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MEASUREMENT OF RESIDUAL STRESSES IN THE COATING DEPOSITED BY BRUSH-PLATING ON A THIN-WALLED SHORT CYLINDER

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Abstract: *Determination of residual stresses was studied in brush-plated nickel coatings deposited from sulphate electrolyte on the outer surface of a short thin-walled cylindrical steel substrate. Residual stresses throughout coating thickness were calculated according to the change of circumferential deformation on inner surface, measured during depositing process. The value of residual stresses was 705 N/mm^2, which is comparable the result 807 N/mm^2 obtained previously with the use of a strip brass substrate, and is approximately three times higher than for the coatings deposited from similar sulphate electrolytes in the bath.*
Key words: *nickel brush-plating***,** *coating, cylindrical substrate, circumferential deformation, residual stress*

1. INTRODUCTION

Brush-plating (electrochemical metallizing) is an effective method for depositing a galvanic coating with a reasonable thickness in limited or selected surface areas. The laying of the coating, however, is accompanied by residual stresses within the coating.

To determinate residual stresses in brush-plated coatings, a conventional deformation method was used where thin strips, cut thin walled rings, or a thin-walled short cylinder served as the substrate.

To decrease the amount of work involved and to enhance the reliability of the results, a short thin-walled cylindrical substrate was fixed so that it enabled the cathode to deform practically freely at the time of brush plating (Lille et al., 1993). For this purpose, an experimental system was developed consisting of a set-up for brush plating, a substrate fixer and a multi-channel strain indicator supplied with a processor. In such a substrate, the coating is deposited by the uniformly rotating anodes with the brushes fed continuous with hydrostatical pressure, which guarantees a relatively homogeneous temperature of the cathode (deposition process). In order to determine residual stresses, circumferential strains are measured by temperature compensated strain gauges on the inner surface of the substrate during coating deposition. The dependence of the deformation obtained on coating thickness is used as experimental information.

Since the derivative of the deformation parameter (the values fluctuate to a great extent) in the calculation equation depend on coating thickness, the experimental data were previously approximated by an analytical expression assuming that the dependence of residual stresses on coating thickness is linear-fractional. The moduli of elasticity of the steel substrate and the nickel coating were assumed to be different in the calculating of residual stresses. This kind of measuring system allows automation of the process of obtaining experimental information and calculating the values of residual stresses depending on coating thickness.

2. FORMULA FOR CALCULATION OF RESIDUAL STRESSES

Residual stresses in one and the same layer are expressed according to the general algorithm of layer growing/removing method the sum of the initial and the additional stresses (Kõo, 1996). Stresses in the superficial layer are called initial stresses. Additional stresses are understood as the stresses which arise in this layer when subsequent layers are applied or previous layers are removed. The coated substrate (part) is usually so rigid that the residual stresses are practically equal to the initial stresses. As a result, the initial stresses are called here residual stresses.

Residual stresses are calculated by the formula, described in (Kõo et al., 1991) and (Lille et al., 1993). The formula was obtained solving an axisymmetric problem of a short cylindrical shell with surface and edge loads within the framework of the technical theory of shells (Boyarshinov, 1973), when residual stresses are considered to be equal in the longitudinal and circumferential directions and the Poisson's ratios of the substrate and the coating are assumed to be the same.

The coating was deposited on a short thin-walled cylindrical steel substrate. Residual stresses in the superficial layer were calculated by measuring the circumferential strain of the substrate ε_t depending on variable coating thickness h (Kõo et al., 1991)

$$\sigma = -\frac{E_1}{1-\mu}\cdot\frac{h_1+\gamma h}{1+F}\cdot\frac{\mathrm{d}\varepsilon_t}{\mathrm{d}h}, \tag{1}$$

where

$$F=\sqrt{\frac{3(1+\mu)f^2}{(1-\mu)g}}\,\Phi, \qquad f=h_1^2+2h_1h+\gamma h^2,$$

$$g=h_1^4+4\gamma h_1^3h+6\gamma h_1^2h^2+4\gamma h_1h^3+\gamma^2 h^4,$$

$\gamma = E_2/E_1$ and E_1, E_2 are the moduli of elasticity of the substrate and coating, respectively, μ is the Poisson's ratio of the substrate, h_1 is the substrate thickness.

The function Φ is

$$\Phi=\frac{\cosh\lambda\sin\lambda\sinh\lambda^*\cos\lambda^*-\sinh\lambda\cos\lambda\cosh\lambda^*\sin\lambda^*}{\lambda^*(\sinh\lambda\cosh\lambda+\sin\lambda\cos\lambda)},$$

where

$\lambda=\frac{\beta l}{2}$; $\lambda^*=\frac{\beta b}{2}$; $\beta=\sqrt[4]{\frac{3(1-\mu^2)(h_1+\gamma h)^2}{r^2 g}}$; l is the length of the substrate; b is the width of the strain gauge and $r = r_0+\frac{\gamma(h_1+h)h}{2(h_1+\gamma h)}$; r_0 is the middle radius of the substrate.

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

An equation for the approximation of experimental information can be developed assuming that the dependence of residual stress on coating thickness is linear-fractional (Lille et al., 2002)

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

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

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

$$\varepsilon_t(h) = \frac{\bar{\sigma}_0}{E_1} \int_0^h \frac{h_2 + h}{(h_2 + ch)(h_1 + \gamma h)} \mathrm{d}h \cdot \qquad (3)$$

Using the computer program *MS Excel* and the calibration results, the experimental data were converted to the circumferential deformation of the substrate ε_t depending on the coating thickness *h*. Thus, the determination of residual stress is reduced to the finding of the constants $\bar{\sigma}_0$ and c from Eq. (3). The constants should be determined so that the measured circumferential deformations $\varepsilon_t(h)$ are approximated in the best way. This problem can be solved by using mathematical programs of regression analysis. In this study, the regression function *genfit* (v*x*, v*y*, *F*) of the computer program Mathcad (Kir'yanov, 2001) was employed.

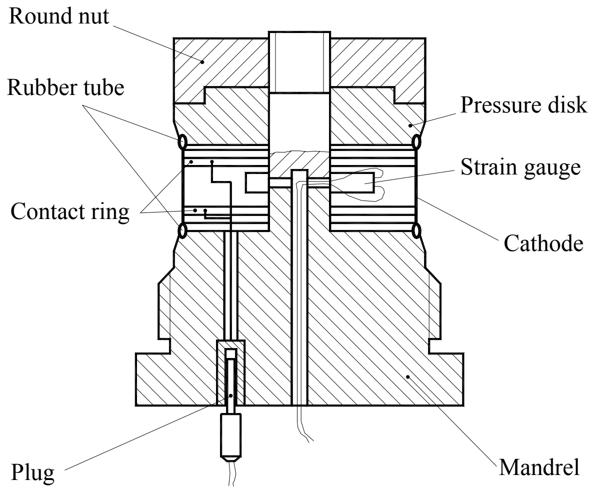
3. EXAMPLE OF APPLICATION

The substrate (outer diameter 50.0 mm, inner diameter 49.2 mm, length 17.0 mm) was turned off from a seamless steel tube with a carbon content of 0.17-0.24% (the modulus of elasticity 198×10^3 N/mm^2, the Poisson's ratio 0.28 and the coefficient of thermal expansion 11.1×10^{-6}). Two temperature compensated strain gauges (KF5P1-15-100-B-12, basic length 20 mm, resistance 100 Ω, gauge factor 2.2 at 20±1ºC, Co VEDA, Kiev, Ukraine) on the inner surface of the specimen were placed in the circumferential direction and covered with moisture proof material, except in the area where the cathode contact ring was located. The substrate was prepared for deposition process. Its outer side was polished with silica paper and cleaned, the thickness of the substrate was measured to 0.002 mm. The substrate was weighed on the Sartorius Balance BA61 (readability 0.0001g). The specimen is attached to the equipment for fixing the substrate, where its end surfaces have a contact with the rubber tube glued to the groove of mandrel and the pressure disk (Fig. 1). Such fixing enables the cathode to deform practically freely and to avoid the flowing of the electrolyte inside the cathode.

Fig.2 shows continuous measurements of deformation on the inner side of a specimen during the process of coating a surface layer on the outer side of the specimen using an experimental system. Fixture was placed in the equipment, specimen was chemically degreased and briefly activated. When deformation readings had stabilized, the first data was recorded and brush deposition process was switched on.

A nickel coating (the modulus of elasticity 176×10^3 N/mm^2, the Poisson's ratio 0.31 and the coefficient of thermal expansion 13.3 × 10^{-6}) was deposited from the electrolyte, elaborated by M. Pille, PhD (Estonian Agricultural University), containing Ni SO_4×7H_2O, 350 g/litre; HCOOH, 60 g/litre; HCOONa×2H_2O, 40 g/litre; $MgSO_4$×7H_2O, 10 g/litre; gravity 1.19±0.01 g/cm^3, pH = 1.57-1.63 (determined at 20 ºC).

a)



b)

Fig. 1. Placing of the substrate onto a fixture for layer growing: a) scheme and b) overall view

Attached to the fixer for the anodes, an anode made of special grade heat-resistant graphite to ensure the ratio 1:5 of anode surface to the surface to be coated, was used. Cotton batting with a thickness of 8-10 mm, fed by hydrostatical pressure from a bottle was employed. The rotating anode swabbed all over the outer surface and the coating was deposited using a current density of 80-83 A/dm^2. The velocity of the anodes was 0.13 m/s.

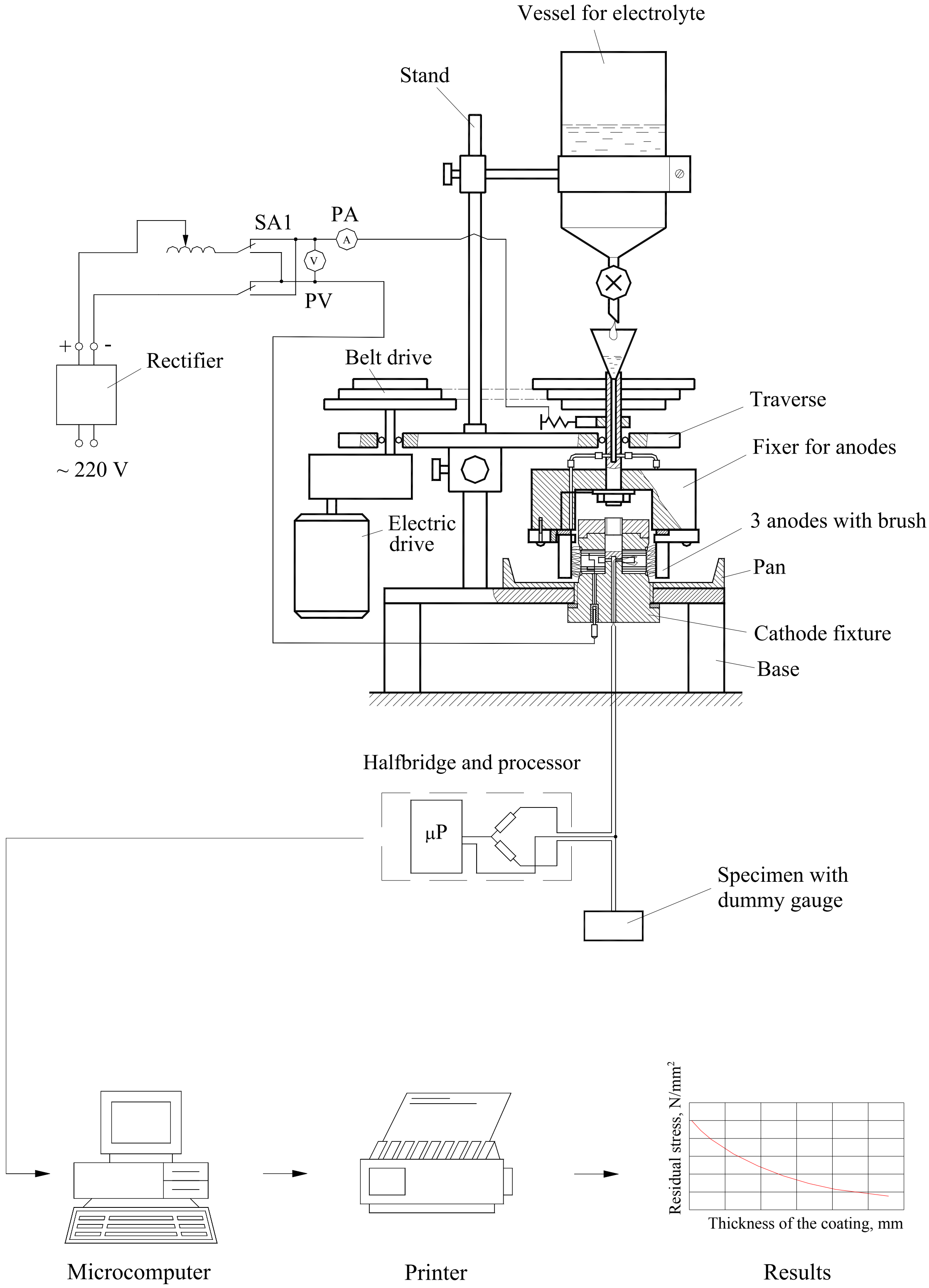


Fig. 2. Experimental system for measuring residual stress in a brush-plated galvanic coating

At the beginning of deposition, temperature rose from room temperature up to 90-95 ºC for 2 -3 min and fluctuated during the process around 2-3 ºC. The results were stored in a multi-channel strain indicator supplied with a processor. The data (average values of two gauges) were entered in a micro-computer as experimental information for the calculation of residual stresses. The process lasted 40 minutes and the deformation readings were recorded with an interval of 60 seconds (which causes produces a layer with a thickness of about 1 μm).
When the process was finished the substrate with the coating was removed from the equipment, and was cleaned, dried and weighed. The final thickness of the substrate with the coating was measured. 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 40 equal parts. Thus we had 40 pairs of readings per single experiment. Since the experiments were carried out under similar conditions, the data of the two experiments were pooled (Fig. 3).

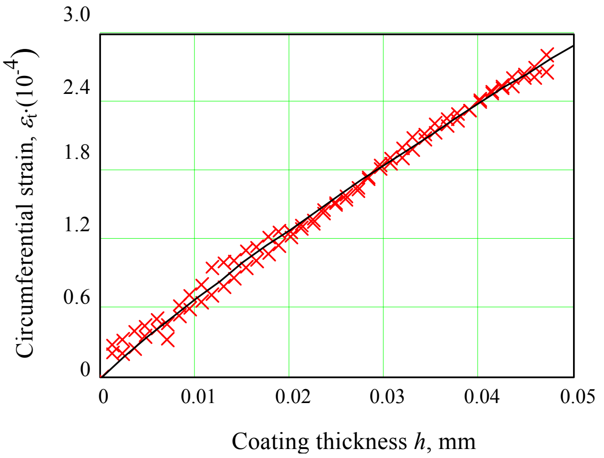


Fig. 3. Experimental values of the circumferential deformation of the inner side of a cylindrical substrate depending on coating thickness and the curve of approximation

In Fig. 4 is shown a change of the residual stresses throughout coating thickness calculated by formula (2).

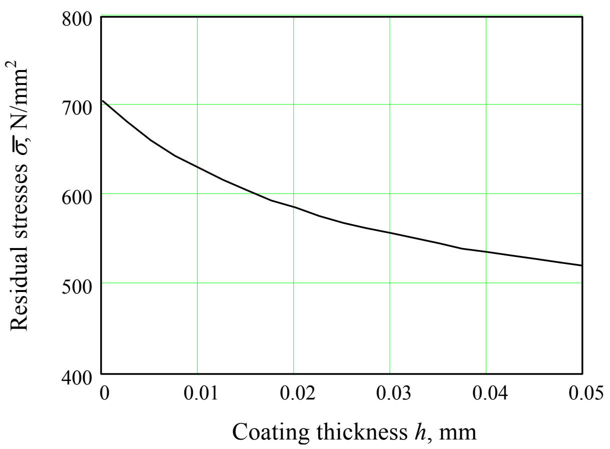


Fig.4. Dependence of residual stresses on coating thickness

The results of approximation are: $\bar{\sigma}_0 = 705$ N/mm^2, $c = 1.69$, the calculated function $\varepsilon_t(h)$ is shown in Fig. 3. The values are comparable to the result $\bar{\sigma}_0 = 807$ N/mm^2, $c = 2.57$, obtained (Lille et al., 2002), when the coating was deposited on the brass strip substrate.

4. CONCLUSIONS

Experimental equipment was presented for determination of residual stresses in brush-plated coatings by continuous registration of the circumferential deformation of a cylindrical steel substrate during deposition process. The obtained results $\bar{\sigma}_0 = 705$ N/mm^2 is comparable to the result $\bar{\sigma}_0 = 807$ N/mm^2 obtained by (Lille et al., 2002) when the coating was deposited on a brass strip substrate.
Comparison of the values of residual stress in nickel coatings deposited from similar sulphate electrolytes by brush-plating on a cylindrical steel substrate and by deposition in the bath on a steel strip substrate (determined stresses are $\bar{\sigma}_0 = 215$ N/mm^2 (Hadian, 1999), $\bar{\sigma}_0 = 204$ N/mm^2 (Wagner, 1975)) shows that the stresses in coatings obtained by the former technique are up to threefold larger.

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