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This letter describes the first observations of x-ray generated ultrasonic signals in materials. The x rays used were the pulsed x-ray beams of continuous energy spectrum taken from a high-energy synchrotron source. The ultrasonic signals were detected with conventional piezoelectric transducers attached to stainless steel specimens.

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The use of short-duration thermal sources to generate ultrasonic signals in materials is not new. A review of the work up to five years ago has been summarized in a review article.[1] Recent publications described in detail the generation of ultrasonic pulses by laser excitations (Ref. 2) and by electrical arcs.[3] The detection of acoustic signals near a sample in an intensity modulated laser beam forms the basis of the photoacoustic spectroscopy (PAS) technique.[4] Also reported has been the generation of acoustic waves by an electron beam in a scanning electron microscope[5] and this interaction has been proposed as a means for investigating microstructural surface features of a material.[6] Similarly, intense x rays can also be expected to be a thermal acoustic source, but in contrast to the above sources, x rays which are exceptionally short wavelength photons can penetrate into the interior of a material to a depth related to the mass absorption coefficient which depends on the x-ray wavelength and the specimen material's atomic number. However, to our knowledge, the generation of ultrasonic or acoustic signals with x rays has not previously been reported. At a recent conference, papers dealing with synchrotron-generated x rays and ultrasonic waves, described a stroboscopic x-ray topography technique to visualize the microdeformations accompanying the propagation of ultrasonic waves through a material.[7,8] In these examples, elastic surface waves and the vibrations of single crystals of quartz were visualized but not generated.

Synchrotron radiation is emitted when particles such as positrons and electrons traveling at relativistic energies are accelerated in a high vacuum in curved paths in a magnetic field. Principal characteristics of this radiation include its high intensity, broad spectral range, high polarization, pulsed time structure, and natural collimation. At Cornell, such a high energy synchrotron source (Cornell High Energy Synchrotron Source: CHESS) is obtained in a parallel mode to the electron storage ring facility (Cornell Electron Storage Ring: CESR), in a region of the storage ring where high bend magnets whose radius is one-third that of normal ones are installed. Although higher energies are possible, CESR operates typically at an energy of about 5 GeV, which results in a critical x-ray energy (E_c) of about 10 keV. Features of the CHESS facility have been summarized by Batterman and Ashcroft[9] and its current status has been described by Mills.[10]

An important characteristic of the beams of x rays available for this experiment is their pulsed nature which is a direct result of the operating conditions of the storage ring. Here, intense bursts of x rays of 0.160-ns duration with a repetition period of 2.56 μs are obtained. The latter corresponds to the synchrotron operating frequency of 390.6 kHz.

Another characteristic of the x rays used in these experiments is their intensity and spectral characteristics. The beam of x rays associated with the synchrotron radiation has a continuous energy spectrum with a photon bunch power as high as 45 kW/mrad. This translates into beam energies of about 7.0×10^{-6} J/mrad for each pulse, which, after collimation, results in a beam energy of about 10^{-3} mJ at the surface of a specimen. By comparison, the typical range of thermal energy used in published laser/ultrasound experiments is approximately 30 mJ while for electrical arcs it is about 2 mJ.

The typical operating environment near a synchrotron is electrically and mechanically very noisy. This influences to a great degree what acoustic measurements are possible. Two transducers were used in these experiments to detect the ultrasonic signals. They were commercially fabricated units in which the piezoelectric element is backed with an absorbent backing and faced with a wear plate of either tungsten carbide or aluminum oxide with the entire assembly encased into a stainless steel holder. Both of the transducers used were designed to operate as broadband sensors, one at a center frequency of about 2 MHz and the other at about 7 MHz. Both had fractional bandwidths ranging from 80 to 120%. The transducer output was amplified 60 to 80 dB by preamplifiers whose bandwidth ranged from approximately 10 kHz to 2 MHz. The low-frequency response of the transducer/amplifier combination was limited principally by the response of the transducer, while the high-frequency characteristics were governed by the preamplifier. The frequency response of the system was determined by applying a step force directly on the transducer element and recording the output signal. The step force was obtained by breaking a glass capillary 0.05 mm i.d. and 0.08 mm o.d. The resultant signal rise time was less than 80 ns. Other transducer/amplifier combinations covering different frequency ranges were tried, but the choice of sensor and amplifier used was determined by resolution and signal-to-noise factors.

To facilitate recording the waveforms with a low-frequency A/D converter and to remove incoherent noise, the signals were displayed with a sampling oscilloscope. A fast photodiode whose rise time was less than 1 ns was used as an

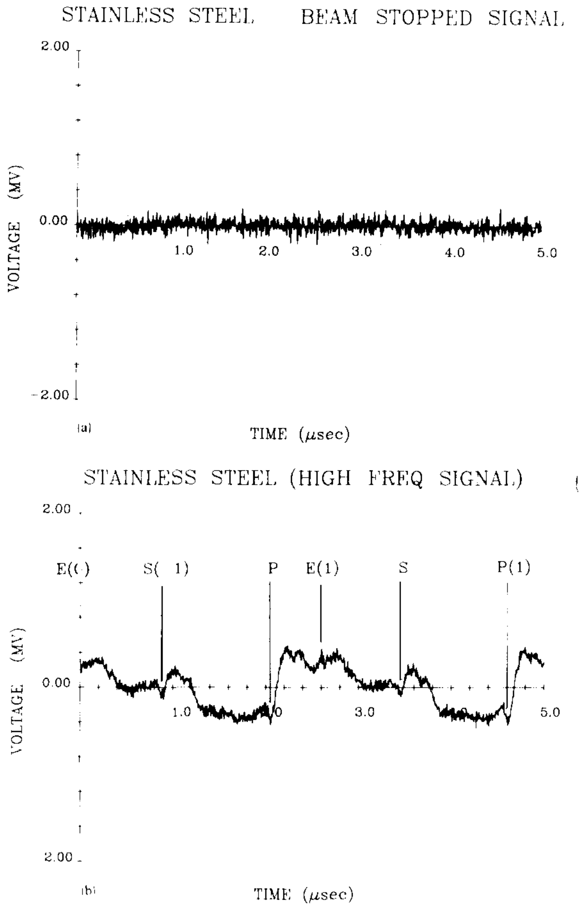

FIG. 1. (a) Detected ultrasonic signal in stainless steel, with x-ray beam stopped. (b) Detected x-ray generated ultrasonic signal in stainless steel with a broadband piezoelectric transducer (7-MHz center frequency). Longitudinal and shear pulse arrivals are denoted by P and S, respectively.

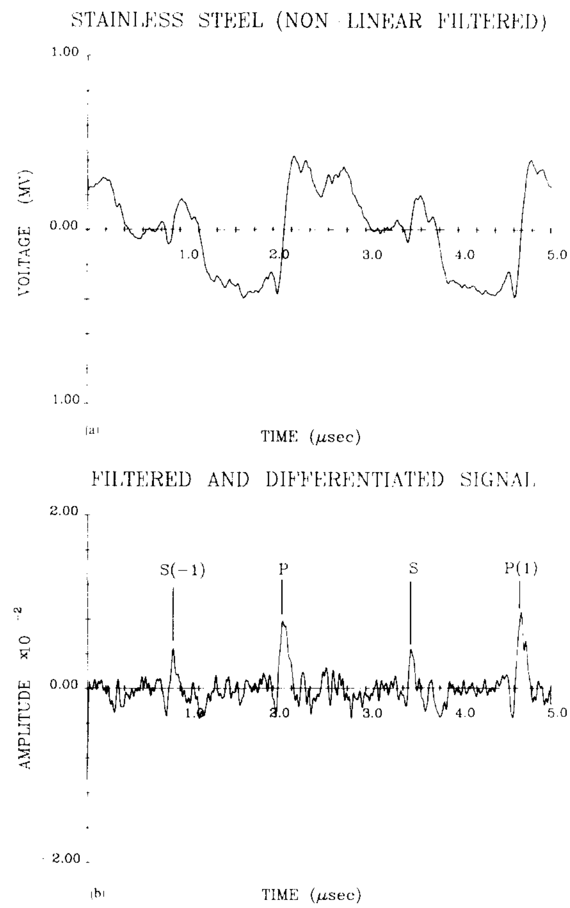

FIG. 2. (a) Digitally filtered x-ray generated ultrasonic signal detected by a broadband ultrasonic transducer [from Fig. 1(b)]. (b) Waveform of (a) differentiated. The arrivals of the P and S pulses are marked.

x-ray detector to generate a fast rise time electrical signal in synchronization with the appearance of the x-ray pulse at the exit of the beam pipe. Sequential sampling was arranged to occur in synchronization with this pulse. This procedure effectively minimized the effects of all non-x-ray pulse related mechanical and electrical results.

The specimens used in the experiments were disks of 304 stainless steel, approximately 6 cm in diameter and 1.14 cm thick. The specimens were held in position normal to the x-ray beam with a specimen fixture which also held the transducer against the specimen at the epicentral position on the back side of the specimen.

To verify that the test area near the specimen was electrically and mechanically quiet, a 1.27-cm-thick disk of brass was placed about 25 cm in front of the specimen to serve as a beam stop. Figure 1(a) shows the data of four signals averaged together after detection by the high frequency, broadband transducer attached to the back side of a specimen. It is seen that there appears to be no structure or other recognizable features in this time record.

When the beam stop was removed, the waveform shown in Fig. 1(b) was observed. The left edge at $t = 0$ corresponds to the interaction of the x rays and the front surface of the specimen. Approximately 2.5 μs later, another excitation occurs. The excitations are labelled $E(0)$ and $E(1)$ in the figure. The sharp downward peak at 2.051 μs, labelled P, coincides with the travel time of a P-wave (longitudinal) pulse to propagate once through the specimen. This appears to indicate that the acoustic source is near the front surface of the x-ray illuminated specimen. Another pulse arriving at 4.609 μs and marked S is the corresponding shear wave pulse propagating once through the specimen. Because the synchrotron radiation pulse repetition rate is approximately 2.5 μs, the pulse marked $S(-1)$ arriving at 0.873 μs corresponds to the shear wave pulse resulting from the excitation $E(-1)$, one cycle prior to the excitation pulse $E(0)$ at $t = 0$ in the figure. The reason for the large increase in signal amplitude (transducer output voltage) immediately subsequent to the P arrival signal is not yet known. We note that the increase of the signal subsequent to the arrival of the shear pulse is considerably less. The rise time of both the P or S pulses is approximately 50 ns, indicating that these signals contain ultrasonic frequency components at least as high as 20 MHz.

The identification of the other echo arrivals corresponding to the multiple internal reflections which are the $3P$, $2PS$, etc., signals in the specimen is complicated by signal attenuation effects and noise which obscures these echoes. Attempts were made to process the signal to determine whether these multiple internal reflections could be detected. Wave arrival time measurements are facilitated if the high-frequency noise can be removed from the waveform. Various filtering procedures are available for this. In Fig.

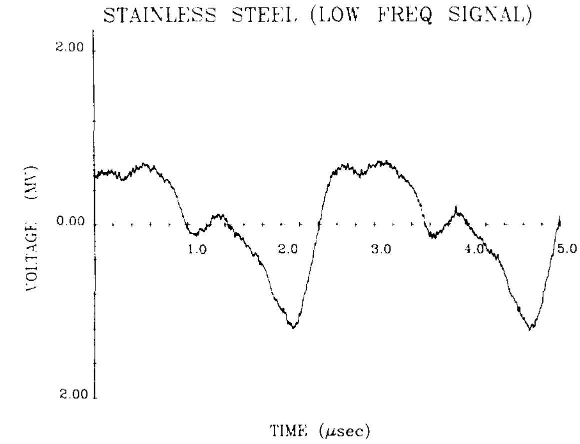

FIG. 3. Detected x-ray generated ultrasonic signal in stainless steel with a low-frequency broadband piezoelectric transducer.

2(a) is shown the result when a nonlinear, center-weighted digital filter is applied to the data of Fig. 1(b). This filter is a low-pass filter whose 6-dB point was at 25 MHz and 20-dB point at 50 MHz. The filter effectively removed all the noise which appears in Figs. 1(a) and 1(b). As a result, the pulse arrivals indicated in Fig. 1(b) are now clearly visible.

Differentiation of the data corresponds to a high-pass filtering operation which is a convenient means for removing the lower frequency components of the signal shown in Fig. 2(a). This method is a convenient means for obtaining a clear identification of the various ultrasonic longitudinal and shear elastic wave pulses propagating in the specimen. The results obtained by this operation are shown in Fig. 2(b). The results confirm that the transducer signal exhibits features which clearly correspond to ultrasonic signals in the specimen rather than being the sole result of a periodic electrical disturbance.

The results obtained with the lower frequency transducer are shown in Fig. 3. The ultrasonic signal appears similar to that obtained with the high-frequency transducer shown previously but it is significantly higher in amplitude. This is to a large extent the result of matching the transducer more closely to the transfer characteristics of the preamplifiers used to amplify the signals. The arrival times of specific wave pulses are more difficult to determine from this time record than from that obtained with the high-frequency broadband sensor and this limits the usefulness of low-frequency transducers in pulse arrival time measurements.

In conclusion, pulsed beams of x rays striking a specimen of stainless steel generate ultrasonic signals containing frequency components at least up to 20 MHz. While in these experiments the sound source appears to have been located near the surface of the specimen, for other materials it may be in the interior at a depth which is a function of x-ray wavelength, energy, and material properties. This is in contrast to arc and laser sound sources which interact with a specimen principally in a region near its surface. Thus, x-ray generated ultrasound can be expected to yield information about the internal properties and microstructure of a material. Its usefulness in this mode as a tool for characterizing the subsurface microstructure of a material remains to be realized. Additional experiments to explore some of these ideas utilizing other materials, surface conditions, various beam cross sections, and x-ray wavelengths are just beginning.

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