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Marian Josko - Marcin Jarmuzek *

HODNOTENIE ADHEZÍVNYCH SPOJENÍ MEDZI POVLAKOM A SUBSTRÁTOM S POUŽITÍM ULTRAZVUKOVEJ SPEKTROSKOPIE

EVALUATION OF ADHESIVE JOINTS BETWEEN COATING AND SUBSTRATE USING ULTRASONIC SPECTROSCOPY

V článku je vykonaná teoretická analýza ultrazvukového impulzného signálu a experimentálne vyšetrovanie na skúšobných vzorkách. Skúšobné vzorky boli vyrobené z konštrukčných ocelí a pokryté povlakmi z tmelov a lakov. Študovali sme predovšetkým citlivosť vybraných parametrov ultrazvukového spektra na zmeny stavu substrátu a priľnavosti. Bolo konštatované, že nepravidelnosti substrátu a hrúbka povlakov ovplyvňujú spektrum ultrazvukového signálu.

In the paper the theoretical analysis of ultrasonic impulse signal and experimental investigations on some specimens was carried out. The specimens were made of constructional steel on which some coatings of automotive putty and lacquer were layered. In particular, the sensitivity of selected parameters of ultrasonic spectrum on changes of condition of the substrate and bonded materials was studied. It was noticed that irregularities of substrate and the thickness of coatings layered, influence parameters of the ultrasonic signal spectrum.

1. Introduction

A lack or a loss of adherence between coatings and substrate are caused by loosening of coating from a substrate. All areas of the loosening can be considered as flat defects. They would be detected by a traditional amplitude-time ultrasonic method, and they can influence also an amplitude-frequency spectrum of ultrasonic signal descended from a space of the joint of coating with the substrate. Some positive examples of application of ultrasonic spectroscopy for evaluation of adhesive bonds are known already [1-3].

The ultrasonic spectroscopy is a very essential supplement to ultrasonic defectoscopy, because through an analysis of ultrasonic signal in frequency domain, we can obtain some additional data concerning detected faults. In some cases, it is possible to receive the fundamental information about shape and orientation of defects as well as about the structure of materials [4], especially using ultrasonic broadband transducers.

The purpose of this paper is an assessment of suitability of spectral analysis of ultrasonic signal, whose sources are medium-damping transducers, for evaluation of adhesive joints of two sorts coating layered on steel substrate. The role of coatings plays an automotive lacquer layers and an automotive putty. The range of our considerations is limited to an assessment of sensitivity of selected parameters of ultrasonic spectrum on changes of substrate condition and bonded materials.

2. Theoretical analysis

On the base of [5], we can express the amplitude of harmonic components of ultrasonic signal h_n by a typical wave dependence:

$$h_n = Af_0\tau \left| \frac{\sin\left(\left(\frac{c}{\lambda} - nf_0\right)2\pi\tau\right)}{\left(\frac{c}{\lambda} - nf_0\right)2\pi\tau} - \frac{\sin\left(\left(\frac{c}{\lambda} + nf_0\right)2\pi\tau\right)}{\left(\frac{c}{\lambda} + nf_0\right)2\pi\tau} \right| \quad (1)$$

where: A – amplitude of ultrasonic signal,
fo – frequency of impulse generation,
τ – duration of impulse,
c – velocity of ultrasonic wave in the medium,
λ – wavelength of ultrasonic wave,
n – natural number.

The wavelength of ultrasonic wave λ can be connected with the dimension of the planar defect d using the below equation:

$$\lambda = zd \quad (2)$$

* **Dr. Ing. Marian Josko, Mgr. Ing. Marcin Jarmuzek**
[1]Poznan University of Technology, Institute of Working Machines and Motor Vehicles, Piotrowo 3, 60-965 Poznan, Poland, Tel.: +48-061-6652247, Fax: +48-061-6652736, E-mail: Marian.Josko@put.poznan.pl
[2]Postgraduate Study Candidate, MPK, Ltd. – Municipal Transport Company, ul. Głogowska 131/133, 60-244 Poznan, Poland, Tel: +48-061-8699361, Fax: +48-061-8791681.

where: d – average size of planar defect on the adhesive boundary,
z – factor of proportionality (grade of commensurability).

Including (2) in the expression (1), the mathematical relationship between the amplitude of harmonic components of ultrasonic signal h_n and average size of planar defect d (for example the dimension of the loosening of coating from substrate), can be presented in the following formula:

$$h_n = Af_0\tau \left| \frac{\sin\left(\left(\frac{c}{zd} - nf_0\right)2\pi\tau\right)}{\left(\frac{c}{zd} - nf_0\right)2\pi\tau} - \frac{\sin\left(\left(\frac{c}{zd} + nf_0\right)2\pi\tau\right)}{\left(\frac{c}{zd} + nf_0\right)2\pi\tau} \right| \quad (3)$$

where: A – amplitude of ultrasonic signal,
f_o – frequency of impulse generation,
τ – duration of impulse,
c – velocity of ultrasonic wave in the medium,
z – factor of proportionality,
d – average size of planar defect on the adhesive boundary,
n – natural number.

It can be supposed that most of harmonic components of the ultrasonic signal are reduced, when the wavelength of ultrasonic wave λ is at least commensurable with the size of defect or considerably smaller than size of the planar defect $\boldsymbol{d}$ ($\lambda \approx d$ or $\lambda << d$). According to [6], both damping and dissipation of ultrasonic wave are the utmost in these cases.

The main parameters and the character of frequency spectrum envelope of sinusoidal ultrasonic impulses, illustrated by dependence (3), can be presented as in Fig 1. The planar defects on the boundary between coating and substrate could influence this spectrum as a band-pass filter, e.g. low-pass or high-pass. It means that defects can remove a certain part of components of the spectrum.

3. Experimental investigations

For investigation of sensitivity of paramount parameters of ultrasonic spectrum on changes of substrate irregularity and bonded materials, steel disc-shaped specimens were selected (Fig. 2). All specimens were made of construction steel, marked 40, according to Polish Standards (PN). Some main parameters of the steel are contained in Table 1. During the first stage of investigations, a number of ultrasonic commercial transducers made by INCO, Unipan and Karl Deutsch Company, at different frequencies, were applied. In the course of fundamental investigation 6L0°10C-INCO transducer was used only.

Some main parameters of substrate material – steel 40, according to PN-93/H-84019 Tab. 1

Chemical constitution (wt.)							Mechanical properties			
C [%]	Mn [%]	Si [%]	Cr [%]	Mo [%]	Ni [%]	Cu [%]	Rm [MPa]	Re [MPa]	A5 [%]	Z [%]
0.41	0.67	0.33	0.09	0.11	0.08	0.12	572	335	19	45

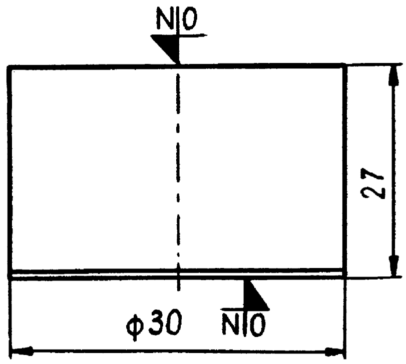

Fig. 2. Shape and dimension of the steel specimen (substrate with coating): N–O – ultrasonic transducer type transmitter-receiver

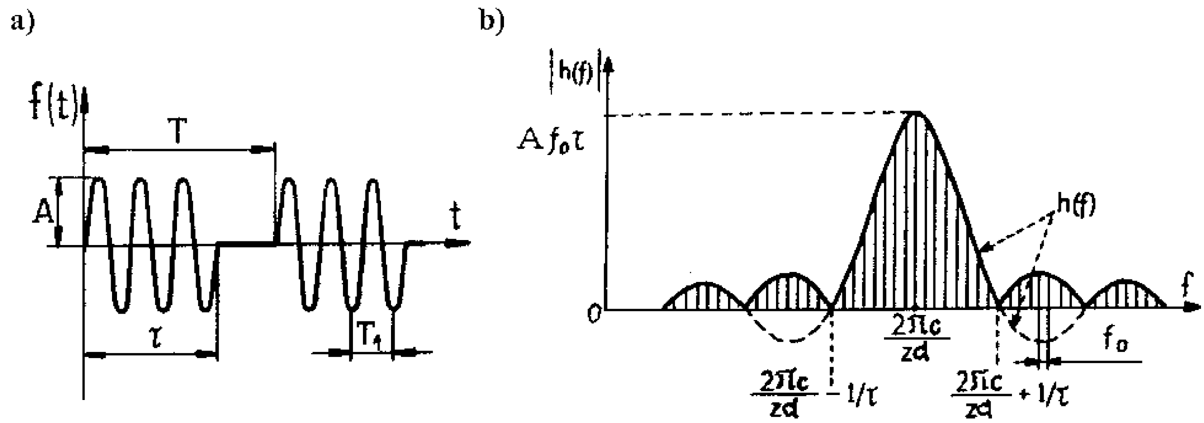

Fig. 1. The illustration of an ultrasonic signal analysis: a) parameters of ultrasonic impulses: f – frequency, A – amplitude, τ -duration of impulse, T – period of impulses, T_1 – ultrasonic wave period, t – time; b) the shape of envelope of the theoretical line impulse spectrum of ultrasonic signal – explanation of all symbols as in expression (3)

For generation and computer treatment of ultrasonic signals an ultrasonic, digital instrument (Ultramet UMT-12) was used. This instrument possessed function FFT and gave possibility automatically to determine f_r – peak (resonant) frequency and b – bandwidth of ultrasonic signals at −6 dB. Other parameters of the ultrasonic signal spectrum were read out from the computer screen using so-called "frozen picture" and special computer cursor with given values of ultrasonic signal spectrum analyzed. These parameters are shown in Fig. 3.

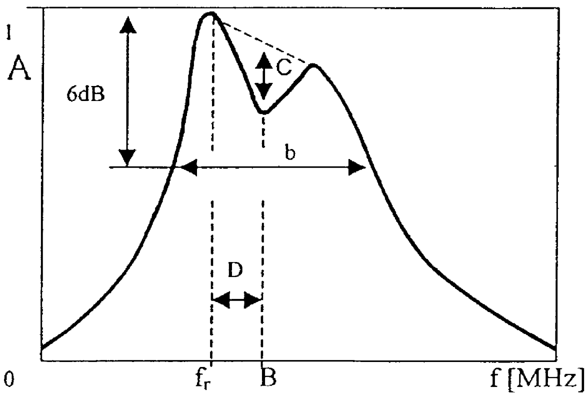

Fig. 3. Parameters of ultrasonic signal spectrum: fr-peak (resonant) frequency, b-bandwidth (−6 dB) of the signal spectrum, B - frequency of the deepest depression, C - depth of the deepest depression, D - parameter $D = |f_r - B|$

The program of an experiment comprised some series of measurements of disc-shaped specimens for a diversified roughness of the substrate and a thickness of the coatings. Some main parameters of the roughness as R_a, R_z, S_m and R_t were determined with aid of surfer analyzer type Taylor Hobson Surtronic 3+. The diversification of substrate was achieved by grinding, sandblasting and shot-peening. On the substrate were layered coatings from automotive acrylic lacquer type PPG-Deltron and automotive polyester putty type Novol. An exact chemical composition and mechanical parameters of both materials used as coatings are reserved by producers. Table 2 reflects the program of preparing the specimens used during the experiment.

The specimens were monitored from the coating side and from the steel substrate side. Figure 4 shows examples of the frequency spectra, obtained in result of FFT transformation. All details of the investigations are enclosed in the thesis [7].

On the support of the data set of all considered parameters of the signal spectra, were plotted some dependencies between the parameters, selected of them are shown in Figs. 5 - 8.

4. The principal conclusions

The theoretical analysis the problem studied and the experiments carried out allow us to recognize a feasibility of ultrasonic spectroscopy for the evaluation of adhesive joints and preliminary

The program of preparation of the specimens for investigations carried out — Tab. 2

Automotive acrylic lacquer - PPG-Deltron			Automotive polyester putty - Novol		
No spec.	Method of substrate preparation	Thickness of coating, [μm]	No spec.	Method of substrate preparation	Thickness of coating, [mm]
01/1	Mechanical grinding, ultrasonic decreasing in acetone	64 ± 5	06/1	Mechanical grinding, ultrasonic decreasing in acetone	0.65 ± 0.05
01/2	Mechanical grinding, ultrasonic decreasing in acetone	62 ± 5	06/2	Mechanical grinding, ultrasonic decreasing in acetone	0.65 ± 0.05
02/1	Sand-blasting EK100, ultrasonic decreasing in acetone	60 ± 5	07/1	Mechanical grinding, ultrasonic decreasing in acetone	1.25 ± 0.05
02/2	Sand-blasting EK100, ultrasonic decreasing in acetone	56 ± 5	07/2	Mechanical grinding, ultrasonic decreasing in acetone	1.20 ± 0.05
03/1	Sand-blasting EK60, ultrasonic decreasing in acetone	60 ± 5	08/1	Mechanical grinding, ultrasonic decreasing in acetone	1.65 ± 0.05
03/2	Sand-blasting EK60, ultrasonic decreasing in acetone	58 ± 5	08/2	Mechanical grinding, ultrasonic decreasing in acetone	1.60 ± 0.05
04/1	Sand-blasting EK40, ultrasonic decreasing in acetone	60 ± 5	09/1	Mechanical grinding, ultrasonic decreasing in acetone	2.40 ± 0.05
04/2	Sand-blasting EK40, ultrasonic decreasing in acetone	62 ± 5	09/2	Mechanical grinding, ultrasonic decreasing in acetone	2.45 ± 0.05
05/1	Shot-peening, ultrasonic decreasing in acetone	60 ± 5	10/1	Mechanical grinding, ultrasonic decreasing in acetone	3.85 ± 0.05
05/2	Shot-peening, ultrasonic decreasing in acetone	56 ± 5	10/2	Mechanical grinding, ultrasonic decreasing in acetone	3.90 ± 0.05

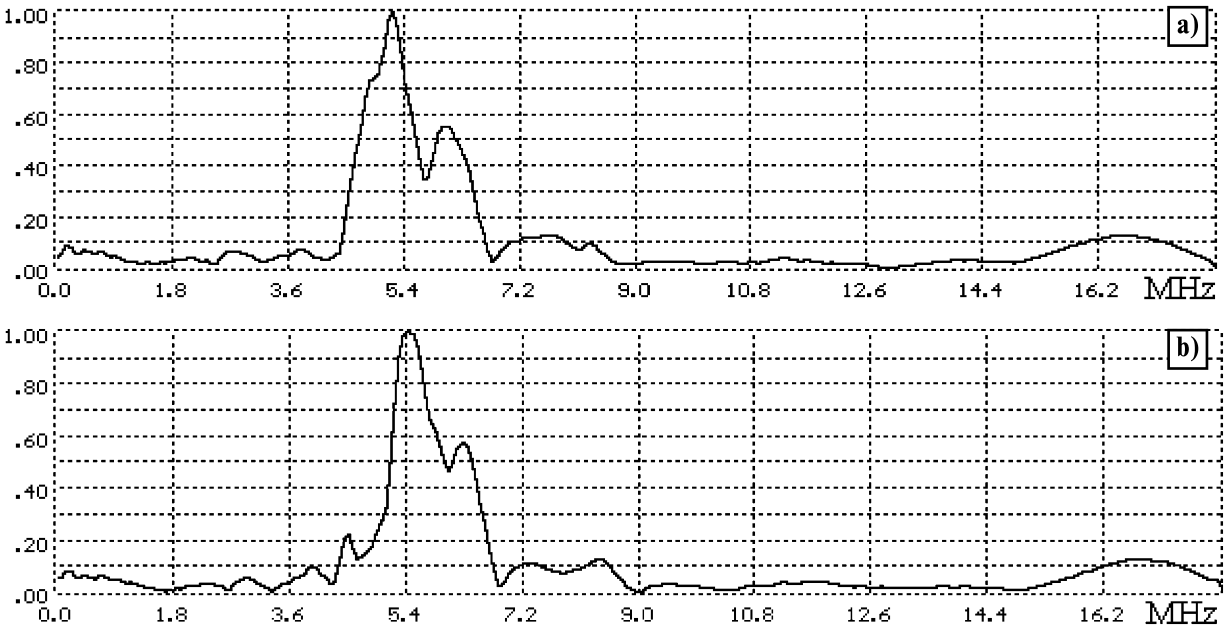

Fig. 4. Examples of frequency spectra for the following two cases: a) putty coating-thickness g = 1.2 mm, measurement from substrate side, b) conditions of measurement as above - g = 1.6mm

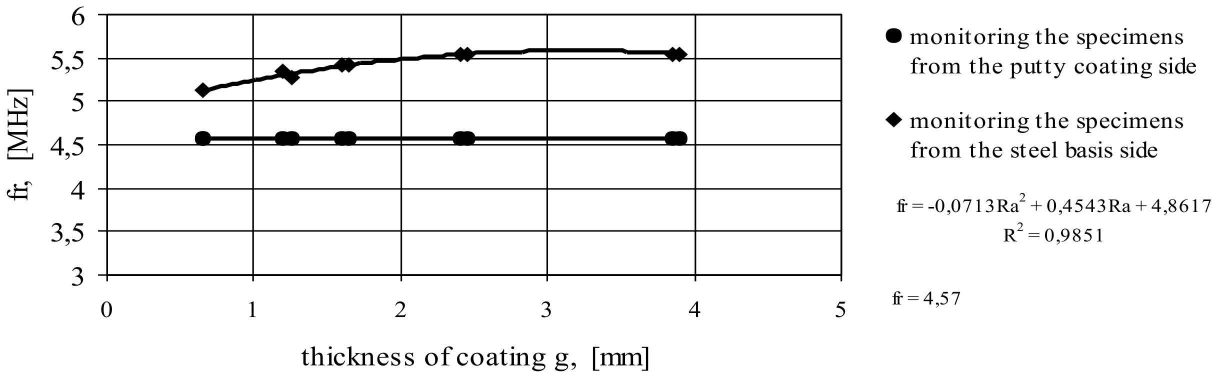

Fig. 5. The relationships between the peak (resonant) frequency - f_r of ultrasonic signal spectrum and the thickness of putty coatings (g)

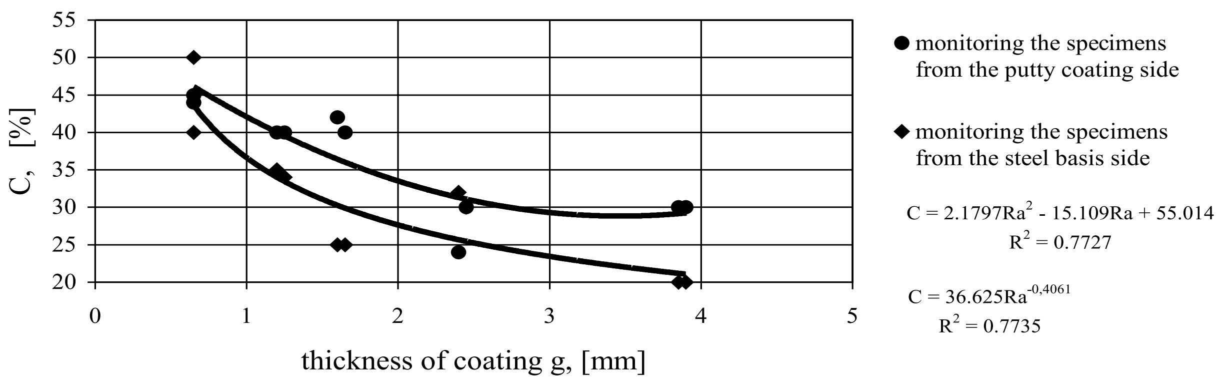

Fig. 6. The relationships between the depth of the deepest depression - C of ultrasonic signal spectrum and the thickness of putty coatings (g)

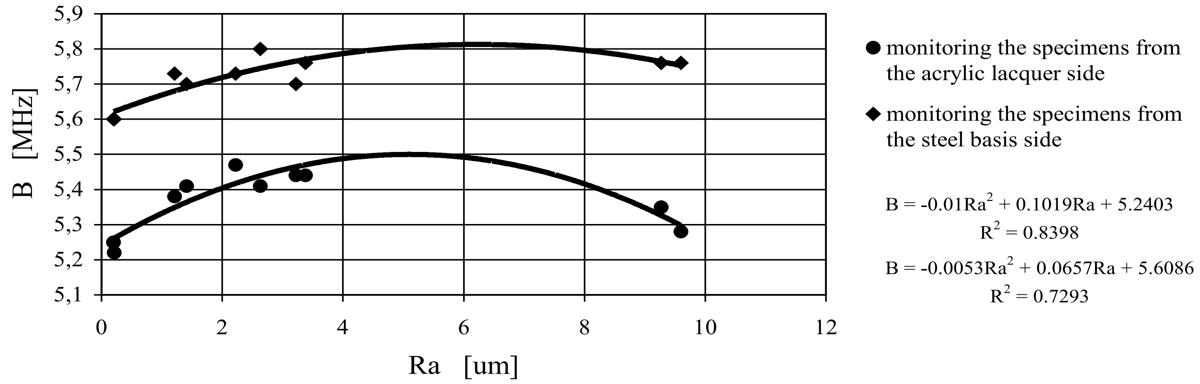

Fig. 7. The dependencies between the frequency of the deepest depression - f_r of ultrasonic signal spectrum and the roughness of substrate (Ra)

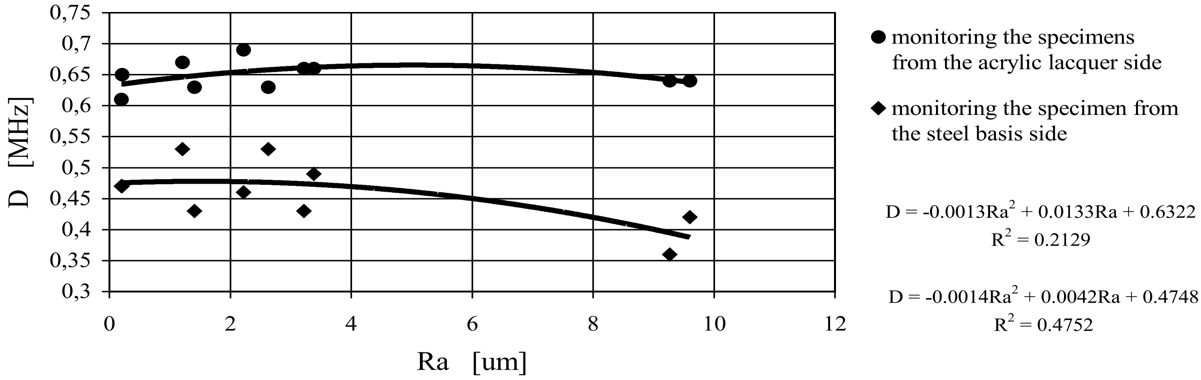

Fig. 8. The dependencies between the parameter - $D = \lfloor fmax - B \rfloor$ of ultrasonic signal spectrum and the roughness of substrate (Ra)

to realize, in determined ranges, an assessment of selected adhesive joints between coating and substrate by the nondestructive method. Particularly, the main conclusions of our investigation can be reduced to the following statements:

- Between the main parameters of the real spectrum of ultrasonic signal and such a parameter of coating as *g* and of the substrate as *Ra*, there are regression relationships (Figs. 5 - 8);
- The most sensitive to change of coating thickness is the depth of the deepest depression of spectrum *C*, and to change of roughness substrate – frequency of the deepest depression *B*;
- The ultrasonic spectrum analysis can be a useful method in the evaluation of adhesive joints type automotive lacquer and putty, connected with the steel substrate of grade 40, according to Polish Standards (PN);
- Both irregularities of the substrate and the thickness of coatings layered, influence the parameters of a ultrasonic signal spectrum, and ultrasonic spectroscopy can be complementary nondestructive method for the evaluation or to diagnosis of adhesive joints type coating-substrate.

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