Pump–Probe Laser Scanning of Surface-Breaking Partially Closed Cracks: Comparison with Finite-Difference Simulations

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Abstract
A novel nondestructive evaluation (NDE) technique is introduced, where the pulsed excitation and cw probe lasers are coupled and the microcrack is scanned below this fixed pump–probe setup. This technique allows the whole acoustic velocity field around the crack to be measured, including reflected and transmitted surface acoustic waves (SAWs), as well as mode-converted bulk waves. From the frequency dependence of the reflection coefficient and time delay of the transmitted SAW, the crack size was determined. The velocity profiles of reflected and transmitted SAW pulses are compared with simulations using the finite difference method (FDM). Agreement with experiment was found by introducing effective interfacial longitudinal and shear stresses obtained by fitting the measured SAW profiles. The reduced-stress model describes not only the SAW profiles but also the signal enhancements seen when the probe laser irradiates the crack position.

Keywords: Laser scanning NDE, surface-breaking cracks, sizing of cracks, finite-difference method, simulation of interfacial stiffness and stress

1. Introduction
In recent years laser-based nondestructive evaluation (NDE) methods have been developed, where either the excitation or probe laser is scanned over the crack position to improve the extraction of information on surface defects. Here we introduce a novel NDE technique, where the pulsed excitation and a continuous-wave (cw) probe lasers are coupled and the sample with the microcrack is scanned below the fixed pump–probe setup. This technique allows the whole acoustic velocity field around the crack to be measured, including laser-excited, reflected, and transmitted surface acoustic waves (SAWs), as well as mode-converted bulk waves. When the pump or probe laser irradiates the crack location usually strong signal enhancements are registered, which allow the accurate identification of the crack position.

While up to now most NDE studies have dealt with open artificial slots or v-shaped cracks, realistic cracks with partially touching crack faces are of increasing interest. Such partially closed cracks are generated, for example, by stress corrosion and fatigue. Here such surface-breaking cracks are generated by impulsive fracture employing nonlinear SAW pulses with shocks. The experimental and theoretical characterization of these partially closed cracks is of enormous practical importance. This will be achieved by measuring the reflected velocity waveforms and by finite difference (FD) simulations using the reduced-stress model, which allows the interfacial stress-tensor components to be varied continuously to describe cracks between completely open and in full contact.

Another important consequence of the scanning method is strong signal enhancement, when the pump or probe laser irradiates the crack opening directly. Under these conditions additional effects are expected as a result of drastic changes in the geometrical excitation and boundary conditions. However, it is difficult to quantify these effects, since microscopic information on the interaction of the laser beam with the crack faces is needed. On the other hand, enhancement effects due to constructive interference of the incoming with the reflected
SAW and mode converted bulk waves can be calculated by the FD method. With this method the influence of stress reduction and distribution on the scattering process and the spatial resolution of the probe on the observed signal enhancement are studied.

2. Experimental

The crack was moved below the pump–probe setup point-by-point, from one side of the crack to the other. The position-sensitive detector recorded the transient deflection of the cw probe laser by the propagating SAW pulse, so the quantity presented here is the surface slope or velocity and not the surface displacement. More details on how these experiments were carried out can be found elsewhere [1]. Analysis of the corresponding acoustic fields for the various possible configurations between pump–probe setup and crack dramatically increases the information content of the NDE analysis. For example, from the frequency dependence of the reflection coefficient and the time delay or phase lag of the transmitted SAW the size of microcracks could be determined independently and compared with measurements by other means, such as microscopy. With this setup it was possible to extend laser ultrasonics into the frequency range of 10–200 MHz, corresponding to well-detectable crack depths of ~30 µm.

3. Finite difference method simulations

Scattering of plane Rayleigh waves by a microcrack was modeled by the FD method. The process was treated as a 2D problem in the \((x_1,x_3)\) domain with the SAW propagating in the \(x_1\) direction, the crack extending along the \(x_3\) axis, and the free surface at \(x_3 = 0\). The spatial FD scheme consisted of two meshes with spatial increment \(h = 1 \mu\text{m}\) each, displaced by \(h/2\) with respect to each other, one for the displacements \(U_i\) and the other one for the stress components \(\sigma_{ik}\). Thus, the stress at each point was calculated on the basis of the displacement gradients, \(U_{ik} = \partial U_i / \partial x_k\) interpolated over the four surrounding points as \(\sigma_{ik}(x_1,x_3) = C_{ijkl}U_{kl}^{\text{int}}(x_1,x_3)\), where the superscript “int” denotes the interpolation. For the time step the predictor–corrector algorithm was used. More details on the FD calculations can be found in [1].

The thermoelastic excitation of short SAW pulses was modeled as a boundary condition at the surface \((x_3 = 0)\) in the form of a dipole stress component \(\sigma_{13}\), applied to the surface with temporal and spatial parameters similar to those employed in the experiment, e.g., 1 ns laser pulse duration and 5 µm half-width of the line source used to launch the SAW. Such a source delivers a Gaussian waveform in terms of the vertical displacement \(U_3\) and an antisymmetric bipolar pulse shape for the surface slope \(U_{31}\), as actually confirmed by the laser-probe setup. Besides the Rayleigh wave, the simulation with such an excitation source describes the generation of all possible acoustic modes, including not only the surface wave but also the longitudinal and shear waves, as confirmed experimentally. Spatial divergence accounts for the stronger attenuation of bulk waves with distance \(r\) from the laser source or crack as \(r^{-1/2}\).

4. Results

With the coupled-laser-scanning technique the originally launched, reflected, and transmitted surface waves, as well as the mode-converted bulk waves can be measured. This includes their pulse shapes or velocity profiles obtained by laser probe beam deflection. While most
pulse profiles are bipolar, a tripolar profile was found for a partially closed crack generated by impulsive fracture with a nonlinear SAW pulse. This clearly indicates that both crack faces, not just the front face, are involved in the reflection process. To simulate the interaction at the crack interface we developed a simple one-parameter model, where the interfacial interaction can be modified continuously between completely open and completely closed. This parameter $\varepsilon$ reduces all stress-tensor components by the same scalar factor ($0 \leq \varepsilon \leq 1$). Within the frame of a mass–spring representation, this corresponds to a weakening of the spring’s stiffness by a factor of $\varepsilon$ between the masses situated on each side of the crack opening. Consequently, this “reduced-stress model” describes the softening of the material’s stiffness by the crack defect. While FD calculations for an open crack ($\varepsilon = 0$) result in a bipolar shape of the reflected SAW, a value of $\varepsilon = 0.08$ could reproduce the measured tripolar profile (see Fig. 1). Of course, such a single parameter cannot describe the real behavior of a partially closed crack. It must be considered as a mean interfacial stress or stiffness averaged over the whole length of the crack. To investigate the influence of different stress components in more detail, a two-parameter model ($\alpha, \beta$) was introduced, where the tensile and the shear stress components could be varied independently. Consistent with the one-parameter simulations, the tripolar pulse shape could be reproduced only for $\alpha = \beta = 0.08$.

![Fig. 1 Comparison of SAW pulses; black line: experiment, dashed: FD simulation $\varepsilon = 0$, grey line: FD simulation $\varepsilon = 0.08$; a) incoming SAW, b) reflected SAW, and c) transmitted SAW](image)

FD simulations were also employed to study potential signal enhancement effects observable at the positions 1 µm from the front or rear edge of the crack. As can be seen, the enhancement at the crack front increases with decreasing stress-reduction parameter or increasing softening of the crack interface owing to stronger reflection and mode conversion of the incoming SAW. Correspondingly, the lower signal amplitude seen at the rear edge decreases further with decreasing $\varepsilon$ parameter. This is in agreement with the expectation that a completely open crack favors stronger reflection and mode conversion of high-frequency components. For $\varepsilon = 0.08$ the signal enhancement at the front edge was roughly a factor of two with respect to the incoming SAW pulse, whereas the signal decreased at the rear edge. For comparison, the enhancement effect of a partially closed crack was simulated for a linear change of the $\varepsilon$ parameter between zero at the crack mouth and one at the tip, representing a crack totally open at the surface and completely closed at the measured crack depth of 50 µm. Since in this case no reflection or mode-conversion takes place at the crack tip, the crack edges exhibit no oscillations and reproduce the bipolar shape of the incoming surface wave. Consistent with the former results, surprisingly similar signal amplitudes with respect to the reflected and transmitted SAW pulses were found for the linear stress gradient and the fitted average value of the single-parameter model.
The motion of the front edge of the crack, which exhibits the calculated enhancement effect, occurs within a distance of a micrometer of the crack. The size of the effect depends on the spatial resolution of the probe. The simulated resolution of 2 µm was less than the spatial resolution of the laser probe used in the experiments. Therefore, the experiments showed significantly lower enhancement effects than the simulations. The signal dependence on the spatial resolution was investigated for a spatial resolution of 2 µm and 4 µm. Essentially no signal enhancement was found for a spatial resolution of 4 µm, whereas it doubles for a resolution of 2 µm with respect to the incoming SAW. It can be assumed that the spatial resolution of the laser probe was ≥5 µm. Thus, according to the FD simulations essentially no enhancement should be detectable experimentally. However, since a partial overlap of the probe beam with the crack opening must be assumed, it would be necessary to know any additional effects generated by direct laser irradiation of the crack faces for a quantitative comparison with experiments. In any case, experimentally an enhancement of ~20% could be extracted from the acoustic velocity field around the crack. The relatively low enhancement seen experimentally can be explained with reasonable system parameter values.

5. Discussion and conclusions

The characteristic tripolar waveform of the SAW reflected from a real crack clearly indicates that the crack faces interact with each other. The simultaneous analysis of SAW reflection, transmission, and signal enhancement effects allows the interfacial stiffness to be estimated. Simulations with two independent interfacial stiffness parameters, namely the longitudinal and shear stiffness, showed that the interaction is governed by contact of the crack walls.

Even the one-parameter reduced-stress model provides an effective interfacial stress parameter that describes the tripolar reflected and dipolar transmitted velocity waveforms. The reduction of the interfacial stress-tensor components to about 8% of the value in the intact lattice of the solid indicates a relatively open crack. Consistent with this finding the two-parameter model yields a correct tripolar shape for the reflected wave only when the tensile and shear stress components have the same value as fitted for the one-parameter case. The variation of the shear-stress component provides new insight into the important role played by interfacial shear stresses in fracture processes.

A quantitative description of the signal enhancement effects observed near the crack in laser scanning experiments is a difficult task, since microscopic properties of the crack and of the interaction of the excitation or probe laser with the crack faces are involved, and exact information on the crack opening and laser beam radius may not be available. Therefore, only a qualitative comparison between experiment and model could be performed. The present FD simulations, using a step width of 1 µm, yield about a factor of two for the enhancement of the motion at the front edge. Values in this range have been reported by several authors for cracks extending perpendicular to the surface. When the spatial resolution of the probe beam is decreased to about 5 µm the enhancement effect disappears. In agreement with this result a moderate enhancement of ~20% has been found under comparable experimental conditions.

References