using Eq. (4), and assuming that the elastic modulus of the tissue was equivalent in both environments (in vivo and in vitro), the apparent ΔK for cracks in the

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Figure 9. Mechanism of crack extension in a dentin CT specimen (male, 19-years-old). (a) fatigue crack originating from the notch; (b) ligaments bridging the crack (white arrows) near the apparent tip; (c) collagen fibrils (black arrow) spanning the crack in Region II behind the crack tip.
restored teeth from the senior patients is 0.68 MPa-m^{0.5}. Note that the stress intensity thresholds for old dentin have been estimated to be ~0.60 MPa-m^{0.5}. Therefore, the estimated apparent driving forces for the restored teeth are reasonable. If the striation spacing for the restored teeth comprised of young and middle aged patients are combined (Table IV) and used with growth rate responses for young dentin (Tables I and III), the apparent ΔK is 0.7 MPa-m^{0.5}. Using the estimates of ΔK in Eq. (5) for a crack length of 1 mm and a geometry factor of unity (F = 1), the average stress range (Δσ) for the restored teeth is 12.3 ± 0.7 MPa. This value is well within the estimates for stresses in restored molars from numerical models simulating the effects of mastication and thermal loading. The aforementioned estimates for Δσ and ΔK in the restored teeth are the first, and to the author’s knowledge, the only estimates for these parameters that have been reported for restored teeth originating from physical evidence.

The present study provided new findings on the mechanisms of cyclic crack extension in dentin and the mechanics of fatigue crack growth in restored teeth. Nevertheless, there are some obvious limitations. The comparison of in vitro and in vivo crack growth did not consider the potential differences in frequency of cyclic loading and stress ratio in the two environments. Estimations for the apparent ΔK and Δσ in the restored teeth were based on results from the CT specimens obtained with stress ratio of 0.1 and frequency of 5 Hz. In dentin there is a decrease in fatigue crack growth rate with increasing frequency and an increase with increasing stress ratio. Also, the maximum cyclic load applied to the CT specimens was consistent over the entire growth history and it is unlikely that oral conditions resulted in a constant cyclic load range within the restored teeth. Lastly, the experiments were conducted at 22°C whereas crack growth in the restored teeth is expected to have occurred over a range of oral temperatures. As such, the estimates for ΔK and Δσ in the restored teeth should be considered first order approximations. Nevertheless, the consistency in fracture surfaces of the CT specimens and restored teeth indicate that the in vitro approach used to examine cyclic crack extension is a viable model for evaluating both the mechanics and mechanisms of crack extension in tooth tissues and that fatigue crack growth is a major contributor to restored tooth fracture.

CONCLUSIONS

An experimental evaluation of striations resulting from fatigue crack growth in dentin was conducted. The effects of age were considered through an evaluation of tissue obtained from the molars of patients representing two age groups. According to an examination of fatigue striations resulting from in vitro experiments and in vivo extension, the following conclusions were drawn:

1. Fatigue crack growth striations were identified on fracture surfaces of CT specimens of coronal dentin and on fracture surfaces from restored teeth. The striations are believed to be a result of blunting and subsequent resharpening of the crack tip.
2. The average striation spacing for the CT specimens of young dentin was 88 ±13 μm and was significantly smaller (p < 0.001) than that in old dentin (130 ± 23 μm). The larger striation spacing on fracture surfaces of dentin from senior patients suggests that aging suppresses the mechanisms that contribute to blunting of the crack tip.
3. The average striation spacing in the restored teeth of young/middle age patients (67 ± 9 μm) was significantly (p < 0.05) smaller than that for the senior patients (89 ± 10 μm). The characteristics and primary wavelength of striations on the fracture surfaces of restored teeth were consistent with those resulting from in vitro experiments and suggests that tooth fracture is indeed a result of fatigue and fatigue crack growth.
4. The estimates for crack growth rate from microscopic measurements of striation spacing were more than three orders of magnitude larger than the macroscopic measurements and true growth rate. The difference indicates that fatigue striations in dentin do not develop every fatigue cycle.
5. The average Bates-Clark numbers for young and old dentin were 5.53E +04 and 8.16E +04, respectively. Using these numbers, the stress intensity range for crack growth in vivo was ~0.7 MPa-m^{0.5} and the corresponding stress range was ~12 MPa.

REFERENCES


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