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Finite element simulation for laser-induced SAW propagation in tooth

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Laser ultrasonic technology, a noncontact nondestructive evaluation method, can be applied to evaluating the properties of human teeth. With a finite element method, this paper studies laser induced surface acoustic wave (LSAW) characteristics propagating in human teeth. Setting up a theory model for laser-introduced surface acoustic wave (SAW) propagating in human incisors, it discusses the temperature field induced by laser irradiate in dental surface, as well as the effects of inhomogeneous enamel and early dental caries (white spot lesion) on LSAWs. Studies in this letter can provide a theoretical basis for nondestructive evaluation of human teeth with laser ultrasonic technology.

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1 Instroduction

Dental caries, tooth decay or lesion, is a kind of common disease that the hard structure of tooth is gradually destroyed. It is caused by the erosion of bacteria in mouth and the defect of teeth. Under favorable circumstances, bacteria in mouth are fermented into acid. Thus, teeth will gradually be dissolved, softened, decalcified and destroyed, eventually cavities existing. In an early stage, dental caries appear in the form of white and opaque spots, called white spot lesion, which is resulted from demineralization. At present, clinical treatment on dental caries still mainly rely on tactile and X-ray treatment. However, these methods cannot diagnose dental caries in an early stage, not can they quantify the demineralization degree, as well as the elastic modulus of tooth structure which directly reflect mineral content in teeth. Methods used for measurement of hard structure of teeth now are mainly as follows[1-2]: Strain Sensor Measurement, nanoindentation hardness experiments, scanning electron microscope. All these methods can be used to measure invitro teeth.

Laser ultrasonic technology[3-5], especially used in measuring irregular objects, is a new nondestructive evaluation method in recent years, which is noncontact and broad bandwidth compared with traditional ultrasonic technology. By controlling the power density of irradiation laser within materials′ damage threshold, the true nondestructive evaluation can be realized. At present, laser ultrasonic technology has been successfully applied to measuring the coating layer thickness of multilay materials, evaluating mechanical properties and residual stress of metals, detecting cracks, etc. Unlike traditional ultrasonic technology, optic generation and reception instrument can be applied with laser ultrasonic technology, so it won′t be restricted by the size of transducers, especially in detecting irregular objects like tooth. It is hopeful that laser ultrasonic technology can be used in online inspecting in vivo teeth in clinical treatment. As far as we are concerned, only professor Wang[6], together with his team in Sydney University has done some researches on evaluation teeth with laser ultrasonic technology. Employing line-source laser to generate surface acoustic waves (SAWs) in excised human teeth and the method of light interference to detect SAWs, this team has detected laser induced surface acoustic waves (LSAWs) in healthy teeth and dental caries in an early stage (white spot lesion) and got velocity dispersion curves of LSAWs propagating in healthy teeth and dental caries in an early stage.

With FEM[7], this letter studies LSAWs propagating in human teeth theoretically. Because of laser irradiation, human teeth will absorb the energy and expand with heat, leading to the ultrasonic waves generation. Not only is it related to teeth′s structure and geometrical property, LSAW velocity also lies on laser, such as pulse width, laser spot diameter, etc. Moreover, lasers can generate ultrasonic waves with different modes. Since FEM can deal with complex structures and numerical solutions of all fields can be obtained, it is convenient to study the effects of teeth′s one or more parameters on the properties of LSAWs propagating in teeth. For example, different properties of dental appearance, various structures of teeth, the changes of thermophysical parameters according to temperature, thermal parameters, odentoschim and so on. In this paper, FEM is used to simulate the interaction between lasers and human teeth to generate SAWs. Allowing for the high anisotropy of human teeth, this letter discusses characteristics of LSAWs′ time domain and frequency domain propagating in teeth with different elastic parameters. It also discusses the effects of dental caries′ thickness in an early stage on LSAWs propagating in it. Studies in this letter provide a theoretical basis for evaluating teeth with laser ultrasonic technology.

2 Calculation model and theory

Human dental coronas mainly consist of enamel, dentin and pulp, the outermost layer of which is the hardest tissue of human body—enamel made up of calcium and phosphor. The thickness of enamel is inhomogeneous, with dental cervix the thinnest. Dentin is surrounded by enamel, inside which are a lot of dentin tubes. Pulp is made up of nerves, blood vessels and lymphatic. The shapes of teeth vary, with incisors the flattest. Since the dental corona is smaller, which leads to the fact that the distance of lasers′ generation and detection is smaller, generally with millimeter range, the effects of teeth′s appearance characteristics--teeth′s radian on acoustic waves′ propagation can be ignored. Incisors can be considered as a homogeneous layer structure made up of enamel, dentin and pulp. Due to the structural characteristics of pulp itself, the pulp layer can be regarded empty. Laser irradiation on teeth′s surface is shown in Fig. 1, where the thickness of typical enamel and dentin are both about 1 mm.

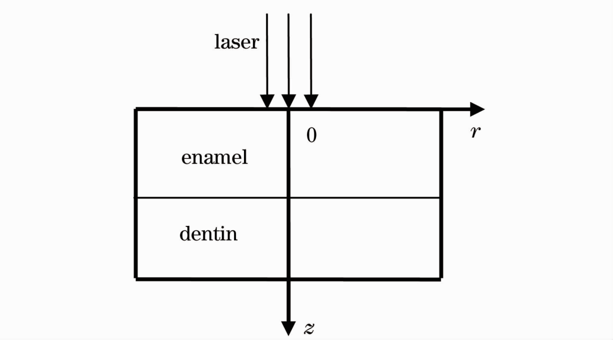

Fig. 1. Schematic of laser irradiation on human teeth.

Laser beams irradiating on teeth′s surface, teeth will absorb laser energy, which will contribute to transient temperature field partially. This course satisfies thermal conduction equation[4]:

$$\rho_i c_i \frac{\partial T_i(r,\ z,\ t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r k_i \frac{\partial T_i(r,\ z,\ t)}{\partial r}\right] + \frac{\partial}{\partial z}\left[k_i \frac{\partial T_i(r,\ z,\ t)}{\partial z}\right] + q, \qquad (1)$$

where $T_i(r,\ z,\ t)$ represents the temperature distribution at t; ρ_i, c_i and k_i respectively stand for density, heat capacity and heat exchange coefficient; $i = f,\ s$, f, s represents enamel and dentin and q is the heat source. Due to optics penetration effect, laser will irradiate into enamel by a certain depth. Laser energy will exponential attenuation along with laser penetration depth. Heat source q is shown as

$$q = \beta(1-R) I_0 \exp(-\beta z) f(r) g(t), \qquad (2)$$

where β is the enamel′s optic absorption coefficient, R is the enamel′s optic reflection coefficient, and I_0 is the peak power density in irradiation center. $f(r)$ and $g(t)$ stand for space and time distribution of laser beams, respectively.

$$f(r) = \frac{1}{\sqrt{2\pi}}\,\frac{2}{a}\exp\left(\frac{-2r^2}{a^2}\right), \qquad (3a)$$

$$g(t) = \frac{8t^3}{t_0^4}\exp\left(\frac{-2t^2}{t_0^2}\right), \qquad (3b)$$

where a is the half width of Gaussian line-source lasers and t_0 is the rise time of laser pulse.

The boundary is regarded to be thermally insulated and a perfect thermal contact at the interface. Initial temperature is 35.2 ℃.

When laser impulse irradiation energy is smaller than melting damage threshold, heat absorption will lead to partial heat expansion, producing transient displacement field. Acoustic waves propagation satisfies equation Navier-stokes:

$$(\lambda_i + 2\mu_i)\nabla(\nabla\cdot U_i) - \mu_i \nabla\times\nabla\times U_i - \alpha_i(3\lambda_i + 2\mu_i)\nabla T_i(r,z,t) = \rho_i \frac{\partial^2 U_i}{\partial^2 t}, \qquad (4)$$

where $U_i(r,\ z,\ t)$ is the transient displacement distribution of acoustic field; μ_i is Lamè constant; ρ_i is the density; α_i is the heat expansion coefficient, in which $i = f, s$, and f, s represent enamel layer and dentin layer, respectively. The upper surface is regarded as a free boundary. Meanwhile, stress and displacement are continuous between layer interfaces.

FEM is a numerical calculation method of solving partial differential equations, which can deal with complex structures conveniently and numerical solutions to the whole field can be got. In the course of SAWs′ generation by the interaction between lasers and materials, heat and displacement are transient and coupling with each other. With FEM, set up thermo-elastic coupling differential equations based on the principle of virtual work, and then solve the equations after dispersing differential equations′ equivalent integration in spatial domains. During calculation, selection of element sizes and time step has a direct effect on calculation accuracy and the center frequency of structural response. Detailed calculation methods of FEM and selection of parameters like time step are explained at length in Ref. [4].

3 Calculation results and discussion

Excited laser wavelength is 266 nm, impulse width is 5 ns, energy is 1 mJ and the half width of focusing line source is 100 μm. With light wavelength around 266 nm, penetration depth of enamel′s light reaches about 0.26 ± 0.01 mm. Unlike metal, optical penetration depth of enamel is larger, so laser is used as a volume heat source. Thermo-physical and mechanics parameters of enamel and dentin used in calculation are shown in Table 1[7]. Transient temperature field of teeth is first studied when impulse laser irradiating on the surface of teeth. Figure 2 shows the increase of teeth surface and the inside when lasers irradiate the teeth surface. The temperature quickly increases to 20 ℃ within about 10 ns at the center of irradiation on teeth surface, which will not damage enamel. Owing to the optic penetration effect, laser irradiates into the inside enamel by a certain depth and are absorbed by medium, producing inhomogeneous temperature field, and the temperature approximately reaches zero below enamel surface by about 0.28 mm. While since typical enamel is about 1-mm thick, almost no temperature increase exists in the dentin inside enamel, which will not damage dentin. Temperature decreases slowly for enamel. In the direction of r, i.e. in the direction of laser spot radius on enamel's surface, almost no temperature increase exists 140 μm away from the center of laser irradiation. Because the thermal diffusion length from thermal conduction coefficient, density, specific heat and laser impulse width is about 0.1 μm, and heat expansion zones is basically within the range of action of laser spot. Consequently, laser wavelength and the size of laser spot are chosen according to the size of hot zones in practical application. Rapid temperature increase of partial areas leads to its heat expansion and the restraint of surrounding medium results in the distribution of stress, so acoustic waves induced by impulse laser are generated in solids.

Table 1 Parameters of Enamel and Dentin

	Heat Expansion Coefficient (10^{-5}/K)	Heat Conductivity [W/(m•K)]	Heat Specific [J/(kg•K)]	Density (kg/m^3)	Young's Modulus /(10^{10}Pa)	Poisson Ratio
Enamel	1.7	0.937	710	2960	7.8	0.3
Dentin	1.1	0.584	1600	2200	1.93	0.3

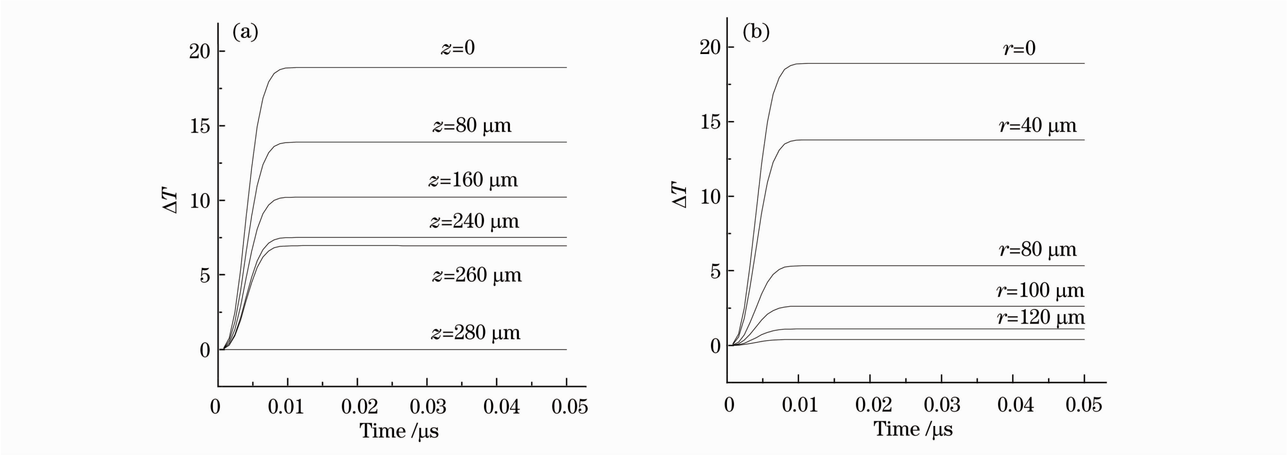

Fig.2. Temperature rise caused by laser irradiation on the teeth. (a) Temperature rise in the direction of depth; (b) temperature rise in the direction of spot radii.

LSAW propagating in homogeneous enamel and dentin are discussed. Figure 3 represents time domain waveform when propagation distance is 1 and 3 mm, respectively. Surface skimming longitudinal wave L arrives first, then Rayleigh wave R comes. Because of the velocity difference between surface skimming longitudinal wave and Rayleigh wave, the longer the propagation distance is, the bigger the arrival time difference will be. Moreover, as propagation distance increases, the dispersion of Rayleigh wave will be more obvious, and the amplitude of Rayleigh wave will weaken. The longer the propagation distance is, the smaller the amplitude value of Rayleigh will be.

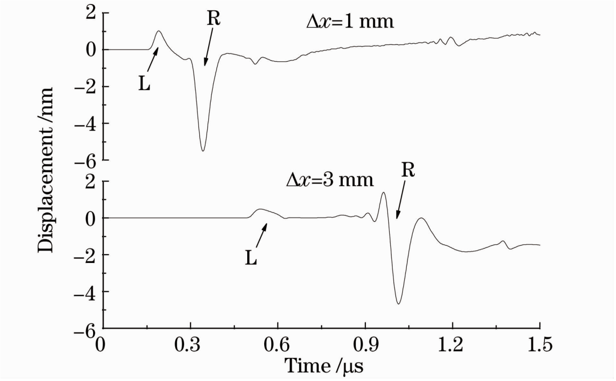

Fig.3. Time domain waveforms of LSAW propagation in teeth

Since the high directional property of enamel's micro-structure contributes to inhomogeneity of its mechanical property[8], both enamel's Young's modulus and hardness decrease from enamel surface to the dentin-enamel junction. Therefore, this paper studies the characteristics of LSAWs propagating in teeth with inhomogeneous enamel whose elastic property and density are inhomogeneous. From enamel surface to the interface of enamel and dentin, Young's modulus decreases by 27%, density decreases by 10%, and enamel mechanical parameter changes continuously. With the application of phase spectrum methods[9] and different time domain waveforms, as well as Eq.(5), characteristics of Rayleigh waves frequency domain are obtained. x_1 and x_2 stand for different propagation distances. Phase spectrums of ultrasonic waves detected at two different points are represented by $\phi_1(f)$ and $\phi_2(f)$. The velocity of acoustic wave can be obtained as

$$V(f)=\frac{2\pi f(x_2-x_1)}{\varphi_2(f)-\varphi_1(f)}. \tag{5}$$

Figure 4 is about the frequency spectrum obtained by time domain signals after FFT. The scope of SAW frequency is within 18 MHz. The center frequency is about 6 MHz. Figure 5 represents the phase velocity dispersion curves of Rayleigh waves propagating in teeth with homogeneous (represented by real line) and inhomogeneous enamel (by dotted line). The upper enamel is harder than the lower dentin, which is similar to the double layer structure (hard coating layer and soft substrate). The wavelength of Rayleigh wave with low frequency is longer which is mainly influenced by the property of lower dentin, while that with high frequency is shorter, which is mainly affected by the property of upper enamel. Thus, velocity with low frequency is small while that with high frequency is big, leading to the anomalous dispersion characteristics. The characteristics of the velocity dispersion are agree with the results in Ref.[6]. When $f\rightarrow 0$, both velocities approximately reach that of Rayleigh wave propagating in pure dentin, which are about 1800 m/s. For inhomogeneous enamel, both of its Young′s modulus and density decreases according to the depth. But the decrease of Young′s modulus is more obvious, so velocity of Rayleigh waves propagating in inhomogeneous enamel decreases, compared with that in homogenous enamel. However, in high frequency area, both velocities tend to change similarly in two situations, which are determined by the property of the top enamel.

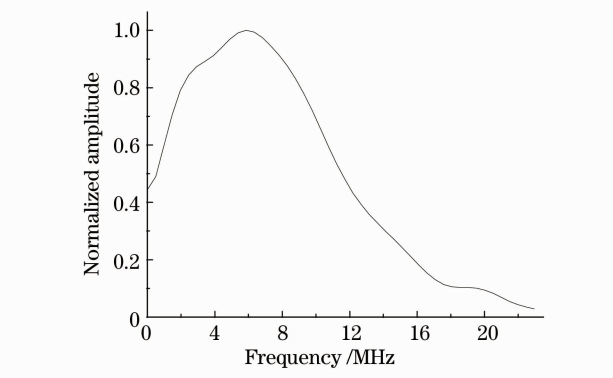

Fig.4. Frequency spectrum of LSAW propagating in teeth

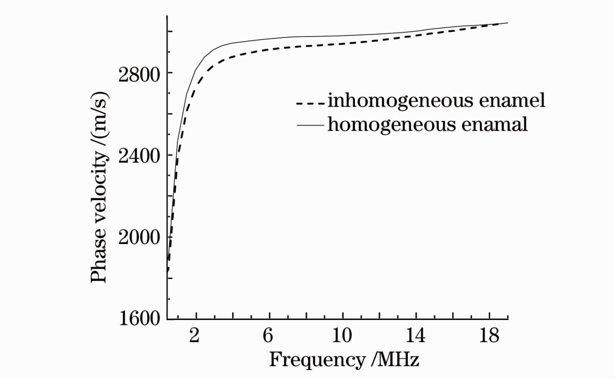

Fig.5. Velocity dispersion of LSAW propagating in teeth with different enamel structures

Smooth white spots with milk white boundaries will gradually form on the surface of teeth after teeth′s demineralization and they will become thicker and thicker. White spots exist at an early stage of dental caries which almost has no clinical features, so if detected timely, they can be restored, preventing serious dental caries forming. Existence of white spots will lead to the decrease of Young′s modulus. The more serious the demineralization is, the smaller the decrease of Young′s modulus will be. Due to the fact that SAW velocity is sensitive to the changes of Young′s modulus, teeth′s demineralization and thickness of white spots can be studied with SAWs. By applying FEM mentioned above, not only can teeth′s inhomogeneity be taken into account, but the effects of dental caries at different stages on ultrasonic waves can also be considered. According to the mechanical properties of white spot layer shown in Ref.[7], this paper discusses the effects of white spot layer′s thickness on SAWs. Teeth with white spots can be regarded as multi-layer structures with homogeneous dentin the lowest layer and inhomogeneous enamel the middle layer. When white spots arise on the outside surface of enamel, its Young′s modulus will decrease. Three cases are discussed where the thickness of white spot layer is respectively 80, 120, and 200 μm and demineralization of the top white spot layer of those three kinds are the same. Figure 6 represents LSAW phase velocity dispersion curves under the circumstances where no white spot layer exists and the thicknesses of white spot layers are different. In low frequency region, waves with long wavelength are mainly influenced by the properties of the lower dentin layer, and the velocities with lower frequency are nearly the same. Moreover, the ratio of dentin Young′s modulus to density is smaller than that of enamel′s. Therefore, SAWs propagate slowly in dentin and the velocity increase with the frequency. While white spot layer has an effect on SAWs mainly in high frequency region. Since white spot layer is softer than the lower enamel layer, the velocity increase first and then decrease. Moreover, the thicker the white spot layer is and the softer the teeth in the same depth are, the smaller SAW velocity will be.

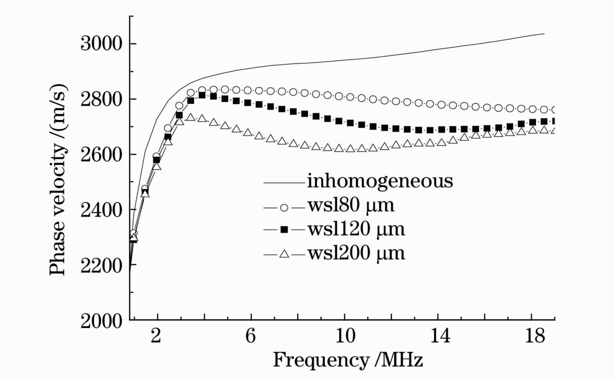

Fig. 6. Influence of white spot layer thickness on the velocity of LSAW propagating in teeth

4 Conclusion

In conclusion, this paper mainly studies the characteristics of SAW induced by pulse laser propagating in teeth. It also discusses time domain characteristics of LSAWs in teeth, and enamel inhomogeneity as well as the effects of dental caries′ thickness (white spot lesion) at an early stage on LSAW frequency domain characteristics. Results indicate that enamel structural properties and the change of white-spot-lesion thickness both have a distinct influence. Researches in this letter provide a theoretical basis for detecting the structures of human teeth and evaluating dental caries with laser ultrasonic technology.

5 Acknowledgements

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