Turkish Journal of Computer and Mathematics Education Vol.12 No.10 (2021), 1645-1650

Research Article

Mechanical Properties of Thin and Thick Coatings Applied to Various Substrates

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Article History Received: 10 January 2021; Revised: 12 February 2021; Accepted: 27 March 2021; Published online: 28 April 2021

Abstract : In this work, theoretical and experimental studies have been carried out to determine the Young's modulus of materials for coatings applied to substrates. It is shown that residual stresses are generated inside thin and thick coatings deposited on a substrate. As a result of these stresses, the strip of the two-layer material is assumed to have some curvature. With the help of bending theory, it was substantiated that the bending stiffness of two-layer materials is a function of the initial radius of curvature generated by residual stresses, the mechanical radius of curvature arising during bending tests, mechanical (Young's modulus) and geometric (width and thickness) characteristics of two-layer systems. The corresponding expression was converted to a second or third order equation to calculate the Young's modulus of the coating undergoing residual stresses.

Keywords: Young's modulus, residual stresses, radius of curvature, thin and thick coatings, bending tests.

1. Introduction

Young's modulus is the most important mechanical property of a material and its measurement is of great importance in applied and fundamental fields [1-10]. In the case of two-layer materials (thin and thick coatings are applied on different substrates [11-14]), which are used in many fields (aerospace, automotive, electronic, etc.) understanding and modeling the mechanical behavior of materials (e.g. practical adhesion, wear, friction, protective properties, also internal stresses) require knowledge of Young's moduli of materials and substrate, and coating [15-23]. As a rule, data on Young's moduli for various materials in their volume form are available from the literature. However, when the same materials are applied to a substrate as thin plates or layers (coatings) [24-39], the Young's modulus values differ significantly. This study aims to determine the Young's modulus of coating materials. Models have been developed to determine the flexural stiffness depending on the initial radius of curvature generated by the residual stresses developing in the coatings, the mechanical and geometric characteristics of two-layer systems. To construct these models, elementary provisions of the theory of beams are used. The derivatives of the functions of these models allow calculating the Young's modulus of the coverage. Young's modulus of a two-layer system is calculated from the slope of the load-displacement curve within the linear deformation (obtained in bending tests), while the ratio of the gap to the sample thickness is infinite. Several residual stress models are included in the model for determining Young's modulus of a coating undergoing residual stresses.

2. Experimental studies of two-layer materials

This work was performed using a three-point bend test on a FLEX 3 instrument (TECHLAB) at room temperature. The distance between the two lower cylindrical supports (each 6 mm in diameter) - span (L) - can be adjusted from 4 mm to 150 mm with an accuracy of 1/20 mm. The traverse was moved by a microcomputer-controlled stepper motor and a speed reducer. The offset corresponding to one step is 25 nm. The slider speed ranged from 0,025 to 1 mm / min. In this work, a constant speed of 0,1 mm / min was used. A full-scale load cell with a sensitivity of 5 mN and a range of 20 N was installed under the crosshead. The upper edge of the support prism (12 mm in diameter) was attached to the other end of the load cell. The sample response (P) to displacement (d) was measured using a load cell as shown in the figure.

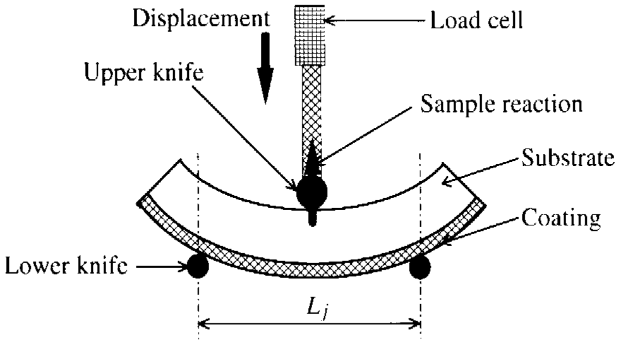


Figure: 1. Scheme of the experiment.

The dependence of the displacement on the load was recorded using a microcomputer and displayed in the form of graphs on the computer screen in real time. The slope of the curve within the elastic region is calculated using the linear regression program. The slope of the experimental curves was corrected to take into account the stiffness with the load cell. For a given gap and a coated sample, 3 curves were plotted. To minimize the effect of polymer relaxation, the samples were placed on the lower supports for 3 min before any testing [40-44]. The mean of the respective slope values was compared with its standard deviation. If the standard deviation was less than 1%, then the data was saved, otherwise a new set of tests was started.

A sample with an epoxy adhesive layer (AY103-HY991, CIBA) applied to a titanium plate 0,295 mm thick (h_s) was used as the object of the study. Titanium platinum was cut into 100*200 mm panels. The panels were ultrasonic degreased in acetone for 2 min. Then they were immersed in a solution of ammonium bifluoride (10 g/l) for 30 s at room temperature. Thereafter, the sheets were washed under running water for 5 minutes and wiped dry. The periphery of the plate was pasted over with thick adhesive tape. Epoxy adhesive was poured onto a metal surface and smeared with a cylindrical glass rod. The glue was cured for 2 hours at 80 °C. After cooling, coated samples are cut into 10*50 mm plates. To remove burrs at the edges of the samples, grinding with fine emery paper was carried out. The finished samples were measured with a micrometer (width $b_c = b_s = b = 8.920 \pm 0.005$mm, thickness of the coated metal h=0,560$\pm$0,005mm). Estimated coating thickness $h_c = h - h_s$=0,265 mm. The width-to-thickness ratio (b / h) of two-layer systems was greater than 5, so the theory of thin plates can be applied. For such systems, the curvature tends to develop in the directions of the Ox and Oy. Nevertheless, the studied polymer / titanium system has a significant curvature only in the longitudinal direction (Ox). The curvature in the direction of width (Oy) was neglected and, therefore, our coating / titanium system was treated as a beam.

3. Theoretical studies of the stiffness of two-layer materials

In the theoretical analysis, two cases were considered. The first case includes an analysis based on the assumption that there are residual stresses in two-layer materials. Young's modulus was calculated from the slope of the load-displacement curves within the linear deformation region of the materials. This method for determining Young's modulus was later extended to the case of a two-layer plate (planar substrate / coating system) without (or with a negligible amount) internal residual stresses in the coating (i.e., zero curvature was assumed). A two-layer material without residual stresses in the coating layer is shown in Figure 2. The coating/substrate interface is taken as the reference plane. The neutral axis is the horizontal axis formed by the intersection of the neutral plane with the cross-section of the beam. There is no deformation in the neutral plane, but it can deform by bending while maintaining its original constant length.

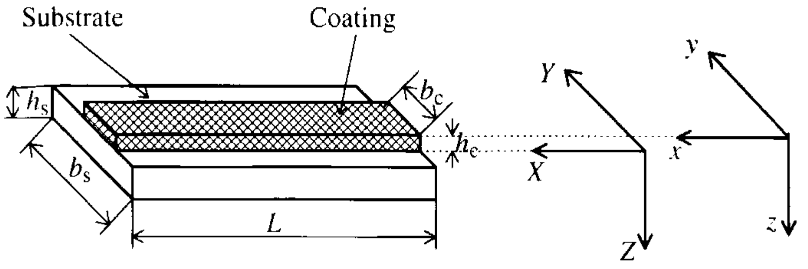
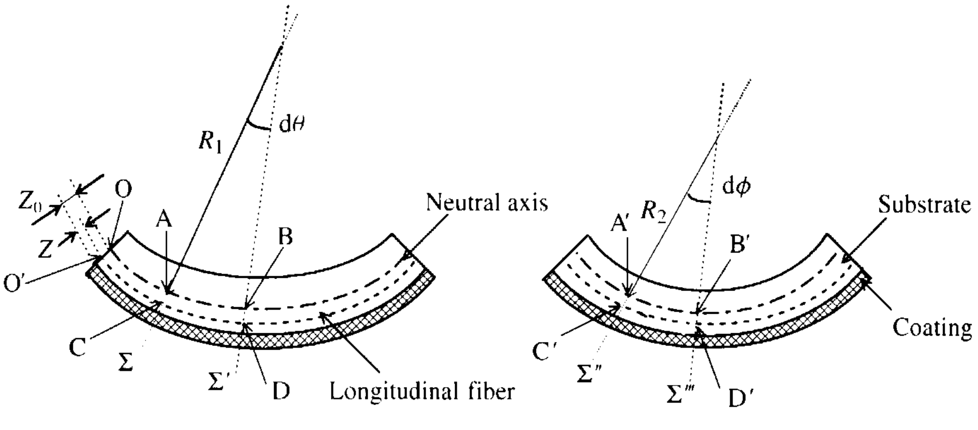


Figure: 2. Scheme of a two-layer material without residual stresses.

Longitudinal fibers (Figure 3) are defined as any of the longitudinal axes (parallel to the neutral axis) in the z direction from the coating/substrate interface.



Before testing

During testing

Figure: 3. Schematic representation of a two-layer system with residual stresses before and during mechanical bending tests.

Unfortunately, residual stresses arise in the process of obtaining the coating layer (deposition, curing, etc.). Due to these residual stresses in the coating, a significant radius of curvature appears in the two-layer system, as shown in Fig. 3. In order to consider this curvature, an additional analysis is performed using the classical beam theory, which includes initially curved bars and beams.

Let us now determine the mechanical distribution of stresses that occur during mechanical tests. According to beam theory, it is well known that the geometry of any curved beam is essential for the distribution of bending stresses. When bending, two different hypotheses need to be considered prompting two different stress distributions:

1) The cross-sectional thickness of the two-layer system is very small compared to the radius of curvature. Then the stress distribution is linear over the thickness of the system as for a flat beam.

2) The cross-sectional thickness is of the same order of magnitude as the radius of curvature. Then there is a nonlinear distribution of stresses.

This study is carried out for coatings applied to sheets. These systems can be viewed as thin plates and, therefore, the thickness of the two-layer system is small compared to its radius of curvature. Thus, we can consider 1 hypothesis for theoretical analysis.

In fact, the following assumptions should be emphasized. First, the geometry (i.e., moment of inertia) of the material in the form of a two-layer plate can be changed due to residual stresses in the coating (Poisson effects). Second, within the displacement range used during mechanical testing of a two-layer system, a non-linear deformation region can be observed. However, for an infinitesimal displacement value, the nonlinear region can be regarded as linear. And finally, residual stresses tend to cause some anisotropy, which remains even after the coating has already been separated from the substrate.

Since Young's modulus is a characteristic of any material, its value should be independent of the experimental parameters, otherwise the measured value should be called imaginary. For the same coated system, we obtain values that do not depend on experimental parameters, such as the mechanical radius of curvature, span size, span to system thickness ratio. Using other models, it is shown that two extrapolations are required to obtain the value of the Young's modulus of the coverage, which does not depend on the experimental parameters. The various values calculated for organic coatings are generally higher than those typically obtained for bulk materials. This can be due to either the mechanical properties of the thin coating or the type of mechanical test. In the case of individual materials (uncoated), Young's modulus calculated for different substrates (using the same equipment and methodology) is in good agreement with the data obtained from tensile tests. The high value of Young's modulus for the coating can be a consequence of the rearrangement of the molecules of the thin organic layer of the coating, at the polymer/metal interface. Finally, the proposed model is shown to be well suited for estimating the Young's modulus of any organic coating applied to rigid materials.

4. Conclusion

This article presents a theoretical analysis for determining Young's modulus of coating materials applied to various substrates using three-point bending tests. The tests were carried out on a strip of two-layer material, which was taken as a curved beam. The initial curvature is due to the occurrence of residual stresses in the coating layer during the preparation of the substrate surface. Residual stresses are calculated using various models. We looked at the residual stresses in order to perform a more rigorous analysis to determine the Young's modulus of the coating material. To calculate Young's modulus of the coating materials, general equations were developed (with or without consideration of in-plane deformations). These equations can be used either without residual stresses in the coating layer or with residual stresses. To determine the Young's modulus of the pavement, load/displacement curves were generated for different span sizes. It was noted that the measured Young's modulus of the coating does not depend on the experimental parameters, such as the mechanical radius of curvature, the span size, the ratio of the span to the thickness of the system, only when the proposed equation is used. The rest of the equations lead to the values of Young's modulus, which depend on the parameters of the experiment. Only after two extrapolations was the true Young's modulus of the coverage obtained. Then the extrapolated values of the Young's modulus of the coverage are in very good agreement with those obtained by our model. Obviously, in this study, the in-plane deformation of the coated system is very small and can be neglected.

5. Acknowledgements

The work was carried out with the financial support of the state project of the Ministry Science and Higher Education of the Russian Federation “Theoretical and experimental research in production and processing of advanced metal and composite materials based on aluminum and titanium alloys”, project No. FSFF-2020-0016.

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