Monitoring material grain size by laser-generated ultrasound

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A noncontact, nondestructive, laser-based method for remote monitoring of material grain size is described. A surface acoustic wave surge, generated in the material under test by a short, high-power laser pulse, is detected optically. The leading-edge rise time of the acoustic signal is found to relate to the material grain size through frequency-dependent scattering. In assuming a Rayleigh scattering model, a good correlation with metallurgical measurements is obtained in steel specimens.

Nondestructive sizing of material grain is required for process quality assurance in several fields. In one common approach, the average grain volume is calculated from ultrasonic scattering coefficients obtained by attenuation measurements. Typically, contact transducers are used for generation and detection of the ultrasound. These entail several drawbacks, including distortion of the measurements due to limited bandwidth, and interaction with the acoustic wave in the contact region.

We report a novel, noncontact, laser-based method for monitoring frequency-dependent ultrasonic attenuation in the near-surface region. A short, high-power laser pulse is used to induce transient, localized thermal stresses, which in turn, generate ultrasound in the material under test (Fig. 1). This thermoelastic, ultrasound generation mechanism, which, for metals, dominates the ablative one due to irradiation levels below $10^3 \text{ W/cm}^2$. A knife-edge technique is employed to propagate along the material surface, then detected using the knife-edge technique. The material attenuates the traversing ultrasound in a frequency dependent process that affects, most notably, the leading-edge rise time of the detected signal. By monitoring this rise time, sufficient spectral information is obtained to extract the material scattering coefficient, from which the mean material grain diameter, $\bar{d}$, is calculated.

Signals with very fast rise times are required for frequency dependent attenuation measurements. The rise time of the laser induced signal depends on the laser pulse rise time, and the spatial distribution of the thermoelastic source. Freely diffracted laser beams generate relatively long ultrasonic rise times due to the gradual intensity decay at the illumination boundary. We were able to eliminate such geometrical effects by introducing a rectangular laser illumination pattern (Fig. 1). The ultrasonic rise times expected from the sharp boundaries of this pattern are comparable to those of the optical pulse.

Figure 1 shows the experimental setup. A Q-switched Nd:YAG laser pulse (6 ns rise time, $\sim 1 \text{ MW/cm}^2$ peak incident flux) was expanded to heat strips of $d = 6$ mm width and $l = 16.5$ mm lateral extent. A knife-edge probe, with a focused, 7 mW HeNe beam, detected the surface signal at $r = 32$ mm. AIST 1075 steel specimens with different grain sizes (Fig. 2), were prepared by cooling at different rates after annealing for 3 h at 870°C (Table I). The specimens were polished to improve optical detection sensitivity.

Figure 3 presents experimental laser strip-generated waveforms, together with theoretical curves to be discussed below. The surface perturbations are dominated by the Rayleigh component, exhibiting two distinct pulses that ensue from the strip’s edges. The delay between the pulses is equal to the acoustic travel time across the strip’s width. Similarly, the polarity inversion is commensurate with the sign reversal of the stress at the front-edge, as compared to the rear-edge of the source. The rise and fall times are shorter than can be obtained with a Gaussian spatial surface source distribution. This feature facilitates the detection of material induced rise-time differences. For example, a faster leading-edge rise time (50 ns) is observed for specimen 1 (Fig. 3(a)), as compared to specimen 4 (130 ns in Fig. 3(b)). In both cases, the leading-edge rise times are longer than the laser pulse buildup ($\sim 6$ ns), or the estimated experimental detection bandwidth ($\sim 25$ ns) limits, so that only material effects can be responsible for the observed rise times. A theoretical model is now required to quantitatively estimate material parameters from the experimental waveforms.

Such a model was derived by considering the thermal loading of a high-power laser pulse on a lossless, homoge-

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neous, isotropic, semi-infinite solid. The material attenuation is included later by introducing suitable attenuation in the Fourier domain. The vertical surface displacement at \( X, u_3(X,t) \), is the integral of the thermoelastic stress contributions of the source's thermal profile, \( \Theta(x,t) \). It can be shown that, for the infinitesimal depth of optical heating in metals,\(^{6,8}\) and for observation points on the line of symmetry of the source,\(^ {8,9}\) only horizontal stress components need be considered, that is,\(^ {6,8}\)

\[
\sigma \int_0^\infty d\xi \int_0^\infty d\eta \left( \frac{\partial}{\partial \xi} \Theta(x,t) \right)^* G_{31}^\text{vert}(x+\xi/2,0) \times (x,t;x_\perp y=\xi=0). \tag{1}
\]

Here \( G_{31}^\text{vert} \) is the Green's function for vertical displacement due to an instantaneous, horizontal point force, and the asterisk denotes convolution with respect to time.

The required model can be calculated from Eq. (1), which includes contributions from all lateral portions of the strip. However, if only leading-edge rise times are of interest, considerable simplification, and a reduced computational load, are possible. Since each differential element in the source excites pulses with an abrupt rise time, the leading-edges of the signal will be determined by the source's elements closest to the observation point, namely, by the central region of the strip. Contributions from the far ends of the source, which are delayed by longer trajectories, do not affect the signal's leading edge. For example, in the geometry used here, the far off-axis contributions arrive after \( [\sqrt{(l/2)^2 + \xi^2} - r]/c_R \sim 300 \text{ ns} \); too late to affect the experimentally observed rise times (50–130 ns). The validity of this short strip approximation for the leading-edge rise times was verified both experimentally and numerically: eight leading rise times were found to be virtually independent of the lateral source dimension; only the tailing portions of the acoustic pulses vary with \( l \).

Under the short strip approximation, the integration over \( VI \) in Eq. (1) is eliminated. As the thermal diffusion over the short pulse buildup time (\(<130 \text{ ns}\)) is small, the laser-induced temperature distribution can be approximated by a rectangular profile of width \( d \), such that Eq. (1) reduces to

\[
u_3(x,t) \big|_{\text{leading edge}} = q(t) \ast \left[ G_{31}(x+d/2,t) - G_{31}(x-d/2,t) \right], \tag{2}
\]

where \( q(t) \) represents the heating laser's temporal profile. This model for the acoustic displacement incorporates the features of the experimental waveform: two inverted, fast rise-time pulses, separated by the flight time across the strip's width, \( d \).

The material scattering and absorption introduce frequency-dependent attenuation, which can be modeled as\(^ {1,10}\)

\[
\exp\left\{ -(\alpha_1 r) - (\alpha_2 r)^2 - (\alpha_3 r)^3 \right\}, \tag{3}
\]
where $f$ is the frequency, $\alpha_i$ ($i = 1,2,4$), are attenuation coefficients, and $r$ is the ultrasonic pathlength in the material. The last term in Eq. (3) corresponds to material scattering which, under the Rayleigh approximation, obeys a fourth-power frequency dependence.\textsuperscript{1,10} The degree of scattering is determined by the mean material grain diameter, $D$, and the surface wave scattering coefficient, $S(R)$, such that\textsuperscript{4,10} $\alpha_4 = S(R)D^4$. For steels\textsuperscript{1} $S(R) = 0.0134 \text{ (us/mm)}^4$. The linear and quadratic frequency attenuation terms in Eq. (3) represent a combination of material absorption,\textsuperscript{3} and the bandpass characteristic of the knife-edge technique.\textsuperscript{3}

Model waveforms, for comparison to the experimental signals, are obtained as follows. First, the unattenuated waveform is evaluated from Eq. (2), using an experimentally measured laser pulse temporal profile, $q(t)$, and analytic expressions\textsuperscript{8} for $G_3$, with special treatment for their discontinuities.\textsuperscript{8} The dispersionless waveform is then Fourier transformed, attenuated in accordance with Eq. (3), and inverse transformed. The resulting waveform is differentiated to obtain the surface displacement slope as detected by the knife-edge probe.

The theoretical curves in Fig. 3 were generated by least-square fitting of the model parameters; amplitude, wave velocity, $c_R$, three attenuation parameters, $(\alpha_R)$, and delay $r/c_R$. Fitting was restricted to the leading portion of the ultrasonic pulses, where good correlation with theoretical waveforms was found. Table I lists typical least-square results for $(\alpha_R)$, calculated $D_M$, and independent metallurgical grain size measurements, $D_M$.

The experimental results demonstrate an increase in the leading-edge rise-time with prolonged specimen cooling times. Although some increase may result from material absorption, scattering has a dominant effect on the rise time, as indicated by the values for $(\alpha_R)$ (Table I). The laser-based ultrasonic results ($D_M$) compare well to those observed in the metallurgical samples ($D_M$). Any discrepancies are well within the experimental errors expected from both techniques. The technique can potentially monitor other material parameters that relate to the ultrasonic velocity ($c_R$), or attenuation ($\alpha_1$ and $\alpha_2$).

The short strip approximation significantly reduces the computational load, yet accurately predicts the leading portion of each of the acoustic pulses. In the trailing portions, which, for the slope sensitive knife-edge detection, appear in reversed polarity in each of the pulses, the model reproduces the experimental waveforms less accurately for larger leading rise times [compare Figs. 3(b) to 3(a)]. Nevertheless, the leading rise times are correctly modeled. Similar effects were found in Ref. 7, where the trailing signal portions were almost eliminated, yet the leading rise time is not affected.

In conclusion, finer spatial resolution, broader bandwidth, improved scanning ability, nonintrusive transduction of the ultrasound, and remote operation are several inherent advantages of the method suggested. These benefits make the technique potentially suitable for a variety of new applications, such as in-process inspection of hot material casting, or testing specimens with limited geometric accessibility. It is emphasized that, unlike the comparative measurements required with contacting transducers,\textsuperscript{9,10} the present technique measures the absolute material attenuation: experimental data is compared to theoretical waveforms. The information extracted is therefore expected to be fundamental and sensitive to a wide range of material properties.

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\textsuperscript{1}H. Willems and K. Goebbels, Met. Sci. 15, 549 (1981).
\textsuperscript{8}A. Aharoni, Ph.D. thesis, Tel Aviv University, 1990.
\textsuperscript{9}C.-C. Chao, J. Appl. Mech. 12, 559 (1960).