Study of Wedge Waves Propagating along Wedge with Different Defects by Laser Ultrasonics Technique

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ABSTRACT

The research focuses on investigating the influence of different defect shapes on wedge waves propagating along line wedge tip by using laser ultrasound technique. Generally, wedge has more or less defect or damage on the tip, which may result in break and bring economic losses. Thus it is necessary to investigate the characteristic of wedge waves propagating along line wedge with defects. The wedge waveguide models with different defect shapes were built by using finite element method. The open of defect is 0.1mm, the depth is also 0.1mm, and the wedge angle is 20°. Multiple mode wedge waves were observed through B-scan. It was found that both reflected and transmitted waves were observed and the reflected and transmitted A\textsubscript{1} mode separated from A\textsubscript{2} mode due to the dispersion characteristics. Meanwhile, it can preliminary estimate the defect shape and determine the position by energy distribution.

1. Introduction

Wedge waves are discovered by Lagasse and his coworkers through numerical study in the early 1970s, which propagate along the tip of wedge \cite{1,2}. Because of their major features: dispersion characteristics, low wave velocity, and strong localization, they can be utilized in information processing devices, biochemical sensor, acoustic sensors, and nondestructive detection and evaluation. Until now, there is no exactly theory about wedge waves. Not only thin plate theory \cite{3}, but also geometric acoustic approximation theory \cite{4} based on the approximations of thin plate theory were proved to be valid only for small-angled wedges. Both finite element method(FEM) and pulse laser generated ultrasound were used to study the propagation of wedge waves. In the linear thickness variation region of waveguide, wave scattered at the region of variable thickness and the stress and displacements fields were determined through numerical simulation at several frequencies and slope angles \cite{5}. Linear and nonlinear Rayleigh wave fields generated by an angle beam wedge transducer were modeled \cite{6}. A simple piezoelectric motor driven by traveling guided waves on a circular cylindrical wedge is presented, which constructed by attaching a metal circular cylindrical wedge to a piezoelectric tube \cite{7}. A new technique for measuring liquid-level utilizing wedge wave is presented and demonstrated through FEM simulation and a corresponding experiment \cite{8}. The scattering problem of plane waves by a perfectly electric conducting wedge, residing at the planar interface of two media with different electromagnetic properties, is investigated \cite{9}. Meanwhile, pulse laser generated ultrasound was first used to excite wedge waves and investigated the relationship between mode number and angle by Jia \cite{10}. Then the preliminary results on the dispersion of phase velocity as function of the curvature were confirmed qualitatively to those theoretically predicted

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Localized acoustic surface waves propagating along an immersed V-groove was researched [11]. Edwards’ work has shown that a wedge can be used as a model of an infinite depth angled defect, as an ocean wedge, or as a sample with varying thickness [12]. The near-gigahertz flexural acoustic waves propagating in thin gold wedge deposited on an ultrathin silicon nitride slab were imaged by using ultrafast optical technique [13]. One-dimensional (1D) guided elastic waves localized at solid edges was observed of an efficient second-order nonlinearity with dominating frequency up conversion experimentally [14]. Yang investigated the behaviors of ASF modes propagation along wedge tips with perfect and imperfect rectangular defects through numerical finite element simulations and experimental measurements [15]. However, most of these precious works focus on the wedge waves propagating along wedge without damage. Generally, wedge tip conditions influence the propagating characteristic of wedge wave mode, and the non-perfect wedge may bring in break and enormous economic losses. Therefore, it is necessary to investigate the characteristic of wedge waves propagating along wedge with defects. In this paper, finite element method was used to simulate wedge wave propagating along wedge with defect, and the influence of different defect shapes on the propagating characteristics of wedge waves are also observed. Then the energy distribution of these wedge waves propagating along wedge with rectangle, triangle, trapezoid, inverted trapezoid and polygon defect is calculated by integrating the power spectra of the wedge waves, and the location of defect is determined. The results can provide theoretical guidance for the positioning and defect shape estimation of wedge defects.

2. Theory Model

Based on thermoelastic mechanism [16], the incident energy density of the laser beam on the surface of wedge is kept below the “maximum permissible exposure”, which refers to the damage threshold of material, to protect the sample from damage. A non-uniform temperature field was generated with transient thermal diffusing. The transient elastic waves were generally excited and transmitted in limited space. A finite element model was developed to simulate laser-induced wedge waves. Defect was regarded as a kind of the non-ideal wedge tip. Since the sample did not have a symmetrical structure, a three-dimensional geometry of laser irradiation on wedge tip was built. This is schematically shown in Fig. 1, where $\theta$ is the angle of wedge.

Based on the theory of FEM [17], considering the temporal and spatial resolutions, very fine meshes that formed near the wedge tip and in the irradiated region. In this study, the time step for solving the problem was set as 2 ns. The mesh size near the heat-affected area and the wedge tip, where wedge waves were propagating along, was set at 5 $\mu$m, while the maximum size of elements away from the tip of wedge was set at 100 $\mu$m. The size of the wedge model was 6mm×5mm (length×depth), the half width of laser line source was 100 $\mu$m. The parameters of the material used in normal temperature are listed in Table 1, note that this excludes the temperature dependence of the parameters of aluminum.
Table 1. Physical parameters of aluminum

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Absorptivity</td>
<td>0.052</td>
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<tr>
<td>Special heat [J/kg· K]</td>
<td>926</td>
</tr>
<tr>
<td>Thermal conductivity [W/(m·K)]</td>
<td>224</td>
</tr>
<tr>
<td>Thermal expansion coefficient (K⁻¹)</td>
<td>2.31e-5</td>
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<tr>
<td>Poisson’s ratio</td>
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<tr>
<td>Young’s Modulus (GPa)</td>
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<tr>
<td>Density (kg/m³)</td>
<td>2700</td>
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<td>Lamé constant</td>
<td></td>
</tr>
<tr>
<td>λ (GPa)</td>
<td>51.2</td>
</tr>
<tr>
<td>μ (GPa)</td>
<td>26.4</td>
</tr>
</tbody>
</table>

3. Results and Discussion

The influence of defect on wedge waves are calculated by the finite element method. Taking 20° wedge for an example, we considered a laser pulse as a line source irradiated on the wedge tip with defects and calculated the structure field based on the theories described in Ref 18. The defect size is 0.1mm×0.1mm (width×depth), and the physical parameters of sample is shown in Table 1. The wedge waveguide models with different defect shape, inverted trapezoid, rectangle, polygon, trapezoid, and triangle, which is shown in Fig. 2, were built, respectively. And wedge waves at different positions with a step size of 0.1mm were recorded by scanning the detection point along the wedge tip, and more than 100 instances were recorded. Subsequently, the space-time domain images of wedge waves with the raw output data of the FEM model were constructed.

![Figure 2. Schematic diagram for different defect shapes](image)
Figure 3. Space-time domain images of numerically simulated wedge waves with different defect shapes

The space-time domain image of numerically simulated wedge waves of different defect shapes are shown in Fig. 3. Here the vertical axis denotes the propagation distance from the source, the abscissa represents the time, and the color displays the measured slope of the surface perturbation on the wedge tip. Multiple wedge waves propagating along wedge or truncation wedge have been studied systematically [19] and it can be easily distinguished from the individual wedge mode based on dispersion curves. As the excited point and detected point are on the same side of defect, modes $A_1$, $A_2$, $A_3$, and $A_4$ are observed separated, nondispersive. The simulated results well correspond with analytical theory. When wave propagation encountered defect, both reflected waves and transmitted waves are observed. It is
seen that there is reflected wave $RA_{11}$ and transmitted wave $TA_{11}$ of $A_1$ mode are observed, at the same time, besides the reflected wave $RA_{22}$ and the transmitted wave $TA_{22}$ mode, the separated $RA_{21}$ and $TA_{21}$ modes with the same velocity of $V_1$ is also obtained as $A_2$ mode propagating. These results can provide theoretical guidance to locate the defect.

![Figure 4. Energy distribution of wedge waves with different defect shapes](image)

However, it is different to gain the influence of different defect shape through the B-scan in Fig. 3. Thus, by integrating the power spectra of the wedge waves, the energy distribution of these wedge waves of different wedge shape is calculated and plotted in Fig. 4, where the vertical axis denotes energy, the abscissa represents the scanning distance. It is seen clearly that the energy has a sharp energy hopping as the distance is about 3mm, which could be used to determine the location of defect. The energy has a gradually increase as the propagation from 0mm to 3mm, which is caused by the wave near the wedge tip area excited by line source focus to the tip as it propagating [14]. In the meantime, it is found that wedge wave has the biggest energy restricted the range of inverted trapezoid defect, this is because the shape of defect edge can be regarded as a new acoustic source where the energy of wedge waves focused.

4. Conclusion

The influence of defect on wedge waves propagating along line wedge tip are investigated by using laser ultrasound technique. The wedge waveguide models with different defect shapes were built and wedge waves at different positions are recorded by scanning the detection point along the wedge tips. As the excited point and detected point are on the same side of defect, modes $A_1$, $A_2$, $A_3$, and $A_4$ are observed separated, nondispersive. The simulated results well correspond with analytical theory. When wave propagation encounter defect, both reflected waves and transmitted waves are observed. It is seen that there are reflected wave $RA_{11}$, $RA_{21}$, and $RA_{22}$, and transmitted waves $TA_{11}$, $TA_{21}$, and $TA_{22}$ are obtained, in which the $RA_{21}$ and $TA_{21}$ mode are separated again from $A_2$ mode after it encounter defect. By integrating the power spectra of the wedge waves, the energy distribution of these wedge waves of different wedge shape is analyzed. The results show that the sharp hopping area of energy are the location of defect, and wedge wave has the biggest energy restricted the range of inverted trapezoid defect, this is
because the shape of defect edge can be regarded as a new acoustic source where the energy of wedge waves focused. This study can provide theoretical guidance for the positioning and size estimation.

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References