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Width gauging of surface slot using laser-generated Rayleigh waves

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ABSTRACT

A method of width gauging of surface slot using laser-generated Rayleigh waves in time domain is presented. A two-step detection is employed in this method, Rayleigh waves are first generated on one side of the surface slot and then on the other side. Incident and reflected Rayleigh waves from surface slot are detected respectively on both sides of the slot in the two detections. Width of surface slot is calculated based on the arrival time of incident and reflected Rayleigh waves. Experiment results agree well with the measured results by digital microscope and validate the feasibility of the proposed method. The approach will open the way for simultaneous measurement of the depth and width of surface slot and provide a potential application for characterization of surface slot in extreme environment and width gauging of subsurface structure.

1. Introduction

Rayleigh waves have been used extensively for locating and, in some cases, characterizing surface-breaking defects and structures in metals. Many researches on Rayleigh waves have been studied by experimental measurement [1–8] and simulation [9–15]. Most of these works concentrated on studying the interaction of Rayleigh waves and the surface slot, for characterization of depth of the surface slot. However, in order to provide full information of the surface slot, width measurement is also required in practice. However, it is not easy to evaluate the width of surface slot where the working space is very limited, or with extreme conditions such as high temperature and/or high pressure.

The width and depth of surface slot were characterized in frequency domain [16]. It was based on the fact that Rayleigh waves with half-wavelength near the depth of surface slot would have a large attenuation. However, the accuracy of width gauging cannot be guaranteed, due to the insensitivity of Rayleigh waves to the width. Wang et al. [12] used finite element (FE) method to study the interaction between Rayleigh waves and surface with open rectangular defects, it was found that the difference between the arrival time of the scattered echoes was linearly related to the depth and width of the slot, but there was no quantitative calculation method to measure the width because of the tangled reflected waves. Kromine et al.[17] developed a technique for detection of small surface breaking cracks using scanning laser source, but a quantitative basis for width evaluation of surface slot was not provided. Cooper et al. [5] experimentally investigated the interaction of surface Rayleigh waves with the rectangular slot, and proposed a formula in function of the time delay between two peaks of the reflected Rayleigh pulse and the width of surface slot, in order to calculate the depth of the slot. Nevertheless, this method needs to know the width in advance. Hampel et al. [18] developed a cascaded image analysis approach based on detecting discontinuities in dense surface deformation vector fields to gauge the width of crack in materials with high precision, but it could not be applied on rough surface and in some extreme environments, such as those with high pressure and/or high temperature. In Most of these works, the methods of pulse-echo and pitch-catch were used to locate the position and to characterize the width and depth of the surface slot. Nevertheless, it should be noted that it is still much difficult to measure the width of surface slot accurately through the methods mentioned above.

In this paper, surface acoustic waves are generated and detected in far-field of surface slot, and a two-step method to gauge the width of surface slot using Rayleigh waves in time domain is proposed. Rayleigh waves are first generated by a line laser and detected by an interferometer on one side of the surface slot and then on the other side. The width of surface slot is calculated based on the arrival time of incident Rayleigh waves and that of reflected Rayleigh waves and the relative distance of the laser source or ultrasonic receiver during the two detections. In addition, this method opens the way for width gauging on curved and rough surface and in extreme circumstances, and also provide a potential application for characterization of the width of subsurface structure.

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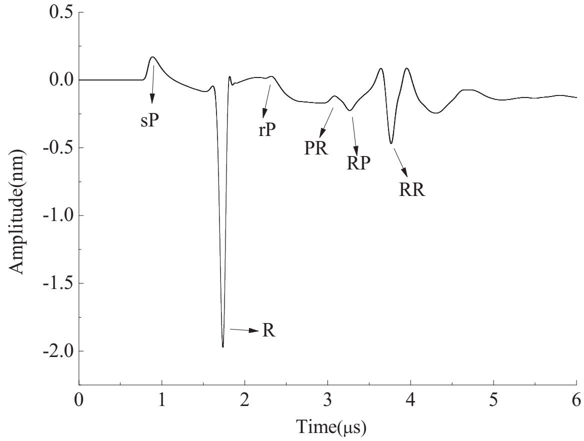

Fig. 1. Schematic of laser-generated Rayleigh wave and its interaction with surface slot.

2. Methodology

Fig. 1 is the simulation results of laser-generated Rayleigh wave and its interaction with surface slot using finite element method (FEM), the symbols sP labels the surface longitudinal wave, *R* the incident Rayleigh wave, rP the reflected longitudinal wave, PR the mode-converted surface wave, RP the mode-converted longitudinal wave, and *RR* the reflected Rayleigh wave from surface slot. Many studies [1–3,5,9–12] have confirmed that the big negative peak in the reflected Rayleigh wave, *RR*, arises from the interaction of Rayleigh waves with the top corner of the slot. Therefore, on the fact that Rayleigh wave is non-dispersive, the distance between laser pulse and ultrasonic receiver, L_1, and the distance from ultrasonic receiver to surface slot, L_2, (as illustrated in Fig. 2) can be calculated by using arrival time of *R* and *RR*, t_R and t_{RR}, which are defined by the large negative peak of the initial and reflected Rayleigh wave, respectively. By moving the laser source and ultrasonic receiver to the other side of the surface slot, or moving the specimen to let the laser source and ultrasonic receiver on the other side of the surface slot, the distance, L_3, L_4 (as shown in Fig. 2) can also be calculated.

When the laser source and ultrasonic receiver are on the left side of the surface slot, based on the flight time of Rayleigh waves through L_1 and L_2, it has

$$\begin{bmatrix} 1 & 0 \\ 1 & 2 \end{bmatrix}\begin{bmatrix} L_1 \\ L_2 \end{bmatrix} = v_R\begin{bmatrix} t_{R1} \\ t_{RR1} \end{bmatrix}, \quad (1)$$

where t_{R1} and t_{RR1} are the arrival time of R_1 and RR_1, v_R is the velocity of Rayleigh wave.

Similarly, when the laser source and ultrasonic receiver are on the right side of the surface slot,

$$\begin{bmatrix} 0 & 1 \\ 2 & 1 \end{bmatrix}\begin{bmatrix} L_3 \\ L_4 \end{bmatrix} = v_R\begin{bmatrix} t_{R2} \\ t_{RR2} \end{bmatrix}, \quad (2)$$

where t_{R2} and t_{RR2} are the arrival time of R_2 and RR_2.

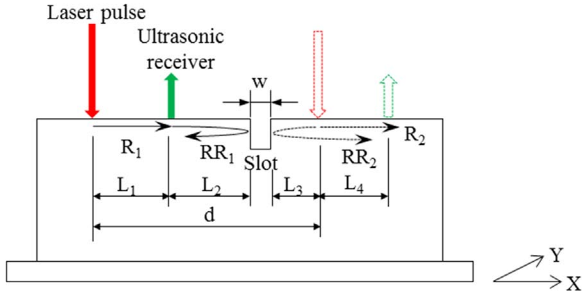

Fig. 2. Surface slot width evaluation method.

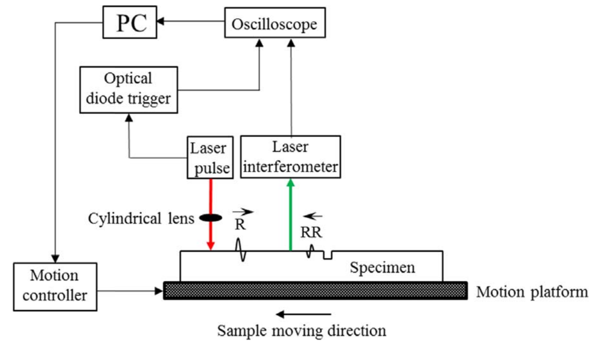

Fig. 3. Schematic of the experiment setup.

Then the width of surface slot can be finally calculated as follows:

$$w = d - L_1 - L_2 - L_3$$

$$= d - \frac{1}{2}v_R(t_{R1} + t_{RR2} + t_{RR1} - t_{R2}), \quad (3)$$

where *d* is the relative distance of laser source or ultrasonic receiver in the two detections.

3. Experiments

The schematic of the experiment setup for gauging the width of surface slot is shown in Fig. 3. A dye laser was used to generate surface acoustic waves in the ablation region of the material. The laser was operated at wavelength of 532 nm with pules duration of 16 ps and a repetition rate of 10 Hz. The energy of the laser pulse is 20 mJ. A cylindrical lens with 100 mm focal length was used to focus the laser to a line, which was oriented parallel to the slot and thus the direction of generated Rayleigh waves was perpendicular to the surface slot.

The specimen surface displacement of the surface acoustic waves was detected by a laser interferometer (WaveTech TWM-532) which is sensitive to the out-of-plane component of the wave motion with a 10 μm spot-size at a 150 mm stand-off distance and has a bandwidth of 400 MHz. The interferometer is based on two-wave mixing in photo-refractive crystal and has a large aperture optical system in order to get more scattered light from the surface of the sample, allowing detections in a far distance. The output signal from the interferometer is recorded by a digital oscilloscope (Agilent DSO-X 3034 A) at the rate of 4 GS/s and sent to a computer for data post-processing. An optical diode trigger is used to trigger the digital oscilloscope, and the motion platform was accurately positioned by motion controller.

The specimen is shown in Fig. 4. The artificial surface slots were finished by wire electrical discharge machining (WEDM) with depth of 2 mm and width of 0.5, 1 and 1.5 mm, on three aluminum plates with the dimensions of 100×50×10 mm^3.

In the experiments, Rayleigh waves were generated and detected on one side of the surface slot, and then on the other side. Temporal profiles of laser-generated Rayleigh waves and reflected Rayleigh waves on both sides of the slot are shown in Fig. 5. The waveforms were averaged 128 times to minimize the incoherent noise in the data and to increase the accuracy of the arrival time of Rayleigh waves. R_1 and R_2 are incident Rayleigh waves from laser source with the velocity of 2940 m/s. The arrival time of R_1 and R_2 is the same, because the distance between the pulsed laser and the interferometer head is the same in the two detections of this experiment. RR_1 and RR_2 are reflected Rayleigh waves from the surface slot. The amplitude of RR_1 and RR_2 are smaller than the amplitude of R_1 and R_2, because when the incident Rayleigh wave comes to the surface slot, some energy goes through the surface slot as transmission Rayleigh wave and only a portion of the wave energy reflects from the slot as RR_1 and RR_2.