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Research Article

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Determination the Properties of Paint Coating and Coating-Substrate System Using Impulse Excitation Technique

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Abstract In this paper we present a novel method that has the potential to evaluate the elastic properties of paint coating material and coating-substrate system. The measurements were carried out using a self-developed system, which is based on Impulse Excitation Technique. Ten rectangular bars of steel with dimensions *:l=10cm, w=5cm, b=1cm* and modulus of elasticity 210 GPa were used as our substrate samples. For each sample, ten layers of coating were applied and the coating thickness was measured. Our developed IET system was used to record the resonant frequency for each sample; then the modulus of elasticity for the coating-substrate system and paint coating material were evaluated using mathematical model for materials in parallel. Results showed that the measured resonant frequency and modulus of elasticity for the coating-substrate system decreases as the coating thickness increases. Furthermore, a high correlation between resonant frequency and the coating thickness was observed indicating that measurement of resonant frequency has the potential to assess coating thickness. The modulus of elasticity for the coating material was found to be independent of the coating thickness. Our developed IET system has the potential to assess the coating thickness and elastic properties of paint coating material and coating-substrate system.

Keywords Impulse Excitation Technique; resonant frequency; elastic properties of coating materials; coating-substrate system

1. Introduction

Spray paint coatings are increasingly being used in today's products and applications such as automotive and aerospace industry, structural applications, art and decorations, and many more. A Spray paint coating is a covering that is applied to the surface of an object, usually referred to as the substrate. The purpose of applying the Spray paint coating may be decorative, functional, or both. Functional Spray paint coatings may be applied to improve the substrate corrosion resistance or wear resistance. The proper mechanical properties and performance of the coatings play a crucial role in the reliability of the products to which they are applied.

Determination of the mechanical properties of coatings has been a great challenge. It is usually impractical to detach the coating from the substrate and then to measure the coating mechanical properties. A convenient way to accomplish this is by using non-destructive or minimally destructive testing methods. One common technique reported by many authors for measuring the mechanical properties of thin coatings is by indentation testing on a nanometer scale, commonly referred to as nano-indentation [1-4], combined with scratch testing [5]. A.A. Roche and J. Guillemenet (1999), calculated residual stress and Young's modulus of the coatings using a one- dimensional analysis based on beam theory where the biaxial modulus for isotropic stress was introduced (thin plate theory). As the strain in the coating causes strain in the substrate, which in turn produces in-plane deformation, the stiffness ratio was introduced. The Young's modulus and internal residual stress of the coatings were found to be dependent on the coating thickness, the extent of reaction and the substrate material [6]. N.A Dolgove (2004) derived an expression which was used to determine the modulus of elasticity for coatings in a tensile test [7]. M.Kubisztal, A.Chrobak, and G.Haneczok (2010) presented a method in measuring the dynamic response of the examined material in the form of a flat rectangular bar subjected to external periodic mechanical stress, i.e., the so-called vibrating reed technique as a non-destructive method. It was shown that this method could be successfully used in optimization of some technological processes of deposition of different coatings on a metallic substrate used in optimization of some technological processes of deposition of different coatings on the metallic substrate [8]. In this work, we developed a non-destructive system both hardware and software for the determination of mechanical and physical properties of paint coatings and the properties of a coating-substrate system mainly elastic modulus and paint coating thickness. The developed system has been designed to measure the elastic properties of a wide range of materials in a non-destructive, highly accurate and fast manner.

2. Materials and Methods

2.1 Developed Impulse Excitation System

Previously, our research team developed a non-destructive testing system based on impulse excitation technique (IET) to be used for different measurements and research applications. This self-designed system was used in this work to evaluate some of the mechanical and physical properties of paint coating material and coating-substrate system. The working principle of this system is based on the excitation of a specimen under testing utilizing light mechanical impulse. The specimen immediately acts as a spring-mass system deforming elastically and produces a transient mechanical vibration. The IET instrument records this vibration, makes an analysis in the time and frequency domains, and measures the dominant vibration of the coating-substrate system, i.e., the resonant frequency. Once the resonant frequency of the specimen under testing is evaluated, valuable information can be provided about elastic properties of the specimen material such as Young's modulus, Shear modulus, and Poisson's ratio. Figure (1) and (2) show our IET software for user interface and IET framework.

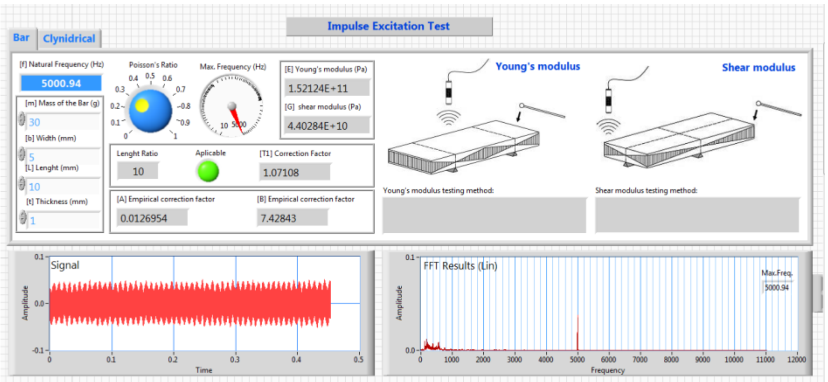

Figure 1: IET software for user interface

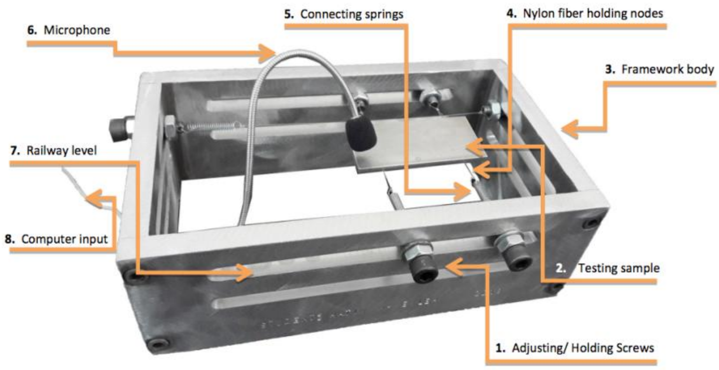

Figure 2: IET framework

2.2. Uncoated substrate Steel Samples

Ten rectangular bar steel with dimensions length, width, thickness (*l=10cm, w=5cm, b=1cm)* were used as our substrate samples. The modulus of elasticity of the steel samples according to the supplier is equal to 210 GPa. All steel bar samples were polished to remove any contamination using the rotational polishing disk then the dimensions and mass were measured using the high accuracy digital micrometer and electronic balance Table (1). For each substrate steel sample, the resonant flexural frequency was measured, and Young's modulus of elasticity was evaluated individually using our IET system before applying any paint coating as shown in Table (2).

Table 1: Uncoated rectangular bar steel sample: mass and dimensions

Sample	Mass (gm)	Length (mm)	Width (mm)	Thicknes s(mm)
Sample 1	387.52	99.98	49.99	9.92
Sample 2	388.78	100.28	49.96	9.92
Sample 3	388.57	100.21	49.93	9.92
Sample 4	386.78	99.87	49.92	9.92
Sample 5	387.97	100.00	49.96	9.92
Sample 6	387.78	99.94	49.93	9.93
Sample 7	388.53	100.15	49.94	9.94
Sample 8	388.87	100.22	49.99	9.92
Sample 9	388.81	100.24	49.99	9.92
Sample 10	387.91	100.05	50.07	9.93

Table 2: Uncoated rectangular bar steel sample: measured resonant flexural frequency and modules of elasticity.

Sample	Resonant Frequency (Hz)	E(GPa)
Sample 1	5126.62	211.24
Sample 2	5093.55	211.14
Sample 3	5093.55	210.73
Sample 4	5144.27	213.56
Sample 5	5113.40	210.64
Sample 6	5115.60	210.83
Sample 7	5095.76	209.27
Sample 8	5091.35	210.51
Sample 9	5089.14	210.42
Sample 10	5115.60	210.02
Average	**5107.88**	**210.84**
SEM	**±5.78**	**±0.35**

2.3. Coated Steel Samples (coating-substrate system)

For each of the ten samples, one layer of paint coating was applied at a time and left to dry. For each layer, the coating thickness was measured using a high precision micrometer. The sample was then placed in our IET system to measure the resonant flexural frequency to evaluate the modulus of elasticity for the coated steel samples(coating-substrate system). This procedure was repeated for ten layers of coating for all ten samples. Applying the coating materials on the steel samples was done using conventional spray paint coatings with different colors for each coating layer.

3. Theory

3.1. Measuring Young's modulus by IET

The standards ASTM E1876-15, ENV 843-2 and ASTM-C1259-08 provide different guidelines for dimensions of rectangular specimens and experimental setup to obtain a reliable elastic modulus by Impulse Excitation Technique IET. For a rectangular bar sample, the elastic properties can be calculated using the sample dimensions, mass, and resonant frequency. The resonant flexural frequency is associated with flexural vibration mode shown in Figure (3), and it is characteristic of Young's modulus of the sample [9]. Figure (3) shows the sample orientation for the flexure mode for rectangular bar samples with length to thickness ratio between 5-20.

Young's modulus can be derived according to:

$$E_m = 0.9465\left(\frac{mf_f^2}{w}\right)\left(\frac{l^3}{b^3}\right)C \qquad \textit{Equation (1)}$$

$$C = 1 + 6.585(^b/_l)^2$$

Where :

E_m: measured Young's modulus

f_f : flexural frequency

m: mass of the rectangular bar sample

w: with of the rectangular bar sample

b: thickness of the rectangular bar sample

C: correction factor used only for samples with length to thickness ratio ≥20

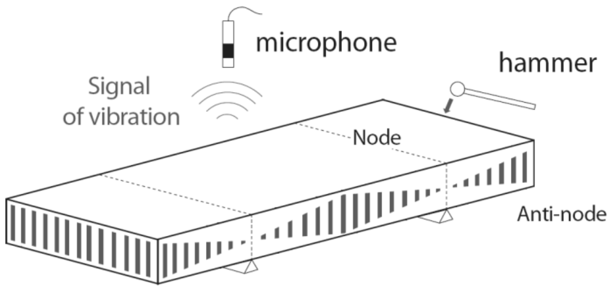

Figure 3: Sample orientation for flexure mode

3.2. Materials in Parallel Model:

For paint coating-substrate system, the following assumptions are made:

1. Paint coating is uniformly distributed on the surface of the material.
2. Perfect bonding exists between the coating and the material with no interface voids.
3. The coating and substrate materials are free of voids.
4. Applied impulse excitation is normal to the coating surface.

Based on the above assumptions, we can assume that our coating-substrate system is similar to sandwich shaped structure. For such structure of steel samples coated with spray paint, the elastic modulus of the coating-substrate system can be calculated using:

$$\frac{1}{E_m} = \frac{v_c}{E_c} + \frac{v_s}{E_s} \qquad \textit{Equation (2)}$$

The modulus of elasticity of coating material is derived from:

$$E_c = \frac{v_c}{(\frac{1}{E_m} - \frac{v_s}{E_s})} \qquad \textit{Equation (3)}$$

Where:

E_m: measured modulus coating-substrate system.

E_c : modulus of elasticity of coating material.

E_s : modulus of elasticity of substrate steel sample.

v_s: volume fraction of substrate steel sample.

v_c: volume fraction of coating material

For the rectangular bar steel sample with dimensions length, width, thickness (*l*,*w*,*b)* coated with paint coating of thickness *(t)* we can write the following equations:

a) volume of uncoated steel sample :

$$V_s = (l) \times (w) \times (b)$$

b) volume of coated steel sample :

$$V_{sc} = (l + t)(w + t)(b + t) \qquad \textit{Equation (5)}$$

c) volume of coating :

$$V_c = V_{sc} - V_s \qquad \textit{Equation (6)}$$

d) volume fraction of steel sample:

$$v_s = \frac{V_s}{V_{sc}} \quad \text{Equation (7)}$$

e) volume fraction of coating material :

$$v_c = \frac{V_{sc} - V_s}{V_{sc}} = 1 - v_s \quad \text{Equation (8)}$$

4. Results and Discussion

For each coating layer, the modulus of elasticity for the coating-substrate system was evaluated by measuring the resonant frequency from the flexural vibration mode using equation (1). Then the modulus of elasticity for the coating material was derived by using equations (3-8). This step was repeated for all ten samples, and the average values were calculated. The average values of the coating layer thickness, measured resonant frequency, modulus of elasticity for the coating-substrate system, and modulus of elasticity of coating material are shown in Table (3-4).

Table 3: Average values of the coating thickness, measured natural frequency, and modulus of elasticity for the coating-substrate system calculated from 10 samples.

Number of coating layers	**Coating Thickness(mm)** mean ten samples	**Resonant Frequency (Hz) mean ten samples**	**Modulus of elasticity of Coating-substrate E_m(GPa)** mean ten samples
0 Layer	0	5107.88±18.28	210.84±1.11
1 Layer	0.022±0.006	5106.14±5.73	209.68±0.81
2 Layers	0.023±0.009	5105.06±5.69	208.99±0.48
3 Layers	0.084±0.060	5101.82±5.46	206.96±0.94
4 Layers	0.101±0.032	5100.53±6.76	204.78±0.81
5 Layers	0.126±0.029	5099.95±6.02	203.30±1.15
6 Layers	0.142±0.020	5098.62±6.00	202.10±0.98
7 Layers	0.159±0.023	5094.65±6.53	200.79±0.51
8 Layers	0.194±0.012	5090.25±7.49	198.99±1.16
9 Layers	0.216±0.017	5092.01±5.91	197.62±1.37
10 Layers	0.283±0.023	5086.90±5.83	193.91±0.96

Table 4: Average values of modulus of elasticity of coating material with standard deviation (SD) and Coefficient of variation (%CV) calculated from 10 samples

Number of coating layers	**Modulus of elasticity of Coating material E_c(GPa) mean ten samples**	**Standard deviation SD**	**Coefficient of variation %CV**
0 Layer	-	-	-
1 Layer	97.69	±61.36	62.81
2 Layers	54.63	±13.50	24.71
3 Layers	74.07	±46.71	63.05
4 Layers	64.35	±7.71	11.99
5 Layers	64.23	±5.23	8.14
6 Layers	62.61	±2.57	4.10
7 Layers	61.19	±5.87	9.59
8 Layers	62.57	±5.24	8.37
9 Layers	62.14	±5.58	8.98
10 Layers	61.60	±4.12	6.68

4.1. Measured natural frequency and coating thickness

The mean values from 10 samples for the measured resonant frequency of the coating-substrate system is plotted as a function of the coating thickness (Figure 4). The figure shows that the measured natural frequency for the coating-substrate system decreases as the coating thickness increases starting from resonant frequency value 5107.88Hz representing the uncoated substrate steel sample (mean of 10 samples). Furthermore, a high correlation between resonant frequency and the coating thickness is observed which indicates that measureing resonant frequency has the potential to assess the coating thickness.

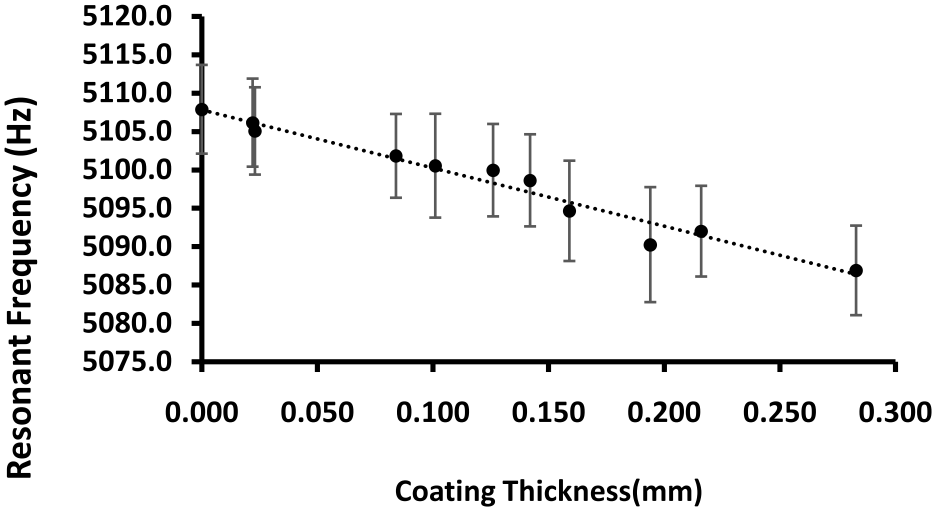

Figure 4: Measured resonant frequency as function of coating thickness

4.2. Modulus of elasticity for the coating-substrate system and coating thickness

The mean values from 10 samples for the calculated modulus of elasticity for the coating-substrate system are plotted against the coating thickness (Figure 5). The figure shows that the modulus of elasticity for the coating-substrate system decreases as we added more coating layers, i.e., as the coating thickness increases starting from the modulus of elasticity of 210.84 GPa (mean of 10 samples) which represents the modulus of elasticity for uncoated substrate steel sample.

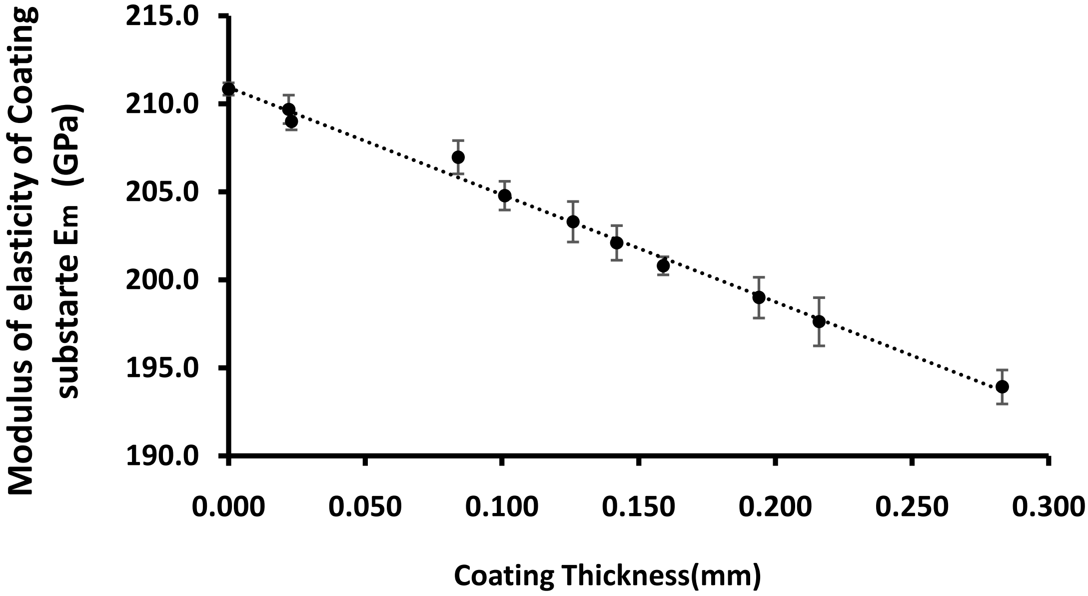

Figure 5: Modulus of elasticity for the coating-substrate system as function of coating thickness

4.3. Modulus of elasticity of coating material and coating thickness

The study of data dispersion helps us to measure the variation of the items among themselves, and it also measures the variation around the average. The coefficient of variation in percent %CV is used as an indicator of the variability and the reproducibility of the measurements.

In our results, the variations in calculating the mean modulus of elasticity for the coating material from the ten samples were significantly high at low coating thickness (layer1: %CV=62.81, layer 2:%CV=24.71, layer3:

%CV=63.05). On the other hand, as coating thickness increased (above layer 3), the variations in the mean modulus of elasticity for the coating material were smaller, and measurements of the mean modulus of elasticity were more stable (layer>3: %CV=4.10 to 11.99).

The mean values from 10 samples for modulus of elasticity for the coating material are plotted against the coating thickness in Figure 6. The modulus of elasticity of the coating material was found to be independent of the coating thickness and showed insignificant differences in relation to coating thickness as measurements became more stable for coating beyond the third layer. The mean value for modulus of elasticity for the coating material calculated from layer 3 to 10 was found to be E_c=62.67±1.22 GPa.

This finding is reasonable since the modulus of elasticity is a property of coating material and is expected to be independent of the coating thickness.

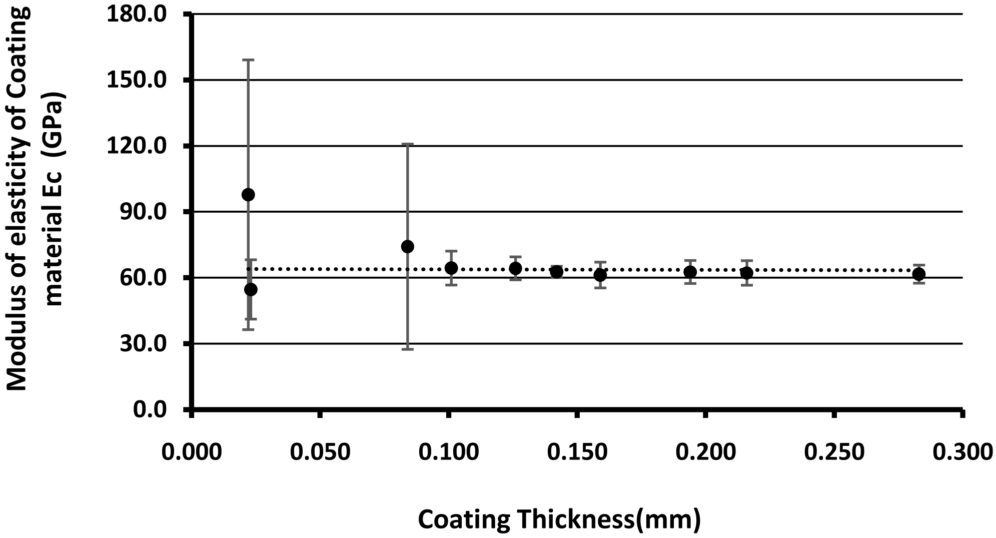

Figure 6: Modulus of elasticity of the coating material as function of coating thickness

5. Conclusions

Impulse excitation technique (IET) is a non-destructive method that evaluates the elastic and damping properties of the material by measuring the resonant frequency and the geometry of a testing specimen. Our research team developed an IET system to find an easy, fast, cheap, accurate and non-destructive way to calculate the modulus of elasticity, the shear's modulus, and Poisson's ratio for different materials. This self-designed system was used in this work to evaluate some of the mechanical and physical properties of paint coating material and coating-substrate system using ten substrate steel samples. For the coating-substrate system, results show that the measured resonant frequency for the coating-substrate system decreases as the coating thickness increases. Furthermore, a high correlation between resonant frequency and the coating thickness was observed indicating that measuring the resonant frequency for the coating-substrate system can be used as a nondestructive method for evaluating the coating thickness. The modulus of elasticity for the coating-substrate system decreases as the coating thickness increases starting from the modulus of elasticity which represents the modulus of elasticity for uncoated substrate steel sample. The modulus of elasticity for the paint coating martial was evaluated after measuring modulus of elasticity for the coating-substrate system using mathematical model for materials in parallel. There was a significant variation in measuring the modulus of elasticity for the coating material at thin coating layers (layers 1, 2, 3) compared to thicker coating layers where the variations in measuring the mean modulus of elasticity for the coating material were smaller, and measurements of the mean modulus of elasticity were more stable. The modulus of elasticity for the coating material was found to be independent of the coating thickness and showed insignificant differences in relation to coating thickness as measurements became more stable for coating beyond coating thickness of 0.1 mm. This finding is reasonable since the modulus of elasticity is a property of coating material and is expected to be independent of the coating thickness. The mean value for modulus of elasticity for the coating material calculated from layer 3 to 10 was found to be E_c=62.67 ±1.22 GPa.

Our developed IET system has the potential to assess the coating thickness and elastic properties of paint coating material and coating-substrate system in cheap, accurate and non-destructive way.

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