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Determination of Young's Modulus of Surface Coating Paint with Impulse Excitation Technique and Analysis of Laser Signals

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Abstract. Polymer coatings of metallic surfaces offer them not only aesthetic value but at the same time provide anticorrosive protection or even improvement of some mechanical properties of the composite structure. The mechanical properties of paints are often negligible although the two aspects considered: aesthetics and durability are related to the mechanical properties of both the base material and the paint. The durability of the paint depends on how it adheres to the substrate, but at the same time a jump in the bending stress value occurs in the separation area of the two materials, which leads to the appearance of shear stress. The shear stress value depends on the ratio of the modulus of elasticity of the base material and the paint. In this paper it will follow, starting from the mechanical properties of the substrate, the metallic sheet in general, to determine the new properties of the assembly of substrate and the two painting layers, also the determination of mechanical properties of the layers. From the analysis of laser signals obtained by the impulse excitation of the samples, one can determine the elastic modulus. These results come to validate the results based on Finite Element Analysis (FEA) of the same samples. From the analysis of Bernoulli's equation for the two situations: the uncovered beam and the painted beam, the ratio of natural frequencies is determined as a function depending on the modulus of elasticity, density and geometric dimensions of the substrate, respectively the same elements of the coating paint. From this ratio, Young's modulus of the paint can be determined.

1. Introduction

By covering the work piece with different layers of paint, it changes its mechanical properties into a composite structure. The new properties of the composite structure will be different from the properties of any of the component materials. Painting is done for both metallic and non-metallic materials. As far as metallic coatings are concerned, it should be borne in mind that ferrous metals are subject to rusting in contact with corrosive environments, and their coating is a vital issue.

At the same time, a bending composite structure exhibits a jump of tension stress at the metal-paint interface, which results in a shear stress [1]. That is why it can be said that the cracking, the most common defect in painting metal surfaces, is due to the different loading of the two components. For this reason, the primer layer applied between paint and metal has an essential role in reducing this jump of tension stress. Therefore, the rigidity of the adhesive film has an important role in preventing cracks. To prevent shear cracking, it would be ideal that the flexural stiffness of the base material be

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equal to the rigidity of the coating [2]. With the polymeric coating of metals, the elastic characteristics of the structure change [3].

To determine the mechanical properties of materials over time, several techniques have been developed, grouped into two large categories: static methods and dynamic methods [4], [5]. The first category includes traction and shear tests. The second category of tests includes acoustic resonance spectroscopy [6-8] and vibration resonance techniques [9-10].

The latest methods, techniques and patents for determining the elastic characteristics of materials are presented in the papers [11-12].

This paper can be included in the category of research on the determination of the mechanical characteristics of some materials by analyzing the vibroacoustic signals obtained from a mechanical impulse and recorded by an acquisition board, having a microphone as a sensor, and by analyzing the vibration motion signals recorded by a laser vibrometer, respectively [13-16].

This paper aims to determine the Young's modulus of paints used for coating steel sheets in refrigeration industry or automotive industry. For this purpose the resonance frequencies of the vibrations of some samples, clamped at one end and free at the other end, before and after painting, are determined. The frequencies of the signals given by a laser vibrometer after applying a mechanical impulse to the samples, by Fast Fourier Transform (FFT) are determined.

2. Vibrational modelling

In the analysis of the bending vibrations of a slender cantilever metal beam, considered one-dimensional and covered on the two surfaces with the paint, the equation Euler-Bernoulli will be considered (Figure 1). Neglecting the effects of shear and rotational inertia, vibration movements are described by the differential equation [17]

$$(EI)_{cb}\frac{\partial^4 Y(x,t)}{\partial x^4}+(\rho A)_{cb}\frac{\partial^2 Y(x,t)}{\partial t^2}=0, \tag{1}$$

where Y(x, t) is the displacement of neutral axis of the beam at x distance to the clamped end, $(EI)_{cb}$ is the flexural rigidity of the entire composite beam, and $(\rho A)_{cb}$ is the mass of the composite beam length unit.

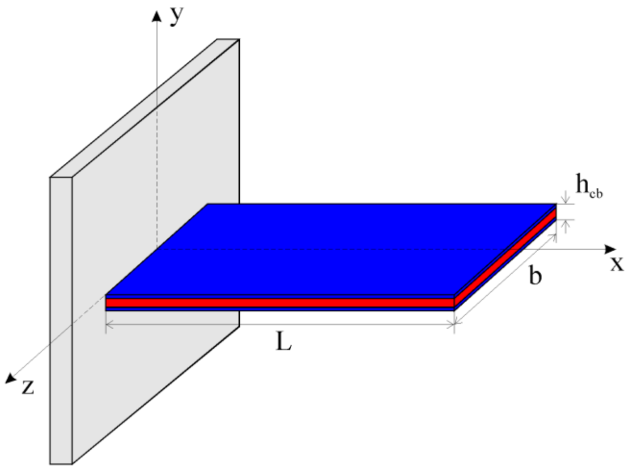

Figure 1. Schematic representation of a three layers beam.

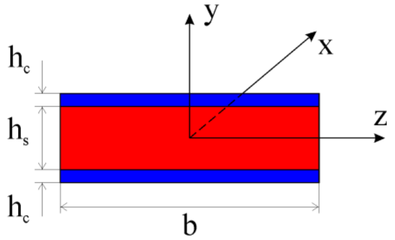

Figure 2. Cross section and its dimensions.

The three layers composite bar has a bending stiffness equal to the sum of the stiffness's of each component material. The paint layers are assumed to be homogeneous, of the same thickness and perfectly adhered to the surface of the metal substrate.

$$\left(EI\right)_{cb} = \left(EI\right)_s + 2\left(EI\right)_c, \tag{2}$$

where the indexes cb, s and c refer to the composite beam, substrate, and paint coats, respectively.

The mass per unit length of the three layers beam is given by the following formula:

$$\left(\rho A\right)_{cb} = \left(\rho A\right)_s + 2\left(\rho A\right)_c. \tag{3}$$

Analytical solving the differential equation (1) can determine the modal shapes and natural frequencies of vibration modes. The resonance frequencies are determined from the characteristic equation corresponding to the clamped–free boundary conditions

$$1 + chX \cos X = 0, \tag{4}$$

where

$$X = L\left(\left(2\pi f_{cb}\right)_i^2 \frac{\left(\rho A\right)_{cb}}{\left(EI\right)_{cb}}\right)^{1/4}, \tag{5}$$

L is the length of composite beam and $(f_{cb})_i$ (i=1,2,…..,n) is one of its natural frequencies.

If only the substrate metal beam is considered, the same characteristic equation is obtained, so it can be written:

$$X = L\left(\left(2\pi f_s\right)_i^2 \frac{\left(\rho A\right)_s}{\left(EI\right)_s}\right)^{1/4}. \tag{6}$$

From equations (5) and (6), taking into account relations (2) and (3), as well by replacing I_s and I_c of cross section (Figure 2), with their correspondent expressions [18], the ratio of the frequencies of one vibration mode for the three layers beam and the substrate beam is obtained

$$\left(\frac{f_{cb}}{f_s}\right)_i^2 = \frac{2\left(EI\right)_c + \left(EI\right)_s}{\left(EI\right)_s} \frac{\left(\rho A\right)_s}{2\left(\rho A\right)_c + \left(\rho A\right)_s} = \frac{1 + \frac{E_c}{E_s}\left[6\left(\frac{h_c}{h_s}\right) + 12\left(\frac{h_c}{h_s}\right)^2 + 8\left(\frac{h_c}{h_s}\right)^3\right]}{1 + 2\left(\frac{\rho_c}{\rho_s}\right)\left(\frac{h_c}{h_s}\right)}. \tag{7}$$

Using the ratios between the natural frequencies of the coated beam and the substrate beam, between the thicknesses and densities of the coating layer and the substrate given by $(f_r)_i=(f_{cb}/f_s)_i$, $h_r= h_c/h_s$, and $\rho_r=\rho_c/ \rho_s$, where the subscriptions c and s correspond to the coating paint and the substrate, then from equation (7) one can determine Young's modulus for coating, so

$$E_c = \frac{E_s}{6h_r + 12h_r^2 + 8h_r^3}\left[f_r^2\left(1 + 2\rho_r h_r\right) - 1\right]. \tag{8}$$

Assuming that the paint layers have very small thicknesses compared to the substrate, i.e. the ratio $h_r \ll 1$, then the cube and square of this ratio can be neglected compared to itself. With this observation equation (8) can be written in the form:

$$E_c = \frac{E_s}{6h_r}\left[f_r^2\left(1 + 2\rho_r h_r\right) - 1\right]. \tag{9}$$

Relationships similar to those given by equations 8 and 9 are obtained by Lopez in the paper [19] and Berill in the works [20-21].

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If in addition to the above observation, it is considered that the covering material has a density much lower than the substrate material, then it is obtained a simplified form for the determination of the modulus of elasticity. It can be used to determine the Young module for thin and low density coating (TLDC)

$$E_c = \frac{E_s}{6h_r}\left(f_r^2 - 1\right) = \frac{E_s}{3h_r}\frac{\Delta f}{f_s}. \qquad (10)$$

3. Numerical simulation

For the numerical simulation of the dynamic behavior of a three layers composite beam, clamped at one end and free at the other end, Finite Element Analysis (FEA) was performed using ANSYS 14.5 software. To construct a 3D model, hexahedral solid layered elements SOLID 186 with three degrees of freedom for each node were used. Element SOLID 186 is defined by 20 nodes that exhibit quadratic displacement behavior. These layered elements allow the definition of layer-by-layer properties, so it is suitable for the multi-layer material model. The geometric model consists of three parts: the substrate and the two paint coating layers. The substrate material is ordinary steel S 235 JR having the following properties E_s=200GPa, ρ_s=7850 kg/m^3, μ_s=0.3, with a rectangular cross section with a length L=240 mm, a width b=40 mm, and a thickness h_s=2mm. For the layers of paint two types of samples were used. The first type had the layer of paint deposited through a single electrostatic crossing and the thickness h_c=90µm, and for the second type of the sample, the deposition was made by two passes having the thickness of the paint layer h_c=180µm. The meshing of coated sample is shown in Figure 3, and the shape of the first vibration mode and corresponding frequency is shown in Figure 4.

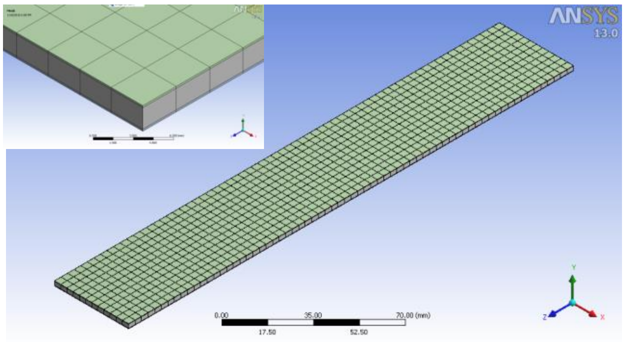

Figure 3. Finite element discretization of beam.

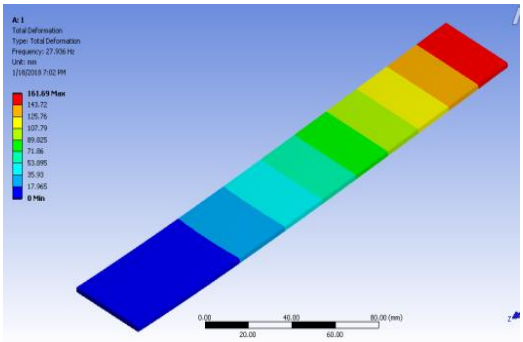

Figure 4. First vibration mode.

4. Measurement of fundamental frequency

The determination of the length L, width b and thickness of the substrate h_s was made by six measurements at six different points. The average of these measurements is for the length of the clamped sample, L=239.42 mm, for the width b=39.25 mm, and for the thickness h_s=1.94 mm.

To determine the thickness of the paint coatings, ten measurements were made in ten different points. The average of these ten measurements gave a thickness of h_{1c}=89.1µm, for one coat of paint and thickness h_{2c}=188.2µm, for coating with two layers of paint.

The purpose of the experimental technique developed in this paper is to determine the natural frequencies of the sample, before and after coating with paint layers. For the experimental determinations a stand (Figure 5) consisting of sample **1,** clamped in the vise **3,** and excited by a mechanical impulse given by a mini hammer **2** was used. The recording of a signal, proportional to the speed of a sample point, is based on the working principle of a Doppler Vibrometer Laser **4**, which emits a luminous signal to the sample vibratory motion and the receiver is a photo detector. The demodulated signal can be viewed on a PC display **5**, and through an acquisition board and computer **6** it is digitalized and used in the Fast Fourier Transform (FFT) program to determine the Fourier Spectrum.

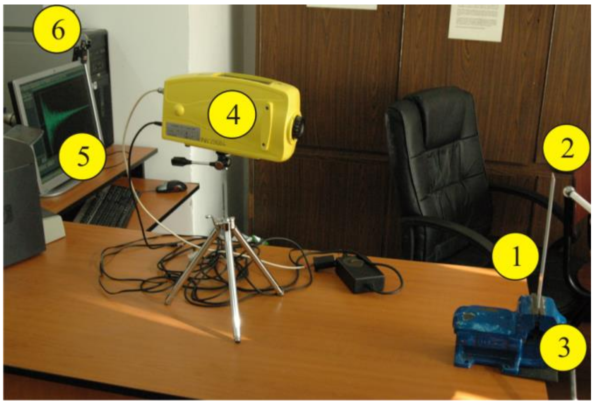

Figure 5. Vibratory set-up employed.

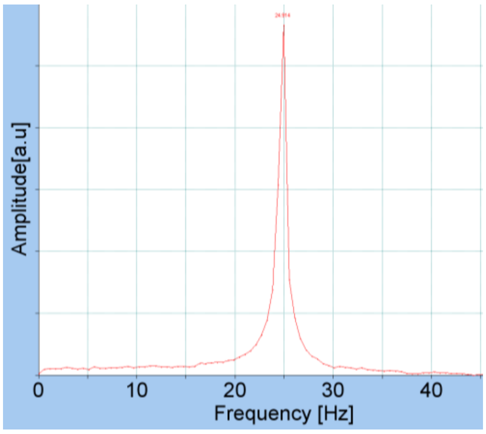

Figure 6. Fundamental frequency from FFT.

5. Results and conclusions

In order to determine the Young's modulus, the signals given by the laser vibrometer are analyzed, and from Fourier Spectrum (Figure 6), the fundamental frequency for each sample is obtained. The numerical determinations of the elasticity modulus of the coating paint for the three analyzed methods equations (8), (9) and (10) are used. The results are given in Table 1 and Table 2. For determining the steel elastic modulus, as a substrate sample, the standardized method presented in the ASTM E 1876-15 was used [22].

In Table 1 are presented the results obtained by experimental measurements on samples that had a single pass through the electrostatic field of paint deposition.

Table 1. Young's modulus of paint, after one pass of the sample through the electrostatic field

Sample frequency (Hz)	Composite sample frequency (Hz)	E_s (GPa) Young's modulus	E_c (GPa) TLDC method	E_c (GPa) Berry method	E_c (GPa) Lopez method
23.398	24.248	199.74	4.580	5.823	4.712

In Table 2 are presented the results of the elastic modulus of the paint determined experimentally from the sample covered by passing twice through the electrostatic field.

Table 2. Young's modulus of paint, after two passes of the sample through the electrostatic field

Sample frequency (Hz)	Composite sample frequency (Hz)	E_s (GPa) Young's modulus	E_c (GPa) TLDC method	E_c (GPa) Berry method	E_c (GPa) Lopez method
23.398	24.824	199.74	4.599	5.987	4.921

The values of the elastic modulus given in the paint catalogs are in the range of 4.7 GPa and 6.3 GPa. In conclusion, by comparing the results obtained experimentally with those given in the specialty catalogs, one can find that the proposed method for determining the Young's module is valid and gives good results for determining the modulus of elasticity of coating paints.

Numerical simulation results, using Modal Analysis (MA), come to confirm once again the validity of the method based on laser measurements.

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