Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, November 2-3, 2006

FEM Simulation Study on Nondestructive Test of Surface Cracks with Laser Ultrasonics

Jaegwon Yoo and S. H. Baik
Korea Atomic Energy Research Institute, Daejon, Korea, jgyoo@kaeri.re.kr

1. Introduction

Recently developed laser ultrasonic technique has many applications in industrial sectors, such as laser ultrasound velocity and attenuation measurements, NDT&E and measurement of grain sizes of materials [1]. The technique with an optical detection system enables one to fabricate a genuine remote sensing system that can be deployed in hostile environments. A 2D finite-element numerical simulation has been developed to investigate the generation of ultrasonic waves in a homogeneous isotropic elastic slab under a line-focused laser irradiation [2]. We, further, carried out the FEM simulation to study the propagation and scattering characteristics of the laser ultrasounds in the case of surface cracks.

2. Methods and Results

In this section we describe the FEM simulation parameters after discussing the models of the thermoelastic wave generation and surface cracks. To relieve computational burden of the computer system, we consider a 2-D model which is legitimately employed in a system that has a symmetry about *x-y* plane. We present simulation results of the ultrasonic wave propagation and scattering in a stainless steel slab having a surface crack on the surface. The material parameters of SUS316L is summarized in Table I.

Table I: Symbols of parameters and values of material constants for stainless steel (SUS316L).

Symbol	Parameter	SUS316L
c_1	Compression wave speed	5790 m/s
c_2	Shear wave speed	3100 m/s
c_R	Rayleigh wave speed	2870 m/s
ρ	Density	7960 kg/m^3
α	Linear expansion coeff..	15.9*10^{-6} K^{-1}
κ	Thermal diffusivity	2.5*10^{-6} m^2/s
k	Thermal conductivity	13.49W/mK
R	Reflectivity	0.94
μ	Shear elastic modulus	78.6 GPa
λ	Lame elastic modulus	195.1 GPa
ν	Poisson ratio	0.293

2.1 Laser Model and Finite Element Method

Since the absorption of a laser pulse can excite the ultrasonic waves on the surface of a sample, the source can be modeled as,

$$q = E(1-R)f(x)g(t) \quad (1)$$

$$f(x) = \frac{2}{\sqrt{2\pi}\varpi} e^{-2x^2/\varpi^2} \quad (2)$$

$$g(t) = \frac{8t^3}{\upsilon^4} e^{-2t^2/\upsilon^2} \quad (3)$$

where ω is the Gaussian width, and υ is the pulse duration time of the laser beam.

The boundary and initial conditions for the thermal (Θ) and ultrasonic (u) waves read

$$\vec{n}\cdot\nabla\theta(\vec{x},t) = 0 \quad \text{and} \quad \theta(\vec{x},0) = 0 \quad (4)$$

$$\sigma_{zx} = \mu\left(\frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z}\right) = 0 \quad (11)$$

$$\sigma_{zz} = \lambda\left(\frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z}\right) + 2\mu\frac{\partial u_z}{\partial z} - \beta\Delta\theta = 0 \quad (5)$$

The numerical simulation based on the finite element method deals with a system of ordinary second-order linear differential equations [3],

$$[K]\{u\} + [M]\{\ddot{u}\} = \{F\}, \quad (6)$$

where [K] is the stiffness matrix determined by the elastic properties of the medium, [M] is the mass matrix determined by the density distribution of the medium and {F} is the applied load vector. The fact that Eq. (6) is identical to a simple mass-spring oscillator system tells us that assembling all elements into a large global matrix system is equivalent to a solid consisting of discrete masses interconnected to one another by springs.

2.2 Surface Crack Model

Numerical modeling based on the FEM requires an appropriate mesh size and time increment according to the frequencies and wavelengths of interest [4]. One should be cautious on choosing mesh sizes, since the larger element size filters short wavelength effects and the smaller size can cause numerical instabilities. To accommodate the crack sizes in FEM simulations, we used the mesh size of 25 μm and the time step of 5 ns.

2.3 Results

Figures 1 and 3 are vector representations of the wavefronts propagating and scattering inside a SUS316L slab that has a surface crack on the top surface. The figures show that the ultrasonic wave is reflected at the crack, mostly in Fig. 1 and almost completely in Fig. 3. As the crack depth becomes deeper, the reflection occurs more on those component waves whose wavelength is much shorter than the crack depth, while the longer wavelength components can be transmitted below the crack by diffractions. Figures 2 and 4 illustrate the time-domain plots of the vertical displacement on the top surface of Figs. 1 and 3 versus the distance from the center of the laser spot. In the front end of these figures there are three distinctive wavefronts propagating to and being reflected at the crack tip. Note that the Rayleigh wave increases its amplitude abruptly at and just before the crack tip. There is nowhere to divert its energy but to be accumulated at the crack tip, since most of the R-wave is localized on the skin of the sample. One can exploit this phenomena to detect a crack location of the sample [5].

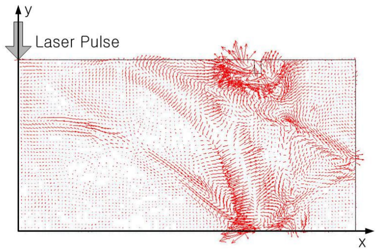

Figure 1. Vector representation of the wavefornts propagating inside a SUS316L slab at t=1.4 μs. The crack on the top surface is 0.2 mm deep and 0.1 mm wide. The crack distance is 3.5 mm from the center of the laser spot.

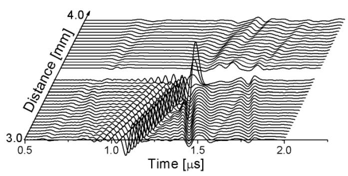

Figure 2. Time-domain plot of the vertical displacement U_y on the top surface of Fig. 1 versus the distance from the center of the laser spot.

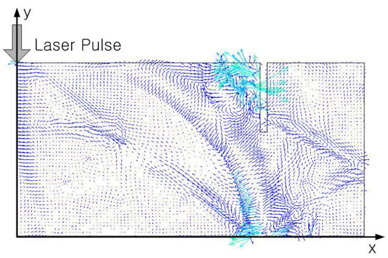

Figure 3. Vector representation of the wavefornts propagating inside a SUS316L slab at t=1.4 μs. The crack on the top surface is 1.0 mm deep and 0.1 mm wide. The crack distance is 3.5 mm from the center of the laser spot.

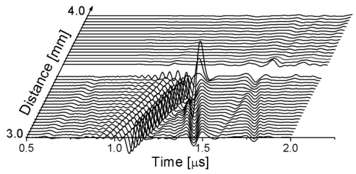

Figure 4. Time-domain plot of the vertical displacement U_y on the top surface of Fig. 3 versus the distance from the center of the laser spot.

3. Conclusion

A genuine remote excitation and detection system of the ultrasound waves can be fabricated with a combination of a pulsed and a cw laser systems, which can be deployed in hostile environments, such as at high temperature or radiation zone, without any physical contacts with samples. The numerical model based on the FEM demonstrates clearly the capability of predicting the location and the width of a crack. It, however, has yet to be studied how to exploit the laser ultrasonics in determining the depth of the crack. Currently we focus our research interests on frequency-domain characteristics of ultrasound in the case of surface cracks, where the ultrashort laser pulse can be used in generating a broadband elastic waves.

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