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COMPARATIVE ANALYSIS OF RESIDUAL STRESSES IN FLAME-SPRAYED AND ELECTRODEPOSITED COATINGS USING SUBSTRATE DEFORMATION AND HOLE-DRILLING METHODS

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Abstract: *In the present study the two protective coating types are tested. Thermal spray hardmetal and electroplated hard chromium coatings are widely used in a variety of applications for wear protection of component surfaces. The laying of the coating introduces residual stresses into the manufactured object.*
The through-thickness residual stress distribution and the modulus of elasticity of flame-sprayed Ni 95% Al5% alloy-based powder coatings are determined by layer removal techniques from a steel thin-walled ringed coated specimen. Residual stresses are determined also by the hole-drilling method, when the coating is flame-sprayed or electrodeposited onto a steel plate. Compressive residual stresses obtained by the deformation method and by hole-drilling are comparable. The values of tensile residual stresses in an electroplated chromium coating obtained by hole-drilling are compared to literature data for coatings deposited in a bath.

Key words: flame-spraying, electroplating, coating, layer removal method, hole-drilling, residual stress

1. INTRODUCTION

The laying of coatings is an effective method for modifying different surface properties of materials (fatigue, fracture, corrosion, wear, friction, etc) [1,2]. In this study two coating types are tested. Thermal spray hardmetal and electroplated hard chromium coatings are widely used in a variety of applications for wear protection of component surfaces.
The laying of the coating introduces residual stresses into the manufactured object. One of the causes of these stresses is the difference between the modulus of elasticity and the coefficient of thermal expansion of the coating and substrate materials.
From the viewpoint of function, the use of coatings is limited by cracking, flanking, spalling, bulking and delamination. These phenomena are directly related to the magnitude of residual stresses (particularly, tensile stresses) and may cause an unexpected failure of a coated machine part. Residual stresses play also an important role in the fatigue life of structural engineering components. In the case of near-surface tensile residual stresses, the initiation and propagation phases of the fatigue process are accelerated; on the other hand, near-surface compressive residual stresses may increase fatigue life.
The layer removal technique (destructive method) is a possible way to determine the distribution of residual stresses throughout the thickness of thick powder coatings. The layer removal method was developed by Kõo et al [3], see also [4-7], according to which the residual stresses and the modulus of elasticity of coatings are determined by testing a thin-walled ringed specimen coated by flame-sprayed Ni95All5 alloy-based powder.
The hole-drilling technique (semi-destructive method) is the most common method for measuring residual stresses and

is sometimes used directly for coated machine parts. This method requires drilling a small hole, typically 1–4 mm in diameter, to a depth approximately equal to its diameter.

In this study residual stresses were determined by layer removal method and hole-drilling method, when the same powder coating was flame-sprayed onto a steel tube and plate and a chromium coating was electrodeposited on a thick steel plate.

2. SPECIMEN PREPARATION AND EXPERIMENTS

Specimens for measuring residual stress were prepared from an ordinary steel tube with about 0.3% carbon content with a diameter of 32/30 mm, and a length of 100 mm (Fig. 1a) and a plate with a size of 90×90×1.5 mm (Fig. 2).

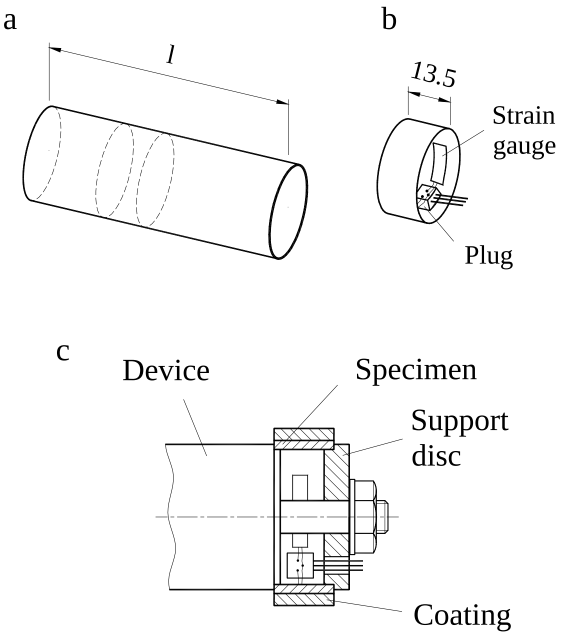


Fig. 1. Coated tube (a), ring specimen and position of strain gauges (b) and specimen's fixing to the device for layer removing (c).

The tube was machined to size on the lathe at a cutting speed of v_c = 50 m/min; cutting feed f = 0.2 mm/r, chip thickness 0.1 mm. The surface of the substrate was activated by blasting before spraying. The tube, fixed to the rotator, was flame-sprayed at a rotating speed of v_{ft} = 1.6 m/min. At the same time, a gas-flame torch positioned at a distance of 200 mm from the substrate was moved longitudinally at a speed of 0.3 m/min and the required thickness of the coating was obtained in the course of 4 and 5 operations. The same coating was sprayed, under similar conditions, on a motionless plate with thickness of 1.5 mm when its edges with a width of 7 mm were fixed to the device (Fig. 2).

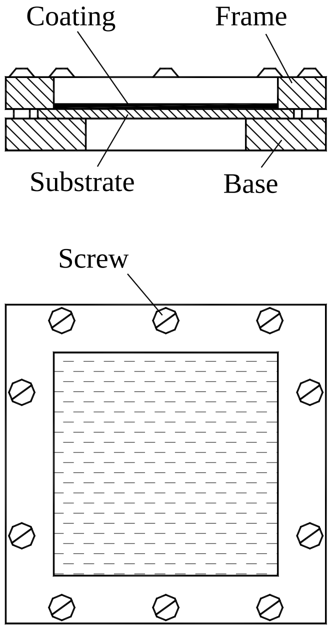


Fig. 2. Steel plate fixed to device for spraying the coating, and the coated substrate.

The final temperature of the substrate material was about 290 °C (heated to greyish blue) The process of cooling was carried out at room temperature. The tube was cut into rings with a width of 14.3 mm with a bronze bond diamond cutting wheel, and 3 specimens from the middle part were investigated. Two strain gauges 2PKB-20-200 GB (with a base length of 20 mm, resistance 200 Ω and gauge factor 2.16 at a temperature of 20±1°C, Engineering Company of Topki, Russia), were glued before cutting to inside surface of a tube in the circumferential direction (Fig.1b), wired and connected to the strain indicator, and initial reading was recorded. After cutting the ring, strain gauges were connected once again to strain indicator, and reading was recorded. The difference in readings was in the same range, as difference resulting just from connecting and disconnecting of strain gauges from the strain indicator. Therefore, residual stresses, caused by cutting the ring substrates from the tube, was not taken into account in the calculation of residual stresses. The specimen was fixed to the device and the layer was ground by a grinding wheel under the following conditions: specimen speed v_{ft} = 40 m/min, cutting speed v_c = 27.5 m/s, cutting feed f = 0.01 mm/r, with a fixed thickness of 0.1 mm (chip thickness 2×45 μm and 1×10 μm) (Fig.1c).

The change in deformation was measured and saved by a strain indicator equipped with the processor. The change in the specimen's diameter resulting from the diametrically applied load F = 49.5 N was measured by a clock gauge after the removal of each layer for determination the modulus of elasticity of the coating material [4].

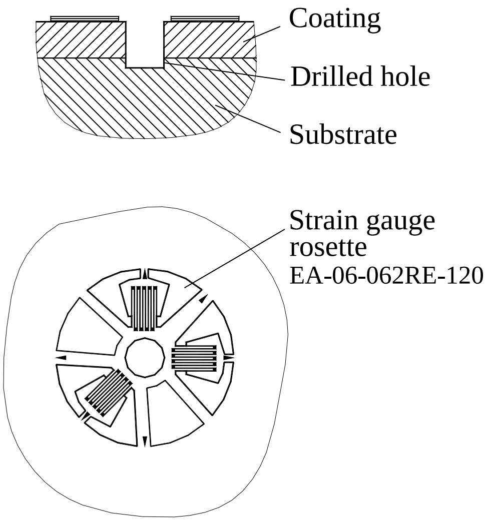


Fig. 3. Installed strain gauge rosette and the drilled hole.

For preparation of a specimen for hole-drilling method, the roughness of the coating on the plate was removed with a cutting wheel and four strain gauge rosettes EA-06-062RE-120 were glued onto the middle region of the substrate. Strain gauge rosette was wired and connected to the *Vishay Strain Indicator and Recorder Model P3* [8]. The precision high-speed milling guide *Vishay* model *RS-200* [9] was accurately centred with an alignment set-up over a drilling target on the rosette and a small hole was drilled through the geometric centre of the rosette (Fig. 3).

A hole was drilled by using a bore with a diamond tip with a diameter of 1.6 mm, and the diameter of the hole was about 1.8–1.9 mm. Readings were recorded by the *Strain Indicator and Recorder* model *P3* for relaxed strains corresponding to residual stresses.

3. CALCULATION OF RESIDUAL STRESS AND RESULTS

When residual stresses are taken to be equal in the longitudinal and circumferential directions and the Poisson's ratio of the substrate and coating is taken to be the same, and assuming that residual stresses are distributed uniformly throughout coating thickness, the derivative $d\varepsilon_t/da$ was replaced by ε_t/a, and [4]

$$\sigma = \frac{E_1}{1-\mu}\cdot\frac{h+\gamma a}{1+F}\cdot\frac{\varepsilon_t}{a}, \qquad (1)$$

where

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

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

$$f = h^2 + 2ha + \gamma a^2, \quad \gamma = E_1/E_2$$

and E_1, E_2 are the moduli of elasticity of the substrate and coating, respectively, μ is the Poisson's ratio, h is substrate thickness and ε_t is the circumferential strain measured depending on the coating thickness a.

The function Φ is

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

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

where

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

and l is the width of the substrate; b is the width of the strain gauge and

$$r=r_0+\frac{\gamma(h+a)a}{2(h+\gamma a)};$$

and r_0 is the middle radius of the substrate.

Determination of the modulus of elasticity of the coating material is presented in paper [4].

As our experimental data (circumferential strain depending on the thickness of the removed coating) fluctuated in a very wide range (having often both positive and negative signs within one experiment) (Fig. 4), it was assumed that residual stresses are distributed uniformly throughout coating thickness. In this case dispersed experimental data may be approximated by a linear relation with the smoothing function using the program *Mathcad 2001i Professional*. The slope of the line, i.e. ε_t/a =1.854×10^{-4}, and residual stresses calculated by formula (1) when E_1=202 GPa, E_2=112 GPa (obtained from our experiment), μ=0.28, h_1=1.042 mm, r_0=15.54 mm, b=4 mm are σ = 34.9 N/mm^2 (compressive stress).

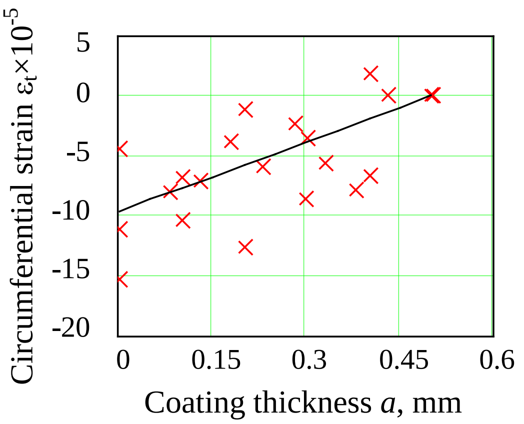


Fig. 4. Experimental values of the circumferential strain ε_t depending on the coating thickness *a*.

Using the hole-drilling method, residual stresses were calculated from measured relaxed strains using the specialized computer program *H-DRILL* [10] for the case of a blind hole assuming that residual stresses are distributed uniformly throughout coating thickness and are equal in two directions (plane state of stresses).

When E_2=112 GPa and μ_2=0.22 residual stresses, obtained by the hole-drilling technique, at a hole depth of 0.2 mm and a hole diameter of 1.9 mm, fluctuated to a great extent and ranged from tensile stress of 8 N/mm^2 to compressive stress of 73 N/mm^2. The mean value was σ = 35.3 N/mm^2 (compressive stress).

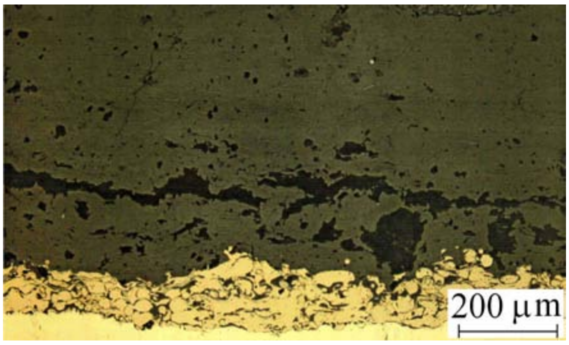
In our opinion, the good agreement of the results obtained with two different methods is random. The relatively large deviation of the results can be explained by the relatively small number of experiments and the anisotropy of the coatings (see the micrograph of cross section in Fig.5a). Nevertheless, the results indicate that both methods are applicable and the obtained results are comparable.

The other experiment was carried out with a brush-plated thick chrome coating. Brush-plating (selective plating, contact plating, swab plating), which is known as a slow method, applied primarily in cases where the areas to be coated are small and somewhat unique [11].

The coating was electroplated from a commercial Selectrons LDT-Chromium (neutral) SPS 5150 Solution (Chromium (III) compounds <6%, Ammonium Hydroxide <15%, Water <79%) onto a thick steel plate 25×45×10 mm. The coated surface was prepared according to the recommendations of technical data sheet and plated at a mean current density of 1.15 A/cm^2, at a mean temperature of T = 30 °C. The desired coating thickness 0.2 mm was estimated from the plating current. Three strain gauge rosettes were installed onto the coating, and holes with a diameter of 1.8 mm were drilled to a depth of 0.2 mm. The calculated mean value of residual stress was 336 N/mm^2, when the modulus of elasticity E_2 = 248 GPa and the Poisson's ratio μ_2=0.31 [12]. Residual stresses varied from 248 N/mm^2 to 405 N/mm^2.

The cross-section of the chrome coating is shown in Fig. 5. The brush-plated coating has a fine crystalline structure which is caused by the high deposition current.

a



b

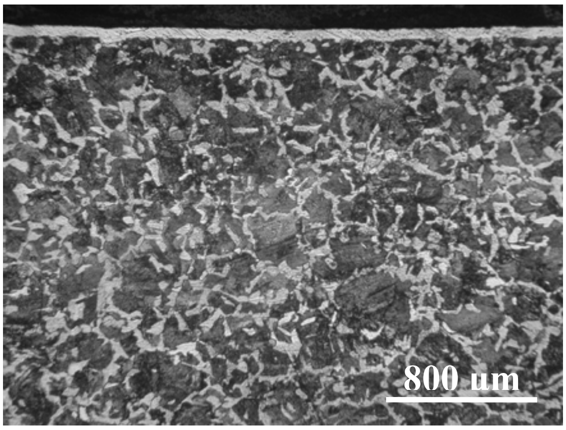


Fig. 5. Micrographs of the cross-section of coatings: (a) flame-sprayed coating on bondcoat (PT-19N-01); (b) brush-plated chromium coating.

According to literature data [13], residual stresses in thin (14 µm) chrome coatings electrodeposited from a bath of standard electrolyte, at a current density of 30 A/dm^2, and at temperatures of T = 55 °C and T = 70 °C, on one side of a strip steel substrate, determined by the deformation method, varies from 310 N/mm^2 to 510 N/mm^2.

The results obtained by the hole-drilling and deformation methods are comparable.

The layer removing technique used for determination of residual stresses is a destructive indirect method. The hole-drilling method is semi-destructive and can sometimes be used directly for coated machine parts. Consequently, based on the present experiments, preferring the hole-drilling method for determination of residual stresses in technological coatings is justified.

4. CONCLUSIONS

Residual stresses were determined throughout the deformation of ring substrates cut from a tube coated with a flame-sprayed powder coating. Further, residual stresses in the coating were determined by layer removal techniques and their values were 34.9 N/mm^2 (compressive stress).

Residual stresses in a flame-sprayed powder coating, deposited on a plate substrate with fixed edges under the same conditions as in the case of deposition on ring substrates, were determined by hole-drilling. The obtained values of residual stresses were 35.3 N/mm^2 (compressive stress).

The values of residual stresses obtained by the two methods are comparable. In the case of relatively thick coatings the hole-drilling method is preferable to the time- and labour consuming layer removing method.

Residual stresses were determined by the hole-drilling method in a brush plated chromium coating deposited on a thick steel plate. Their mean value was 336 N/mm^2 (tensile stress), which is comparable to the value of residual stresses in a chromium coating deposited from a bath of standard electrolyte on one side of a strip substrate and obtained by the deformation method.

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6. ADDITIONAL DATA

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