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Peculiarities of Optoacoustic Excitation and Propagation of Plate Waves in Thin-Walled Objects

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Abstract

Increasing the efficiency of non-destructive control of lamellar materials with single and double-layer structure is an urgent scientific and technical task. The aim of the work was to investigate the peculiarities of excitation and reception of plate waves (PW) in single-layer and two-layer materials by pulsed laser radiation in relation to detection of cracks in them and estimation of layer thickness at one-sided sounding. A methodology has been developed and experimental studies of the influence of moving the area of laser generation of PW over the surface of dural samples relative to the crack simulator of different depth with the subsequent reception of the signal at a characteristic angle of inclination have been carried out. A significant change in the structure of the wave front at localization of the moving wave source zone in the vicinity of the crack simulator was found, accompanied by a change in the ratio of extreme values of amplitudes of the received asymmetric mode A^{extr} up to 14–15 dB. At receiving the symmetric s_0 mode the value of A^{extr} does not exceed 3–4 dB. The interpretation of this effect is given. A method and scheme of thickness measurement of two-layer materials with metallized coating and non-metallic base (glass-textolite) is proposed and developed, where samples with copper coating and glass-textolite base of different thickness are used as an example. In this case, the velocity or propagation time of PW, between two small aperture (non-directional) transducers with an acoustic base of 43 mm, is used as an informative parameter. In this case, the estimated sensitivity of the measured circuit to changes in the thickness of the metal coating is of 0.5 μm, and the base – twice as much.

Keywords: optoacoustics, ultrasonic plate waves, cracks, thickness gauging

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Особенности оптоакустического возбуждения и распространения пластинчатых волн в тонкостенных объектах

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Повышение эффективности неразрушающего контроля пластинчатых материалов с однослойной и двухслойной структурой является актуальной научно-технической задачей. Цель работы заключалась в исследовании особенностей возбуждения и приёма пластинчатых волн (ПВ) в однослойных и двухслойных материалах импульсным лазерным излучением (ЛИ) применительно к обнаружению в них трещин и оценки толщины слоёв при одностороннем прозвучивании. Разработана методика и проведены экспериментальные исследования влияния перемещения области лазерной генерации ПВ по поверхности дюралевых образцов относительно имитатора трещины разной глубины с последующим приёмом сигнала под характерным углом наклоном β_I. Установлено существенное изменение структуры волнового фронта при локализации зоны движущегося источника волн в окрестности имитатора трещины, сопровождающееся изменением отношения экстремальных значений амплитуд принимаемой асимметричной моды A^{extr} до 14–15 дБ. При приёме же симметричной s_0 моды величина A^{extr} не превышает 3–4 дБ. Дана трактовка этому эффекту. Предложена и разработана методика и схема толщинометрии двухслойных материалов с металлизированным покрытием и неметаллическим основанием (стеклотекстолит), где в качестве примера использованы образцы с медным покрытием и основой из стеклотекстолита разной толщины. В данном случае в качестве информативного параметра используется скорость или время распространения ПВ, между двумя малоапертурными (ненаправленными) преобразователями. При этом оценённая чувствительность измеряемой схемы к изменению толщины металлического покрытия составляет 0,5 мкм, а основы – более чем в 2 раза хуже.

Ключевые слова: оптоакустика, ультразвуковые пластинчатые волны, трещины, толщинометрия

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Introduction

The problems of highly sensitive and productive non-destructive testing of thin-walled lamellar materials, a wide range of products with both single-layer and double-layer structure for the presence of defects in them in the form of cracks, delaminations, volume defects take place in various branches of modern production [1]. One of the most effective directions for solving these problems is associated with the use of acoustic methods of probing objects using Lamb waves (LW) or plate waves (PW), which have a different structure of the wave front under certain conditions of ultrasonic sounding input [2]. The use of combined optoacoustic methods is of considerable interest, where the excitation of ultrasonic sound in the object is performed as a result of interaction of pulsed laser radiation (LR) with the surface layer of the object material with a duration from several tens to 1 nano-second or less, and the receiving – by traditional contact transducers [3–8].

In this case, there is a fundamental possibility to control the excited modes by changing the configuration of the spot of the laser beam incident on the object, ensuring the conditions of maximum sensitivity of control in the detection of defects, determining the amplitude, amplitude-frequency characteristics of the probing signal, as well as the speed and other acoustic parameters. In general, most of the works in this field of research are aimed at the study of single-layer materials, which have both non-flaws and structural changes as a result of a certain technological process during production or operation. As for two-layer structures, the research in this direction is mainly theoretical. In known works, for example [3, 4, 9], the so-called nonlinear (evaporative) mode is used for excitation of Lamb waves, and the laser beam energy is concentrated in the form of a spot of rather small radius, which affects the instability, as well as the limitations of measurements. The waves are received from the end of the plate material, which is significantly different from the optimal conditions under which the control of real thin-walled products with (or without) a protective coating is carried out. In [10] it was reported about the detection of a crack simulator by a Lamb wave located from the oppositional side of the plate surface. A similar effect of significant amplification of the signal amplitude when the spot of the laser beam passes through the simulated defective area in the form of a technological slot with a width of 20 µm was found when using a Rayleigh wave as a probing wave in [3]. In more detail, both experimentally and theoretically, this phenomenon is studied in [5]. Moreover, the object of study was real micron-sized fatigue cracks. The analysis of the carried out works on the issues of research of combined optoacoustic control by plate waves of thin-walled materials, including two-layer ones, indicates their insufficiency for understanding a number of peculiarities of wave field formation at their excitation and reception, as well as when interacting with non-flaws in materials. And this is very important for solving production tasks in the field of mechanical engineering, aircraft construction, electronics, etc.

The aim of the work was mainly to investigate new features of the optoacoustic (OA) method of testing of single-layer materials by Lamb waves with a crack-type defect, as well as to determine the possibilities of excitation of lamellar waves in 2-layer thin-walled materials for their thickness measurement.

Methodology and setup for experimental studies. Schematics of the optoacoustic method of excitation of plate waves by optoacoustic method in a single-layer and two-layer plate

The schemes of the experimental studies are illustrated in Figures 1 and 2.

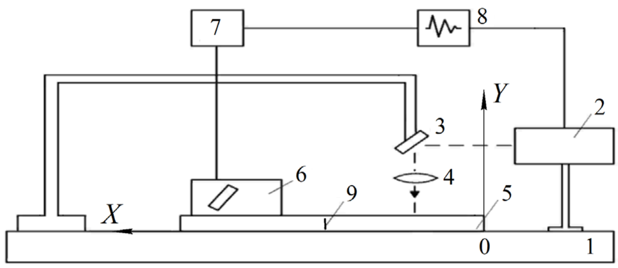

Figure 1 – Scheme of experimental modeling of the processes of excitation of Lamb waves by the OA method and their receiving by an inclined piezoelectric transducer (probe): 1 – support; 2 – pulse-laser radiation generator; 3 – laser light reflector; 4 – focusing device; 5 – the sample under study in the form of a plate without a defect and a defect in the form of a crack on the opposing surface of depth *h*, mounted on a platform (not shown) with the ability to move relative to the spot of the laser beam; 6 – inclined transducer or probe; 7 – electronic unit with an amplifier for receiving electrical oscillations from the probe; 8 – oscilloscope; 9 – crack simulator

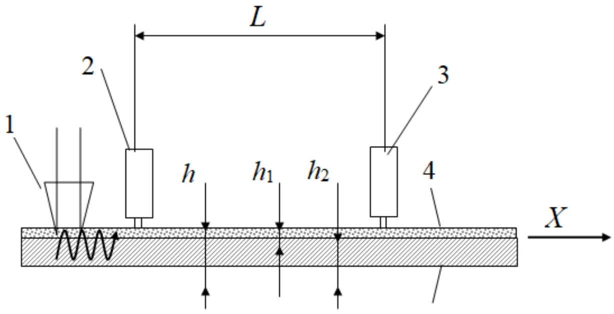

Figure 2 – Sheme of the combined optoacoustic method control by plate waves of thin-walled two-layer materials on the example of thickness measurement of plates with glass-textolite base and metal coating: 1 – laser beam; 2 and 3 – small aperture probes; 4 – coating layer; 5 – plate base

The first scheme is the basic one and is aimed at studying the peculiarities of the mechanism of conversion of pulsed laser radiation into Lamb waves and detection of discontinuities such as crack and others in a single-layer plate. The evaluation of the possibility of thickness measurement of thin two-layer plates is performed according to the 2nd measurement scheme. In contrast to the known studies, for example [4, 6, 9], OA wave excitation is carried out in a linear, pre-evaporation regime, i. e. at $J < J_0$ [1], where J_0 is the threshold value of the intensity of the influencing LR. In this situation, the area of LR influence on the surface of a single-layer plate looks like a circular spot with a diameter of $d = 5$ mm, and in the study of a two-layer plate it is similar to a long strip with a width of 1–2 mm.

The object of research

Single-layer plate

The material of the plate is 0.75 mm thick duralumin. On the surface of each of the "defective" plates, lying in opposition to the surface of the LI fall, simulators of cracks are made in the form of a slit with a width of 0.03 mm and depth h = 0.1–0.3 mm. The plate is made with the possibility of moving relative to the area of impact on it with a frequency of 20 Hz pulsed laser radiation to generate LW.

The excited Lamb waves are received by the ultrasonic probe with a variable prism angle β (or the angle of incidence of the longitudinal wave on the object surface) and then fed to an amplifier, oscilloscope and signal processing unit, as shown in Figure 1. In order to eliminate possible superposition of waves re-reflected from the lateral boundaries of the sample, kerfs are made symmetrically at an angle to the axis of the plate, which play the role of reflectors. During the research, attention was paid to the elimination of possible measurement errors caused by the precise positioning of the probe with a variable angle of reception and the spot of the laser beam. To increase the stability of measurements, the plate was pressed and held by magnets to the steel base of the moving platform of the carriage by magnets located outside the zone of propagation of the LW front.

Positioning accuracy of the distance L from the center of the laser beam spot to the front edge of the receiving probe prism 0.1 mm. The operating frequency of the receiving probe is 1.22 MHz. To eliminate the effect of laser radiation scattered by the object surface on the ultrasonic probe, which creates noise interference, a special coating is applied.

According to the scheme of object sounding (Figure 1), the relative movement of the source of LW localized in the area of the round spot of the LR beam towards the receiving transducer is performed, crossing the area of the surface under which the crack simulator is located, which serves as a scatterer or reflector of waves. The parameters of the acoustic signal received by the transducer are measured as the acoustic base L changes between the center of the laser beam spot and the transducer at a predetermined wave reception angle β. and According to the data on the change of the LW propagation time Δt when the transducer is shifted to the distance ΔL, the wave velocity is determined and the frequency f of the received LW mode is "programmatically" estimated.

Two-layer plate

Figure 2 shows the experimental scheme of testing of the combined optoacoustic method for the control of thin-walled two-layer materials with a metallic coating and a composite nonmetallic base or substrate with respect to their thickness measurement also by shadow method. However, as the analysis of the features of the wave field structure formation in lamellar materials [2] shows, the parameter correlating with the change in the thickness of the coating h_S and the substrate h_B of the samples is the velocity of the PW or the time τ_P of the acoustic signal propagation between two identical low-aperture probes located at the fixed distance from each other.

In reality, it is of interest to measure exactly the change of signal propagation time between probes caused by the change of only the coating thickness $\Delta h_P = h_{P0} - h_P$ or only the base of the material $\Delta h_B = h_{B0} - h_B$, for which the measured time intervals are respectively $\Delta\tau_B = t_B - t_{B0}$ and $\Delta t_B = t_B - t_{B0}$, where t_{00} correspond to the time of PW propagation through the sample with the initial thickness h_{00}. The measurement also took into account that $\{\Delta t_P, \Delta t_B\} << t_{00}$. The change of thickness of each layer was carried out according to a special technology, and the determination of their thickness was carried out both with micrometer and according to weighing data on electronic scales of VLG-2 type.

The necessity of using exactly the proposed scheme and design of the receiving probe for measurements is due to the peculiarities of acoustic properties of such materials, including low velocity of ultrasonic propagation and attenuation in the base, which complicates the reception and processing of signals with the help of traditional measurement schemes using inclined ultrasonic probes [1]. In this case, attention is paid (which is very important) to the determination of the desired value of Δt with the change of the thickness of the metal coating and nonmetal base, measured experimentally on the basis of the time interval meter И1-8 according to the traditional scheme [5]. In this case, the sensitivity to the change of the measured time interval is of the order of 3–4 ns. To perform the studies, samples from foil-coated textolite with thickness of 0.140 mm were cut out, and then, using a special technology, before each measurement, the thickness of the coating or base layer was reduced, determining each time the mentioned time parameters.

The basic results of experimental studies

The results of the research are illustrated in Figures 3–6 with the given data concerning a number of features of PW excitation and propagation in single-layer and double-layer plates. Moreover, Figure 3 presents oscillograms of symmetric and asymmetric Lamb waves excited by pulse-laser radiation, received by prismatic probe at two characteristic angles – β_1 and β_2. And Figure 4 illustrates the "reaction" of the acoustic signal of Lamb waves to the change of the signal amplitude profile $A(x)$ in the vicinity of $x \subset x_{cr} \pm \Delta x$, where x_{cr} is the coordinate of the crack simulator made on the back side of the plate. Figure 5 characterizes the given data of the influence of the depth of the model crack on the maximum change of the acoustic signal amplitude $A^{extr} = \dfrac{A_{\max}}{A_{\min}}$ when receiving waves at angles β_i.

The interpretation of the significant ("resonance") change of the signal amplitude is given using Figure 6, where an analog of the Rayleigh wave signal amplitude dependence when crossing a region with a surface crack located on the contact surface of an object is given. The possibilities of using plate modes for thickness measurement of two-layer materials on the example of metal-nonmetal pair (copper-textolite) are illustrated in Figure 7.

Single layer plate

As the main and important results of the experimental studies, let us emphasize the following. Firstly, it refers to the peculiarities of ultrasonic probe receiving at varying the angle of the probe prism, as well as the influence of the crack simulator on the amplitude parameters of the signal. So it is established that the Lamb wave received at the angle of the probe $\beta \rightarrow \beta_1 = 30°$ is a symmetric s_0 mode, the measured frequency of which with an error not more than 3–4 %, is $f_1 \approx 1.15$ MHz, which is slightly lower than the measured operating frequency of the probe ($f_W \approx 1.22$ MHz) At the same time other modes are absent. As the angle of wave reception decreases to $\beta_2 \rightarrow 24–26°$, a significant change in the structure of the wave field is observed, accompanied simultaneously by the presence of 2 modes – symmetric and asymmetric, and, as can be seen, the latter prevails in amplitude several times over the s_0, and in frequency – exceeds f_1 practically 3 times, as $f_2 \approx 3.35$ MHz. At the same time, as preliminary calculations show, the velocity of the s_0 mode is of 5250–5300 m/s.

Secondly, as can be seen in Figure 4, the passage of the laser beam spot in the vicinity of the crack location coordinates $x \subset x_{cr} \pm \Delta x$ is accompanied by the most significant change in the dimensionless amplitude parameter and its profile $A^{extr}(x)$ when receiving exactly the asymmetric mode. In this case, the value of A^{extr} reaches 13–15 dB, which is practically by 10 dB more than in the case of receiving at probing the sample so symmetric Lamb's mode. At the same time, when the spot of the laser beam is closer to the receiving probe than the crack simulator, then, as can be seen in Figure 4, the observed amplitude of the reflected signal of the above mentioned modes can be comparable to the amplitude of the probing ("direct") signal. The former indicates the possibility of using not only the shadow but also using the partitioned combined measurement regime in the control of plate objects.

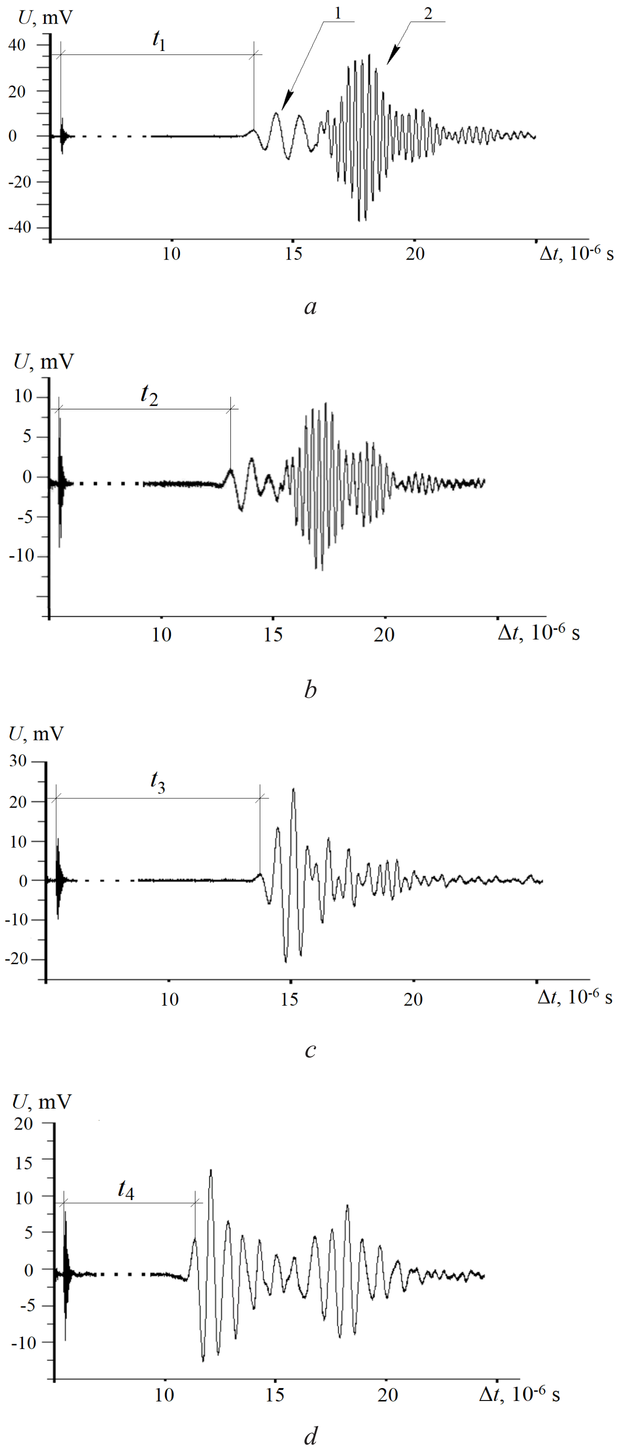

Figure 3 – Characteristic oscillograms of Lamb waves excited by pulsed-laser radiation Lamb waves received by prismatic probe at the angle β = 30° (Figure *a* and *b*) and β = 26° (*c* and *e*) at sliding of the laser beam spot on the surface of the sample plate located in opposition to the crack simulator: in Figure 1*a* – plate mode s_0 symmetric – 1, and 2 – asymmetric mode; time delay between the moment of LW excitation and reception by the transducer of the symmetric mode t_i, μs = 12.97 (*a*); 12.29 (*b*); 14.27 (*c*); 10.14 (*d*)

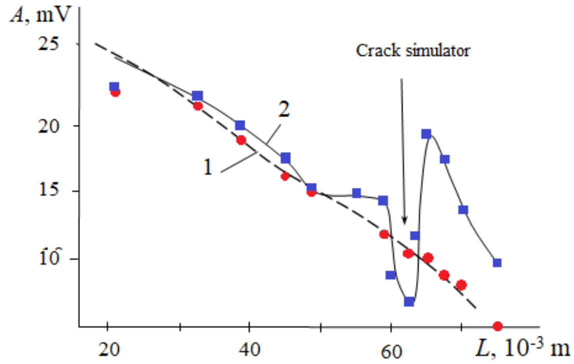

Figure 4 – Dependences of the normalized amplitude of the symmetric (1) and asymmetric (2) modes of the Lamb wave in a plate with a crack simulator on the distance between the spot of the laser beam on the object and the receiving tilted ultrasonic probe: frequency of the received mode *f*, MHz = 1.15 (1)

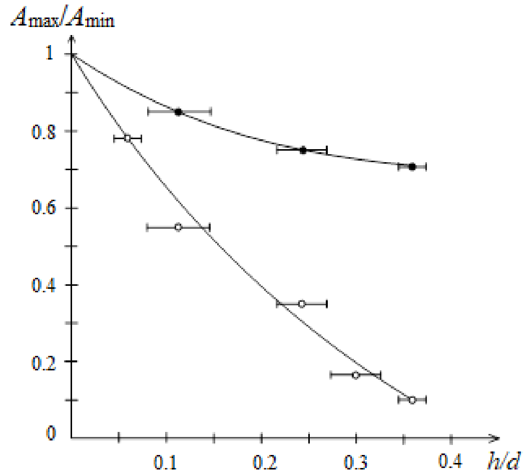

Figure 5 – Influence of the crack simulator depth on the relative maximum amplitude of symmetric (s_o) and asymmetric (*a*) modes received at frequency *f*, MHz = 1.15 (1) and 3.38 (2), respectively, when the spot of the laser beam slides along the surface of the plate, oppositional to the position of the defect – crack imitator

It is necessary to pay attention to the fact that despite the difference in the structure of the excited fields, a similar "resonance" effect, characterized by a sharp change in the amplitude parameter A^{extr}, occurs in the case of Rayleigh wave generation, when moving the spot of the laser beam directly through the area of the crack simulator [3], where the latter was a groove with a transverse dimension of 20 μm. A similar effect was observed in Figure 6 [5], where real fatigue cracks with opening of their mouths of micron dimensions served as a surface wave scatterer. And the spot of the laser beam moving through the crack had the form of an elongated strip of width *d*. Qualitative consideration of the mechanism of LW generation shows the following. If the problem simplified and is one-dimensional, then as a source of generation by laser radiation of waves of elastic oscillations we can consider two sections of the sample surface with widths a and b ($d = a + b$). They are separated by an infinite crack with coordinate $x_1 = 0$, on the surfaces of where the region closer to the probe ($0 \geq x_1 \geq a$) and behind it ($b \geq x_1 \geq 0$) are the sources of the laser generated Rayleigh waves having a wavelength $\lambda_R = C_R f_W^{-1}$, where f_W is the operating frequency of the receiving probe. Under the conditions laser pulse duration $\tau << f_W^{-1}$, spectrum of excited waves is broadband, crack depth $\delta > 0.5\lambda_R$, the boundary conditions on the crack surface are free ($\sigma_{ik} = 0$). Then according to [11] "the largest value of the maximum of the measured amplitude (or the manifestation of "resonance") should occur at the characteristic ratio d/λ_R and b/a – determining the optimal position of the laser beam spot. As presented in Figure 6, ratio $d/\lambda_R \to 2$.

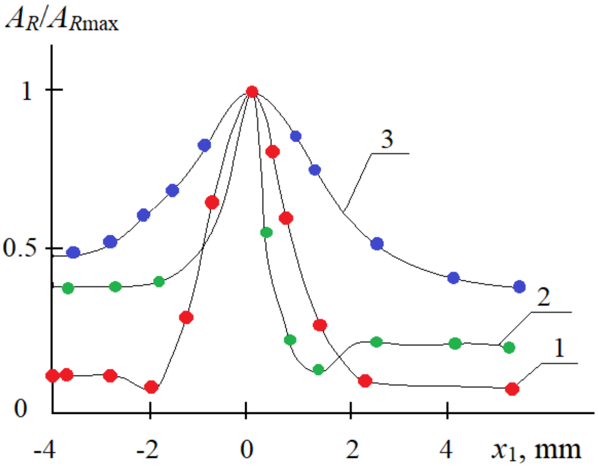

Figure 6 – Features of variation of the normalized Rayleigh wave amplitude depending on the position of the laser beam spot as a long strip relative to the crack position x_1, obtained in [5], where dimensionless width of the laser beam spot $b^* = b/\lambda_R = 2(1)$; 1 (2); 5 (3)

Taking into account the peculiarities of the formation of the excited fields of Lamb and Rayleigh waves and their propagation, it should be concluded that by varying not only the angle of wave reception β and the operating frequency, but also the shape of the laser light spot, it will be possible to significantly improve the efficiency of inspection of plate materials, including two-layer materials.

Two-layer plate

Figure 7 presents data illustrating the possibility of thickness measurement of thin two-layer materials of metal-nonmetal type using as a receiving device the developed low-aperture probes with the operating frequency of 1.8 MHz and the size of the working surface of waveguides in the direction of wavefront propagation not more than 0.3 mm. The studied samples, as mentioned earlier, are made of foil glass-textolite with significantly different (many times) physical-mechanical and acoustic properties, including ultrasonic attenuation, velocity, elastic moduli, etc., which was the reason for the development of the proposed device and measurement scheme. Expansion of measurement capabilities with the help of the proposed scheme (Figure 4) is achieved due to the fact that the low-aperture transducers, which are non-directional, are used for receiving the plate waves. This allows, unlike traditional schemes [1, 2], not to make (under predetermined conditions) a special adjustment of the radiation-receiving angles to adapt the reception of a number of elastic modes. In particular, it concerns acoustic diagnostics of two-layer materials. In this case, we selected not only the operating frequency of the receiving transducer ($f = 1.8$ MHz) but also the transducer waveguide transverse size and working surface, which are 0.3 mm.

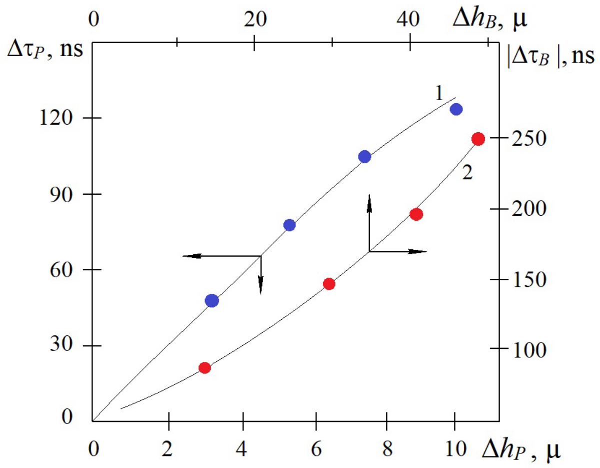

Figure 7 – Effect of varying the thickness of the metal coating Δh_P (1, ●) and the specimen base (or substrate) Δh_B (2, ●) on the variation of the plate wave propagation time $\Delta\tau_P$ and $\Delta\tau_B$, where $\Delta\tau_B \leq 0$

The data obtained for the first time and concerning the proposed method of estimation of thickness reduction of metallic coating Δh_P or nonmetallic substrate Δh_B of the sample by the change of propagation time of the excited lamellar mode $\Delta\tau_P$ and $\Delta\tau_B$, respectively, are shown in Figure 7. As can be seen, the time parameters $\Delta\tau_P$ and $\Delta\tau_B$, characterizing the change in the time of propagation of the plate waves similar to s_0 mode at decreasing the thickness of the coating or substrate, differ from each other both in sign and magnitude. Thus, reduction of the substrate thickness Δh_B is accompanied by a decrease in the time of wave propagation between the probes (i. e., $\Delta\tau_B$<0), which, of course, is accompanied by an increase in the velocity of the plate mode by the value ΔC~$\Delta\tau_B$. If the coating thickness is reduced Δh_B, the opposite situation is observed – $\Delta\tau_P$ increases, and the value of ΔC< 0. The reason of such course of dependences $\Delta\tau_P = F_P(\Delta h_P)$ and $\Delta\tau_B = F_B(\Delta h_B)$ is caused by the peculiarities of influence of elastic Young's moduli $\{E_P, E_B\}$, Poisson's coefficients $\{\upsilon_P, \upsilon_B\}$ and densities $\{\rho_P, \rho_B\}$ of the contacting layers in the plate, and also – initial geometrical parameters, including $\varepsilon_{PB} = h_P/h_B$, in the formation of the resulting wave field.

Reducing the thickness of the coating leads to a decrease in ε_{PB} and the effective Young's modulus of the plate material ($\Delta E_e < 0$), which predominantly affects the growth of the propagation time of the plate waves signal. It can also be easily shown that as the height of the substrate material, which has much lower elasticity than the coating, decreases, the magnitude of E_e and the wave velocity C will increase due to the decrease in the time interval $\Delta\tau = \Delta\tau_B$.

As experimental data show, using one-sided sounding of materials having the above (or similar) structure, it is possible to evaluate not only the change but also the thicknesses of two-layer materials when the ultrasonic sounding is introduced into the object through the metal coating. It is in this case that the best matching of acoustic impedances of the transducer waveguides with the object of study and effective transfer of the probing wave energy to the receiving ultrasonic probe is achieved. It should be noted that at excitation and reception of plate waves from the substrate side, the amplitude of the probing signal is much smaller – by more than two tens of dB.

It should be noted that measurement of the mentioned time intervals $\Delta\tau_P$ and $\Delta\tau_B$ in practice is performed with an accuracy of no worse than 4–5 ns, which allows estimating changes in coating thickness with an accuracy of 0.4–0.5 microns, and in the base – 2 or more times worse.

Conclusion

A technique has been developed and the features of excitation and reception of plate waves in single-layer and double-layer materials have been investigated in relation to the detection of crack-type defects and their thickness measurement by an optoacoustic method combining exposure of the material surface to pulsed laser radiation with a wavelength of 1.06 μm in the pre-evaporation mode and reception of plate waves by inclined and ultrasonic low-aperture probes.

The data on acoustic parameters of excited modes were obtained when moving a circular spot of the over the surface of a dural plate with a simulated crack of different depth on the oppositional surface depending on the position of the laser beam spot and with the subsequent reception of the signal at characteristic inclination angles β_I. The change of the wavefront structure at localization of the moving wave source zone or laser spot in the vicinity of the crack simulator, accompanied by a significant (similar to resonance) change in the ratio of extreme amplitude values of the received asymmetric (a) mode A^{extr}, where A^{extr} reaches up to 14–15 dB. At reception of the symmetric s_0 mode the value of A^{extr} does not exceed 3–4 dB. At the same time, the reflectivity of an asymmetric Lamb waves mode is higher than that of the s_0 mode. The observed effect is interpreted on the basis of the previously obtained data on Rayleigh waves excitation when a sliding spot of the laser beam crosses a crack.

The technique and scheme of the combined optoacoustic method of thickness measurement of two-layer materials with metallized coating (copper) and non-metallic base or substrate (glass-textolite), where low-aperture (non-directional) transducers are used as receivers for measuring time parameters of waves excited by pulsed-laser radiation, is proposed. It is shown that for the given (or similar) combination of the properties of the contacting materials, the reduction of the coating thickness Δh_P is accompanied by a decrease in the velocity of the plate wave and an increase in the time of wave passage between the sensors. According to the obtained data, it is established that the sensitivity of the proposed technique with respect to the control of coating thickness can be of 0.4–0.5 μm, which is practically nearly twice as much better than controlling the thickness of the substrate.

As a result of analyzing the data obtained earlier by others and by us, as well as the achieved successes in the development of optical equipment, it is necessary to pay attention to the possibility of increasing the efficiency of the optoacoustic testing of single-layer and double-layer materials of thin-walled

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products for the presence of cracks, delaminations, bonding defects, different thicknesses of materials according to the velocity data of plate modes, their amplitude and frequency characteristics. At the same time, due to the broadband nature of acoustic signals excited by pulse-laser radiation and the possibility of controlling the directionality of plate modes in the object both during their excitation and (which is very important) the angles of reception by electronic or mechanical means, it is possible to significantly increase the informativeness and reliability of readings of both symmetric and asymmetric modes taken in a short time.

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