
Shadow optoacoustic method for measuring thermophysical characteristics of condensed materials under intense impulsive heating

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Abstract

The results of the development of a contactless remote technique for studying thermal characteristics of condensed matter under intense pulsed heating are presented. This technique involves measuring the speed of sound basing on the time of passage of a probing optoacoustic pulse in a target. To record an acoustic response, a schlieren system based on the shadow technique for visualizing optical phase nonuniformities was developed.

Keywords: physics of high energy density; laser optoacoustic, shadow method; schlieren system.

1. Introduction

The studies in the field of physics of high energy density (HED) in matter are of great priority. Owing to the experimental facilities of new generation, it became possible to produce a substance with extreme parameters in...
macroscopic quantities in a laboratory, thus ensuring obtaining of critical data on radiation physics, shock waves, hydrodynamic stirring of substances, equations of state, and relativistic plasma. Presently, one of the pressing problems of experimental HED physics is the development of methods and instruments for measuring various thermal characteristics of substances and studying their equations of state. When a substance is exposed to intense heating, its thermodynamic characteristics (pressure \(P\), temperature \(T\), and density \(\rho\)) change. The thermodynamic state of a substance can be characterized by at least two parameters in different combinations: \((\rho, T\)), \((\rho, \varepsilon)\), \((P, T)\), and \((P, \varepsilon)\), whereas the internal energy. To characterize the thermodynamic state of a substance, it is necessary to measure, e.g., \(P = P(\rho, T)\), \(P = P(\rho, \varepsilon)\), and \(V_S = V_S(\rho, \varepsilon)\), where \(V_S\) is the velocity of sound. During heating, the substance in the region of interaction may undergo several phase transitions (melting, evaporation, and transition to the plasmastate). In each of these phases, the substance possesses certain acoustic characteristics, such as the speed of sound propagation and the coefficient of absorption of an acoustic wave. In this case, the studied region itself is a source of ultrasonic waves of certain frequency and amplitude. The speed of sound propagation in a solid is indirectly related to the substance temperature. The acoustic wave passes distance \(L\) in the substance within time \(t = L(T)/V_S(T)\). Differentiating this equation with respect to the temperature yields [Fortov et al. (2008)]

\[
\frac{dt}{dT} = V_S(T) \frac{dL(T)}{dT} - L(T) \frac{dV_S(T)}{dT} \frac{1}{V_S^2(T)}
\]

(1)

Because substances expand during heating, both speed of sound \(V_S\) and path length \(L\) in a substance generally depend on the temperature \(T\). However, for most substances, \((dL/L)dT \sim 10^{-6} K^{-1}\), while \((dV_S/V_S)dT \sim 10^{-4} K^{-1}\); therefore, the thermal expansion of substances during heating can be disregarded and \(L\) can be considered constant. Then,

\[
\frac{dt}{dT} = -\frac{L}{V_S(T)} \left( \frac{1}{V_S(T)} \frac{dV_S(T)}{dT} \right) = -\mu \frac{L}{V_S}
\]

(2)

where coefficient

\[
\mu = \frac{1}{V_S(T)} \frac{dV_S(T)}{dT}
\]

(3)

characterizes the temperature dependent change in the velocity of sound in the substance.

Optical methods are used to generate sound in a wide frequency range from quite low acoustic (\(10^{-4}\) to \(10^4\) Hz) to hypersonic (\(10^6\) to \(10^9\) Hz) frequencies; however, because of the low efficiency of the light to acoustic energy conversion, the optoacoustic effect became practically applicable only after the appearance of lasers. The high intensity and directivity of laser radiation and the possibility of being focused into a spot, the dimensions of which are actually diffraction limited, ensure the excitation locality of acoustic waves, and the short pulse duration (\(10^{-8}\) to \(10^{-10}\) s) is the required time resolution of measuring the velocity of sound in the target substance.

2. Experimental setup

Figure 1 shows the optical diagram of the experimental setup for measuring the velocity of sound in a condensed matter subjected to pulsed heating. Radiation of a pulsed Nd:YAG laser (wavelength \(\lambda = 1.064\) μm) is focused with lens \(L1\) to the target surface. Pulse duration \(\tau\) was varied in experiments from 15 to 40 ns; the energy range was 1–100 mJ. Radiation focused at the target surface excites an acoustic wave that, propagating in the substance at velocity \(V_S\), reaches the surface on the opposite side of a sample within time \(t\). If thickness \(h\) of the target is known, measuring delay time \(t\) of the acoustic response relative to the optoacoustic action allows calculation of the velocity of sound (Fig. 1, inset): \(V_S = h/t\). [Kuznetsov et al. (2006)].

To detect an acoustic response, an optical system based on the schlieren method, which belongs to the shadow techniques for visualizing optical phase nonuniformities widely used in optics, was developed. The schlieren method utilizes the well known optical procedure of Fourier filtering of a light beam with a nonuniform phase distribution over the cross section using lens $L_2$ (receiving objective) and an amplitude filter (knife diaphragm), a screen with a straight sharp edge nontransparent for light and located in the lens’ focal plane (plane of spatial frequencies) (Fig. 1). The inverse Fourier transform is performed with lens $L_3$ (visualizing objective lens). The Foucault knife overlapping a half of the Fourier plane actually realizes a unidimensional Hilbert transform of an optical signal, which is largely analogous to differentiation and thus accounting for visualization of phase nonuniformities. The knife diaphragm in the lens’ focal plane transforms distortions in the reflected wave front into an intensity change, which is recorded by a photodetector (PD). As the radiation source of the system for optical detection of the acoustic response, a CW single frequency YVO$_4$:Nd$^{3+}$ solid state laser with intracavity generation of the second harmonic ($\lambda= 532$ nm) at a power of 50 mW (the spectral line width <5 MHz, the optical noise level~0.1% rms) is used. Lens $L_4$ focuses the probing beam to a sample.

The system for detecting the reflected beam consists of lenses $L_2$ and $L_3$, the knife diaphragm, and PD $D_1$. Beam splitting plate $BS$ and lens $L_5$ focusing laser radiation to PD $D_1$ is used for photoelectric recording of Nd:YAG laser pulses. After preamplification, electric signals from PDs are recorded by a digital oscilloscope.

Figure 2 shows typical oscillograms of signals from PDs $D_1$ and $D_2$: a pulse of the Nd:YAG laser exciting an acoustic wave in a 2.0 mm thick target manufactured from an aluminum alloy and acoustic responses recorded by the schlieren method on the opposite side of the target surface. Measurements were performed in the thermostatting regime at the temperature of a sample of 25°C.

The maximum of the first peak in the oscillogram (Fig. 2b) corresponds to a time delay of an acoustic response of $374 \pm 1$ ns relative to the exciting laser pulse (Fig. 2a); the second peak is delayed by $770 \pm 1$ ns. The time delays of recorded signals of these acoustic responses depend on the mutual positions of the focal points of the acoustic pulse exciting and probing radiations. Within the experimental error, the amplitudes of signals of acoustic responses are linear functions of the pulse energy of the Nd:YAG laser. Acoustic responses were reliably recorded at energies as low as 1 mJ with a signal to noise ratio of ~2.

When the probing pulse moves over the target surface relative to the focal spot of the Nd:YAG laser radiation, to the right or left (in the plane of Fig. 1) with respect to the focal point of the power pulse, the amplitudes of acoustic responses are inverted. If the focal points of the exciting and probing radiations on the opposite sides of the target are positioned at a minimum distance from each other equal to the target thickness, only the first acoustic response with a time delay $t = 319 \pm 1$ ns (Fig. 2c) is recorded; this delay corresponds to a sound propagation speed in the substance $V_S = (6.27\pm0.02) \times 10^5$ cm/s. (The tabulated values of the speed of a longitudinal acoustic wave are $V_S = 6.26 \times 10^5$ cm/s in pure aluminum and $V_S = 6.32 \times 10^5$ cm/s in aluminum alloy 5056 at $T = 20$°C.) The second peak in the acoustic response observed in oscillograms for a position of the focal points of the exciting and probing radiations, which are displaced with respect to the normal to the surface, corresponds to a strain of the sample surface by a transverse acoustic wave ($V_S = 3.08 \times 10^5$ cm/s and $V_S = 3.19 \times 10^5$ cm/s in aluminium alloy 5056 at $T = 20$°C).

3. Measurement results

To refine the technique described, a target in the form of a disk 40 mm in diameter and 1.83 mm in thickness (1440 aluminum alloy) was used as the test object. The experimental studies of the temperature dependence of the velocity of sound in aluminum were performed at the cooling stage of the target preliminarily heated to $T = 400$°C. The measurements were conducted in the temperature range 400–150°C using a platinum thermistor (HEL-700-U-1-A Honeywell) included in a bridge circuit and ensuring an accuracy of 0.1°C. The temperature sensor is mounted in a 0.8 mm diameter hole at a distance of 5 mm from the excitation region of the acoustic wave. To ensure a proper thermal contact between the target and temperature sensor, the hole was filled with a heat conducting paste.
Fig. 1. Schematic diagram of the schlieren method for recording optoacoustic signals: (L1–L5) lenses, (BS) beam splitter, and (D1, D2), photodetectors.

Fig. 2. Oscillograms of signals from PDs D1 and D2: (a) Nd:YAG laser pulse exciting an acoustic wave; (b) acoustic responses recorded on the opposite side of the target surface; and (c) acoustic response for the focal points of the Nd:YAG laser beam and the probing beam located on the opposite sides of the normal to the target surface.

Fig. 3 shows the experimental dependence of the sound velocity of longitudinal acoustic waves by temperature during slow cooling of the aluminum sample, placed in a thermostat. The approximation of the experimental temperature dependence by a linear function yields the following value of the temperature coefficient of the velocity of sound in the sample:

$$\frac{\Delta V_s}{\Delta T} = (-1.49 \pm 0.09) \times 10^{-3} \text{cm/(s } ^\circ \text{C)}$$ (4)
In conclusion, it should be noted that, in the presence of vibrations of mechanical elements of the setup, the statistical error in measurements of time intervals is determined by fluctuations of the mutual location of the focal points of the exciting and probing radiations. In measurements of acoustic responses with a high time resolution, the optical system must be vibroinsulated to a maximum degree. In our case, under the conditions of the experimental room, the statistical measurement error was ±1 ns.

4. Conclusion

The described optoacoustic technique for studying the thermal parameters of condensed substances subjected to pulsed heating allows contactless measurements on targets with a characteristic size of ~1 mm. The linearity of acoustic responses also makes it possible to use the developed schlieren technique for direct investigation of the processes of volume absorption of an ion beam by a condensed substance.

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References