APPLICATION OF THE METHODS FOR PROCESSING SIGNALS FROM ULTRASONIC SURFACE WAVES DURING THE STUDY OF INDUCTION-TEMPERED MATERIALS

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Abstract

The paper presents results of the study of induction-tempered materials by means of ultrasonic surface waves. It comprises analysis of material mechanical properties, measurement of the velocity of ultrasonic surface waves and processing of ultrasonic wave signals (spectral and cross-spectrum analysis). The approach can be used for the identification and assessment of layered materials.

Keywords: Ultrasonic surface waves, signal processing, induction-tempered materials, spectral and cross-spectrum analysis, assessment of layered materials.

Introduction

The combination between high hardness and strength of surface-hardened layers (SHL) on one hand, and high impact strength and in-depth toughness on the other hand, is one of the requirements to a large set of industrial parts. That requirement is satisfied by performing material surface tempering. It is realized via induction heating of the surface layer, yielding a material with high-hardness surface layer and smooth change of bulk properties [1].

The application of classical methods to evaluate layer thickness (i.e. metallographic methods and micro-hardness measurements) [1] is expensive and ineffective for a large number of products. Hence, methods of nondestructive assessment of the thickness and properties of surface-treated materials are actual and perspective [3-9].

The methods of signal processing are widely applied in geophysics when treating seismic surface waves. Their use in studying induction-tempered materials is a new and actual trend, making possible the clarification of the ultrasonic wave propagation in layered materials.

The aim of the present work is to study the dependence between the mechanical and acoustical properties of surface-hardened materials, when performing analysis and processing of signals from surface ultrasonic waves.

Materials

Surface-hardened layers (SHR) on cylindrical specimens are studied. Specimen diameter and length are 22 mm and 200 mm, respectively. Specimens are initially ground and subjected afterwards to induction tempering with different durability. Specimen processing regimes are experimental and they aim at fabricating layers with different thickness. Layer micro-hardness

HV is measured by means of micro hardness meter applying load of 100 g. Table 1 gives tempering durability (τ), results of hardness measurements ($HV_{0.1}$) and effective thickness of the surface layers (d_{eff}). Three areas are distinguished in the surface-treated material: a layer with high surface hardness, transitory area with lower hardness and an area in bulk with unchangeable structure and properties. There is no sharp boundary between those areas. Hence, to characterize the SHR, researches introduce the term "layer effective thickness" (d_{eff}). That thickness is conditionally determined as a thickness where hardness is by 100 units larger than the in-depth hardness [1].

Table 1

No	τ, s	$HV_{0.1}$	d_{eff} , mm
1	0	257	0
2	15	549	0,25
3	25	412	0,8
4	40	412	2,2
5	60	766	3,3

Fig.1 shows micro-hardness distribution within the cross section of some specimens belonging to series given in Table 1.

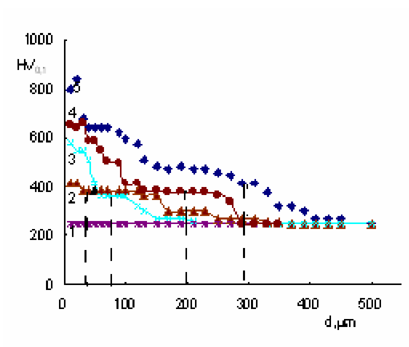

Fig. 1. Micro-hardness distribution in the specimen cross section

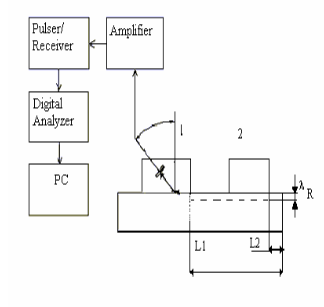

Fig. 2. Experimental setup for ultrasonic studies

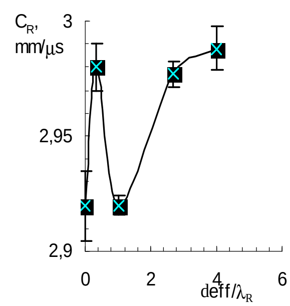

Fig.3. Change of surface wave velocity by parameter d_{eff} / λ_R

Fig. 2 shows an experimental setup for ultrasonic studies. A computerized ultrasonic instrument produce of Optel company [19] with 4 MHz frequency is used for that purpose. It consists of a generator and receiver of ultrasonic waves OPGUD, and an ultrasonic card OPKUD-01/100, integrated within a PC, class Pentium III. The ultrasonic instrument has a block for measuring the time of ultrasonic impulse propagation with an accuracy up to 10 ns. The equipment has 8 bits resolution and sampling rate of 100 MHz. To attain a higher accuracy of measurement, we undertake measures for maintaining constant conditions for the generation of acoustic signals, and we use one and the same liquids.

Surface ultrasonic waves called after the English scientist Rayleight propagate on the surface of the cylindrical specimens, parallel to the specimen axis. They are excited by an angular ultrasonic transducer with variable angle, at an angle of refraction close to the second critical angle of a system plexiglass-steel. The depth of penetration is of 1-1.5 λ_R order, where λ_R is wave length and it is approximately equal to 0.7-0.8 mm for frequency 4 MHz. Using an echo-method, we register and record in digital form echo-signals transmitted from the specimen upper edge to the sensor. The transducer moves along the specimen length covering different distance x (from 5 to 50 mm with an interval of 1 mm). The acoustic path of the ultrasonic waves, when applying the echo-method, is denoted by L and $L = 2.x$.

Velocities of the surface waves are measured according to (1), and they are averaged using results of several measurements at different distances. Different methods of recording the time of impulses registered are used (time recording with respect to initial point and time recording with respect to maximal value of the signal envelope).

(1) $C_R = 2(L_2 - L_1)/(t_2 - t_1)$,

where C_R is velocity of the Raleigh surface ultrasonic wave, L_1 and L_2 are acoustic paths of the ultrasonic waves ($L_1 = 2x_1$, $L_2 = 2x_2$), x_1 and x_2 are distances from the sensor center to the end of the specimen, t_1 and t_2 are times of registering the surface wave signals for distances x_1 and x_2. Fig.3 shows an experimentally found relation between velocities of surface waves and parameter d_{eff} / λ_R. For layers with thickness commensurable to λ_R we observe decrease of the values of C_R until attaining values close to ones typical for the non-processed material. For layers larger than λ_R velocities of the surface waves increase by 2% as compared to the initial velocities.

Processing of signals from ultrasonic surface waves

Under the presence of a surface layer, when the physico-mechanical properties of material surface differ from those of material bulk, dispersion of the velocity of the ultrasonic surface wave is observed [8,11,16-18]. We check here the hypothesis that the presence of layers with different structure and properties resulting from thermal treatment affects the signal shape and the spectral characteristics of the ultrasonic impulses. Hence, we pose two problems. The first one is to follow the ultrasonic wave evolution along the length of each specimen by measuring the change of the signal spectra. The second problem is to find the law of variation of signals from materials with layers of different thickness and to compare those signals with ones coming from non-layered materials.

The registered signals from surface acoustic ultrasonic waves are processed applying a specific method which comprises procedures of signal equalizing and smoothing; Fourier image and determination of the spectrum parameter (real and imaginary part, phases and amplitudes, respectively). To assess difference between signals coming from a specimen without a layer and one with a layer, we use a cross-spectrum analysis [11-18]. It enables us to find correlations between signals obtained for one and the same distance and shifted with respect to time. We can also study the phase difference between those signals [8,9, 17].

As for the actual experimental setup, only the signal reflected by the specimen edge can be recorded and processed. Hence, we can not assess damping by comparing successive echoes, as in the traditional echo method, and the signal amplitude can not be used as an information parameter. Fig.4 shows processed ultrasonic wave signals from a material in a time window, and the signals are registered for different acoustic paths (L,mm). They are equalized with respect to amplitude and position in the time window (Fig.46), and they are also smoothed. Several methods for signal smoothing are checked, and smoothing by creeping averages is chosen, considering three weightless points.

Fourier images of the signals are found. The small sampling frequency limits result plausibility for frequencies higher than 10 MHz i.e. in a range where the characteristics of the mechanical (ultrasonic) surface waves can be affected by the change of material properties within a layer with thickness commensurable to the depth of wave penetration. Thus, the spectral characteristics are calculated from the Fourier images for frequency up to 7 MHz, only, where the signal exceeds the maximum by -30dB. It is supposed that the expected effect could be better expressed considering the complex spectrum compounds or spectrum phase. The size of the time window is assumed to be equal to the period of signal x(t), and it is denoted by T, while the initial moment – by t_0 , and the circular frequency is $\omega = 2.\pi.f$. Figures 5 a,c show spectra S of signals from specimens without a layer d_{eff} =0 (a) and in case $d_{eff} > \lambda_R$ (c). No spectrum significant change is observed.

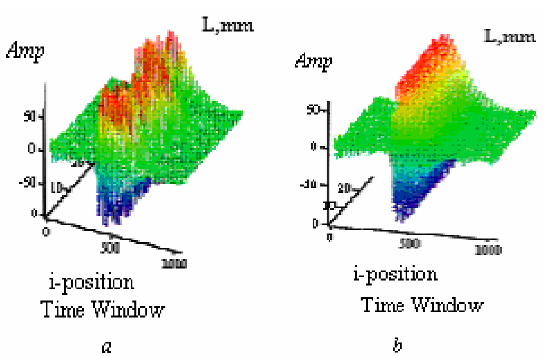

Fig.4a Fig.4b

Fig.4. Signals after being smoothed and equalized with respect to position (a) and amplitude (b) in the time window, changing the acoustic paths.

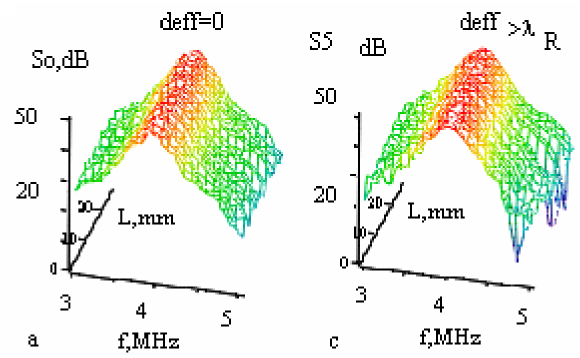

Fig.5a Fig.5c

Fig.5. Spectra of signals from specimens №1- d_{eff} =0 (a), №5- $d_{eff} > \lambda_R$ (c)

Cross-spectrum analysis

To study the signal evolution regarding the path covered by the ultrasonic wave along the specimens, we employ some elements of the cross-spectrum analysis, i.e. a cross-correlation and cross-spectral function.

The cross-correlation function $CRF(\tau)$ characterizes the change of a specific signal $x(t)$ as compared to another one $y(t+\tau)$, shifted in time τ (10)

(2) $CRF_{xy}(\tau) = \frac{1}{T}\int_{t_0}^{t_o+T} x(t)y(t+\tau)dt$, where $x(t)$ is the signal recorded at a distance x and time t, $y(t)$ is another signal recorded at the same distance but shifted in time τ .

To assess the interrelation between the spectral components of the two signals, we use a cross-spectral density or a cross-spectrum. Its is a Fourier image of the cross-correlation function being expressed by the relation

(3) $$CS_{xy}(f) = \int_{-\infty}^{\infty} CRF_{xy}(t)e^{-j2\pi f\tau}d\tau$$

The cross-spectrum is found via (11) [11,15,17]

(4) $CS_{xy}(f) = F[x^*(t)y(t+\tau)] = S_x^*(f)S_y(f)$, where $S_x(f)$ is the Fourier image of $x(t)$, $S_x^*(f)$ is an image complex-conjugated to $S_x(f)$, and $S_y(f)$ is the Fourier image of $y(t)$ respectively.

(5) $CS_{xy}(f) = CO(f) + iQ(f) = |CS_{xy}|\exp\{i\Phi_x\}$, where $CO(f)$ is the real part, $Q(f)$ is the imaginary one, and Φ is the phase of the cross-spectral function.

The phase of the cross-spectrum CS(f) is found as in [8,11,17] and it determines the phase differences between the studied signals in the specified frequency range.

(6) $$\Phi_{xy}(f) = arctg\left(\frac{\text{Im}(CS_{xy}(f))}{\text{Re}(CS_{xy}(f))}\right).$$

Differentiating phase $\Phi(f)$ we find time proportional to the change of the group velocities of the surface waves propagating in non-processed materials and in materials with surface-hardened layer, for one and the same distance.

(7) $\tau_{\Phi}(f) = d\Phi(f)/df$.

To assess the effect of the structure and properties of surface-hardened materials, signals from ultrasonic surface waves are compared to those coming from initial materials without a layer. Using the cross-spectral characteristic, we calculate according to (6), and those differences prove that signals are comparable for one and the same distance. Fig.6 shows calculation results for a correlation between signals from materials with layers less than (a), equal to (b) and larger than (c) the wave length, on one hand, and signals coming from materials without a layer, on the other hand.

Specimens with different layers (Fig.7) are distinguished in $\Phi_{xy}(f)$ depending on $deff/\lambda_R$. There is an exception in the results for specimens with a layer thickness of an order equal to the wave length. The increase of the thickness of SHL yields increase of the phases of cross-spectra $\Phi_{xy}(f)$. When $deff/\lambda_R$=1 the slope is reverse.

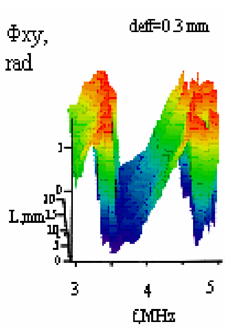

Fig.6a

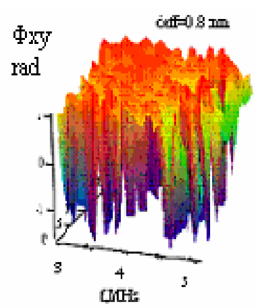

Fig.6b

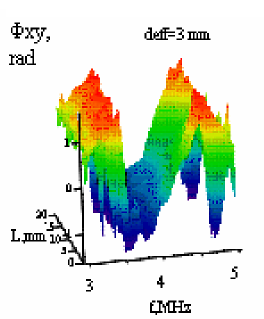

Fig.6c

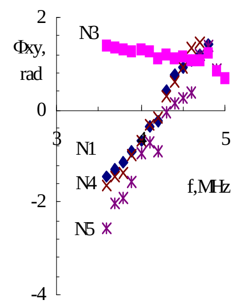

Fig.7a

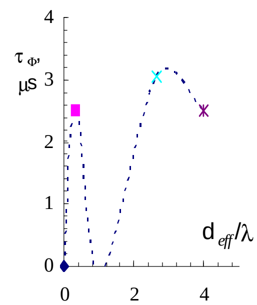

Fig.7b

We see that the change of parameter τ_{Φ} in a positive direction shows increase of the group velocity, and its change in a negative direction – subsequent group velocity decrease. It is observed that the character of the curve shown in Fig.7 b is quite similar to that of the curve shown in Fig.3, and small changes are recorded. The experiments and mathematical processing performed prove that changes of material structure and properties resulting from the application of surface induction tempering weakly affect the signals from surface ultrasonic waves, i.e. signal spectral and phase characteristics, respectively. Yet, they are accessible for analysis employing ultrasonic equipment. The experiments performed are not sufficient but they help to the disclosure of the change of parameters of surface waves when the latter propagate in materials with SHL.

Conclusion

Based on the experiments, we can conclude that the method of spectrum and cross-spectrum analysis is applicable to the study and assessment of the thickness of surface-hardened layers. The different structure and properties of hardened materials change spectra and phases of signals from surface ultrasonic waves. Dependences of the signal phases are found in the frequency range considered. Characteristic times of wave passing are found and they are a measure for the change of the wave group velocities. Small changes of phases are registered in a narrow frequency range. The use of parameter "phase growth" is appropriate when relating it to the frequency growth ($\tau_{\Phi}(f) = d\Phi(f)/df$) where different thicknesses of SHL are established.

Using the cross-spectrum analysis, one can study small differences between signals and can thus increase accuracy and efficiency of the studies.

Our study shows that a generalized dependence for the estimation of the thickness of SHL by applying ultrasonic surface waves is not an easy task, due to the inaccuracy of the classical methods of layer study, lack of sharp boundary between areas and insufficient amount of experimental data. Yet, the results found are useful for further studies.

References

[1] Buchkov A. Thermal treatment, Tehnika, 1991,Sofia (Bulgarian)

[2] Mihara T. et al. Measurement of carburized depth in low alloyed steel by using attenuation spectrum of ultrasonic Rayleigh wave, J.of JSNDI,1989,38 (10), 898-903.

[3] Takahashi F. et al. Intelligent Measurement and diagnostic techniques for non-destructive inspections, Hitachi Review Vol.48 (1999),No5.

[4] Vincent A., A. Moughil, Ultrasonic chatacterization of zirconia-based thermal barriers, NDT Int.Vol.22,No5,1989.

[5] Theiner W. R. Kern, Process-integrated nondestructive testing of ground and case hardened parts, PINT NDT-ECNDT Barcelona, 2002.

[6] Kumar Anish, Shankar V., T.,Jayakumar and all , Nondestructive Measurements of coating thickness Ultrasonic Velocity Measurements, Mat.Evaluation, June 2002,791-794.

[7] Hatanaka H., I.Kajigaya, T. Arakawa, Ultrasonic Testing with a Signal Processing method for thermal Sprayed coatings, Materials Evaluation, June2004, 683.

[8] Nagashima Y., A.Watanabe, F. Takanashi, Y. Kawamata, Non-destructive Evaluation on Nitrided layer Integrity of Turbine Components by a combined method of ultrasonic and eddy current techniques, 15th Con NDT,824-834.

[9] Berndt H. , Johnson G.C., Using Phase slope for arrival time determination, NDTnet, April 2006,Vol.11,No 4.

[10] Victorov A. Rayleigh and Lamb waves, Physical Theory and Application, Plenum Press, New York,1967, p.154.

[11] Skuchik E., Fundamentals of acoustics, Vol.1, Mir, Moscow, 1976 (Russian).

[12] Kolesnikov A., Acoustic measurements, "Sudostroenie", Leningrad, 1983 (Russian).

[13] Ivanova Y., T.Partalin, T. Avdjieva, M. Mihovski, Al. Popov, Ultrasonic characterizaion of superficial layers in hardened steels, Xth National Congress on Theoretical and Applied Mechanics, 13-16 September 2005, Varna, Bulgaria.

[14] Guide to OPKUD and OPBOX-ultrasonic testing units- technical data, http://www.optel.pl.

[15] Hartmann D., Cross Spectrum Analysis, ATM 552 Notes, Section 6c, p.157, Internet.

[16] Methods of nondestructive testing, Ed. R.Sharp, Publ.House Mir, Moscow,1972 (Rus.).

[17] Zywicki D., Advanced signal processing methods applied to engineering analysis of seismic surface waves, PhD Dissertation, Georgia Institute of Technology, 1999.

[18] Petersen G. Notes on ultrasonic phase and group velocity measurements, RITEC Inc, Internet, Web:RitecInc.com.