# Residual Stresses

Edited by
V. Hauk, H.P. Hougardy, E. Macherauch und H.-D. Tietz

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## Determination of Residual Stresses in the Coat Deposited by Brush Plating

H. Lille, J. Kõo, J. Valgur, Estonian Agricultural University, Tartu (Estonia)

### Introduction

For determination of residual stresses in brush plated coats the thin strips and cut thin-walled rings are used as cathodes. Then the deflections arising during the coating deposition are considered as experimental data. In case of fixed cantilever strips the deflection of the free end and of cut rings the change of slit width are measured. In order to establish the relation between deflection and coat thickness, required for data processing the discrete method is used. According to this labour-consuming method series of experiments are carried out with similar cathodes depositing the coats of various thickness on them.

To decrease the amount of work involved and increase the reliability of results a short thin-walled cylindrical cathode fixed at the time of brush plating was taken into use by the authors. In such cathode the coating is deposited by uniformly rotating anodes with brushes fed by hydrostatical pressure. To determine the initial stresses the circumferential strains are measured by shelf-thermocompensated strain gauges on inner surface of the cathode during the coat deposition.

### Formula for Initial Stress Calculation

The coat is deposited on a short thin-walled cylindrical cathode with a radius of the middle surface $r_0$, thickness h and length l (Fig. 1). The moduli of elasticity and Poisson's ratios of cathode and coat are accordingly $E_1, E_2$ and $\mu_1, \mu_2$.

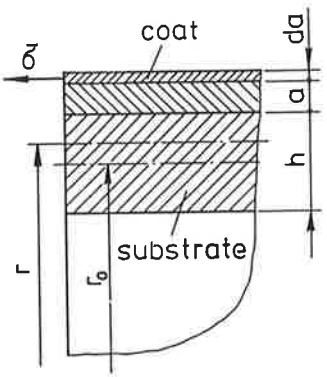


Fig. 1: Fragment of edge of cathode with coat

Initial stress in the superficial layer is calculated by measured circumferential strain of cathode $\epsilon$ dependent on changing

thickness a (1):

$$\bar{\sigma} = -\frac{E_1}{1-\mu}\,\frac{h+\gamma a}{1+F}\,\frac{d\epsilon}{da},$$

where $\gamma = E_2/E_1$, $\mu = \mu_1 = \mu_2$,

$$F = \sqrt{\frac{3(1+\mu)}{1-\mu}\,\frac{f^2}{g}}\;\frac{ch\lambda \sin\lambda\, sh\lambda^* \cos\lambda^* - sh\lambda \cos\lambda\, ch\lambda^* \sin\lambda^*}{\lambda^*(sh\lambda ch\lambda + \sin\lambda \cos\lambda)},$$

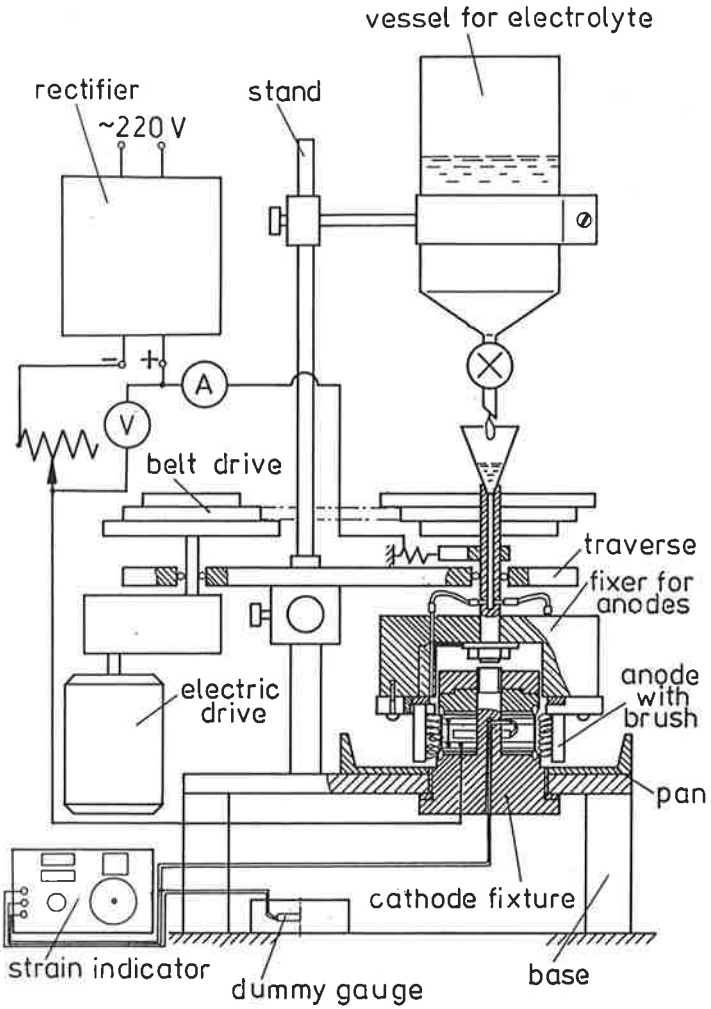


Fig. 2: Set-up for brush plating and measuring of deformations

$$f = h^2 + 2h\alpha + \gamma a^2 , \quad g = h^4 + 4\gamma h^3 a + 6\gamma h^2 a^2 + 4\gamma h a^3 + \gamma^2 a^4 ,$$

$$\beta = \sqrt[4]{\frac{3(1-\mu^2)(h+\gamma a)^2}{r^2 g}} , \quad \lambda = \frac{\beta l}{2} , \quad \lambda^* = \frac{\beta b}{2} ,$$

$$r = r_o + \frac{\gamma(h+a)a}{2(h+\gamma a)} .$$

Note that unlike in work (1) the coefficient F of the present formula for initial stress is taking into consideration the width of strain gauge b integrally.

Set-up for Brush Plating and Equipment for Strain Measuring

The equipment that consists of a set-up for brush plating, a cathode fixer and a strain indicator was used for investigation of initial stresses (Fig. 2).

The distance between the rotating anodes with brushes and the cathode of the set-up is changeable with the help of shifting the anodes in the fixer for anodes in radial direction. The velocity of the anodes can be regulated gradually within the limits of 0.13 to 0.62 m/s. The brushes are fed hydrostatically, keeping the electrolyte in the funnel on a level by regulating the dropping intensivity.

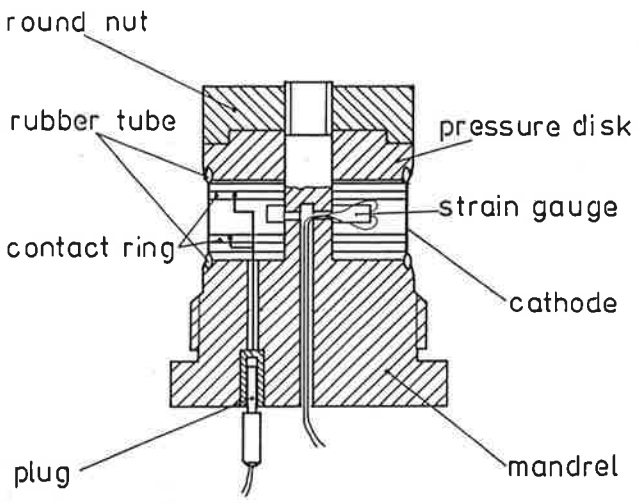


Fig. 3: Cathode fixture

The cathode is attached to the fixture (Fig. 3), where its edges have a close contact with the rubber tube glued to the croze of mandrel and pressure disk. Such a fixing enables the cathode to deforme practically freely and staunches the electrolyte flowing to the strain gauges glued to the inner surface.

Strains are measured with a static strain indicator for manual data acquisition ИСД-3, while the strain gauges are connected by the scheme of half-bridge, the arms of which are the working gauge and dummy gauge. The strain indicator enables the switching of twenty pairs of strain gauges manually.

Initial Stresses in Nickel Coats

The method described above was used for determination of initial stresses in nickel coats. The cathodes (Fig. 4) were turned off of broached steel tube 46x2.5 mm (material: Steel 20, $E_1$ = 198 GPa, $\mu_1$ = 0.31, coefficient of thermal expansion $\alpha = 11.1 \cdot 10^{-6}$ 1/K) and ground with sandpaper. Dimensions of the cathode were chosen proceeding from the sizes of strain gauges and contact rings and also for technological consideration.

The current densities changing on a large scale (15 to 100 times larger than for deposition in electrolyte bath) and changing due to this temperature on the deposition surface are typical of brush plating of the coat by the use of moving cathodes or anodes. The temperature on the deposition surface is changed especially at the beginning stage of the process increasing during 2 to 3 minutes as high as 90 to 95 °C. Thus the main problem of strain measuring is the holding of working and dummy gauges at the same temperature.

To eliminate the influence of temperature changes the shelf-thermocompensated strain gauge type КФ 5П1-20-200-Б-12 (base length 20 mm, coefficient of thermal expansion for steel cathode $\alpha = 12 \cdot 10^{-6}$ 1/K, gauge factor 2.2, working temperature -70 to +200 °C) of Co "VEDA" (Kiew, Ukraine) was taken into use. Two gauges were glued to the inner surface of the cathode symmetrically in relation to the diametre and length (glue БФ-2) and covered with a layer of the same glue after thermal processing (Fig. 4).

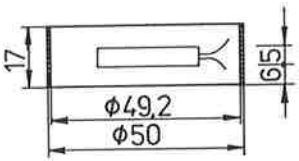


Fig. 4: Dimensions of cathode and position of strain gauges

The cathode with gauges within the fixture was heated from 20 to 100 °C. The readings were registered at 5 degrees interval holding the temperature of the dummy gauge at 20 ± 0.5 °C. It was observed that at the temperatures ≥ 60 °C the deviations did not exceed a scale value of the strain indicator (≈ $1 \cdot 10^{-5}$ pps). Such a result allows to infer that the strain indicator enables the determination of strain of the cathode with sufficient accuracy.

Nickel coat was deposited from electrolyte $NiSO_4 \cdot 7H_2O$ - 350 g, HCOOH - 60 g, $MgSO_4$ - 10 g, $H_2O$ - 1000 g at the current density 8.0 to 8.3 kA/m². Three nickel anodes (area of each 11x17 mm, relation of anode area to cathode area 1:5) were used, with

8 mm-thick folded cotton brushes attached to them. The velocity of anodes with brushes was 0.13 m/s. The readings of strain indicator were registered after 40 to 42 second interval which causes ≈ 1 μm-thick layer to be deposited. The thickness of the coat was calculated by the increase in weight of the cathode. The elastic parameters were taken equal to $E_2$ = 207 GPA, $\mu_2$ = 0.31 (2). The results of strain measuring (average values of two gauges) are shown in Figure 5. The derivative of strain calculated by the method of regularization (3) and the initial stresses calculated by the formula considered above are shown in the same figure.

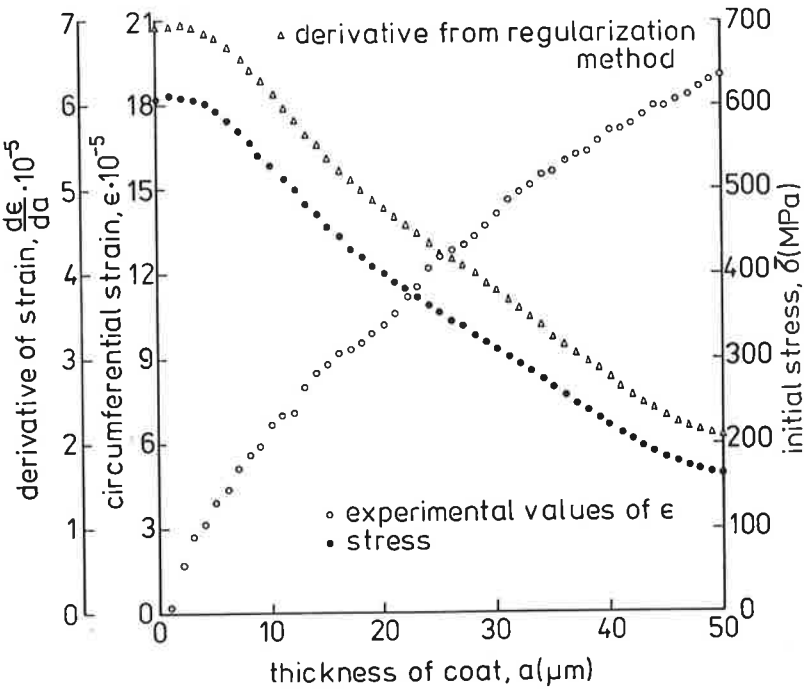


Fig. 5: Dependence on the thickness of the coat of the circumferential strain, derivative of strain and initial stress

Conclusions

1. The method of continuous growth described in the article enables the determination of initial stress in the brush plated coat by the circumferential strain of the short thin-walled cylindrical cathode.
2. The Tihonov's method of regularization could be reccommended as an effective method of approximation of experimental data and calculation of derivative.
3. The values of initial stresses in the brush plated 50 μm-thick coat on the interface of substrate and coat and in the superficial layer of the coat are 688 and 213 MPa respectively.

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