The effects of tubule orientation on fatigue crack growth in dentin

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Abstract: The fracture of restored teeth is a significant obstacle to lifelong oral health. Recent studies suggest that fatigue cracks originate at flaws introduced during cavity preparation and that fatigue crack growth is a principle cause of restored tooth fractures. In this study, the rate of fatigue crack growth in bovine dentin was estimated under mode I cyclic loading. Double cantilever beam (DCB) specimens were obtained from bovine molars and subjected to high cycle fatigue loading ($10^5 < N < 10^6$). The fatigue crack growth rates were measured and used to estimate the crack growth exponent and coefficient according to the Paris Law. The average fatigue crack growth exponent was $4.7 \pm 0.6$ for crack growth parallel to the dentin tubules, which was significantly larger than $4.3 \pm 0.5$ for crack growth perpendicular to the tubules ($t$-test, CI $> 80\%$). Although the crack growth rates varied considerably, there was no significant dependence on tubule orientation or tubule density. However, specific features of the fracture surfaces and tendencies for crack curving away from the tubules suggested preferential fatigue crack growth parallel to the dentin tubules. Results from this study are being used to guide an experimental investigation of fatigue crack growth in human dentin. © 2003 Wiley Periodicals, Inc. J Biomed Mater Res 67A: 78 – 86, 2003

Key words: crack; dentin; fatigue; fracture; tubule; restoration failure

INTRODUCTION

The long-term success of dental restorations is often limited by recurrent caries, cavo-surface margin adhesion, and tooth fracture. Despite marked improvements in restorative practices and materials in the last century, the likelihood of restored tooth failure remains between 33 and 40%.1–4 With increasing numbers of dentate adults, more effective restorative methods are required to maintain the permanent dentition and facilitate life-long oral health.

Several independent studies have shown strong correlations between tooth fracture and dental restorations. Gher et al.5 reported a clinical survey of 100 fractured teeth in which 92 cases involved teeth that had been previously restored. In a study of 102 cracked teeth, Cameron6 reported that only five were unrestored. Similarly, Eakle et al.7 examined 206 fractured posterior teeth and found that $>93\%$ had been previously restored. Though not the most common cause of restoration failure, tooth fracture may be the most undesirable as it often results in subgingival cracking and may require total tooth extraction.5 Many studies have evaluated the fracture resistance of molars with composite and amalgam restorations in vitro. Although some investigators discovered that composites provide greater resistance to tooth fracture,8,9 others contend that the cavity preparation sacrifices the tooth’s integrity and that the fracture resistance is predominantly independent of restoration material.10 Clinical evaluations of posterior teeth with composite restorations have shown an incidence of tooth fracture nearly equivalent to that of teeth with amalgam restorations.11

Based on the prevalence of restored tooth fracture, the fracture toughness ($K_{IC}$) of enamel and dentin has been studied.12–16 El Mowafy et al.14 found the $K_{IC}$ of human dentin to be $\sim 3.0 \text{ MPa} \cdot \text{m}^{0.5}$. More recently, Iwamoto and Ruse17 reported that the fracture toughness of dentin was dependent on tubule orientation; $K_{IC}$ for crack propagation perpendicular to the tubules (1.13 MPa · m$^{0.5}$) was significantly lower than for parallel to the tubules ($\sim 2.0 \text{ MPa} \cdot \text{m}^{0.5}$). Similar to dentin, the $K_{IC}$ of enamel is reportedly dependent on...
structural orientation and ranges from 0.7 to 1.5 MPa \cdot m^{0.5}.^{16} Although these studies provide a useful measure of bulk fracture resistance, they are commonly performed using monotonic loads and ignore the cyclic nature of mastication. Arola et al.\textsuperscript{18} studied the potential for fatigue crack growth as a cause of fracture in molars with amalgam restorations. It was found that cusp fracture in molars with MOD amalgam restorations could occur within 25 years if cracks as small as 25 \(\mu\text{m}\) were introduced in the dentin along the margins. Such a flaw is well within the ranges measured for conventional diamond burrs in enamel\textsuperscript{19} and dentin.\textsuperscript{20} Furthermore, the fatigue life could be reduced to as little as 5 years if initial cracks longer than 100 \(\mu\text{m}\) were imposed.\textsuperscript{18} Therefore, fatigue crack growth could be the primary contributor to restored tooth failures.

In this investigation, the fatigue crack growth properties of bovine dentin have been studied. Bovine dentin was used as a model for human dentin because of its availability and similar structure.\textsuperscript{21,22} The rate of fatigue crack growth was evaluated in terms of the dentin tubule orientation and tubule density.

**MATERIALS AND METHODS**

**Specimen preparation**

Fully erupted maxillary molars were sectioned from the upper jaw of mature cows (1–3 years of age) within 12 h of slaughter. Special care was taken to avoid damaging the teeth during extraction. Excessive flesh was removed and each molar was examined for the presence of disease or decay. Noncarious molars were stored immediately in a calcium-buffered saline bath at 2°C and carious teeth were discarded. The teeth were then cast within a cylindrical ring using a polyester resin to provide a foundation for sectioning [Fig. 1(a)]. Primary sectioning was performed using a numerically controlled slicer/grinder (K.O. Lee Model S3818EL, Aberdeen, SD) under continuous flood coolant to minimize effects of heat and dehydration. Diamond impregnated slicing wheels with 220- or 320-mesh abrasives were used to section the teeth along the mesial-distal or buccal-lingual axis of the teeth to obtain slices with desired tubule orientation [Fig. 1(b)].

Secondary sections were introduced as necessary to form double cantilever beam (DCB) specimens (Fig. 2). A longitudinal groove 0.30 mm in width was introduced in the

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**Figure 1.** Primary sectioning of a bovine maxillary molar. (a) A molar cast in a ring fixture. Primary sectioning was conducted along the mesial distal axis after removal of the upper crown section. (b) A mesial-distal tooth section with an outline of a potential specimen location.

**Figure 2.** Double cantilever beam (DCB) specimen geometry and dimensions. (a) A completed DCB specimen. (b) Dimensions of the DCB specimen in millimeters (drawing not to scale).
specimens to channel the direction of crack growth under cyclic loading. Holes of 1.5-mm diameter were drilled in the DCB specimens using a miniaturized CNC milling machine (Dyna Myte CNC Milling Machine, Model 2400, El Segundo, CA) and high-speed steel drill bits. The holes enabled application of cyclic opening loads through 1.4-mm load pins, similar to a standard compact tension (CT) specimen. The notch tip of each specimen was sharpened using a razor blade and 9-μm diamond paste. Sharpening of the notch facilitated stable crack initiation.

Fatigue crack growth

The dentin specimens were subjected to zero-to-tension opening (Mode I) loads, using a universal testing system (EnduraTEC Model ELF 3200, Minnetonka, MN) with an electro-magnetic actuator. The unit has a maximum load capacity of 225 N and sensitivity of ±0.01 N. All specimens were submerged in a calcium-buffered saline bath at room temperature to maintain moisture content during fatigue loading. Load control fatigue was used with maximum pin loads of between 9 and 16 N and frequency fixed at 5 Hz. Sine wave loads and cyclic stress ratios \( R = \sigma_{\text{min}}/\sigma_{\text{max}} \) of 0.1 were used with all specimens. Just before loading, the expected crack path was stained with dilute silver nitrate (concentration ≤10%) to improve visual contrast between the crack and dentin. The actuator displacement was monitored visually after the beginning of cyclic loading to identify subtle changes; crack initiation was often evident through an increase in compliance. The saline bath was periodically drained (approximately every 25,000 cycles) and the notch tip was observed visually for crack initiation using a scaled optical microscope (Meopta, Model PM 60; 60x). Once a crack was evident at the razor notch, its initial length \( (a) \) was measured on the front of the specimen with the microscope and recorded. Crack illumination was accomplished via a focused white light beam oriented behind the specimen.28 Because of the relative translucence of dentin, the crack would appear bright, contrasting with the yellow/brown background of the stained dentin. 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 25,000 and 100,000 cycles. A single experiment typically lasted between 3 and 6 days, although the total elapsed time depended on the rate of crack growth, the extent of crack growth achieved, and the incidence of crack divergence or curving.

The incremental fatigue crack growth rate \( (da/dN) \) was evaluated using the Paris Law24 according to

\[
\frac{da}{dN} \bigg|_{\theta_1, \theta_2} = C(\Delta K)^m
\]

where \( \Delta K \) is the stress intensity range, and \( da \) and \( dN \) represent the incremental changes in crack length and number of cycles, respectively. The Paris Law parameters \( C \) and \( m \) represent the fatigue crack growth coefficient and exponent, respectively, which are considered material constants and are defined here in terms of the tubule orientation \( (\theta_1, \theta_2) \). The stress intensity range was estimated form the energy release rate calculated according to the opening load range \( (\Delta P) \) and the beam geometry.25 The crack growth rate \( (da/dN) \) and Paris Law parameters were evaluated with respect to the dentin tubules. The tubule orientation was defined in terms of an out-of-plane tubule angle \( (\theta_1) \) and an in-plane angle \( (\theta_2) \) relative to the fracture surface (Fig. 3). Visual measurements of tubule angle were made as a function of the two principal tubule angles using a scanning electron microscope (SEM; JEOL Model JSM-5600). The orientation angles were not known before specimen fracture. Crack growth rates for each specimen were plotted as a function of stress intensity range \( (\Delta K) \) on a log-log scale to estimate the fatigue crack growth exponent \( (m) \) and coefficient \( (C) \). A complete crack growth curve for a DCB specimen is shown in Figure 4(a); the cyclic crack growth rate \( (da/dN) \) for the specimen is shown in log-log scale in Figure 4(b). For clarity, the three primary regions of crack growth are indicated. Region I represents the onset of crack initiation, Region II corresponds to stable crack growth, and Region III represents unstable crack growth just before specimen fracture. Any data points that visually appeared part of Region I or Region III were excluded in the determination of the Paris Law parameters. A power law trendline was fit to the remaining Region II data to obtain an estimate for \( C \) and \( m \). A comparison of the fatigue crack growth parameters was conducted as a function of the tubule orientations using a Student’s \( t \)-test.

Fracture surface evaluation

According to Eq. (1), the cyclic crack growth rate was evaluated as a function of tubule orientation to identify the effects of structure on crack propagation in dentin. To determine the tubule orientation present in each specimen, the
fracture surface morphology was observed (after fracture) using a scanning electron microscope (SEM). Each specimen half was sputtered with gold palladium (after fracture) to enhance conductance of the fracture surface and then placed in an aluminum fixture for observation.

In addition to SEM observation, a contact profilometer (Hommel Model T8000, New Britain, CT) was used to analyze the surface topography of each fracture surface as a function of the tubule orientation. The average surface roughness (Ra), peak-to-valley height (Ry), skewness (Rsk), and 10 point roughness (Rz) were measured using a traverse length of 1.5 mm and cutoff length of 0.25 mm. Measurements were taken in regions where stable crack growth data was obtained in order to assure that the profile and roughness corresponded to Region II behavior.

RESULTS

Stable fatigue crack growth was achieved in 21 DCB specimens subjected to mode I fatigue loading. The fatigue crack growth rates (da/dN) from each specimen are shown in terms of stress intensity range (∆K) in Figure 5, and for comparison, the results are grouped according to similar tubule orientation. Seven of the datasets represent crack growth approximately perpendicular to the tubules [θ1 = 90°, Fig. 5(a)], and 14 datasets represent growth in plane (θ1 = 0°) with the tubules. The specimens with in-plane tubules were further classified in terms of an in-plane angle (θ2) <45° [Fig. 5(b)] or >45° [Fig. 5(c)]. The fatigue crack propagation rates for all specimens were between 8.53E-7 and 1.74E-5 mm/cycle and occurred over a range of ∆K from 1.00 to 2.16 MPa · m0.5.

Crack growth rate

A large variation in crack growth rate was observed in specimens with similar in-plane tubule orientations. Results for specimens with θ1 = 90° spanned the entire range in observed growth rates and defined the upper and lower bounds of all the experimental results. There was no significant difference in the crack growth rate between in-plane (θ1 = 0°) and out-of-plane (θ1 = 90°) tubule orientations. Crack growth rates from each θ1 orientation appear to be randomly distributed. However, the growth rates for specimens with in-plane (θ2) angle <45° were generally lower than for specimens with θ2 > 45° at a given ∆K. Growth rates for specimens with in-plane tubules θ2 > 45° are biased slightly toward higher growth rates [Fig. 5(c)]. Cyclic crack growth in specimens with out of plane tubules (θ1 = 90°) appeared least consistent, with the growth rates spanning the upper and lower bounds of all experimental growth rates [Fig. 5(a)]. The stress intensity range characterizing fatigue crack growth was notably lower for in-plane fracture when θ2 > 45° [Fig. 5(c)].

Paris Law parameters

Assuming a power law response consistent with the Paris Law (Eq. 1), the crack growth exponent (m) and coefficient (C) were determined for each specimen and are listed in Table I. The crack growth exponents ranged from 3.71 to 5.74, with a mean of 4.3 ± 0.5 for θ1 = 90° and 4.7 ± 0.6 for θ1 = 0°. These means are significantly different at a >80% confidence interval according to the Student’s t-test. Thus, the results indicate that the average crack growth exponent (m) from fracture parallel to
the tubules is higher than for perpendicular fracture. There was no significant difference in the crack growth exponent for dentin specimens with \( \theta_2 < 45^\circ \) and \( \theta_2 > 45^\circ \), despite the noted differences in crack growth rate. The overall average crack growth coefficient (C) for bovine dentin was determined to be \( 1.1 \pm 0.8 \times 10^{-6} \) (mm/cycle; MPa m\(^{0.5}\)) -\(^{m}\), with no significant dependence on tubule orientation.

Fracture surfaces

Typical SEM micrographs of fracture surfaces from the dentin specimens are shown in Figure 6. The tubule orientation and unique features attributed to the mechanisms of crack growth were very apparent on most fracture surfaces. Figure 6(a) represents a fracture surface with in-plane tubules (\( \theta_1 = 0^\circ \)), whereas Figure 6(b) displays a specimen surface with out-of-plane tubule orientation (\( \theta_1 = 90^\circ \)). In general, out-of-plane angles (\( \theta_1 \)) of \( \sim 0^\circ \) and \( 90^\circ \) were observed, with \( \theta_1 = 0^\circ \) fracture surfaces usually exhibiting an in-plane angle (\( \theta_2 \) from Fig. 3), ranging from 0 to 75\(^\circ \). Tubule diameters ranged from an average of \( \sim 2-3 \mu m \) in dense areas to nearly 5 \mu m in areas of lower tubule density [e.g., Fig. 6(c) and 6(d)]. The tubule density ranged from a high of \( \sim 30,000 \) per \( mm^2 \) to as low as 1,700 per \( mm^2 \). The low tubule densities may have resulted from tubules that were obscured by a rough, smear-like surface often accompanying fracture perpendicular to the tubules [Fig. 6(d)]. To investigate the effect of tubule density on crack growth rate, \( da/dN \) for specimens with \( \theta_1 = 0^\circ \) and \( \theta_1 = 90^\circ \) was plotted as a function of tubule density in Figure 7(a) and Figure 7(b), respectively. The crack growth rate was calculated at \( 1.6 \) MPa m\(^{0.5}\) for \( \theta_1 = 90^\circ \), and \( 1.4 \) MPa m\(^{0.5}\) for \( \theta_1 = 0^\circ \). Crack growth was extrapolated for several data sets to enable estimation of the crack growth rate at a single stress intensity range within each \( \theta_1 \) orientation. The crack growth rate appears randomly distributed [Fig. 7(a,b)] with respect to the tubule density for both orientations. As a result, no significant correlation could be made between tubule density and differences in fatigue crack behavior.

The fracture surface morphology for crack growth perpendicular to the tubules [Fig. 6(b,d)] appeared rough and more textured than that for growth in-plane with the tubules [Fig. 6(a,c)]. Surfaces from specimens with \( \theta_1 = 0^\circ \) were notably smoother and more uniform, whereas fracture perpendicular to the tubules often resulted in an irregular surface with evidence of very small areas of subcrack growth. As expected from visual observation, surface roughness measurements of the fracture surfaces revealed a significantly higher average surface roughness (\( R_a \)) for

![Figure 5](image-url)

**Figure 5.** Fatigue crack growth in the DCB specimens. (a) Seven specimens displayed fracture perpendicular to tubules. (b) Five fractured in-plane (\( \theta_1 = 0^\circ \)) with \( \theta_2 \) between 0\(^\circ \) and 45\(^\circ \). (c) Nine fractured in plane (\( \theta_1 = 0^\circ \)) with \( \theta_2 > 45^\circ \).
fracture surfaces perpendicular to the tubules ($\theta_1 = 90^\circ$) compared to fracture in-plane with the tubules ($\theta_1 = 0^\circ$). The $R_a$ for $\theta_1 = 90^\circ$ specimens was determined to be $3.97 \pm 0.79 \mu m$, which was significantly higher ($t$-test, CI $>99.5\%$) than $1.88 \pm 0.44 \mu m$ for $\theta_1 = 0^\circ$ specimens.

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*aOut-of-plane dentin tubule angle ($\theta_1$).

*bCorrelation coefficient of power law curve fit.

TABLE I
Paris Law Parameters for Bovine Dentin as a Function of Tubule Orientation

Figure 6. SEM micrographs of several fracture surfaces. (a) Fracture parallel with the tubules at high tubule density ($\times$500, bar = 50 $\mu m$, $\theta_1 = 0^\circ$, $\theta_2 = 50^\circ$). (b) Fracture perpendicular to the tubules at high tubule density ($\times$750, bar = 20 $\mu m$, $\theta_1 = 90^\circ$, $\theta_2 = 0^\circ$). (c) Fracture parallel with the tubules at lower tubule density ($\times$500, bar = 50 $\mu m$, $\theta_1 = 0^\circ$, $\theta_2 = 30^\circ$). (d) Fracture perpendicular to the tubules at lower tubule density ($\times$500, bar = 50 $\mu m$, $\theta_1 = 90^\circ$, $\theta_2 = 0^\circ$).
DISCUSSION

The fatigue crack growth rates in bovine dentin varied widely between the two primary tubule orientations ($\theta_1$) of 0° and 90°. Growth rates were expected to be higher for crack propagation perpendicular to the tubules, based on the lower $K_{IC}$ observed by Iwamoto and Ruse\textsuperscript{17} for crack growth perpendicular to the dentin tubules and on the preferential crack growth direction observed in restored molars by Arola et al.\textsuperscript{18} Nevertheless, other notable trends suggested that fatigue crack growth in dentin is orientation dependent. All crack curving occurred in specimens with (approximately) in-plane initial crack growth ($\theta_1 = 0^\circ$). Despite the longitudinal groove designed to channel the crack, the crack “preferred” an orientation of growth other than in plane with the tubules. Furthermore, many specimens with $\theta_1 = 0^\circ$ revealed small “ledges” of near perpendicular fracture (Fig. 8) that briefly occurred before the crack was redirected back in plane by the backside groove. Although the crack growth rates for specimens with $\theta_1 = 90^\circ$ were not significantly different than specimens with $\theta_1 = 0^\circ$, they did not exhibit crack curving. These observations suggest that fatigue crack growth in dentin is preferential to extension perpendicular to the tubules, although the crack growth rate was not significantly different between $\theta_1$ orientations. There may be other factors related to aging or physiological processes that reduce the fatigue crack growth resistance of dentin for $\theta_1 = 90^\circ$ preferentially. Additional research is necessary to confirm this statement.

Experimental results suggest that the crack growth rate for $\theta_1 = 0^\circ$ may be a function of in-plane ($\theta_2$) tubule angle. In Figure 6, specimens with $\theta_2 > 45^\circ$ are concentrated at higher growth rates than the response of specimens with $\theta_2 < 45^\circ$. Although there is a much larger distribution in growth rates for $\theta_2 < 45^\circ$, all crack growth rates for this orientation are slightly (or significantly) higher than $\theta_2 > 45^\circ$ specimens. Unfortunately, no clinical observations are available for comparison to this observation. The in-plane tubule angle encountered by a crack \textit{in vivo} may vary with its location. It is possible that tubules oriented at shallow angles (i.e., $\theta_2 < 45^\circ$) relative to the crack path serve to arrest the crack because of their large radius (0.5–2.0 µm) compared to the crack tip. This would result in lower crack growth rates, as observed in this study. By a similar argument, tubules oriented at sharper angles (i.e., $\theta_2 > 45^\circ$) could act as flaws that facilitate higher crack growth rates by effectively lowering the material density along the projected growth direction.

The Paris Law parameters for a material consist of a crack growth coefficient ($C$) and exponent ($m$). When available, they permit an estimation of the cyclic crack growth rate and failure resulting from fatigue. The

Figure 7. Changes in crack growth rate as a function of tubule density. (a) Specimens with fracture parallel to the tubules ($\theta_1 = 0^\circ$). (b) Specimens with fracture perpendicular to the tubules ($\theta_1 = 90^\circ$).

Figure 8. In-plane fracture surface ($\times 500$, bar = 50µm) showing a small ledge of perpendicular fracture (arrow).
value of m indicates the sensitivity of a materials’ crack growth rate (da/dN) to the stress intensity range (AK) at the crack tip.24 In general, m is lower for more ductile materials (typically around 3), and increases to above 10 for extremely brittle materials such as ceramics or concrete.26 The values of m for bovine dentin from this study were determined to range from 3.71 to 5.74, which is close to the range published for compact bone of 2.8 to 5.1.22 Chemically, dentin and bone have similar ratios of organic and mineral content, and similar collagen fiber matrices reinforced with apatite crystals. Therefore, similar fatigue behavior would not be unexpected. Within specific tubule orientations, the average crack growth exponent was determined to be slightly higher for fracture in plane with the tubules (θ₁ = 0°, m = 4.67) than for fracture perpendicular to the tubules (θ₁ = 90°, m = 4.34). There was no significant difference in m between in plane tubule angles < 45° or >45°. It was expected that dentin would exhibit a larger m for fatigue crack propagation perpendicular to the tubules, based on the reportedly lower fracture toughness.17 At present, there is no other published data on fatigue crack growth in dentin or its dependence on tubule orientation, so no direct comparisons can be made to validate these results. Future studies are needed for comparison of these results and to evaluate the Paris Law parameters for human dentin.

Many of the specimens in this study exhibited some Region III behavior before complete fracture. In theory, the Mode I fracture toughness (KIC) of dentin could be determined from the x-intercept of a vertical asymptote extending down from the region III curve immediately before fracture.26 This method assumes that the plastic zone remains small even during Region III crack growth, which is a good approximation for brittle materials (based on G.R. Irwin’s energy model). For the dentin specimens examined in this study, the extrapolated KIC ranged from ~1.3 to 2.8 MPa · m0.5, which agrees well with that reported earlier from experiments comprised of monotonic loading.27 Both the maximum and minimum of this range represent results from specimens with in-plane tubules (θ₁ = 0°). The range in KIC for dentin estimated for specimens with out-of-plane (θ₁ = 90°) tubule orientation was nearly as high (1.5–2.5 MPa · m0.5). There were no significant differences in the estimated KIC for the specimens with the two primary θ₂ orientations. Note that the fracture toughness could not be extrapolated from the results of all specimens due to instances of crack curving and arrest. In 1986, el Mowafy and Watts14 found KIC of human dentin with in-plane tubules and θ₂ ≈ 0° to be ~3.0 MPa · m0.5. More recently, Iwamoto and Ruse17 found the fracture toughness of human dentin to be 2.02 ± 0.18 MPa · m0.5 for θ₁ = 0° and θ₂ = 0°, 1.97 ± 0.17 MPa · m0.5 for θ₁ = 0° and θ₂ = 90°, and 1.13 ± 0.36 MPa · m0.5 for θ₁ = 90°. Considering the variation in published values, the range in KIC estimated from results of this study (1.3 < KIC < 2.8 MPa · m0.5) agrees quite well. Yet, the fracture toughness for θ₁ = 90° was not found to be significantly less than that for θ₁ = 0°. Overall, the fracture toughness of bovine dentin compares well with that of human dentin.

Tubule densities in this study ranged from a high of ~30,000 per mm² to a low of ~1,700 per mm². The median tubule density from this study (20,000 per mm²) is in agreement with densities published by Schilke et al.21 for the dentin of bovine incisors and also very similar to that found in the middle layer (18,781 ± 5855) and deep layer (21,343 ± 7290) of human dentin.21 Yet, many of the specimens with θ₁ = 90° appeared to have very low tubule densities, much less than those reported in other studies. The tubules may have been concealed by features of the fracture surface or by smeared dentin. Nevertheless, no significant correlation between density and crack growth rate could be made as evident from Figure 7(a,b).

Several aspects of the testing procedure and specimen evaluation could have influenced the experimental results. The resolution of crack growth measurement was limited by the magnification (and reticle) of the microscope used to monitor the crack length. Other potential sources of error include the difficulty in determining the out-of-plane tubule angle θ₁. The out-of-plane tubule angle was estimated by SEM observation of the fracture surface. However, the θ₁ angles measured in this study were visual approximations, and thus variations from the estimated values are a possible source of error as well.

In addition to experimental concerns, other contributing factors may have affected the fatigue behavior of the bovine dentin. Age of the molars used, the presence of decay, demineralization, chemical differences, and storage conditions are all considerations. Specimens were stored in a calcium-buffered saline solution to maintain moisture and mineral content, as recommended by Gustafson et al.29 However, a more recent study suggests that calcium-buffered saline allows demineralization over time, which could alter the mechanical behavior of dentin in storage.30 Similarly, the mechanisms of crack growth in human dentin may be dependent on variables such as age, disease, or masticatory habits of a particular individual. The interrelationship between the collagen matrix, tubules, and mineralized components of dentin is known to change significantly with aging and caries.31 An understanding of the corresponding changes in fatigue and fracture behavior is essential to minimizing tooth fracture and improving the effectiveness of restorative dentistry. Despite obvious limitations, this study represents one of the first fundamental evaluations on fatigue crack growth in dentin. Given the likely contributions of fatigue and crack growth to tooth fracture, results from this study will serve as a foun-
dation for further research on the mechanical behavior of dentin and tooth failure.

CONCLUSIONS

An in vitro experimental analysis of cyclic crack growth in bovine dentin was conducted. Results from this study support the following conclusions:

1. Fatigue crack growth in dentin is dependent on the tubule orientation. The rate of crack growth was not significantly different for crack growth perpendicular and parallel to the tubules. However, the direction of crack extension appeared preferential to growth perpendicular to the tubules. The crack growth rate ranged from 8.53E-7 to 1.74E-5 mm/cycle and was dependent on the in-plane tubule angle ($\theta_2$). Crack growth rates were higher for $\theta_2 > 45^\circ$ compared with $\theta_2 < 45^\circ$.

2. The average Paris Law parameters for bovine dentin were determined to be: $C_{90} = 1.0E-6 \pm 9.9E-7$, $m_{90} = 4.3 \pm 0.5$ for crack growth perpendicular to the tubules; $C_{0} = 1.2E-6 \pm 7.6E-7$, $m_{0} = 4.7 \pm 0.6$ for crack growth parallel to the tubules. The in-plane tubule angle ($\theta_2$) did not have a significant effect on the Paris Law constants.

References