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PROPAGATION PARAMETERS OF ULTRASONIC WAVES IN POLYMER COMPOSITES

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The non-contact ultrasonic technique of wave generation was used to test polymer composites. Transient elastic waves were generated with a Nd:YAG pulsed laser. Measurements aiming at the determination of the macroscopic parameters of propagation of bulk waves (amplitude, velocity and frequency distribution) were made in a unidirectional glass/epoxy (GFC) and isotropic polyvinyl chlorid plastic (PVC) thick plate. The influence of a constrained surface on the ultrasound parameters is discussed. The variations of the macroscopic parameters of propagation as functions of distance from the epicentrum were studied. PZT-ceramic standard ultrasound probes were used as receiver.

1. Introduction

There are many techniques that have been used for determining the macroscopic properties of materials or for detecting flaws and inhomogeneities. The use of active ultrasonic techniques for nondestructive materials evaluation has the advantage of a direct connection between the characteristics of the wave propagation and the mechanical properties of the material. The passive acoustic emission techniques are able to monitor the integrity of a large structure and to investigate dynamic failure processes in materials. Ultrasonic waves can be generated in a solid by many means corresponding to different dynamic loading of the specimen. These include ultrasonic plane-wave techniques which utilize a specific transducer excited by a burst pulse or continuous-wave excitations generating waves in the specimen. A recent alternative to the plane-wave technique is that utilizing transient signals generated by a source of small aperture. Transient elastic waves are generated on the surface of the specimen by broad band excitation sources which include a steel ball impact, a laser impact, a fracture of a capillary or a pencil lead, and a bombardment with electron beams. The advantages of this method include the possibility of determining the wave speeds of all the waveforms resulting in a solid from a single excitation pulse.

The focusing of a laser beam on the surface of a solid has been recognized recently to be a powerful mean for generating acoustic waves. The mechanism of the laser generation of an ultrasound has been shown by White [1] to be thermoelastic at low laser energy densities; the source can be represented as a dipole strength parallel to the surface of the specimen. At a hight power level, the laser source operates in the ablation regime by vaporizing a small amount of the surface material. Thus it can be modelled by a force normal to the surface of the specimen. The radiated field of such a source resembles a monopole radiating strongly in all directions from a source point (Hutchins [2]). Using numerical solutions for the free-surface Green's function, Scruby [3] derived one of the first three-dimensional models for ultrasonic generation in solids. Despite an idealized point source approximation of the experimental illumination spot, this model predicts correctly the salient features of experimental waveforms. The analytic considerations of Rose [4] about a point of dilation just below the surface of an elastic halfspace (due to thermoelastic mechanism) leads to a reasonable qualitative agreements with experiment, but do not relate all the relevant material and laser parameters to the displacement field. Later, Schleichert [5] described the optical generation of elastic waves in the thermoelastic regime taking into account the structure of different laser modes, the optical, thermal and elastic material properties as well as the finite area of a capacitance transducer. The theory of transient wave propagation in bounded isotropic materials has been established by Scruby [6]. The application of a laser point-source for the generation and detection of ultrasonic waves in thin platelike specimens has been described by Hutchins [7], Nakano and Nagai [8] and Hurley [9]. These studies, were focused on measurements of the lowest-order symmetric and antisymmetric Rayleigh-Lamb wave modes in specimens which are elastically isotropic. The ultrasound velocities (with a resolution $\approx 2.5\%$) as a function of frequency were measured to determine the dispersion curve, from which the Young's modulus was deduced and their temperature dependences have been succsessfuly measured up to 1500 K. Besides, some restrictions on using the lowest plate modes to extract the elastic modulus and thickness information of a thin plate were noted. Viscoelastic dissipation effects of the medium have also been considerd by Waver [10]. The methodology for measuring the intrinsic ultrasonic attenuation and dispersion within a broad frequency band (nearly 6 octaves) in different polymers using laser ultrasonic techniques has been presented by Pouet [11]. He used the ablation mechanism for the ultrasound generation in order to obtain signals of high enough acoustic energy at the epicenter. This methodology enables the measurement of the frequency dependence of attenuation and phase velocity over a broad frequency band.

The ultrasound signals generated by a laser, such as the Q-switched lasers, are broadband signals in nature and do not display a clear central frequency. The selection and use of traditional narrow band ultrasonic sensors, such as the PZTs, is therfore questionable and the measurement of such broadband signals is susceptible to noise interference. Also, since broadband signals have no clear acoustic central frequency, it is difficult to ascertain the defect sizes that can be resolved. Modulated laser pulses can narrow the bandwith of ultrasonic signal improving the signal-to-noise ratios by providing a direct control over the central frequency of the ultrasound. Both the spatial and temporal modulation of laser sources have been implemented experimentally using a variety of techniques for the bulk and surface wave modes. The purpose of modulation, whether spatial or temporal, is to create a clear spike in the signal frequency spectrum centered around some desired frequency so that a narrow band sensor, such as a PZTs one, can be readily used, and/or band pass filters can be used in the receiving electronics for the broadband sensor, such as interferometers, to improve noise rejection (Sanderson [12]).

The extension of the laser ultrasound technique to measurements of elastic constants of anisotropic materials has been reported for composites by PICHE [13] and along the principal axes in germanium single crystals by AUSSEL [14]. In addition, a laser-generated ultrasonic bulk wave (CASTAGNEDE [15]) and a surface one (CHAI [16]) were also applied to the determination of elastic constants of anisotropic materials. SCRUDER [17] recorded waveforms at a series of positions along lines both parallel and perpendicular to the fibre axis in carbon/epoxy. Velocity profiles of major arrivals have been determined and shown to correspond to the group and phase velocities for quasi and pure bulk wave modes. A recent application of such measurements to characterize anisotropic materials has focused on inverting ultrasonic group velocities, obtained from pulse arrival time data, in signals that propagated in nonprincipal directions in an uncut specimen in order to obtain the matrix of its elastic stiffness. The determination of all the wave speeds from one detected waveform resulting from a single excitation pulse was described by KIM [18]. The determination of both longitudinal and shear wave speeds in an isotropic solid from the waveform detected by an arbitrary located sensor described was first. Then, measurements of the wave speeds made in various directions in silicon single crystal plates were analysed. The effect of the deviation of the propagation direction between the energy and phase bulk wave-mode fronts, detected by suitably positioned sensors in the anisotropic materials, was considerd too. Angular amplitude directivity patterns of bulk waves in carbon/epoxy:unidirectional and cross-play, and the acoustic ray focusing was considerd by CORBEL [19]. The scan images of very thin (145 µm) graphite/epoxy laminates and silicon wafers, which represents the detailed spatial and temporal characteristics of the elastic wave field in a specimen, were obtained by VEIDT [20]. The features of such an image can be directly related to the material's anisotropy and macrostructure. Basing on laser generation and laser detection of acoustic waves, the stiffness tensor of a polymer matrix composite has been measured by GUILBAND [21]. The model developed predicts accuratly the focusing effects caused by anisotropy and the spreading of the signals caused by the dispersion and attenuation. Despite the dispersion and echos overlapping, the stiffness coefficients are identified with good reliability from the group velocities of bulk waves. This work is concerned with transient acoustic radiation generated by a laser in a polymer matrix composite. This is motivated partly by the desire to understand how the acoustic emission transients caused by growing defects propagate in composites. This work is an extention of the work of previous authors [15 – 19] aimed at characterizing the material quantitatively by using the laser technique. However, not only the wave propagational effects, such as signal attenuation, dispersion and radiation must be known, but also the effects of the measurement system, particulary the sensor and its coupling to the specimen, so that a correct relationship between the measured signal amplitudes and the source-receiver separation can be established [22].

The purpose of the present work was to generate and detect ultrasonic bulk wave modes first in a quasi isotropic, homogeneous and uniform, viscoelastic material. Hence, a 20 mm thick polyvinylchlorid plastic (PVC) plate has been chosen. Secondly, an anisotropic heterogeneous, polymer matrix composite was considered, using a 17 mm thick composite plate made of unidirectional glass fibres impregnated in an epoxy matrix. For these two samples scan images have been measured and compared.

From these experiments an understanding of how the composite response evolves as a function of the source-receiver separation has been gained.

The knowlege obtained from the isotropic case is applied to identify the various wave arrivals in the waveforms of the anisotropic specimens. In contrast to the foregoing [17, 19], the focus is on the variation of the ultrasonic amplitude at an oblique orientation using data at the epicenter for comparison. Commercial sensors made of PZT-ceramic and the contact technique for receiving ultrasonic waves were applied. The purpose of the experiments in a thick PVC plate was to verify the wave modes, the wave velocity and the amplitude distribution of the ultrasound generated by a laser.

This paper is organized as follows: In Sec. 2 the measuring set and procedure are presented. The experimental results are described in Sec. 3. First, the amplitude distribution is discussed. Then, the results of measurements of velocity are discussed. At the end of the paper, in Sec. 4, the experimental results are compared and discussed.

2. Procedure: setting up and measurement

For the excitation of the ultrasound, a Q-switched Nd:YAG laser (with a built-in nonlinear crystal) has been used. Laser pulses were emitted with a frequency equal to 2 Hz. An electromagnetic wave of length $\lambda = 532$ nm and energy — 1.7 mJ with a temporal width of 10 ns was focused down to a spot of 1.5 mm on the sample face. The pulse-to-pulse fluctuation of the laser energy was about 5%. The power density deposited on the tested sample surface was 10 MW/cm^2. Some ablation of the sample did occur leaving small pits in its surface.

Noncontact, capacitance or electromagnetic acoustic transducers, optical interferometric sensing systems available now are capable of detecting surface motions. Although they possess a broad frequency response, the sensitivity of such systems is at most by an order of magnitude higher than that provided by piezoelectric sensors. Furthermore, such an expensive instrument was not available for us. For this reason, piezoceramic contact transducers were used in this study to detect the ultrasonic signals. Piezoelectric ultrasonic probes were used to measure the deformation of the surface caused by the ultrasound wave. The measurements were performed using Panametrics standard ultrasonic probes; a probe for the measurement of AE with a resonance frequency of 160 kHz, and ultrasound broadband probes; 2.25 MHz of bandwidth of about 94.4%. The diameter of the transducers in all the probes was 12.7 mm. The medium which coupled the probe to the sample surface was an aqueous solution of glycerine or Panametrics resin. Additional details of the measurement system has been described previously [23]. The amplitude distribution and wave-front arrival times were measured in thick plates (for the PVC plate the distance from the source ($h \geq 20$ mm) was much larger than the acoustic wavelength $L \cong 3$ mm). Initially, we have to verify the wave modes which were generated by the laser in thick plates. Measurements of the arrival time by the transmission method, with the probe adhered to the sample surface in different positions (Fig. 1 b), were made to verify waves which propagate under the surfaces and in the bulk of the specimens. In a few experiments we have coupled a plexiglass plate on the surface between acoustic source and the probe to eliminate surface waves. In this way it has been proved that the measured waves were bulk waves.

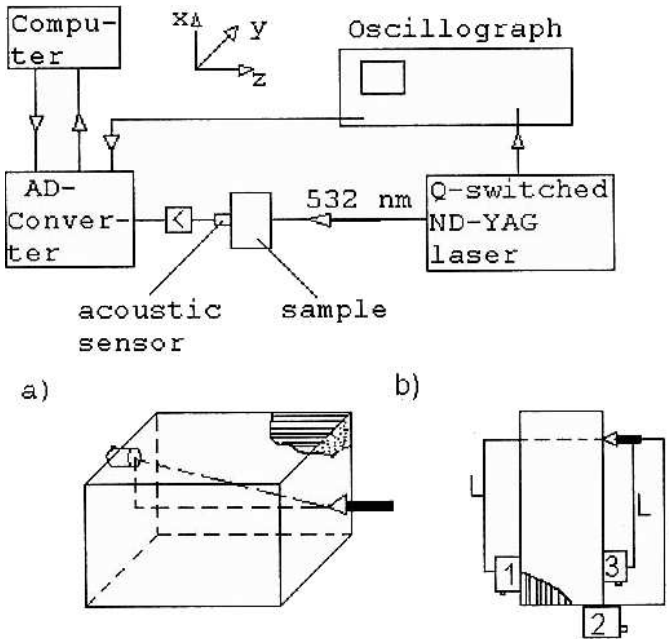

Fig. 1. Measuring stand with Nd:YAG laser; a) measurements in GFK-cuboid; b) measurement in GFK- or PVC-plate.

The amplitude distribution versus distance from the epicenter were deduced from the variations of peak to peak magnitude of each remote acoustic pulse. The measurements of the maximum amplitude of the first arriving pulse of the acoustic wave (longitudinal-L or shear-T) was performed every 0.1 mm within 4 seconds. A mean amplitude value from eight measurements at one point was established to be the result. The measurements in a PVC plate were made using a 2.25 MHz probe for the longitudinal (L-probe) or shear (T-probe) waves. The X − Z plane of measurements intersected first ($y = 0$) the epicenter of the acoustic source. During the amplitude distribution measurements, the probe moved in precise steps from its initial position in one X − Z plane along a straight line changing in this way the direction of the shortest path from the source to receiver (Fig. 1). For measurements with a shear probe, the probe was coupled by resin to the surface and the set plate-probe changed the distance to the laser illumination point in the same way as previously. The first pulse in the time window for a dilatation wave was recorder at the points of measurements. Next, a frequency spectrum was determined using a fast Fourier transformer. The mean value (for two measurements made at one point) of the frequency for the pulse of dilatation waves of maximum amplitude changes was taken as the result of the measurement. Both the control of the probe movement and the recording of the results were performed by a PC computer. The surface on which light falls was either free or constrained with a plexiglass plate and silicon oil.

When the measurements in one plane were finished, the probe was moved transversly 2 mm to a next plane (from position $y = 2 \cdot i$ to $y = 2 \cdot (i+1)$ for $i = \pm 0, 1, 2, ..., 10$). An area of 50 mm×100 mm was scanned in this way.

The velocity of wave was calculated as a sonic distance divided by time of flight. The arrival times of the wave packets that propagated through the medium at their energy velocity were measured directly on the digitized waveforms.

The experiments carried out concerned two materials: isotropic polyvinyl chloride plastic and epoxy resin reinforced unidirectional with glass fibre. The GFC specimens had the form of a thick plate (17 mm) or a cuboid, the dimensions of which were 31 mm×60 mm×70 mm.

3. Experimental results and assessments

3.1. Amplitude distribution in the PVC- and GFC-plates

The amplitude distribution in the PVC plate for the longitudinal and shear waves in the X−Z plane accrossing the epicenter is presented in Fig. 2. The amplitude of the longitudinal wave falls down nonlinearly, while the amplitude of the shear wave (the axis of the polarization direction of the T-probe was X−X) falls down linearly as a function of distance from the centre. When the axis of the polarization direction of the T-probe was Y−Y, the measured amplitudes were about 10 dB smaller but the measurement accuracy was rather poor.

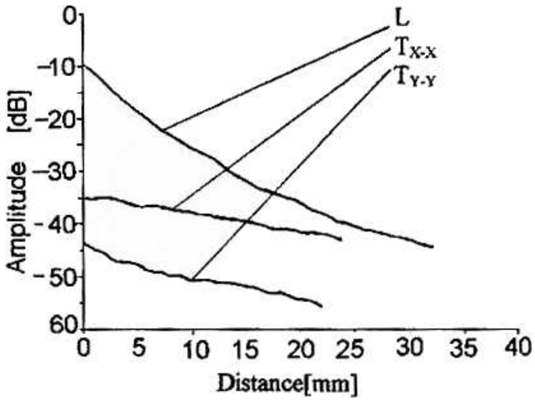

Fig. 2. Comparison of amplitude distribution of longitudinal (curve-L)- and shear (curves T_{X-X}, T_{Y-Y} in one plane X−Z, $y = 0$) waves versus distance from the epicenter in the PVC plate, probe 2.25 MHz; T_{X-X}-direction of polarization X−X, T_{Y-Y}-direction of polarization Y−Y.

The amplitude of the longitudinal wave is greater than that of the shear wave in the whole measuring range; the differences are about 25 dB near the epicenter. The longitudinal wave is generated as a primary wave in the acoustic source. The shear wave is generated by the transformation of the longitudinal one during the reflexion at the surface where the laser beam incident. This transformation is accompanied by energy losses. This is one of the most important reasons of the amplitude differences. However moving from the epicenter the differences quickly vanish. It is supposed to result from the fact that far from the epicenter the thermoelastic mechanism of wave generation is more effective as the ablation one. Secondly, for the set up configuration presented in Fig. 1 b (probe T in position 1, axis of polarization in the direction X – X) and the measurement procedure, the measured amplitude of the shear wave depends in any position on the attenuation and directivity pattern of the sound source. It appeared that the measured amplitude of the longitudinal wave depends additionaly on the incident angle to the probe; this is probably the reason for the nonlinear relation in Fig. 2 (curve L).

The results of the amplitude distribution measurements with the probe 2.25 MHz coupled on the edge of the PVC-plate (see Fig. 1, probe in position 2) are presented in Fig. 3. This time, the amplitude of the shear wave (axis of polarization direction T-probe X – X) is greater that the longitudinal wave in the whole measuring range. It results from the amplitude directivity patterns of the sound source for the longitudinal and shear waves [3]. The amplitude of longitudinal wave falls down nonlinearly as function of the distance from the centre, but for the amplitude distribution of the shear wave we can write a linear relation. The nonlinear relation of the amplitude distribution of the longitudinal wave can be approximated by two linear equations. From this amplitude directivity patern it is obvious that for $x \in (10\,\mathrm{mm}, 15\,\mathrm{mm})$ there should be a change of the dominating mechanism of the ultrasound generation from the ablation mechanism neare the epicenter to the thermoelastic one far from the epicenter.

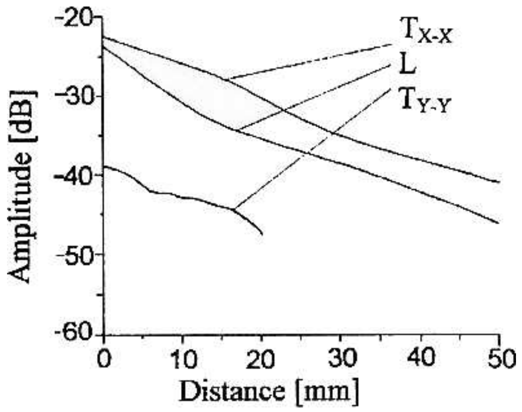

Fig. 3. Comparison of amplitudes of longitudinal (curve-L)- and shear (curves T_{X-X}, T_{Y-Y}) — wave distribution versus distance from epicenter, probe 2.25 MHz coupled on edge in PVC plate; T_{X-X}-direction of polarization X – X, T_{Y-Y}-direction of polarization Y – Y.

Figure 4 shows a 3-D scan of the amplitude distribution of a longitudinal wave in the PVC-plate. A maximum value of the amplitude occurs in the direction of the laser ray. It confirms once more that first of all we have to do with an ablation mechanism of the ultrasound generation. Although the material is isotropic, the amplitude falls by 6 dB in the range of angle $16^\circ < \alpha < 18^\circ$ but non-uniformly in the different directions of propagation. The reason for it is probably the nonsymmetric energy distribution in the acoustic source which results from the imperfection of the laser ray.

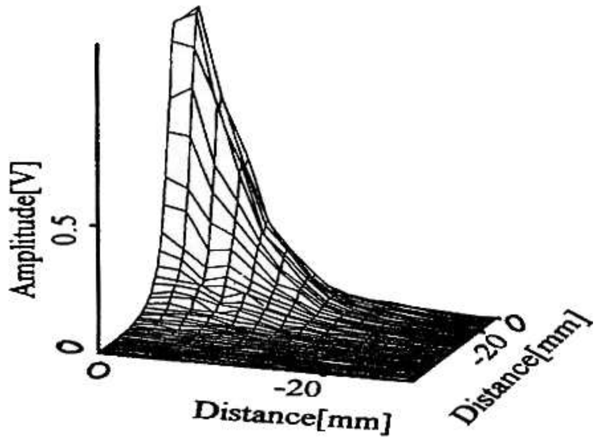

Fig. 4. The 3-D amplitude distribution of a longitudinal wave in the PVC plate measured by the 2.25 MHz probe.

The scan image of the amplitude distribution of the longitudinal wave was measured also for a GFC plate with a free surface (Fig. 1 b). The maximum value of the amplitude occurs in the direction of the laser ray. The amplitude falls by 6 dB in the range of the angle α (for path $y = 0$ or $x = 0$) which is illustrated in Table 1. It is well known that the properties of the GFC plate depends on the direction of investigation. The measurements of 6 dB fall ab of the amplitude using a 2.25 MHz-probe confirm it. However the same measurements with an AE-probe do not lead to such a conformation. The resonance frequency of the AE-probe was 160 kHz. For the ultrasound wave of that frequency, the investigated GFC plate (in the direction X – X or Y – Y near the epicenter) was almost homogenous.

Table 1. Amplitude distribution for the GFC plate.

	2.25 MHz sensor	AE sensor
Fibre direction (X – X)	$\alpha = 33°$	$\alpha = 36.5°$
Perpendicular to fibre (Y – Y)	$\alpha = 24.5°$	$\alpha = 36°$

After the normalization of the values of the amplitude in the epicenter (e.g. the amplitude for each experimental curve is for $\alpha = 90°$ equal to 0 dB), we can compare this relation as shown in Fig. 5. First of all it is evident that the results of the amplitude distribution depends on the receiving probe. The amplitudes measured with AE transducers fall much slower than those measured with a 2.25 MHz probe.

The amplitude of a longitudinal wave in the Y – Z plane (isotropic plane, perpendicular to fibre, $x = 0$) is decreasing almost linearly with the angle $\beta = 90 - \alpha$ [deg] (see Fig. 5 a).

In the X – Z plane (in the fibre direction, $y = 0$), the amplitude of a longitudinal wave as function of the angle to fibre falls nonlinearly (see Fig. 5 b). However, these relations can be represented by two linear functions.

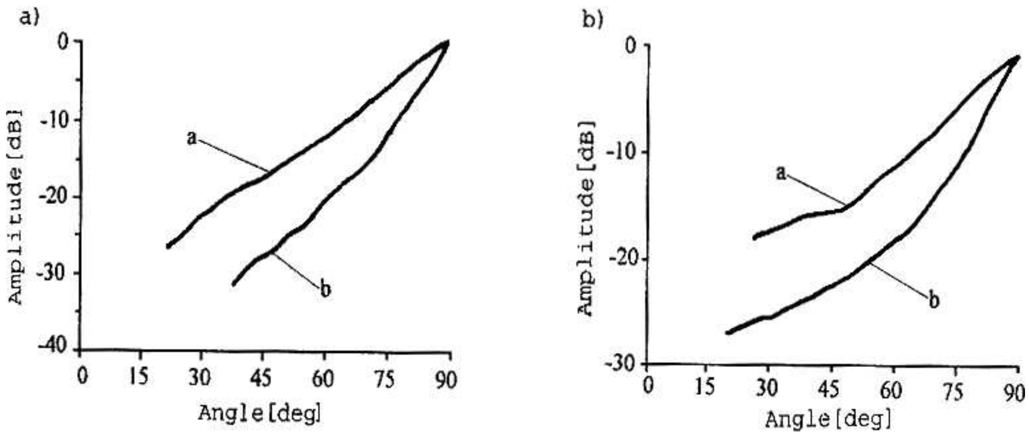

Fig. 5. 1-D amplitude distribution in a GFC plate; a) measurements perpendicular to fibres b) measurements in the fibre direction; a — curve measured with an AE-transducer, b — curve measured with a 2.25 MHz transducer.

From these relations it is evident that near the epicentrum (on the surface oposite to the source) the properties of the composite are not so strongly dependent on the direction of investigation. Figure 6 shows a 3-D scan of the amplitude distribution of a longitudinal wave in a GFC cuboid (see Fig. 1 a). The maximum value of the amplitude occurs in the direction of the laser ray (which is now parallel to the fibre, i.e. $\alpha = 0°$). The amplitude falls by 6 dB in the range of the α angle; in the X−Z plane, $\alpha = 8°$; in the Y−Z plane, $\alpha = 8.6°$. This means that the energy flux is concentrated along the fibre. From another point of view we know that the elastic properties of composites are also strictly related

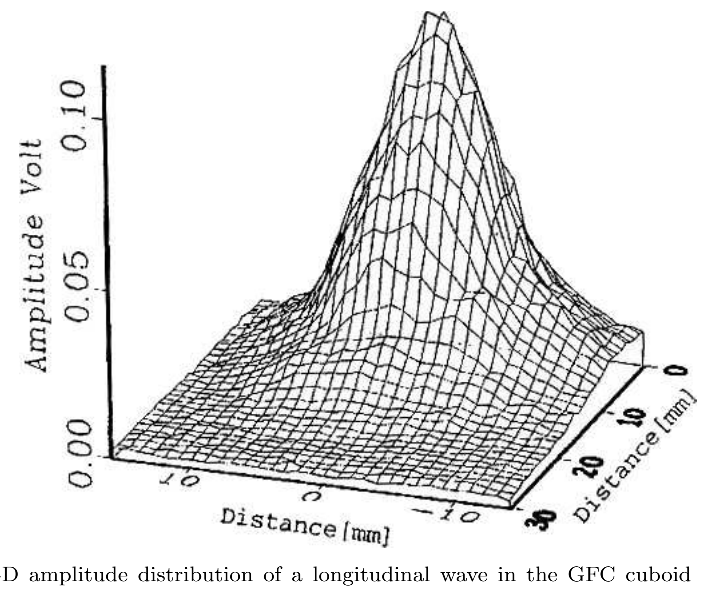

Fig. 6. The 3-D amplitude distribution of a longitudinal wave in the GFC cuboid measured with a 2.25 MHz transducer.

to the fibre direction. Moving a little away from fibre direction, there is a drastic fall of the amplitudes.

The surface of a composite appears to be never completely free from stresses. Usually, the composite surface has a protective resin coating. In our tests, the surface of the GFC plate was constrained additionally with silicon oil and a plexiglass plate. These constraining layers cause a 30 dB increase in the amplitude of a longitudinal wave launched near the epicentre. The amplitudes measured in the fibre direction are always higher than those measured in the direction perpendicular to the fibre. When, however, the surface is free, i.e.without a silicon oil or a plexiglass plate, the difference is less than 5 dB. In the case of a constrained surface, the amplitudes measured in the direction perpendicular to the fibre (in the Y−Z plane) fall much more rapidly as those measured in the fibre direction (in the X−Z plane). When the surface is constrained, the thermoelastic stresses in the acoustic source as well as the amplitude of the generated waves increase. Depending on the angle between the acoustic ray and the fibres, this increase of the amplitude is different. It is the greatest in the fibre direction. It should be mentioned that such an anisotropy occurs as well due to the application of the near-infrared laser. This laser provides the optical absorption localized on the glass fibres [19]. No such anisotropy occurs if the absorption takes place in the epoxy resin, as in the case of a CO_2 laser.

3.2. Measurements of the velocity and frequency

The measured velocity of longitudinal and shear waves in an isotropic PVC-plate depends on the position of the receiving probe; the differences of the results reaches 6%. When the probe was coupled to the surface opposite to the source, the velocity was $c_L = 2366\,\mathrm{m/s}$ for the longitudinal wave and $c_T = 1064\,\mathrm{m/s}$ for the shear one whereas for the probe coupled to the edge the velocitis were $c_L = 2246\,\mathrm{m/s}$ and $c_T = 1131\,\mathrm{m/s}$.

This means that the accuracy of the measurements of the velocity of the longitudinal or shear waves did not exceed 6%. For comparison the velocity of a wave was eneasured by transmitter-receiver probe of 2.25 MHz placed onto the PVC-plate. The velocity of the longitudinal wave was 2246 m/s and for shear one 1131 m/s. The velocity of the wave was calculated as the sonic distance divided by the time of travel. The position of the source in the X−Y surface was known quite exactly i.e. with a tolerance of ±0.75 mm. The acoustic source excited by the laser is buried in the material. Thus, its position under the surface can be only approximated. In this work, we have taken into account that the acoustic source lies 0.3 mm under the surface. The sonic distance was the shortest path between the source and the receiver. However, the assumption that the probe is a point receiver was not valid since the diameter of the probe of 12.7 mm was too large. Thus, the shortest sonic path from the source to the receiver was measured very roughly when the probe was not in the epicenter. When the probe is coupled on the edge, such a problem does not exist and the accuracy is as high as for the transmitter-receiver method.

Figures 7 and 8 show the dependence of the longitudinal wave velocity on the angle between the wave and the fibre measured in a GFC plate (with free surface) by a 2.25 MHz transducer and an AE-transducer.

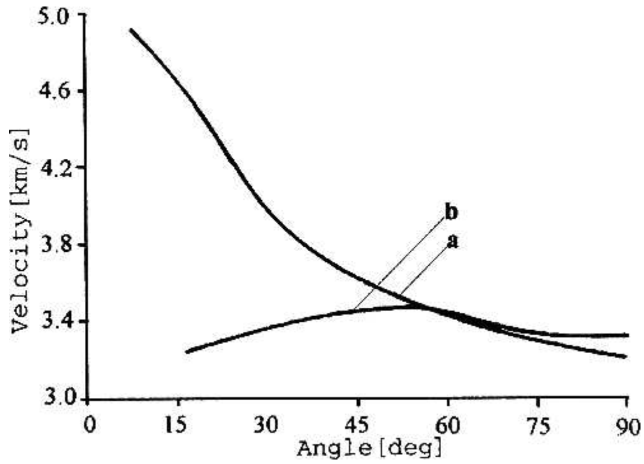

Fig. 7. Velocity of the longitudinal pulse in a GFC plate measured with a 2.25 MHz transducer. Curve a — measurement in the X – Z plane, curve b — measurement in the Y – Z plane.

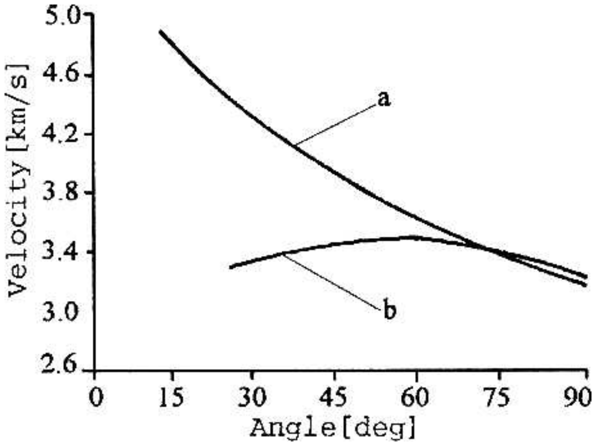

Fig. 8. Velocity of a longitudinal pulse in a GFC plate measured with an AE-transducer. Curve a — measurement in the X – Z plane, curve b — measurement in the Y – Z plane.

The velocity of a longitudinal wave measured in the X – Z plane depends nonlinearly on the angle β to the fibres. In the Y – Z plane perpendicular to the fibres (the isotropy plane), the measured velocity of a longitudinal wave has a local maximum for angle $\beta \cong 60°$, but the phenomenon is difficult to explain. One possible reason is that the Y – Z plane may not be a perfectly isotropic one for this particular composite. However, the measurement accuracy is 6%, as found for the isotropic materials. From this point of view, the velocity in plane perpendicular to the fibre should be constant. There are differences between the results of velocity measurements obtained with a 2.25 MHz probe and an AE one. The differences are less than 10%. As it was supposed from the analysis of the amplitude distribution in the GFC cuboid, the energy flux should be concentrated along the fibre. The results of the velocity measurements in the GFC-plate corroborate this conclusion. The velocity of longitudinal wave is the greatest in the fibre direction (over 5000 m/s) and falls rapidly to about 3400 m/s with increasing deviation from this direction.

The assumption that the pulses of a longitudinal wave of maximum amplitude measured with a 2.25 MHz transducer would vibrate with a frequency of about 2.25 MHz appeared not to be true.

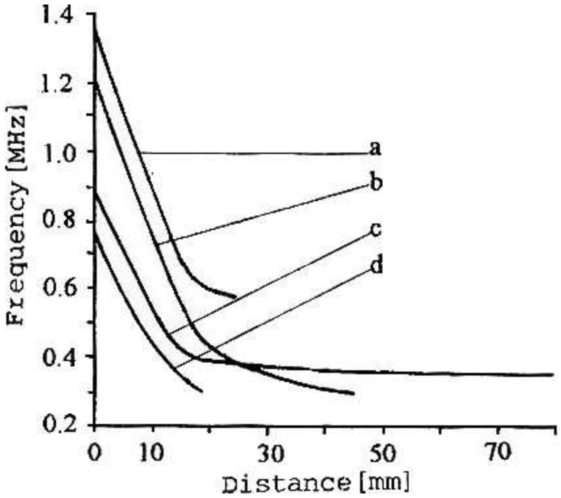

Fig. 9. Frequency distribution of a longitudinal wave: in a GFC plate with free surface measured in the direction perpendicular to fibres (curve a) or in the fibre direction (curve b); and in a GFC plate with constrained surface measured in the fibre direction (curve c) or in the direction perpendicular to the fibres (curve d).

The results of measurements in a GFC plate made with a 2.25 MHz probe shows that the vibration frequency of these pulses depends on the direction of investigation and the state of the surface. Figure 9 shows the frequency distribution of a longitudinal wave generated in a GFC plate by a laser. The vibration frequency in the epicentre is about 1.35 MHz for a free surface, whereas in the case of a constrained surface it is about 0.85 MHz. A vigorous decrease in the frequency up to 0.4 MHz near the epicentrum (distance up to 30 mm) is observed. When the distance from the epicentre increases, this decrease is systematic, probably because the flux of the wave energy is concentrated along the glass fibre. It should be mentioned that the measurement accuracy is rather low and equals to about 15%.

4. Conclusions

The investigation has shown that the laser light of a power density of 10 MW cm^{-2} when incident on the polymer surface causes the formation of an acoustic source, mainly due to the ablation mechanism and, to a small degree, to the thermoelastic mechanism.

The generation of an ultrasound by the ablation mechanism is more effective neare the epicenter, whereas the thermoelastic mechanism is still present and makes it possible to measure the amplitude of the ultrasound waves far from the epicenter. The laser generated wave neare the epicenter propagates with a frequency much heigher than that of waves far from the epicenter. In isotropic materials, the amplitude directivity patterns are almost symmetrical in relation to the normal to the surface. The wavefronts generated by the laser in composite materials are more complex than the near-spherical wavefronts in isotropic polymers. The test results show the interdependance of the state of the test piece surface, anisotropy, anelasticity and the elastic wave propagation. The constraining layers cause a 30 dB increase in the amplitude of a longitudinal wave launched near the epicentre. The amplitude distribution and velocity of waves in composites depend on the direction of propagation. The measured velocity of a longitudinal wave refers to the group velocity rather than phase one. There are differences up to 10% between the results obtained with a 2.25 MHz-probe and an AE one. The measurements accuracy is: for the amplitude distribution 3% and for the velocity 6%. For measurements far from the epicenter the use of a probe of shear waves coupled with a resin to surface is very effective.

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