Characterization of Elastic Properties of Metals and Composites by Laser-Induced Ultrasound

V.V. Kozhushko, V.P. Sergienko, Y.N. Mirchev and A.R. Alexiev

Abstract The development of new materials and composites with desired mechanical properties requires methods for evaluation of their elastic moduli. The direct measurements of the shear and longitudinal ultrasonic pulse are the simplest approach for solution of these tasks. Among the drawback of the traditional ultrasonic methods are narrow bandwidth and necessity of the relatively large volume of the material for testing. Laser excitation of ultrasound is based on optoacoustic conversion that induces bulk pulses of about tens nanosecond duration and can be applied for time-resolved measurements of velocities. The paper considers several experimental arrangements, which combine laser excitation of probe ultrasonic pulses and their detection for measuring the velocities of longitudinal and shear pulses. The features of detection in single crystal and polycrystalline nickel as well as steel specimens are discussed.

Keywords Laser-induced · Ultrasound · Scattering · Elastic moduli · Non-destructive testing · Optoacoustics

1 Introduction

The ultrasonic waves imply spreading of mechanical motion of particles with frequencies above megahertz that is evidently connected with the elastic properties of media. Considering simple case of isotropic media, there are two modes of longitudinal or compression and shear or transverse wave propagation. The velocities

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of these modes depend on the stiffness tensor and density of material according to the expression:

$$C_{\mathrm{L}} = \sqrt{\frac{\lambda + \mu}{\rho}}, \quad C_{\mathrm{S}} = \sqrt{\frac{\mu}{\rho}}, \tag{1}$$

where C_{L} and C_{S} are the longitudinal and shear velocities of material, λ, μ are Lame constants connected with a stiffness tensor in Voigt notation as $C_{11} = \lambda + 2\mu$, $C_{44} = \mu$ for isotropic material, and ρ is the density of material [1].

Thus, the measurements of the velocities of ultrasonic waves or more generally pulses, which comprise of wave packet, yield the moduli of material. Two tasks have been solved, namely: the excitation of media and detection of these disturbances in time. The time-resolved methods employ short pulses with broadband spectra in contrast to the resonant methods, which measure disturbance during the long-time period and consider narrower frequency range, but in the both approaches, the dimensions of the specimens bind the experimentally obtained data with stiffness tensor. The advantage of the pulse-resolved method is a simple calculation of the moduli on the base of experimental data, while the resonant methods can be employed for materials, which have anisotropy of elastic properties owing to the texture or residual stresses induced by rolling or local overheating. The numerical methods for solution of the direct problem of modal analysis can be employed for evaluation of the specimen with anisotropy of elastic properties. These approaches allow the measurements of the propagation velocities of shear and longitudinal pulses and determination of the stiffness tensor that is keynote task of material science.

Nowadays ultrasound solves numerous tasks of non-destructive testing, properties evaluation and noninvasive medical diagnostics that evidently means appropriate excitation of probe pulse and the following successful detection. There are established well-known approaches of ultrasound excitation and detection as, for instance, by piezoelectric or electromagnetic acoustic transducers.

The materials of the sensitive elements of piezoelectric transducers are lead zirconate titanate (PZT) ceramics or polymeric films of polyvinylidene fluoride (PVDF), which have been polarized. Transducers employ inverse and direct piezoelectric effects to switch between operation in transmitter–receiver modes for excitation of the probe pulses and detection of its returned part. The thickness and the area of the sensitive element determine the operational bandwidth, capacity, sensitivity and other characteristics of single transducer. Applied high voltage pulse induces deformation and launches probe ultrasonic pulses; afterwards the transducer is switched into the receiving mode. In order to deliver the probe pulses the acoustical contact is provided between transducer and specimen by couplant, such as liquid or gel. There are transducers, which induce longitudinal pulses with spectra covering different bands up to hundreds megahertz. It should be mentioned that this is cost-effective method, which needs a couple of integrated circuit chips and high voltage power supply. The most often highlighted drawback of piezoelectric transducers is mechanical contact that reduces the operational bandwidth. There is alternative solution called dry contact, which employs a thin rubber layer attached to the transducer's front surface. It can pass sufficient amount of the pulse energy into specimen, when the couplant is harmful for the specimen or surface treatment is difficult. Obviously, dry contact approach also suffers from the reduction of the operational bandwidth. The excitation of shear pulse employs internal reflection of initially longitudinal pulses from the prism surface. The evaluation of moduli can be carried out by immersion of the specimen in water bath with a remark that liquids convert shear waves to longitudinal waves. It is noteworthy that piezoelectric transducers can be applied for task of moduli evaluation to the largest set of materials as porous media, plastics, fiber-reinforced composites, dielectrics, alloys, metals, etc.

The electromagnetic acoustic transducers (EMATs) can be applied for noncontact excitation and detection of ultrasonic pulses owing to Lorenz forces in conductive materials and/or forces on the magnetization vector and magnetostrictive effect in ferromagnetic metals. The operational bandwidth of EMATs depends on the properties of the materials and for both cases of excitation and detection can exceed 50 MHz [2]. The generation of transient electromagnetic field requires powerful current source to feed coil in biasing permanent magnetic field. The sensitive elements of these transducers are simple varnished copper wire coils, which are set in the biasing permanent magnetic field. The arrangements of the permanent biasing magnets allow excitation of longitudinal and shear waves propagating perpendicular to the surface of specimen. The main shortcoming of the technique is low efficiency of conversion for pulse excitation since the skin depth decreases penetration of transient electromagnetic field that limits the high-frequency excitation. The amplitude of the coil signals, induced in detection, decreases with distance from the metal surface or gap between coil and specimen that requires as close as possible location for better performance.

The laser-induced ultrasound or optoacoustics is a technique, which overcomes some shortcomings of conventional methods [3, 4]. The main advantage of optoacoustic pulses relates to the noncontact excitation of ultrasound with essentially broadband spectrum. There are several all-optical arrangements, which comprise of laser excitation and detection units and are very attractive for industry due to the capability of operation without surface treatment at elevated temperature. Unfortunately, all-optical laser-induced ultrasound is a very expensive tool while numerous tasks of properties evaluation can be solved in laboratory conditions by combination of laser excitation and one of the conventional transducers as, for instance, piezoelectric transducers or EMATs, which are used only for detection and can be called, respectively, as sensors or detectors of broadband ultrasonic pulses. The aim of the paper is to show advantages of laser-induced ultrasound in comparison with traditional approaches for solving the task of bulk velocity measurements. The paper considers several experimental arrangements and deals with measurements in single crystal Ni(100), polycrystalline nickel and steel 40× (Russian notation) or 5140 (American notation) that reveals features of excitation, elastic mode conversion, ultrasonic scattering and detection methods.

2 Excitation and Detection of Optoacoustic Pulses

As it was mentioned before, optoacoustics implies generation of the ultrasound due to the conversion of the laser pulse energy. An example of experimental arrangement is present in Fig. 1. The Q-switched solid state Nd:YAG laser operating on a wavelength of 1.064 μm or 532 nm with pulse duration of <10 ns is a typical source used for the excitation of broadband ultrasonic pulses. The needed energy is about 10 mJ per pulse and the maximum power density at the specimen's surface is below 20 MW/cm^2, which is a limit for thermoelastic excitation. The fast photodiode as, for instance, Hamamatsu S5971, triggers the digital oscilloscope with the analogue bandwidth of at least 100 MHz. The coaxial cable connects the input of oscilloscope with the output of broadband preamplifier, which increases the signal induced in the sensitive element of detector or transducer. The oscilloscope usually averages the signals for reduction of a noise of electronics.

The measurements of longitudinal pulses velocity employ the specimens in the form of plate or disk with parallel faces for time-resolved detection of the series of echoes or reverberations. The efficiency of laser radiation conversion to elastic pulses depends on both properties of absorbing and transparent media and parameters of laser radiation, such as spot geometry and envelope of the pulse intensity. The absorption coefficient defines penetration depth and the volume of the material, where the heat sources are deposited. The absorption of optical or near infrared radiation is above 10^4 cm^{-1} in metals, but it is noteworthy that significant a part of radiation can be reflected by the surface. The in-depth penetration of optical radiation is not more than several tens of nanometers from the interface with transparent medium hence the heat sources localize at the surface of the metal. The heat capacity, density and heat conductivity define the process of heat spreading from the initially deposited sources. The heat penetration depth can be obtained from expression $\sqrt{\chi\tau}$, where χ is the heat diffusivity of material and τ is the laser pulse duration. This expression defines the heat diffusion length $\sim$0.5 μm into nickel and around 1 μm for aluminum and copper, which are relatively good heat conductors. These distances are significantly smaller than traveling path of acoustical pulse during the same time, therefore the interaction of heat and elastic waves can be omitted and the solution of heat distribution and acoustical waves obtained consistently. The local nonstationary increase of the temperature involves

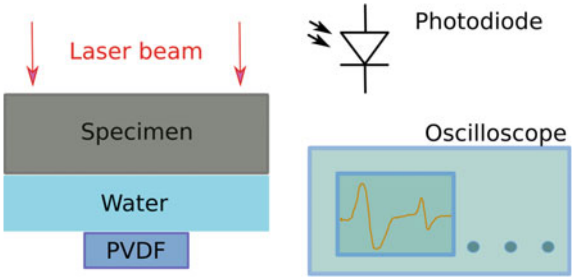

Fig. 1 Arrangement for measurement of laser-induced longitudinal pulse velocity

fast expansion and excitation of the elastic pulses, which duration is comparable with laser pulse envelope. The method of transfer functions can be applied for separation parameters of laser radiation such as envelope of the laser pulse intensity and the form of the laser spot from the properties of transparent and absorbing media, where the ultrasonic pulses can be induced [3].

The simple one-dimensional approach implies dominant excitation of longitudinal pulses that can be managed by wide laser spot in comparison with traveling distance of sample thickness. This is the most often used approach for solution of numerous tasks of non-destructive testing and properties evaluation. The Fourier transformation allows the calculation of the spectra of induced pulses that is well described in the literature. The spectrum of the excited longitudinal pulse can be expressed as follows:

$$P(f) = K(f) I_0 L(f), \tag{2}$$

where $K(f)$ is a transfer function describing the efficiency of optoacoustic transformation, which depends on the properties of absorbing and transparent media, I_0 is the intensity of the laser pulse and $L(f)$ is the spectrum of the envelope of the laser pulse. Thus, the spectrum of optoacoustic pulse is proportional to the spectrum of the laser pulse that relates to thermoelastic regime of excitation with fluence <20 MW/cm^2 on the metal surface. The efficiency of conversion can be around 1 Pa/(W/cm^2) and it is frequency dependent but some arrangements diminish this dependencies due to insignificant variation in the bandwidth of the laser intensity envelope spectrum [5]. The pressure pulses with peak amplitude of 20 MPa and strain up to 10^{-4} can be launched in metal. The increasing of the laser fluence leads to the ablation mode, where the sublimation of the overheated layer of material exerts normal to the surface of the specimen and induces dominantly longitudinal elastic pulse.

An example of signal detected in single crystal nickel disk by piezoelectric transducer is present in Fig. 2. The transducer's sensitive element is 25 μm-thick PVDF film of 2 mm diameter. The operation of the amplifier in 'short-circuit current' mode allows detection of the frequency in the range from 3 MHz up to 90 MHz at the level −20 dB [6]. The part of the primary pulse passes the metal–water interface while the rest part of the pulse reflects back to the volume of the specimen. The transition (T) and reflection (R) coefficients for amplitude of pulse, which propagates from medium with impedance z_1 to medium with impedance z_2:

$$T = \frac{2z_2}{z_1 + z_2}, \quad R = \frac{z_2 - z_1}{z_1 + z_2}, \tag{3}$$

where z_1 and z_2 are the acoustical impedances of media. The reflection coefficient for nickel–water interface is $R = -0.94$, where the negative sign means the changes of pulse phase to opposite one's as, for instance, from compression to dilatation. The phase of presented pulses are conserved due to additional reflection at nickel–air interface with $R = -1$ due to the fact $z_2/z_1 \ll 1$. It is noteworthy that the attenuation of ultrasound in coupling water layer increases with the square of the frequency that should be taken into account.

The efficiency of excitation of longitudinal pulses is higher in ablative mode but leads to insignificant damage of the surface that is acceptable for the solution of the task of moduli evaluation. However, the immersion of the specimen in optically transparent liquid also increases the efficiency of optoacoustic conversion that worth to be discussed. The boundary conditions of equality of the temperatures and heat fluxes take place at the interface water–metal, but the temperature raising in liquid induce stronger thermoelastic strain because of at least one order of magnitude higher thermal expansion coefficient. Because the acoustical impedances of liquids are lesser but comparable with those of metals, hence the next point relates to the acoustic loading of the interface, since it is some intermediate case between acoustically free and rigid boundary conditions [5]. The experiments show increase of the efficiency of longitudinal pulse excitation by modification to the initially dry interface to liquid covered. This is simple way to increase peak-to-peak amplitude and magnifies the low frequencies part of the spectrum. The estimations show that the temporal form of laser-induced pressure pulse is close to the envelope of laser pulse intensity and has pronounced compression phase for one-dimensional approach. The launched probe pulses undergo changes of spectrum and wave front during the propagation in the specimen that decreases the peak-to-peak amplitude.

The primary longitudinal pulse arrives at about 1.8 μs after triggering of photodiode that includes traveling time through the coupling water layer and time for passing the specimen. The echoes or reverberations arrive for the same time, afterwards. The interval between zero-crossing points of neighboring pulses corresponds to the time required for traveling over double thickness of the specimen that can obviously be used for evaluation of the velocity. The obtained value of longitudinal velocity is 5.32 ± 0.02 km/s. The peak-to-peak amplitudes of the

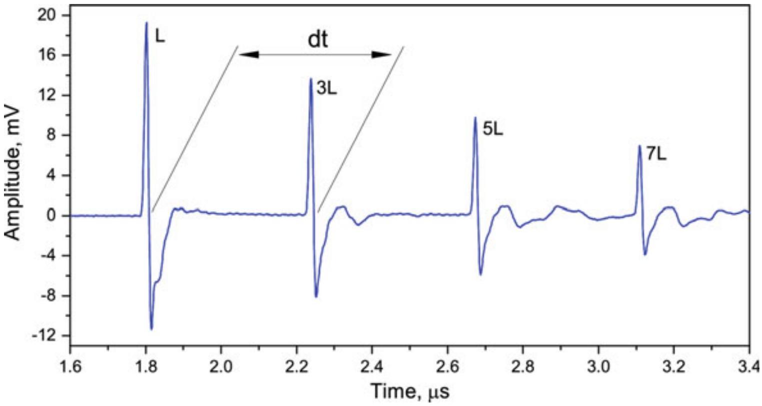

Fig. 2 Optoacoustic signal in 1.16 ± 0.02 mm-thick Ni(100) single crystal disk measured by PVDF transducer. The *symbols* near pulses show the pass distance in number of thicknesses, for instance, *L* means one and 3*L*—three thicknesses for longitudinal pulse

pulses state decay due to the losses, which comprise of attenuation and diffraction. The possible reasons of attenuation are considered below, while diffraction is the more general phenomenon. The initially induced pressure pulse has plane wave front with Gaussian distribution of pressure amplitude over it cross-section, which relates to the area irradiated by laser beam. The present signal was induced by laser beam of 6 mm diameter and it detected by PVDF sensor with 2 mm diameter of the sensitive element. Ultrasonic beam should possess axial symmetry and spreads into the bulk of the specimen. The axial location of the sensor yields the best capability for longitudinal pulse detection. The influence of diffraction can be expressed as

$$D = \frac{\lambda x}{a^2} \tag{4}$$

where D is the diffraction factor, λ is the wavelength of ultrasound, x is the traveling distance, a is the diameter of the laser spot on the metal surface. The diffraction is negligible for selected frequency or wavelength when $D < 1$ and the wave front can be considered as plane at the axis of the beam. The wave front changes with propagation distance and in the far diffraction zone, it can be considered as spherical that corresponds to the case $D > 1$ defining conditions for one-dimensional arrangement. The situation is complex for broadband pulse spectrum, which experience deviation of wave vectors from the axial propagation. These deviations involve waves during propagation starting from low-frequency part to the highest part of pulse spectrum. It is assumed that dispersion is negligible, while declined waves induce both reflected and refracted shear and longitudinal pulses [1]. This explains the distortions between echoes of longitudinal pulse in Fig. 2.

The piezoelectric transducers can be applied to any kind of materials from polymers to metals and their main advantage is good sensitivity with possibility to operate in the bandwidth compared with noncontact laser methods. The electrical signal of sensitive element should be delivered to input of oscilloscope that requires the using of amplifier with broadband operation. The present signals were obtained by PVDF film sensor with preamplifier which operates in ‘short-circuits current’ mode, which provides broader and mainly high-frequency detection and insensitive to the slow pressure variations. The time constant $T = 2\pi RC$ is product of sensitive element capacity and resistor in electrical circuit. The detection of the frequencies about 100 MHz is possible when time constant <5 ns that is fulfilled in our circuit with the sensitive element capacity of 12 pF and 50 Ω input of resistor. The charge induced on the electrodes of the sensitive element flows through the resistor. This voltage drop is connected with the positive input of operational amplifier. The output signal of operational amplifier is time derivative of the pressure pulse in contrast to the ‘voltage’ detection mode, which allows increasing the sensitivity in low-frequency range for detection of the narrower frequency bandwidth by increasing the time constant. The thickness resonance of 25 μm-thick PVDF film yields the high frequencies border of about 90 MHz at −20 dB level (construction details are present in [5]). It is possible speculate about widening the frequency range by using of the commercially available thinner films of 9 μm, but due to the frequency increasing attenuation of ultrasound in water, the thickness of coupling layer reduced with decreasing of interval between echoes in water.

Contactless detection of laser-induced ultrasound by EMAT transducer is well-promising approach for solution of numerous tasks of material science. The sensitive element of designed EMAT transducer is simple pancake coil of Ø5 mm with 10 windings of lacquered copper wire of Ø0.15 mm (see Fig. 3). The estimated inductance of the coil is 0.2 μH. The coil is placed at the center of cylindrical NdFeB permanent magnet with the inner diameter of 13 mm and the outer diameter of 25 mm. The measured field of 0.25 T partly magnetizes the specimen but it is far from the saturation of magnetization. The operational amplifier is close integrated with coil and it is placed in aluminum housing. The previous experiments demonstrated time-resolved detection of laser-induced longitudinal optoacoustic pulses in 0.4 mm-thick steel, where the spectrum of the primary pulse was in the range from 5 MHz up to 200 MHz [7].

The measurements were carried out with the same power density as in the case of PVDF sensor and, therefore laser-induced pressure pulses should have the amplitude, but peak-to-peak amplitude of signals is lower. The main contribution to the detected signals is due to the magnetostriction of nickel. The absence of the coupling water layer yields the faster arriving of the laser-induced longitudinal pulse afterwards the shear pulse appears. It is noteworthy that the area of the coil is comparable with the cross-section of the beam of about 6 mm that allowed detection of laser-induced longitudinal and shear pulses. The beams of these pulses have different directivity and continuously change the wave front. The top water layer increased the amplitude of initially induced longitudinal pulse and other pulses, which were induced due to at least one conversion of longitudinal beam. The fact of increasing of longitudinal pulse intensity is well-known [6]. However, water layer did not significantly change the amplitude of pure shear pulses since their efficiency of excitation depends mainly on the spatial distribution of the laser intensity at the surface. The reflection of deviated pulses induces two modes every time. Figure 4 clearly shows the complexity of ultrasonic field even in single crystal specimen. The obtained values of longitudinal and shear waves were 5.23 ± 0.02 km/s and 3.69 ± 0.02 km/s, respectively. It proves the fact that direction $\langle 100 \rangle$ of cubic crystals is soft with the lowest values of the velocities.

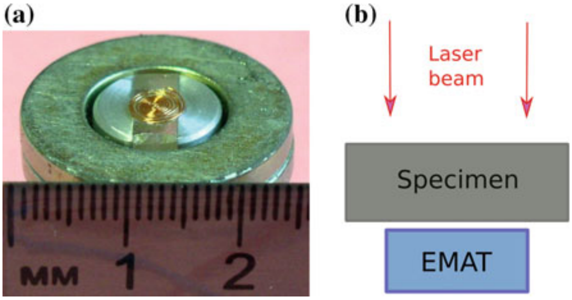

Fig. 3 Image of the detection coil in the *middle* of EMAT permanent magnet (**a**), experimental arrangement (**b**)

By considering in Fig. 2 the signal, obtained by PVDF sensor, one can conclude that the distortions between the reverberations are caused by refracted and converted pulses at nickel–water interface to longitudinal pulses propagating towards detector. Obviously, the shear pulses are deviated from the normal to the surface and pass longer distance than the specimen's thickness that is difficultly to estimate but can be used as the first approximation [7]. The considered experimental arrangement allows using the arriving time of the primary longitudinal pulses for velocities measurements that is very attractive in the case of strong damping of ultrasound, when the peak-to-peak amplitude of echoes signal is very low.

3 Attenuation and Scattering of Ultrasonic Pulses

The attenuation of ultrasound relates to the irreversible conversion of the elastic energy to heat. The damping is attributed to several phenomena such as hysteresis, thermoelastic damping and internal friction associated with defects such as the

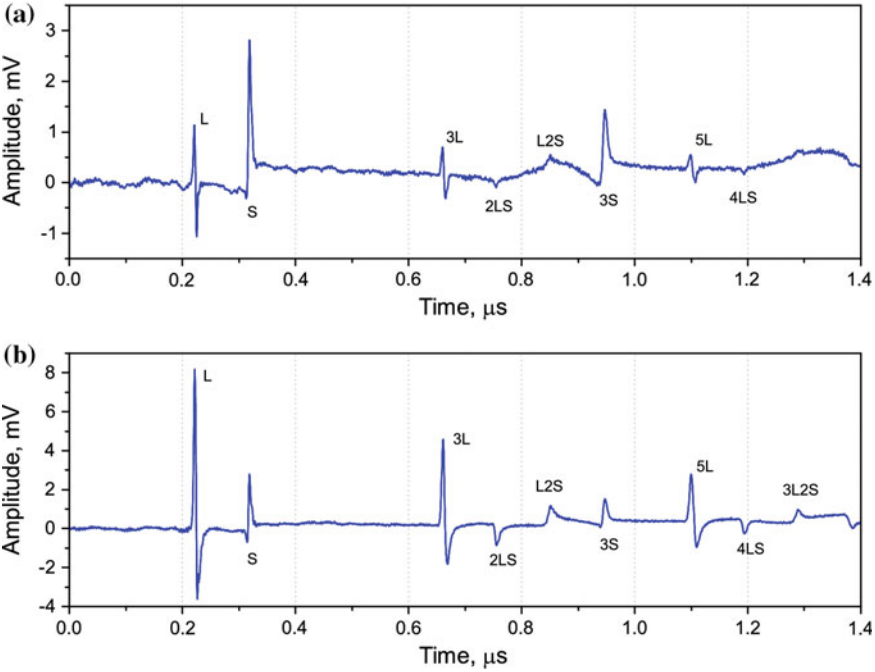

Fig. 4 Optoacoustic pulses, detected in 1.16 ± 0.02 mm-thick Ni (100) disk, by EMAT in accordance with experimental arrangement without water layer (**a**). The irradiated surface of the disk was immersed in water, while the laser energy and position of the specimen were fixed. The peaks are assigned by mode of traveling pulses as longitudinal (*L*) and shear (*S*), where the *number* before letter means quantity of the pass thicknesses for this mode

atoms of impurities and dislocations. Generally, the attenuation increases with frequency while some terms demonstrate different frequency dependences and therefore dominate in different frequency ranges. It is rather difficult task to separate the contribution of different factors into experimentally measured attenuation of ultrasound. The damping of ultrasound reduces mainly the high-frequency part of the spectrum and, therefore, the peak-to-peak amplitude.

The single crystal materials possess anisotropy of physical properties in contrast to glasses and polymers, which are examples of isotropic materials. The most metals and composite materials can be considered only as statistically isotropic media that means their properties are equal for different directions at the distances, which are significantly larger than the sizes of local inhomogeneities. As polycrystalline materials comprises of randomly oriented grains their size strongly influence on the scattering, which implies conversion of initially propagating ultrasonic waves at the grain boundaries to refracted and reflected waves of both modes. Thus, the scattering also decreases the amplitude of the probe pulse with distance. The unified theory of scattering has defined dependences of attenuation α for three possible regimes according to the relation of propagating wavelength and mean value of grain size [8]:

(i) Rayleigh scattering, $d < \lambda$ for $\alpha \propto d^3 f^4$;
(ii) Stochastic scattering, $d \approx \lambda$ for $\alpha \propto d f^2$;
(iii) Geometric scattering, $d > \lambda$ for $\alpha \propto 1/d$.

These expressions were used in numerous attempts to reveal the mean value of microstructure of polycrystalline materials by measured attenuation. In order to estimate the regime of scattering for operational bandwidth of laser-induced ultrasound, the value of longitudinal velocity in metals is around 5 km/s that means the bandwidth from 1 MHz up to 100 MHz comprises of the wavelengths from 5 mm down to 50 μm, respectively. The mean value of grain size is around 50 μm and, therefore, the scattering should be described in the terms of Rayleigh and stochastic scattering. This transition regime has some specialties. Unfortunately, experiments show discrepancy with theoretical estimations and the task of microstructure evaluation by measured attenuation of ultrasound is not solved up to now. Clearly, elastic moduli of single crystal cell should be averaged over all possible grain orientations to characterize the macroscopic value of elastic moduli. The averaging procedure uses invariant of anisotropy, which shows how strong is difference of moduli for statistically isotropic medium, $\varepsilon = C_{11} - C_{12} - 2C_{44}$.

The invariants show the degree of anisotropy and can be used for estimation of the velocities in statistically isotropic media without texture. The elastic moduli of metals with cubic cell and the invariants of anisotropy are present in Table 1. Voigt averaging procedure gives the upper value for velocities operating with stiffness tensor in contrast to Reuss procedure, which employs compliance tensor and Hill procedure, which gives a mean value of the mentioned above Voigt and Reuss averaging procedures [2, 8].

Table 1 Moduli of single crystal cells and calculated anisotropy invariants

Material	C_{11} (GPa)	C_{12} (GPa)	C_{44} (GPa)	ε (GPa)
Fe	229.3	134.1	116.7	−138.2
Ni	248.1	154.9	124.2	−155.2
Cu	168.4	121.4	75.4	−103.8
Al	109.3	57.5	30.1	−8.4

According to the unified scattering theory, the averaged values of longitudinal and shear velocities are defined as

$$C_L = C_{11} - 2\varepsilon/5, \quad C_S = C_{44} + \varepsilon/5 \tag{5}$$

that means that the value of longitudinal wave velocity is higher in polycrystals in contrast to shear velocity, which is lower for considered metals with cubic cell. According to the calculated values of anisotropy invariant, the aluminum demonstrates the lowest scattering of elastic waves. The strong anisotropy implies multiple scattering with conversion of elastic waves that produces disturbance over the whole specimen, but in contrast to the optical scattering elastic waves can be coherent in time with the ballistic waves [9].

Besides the grain microstructure, ferromagnetic materials possess domain structure, which contributes additional noise, since specimen is not completely magnetized. The mean value of domain size is comparable with the grain size in the case of polycrystalline materials. The signals obtained by PVDF and EMAT in 2.4 mm-thick polycrystalline nickel disk are present in Fig. 5. Piezoelectric transducer demonstrates higher peak-to-peak amplitude of longitudinal pulses, while EMAT detects primary longitudinal pulse and the following 'microstructure's noise', which masks the shear pulse and the first reverberation 3L, which can be identified only due to the signal of PVDF. The measured velocity of longitudinal pulses by PVDF sensor is 5.73 ± 0.02 km/s and it is equal to 5.71 ± 0.02 km/s by EMAT. The obtained signals reveal the complexity of shear pulse's detection in the case of polycrystalline specimens.

Among the results of the unified theory is conclusion about stronger scattering of shear waves in comparison with longitudinal waves in the transition regime from Rayleigh to stochastic scattering, where the scattering satisfies weaker the second power law frequency dependence for longitudinal waves in such strongly anisotropic material as iron. The favorite conditions for longitudinal pulse excitation yielded the range from 5 up to 200 MHz in 0.4 mm-thick steel that was possible due to the short traveling distance and conserved coherent ballistic waves [10]. However, the scattering of the laser-induced longitudinal probe pulse disturbs the whole volume of the specimen and proper detection of coming later shear pulse is very difficult due to the microstructure's noise, which conceals the weak shear pulse as it is shown in Fig. 5b. The possible solution relates to suppression of the longitudinal pulse excitation and magnification of the shear pulses. Such arrangement can be carried out by cylindrical lens, which focuses the laser radiation into elongated spot with lateral size about 50 μm as it is present in Fig. 6. The form of

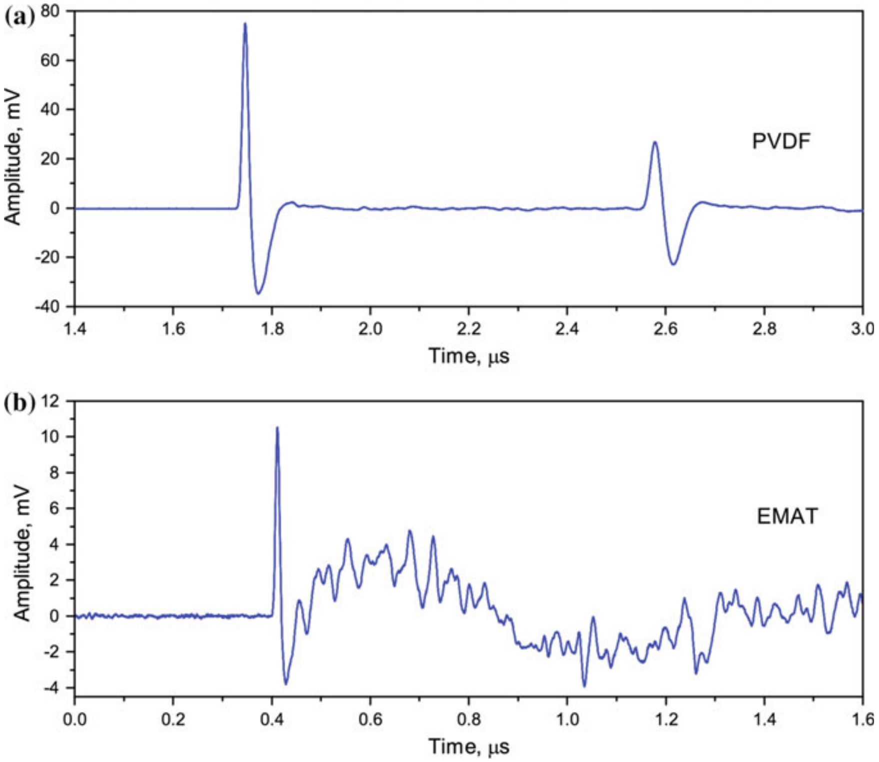

Fig. 5 Optoacoustic pulses detected in 2.4 ± 0.05 mm-thick polycrystalline nickel disk by PVDF (**a**) and EMAT (**b**) transducers, while the power density was equal for both cases

induced wave front can be complex for longitudinal and shear ultrasonic beams, but its mean position is around moving cylindrical surface in the far diffraction zone. The focusing induces the ablation of material and launches initial longitudinal waves normally to the surface while shear waves spread within the narrower angle in bulk [11]. The application of half-cylindrical specimen's form and noncontact detection by EMATs is obvious.

The evaluation of the properties of construction materials such as steel is important task of material science. Because steel is the complex composite of iron, carbon and other elements, the microstructure has significant local inhomogeneities and the propagation of high frequencies is challenge. The half-disk specimen of steel 40× (Russian notation) was prepared on turn/mill machine with nominal radius of 10 mm and thickness of 5 mm, see the Fig. 6b. The steel 40× contains about 0.40% of carbon and more than 0.8%, but less than 1.5% of chromium. American notation of the similar steel sort is 5140 that can be used for references. The series of signals measured in steel specimen according to the sketch in Fig. 6a are present in Fig. 7. The signals were averaged 64 times for reduction of electronics noise. This arrangement allowed to decrease sensitivity of EMAT to the

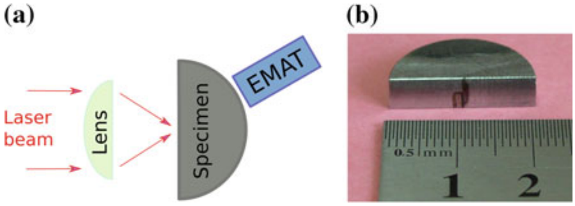

Fig. 6 Experimental arrangement of efficient excitation of shear optoacoustic pulses (**a**), 5 mm-thick specimen of steel 40× (Russian notation) with the radius of 10 mm (**b**), where the *black vertical* sign is the imprint of the laser spot

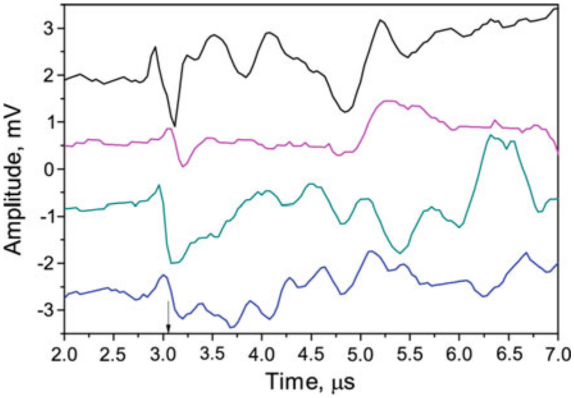

Fig. 7 Optoacoustic signals measured at four different loci of cylindrical surface of the steel 40× specimen. Signals are vertically shifted. The *arrow points* out the mean value of arriving time of shear pulses at 3.06 μs

disturbance induced by primary longitudinal pulse and to recognize the shear pulses arriving at about 3.05 μs afterwards the scattered ultrasonic waves or ‘microstructure’s noises’ come.

The mean experimental value of the shear pulse velocity in series of measurements was calculated from the ratio of radius and mean time of zero-crossing point. The accuracy of velocity estimation relates to the errors of traveling distance and measuring time interval from the exciting laser pulse to the arriving of the ultrasonic pulse. The slide gauge yields the actual radius of the half-disk 10 mm that is used for calculation. The thickness can be measured with the accuracy of 0.05 mm, that yield the instrumental mistake of about 0.5% for the distance 10 mm, while the relative error decreases with traveling distance. The oscilloscope with analogue bandwidth of 200 MHz and discretization rate of 1 GS/s was used that provided the temporal resolution about 5 ns. The relative error of velocity measurements is the sum of the relative errors for distance and time. Since the velocity of shear waves is less than the velocity of compression waves the contribution of relative value of time error for shear pulse is less and yields 0.2% for presented steel 40× specimen with the radius of 10 mm. The total relative mistake of shear velocity measurements is 1.2%. The measured shear pulse velocity is 3.27 ± 0.04 km/s. The measured by hydrostatic weighting method density of specimen is 7810 ± 10 kg/m^3 and calculated shear modulus is 83 ± 2 GPa, which is reasonable in comparison with table values.

4 Discussions

The irradiation of the metal specimen surface by nanosecond laser pulses induces shear and longitudinal ultrasonic pulses while their directivity and efficiency depend on the transparent media properties and the intensity distribution over the laser spot cross-section. In order to achieve better temporal resolution in measurements, the highest frequencies should be launched into material and detected by transducers, but the scattering and attenuation significantly reduce mainly in this part of the spectrum. The wide spot of laser beam launches the longitudinal pulse due to the thermoelastic sources at air–metal interface that implies bipolar temporal form of signal with dominated high-frequency part of the spectrum. The covering of the metal surface by transparent liquid allows one to increase the low-frequency part of the spectrum and launches the longitudinal pulse with pronounced compression phase. The fluence above 20 MW/cm^2 overheats and evaporates surface's particles, which exert normal to the surface and increase the amplitude of longitudinal pulses.

The shear pulses generation requires strong gradient of heat deposited sources at the surface of the specimen that can be done by focusing the laser radiation. The round laser beam spot launches shear waves into the bulk of the material, unfortunately, their directivity is not normal to the surface [9]. The small linear size of the source can be consider in the far zone as a point source but the amplitude of the pressure quickly decreases with distance. The appropriate solution uses cylindrical lens and half-cylindrical specimen. The laser spot is located along the geometrical axis of half-cylinder or half-disk. Among the advantages is the quasi-cylindrical divergence, which allows decrease the influence of diffraction and partly conserve the low frequencies of the pulse spectrum in comparison with point-like source, since diffraction influences on the form of the ultrasonic beam and the spectrum of the pressure pulse. The bandwidth of the transducers for detection of laser-induced ultrasound should consider the range from 5 MHz up to 50 MHz with some deviations due to the anisotropy of the material and the microstructure.

The broadband detection should measure the useful part of ultrasound spectrum. Obviously, there are no conditions for equality of loss during propagation as well flat sensitivity over the bandwidth, which is induced initially. Despite the essentially broadband spectrum of laser-induced ultrasonic pulses the detection is possible only for narrow range, which should contain mean and high frequencies corresponding to the range from 20 up to 50 MHz in the case of polycrystalline metals or steels. The capacity of 2 mm diameter sensitive element of PVDF transducer provided the operation in the 'short-circuit current' mode in contrast to 'voltage' detection mode [10]. This frequency range is comparable with the bandwidth of optical detection systems, which operation region is significantly narrower to their capabilities band in the case of polycrystalline specimen [11].

Actually optical methods employ different type of interferometers, which are sensitive to vertical displacement or velocity of the surface particles. It was stressed before that the presence of the short transient ultrasonic pulse induces the noise of microstructure over the whole volume of the specimen. These elastic waves are coherent and arrive after the primary longitudinal pulse to the area of the detection laser spot with a diameter about tens of micrometers. The contribution of scattered field depends on the laser spot locus and in the case of coarse microstructure its amplitude can be comparable with displacement induced by primary pulse or echoes therefore the measurements of the shear pulses is more difficult task for optical methods. EMAT and PVDF transducers show some advantages at measuring bulk ultrasonic pulses in metal due to intrinsic averaging of the useful signal over the larger area in comparison with optical methods. As the area of piezoelectric sensor is more than 100 times larger, these transducers demonstrate higher peak-to-peak amplitude in comparison to the 'microstructure's noise' and better sensitivity to the useful probe pulse and its echoes. EMATs also average the signal at the surface of the specimen over the area of coil. Despite unique capabilities regarding operation at elevated temperatures, noncontact excitation and detection of ultrasound via all-optical technique suffers due to impossibility to highlight useful signals or reverberations of the pulses from the scattered ultrasonic field or 'microstructure's noise'. The averaging of the signals over several detection points does not widens the spectrum and does not improve the accuracy of time-resolved measurements since the coherent ballistic and scattered waves propagate along the specimen distance [9].

The task of estimation of mean grain size of polycrystalline materials is very attractive for material sciences and industry since microstructure strongly influences on strength and hardness. There were carried out numerous experiments, which stated the decrease of the attenuation with smaller size of the grains. This task seems to be very similar to determination of the scatterer size in turbid media by measuring the intensity diagram of scattered optical waves. The lengths of diffusion and attenuation are defined in penetration depth distance, where the radiation is coherent and the amplitude decays. The laser-induced acoustical pulses are essentially broadband and experience multiple scattering at the grain boundaries that changes the spectrum and wave front of ultrasonic beam with distance. The immersion methods with piezoelectric sensors measure averaged ballistic waves, which experience moderate deviation from the initial direction of ultrasonic beam propagation. The optical methods are very sensitive to the scattered ultrasonic field, which is coherent in the case of low attenuation but arrives later to the locus of the detection laser spot. The signals of EMAT show both features due to the integrating the ballistic waves over the area of the detection coil while the scattered coherent field over the same area yields 'microstructure's noise'. The presence of coherent and incoherent ultrasonic radiation for a wide range of ratio between the diffusion length and sample thickness is feature of acoustic scattering and measurements.

The induced disturbance decays slowly in the thicker specimen while the thinner specimens require shorter probe pulses and broader bandwidth.

The direct measurement of longitudinal and shear pulse velocities is not single approach for moduli evaluation. Ultrasonic and electromagnetic acoustic resonances are competitive techniques. Laser-induced resonant ultrasonic spectroscopy (LRUS) is an alternative method, which uses lasers for excitation and for measuring the elastic properties of the specimen with defined geometry [12]. The detection of the vertical particle displacement by laser interferometer at the surface of the specimen yields the vibrations' modes distribution, which depends on density and averaged stiffness tensor of the material. The correct identification of the modes uses convergence of the experimental results and modeling by varying moduli.

5 Conclusions

The laser-induced ultrasound is rapidly developing technique, which allows efficient excitation of bulk and surface ultrasonic pulses with essentially broad spectrum. The diffraction, attenuation and scattering lead to distortion of the wave front and to narrowing spectra of pulses propagating in the polycrystalline materials that decrease the peak-to-peak amplitudes with traveling distance, while the accuracy of the task of velocities measurement requires high frequencies detection. The measurements of longitudinal pulse velocity can be carried out by variety of the experimental arrangements but due to the noise of microstructure, the intrinsic instrumental averaging of PVDF transducers yields better performance. The initial localization of shear pulse sources along the cylinder axis and efficient excitation owing to focusing demonstrated successful combination of laser-induced pulses with EMATs, which are well-promising noncontact detection tools in the case of ferromagnetic materials, that can be employed for solutions of tasks both as material science as non-destructive testing.

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