Photothermal radiometric time-domain inspection of solid specimen by moving line heat source

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Abstract. The time-domain response of the temperature of solid specimen surface illuminated by a linearly-focused laser beam scanning over a solid specimen surface was theoretically formulated. The waveform is composed of surface diffusion and reflection components, both of which are represented by incomplete Gamma functions. Experimental results show photothermal radiometric signal increase caused by the reflection of heat flow at the internal defect boundary and agreed with calculated data qualitatively.

1. Introduction
Photothermal radiometry or active-thermographic inspection, in which modulated [1], pulse [2], or moving laser beam heats up samples [3], has become more and more important in industrial applications. For non-destructive inspection (NDI) applications, real-time thermographic technique is highly applicable to airplane industry. On the other hand, moving heat-source method has an advantage in spatial resolution. However, the extremely fast movement of heat source, such as 100m/sec [3], is required for inspection of materials with high thermal conductivity (metals) by the latter method.

In this study, the model that a line-focus laser beam scans over specimen surface was analyzed, and its time-domain response was formulated theoretically. The experiments by a thermo-tracer with real-time response were performed to analyze time-domain response of the temperature of specimen surface. The adoption of time domain waveform and its external control utilizes other degree of
freedom in instrumentation in the NDI field with thermography.

2. Principle

For theoretical formulation, a solid specimen with a depth of \( d \), width \( 2x_0 \), and an undersurface slit-type defect was assumed. A top of the defect is located at the depth \( \sigma \) from the top surface, where the focused laser beam moves. To analyze temporal behavior of the temperature variation of the specimen surface, we assume a model shown in Fig. 1. A line-focus laser beam with a length \( L \) aligned along \( y \)-axis starts from \( x=-x_0 \) at time \( t=0 \) with a velocity \( v \). Since the top of an internal rectangular-shaped simulated defect is located at \( z=-\sigma \), its image plane lies at \( z=-2\sigma \). Here we denote the \( x \)-coordinates of observation and a laser beam position as \( x \) and \( x_0(t) \), respectively. The coordinate of heat source is described by the equation;

\[
x_0(t) = -x_0 + v \cdot t
\]

The region where thermal wave reflected at the image plane \( z=-2\sigma \) enters the observation point \( x \) is \( x_1' \leq x \leq x_2' \). The temporal behavior of the temperature field is described by an integration of a space-temporal Green’s function for a moving heat source \([4]\) in a time region of \( t_1' \leq t \leq t_2' \) which corresponds to the above spatial limitation.

After the temporal integration, the temperature waveform observed at a given observation coordinate \((x, y=0, z=0)\) is described by the summation of two terms representing surface diffusion and reflection of thermal wave \([5]\), respectively.

\[
T_0(x, 0, 0, t) = \frac{q}{4\pi\kappa\rho c} \cdot \Gamma(0, \frac{(x-x_0)^2}{4\kappa t})
\]

\[
T_1(x, 0, 0, t) = \begin{cases} 
\frac{q}{4\pi\kappa\rho c} \cdot \left[ \Gamma(0, \frac{(x-x_0)^2+(2\sigma)^2}{4\kappa(t-t_1')}) - \Gamma(0, \frac{(x-x_0)^2+(2\sigma)^2}{4\kappa(t-t_1'_{\ell})}) \right] & t > t_2' \\
\frac{q}{4\pi\kappa\rho c} \cdot \Gamma(0, \frac{(x-x_0)^2+(2\sigma)^2}{4\kappa(t-t_1')}) & t_1' < t < t_2' 
\end{cases}
\]

where \( \Gamma(0, \xi) \) is an incomplete Gamma function and the parameter \( \kappa \) represents thermal diffusivity.

3. Experimental apparatus and specimens

The experimental setup is shown in Fig. 2. For a heat source, second harmonics of Nd-YAG diode laser-pumped solid-state laser (DPSSL) with wavelength of 532nm was used. Its beam was expanded with a concave lens and a pair of convex lens. A collimated beam was incident into a right-angle prism and a plano-convex lens both attached to a moving slider. As a slider, linear-motor slider (ORIENTAL MOTOR, EZ limo) with a moving speed ranging from 1mm/s to 2000 mm/s and a span of 100 mm was used. A thermal image was observed by a thermo-tracer (NEC San-ei, TH 9100) with a temperature resolution of 0.06K was used. The thermal image was recorded by a personal computer (PC) connected with an IEEE 1394 bus. The real-time (30 flames/sec) thermal response was recorded by a PC. The specimens used in this experiment were polyoxymethylene plastic (delrin),
brass and stainless steel (SUS304). Stainless steel specimen has a cuboid shape with a size of 25mmx40mmx4mm. The specimen surface was coated by black-body paint with an absorbance of 0.94. Inside of the specimen, rectangular slits with a width of 10mm and depths of 0.5, 1.0, and 1.5mm were fabricated along the focused laser beam.

4. Experimental results

Fig. 3 (a) shows temporal variation of the surface temperature waveform on SUS304 specimen, or 18Cr-8Ni alloy specimen without undersurface defect: (density $\rho = 7920$ [kg/m$^3$], specific heat $c = 0.499$ [kJ/(kg·K)], and thermal conductivity $\lambda = 16.0$ [W/(m·K)], its thermal diffusivity is obtained as $\kappa = 4.04$ [mm$^2$/sec]). The data was obtained for laser power of 224mW, and the slider velocity 1mm/s. Fig. 3 (b) represents that obtained for the specimen with undersurface defect located at the depth of 0.5mm. Figure shows apparent photothermal signal increase at the center (red) of the defect caused by the reflection of heat flow at the shallower internal defect interface. The points A, B and C represent center, prior to the center, after the center. B and C both located with distances of 5mm apart from the center (1 sec=30 frames). The waveform at the center for the same condition was calculated with the theory described in section 2 and shown in Fig. 3 (c). Solid and broken curves represent surface temperature variation with and without the internal defect, respectively. The theoretical analysis agreed with the experimental data qualitatively.

5. Conclusion

Experimental results show photothermal radiometric signal increase caused by the reflection of heat flow at the internal defect boundary. This scheme has an ability to detect internal defects with a good spatial resolution, and has an advantage to adjust moving velocity change to specimens and to utilize time-domain control by laser light pulse width or frequency modulation for materials with high thermal conductivities such as metals.
Fig. 3  (a) Temporal behaviour for the specimen without an internal defect (top). (b) Signal waveforms for the specimen with internal defect located at the depth of 0.5mm (middle). (c) Calculated waveforms based on the Eqs. (2) and (3) for the same condition (bottom).

References
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