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DETERMINATION OF RESIDUAL STRESSES IN GALVANIC COATING FROM THE MEASURED LONGITUDINAL DEFORMATION OF A TUBULAR SUBSTRATE

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¶ **Abstract:** *A technique was developed for determination of residual stresses in the galvanic coating by measuring the longitudinal deformation of a tubular substrate during deposition process. The substrate was fixed by one end and the displacement of the free end was determined by measuring of the deformation of the elastic element. An adequate calculation formula is presented.*
The experimental data were approximated by an analytical expression assuming that the dependence of residual stresses on coating thickness is linear-fractional. The moduli of elasticity of the copper substrate and the nickel coating were assumed to be different in the calculation of residual stresses.
Residual stresses were calculated in a galvanic nickel coating deposited on three tubular substrates (∅2.9/1.8 mm, ∅2.75/1.3 mm, ∅1.9/0.6 mm) from Watt's electrolyte. The values of tensile residual stress 180±5 N/mm^2 were observed in all coatings. The values of residual stresses are compared to those found in the literature.
Key words*: residual stresses, measuring technique, longitudinal deformation, tubular substrate, nickel coating.*

1. INTRODUCTION

Galvanic coatings are applied mainly for decorative and corrosion protective purposes and for restoring the surfaces of machine parts. The deposition of coatings is accompanied by residual stresses. Depending on the value and sign, residual stresses may play a positive or a negative role. High residual stresses in the coating may cause its cracking, flaking, debonding, etc. It is known that residual compression stresses in the coating increase the fatigue resistance of the coated part (Tushinski et al., 2002). Tensile residual stresses commonly cause harmful effects.
In order to produce the favorable residual stresses in the coating, optimization of the technological processes has to be realized. Optimization depends on the improvement of measuring techniques and development of methods for evaluation of residual stresses.
One of the methods for determination of residual stresses in the coating, used in laboratory or in industrial investigations, is measurement of the longitudinal deformation of a straight strip (Popereka, 1961; Weil, 1970; Wagner, 1975;) or a cylindrical (Ignat'ev, 1995; Adzhiev et al., 1976) substrate. This method was first proposed by M. Popereka in 1961. Various experimental devices, based on this method, have been developed since for measuring residual stresses (Dvořák&Vrobel, 1971; Wagner, 1975; Adzhiev et al., 1976; Shluger et al., 1980; Krutskich et al., 1982). A Dvořák and L Vrobel used a straight strip substrate prestressed by an elastic element, and recorded longitudinal deformation by means of a deviation meter. This instrument has been commercially available and is known as the EFCO Internal Stress Meter. However, the effect of prestressing the substrate by an elastic element was not taken into account. J. Kõo (Kõo, 1979) showed that prestressing of the substrate by an elastic element, unlike prestressing by a weight, has an effect on the value of residual stresses. This finding was experimentally proved and the results were presented in work (Ryabchikov et al., 2002). In the present study, a generalized formula (Kõo et al., 2000) is used for the calculation of residual stresses in coatings by measuring the longitudinal deformation of a hollow cylindrical substrate prestressed by an elastic element.
A nickel coating, one of the oldest protective-decorative galvanic coatings, was chosen for testing the measuring technique. A nickel coating can be deposited on copper, brass, steel and other basic metals. Data for comparison of the results of our experiments with those obtained by other researchers can be found in literature. The measuring system used is capable of measuring both tensile and compressive stresses with equal accuracy. The longitudinal deformation of a tubular substrate was reduced to the deflection of the middle of an elastic element manufactured as a beam with constant stiffness. The deformation of an elastic element during deposition process was measured by four foil strain gauges glued onto its outer surfaces. The deformation signals were stored in the processor of a multi-channel strain indicator and were further entered in a microcomputer. This kind of measuring system allows automation the process of obtaining experimental information and calculation of the values of residual stresses depending on coating thickness. Note that it is possible to calculate initial stresses in the coating from the measured deformation of a specimen at any stage of electrodeposition.

2. CALCULATION OF THE RESIDUAL STRESSES

According to a generalized algorithm of layer growing/removing methods (Kõo, 1996), residual stresses in a coating can be calculated as the sum of the initial (superficial) stresses and the additional stresses. Additional stresses in the coating can be calculated if initial stresses are known. Since in the surface physics of materials there exist no theoretical methods for determination of initial stresses, various experimental methods have been worked out for this purpose, among them the method of measuring the longitudinal deformation of a wire substrate.
A method of measuring longitudinal deformation for determination of residual stresses in a long homogeneous cylinder by removal of thin cylindrical concentric layers was proposed by Heyn and Bauer (Heyn&Bauer, 1911). In (Perakh, 1976; Ignat'ev, 1995) it is shown that calculation of residual stresses is possible from the longitudinal deformation of a cylindrical substrate, measured during coating deposition.
In present study a generalized formula of measuring the longitudinal deformation of a long hollow cylindrical substrate for

determination of initial residual stresses (further residual stresses) in coatings, presented in (Kõo, 2000), is used:

$$\bar{\sigma}(h) = -\frac{E_1}{2(1-\mu_2)\varphi(h)}\left\{\frac{\psi(h)}{l_1} + \frac{C}{\pi E_1}\left[\frac{l_2}{l_1}\frac{\psi(h)}{r_1^2 - r_0^2} + 1\right]\right\}\frac{\mathrm{d}w(h)}{\mathrm{d}h}. \quad (1)$$

Here

$$\psi(h) = r_1^2 - r_0^2 + \vartheta\left[1 + \frac{2(\mu_1 - \mu_2)^2 r_1^2}{2(1-\mu_2^2)r_1^2 + (1-\mu_2^2+\gamma)(2r_1+h)h}\right](2r_1+h)h,$$

$$\varphi(h) = \left[1 - \frac{2(\mu_1-\mu_2)(1+\mu_2)r_1^2}{2(1-\mu_2^2)r_1^2 + (1-\mu_2^2+\gamma)(2r_1+h)h}\right](r_1+h),$$

where

$$\vartheta = \frac{E_2}{E_1}, \quad \gamma = \vartheta(1-\mu_1^2)\left[\frac{(r_o^2+r_1^2)}{(r_1^2-r_0^2)} - \frac{\mu_1}{1-\mu_1}\right] + \mu_2(1+\mu_2).$$

E_1 and E_2 are the moduli of elasticity of the substrate and the coating, respectively; μ_1 and μ_2 are the Poisson's ratio of the substrate and the coating, respectively; l_1 is the length of the coating; l_2 is the length of the free substrate, h is the current thickness of the coating; r_0 is the inner radius of the substrate, r_1 is the outer radius of the substrate; C is the rigidity of the elastic element; $w(h)$ is the longitudinal displacement of the upper end of the substrate.

When using formula (1), it should be taken into account that differentiation of the measured experimental data $w(h)$ is an ill-posed problem. To obtain reliable results, special methods for numerical differentiation of experimental data, or their preliminary approximation, can be used.

An equation for approximation of experimental information can be developed assuming that the dependence of residual stress on coating thickness is linear-fractional (Kõo, 2000)

$$\bar{\sigma}(h) = \bar{\sigma}_0\frac{h_2 + h}{h_2 + c\,h}, \quad (2)$$

where $\bar{\sigma}_0$ is residual stress at the beginning of deposition (h = 0) and c is a dimensionless constant; h_2 is the final thickness of the coating.

Taking into account expression (2), the following equation is obtained from (1) for the approximation of the measured displacements:

$$w(h) = -\frac{2(1-\mu_2)}{E_1}\bar{\sigma}_0\int_0^h \frac{h_2+h}{h_2+c\,h}\left\{\frac{\psi(h)}{l_1} + \frac{C}{\pi E_1}\left[\frac{l_2}{l_1}\frac{\psi(h)}{r_1^2-r_0^2} + 1\right]\right\}^{-1}\varphi(h)\,\mathrm{d}h. \quad (3)$$

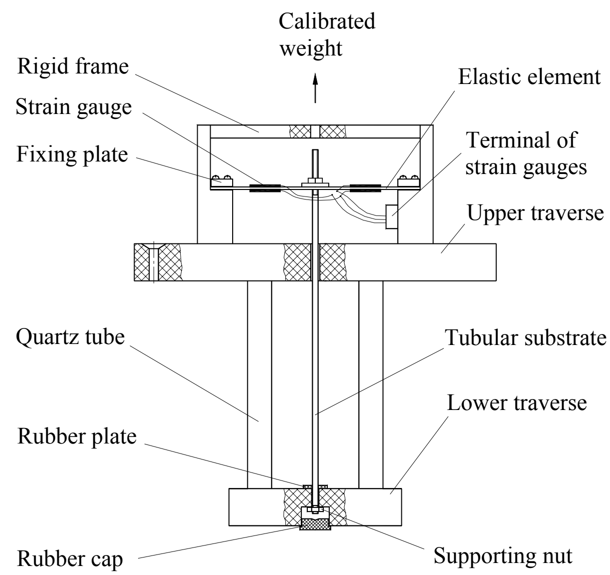
Determination of residual stress is reduced to the finding of the constants $\bar{\sigma}_0$ and c of equation (3). The constants should be determined so that the measured displacements $w(h)$ are approximated in the best way. This problem can be solved by using modern programs of regression analysis. In our calculations the regression function *genfit* of the computer program *Mathcad 2000i* is used.

3. EXPERIMENTAL DEVICE AND PROCEDURE

An experimental measuring system used for determination of residual stresses is described in an earlier paper (Ryabchikov et al., 2003). Hence the present study deals with the parts which have been remodeled.

A device was designed for fixing a tubular substrate at one end and for prestressing by an elastic element and a calibrated weight at the other (Fig. 1). The main material was plexiglass, which does not contaminate the electrolyte. Quartz tubes were used for the stands, because quartz has a very small (practically zero) coefficient of thermal expansion and it allows to use various substrate materials. The displacement of the upper end of the substrate was reduced to the deflection of the middle of the elastic element. The deformation of an elastic element was measured by strain gauges (KF5P1- 15-100-B-12, basic length 15 mm, resistance 100 Ω, gauge factor 2.2 at 20±1 ºC, Co VEDA, Kiev, Ukraine) glued in the longitudinal direction onto the free surfaces of the element and joined to form a half-bridge. The other half-bridge forms a part of a strain indicator including also a microprocessor. A device with a such design allows to measure both tensile and compressive stresses, with the equal accuracy, during electrodeposition process.

a)



b)

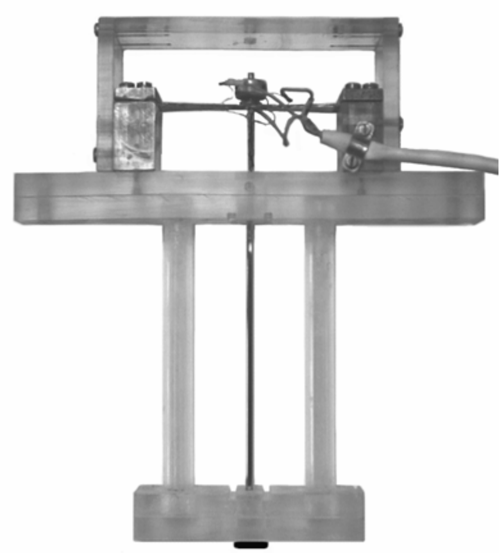


Fig. 1. Equipment for fixing the tubular substrate and the elastic element: a) scheme and b) overall view

Calibration of the measuring technique represents a separate experiment. The elastic element was loaded with weights in the middle to reproduce a deflection which is equal to the deflection occurring during the deposition process. The deflection was measured by a dial clock gauge with an accuracy of 0.002 mm. It was found that one measuring unit of the deformation indicator corresponded to 2.4×10^{-4} mm and the stiffness coefficient of the elastic element was C = 134.9 N/mm.

The copper tubes with different diameters were used as the substrate. Copper was chosen as the material of the substrate in order to attain a higher sensitivity.

Next, the substrate was prepared for deposition process. Its surfaces were polished with silica paper, the diameter of the substrate was measured to ±0.01 mm. The substrate was weighed on the Sartorius Balance BA61 (readability 0.0001 g), placed in the equipment, cleaned by acetone and viennese lime and chemically activated. The equipment was immersed in the electrolytic cell and fixed; a calibrated weight of 20.6 N was suspended from a wire. When the deformation readings had stabilized, electrodepositing process was switched on.

A nickel coating on the part of the substrate with a length of about 100 mm was deposited from Watt's bath containing $NiSO_4\times7H_2O$ – 350 g/litre; Ni Cl_2 $\times6H_2O$ - 45 g/litre; H_2BO_3 - 35 g/litre at a cathode current density of 3.0±0.05 A/dm^2, temperature 55±0.1°C and pH = 5.1. The deposition process lasted 250 minutes. The deformation readings were recorded with an interval of one minute and were stored in the microprocessor of strain indicator. As cathode thickness increased continuously to attain constant depositing speed, the current was corrected manually. Final thickness was measured to 0.01 mm. The measured coating thickness was corrected using a weight, by calculating average coating thickness from the difference in the specimen's weight before and after deposition. According to the deformation readings, coating thickness was divided into 253 equal parts; thus we had 253 pairs of readings per single experiment. The deformation of an elastic element depending on time was converted to the longitudinal deformation of the substrate according to the calibration results and was further used as experimental information.

3. RESULTS OF EXPERIMENTS

Three experiment series with different tubular substrates were carried out: 1) using the substrate with the inner/outer diameter of 2.9/1.8 mm and length of 176 mm; 2) using the substrate with the inner/outer diameter of 2.75/1.3 mm and length of 176 mm; 3) using the substrate with the inner/outer diameter of 1.9/0.6 mm and length of 165 mm.

The signals of the deformation of the elastic element were stored in the microprocessor of a strain indicator with an interval of 1 min during the process of coating deposition. Deposition process lasted for 252 minutes. This information was considered the experimental data and was directly entered in the computer for the further processing. The signals of deformation depending on time were converted, according to the calibration results, to the contraction of the substrate w depending on the coating thickness h. Since all experiments were carried out under similar conditions, the data of the three experiments (253 readings in each) were pooled.

As an example, the results of the second experimental series are presented. In the calculation of the residual stresses, the following values were used: $E_1 = 98\times10^3$ N/mm^2; $E_2 = 178\times10^3$ N/mm^2; $\mu_1 = 0.34$; $\mu_2 = 0.31$; $l_1 = 97$ mm; $l_2 = 79$ mm; $r_0 = 0.65$ mm; $r_1 = 1.38$ mm; $h_2 = 0.15$ mm; $C = 134.9$ N/mm. An equation (3) was used for approximation of experimental data. The purpose was to find the unknown constants, i.e. the initial values of residual stress $\bar{\sigma}_0$ and the dimensionless parameter c. The problem was solved by using the program *Mathcad2001i Professional* (Kir'yanov, 2001) with the smoothing function *genfit* (v*x*, v*y*, *F*). The obtained function $w(h)$ is shown in Fig. 2. As the values do not fluctuate to a great extent and remain in the zone with a sufficiently uniform width, they can be approximated by an analytical formula.

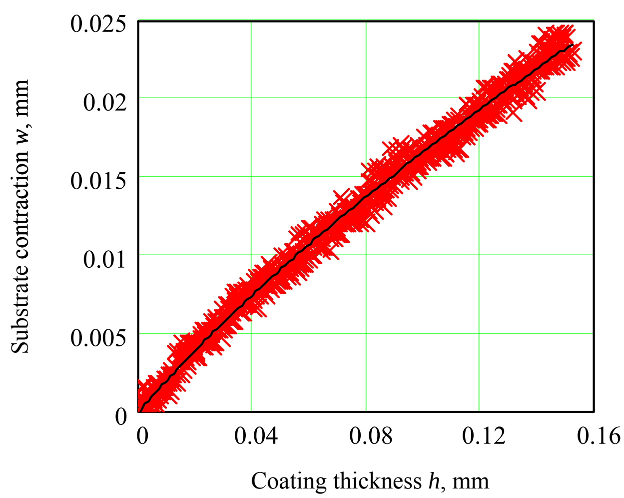


Fig. 2. Experimental values of the contraction of the tubular substrate depending on the coating thickness, and the curve of approximation

The results of the approximation are $\bar{\sigma}_0$ = 180 N/mm^2 and c = 1.91. It is evident that the approximation of the experimental data using the presented formula is satisfactory. In Fig. 3 is shown a change of the residual stresses throughout coating thickness calculated by formula (2).

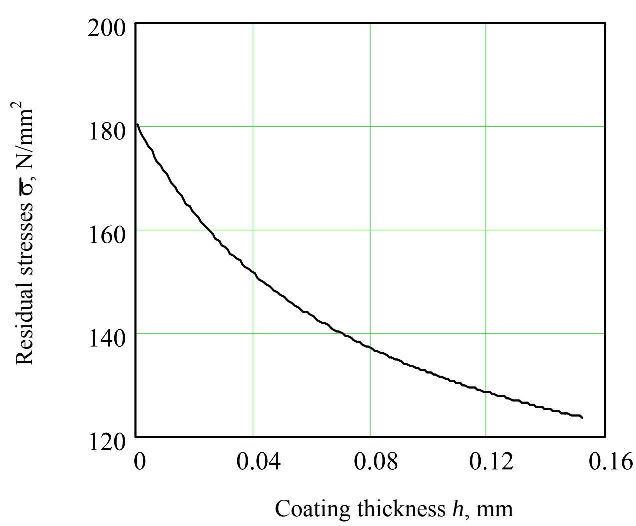


Fig. 3. Dependence of residual stresses on the coating thickness

Residual stresses for the first and for the third experiment series are 175 N/mm^2 and 185 N/mm^2, respectively.
The obtained values of residual stresses are comparable to the result 205 N/mm^2 obtained in our earlier work (Lille & Ryabchikov, 2000), where residual stresses were determined in a galvanic nickel coating deposited from Watt's electrolyte by measuring the longitudinal deformation of a copper wire substrate. S.E. Hadian (Hadian, 1999) measured the residual stresses, using an EFCO Internal Stress Meter, in a nickel coating deposited from Watt's electrolyte (pH = 3.5; 60ºC; 4.0 A/dm^2) on a steel substrate and the value was 215 N/mm^2, which is comparable to our result. E. Wagner (Wagner, 1975) determined the residual stresses as 204 N/mm^2 in a nickel coating, deposited from Watt's electrolyte (pH = 4.0; 50±1ºC; 5.0 A/dm^2), by measurement of the longitudinal deformation of a steel strip substrate.

4. CONCLUSION

The results of the experiments and the calculation of the residual stresses in nickel coatings, using the presented experimental technique, allow to draw the following conclusions.
An experimental equipment was developed for determination of residual stresses in galvanic coatings by the registration of the longitudinal deformation of a tubular substrate during deposition process.
It was assumed that initial stresses change linear-fractionally throughout coating thickness. Residual stresses were calculated in a galvanic nickel coating deposited from Watt's electrolyte on three copper tubular substrates with different dimensions. The values of the residual stresses were obtained in the same range of 180±5 N/mm^2 and are comparable to those presented in the literature.
The method and the experimental equipment can be used for determination of initial tensile or compressive stress with equal accuracy by measuring the longitudinal deformation of a tubular substrate during the process of coating removal (destructive method).

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