Directivity measurements in aluminum using a laser ultrasonics system

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Abstract. A laser ultrasonics system was setup to measure the directivity (angular dependence pattern) of the amplitude of ultrasonic waves generated in aluminum samples. A pulsed Nd:YAG laser operating at 1064 nm optical wavelength, with typical pulse width (FWHM) of 8 ns, and energy per pulse of 450 mJ, was used to generate the ultrasound waves in the samples. The laser detection system was a Mach-Zehnder interferometer with typical noise-limited resolution of 0.25 nm (rms), frequency range from 50 kHz to 20 MHz, and measurement range from -75 nm/V to +75 nm/V. Two different optical spot sizes of the Nd:YAG laser were used to generate waves in the ablation regime: one was focused and the other was unfocused. Using the obtained data, the directivity graphics were drawn and compared with the theoretical curves, showing a good agreement. The experiments showed the directivity as a function of the optical spot size. For a point ultrasonic source (or focused optical spot), the directivity shows that the longitudinal waves present considerable amplitude in all directions. For a larger ultrasonic source (or an unfocused optical spot) the directivity shows that the longitudinal waves are generated with the higher amplitudes inside angles around ±10°.

1. Introduction

The laser ultrasonics technique typically has a pulsed laser that generates ultrasound waves and an interferometer to detect the waves. When inspecting a sample, these two devices can be positioned in the same side of the sample, to perform a single-sided measurement or a single-sided pulse-echo measurement, or they can be placed in opposite sides to make a direct transmission or oblique transmission measurements [1]. In these cases one can consider the relative position between the generation laser spot and the interferometer spot. The directivity or angular dependence is important to show where the generator and the detector should be placed for a better detection when inspecting a sample. Also it is important to characterize the laser ultrasonic source as in the work of Hutchins et al [2], Edwards et al [3], and Pouet et al [4]. In this work, the directivity measurements are presented for a laser ultrasonics source in ablation regime.

2. Theory

The theory used to draw the theoretical curves gives the directivity pattern for an ablation laser ultrasonic source [1], [2], [5]. In reference [1], the authors considered that the ablation source was
focused to a small area and the finite source size effects were not included. However, in this work, the size of the source is relevant and a function was included to account for the size of the optical spot. The equation that gives the angular dependence of the longitudinal wave in the ablation regime is [1]:

\[
U(\theta) \equiv \frac{2k^2 \cos \theta (k^2 - 2 \sin^2 \theta)}{(k^2 - 2 \sin^2 \theta)^2 + 4 \sin^2 \theta (1 - \sin^2 \theta)^2 (k^2 - \sin^2 \theta)^2} \\
\theta \sin \theta (1 - \sin^2 \theta)^2 (k^2 - \sin^2 \theta)^2
\]

(1)

where \( k \) is the ratio between the longitudinal wave velocity and the shear wave velocity, and \( U \) varies with the angle \( \theta \) in the farfield. The following equation was used for taking into account the size effect of the laser ultrasonic source [1]:

\[
\gamma(\theta) = \frac{J_1(2\pi a \sin \theta / c_L)}{2\pi a \sin \theta / c_L}
\]

(2)

where \( J_1 \) is the Bessel function of the first kind, \( f \) is the frequency of the ultrasound wave, \( a \) is the radius of the source (optical spot) and \( c_L \) is the velocity of the longitudinal wave. Multiplying equations (1) and (2), one can obtain the equation that gives the angular dependence, including the optical spot size effects:

\[
u_r(\theta) = U(\theta)\gamma(\theta)
\]

(3)

3. Experimental setup

The laser ultrasonics system was composed of a pulsed Nd:YAG laser to generate ultrasonic waves, an optical interferometer to detect the waves, and optical components. The Nd:YAG laser provided optical radiation at 1064 nm wavelength, with minimum pulse width (full width at half maximum - FWHM) of 8 ns, and energy per pulse of 450 mJ. The optical interferometer was a Mach-Zehnder type with typical noise-limited resolution of 0.25 nm (rms), frequency range from 50 kHz to 20 MHz, and measurement range from -75 nm/V to +75 nm/V.

The Nd:YAG laser and the interferometer were positioned in opposite sides of the sample, as shown in figure 1. The Nd:YAG laser beam was firstly deflected by the mirror \( M_1 \) and after by the mirror \( M_2 \). These mirrors were used to set the position of the generation laser spot. After the mirror \( M_1 \), there is an attenuator and a photodetector that detects the stray laser beam and generates a trigger signal that is connected to the oscilloscope trigger input. A converging lens was used in the experiments that needed a reduced (or focused) spot size in the generation side. The interferometer spot was focused over the sample surface, using its own coupled lens set. Its displacement output was connected to the oscilloscope channel.

![Figure 1. Experimental setup.](image-url)
The relation used to determine the angle was \( \theta = \tan^{-1}(x/h) \) and each waveform detected was related to its corresponding one. The origin of the \( x \) axis was the epicenter of the wave. This point was experimentally set through the alignment of the generation spot and the detection spot using an auxiliary semi-transparent sample. A correction factor for the experimental amplitude was included to account for the flat shape of the sample: the experimental amplitude was divided by \( \cos \theta \).

Two different optical spot sizes of the Nd:YAG laser were used to generate waves in the ablation regime: one was focused using the lens and the other was unfocused, without any lens.

4. Results

The first measurement was the directivity of the ultrasound generated by a focused laser beam, in the ablation regime, in an aluminum 6061 T6 sample with thickness of 4.6 mm. A convergent lens with 200 mm of focal length was used to provide a point source in the generation side. The sample was positioned on the focus. The Nd:YAG laser was operated using an energy of 55 mJ and the pulse width (FWHM) was approximately 17 ns. The laser spot radius was approximately 150 \( \mu \)m so the density of energy was approximately 78 J/cm\(^2\). The other surface of the sample, where the spot of the interferometer was positioned to detect the ultrasound, was polished to obtain a better signal to noise ratio at the output of the interferometer. The ultrasonic waveforms were acquired from -13\(^\circ\) to +75\(^\circ\) and they are shown in figure 3. The data obtained from the waveforms of figure 3 were used to draw the directivity of the longitudinal wave graphic, shown in figure 4. The squares are the experimental data and the solid lines were drawn using equation (3).

As can be seen in figure 4, the experimental data present a good agreement with the theory.

The same experimental setup and methods used in the former case were used to measure the directivity of ultrasonic waves generated by an unfocused laser beam, again in ablation regime, in an aluminum 2024 sample, with thickness of 9.6 mm. The energy used was approximately 250 mJ and the pulse width (FWHM) of approximately 12 ns. In this case, the lens was not used and the spot radius was approximately 3 mm at the sample surface so the density of energy at the sample was around 0.9 J/cm\(^2\). The waveforms were acquired from -15\(^\circ\) to +64\(^\circ\), and they are shown in figure 5.

The waveforms of figure 5 have a different shape compared to the waveforms showed in figure 3 due to their different density of energy [1].
The data obtained from the waveforms of figure 5 were used to plot the graphic shown in figure 6. Again, the squares are the experimental data and the solid line, the theory. The longitudinal wave directivity for the non focused spot, shown in figure 6, presents the waves with higher amplitude in a direction narrower than the direction for the waves using a focused spot. The experimental data agrees with the theory up to around 20°. The disagreement for angles larger than 20° is attributed to a residual thermoelastic generation. The thermoelastic directivity has a side lobe around 60° [1], similar to the small side lobe shown on the experimental data in figure 6. Although the predominance of the ablation regime, the thermoelastic effect becomes apparent due to the lower optical density of energy used.

5. Conclusion
For a point ultrasonic source (or focused optical spot), the directivity shows that the longitudinal waves present considerable amplitude in all directions. For a larger ultrasonic source (or an unfocused optical spot) the directivity shows that the longitudinal waves are generated with the higher amplitudes inside angles around ±10°. This is interesting for the generation of waves in the central direction, to perform a single-sided pulse-echo inspection or a direct transmission inspection. With the unfocused spot, a reduced density of energy is used since the spot area is bigger than the focused spot, nevertheless generating high amplitudes in the central direction. Also, using the non focused optical spot the detector must be positioned near the epicenter to detect the waves. On the other hand, it is not suitable to perform a single-sided inspection or an oblique transmission inspection. In this case the focused optical spot appears to be more suitable. In conclusion, the experiments suggest that the angular dependence pattern can be seen through the Huygens principle, having the waves spreading out at large angles for a small optical spot size compared to the acoustic wavelength. For optical spot sizes greater than the acoustic wavelength, the waves interfere constructively in the region in front of the acoustic source and destructively outside this zone.

Acknowledgments
The authors would like to thank Dr. Chiaki Miyasaka and the students John Mulry and Robert Cyphers. One of the authors (JMSS) acknowledges the provision of a scholarship from CNPq, process number 142191/2007-8, and an international scholarship from CAPES, process number 4697/08-1.

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