Possibilities of Using of Surface and Subsurface Waves' Amplitude-Angle Characteristics for Control of Materials with Surface-Hardened Inhomogeneous Layer

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Abstract

Improving the efficiency of ultrasonic control of hardened surface layers of metal products with a heterogeneous structure obtained using different technologies is a pressing problem of industrial production. The purpose of this work was to investigate the possibilities of measuring the depth of the surface inhomogeneous layer of steel objects on the basis of the use of amplitude and amplitude-angle characteristics of surface and subsurface transverse waves.

The analysis of ultrasonic methods of control of physical and mechanical properties of metals by using surface and subsurface waves and experimentally investigated amplitude-angular characteristics of surface waves, the maximum angle of which increases by 3° at change of dimensionless layer depth h_λ from zero to 0.82. For the first time, the ratio of normalized amplitudes of surface waves taken at certain angles on the amplitude-angle characteristic curve obtained in the echo mode was proposed to be used as correlating parameters with the depth of the hardened layer. As a result of this research, the possibility of using a phased array transducers to solve the above problems.

The effect of the hardened layer depth varying from zero to five in the working frequency range of 1.8–10 MHz on the peculiarities of the refraction effect (including interference) and dependence of the subsurface wave amplitude on the acoustic base has been studied, making it possible to establish conditions that provide for the determination of the hardened layer depth.

Circuit solutions have been offered in order to increase the efficiency of control of properties of the surface layers of metal articles on the basis of utilization of small-aperture transducers and ultrasonic reflectors making it possible to form fields of surface waves of different directional pattern.

Keywords: surface and subsurface waves, ultrasonic reflectors, amplitude-angle characteristics, ultrasonic reflectors.

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Возможности использования амплитудно-угловых характеристик поверхностных и подповерхностных волн для контроля материалов с поверхностно упрочнённым неоднородным слоем

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Повышение эффективности ультразвукового контроля упрочненных поверхностных слоев металлоизделий с неоднородной структурой, полученных по различным технологиям, является актуальной проблемой опытно-промышленного производства. Целью данной работы являлось исследование возможностей измерения глубины поверхностного неоднородного слоя стальных объектов на основе использования амплитудных и амплитудно-угловых характеристик поверхностных и подповерхностных поперечных волн.

Проведён анализ ультразвуковых методов контроля физико-механических свойств металлов с использованием поверхностных и подповерхностных волн и экспериментально исследованы амплитудно-угловые характеристики поверхностных волн, максимальный угол которых увеличивается на 3° при изменении безразмерной глубины слоя h_λ от нуля до 0,82. Впервые предложено использовать в качестве коррелирующих параметров с глубиной упрочнённого слоя отношение нормированных амплитуд поверхностных волн, взятых под определёнными углами на кривой амплитудно-угловой характеристики, полученной в эхо-режиме. В результате проведённых исследований была выявлена возможность использования преобразователей с фазированной решёткой для решения вышеуказанных задач.

Исследовано влияние глубины упрочнённого слоя, изменяющейся от нуля до пяти в рабочем диапазоне частот 1,8–10 МГц, на особенности эффекта преломления (в том числе интерференции) и импенданса амплитуды подповерхностной волны на акустической базе, что позволило установить условия, обеспечивающие определение глубины упрочнённого слоя.

Предложены схемные решения для повышения эффективности контроля свойств поверхностных слоев металлических изделий на основе использования малоапертурных преобразователей и ультразвуковых отражателей, позволяющих формировать поля поверхностных волн различной направленности.

Ключевые слова: поверхностные и подповерхностные волны, ультразвуковые отражатели, амплитудно-угловые характеристики, ультразвуковые отражатели.

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Introduction

To improve the strength and performance characteristics of a significant number of industrial objects their surface hardening is carried out using various technologies, including thermal, thermo-chemical, mechanical processing, etc., which requires nondestructive testing. On the other hand, depending on operating conditions in the surface layer of a significant number of objects begin to occur degradation phenomena, accompanied by changes in the structure of materials and their physical-mechanical properties (PM) properties in result of thermal, thermal force, redox processes, which also requires a diagnosis of this factor. As shows the analysis of the interaction mechanism of elastic waves with metals and the presence of correlation of acoustic and PM properties, ultrasonic (US) methods are promising for the testing and diagnosis of the above objects.

Depending on specific conditions the traditional methods used for acoustic measurements in homogeneous materials and based on the presence of a phenomenological or correlation relationship between the PM properties and the velocity of a particular wave mode can be used. In first case we are to measure the time of volume wave propagation from contact surface to the "conditional" boundary of the HSL with the base and back to the piezoelectric transducer (PET). In the other case, the time of surface wave passage at a given acoustic base is measured. Principally, the dependences of the velocity of longitudinal (L), transverse (T), and surface (S) waves on the UPS depth can be obtained using the amplitude-angle characteristics, based on the Snellius formula:

$$\beta^*_{L,T,R} = \arcsin(C_1 / C_{L,T,R}), \tag{1}$$

where the specified angles correspond to extremums of amplitudes of ultrasonic modes reflected or passed into the object.

As well as to suggest some schemes to improve the efficiency of testing of such objects using small-aperture transducers and surface wave reflectors. The presence of a non-uniform layer on the surface of the body with elastic properties will in one way or another affect the acoustic path of the measuring system during the input-reception and propagation of these ultrasonic waves in the material of the objects, which are similar to a waveguide. In this case, it is of interest to pay attention to the features of dispersion and refraction effects in such waveguides, as well as to use them to improve the techniques and tools of acoustic measurements with regard to determining the depth of the HSL. At the same time, attention is paid to the nature of changes in the amplitude-angle parameters of the sources-receivers of ultrasonic waves depending on the depth of the hardened layer, the acoustic base and the frequency of the wave.

This work deals with an experimental study the features of excitation and propagation of weakly damped quasi-relief and non-uniform transverse subsurface waves in metals with a non-uniform surface layer, the influence of the latter and the wave frequency on the amplitude-angle characteristics and distribution of ultrasonic waves introduced into objects, as well as to offer some schemes to improve the effectiveness of control of such objects using small aperture transducers and reflectors of R waves. In the first stage of the work below, a brief analysis of the most well-known methods and means of control of objects with a heterogeneous surface layer is given and the technique features of measurements at near-critical angles of input-acceptance of ultrasonic in objects with different depths of hardened layer are considered. The conditions for using the refraction of subsurface transverse waves to determine the depth of HSL by amplitude-distance data are studied.

Analysis of features of acoustic diagnostics of surface strengthened layers

Currently, there are dozens of technologies that change the structure of the surface layer and its physical and mechanical properties to a depth of a few microns to cm and more [1–3], which requires the use of different techniques and measuring tools that implement them without destroying the object. At the same time, when controlling the PM of homogeneous materials is used as a basic parameter, most correlated with a number of PM properties and their structure, the velocity of various modes, having a relationship with the dynamic Young's modulus (E), Poisson's ratio (μ), metal density (ρ), according to the phenomenological formula [4, 5]:

$$C = C_{L,T,R}(E, \rho, \mu) = (E/\rho)^{0.5} F_{L,T,R}(\mu). \tag{2}$$

The mentioned elastic properties of materials quite often have a good correlation with such PM properties of metals as hardness, tensile strength, etc., which forms the basis for using acoustic measurement techniques to diagnose the PM properties of the object both in the volume and directly in the surface layers of products subjected to hardening, et al.

According to known studies, as well as those conducted by us, in the case of treatment of metal surface by high-frequency currents, cementation, laser annealing, boriding, nitriding, etc., the above mentioned PM parameters correlate well with the data on the velocity of the above modes [5–7]. At same time, maximum changing of velocity of one or another wave mode does not exceed 2–3 %, metal density – nearly 1 %, Young's modulus – 5–6 %. So that is:

$$\varepsilon_m = \Delta\Xi_m/\Xi_m) = \{\Delta C/C_{L,T,R}, \Delta E/E, \Delta\rho/\rho\} << 1,$$

where $\Delta\Xi_m = \Xi_m(0) - \Xi_m(h)$.

Thus, in relation to the above physical parameters, the HSL can be considered weakly homogeneous, and to obtain reliable results, it is necessary to take into account a number of errors caused by wave field diffraction, changes in the hardness profile of the material along the depth of the HSL, surface roughness, the quality of the acoustic contact and others. To simplify the HSL depth measurement procedure, in the work [6] developed measuring scheme, sounding the object by a surface wave at discrete frequencies ν_i. Then according to the data of phase (time) shift dependence on frequency the desired depth of the layer is determined.

In order to level some of the former factor, we suggested [7] to use spectral analysis of the probing pulse signal and determine the phase velocity of the wave for each of the j-th harmonic by its phase change ($\Delta\varphi_j$) between two receiver transducers with a small aperture of the working surface mounted at distance l_{12} one behind the other. I. e., on the basis of the obtained frequency dependence $\Delta C/C_R(\nu)$, using the Oulder formula, it is possible to solve the inverse problem, estimating not only the layer height, but also restoring the distribution of elastic moduli and other PM properties over the layer height.

It should be noted that a high degree of localization of HSL depth measurements is achieved by using PET not surface but volume waves with an operating frequency of 15 MHz and more, introduced into the object at a characteristic angle [8]. The conditional "structural" boundary of the HSL with metal base serves as a "reflector". In this case, the layer height is determined according to the pulse echo travel time data Δt_{ef} from the coordinate of source wave input into the object to the coordinate of the receiving PET after reflection of the wave front from the base structure boundary. As for the determination of the required value of Δt_{ef}, it is determined according to the program of analysis of the probing signal scattering field from the specified boundary developed for each metal hardening technology. So, this boundary is a peculiar ensemble of "point scatterers" and is determined using a correlation function derived from a statistical data set. So that the required thickness of the HSL can be represented in a simplified form:

$$h = 0.5C_1\,\Delta t_{ef},$$

where C_1 is ultrasonic velocity in in transducer prism material and Δt_{ef} is some effective time, depending on the structure of the material to test, the ratio of ultrasound in contacting materials, and the angle of incidence on the surface of the object.

The disadvantage of the method is that the required accuracy and reliability of measurements are achieved at $h > 3$ mm. At the same time, in most cases, it is necessary to determine the thicknesses of the HSL less than 3 mm.

In work [9] have been developed an ultrasonic method of controlling the depth of HSL of steel rolls of sufficiently large depth. It was shown that at sufficiently large thicknesses of the HSL on the course of the dependence $A(x)$ has a significant influence of the interference of surface and subsurface diffracting waves. As stated, if $h_\lambda >> 1$ (where h is tens of mm), the distance between the maxima of the studied dependence serves as informative and correlative parameters with the depth of the layer. It is to be expected that for $h_\lambda < h_\lambda$* curves $A(x)$ are to be monotonically decreasing dependences. And is assumed that this will make it possible to identify the conditions that ensure the establishment of an unambiguous relationship between the amplitude parameters of the ST mode and the thickness of the HSL for the characteristic acoustic base between the measuring probes.

Proceeding from the analysis of possible variants of methods and means of definition of HSL depth, as well as taking into account the importance of solving this problem for a variety of objects created by industry, the subject of the present research and development are: amplitude-angular characteristics of steel samples with HSL depth h = 0–1.5 mm, taken in the transmission and reflection mode and scheme solution proposal for increase of control efficiency; refraction phenomena in frequency range 1.8–10 MG and definition of conditions eliminating appearance of extremums of $A(x)$ curve;

improvement of HSL depth measurement schemes according R velocity using reflectors of different design. Thus, based on the analysis of possible options for methods and means of determining the depth of HSL, as well as given the importance of solving this problem for the variety of objects created by industry, the subject of this study are the amplitude-angle characteristics of surface R-waves and amplitude dependence of subsurface transverse waves on the depth of HSL, at different frequency and value of the acoustic base, which can be used to improve control of the depth of inhomogeneously hardened layers of metal items.

About amplitude and amplitude-angle methods of measurement

These methods are simple enough and can be divided into two groups. The first group should include methods traditionally used to determine velocity of surface and volume waves in homogeneous bodies using data of amplitude-angle characteristic of waves reflected from object surface (for example, goniometer method) or subsurface or Rayleigh modes introduced into object [5]. In this case, the amplitude extremum angles serve as informative ones. In particular, at introduction of elastic modes into solid body, at angles $\beta = \arcsin(C_1/C_{L,T,R})$ the amplitudes of excited waves in the object are maximal. I. e., this case corresponds to the phenomenological connection between $\beta_{L,T,R}$ and $C_{L,T,R}$. So, the considered variants of HSL creation will cause predominantly decrease of elastic properties and spreading rate of ultrasonic waves, especially of R waves, which energy is localized in the surface layer with depth $h_\lambda^* \approx \lambda_R$. Therefore, it should be expected that the increase of h_λ will cause the increase of β_m at which the maximum amplitude of the R wave A_{Rm} will be observed because:

$$\partial\beta_m/\partial h_\lambda = (\partial h_\lambda/\partial C_R)(\partial C_R)/\partial\beta_m > 0,$$

where using formula (1) and data [4, 8], we obtain that $\partial h_\lambda/\partial C_R < 0$ and for the second factor is true: $\partial C_R/\partial\beta_m = -C_R^2\cos\beta_m/C_1 < 0$.

It should be noted that the traditional realization of this method of determining the C_R mode rate in the shadow regime and the use of two identical transducers for radiating – receiving R-wave and setting the angle of maximum β_m is difficult in factory conditions, because in the vicinity of $\beta \rightarrow \beta_m$ $\partial A_R/\partial\beta \rightarrow 0$. If the angle of the receiving transducer is fixed (Figure 1), however, as can be easily shown, the behavior of the curve $A_R(\beta)$ in the vicinity of $\beta_m \pm \Delta\beta$ will change, which will lead to a decrease in measurement accuracy. Taking into account the fact that the curve of dependence $A(\beta)$ is similar to a parabolic curve, it should be assumed that a higher accuracy of the HSL depth measurement can be achieved not by measuring β_m, but (as suggested in this work) by measuring the ratio $A_R(\beta_i)/A_{Rm}$ in the left ($i = 1$) or right (2) branch of dependence $A_R(\beta)$, where β_i corresponds to the angle of wave incidence in the transducer to the object at which $A_{Rm}/A_R(\beta_i)$ should be maximum.

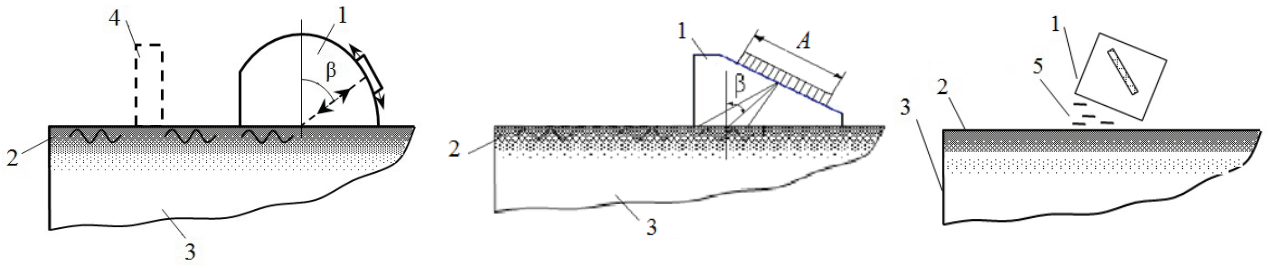
In [9] for sufficiently large thicknesses of HSL, where the use of methods based on the connection velocity of the elastic mode (or other parameters associated with it) with the depth of HSL suggested to use the effects based on the refraction of the introduced into the controlled object subsurface transverse waves. Moreover, the presence of a velocity gradient $\nabla V_T(z)$ in the surface layer can significantly change the wave field, which is demonstrated in the development of the method of controlling the depth of hardened steel rolls, where the problem of relating the HSL depth and its properties with data dependence $A_{ST}(x)$, which has maximums, caused by interference of surface and diffracting in the subsurface layer wave. As stated, if $h_\lambda >> 1$ (where h is tens of mm), then range $h_\lambda < h_\lambda^*$, at which curves $A_{ST}(x)$ are monotonically decreasing dependences. (As there show [5] the velocities of the transverse subsurface wave C_{ST} and the one excited at the angle of incidence $\beta < \beta_2$ in an object with a homogeneous structure C_T are the same, i. e. $C_T = C_{ST}$). It is assumed that this will make it possible to identify the conditions that ensure the establishment of an unambiguous relationship between the amplitude parameters of the ST mode and the thickness of the HSL for the characteristic acoustic base between the measuring transducers.

Proceeding from the analysis of possible variants of methods and means of the HSL depth evaluation, as well as taking into account the importance of solving this problem for a variety of objects created by industry, the subject of the present research and development are: amplitude-angular characteristics of steel samples with HSL depth $h = 0$, -1.5 mm, taken in the transmission and reflection mode and scheme solution proposal for increase of control efficiency; refraction phenomena in frequency range 1.8–10 MHz and definition of conditions eliminating appearance of extremums of $A_{ST}(x)$ curve; improvement of HSL depth measurement schemes according to R velocity using reflectors of different design. Thus, based on the analysis of possible options for methods and means of determining the depth of HSL, as well as given the importance of solving this problem for the variety of objects created by industry, the subject of this study are the amplitude-angle characteristics of surface R-waves and amplitude dependence of subsurface transverse waves on the depth of HSL, at different frequency and value of the acoustic base, which can be used to improve control of the depth of inhomogeneously hardened layers of metal items.

Research Techniques

Schemes for amplitude-angle measurements

Experimental schemes of research to identify the possibility of improving the HSL depth diagnosis on the basis of the amplitude-angle characteristics of the HSL mode, as well as the use of the phenomenon of subsurface wave refraction are explained in Figure 1.



a *b* *c*

Figure 1 – Schemes of experimental studies of the effect of the angle of incidence of ultrasonic waves and the acoustic base on the excitation and receiving of transverse subsurface and surface waves in samples with a hardened heterogeneous layer and using ultrasonic transducers with a constant point of acoustic beam exita sliding acoustic contact (*a*), with phased array (*b*), with a liquid wedge (*c*): 1 – ultrasonic transducer with a variable angle of the ultrasonic waves input-receiving with a sliding contact (*a*), phased array (*b*) and liquid wedge (*c*); 2 – hardened surface layer; 3 – test specimen; 4 – ultrasonic reflector; 5 – liquid wedge

Surface wave

The first measurement scheme can operate in echo mode and shadow mode. Moreover, the latter requires the use of two PET transducer with a smoothly varying angle of incidence of the wave, by controlling which (as mentioned earlier) is determined the maximum amplitude A_{Rm} and the corresponding angle β_m. In this work, mainly an echo mode is used, which allows to increase operability and accuracy, which is achieved by using a prismatic sample edge as a reflector.

During the studies, the influence of the dimensionless depth of the HSL on the course of the dependence $A_R(\beta)$ is studied in detail. So, the conditions under which it is possible to achieve maximum sensitivity to changes in its parameters – the wave amplitude and the angular shift β of the maximum A_{Rm} – are determined. The operating frequency of 1.8 MHz was chosen as the base frequency for the studies, which allows leveling the effect of attenuation on the amplitude-frequency parameters of the wave. The PET is made with a sliding protector and an external cylindrical surface, contacting with the prism sounding duct. When conducting research in the angular range of β = 58–72°, the error of setting the angle of incidence did not exceed 0.2°.

It should be noted that during the research we studied the possibility of using the FAZOR-4 device and the PET with electronically controlled phased array to solve the assigned tasks.

Radiation of ultrasonic waves is carried out by a matrix of 16 elementary piezoelectric plates, to which are fed (received) electric pulses, shifted in phase, realizing the oscillating acoustic beam and changing the directional diagram of the transducer.

Subsurface transverse waves

The influence of refraction on the acoustic path of excitable subsurface waves was studied both in the echo and shadow modes. Working range 1.8–10 MHz. Mainly contact inclined PET with prism angle were used, which excite ST mode under the second critical angle β_2 = 58°. To find out the peculiarities of the interference effect, a probe with a local immersion bath (water) and working frequency of 10 MHz, operating in echo mode and with the possibility of changing the angle of incidence β in the near-critical range β = 24–26° was made.

Results of experimental studies and their discussion

Amplitude-angle characteristics of surface R waves

The main results of experimental studies of the influence of HSL depth on amplitude-angle characteristics of *R* waves are shown in Figures 2–4, and *ST* wave refraction when varying the acoustic base in Figures 5–7. Figure 2 shows characteristic changes of the wave amplitude curves from the angle of incidence of the excitation mode on HSL samples, in the reflection mode realization. As expected, the experimental $A_R(\beta)$ curves obtained according to the scheme shown in Figure 2 look like a parabola with the branches facing downward, shifting together with the maximum A_{Rm} to the region of high values of β with an increase in the dimensionless depth h_λ. As it was found using the given scheme of sounding in the echo mode the value of Δβ is nearly 3° at $h_\lambda = 0.82$ as well as the change of *R* wave velocity being nearly by 1.8 %. As for the change in the width of the curve $A_R(\beta)$, its value, taken at the level of 10 dB changes only by a few percent.

Note that the above results are also confirmed by the data in Figures 3*a* and 3*b* obtained using a phased array transducer, although the value of the angular shift Δβ is somewhat smaller than that obtained earlier. As for the change in the angular width, it is almost the same. Further studies have shown that the reduction of the elements that make up the aperture of the phased transducer is accompanied by a significant broadening of the amplitude-angle characteristic $A_R(\beta)$. Thus, for example, a change in the number of radiating elements in the form of a 12 mm long strip from 16 to 4 causes a 3.7–3.6 times change in its angular width β at 20 dB. It is obvious that in order to use such systems in practice it is necessary to increase the resolution (angular) ability of measurements, to specify the features of acoustic matching and geometry of the sound duct when working at different frequencies, which is very important.

Perspectivity of using such an approach to solve this problem is to significantly reduce the influence of the subjective factor on the measurements. At the same time, it is necessary to clarify the features of PET with phased array at swinging of acoustic beam in the vicinity of the angle of incidence on the sample β = 64–65°.

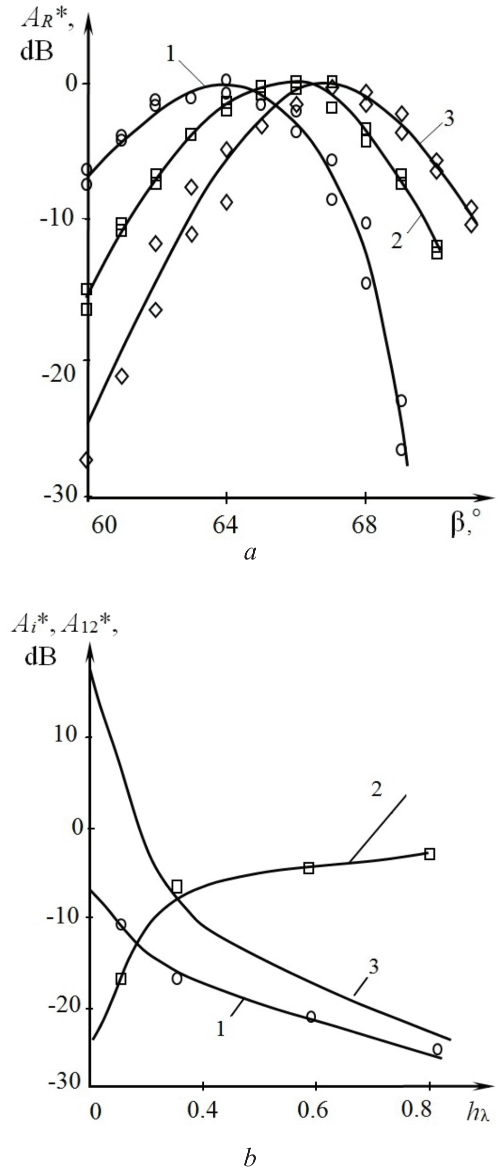


Figure 2 – Dependences of the surface *R* wave amplitudes (explained by the formulas (3)), on the angle of ultrasonic wave incidence on the sample (*a*) and the depth of the hardened layer (*b*). *a*: A_R^* – the normalized amplitude at $h_\lambda = 0$ (1); 0.32 (2); 0.82 (3); *b*: A_i^* – relative wave amplitudes taken for fixed angles at the left (1) and right (2) branches of the curve $A_R^*(\beta)$, where $\beta_1 = 60°$ (1) and $\beta_2 = 69°$ (2); $A_{12}^* = A_2^*/A_1^*$

It is necessary to clarify that a preferential decrease of the wave velocity *R* with increasing depth of the PET and a subsequent move towards saturation of the function $C_R(h_\lambda)$ are caused by peculiarities of change in effective values of the modulus of elasticity *E* and density of the surface layer of material depending on coordinate *z* by the depth of wave localization equal to $h \approx \lambda$. Using formula (1) the value of the wave velocity R can be estimated by assuming that it propagates in a homogeneous material layer with constant (effective) values of the Young modulus E_e and density ρ_e:

$$E_e \approx \int_{h_R}^{0} Q_1 E^{-1} dz, \ \rho_e \approx \int_{h_R}^{0} Q_2 dz,$$

where $Q_i = Q_i(z)$ – specific coefficients that take into account the spatial distribution of the above properties of the elementary layers of the material of thickness dz. (In this case, we neglect the change in the Poisson's coefficient value).

The use of the method of HSL depth measuring according to angular displacement value $\Delta\beta$ significantly depends not only on the depth of HSL and its elastic properties, but also on the accuracy of angle β_m setting. The complexity of this operation is caused by finding the angle of maximum of the field amplitude, in the vicinity of which $\partial A/\partial\beta \to 0$, which significantly affects the accuracy of R mode velocity estimation and, naturally, the determination of HSL depth. On the basis of the experimental data obtained and its analysis it is suggested to improve the efficiency of the measurement procedure.

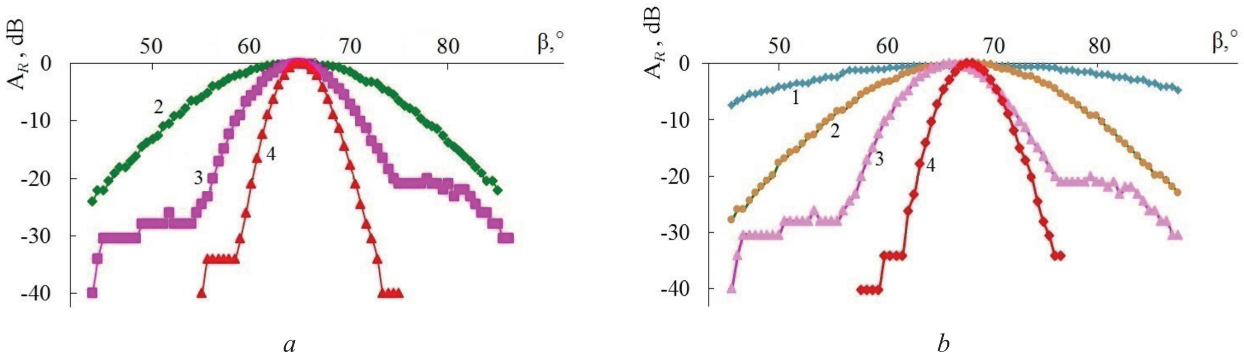


Figure 3 – Amplitude-angle characteristics of ultrasonic transducer with phased array when varying its aperture, determined by the number of radiating elements in the form of plates of length 12 mm for sample with the hardened surface layers depth of $h_\lambda = 0$ (*a*) and 2.2 (*b*); dependence 1 – 2 plates; 2 – 4; 3 – 8; 4 –16

The essence of the suggested method is the ratio of normalized amplitudes $A_R(\beta_i)\ (A_{Rm})^{-1}$, measured on one or two branches of $A_R(\beta_i)$ at $h_\lambda = 0$ (beforehand) and in the process of measurements, which is the most sensitive parameter with respect to the angle shift of the considered above dependence. I. e., first, to estimate a specific depth of HSL we conduct receiving and measurement of signal amplitude A_{Ri} at fixed one or two-angle β_i on the left ($i = 1$) and (or) right ($i = 2$) branches of $A_R(\beta)$, and then we measure its maximum A_{Rm}. Finally, it was suggested to use the ratio of normalized amplitudes as correlating informative parameters to estimate the HSL depth:

$$A_i^* = A_{Ni}/A_{N0i} = (A_{Ri}/A_{Rm})(A_{R0i}/A_{R0m})^{-1};$$
$$A_{12}^* = A_{N1}/A_{N2} = k^0 A_{R1}/A_{R2}, \quad (3)$$

where the index 0 corresponds to the situation when $h = 0$, and $k^0 = A_{R02}/A_{R01}$ is some constant, determined with maximum precision before measurements are taken.

Thus, for example, the value of $A_{Ri}^*(h_\lambda)$. when varying h_λ in the range of 0–0.82 can change by 20 dB or some more. If you use the parameter A_{12}^*, its variation reaches more than 35 dB. At the same time, the sensitivity of these parameters to changes in the layer depth is maximal for $h_\lambda < 0.4$ and reaches a minimum for $h_\lambda > 0.5$–0.6.

Thus, it is necessary to suppose, that by choosing the receiving angles for the considered amplitude-angle relation and the operating frequency R of the wave, it is possible to control the sensitivity and accuracy of HSL depth definition. This is confirmed by the former curves in Figure 2*c*, which are plotted on the basis of experimental data.

Let us note that the problem of precise setting of the angle of incidence (reception) of the primary ultrasonic source β_i (up to 0.1°) can be easily solved by fixing its body in one or two positions with sufficient accuracy, for example by using special stops-restrictors. As for measuring of the wave amplitude at β_m, included in expression $A_R(\beta_i)(A_{Rm})^{-1}$. As can be seen from Figure 2, a high accuracy of the angle β_m is not required, because the error of magnitude and A_{mi} measurements in the vicinity of $\beta = \beta_m$ is the smallest. Preliminary tests of the suggested method of measurements on samples hardened by high-frequency hardening with depth from 0.5 to 1.5 mm showed a principal possibility to estimate the HSL depth with an error not exceeding 15–20 % and roughness of the contact surface of samples smaller than 5 µm. As studies have shown, the use of the echo mode for ultrasonic control is generally preferable to the shadow one, which requires a significant complication of the device, as well as an increase in its dimensions.

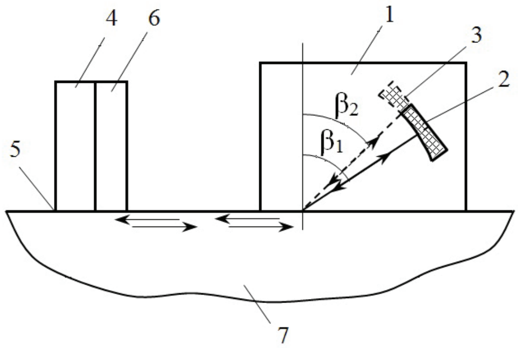


Figure 4 – Suggested operation scheme of ultrasonic device for the hardened surface layers depth testing: 1 – piezoelectric transducer; 2 and 3 – primary probe of the ultrasonic signal in two positions for measuring its amplitude at fixed angles β_i; 4 – reflector of the surface *R* wave, and 5 – its boundary *R* waves reflection; 6 – noise-reflective boundary area; 7 – object

In order to expand the capabilities of the method and increase its efficiency, we developed and tested a prototype device containing PET and an *R*-wave reflector, which is explained in Figures 8–9. In this case, the size of the device is significantly reduced, productivity is increased, and the possibilities of its application are broadened. A more detailed description of it is given in section 4.

Note that the above results are also confirmed by the data in Figures 2*a* and 2*b* obtained using a phased array transducer, although the value of the angular shift Δβ is somewhat smaller than that obtained earlier. As for the change in the angular width, it is almost the same. Further studies have shown that the reduction of the elements that make up the aperture of the phased transducer is accompanied by a significant expansion of the amplitude-angle characteristic $A_R(\beta)$. Thus, for example, a change in the number of radiating elements in the form of a 12 mm long strip from 16 to 4 causes a 3.7–3.6 times change in its angular width β at 20 dB. It is obvious that in order to use such systems in practice it is necessary to increase the resolution (angular) ability of measurements, to specify features of acoustic matching and geometry of the sound tube when working at different frequencies, which is very important. Perspectivity of use of such approach for the decision of the given problem consists in essential reduction of influence of the subjective factor on carrying out of measurements. At the same time it is necessary to clarify the peculiarities of PET operation with phased array when the acoustic beam is swinging in the vicinity of the angle of incidence on the sample β = 64–65°.

Peculiarities of transverse subsurface wave refraction in samples with a surface inhomogeneous layer

As it is known, under conditions of a longitudinal wave incidence on body at an angle $\beta < \beta_R = \arcsin(C_1/C_R)$ along with a Rayleigh wave a transverse subsurface wave with an amplitude A_{ST} which has ~10 % higher velocity is excited. And with increasing $\Delta\beta = \beta_R - \beta$ the amplitude factor $A_{TR} = A_{ST}/A_R$ is an increasing function of the angular shift, reaching a maximum at some value $\beta < \beta_R$. If $h = 0$, then when varying Δβ from zero to $\Delta\beta = \beta_R - \beta_2$, where $\beta_2 = \arcsin(C_1/C_T)$, though there is an increase in A_{TR}, but, nevertheless, in the whole range of angles significantly prevails surface mode (almost one order).

Studies performed of the amplitude-angle dependences of the $A_{TR}(\beta)$ according to a technique similar to that used above for the study of the *R* wave, showed the following. Thus, at HSL thickness $h_\lambda \approx 0.82$ the maximum value of $A_{TR} \approx 1$, and at $h_\lambda^* \approx 2.5$, the transverse wave prevails in a significant range of angles (Figure 5). And the angular width of normalized dependences of the function $A_{ST}(\beta)$, taken at the level of 20 dB when the distance to the reflecting edge of the sample changes twice differs within 5 %. Note that the knowledge of the behavior of the dependences studied at different frequencies makes it possible to significantly increase the signal-to-noise ratio and the accuracy of measurements.

Since the change of HSL depth has a significant effect on the course of the $A_{TR}(\beta)$ function, it is of interest to use such dependences to solve the inverse problem to determine the HSL depth. But for this purpose it is necessary to take into account the influence of the object surface roughness on the A_{TR} attenuation and to ensure a high stability of the acoustic contact in the measuring system. As for the behavior of the $A_{ST}(l_\lambda)$ dependence, the effect of roughness can be reduced due to the peculiarities of the formation of the wave front of subsurface waves [5].

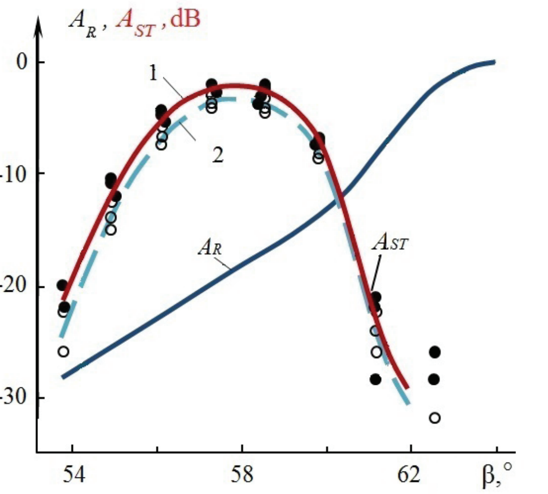


Figure 5 – Amplitude-angle characteristics of transverse subsurface *ST* waves (1, 2) and surface *R* waves (3) at $f = 5$ MHz in a sample with a hardened layer depth of $h_\lambda = 2.5$; the sound mode is echo; dimensionless distance to the reflecting boundary $l_\lambda = 34$ (1, ●); 68 (2, ○)

Figures 6 and 7 show characteristic dependences of the investigated wave amplitude reflected on the acoustic base length at $\beta_2 = 58°$, as well as the incident angle on the sample in the near-critical mode (Figure 7). In the second case the immersion method of acoustic contact creation is used, providing removal of the influence of ultrasonic attenuation in the probe prism and high-precision adjustment of the angle β by means of a screw mechanism with a step of less than 0.2° in the range of β = 24.5–26°. It was found that with $h_\lambda \approx 2.5$ and less, the logarithmic dependencies A_{TR} on the dimensionless acoustic base obtained both in the shadow and in the echo way are predominantly close to linear. This difference in amplitude reaches up to 20 dB and more, which is determined by the choice of operating frequency and acoustic base. It is interesting that when the characteristic value $h_\lambda > 2.5$–3 is exceeded, the refraction phenomenon leads to a significant change in the behavior of the studied dependence on the acoustic base, caused by the interference effect.

According to the theoretical model and the suggested method [9], the HSL depth is determined with an accuracy of up to 10 %, using data on the coordinates of the location of the maximums of the $A_{ST}(l_\lambda)$ dependence. However, this accuracy is provided at $h_\lambda > 10$ only. Another difficulty of using this method is related to the complication of the procedure of measurements, caused by the need to search for the maximum.

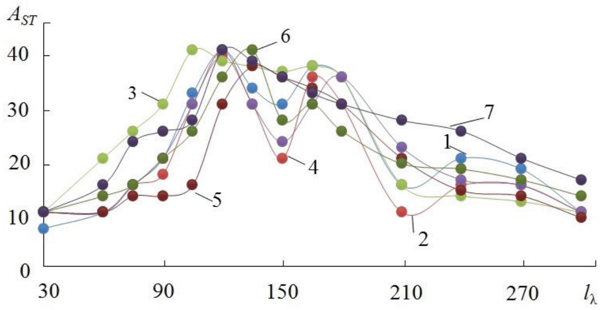


Figure 6 – Dependence of subsurface transverse wave amplitude in reflection mode on the distance to the reflecting edge of the sample in the hardened surface layers with depth of $h_\lambda = 5$ when implementing the immersion acoustic contact and varying the angle of incident wave in the vicinity of its second critical value $\beta = \beta_2$: β°= 24.5° (1); 24° (2); 23.5° (3); 23° (4); 25° (5); 25.5° (6); 26° (7)

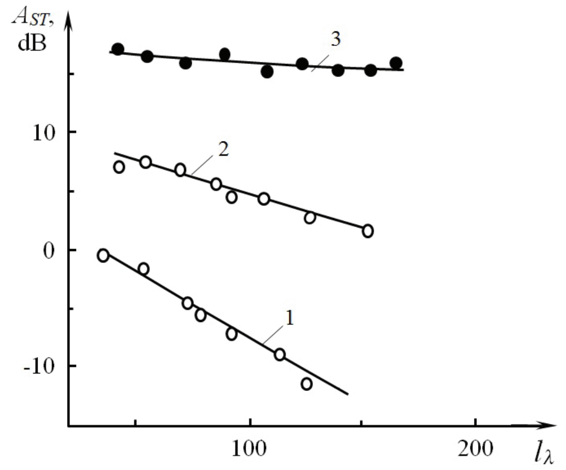


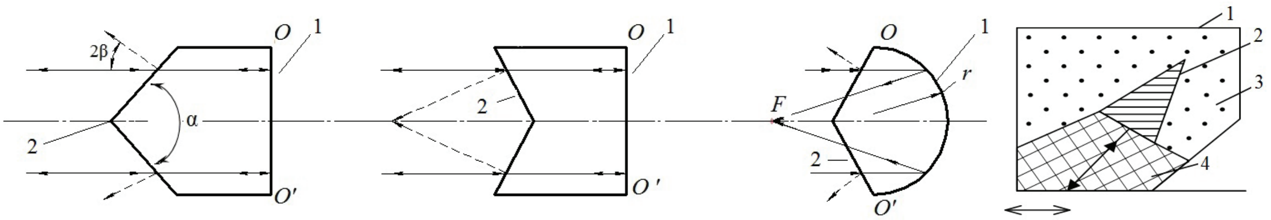
Figure 7 – Dependence of subsurface transverse wave amplitude in the reflection mode on the doubled distance to the reflecting face of the sample with different depth of the hardened layer: $h_\lambda = 0$ (1); 0.82 (2); 2.5 (3): prism angle $\beta = \beta_2 = 58°$; $f = 5$ MHz

Based on the studies of excitation and propagation of subsurface *ST* waves in samples with HSL, we can conclude that the amplitude dependences on the operating frequency and acoustic base of the sounding, as well as the angle of incidence β on the objects to study can be the basis of HSL measurement techniques when $h_\lambda \leq 2.5$. Thus, on the one hand, this will expand the range of the tested depth of the layer of surface-hardened metals and, on the other hand, provide conditions for detecting discontinuities in the surface area of *ST* waves due to levelling the influence of interference caused by refraction on the measuring process.

On the features of acoustic measurements using surface wave reflectors

Below we firstly suggest acoustic schemes aimed at improving the accuracy of the physical and mechanical properties of the surface layers of metal products measured by surface waves, including the depth of HSL and hardness distribution over the depth of the heterogeneous layer, mechanical stress, the degree of micro-damage, etc.

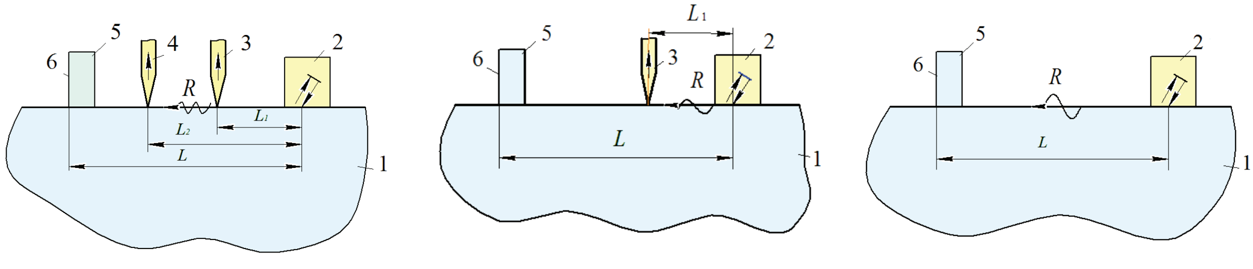
Thus, Figure 8 illustrates some features of surface and subsurface wave reflector designs functioning (top view), where the boundary area (boundary) of the contact between the opposing edge of the device and the control object 1 serves as a reflector of the reference (useful) signal. The oppositely contacting area of the device with the controlled object (boundary 2) has different shape providing elimination of noise background of the *R*-waves reflected from it (schemes *a*, *b*, *c*). The waves passing through this boundary are transformed into a Stonley wave [5] and after reflection from boundary 1 they return to the transducer in reverse order. By changing the shape of the boundary 1, it is possible to change the directional pattern of the *R*-wave field, providing, for example, their focussing.



a *b* *c* *d*

Figure 8 – Reflector design schemes of the surface (*a*, *b*, *c*) and subsurface (*d*) waves. *a*, *b*, *c* – top view: 1 – reflection area (boundary) of surface waves received by the transducer operating in the echo mode; 2 – “noise-reflecting” boundary”, eliminating penetration of surface waves reflected from it onto the transducer; *d* – side view: 1 – body; 2 – reflecting body; 3 – ultrasound wave absorber; 4 – sound tube

The schemes shown in Figure 9 are intended to improve the reliability and accuracy of acoustic measurements. For this purpose it is suggested to emit and receive ultrasonic waves both prismatic and small-aperture (or non-directional) transducers with point contact of working surface of “waveguide” of transducer [10, 11], or in the form of a narrow strip. And their working surface may be from 0.01 to 1 mm^2. And in the first case, when working even in the megahertz range (1–5 MHz) acoustic contact is “dry” (without contact medium), which is very important for stable measurements. In some conditions at high-precision measurements the metal structure, characterized by metal grain size, diffraction, unequal clamping of receiving transducers can influence the stability of acoustical contact, which leads to error of measured time interval and wave velocity.



a *b* *c*

Figure 9 – Schemes of evaluation of the surface inhomogeneous layer properties according to the amplitude and velocity of ultrasonic waves using its reflectors and small-aperture probes: 1 – sample; 2 – ultrasonic inclined transducer; 3 – and 4 – small aperture probes; 5 – reflector; 6 – opposition face of the surface wave reflector

However, taking into account that used transducers are “non-directional”, it turns out that by sounding the object in two directions, where the “second source” of the *R* wave is the reflector, the required velocity $C_R \rightarrow 2l\,(t_1 + t_2)^{-1}$, where t_1 and t_2 are the *R*-wave propagation times between the transducers in the forward and reverse directions. In this case measurement errors are leveled, subtracted.

The diffraction error is determined by the location of the receiving probe in the near zone, determined by the value of function $F(l/\lambda_R^{-1}, a/l/\lambda_R^{-1})$, where a characterizes the aperture of the surface wave transducer. So, by placing the ultrasonic reflector on the opposite side of the receiving probe and by changing the shape of the reference reflecting boundary of surface waves of the reflector, it is possible to substantially level this error by taking the reflected signals of the indicated probe with small aperture in the reverse order. Similar velocity measurements (but with a larger error) can also be realized by using measurement schemes on Figures 9*b* and 9*c*. However, in this case, it is necessary to ensure reliable stability of the acoustic contact. It should be noted that the same schemes can also be used to determine the attenuation of the wave amplitude by the surface layer structure.

Experimental research conducted at 1.8 and 2.5 MHz showed that when a steel prismatic reflector contacts a thin layer of contact medium with the same base, the coefficient of reflection from the reflector's oppositional (reference) boundary is more than 30 dB higher than that from the front boundary. Reflection coefficient of the wave increases noticeably if the normal to the wave front is inclined by more than 30°. A change in dimensionless thickness of the gap filled with fluid between the contact surface of the reflector and the object from zero to $h_\lambda = 0.04$ will have practically no effect within 1–1.5 dB on the reflected wave amplitude change.

Conclusion

The shot analysis of traditional ultrasonic methods of control of physical and mechanical properties of homogeneous metals has been carried out and the acoustic path of weakly attenuated surface and transverse subsurface waves in steel specimens with a heterogeneously surface layer has been studied experimentally, including its effect on the amplitude-angle characteristics of surface waves and peculiarities of the subsurface wave refraction effect during changes in the acoustic base and operating frequency (1.8–10 MHz).

It was found that varying of the dimensionless depth of surface-hardened layer from $h_\lambda = 0$ to 0.82 is accompanied by an increase in the peak angle of the amplitude-angular characteristic surface wave at the operating frequency of 1.8 MHz up to nearly 3° with a change in its angular width of not more than 3–4 %.

On the basis of obtained data analysis we suggest the method of a hardened layer depth measuring. It firstly, includes using the ratio of normalized amplitudes measured for fixed optimal angles at one or both branches of the amplitude-angle curve in the absence and presence of sample hardening as an informative parameter (parameters) correlating with it.

On the basis of obtained data analysis we suggest the method of surface-hardened layer depth determination which consists in using the ratio of normalized amplitudes measured for fixed optimal angles at one or both branches of amplitude-angle dependence in the absence and presence of sample hardening as an informative parameter (parameters) correlating with it. It is shown that varying the surface-hardened layer depth in the above range is accompanied by changing the value of the suggested amplitude parameter by up to 20–30 dB. For practical realization of this method it is suggested to carry out measurements in the echo mode using a reflector of the design presented in the work. As an alternative variant the measuring system with the phased array transducer and working frequency of 4 MHz has been tested for the first time. It qualitatively confirms the results obtained above and testifies (with an appropriate improvement) about the prospects of such a method for depth control of the hardened surface layers.

A set of studies on excitation and propagation of subsurface transverse waves by using the shadow and echo methods at 1.8–10 MHz operating frequencies was carried out at changes of dimensionless surface-hardened layer depth in the range of $h_\lambda = 0–5$ and the wave incidence angle. For the first time the conditions eliminating the refraction effect accompanied by interference phenomena on the subsurface wave amplitude dependence course character with the acoustic base increase have been determined that is realized at $h_\lambda < 2.5–3$ and enables the method of their estimation to be offered, and also increases the reliability of detecting subsurface and surface defects in objects with surface-hardened layers.

An analysis of increasing the efficiency of checking the properties of surface layers of metal items on the basis of the proposed schematic solutions, including the use of small-aperture transducers, as well as surface wave reflectors, by changing the geometry of which it is possible to form fields of surface waves of different directional pattern. Studies have shown that when a steel prismatic reflector is in contact with the surface of the sample through a thin layer of liquid, the reflection coefficient from the opposition (reference) boundary of the reflector is of 30 dB higher than from the front boundary.

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