ABSTRACT

Localized heating produced by absorption from a pulsed laser provides an efficient noncontacting source of ultrasonic waves in materials. This paper describes the results of experiments conducted to illustrate the feasibility of this type of source for microstructure characterization in metal and ceramic materials. Piezoelectric and capacitive wide bandwidth detection transducers have been used to record attenuation and scattering in these materials for comparison with the conventional pulse echo technique. The laser source was found to be an efficient, versatile, and wide bandwidth noncontacting source.

INTRODUCTION

Unique microstructural properties, such as grain size, are responsible for the mechanical properties that make most materials useful. Ultrasonic measurements are well suited for microstructure characterization because the waves penetrate the material to an adequate depth and are usually scattered from microstructural features of interest [1-3]. One of the more desirable microstructural requirements of modern materials is a very small grain size, typically on the order of microns. To obtain a sufficient cross section of these small grains for measurements, high frequency ultrasonic waves must be used. Unfortunately, standard piezoelectric transducers are only marginally useful for high frequency operation because the materials must be very thin, and the transducers have limited power output capability. Also, the fragility of these transducers usually requires that they be mounted on some sort of supporting structure or delay line. The ultrasonic measurement must then contend with unwanted, and often large extraneous reflections, produced within this delay line, which can often dwarf the signals of interest. Piezoelectric transducers also require direct contact with the material under study, which is often undesirable.

Recently, much work has been concentrated on developing pulsed lasers as a source and receiver for noncontacting ultrasonic measurements [4,5]. The results to date are very promising in that, as a source, the laser is efficient and very controllable. Unfortunately, the laser detector is not yet as sensitive as the piezoelectric detector and therefore is limited to situations in which large signal amplitudes can be created.

This paper describes the use of the pulsed laser source to record microstructural scattering by measuring attenuation. A capacitive transducer was used for characterization of the laser pulse and a contact
piezoelectric transducer mounted on a delay line was used for recording multiple echoes through the sample for the attenuation measurements. The goal of this work was to quantitatively characterize the laser source as a tool for measuring attenuation and to compare the results with the conventional pulse echo piezoelectric technique. A set of three Inconel samples with different grain sizes were used for the measurements because they exhibited different amounts of scattering and attenuation.

ELASTIC WAVE GENERATION

Generation of elastic waves in materials by pulsed laser absorption has been shown to occur by two processes: thermoelastic expansion and ablation from the surface [5]. These two mechanisms possess very different source characteristics for elastic waves. Fig. 1 shows the surface displacement on the back side of a 0.5-in. thick plate of stainless steel from absorption of a laser pulse by a clean surface on the front side. The displacement was measured by a capacitive transducer in close proximity (~10 μm) to the surface with a bandwidth greater than 100 MHz. The laser pulse was about 5 mm in diameter and had an energy of 15 mJ green light from a Nd/YAG laser with a pulse width of about 10 ns. The surface displacement was recorded by a transient digitizer and exhibited a peak value of about 2 x 10^-10 m. The resulting displacement is essentially that due to a horizontal force couple applied to the front surface directly above the capacitive detector [6]. Both longitudinal and transverse components are observed. This signal, however, is not effective at exciting a high frequency piezoelectric contact transducer for recording the echoes in an attenuation measurement. In contrast, a dramatic improvement is observed when either high laser power or a light coating of oil is used on the surface to produce an ablative source. The resultant displacement is shown in Fig. 2 and coincides to that of a point normal force applied at the surface, which results from the momentum transfer due to the ablation process.

The ablative source produces longitudinal and transverse elastic waves in the material [6]; however, the largest normal surface displacement comes from the longitudinal component which results in the very rapid positive pulse surface displacement shown in Fig. 2. Multiple echoes of this rapid pulse are also evident from Fig. 2, which could be used directly for attenuation measurements. The Inconel samples chosen for the comparative attenuation measurements exhibited rather high attenuation values, which resulted in a poor signal-to-noise ratio with the capacitive detector used. Work is under way to construct an improved capacitive detector with increased sensitivity, while maintaining the wide bandwidth, to use these waveforms directly for attenuation and scattering measurements. On the other hand, this pulse was very effective at exciting a 75-MHz contact piezoelectric transducer, which was sufficiently sensitive for attenuation measurements.

The laser optical pulse was directly measured by a photodiode to have a pulse width of about 10 ns. Fig. 3 shows the spectral amplitude of both the laser pulse and the sharp longitudinal displacement pulse as measured by the capacitive detector. Clearly, both are of very wide bandwidth, with the longitudinal pulse limited by diffraction and microstructural scattering.
Fig. 1. Normal surface displacement of a .5" stainless steel plate measured by a capacitive transducer from absorption of the laser pulse by a clean surface.

Fig. 2. Normal surface displacement as in Fig. 1 from absorption of the laser pulse with a light oil coating on the surface.
Fig. 3. Amplitude spectrum for the laser pulse measured by a photodiode compared to the detected longitudinal pulse of Fig. 2.

DIFFRACTION CALCULATION

In order to account for diffraction as in the conventional attenuation measurement, the laser source is approximated by a normal point force applied to the sample surface. This is adequate as long as the spot size is small compared to the wavelength. The spot size used was about 200 μm, which is on the order of the ultrasonic wavelength, so this criterion is not exactly satisfied; however, the results indicate no serious effects due to a finite spot size. This type of source produces a diverging wavefront consisting of longitudinal and transverse components; however, most of the energy at high frequencies comes from the initial longitudinal pulse which produces a radiation pattern in the material with spherical surfaces of constant pressure (neglecting transverse strains) as shown in Fig. 4 (for kz ≫ 1)

\[ P(r,θ) = \frac{ikr}{r} \cos(θ) \]  \hspace{1cm} (1)

The net signal amplitude detected by the piezoelectric disk transducer is given by:

\[ \int P \, dσ = \frac{1}{2} \log[1+(a/z)^2] + \sum_{p=1}^{∞} \frac{(ikz)^p[(1+(a/z)^2)]^{p/2} - 1}{p \cdot p!} \]  \hspace{1cm} (2)

which for \((a/z)^2 < 1\) is proportional to: \(π/S\), where \(S = zλ/a^2\), with \(λ\) the ultrasonic wavelength. Typically, as here, the experiment is performed primarily in the large z region (\(z ≫ a\)). The diffraction correction for each echo pair, from which the attenuation is calculated, accounts for the spherical divergence of the radiation, and becomes for the (nth) echo simply 20 \(\log[z_n/z_{n+1}]\).
Laser pulse

\[ P \alpha e^{ikr} \cos(\theta) \]

Normal point force

Sample

Buffer rod

Piezoelectric transducer

Fig. 4. Geometry of the pulsed laser generation piezoelectric detector measurement showing a surface of constant pressure inside the material due to the ablation source.

ATTENUATION MEASUREMENT

Figs. 5a-5c show the recorded waveforms used for the attenuation measurements of three Inconel samples, all 0.25 in. (6.35 mm) thick. Nominal grains sizes were: No. 1, 22 \( \mu \text{m} \), No. 2, 76 \( \mu \text{m} \), and No. 3, 106 \( \mu \text{m} \). One striking characteristic of these waveforms is that they are essentially completely free of any extraneous signals reflecting from the glass delay line.

These reflections were significantly larger than the echo signals when the piezoelectric transducer was excited electrically and used as the source as well as the detector. In fact, the signal-to-noise ratio under these conditions was not large enough to make the attenuation measurement with this transducer. Therefore, a lower frequency transducer (center frequency 20 MHz) was used for the comparison between the electrical and laser source methods. Clearly, the laser source coupled with piezoelectric detectors would be very useful for backscatter measurements because then the high amplitude generating capacity and wide bandwidth of the laser source is used with the high sensitivity of the piezoelectric detector. This is evident in the clarity with which the backscatter from the material microstructure is resolved (Figs. 5a-5c).

Attenuation measurements for the Inconel samples by both the laser source and conventional piezoelectric source are compared in Fig. 6. As mentioned above, the piezoelectric source method utilized a low frequency transducer to obtain an adequate signal-to-noise ratio. The laser source results extend up to higher frequencies and were limited at the low frequency end by the bandwidth of the detecting piezoelectric transducer. Both results incorporate the appropriate diffraction corrections and agree
Fig. 5a-c. Recorded through transmission longitudinal waveforms for three samples of Inconel with different attenuations using the laser source and a 75 MHz piezoelectric transducer with a glass delay line.
Fig. 6. Comparison of the measured attenuations in the three Inconel samples between the laser and piezoelectric source methods.
where they overlap. The laser source technique does not yield a direct measure of the sample/piezoelectric transducer interface reflection coefficient. This was determined experimentally by pulsing the piezoelectric transducer electrically and recording the reflected signal. These results are not intended to suggest that using the laser source in this way is the preferred method for making attenuation measurements. Rather, they are intended to further the understanding of the laser source and show how it may be used effectively.

CONCLUSIONS

The pulsed laser has been used as an efficient source for elastic wave generation in materials. In particular, longitudinal waves of higher amplitude have been recorded than could be produced with conventional electrical excitation of piezoelectric contact transducers. This is directly related to the absorption of optical energy and subsequent ablation of material (externally applied) at the surface. The laser pulse produces very wide bandwidth signals, is noncontacting, and can be modeled as a point source when small spot sizes are used. The ablation regime has been found to be very useful for microstructural scattering measurements.

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REFERENCES


