Experimental and numerical studies for nondestructive evaluation of human enamel using laser ultrasonic technique

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In this paper, a nondestructive laser ultrasonic technique is used to generate and detect broadband surface acoustic waves (SAWs) on human teeth with different demineralization treatment. A scanning laser line-source technique is used to generate a series of SAW signals for obtaining the dispersion spectrum through a two-dimensional fast Fourier translation method. The experimental dispersion curves of SAWs are studied for evaluating the elastic properties of the sound tooth and carious tooth. The propagation and dispersion of SAWs in human teeth are also been studied using the finite element method. Results from numerical simulation and experiment are compared and discussed, and the elastic properties of teeth with different conditions are evaluated by combining the simulation and experimental results. © 2013 Optical Society of America

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1. Introduction

Dental caries (tooth decay or lesion), which is the primary cause of oral pain and tooth loss, is one of the most predominant diseases in which the hard structure of the tooth is gradually destroyed. People are susceptible to this disease throughout their lifetime. It can be arrested and potentially reversed in its early stages, but is often not self-limiting and without proper care, caries can progress until the tooth is destroyed [1]. In their early stages, dental caries appear in the form of opaque and white spots on the surface of enamel, which are called white spot lesions (WSLs). Therefore, it is very important to identify WSLs for early treatment. WSLs are initiated by excessive mineral dissolution of the dental enamel, known as demineralization, which is caused by erosion of plaque bacteria. However, the WSL and the level of enamel demineralization are difficult to detect with traditional clinical methods (visual and tactile assessments) and radiographic methods [2–4]. The elastic modulus of dental hard tissue directly reflects the mineral content in teeth. At present, many methods can be used to measure the elastic modulus of teeth, such as nanoindentation, scanning electron microscopy, and strain sensors [5–7]. But all these methods can only be applied to extracted teeth and are difficult to use in clinical measurement, because they cannot non-destructively evaluate the elastic constants of enamel and they are contact detection methods.

Ultrasonic surface acoustic waves (SAWs) have been widely used in the field of nondestructive evaluation (NDE) for determining the elastic modulus of many kinds of materials, such as thin films,
functional-graded materials (FGMs), and surface materials [8–10]. The propagation velocity of the SAW is particularly sensitive to the elastic properties of all the materials layers it probes. A SAW is dispersed and its velocity varies with frequency in a complex inhomogeneous structure, such as an FGM, a multilayer system, and so on [8–12]. Through determining the velocity at different frequencies, a dispersion curve of SAW can be obtained to evaluate the elastic properties of dental enamel and determine the state of the enamel demineralization.

Contact transducers, which are usually made of piezoelectric materials, are used to generate and detect ultrasound waves in conventional methods. The conventional ultrasonic techniques are mainly used to measure the velocity of the ultrasonic wave [13–15] and the internal structure of human teeth, such as the thickness of dental enamel [16–20]. But the tooth is too small to generate and detect SAWs on the surface through contact transducers: size limits spatial resolution, without proper coupling the energy of the acoustic wave is difficult to transfer into the tooth, surface preparation of teeth is sometimes required, etc. All these drawbacks make in vivo measurements impossible. In addition, the SAW generated by the transducer is narrow-bandwidth. Consequently, it is difficult to evaluate the elastic properties of teeth through a SAW, which is generated by conventional methods.

The laser ultrasonic (LU) technique [21–26], which is a new NDE method in recent years, generates ultrasonic waves using a laser and detects ultrasonic signals using a laser detector. The LU technique has many advantages, which can make it a potential NDE method for dental clinical application. Laser beams can be focused onto small objects or samples with intricate shapes and provide better spatial resolution. The LU technique can perform excitation and detect SAWs without contact and with remote control, the laser energy can be maintained at a low level to ensure nondestructive thermoelastic operation, and the technique can generate high-frequency (broadband) ultrasounds that make it a very good method for materials’ property evaluation. It can also perform online testing depending on its high signal-processing speed. Blodgett [27] has used the LU technique to determine the characterization of the internal structure of teeth. Wang and co-workers [25,28,29] have performed some qualitative experimental research studying the evaluation of the Rayleigh velocity of the human tooth using the LU technique and the narrowband SAW technique. All these above works and their advantages show that the LU technique is a potential NDE method that can be used for evaluating the elastic properties of in vivo teeth in clinical treatment.

In this paper, the finite element method (FEM) [26,30–32] is used to numerically simulate the SAW propagating in human teeth with different severity lesions. In the experiment, the scanning laser line-source (SLLS) technique is used to nondestructively generate a SAW on human sound teeth and carious teeth with different severity lesions. A series of equally spaced SAW signals are detected by a laser-Doppler vibration meter and used for determining the dispersion curves through a two-dimensional fast Fourier translation (2D-FFT) method. The dispersion curves are obtained for evaluating the elastic properties of human teeth. The numerical simulation and experimental results are presented and discussed. The results demonstrate the potential of the LU NDE technique for future clinical tests.

2. Physics Model and Calculation Theory

Human teeth mainly consist of enamel, dentin, pulp, spongy bone, and periodontal ligament. The outermost layer of dental coronas is the hardest and most mineralized tissue of human body-enamel, which is made up of 8%–12% water, 85%–95% hydroxyapatite, and 2%–3% proteins and lipid [33]. The thicknesses of both enamel and dentin in different teeth and even at different positions of the same tooth are different. Dentin is surrounded by enamel, and there are many dentin tubes inside of it. In the incisor, the thicknesses of enamel and dentin are about 0.8–1.5 mm and 2–3 mm, respectively, and in the molar, the thicknesses of enamel and dentin are about 0.9–1.7 mm and 3–4 mm, respectively. Pulp is made up of nerves, blood vessels, and lymphatic. Although teeth have different shapes, their basic structures are approximately the same. The FEM is used to simulate laser generating SAW and the propagation of SAW on human teeth with different severity lesions. The finite element model is constructed based on the extracted human incisor tooth. Because the lip surface of the incisor is smooth and flat, in this region, the thickness and materials properties of enamel and dentin can be treated as approximately homogeneous materials with two layers. The pulp can be regarded as empty because of its structural characteristics. The physical model is shown in Fig. 1.

The model is constructed with 10 mm width (L) and 4 mm depth (H); the upper layer is enamel and the substrate is dentin. The thickness of the enamel layer \( H_{\text{enamel}} \) is 1 mm. The enamel and dentin are regarded as isotropic materials. The width of the caries region is 2 mm, and the depth is changed with the corrosion degree.

![Fig. 1. Physics model of SAW propagating on human tooth.](image-url)
By the thermoelastic mechanism, the SAW can be excited nondestructively on the surface of enamel using a pulsed laser. This process includes not only the transient thermal diffusion, but also the excitation of transient elastic waves and their transmission in a limited space. To describe the laser generation of ultrasound in the thermoelastic mechanism, one must solve simultaneously the heat equation and the acoustic wave equation. The classical thermal conduction equation can be described as

$$\rho_i c_i \frac{\partial T_i}{\partial t} = \frac{\partial}{\partial x} \left( k_i \frac{\partial T_i}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_i \frac{\partial T_i}{\partial y} \right) + Q, \quad i = e, d,$$

where $T_i(x,y,t)$ represents the temperature distribution at time $t$, and $\rho_i$, $c_i$, and $k_i$ are the density, the thermal capacity, and the thermal conduction coefficient, respectively. And $i = e$, $d$, where $e$ and $d$ represent enamel and dentin, respectively. $Q$ is for the heat source. Due to the optics penetration effect, the laser will irradiate into enamel by a certain depth, whose laser energy absorption will attenuate exponentially along with the laser irradiation depth. The heat source $Q$ is shown as follows:

$$Q = \beta (1 - R - T) I_0 e^{-\rho_0 x} \frac{x}{x_0} e^{-\left(\frac{x^2}{2 \sigma_0^2}\right)} \frac{t}{t_0} e^{-\left(\frac{t^2}{2 \sigma_0^2}\right)},$$

where $\beta$ represents enamel’s optic absorption coefficient, and $R$ and $T$ represent enamel’s optic reflectivity and transmissivity, respectively. $I_0$ represents the peak power density in the irradiation center, $\sigma_0$ represents the half-siding of Gaussian line-source lasers, and $t_0$ represents the rise time of the laser pulse. The boundary is regarded as thermally insulated as having a perfect thermal contact at the interface. The initial temperature is 293 K. When laser impulse irradiation energy is smaller than the melting damage threshold, heat absorption will lead to partial heat expansion, producing a transient displacement field. Acoustic wave propagation satisfies the Navier–Stokes equation

$$\frac{1 - \nu_i}{(1 + \nu_i)(1 - 2\nu_i)} \nabla \cdot \mathbf{U}_i - \frac{E_i}{2(1 + \nu_i)} \nabla \times \nabla \times \mathbf{U}_i - \frac{\alpha_i}{1 - 2\nu_i} \nabla T_i(x,y,t) = \rho_i \frac{\partial^2 \mathbf{U}_i}{\partial t^2},$$

where $\mathbf{U}_i$ denotes the displacement vector field, $\alpha_i$ is the thermoelastic expansion coefficient, $\rho_i$ is the density, and $E_i$ and $\nu_i$ are the elastic modulus and Poisson ratio, respectively. And $i = e$, $d$, where $e$ and $d$ represent enamel and dentin, respectively. The upper surface is regarded as a free boundary. Meanwhile, stress and displacement are continuous between layer interfaces. The boundaries of the left and right sides are set as low reflection boundaries for reducing the reflected waves.

The thermodynamics parameters of enamel and dentin are given in Table 1.

For simulating the influence of the WSL on wave propagation properties, the materials in the middle of the enamel layer are defined as caries regions (as shown in Fig. 1). The width of the WSL is 2 mm. The early caries’ elastic properties are mainly reflected by the elastic modulus. For simplicity, the distribution function of the elastic modulus and the depth of the WSL region in the enamel layer can be expressed as follows:

$$E(y) = \begin{cases} a \cdot y + b, & (4 \text{ mm} \leq y \leq 6 \text{ mm}, 0 \leq y \leq H_{\text{caries}}); \\ E_{\text{enamel}} - (others); \\ \end{cases}$$

$$\begin{align*}
H_{\text{caries}} &= (1.25 - 1.25\omega)H_{\text{enamel}} \\
0.2 \leq \omega &\leq 1.
\end{align*}$$

where the $E_{\text{enamel}}$ is the elastic modulus of enamel, $H_{\text{enamel}} = 1 \text{ mm}$, $H_{\text{caries}}$ is the depth of caries, and $\omega$ is defined as the coefficient of demineralization. When $y = 0$, the elastic modulus of caries at the surface is equal to $\omega \cdot E_{\text{enamel}}$, and when $y = H_{\text{caries}}$, the value is $E_{\text{enamel}}$. Then the elastic modulus of caries is continuously changed with $y \cdot \omega$ represents the corrosion degree of carious teeth. The smaller $\omega$ is, the larger the corrosion degree is, and the deeper the carious region is.

In the course of ultrasound wave generation by the interaction between lasers and human teeth, the heat and displacement fields, which are transient and coupling with each other, are solved by the FEM. The FEM is a numerical calculation method for solving partial differential equations, and can obtain the numerical solutions of the whole field. It can set up thermoelastic coupling differential equations based on the principle of virtual work, and solve the equations after dispersing equivalent integration of differential equations in spatial domains. The FEM is used to calculate the propagation properties of the SAW, which is generated by lasers. During the calculation, selection of element sizes and time step has a direct

<table>
<thead>
<tr>
<th>Table 1. Thermodynamics Parameters of Enamel and Dentin in Human Tooth [34]</th>
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<tr>
<td><strong>Elastic Modulus (GPa)</strong></td>
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<tr>
<td>Enamel</td>
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<td>Dentin</td>
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effect on calculation accuracy and the center frequency of the structural response. In the simulation, the time step is 0.5 ns, and the total number of time steps is 6000. For spatially resolving the propagating waves, the element size should be fine enough. So the element size is 20 μm. Detailed calculation methods of the FEM and selection of parameters such as time step are explained at length in [26,31,32].

3. Experimental Measurement Setup and Methods

A. Sample Preparations and Method
Among the various teeth, the incisor is a better choice for initial studies because its front surface has the largest flat area of enamel. In addition, the thickness of enamel is relatively constant (~1 mm) over a wide region near the center of the incisor lip face. In molars, the uneven thickness of enamel and the different surface curvature will influence the dispersion curves of the SAW. So for eliminating these influences on the dispersion curves, the incisors were chosen as samples rather than molars. Experimental research studying SAWs propagating in molars with WSLs will be the subject of our future work. However, it is unusual for a natural lesion to occur on the lip surface of an incisor, so artificial WSLs are created for experimental study. The artificial WSL, which is similar to the natural WSL, has been widely used for replacing natural lesions in dental research [28,35]. An extracted sound human incisor is selected for the experiment and fastened to a translation platform.

For reducing as much as possible the influence on SAW dispersion of the different morphology structures of different teeth, the experiment is performed only on the one tooth at different demineralization conditions. The measurements are made along the tooth axis as shown in Fig. 2. First, the incisor with sound condition, which is named tooth-1, is scanned by the laser line source, and the detection ultrasonic signals are recorded. Then, the tooth is coated with a protective layer of gummed paper while leaving windows of about 4 × 2 mm exposed. For creating artificial WSL by demineralization, the exposed windows of the tooth are coated with some gels, which contain 30% volume fraction of H₃PO₄. The incisor is treated for 5 min and then cleaned without anything on the surface. At this condition, the tooth is named tooth-2 and is used to perform the next experiment. Lastly, the tooth is treated for another 5 min at the same regions for deep demineralization. This treated incisor is named tooth-3. In the experiments of three conditions, the laser line source and the detection laser always irradiate at the same place on the incisor surface (as shown in Fig. 2). The SAW signals are detected and recorded at each condition. By doing this, the changes in the SAW dispersion are only dependent on the elastic modulus variation, which arises from demineralization.

B. Experimental System
We built an experimental system for detecting SAW generation using a scanning laser source in human teeth. Figure 3 shows a schematic of the laser NDE system for SAW measurements. A pulsed laser source with a wavelength of 266 nm and 7 ns duration is generated by a Nd:YAG laser. And the repetition rate of the laser source is 10 Hz. The laser source is reflected and focused into a thin line after a 266 nm reflector and a cylindrical lens, which are placed on a precise motorized translation platform for scanning the line source. The line-source dimension is measured to be ~3 × 0.08 mm, and the laser pulse energy is ~2 mJ. For getting the peak power density at the excitation spot (Ppeak), two energy probes were used to measure the energy of the laser beam (E1) reflected by a beam splitter and the energy of the laser irradiated on teeth (E2), respectively. The energy ratio \( r = E_2/E_1 \) of these laser beams can be calculated, and by measuring the energy \( E_1 \), we can calculate the energy of the laser beam that is irradiated on the teeth in real time. The peak power density \( P_{\text{peak}} \) can be calculated as

\[
P_{\text{peak}} = \frac{E_2}{\Delta t \cdot \Delta S} = \frac{r \cdot E_1}{\Delta t \cdot l \cdot w}.
\]

where \( \Delta t \) is the pulse duration of the source laser, \( \Delta S \) is the area of the line source, and \( l \) and \( w \) are the length
and width of the laser source, respectively. In this paper, \( E_1 = 1 \text{ mJ}, \ r = 0.9, \ \Delta t = 7 \text{ ns}, \) and \( \Delta S = l \cdot \omega = 3 \times 0.08 \text{ mm}^2, \) so the calculated \( P_{\text{peak}} \) at the excitation spot is about 53 MW/cm². Reducing the linewidth can increase the bandwidth of the generated SAW, but this will also increase the energy density of the irradiating laser at the same time. According to the studies by Wang et al. [28], for not damaging the enamel, the \( P_{\text{peak}} \) is controlled under 100 MW/cm² to ensure that the ultrasonic wave is generated in the thermoelastic mechanism and our experiments are nondestructive. A photodiode with a rise time of \( \sim 100 \text{ ps} \) receives the laser beam reflected by a beam splitter and triggers the TDS3054B digital oscilloscope to record signals.

The generated SAW signals with a wide frequency bandwidth are detected by a laser-Doppler vibration meter (Polytec OFV-5000 and OFV-50X). A 633 nm continuous-wave laser is generated by the laser probe and reflected by a triple prism, and then irradiates on a point of the tooth surface. The average power of the probe laser is not larger than 1 mW. This precision optical transducer is based on optical interference and the Doppler effect, sensing the frequency shift of backscattered light from a moving surface. The optical system is packaged in the sensor head. The preamplifier and signal decoder modules are assembled in the controller. The displacement of the ultrasonic wave with high signal-to-noise ratio (SNR) can be detected and processed by the sensor and controller. It can determine the vibration velocity and displacement of the ultrasound wave at a fixed point of human teeth. With a wide frequency range from 0 to 24 MHz, the vibrometer can be used to detect the SAW with a wide bandwidth, which is below 20 MHz. The output of the vibrometer is passed to the oscilloscope for recording the ultrasonic signals. The multiple waveforms of ultrasound waves are averaged 128 times to improve the SNR.

The SLLS technique is used to excite a series of SAW signals for dispersion analysis. The scanning direction is parallel to the propagation direction of the generated SAW, and is perpendicular to the line source. At the initial moment, the laser line source is 4 mm away from the detection point, which is not removed, and then scans close to the detection point. The scanning distance is 3 mm, and every step is 0.05 mm. SAW signals are recorded at every step.

C. Determining the Dispersion Spectrum of SAW

To determine the dispersion curve, a series of generated surface waves from numerical simulation or experiment are measured through scanning the laser line source with equal steps along the propagation path.

The recorded signals are band-pass filtered (0.1–25 MHz) to reduce the low- and high-frequency noise. A method that involves a 2D Fourier transformation of the time history of the recorded waves is used to obtain the dispersion curve of the SAW. The 2D Fourier transformation method [36] is an extension of the one-dimensional (1D) phase spectrum method, and it converts a signal from the time \((t)\)–space \((x)\) plane to the frequency \((f)\)–wavenumber \((k)\) planes through the equation as follows:

\[
H(k,f) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} u(x,t)e^{-i(kx+ft)} dx dt.
\]

where \(u(x,t)\) is the time–space plane signal of the SAW, and \(\omega\) is the angular frequency. Then the amplitudes and wavenumbers of individual modes may be measured.

For analyzing the SAW signals from numerical simulation or experiment at discrete times, the discrete 2D FFT may be defined in a similar way to the 1D FFT. A detailed description of the procedure involved to obtain the dispersion curves is given as follows. First, an array (in column order) was created from experimentally or numerically gaining the time histories of the ultrasonic waves received at a series of equally spaced positions along the propagation path. Second, a temporal Fourier transform of each column was carried out to obtain a frequency spectrum for each position. At the stage, an array with the spectral information for each position in its respective column was obtained. Then, we carried out a spatial Fourier transform of each row formed by the components at a given frequency to obtain the amplitude-wavenumber-frequency information. By using the 2D-FFT method, the results of this transformation will be a 2D array of amplitudes at discrete frequencies and wavenumbers. Finally, the velocities of the SAW can be calculated according to the relation \(\nu(f) = 2\pi f / k(f)\), where \(k(f)\) is the wavenumber value of the maximum amplitude at each discrete frequency. Window functions such as the Hanning window may be used to reduce leakage, and zeros may be padded to the end of the signal to enable the frequency and wavenumbers of the maximum amplitude to be determined more accurately. Alleyne and Cawley [36] studied the numerical and experimental results to measure the dispersion curves of Lamb waves propagating in three different thicknesses of steel plates. The results show that the agreement with the theoretical curve is excellent, the maximum error being less than 1%. They demonstrate that the dispersion curves of SAW can be obtained accurately through the 2D-FFT method.

4. Results and Discussion

A. Numerical Results of the Heat Effect of Laser Ultrasound on Human Teeth

To generate SAW efficiently, the source laser needs to be strongly absorbed by enamel, such that more incident radiant energy can be converted into elastic-wave energy. Efficient SAW generation depends upon the enamel’s absorption characteristics at the optical wavelength of the pulsed laser. In enamel, UV light is well absorbed, and the hydroxyapatite has strong absorption peaks in the \(\sim 7 \mu m\) and
9–11 μm regions due to the carbonate and the phosphate groups in its mineral structure, respectively [33,34,37].

A Q-switched pulsed Nd:YAG laser is usually used to generate ultrasonic waves on the sample. The optical parameters of enamel at different laser wavelengths of the Nd:YAG laser are shown in Table 2. With its high absorption, low reflectivity, and transmissivity, the 266 nm pulsed laser is used to generate ultrasonics on the surface of human teeth in simulation and experiment. In the simulation, the excited laser impulse width is 7 ns, the maximum power density is $10^8$ W/cm$^2$, and the width of the focusing line source is 80 μm.

The initial temperature of the tooth is 293 K. The transient temperature field of the tooth is studied when impulse laser irradiation impacts the surface of the tooth. Figure 4 shows the temperature increase of the tooth inside when lasers irradiate the tooth surface. Owing to the optical penetration effect, the laser irradiates into the inside enamel by a certain depth and is absorbed by the medium, producing an inhomogeneous temperature field. In the direction of $y$, the temperature quickly increases to 313 K within about 80 ns at the center of irradiation on the tooth surface. The temperature rise of the tooth surface is too low to damage the enamel. And the temperature rise approximately reaches zero below the enamel surface by about 0.20 mm. Since typical enamel is about 1 mm thick, almost no temperature increase exists in the dentin inside enamel, which will not damage dentin. But because of the low thermal conductivity in enamel, the temperature decreases slowly—only a 1 K decrease within 30 μs. Rapid temperature increase of partial areas leads to its heat expansion, and the restraint of the surrounding medium results in the distribution of stress, so acoustic waves induced by the impulse laser are generated in solids.

B. Numerical Simulation and Experimental Results of SAW Propagating in Human Teeth with Different Severity Lesions

On the basis of the theories and finite element model described earlier, SAWs generated by 266 nm pulsed laser line sources in human teeth are simulated. Ultrasonic waves propagating in sound teeth ($\omega = 1.0$) and carious teeth with different corrosion degrees ($0.2 \leq \omega \leq 1.0$) are simulated. Figure 5 represents the time domain waveforms of ultrasonic waves, with different distances away from the laser source, propagating in sound teeth and carious teeth with $\omega = 0.6$.

In Fig. 5, the surface skimming longitudinal wave $L$ arrives first, and then comes the SAW. And it is obvious that the velocity of the surface skimming longitudinal wave and the SAW in the sound tooth [shown in Fig. 5(a)] is faster than that in the carious tooth [shown in Fig. 5(b)]. The calculated average velocities of the surface skimming longitudinal wave and SAW are $\sim 6480$ and $\sim 3250$ m/s, respectively, in enamel of sound teeth. And in WSL regions of carious teeth with $\omega = 0.6$, the average velocities are $\sim 6250$ and $\sim 2890$ m/s. As propagation distance increases, the distance between the surface skimming longitudinal wave and the SAW becomes bigger, and the dispersion of the SAW in carious teeth becomes more obvious.

In experiment, an incisor is used as a tooth sample because its front surface has a large flat area of enamel. The first measurement is performed on the center surface of tooth-1, which is a sound incisor. The laser line source moves from 4 to 1 mm away from the detection point in 0.05 mm/step in order to achieve scan. A series of ultrasonic waves generated by the SLLS technique are detected on a fixed point of enamel. The signals are averaged 128 times and band-pass filtered (0.1–25 MHz) for increasing the SNR. The waveforms of SAW in tooth-1 are shown in Fig. 6(a). The average velocities of the surface skimming longitudinal wave and SAW are $\sim 6395$ and $\sim 3238$ m/s. And the velocity of SAW in enamel of the sound incisor is close to $3100–3200$ m/s, reported by Peck et al. [13], and $3143 \pm 51$ m/s, reported by Raum and Brandt [14].

On the center surface of enamel, the 4 × 2 mm artificial WSL is created by 30% H$_3$PO$_4$ gels. Tooth-2 and tooth-3, which are the same sound teeth used before, are treated for 5 and 10 min, respectively. Then, a series of SAW signals are detected and recorded. In all the experiments, the exciting and the detecting laser always irradiates on the same

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**Table 2. Optical Parameters of Enamel at Different Wavelengths of Nd:YAG Laser**

<table>
<thead>
<tr>
<th>Wavelength of Generating Laser [nm]</th>
<th>Transmissivity [%]</th>
<th>Reflectivity [%]</th>
<th>Absorption Coefficient (1/m)</th>
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<tr>
<td>266</td>
<td>0.1</td>
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<tr>
<td>1064</td>
<td>25</td>
<td>60</td>
<td>120</td>
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Fig. 4. Calculated temperature distribution in enamel for a laser pulse with pulsewidth of 7 ns and a maximum power density of $10^8$ W/cm$^2$.
position of the incisor surface. The waveforms detected on tooth-2 and tooth-3 are shown in Figs. 6(b) and 6(c), respectively. The differences of waveforms between tooth-2 and tooth-3 are very small. But comparing with the Fig. 6(a), these waveforms have obvious dispersion. The average velocities of the surface skimming longitudinal wave and SAW are $\sim 6270$ and $\sim 3108$ m/s, respectively, on tooth-2. The average velocities of the surface skimming longitudinal wave and SAW are $\sim 6195$ and $\sim 2905$ m/s, respectively, on tooth-3. The SAW velocity in tooth-3 is lower than that in tooth-2. This is because tooth-3 was treated with a long time for demineralization; the elastic properties of enamel in tooth-3 changed more than those in tooth-2.

As shown in Figs. 5 and 6, the waveform profiles of numerical simulation have good agreement with the experimental results. And the velocities of ultrasonic waves are close to the measured results. The frequency spectra of SAW signals obtained from numerical simulation and experiment in sound teeth are shown in Fig. 7. The frequency spectra can be obtained from the amplitude-frequency information using the 2D-FFT method, and the detail procedure can be seen in Section 3.C. The figure demonstrates good agreement in both the bandwidth (0–20 MHz) and center frequency ($\sim 6.5$ MHz). The results show that the finite element model can accurately predict the propagation properties of SAWs in human teeth with different demineralization conditions.

C. Comparison of Numerical and Experimental Results for Evaluating the Elastic Properties of Human Teeth

Through the 2D FFT, SAW signals are processed and then the phase velocity dispersion curves of the SAWs can be obtained. The experiments and simulations are performed on the same incisor with different demineralization conditions, and the exciting and detecting lasers always irradiate on the same position of the incisor surface. By doing this, the changes in the SAW dispersion are only dependent on the elastic modulus variation, which arises from demineralization. Using dispersion curves for evaluating the elastic properties of teeth is based on an important property of the bandwidth SAW. It can be summarized as follows: the SAW velocity ($c_R$) is
dependent on the elastic constants of the material depth it probes. The SAW penetration depth $z$ can be determined by the following equation:

$$z \approx \frac{\lambda}{c_R f}.$$  \hspace{1cm} (7)

where $f$ is the frequency of the SAW. So the velocity of the SAW at different frequencies reflects the elastic constants of teeth at corresponding depths, and then the dispersion curves can be used to evaluate the elastic properties of human teeth.

Figure 8(a) shows the simulation dispersion curves of SAW propagation in human teeth with different corrosion degrees $\omega$ ($\omega = 0.2, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0$). In the carious region, the elastic modulus of the WSL is continuously changed with depth $y$. $\omega$ represents the degree of demineralization; the smaller the $\omega$ is, the smaller the elastic constant of WSL is, and the deeper the WSL region is. The detailed relationships, which can reflect the actual elastic property distribution of the WSL, are shown in Eqs. (4.1) and (4.2).

As shown in Fig. 8(a), the velocity dispersion curves with different $\omega$ have very significant differences between each other. All dispersion curves begin at a low value $\sim 2000$ m/s, which is the velocity of the SAW propagating in pure dentin, at $\sim 0.8$ MHz. It can be explained that the velocity of the SAW with long wavelength ($\lambda \geq 1$ mm) is mainly influenced by the elastic property of underlying dentin in the low-frequency region ($f < 2$ MHz). Since the thickness of enamel is 1 mm, the depth that the low-frequency SAW can probe is bigger than 1 mm, so the propagation structure can be considered as a multilayer system. With the increasing of frequency, the velocity of the SAW with short wavelength ($\lambda < 1$ mm) is gradually influenced by the property of upper enamel and WSL.

When $\omega = 1.0$, the tooth does not have a WSL region; the velocity increases with frequency quickly and reaches the value of $\sim 3250$ m/s at $\sim 5$ MHz and then remain constant. The SAW velocity with frequency $5$–$20$ MHz is only dependent on the elastic properties of upper enamel. And in the high-frequency region, the velocity remains constant because the elastic properties of enamel do not change with depth.

When the WSL arises on the surface of enamel ($\omega < 1.0$), the carious region is regarded as a three-layer system (dentin–enamel–WSL) and the elastic modulus of WSL is changed with depth $y$. With the increase of frequency, the depth that the SAW can probe decreases, and the velocity of the SAW increases and begins to be influenced by the elastic properties of upper enamel and WSL. Because of the decreasing of SAW penetration depth, the SAW begins to be mainly influenced by the properties of WSL, whose elastic modulus is smaller than enamel’s. When the frequency increases to a certain value, the velocity reaches a maximum value and then begins to decrease.

In Fig. 8(a), with the decrease of $\omega$, the maximum value of velocity decreases gradually, and the frequency at the maximum velocity and the velocity in the high-frequency region decrease too. Because the depth and the elastic constants of WSL are...
changed with \( \omega \), the smaller the \( \omega \) is, the smaller the elastic constant of WSL is, and the deeper the WSL region is. So the maximum velocity at certain frequency can reflect the depth of WSL qualitatively. Combined with experimental results, the dispersion curves of the SAW can be used to evaluate the elastic modulus of the WSL.

Figure 8(b) shows the experimental dispersion curves of SAW propagation in the same tooth with different demineralization conditions. The three dispersion curves begin at \( \sim 2000 \text{ m/s} \) at \( \sim 7 \text{ MHz} \) and then decreases to a constant value \( \sim 3090 \text{ m/s} \) with the increase of frequency. In tooth-3, the velocity increases to the maximum value \( 2945 \text{ m/s} \) at \( 20 \text{ MHz} \) frequency regions, but there is an obvious difference in the 4–10 MHz region, where the depth of the WSL can be reflected. This is because the velocity in the low-frequency region is mainly influenced by the properties of dentin. The phase velocity of SAW in tooth-1 quickly increases with frequency and reaches the value of 3238 m/s at \( \sim 10 \text{ MHz} \) and then remains constant. Because of the artificial WSL's existence, the velocity of tooth-2 increases to a maximum value \( \sim 3110 \text{ m/s} \) at \( \sim 7 \text{ MHz} \) and then decreases to a constant value \( \sim 3090 \text{ m/s} \) with the increase of frequency. In tooth-3, the velocity increases to the maximum value \( 2945 \text{ m/s} \) and then decreases to \( 2900 \text{ m/s} \) with the increasing of frequency. In the high-frequency region, the SAW velocity remains approximately constant, which means that the elastic properties of the WSL do not change significantly with the depth at surface regions. The results show that the experimental dispersion curves have a similar trend to the curves of simulation. They demonstrate that the thickness of the WSL in tooth-3 is bigger than that in tooth-2, and the elastic constant in the surface region of the WSL is smaller than that in tooth-2. The significant differences among the three dispersion curves can clearly discriminate the teeth with different conditions. This means that the LU technique can be used to diagnose the WSL by discriminating the dispersion curves.

Comparing Figs. 8(a) and 8(b), the dispersion curves have a similar trend in the 0–4 MHz and 10–20 MHz frequency regions, but there is an obvious difference in the 4–10 MHz region, where the depth of the WSL can be reflected. This is because the depth of the WSL is difficult to control and test, and the elastic properties of the WSL changed with depth through a complex relationship. The depth is difficult to measure nondestructively. By using the SAW dispersion method, it can just diagnose the depth of the WSL qualitatively to discriminate the corrosion degree of carious teeth.

However, the demineralization degree of teeth is mainly reflected by the elastic modulus at surface regions. Combining the numerical simulation method with experiment, the elastic modulus of teeth with different conditions can be calculated at surface regions. Figure 9 shows the simulated and experimental dispersion curves for the teeth with different conditions. The experimental results were in good agreement with the curves from the numerical results at high-frequency regions (\( f > 10 \text{ MHz} \)), and the maximum error between them was less than 1%. Compared with numerical results, the possible uncertainty of the experimental data is mainly caused by two factors. One is the experimental signal's SNR. The noise will affect the amplitude-wave-number-frequency information of SAW signals, and the accuracy of the dispersion curve will be decreased. The other is that the elastic modulus' depth distribution of WSL may not be strictly linear. So there are some differences between the experimental dispersion curves and the numerical curves. The uncertainty of the experiment can be eliminated as much as possible through using various methods to ensure the accuracy of the experimental results. At the surface regions of enamel, the elastic moduli of tooth-1, tooth-2, and tooth-3 are inversed to be \( 95, 73 \), and \( 57 \text{ GPa} \), respectively. The results demonstrate that the SAW dispersion method based on the LU technique can be used to evaluate the elastic properties of human teeth with different conditions.

5. Conclusion

In this paper, the FEM was used to numerically simulate the characteristics of the SAW induced by a pulsed laser propagating in human teeth with different corrosion degrees. The excitation efficiency of the laser with different wavelengths and the heat effect of the laser on teeth were studied. The simulation results showed that the \( 266 \text{ nm} \) laser would not damage the tooth under the power density \( 100 \text{ MW/cm}^2 \).

The LU technique was used to excite and detect the SAW propagating in human teeth with different conditions nondestructively. A series of SAW signals was generated using the SLLS technique for dispersion analysis through the 2D-FFT method.
The experimental dispersion curves of the SAW were obtained for evaluating the elastic properties of sound tooth and WSL, and they matched well with the simulation curves. Combining the simulation results, the elastic modulus of the sound tooth and WSL at surface regions was calculated.

We demonstrated that the LU technique is sufficiently sensitive to nondestructively evaluate the elastic properties of teeth with different conditions. And this technique can be further utilized to study human dental enamel with different topography structure or other features.

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References


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