PAPER • **OPEN ACCESS**

Determination of residual stresses in multi-layer plasma coatings

To cite this article: V I Bogdanovich and M G Giorbelidze 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **511** 012005

IOP Conf. Series: Materials Science and Engineering **511** (2019) 012005 doi:10.1088/1757-899X/511/1/012005

Determination of residual stresses in multi-layer plasma coatings

V I Bogdanovich and M G Giorbelidze

Samara National Research University, 34, Moskovskoe Highway, Samara, 443086, Russian Federation

E-mail: bogdanovich@ssau.ru, m.giorbelidze@ssau.ru

Abstract. Method of determination of residual stresses in multi-layer coatings produced by plasma gas-thermal deposition is suggested. Residual stresses in a three-layer plasma coating Ni60Cr15 – NiCr80-20 + CaF_2 are determined. Evaluation of power effect of the plasma arc on the residual stresses distribution pattern in the coating, the sublayer, and the substrate is carried out.

1. Introduction

Residual stresses are among the primary reasons of destruction of plasma gas-thermal coatings. As a result, there are a lot of papers dealing with this problem, and the papers [1-18] should be distinguished. Nature of residual stresses development along with a number of reasons causing them constitutes some difficulties in modelling of these processes.

During plasma coating formation, powder material particles heated up to the melting temperature and accelerated by the stream, hit the part surface, and they are deformed on the surface. After crystallization of the melted particles, microscopic stresses balanced in the micro-volume of the whole particle material originate on the surface. According to the experience [1-3], adhesion and cohesive strength is not determined by the particle material strength, but by the attraction strength between the adjacent particles. Taking into account the fact, that the coating can consist of some layers of different materials, the macroscopic stresses attract the most interest. They are balanced in the volume that is essentially larger than the volume of a particle, and commensurable with the thickness of the whole coating or separate deposited layers. It allows to substitute modelling of microscopic stresses development process for modelling of macroscopic stresses development process and to consider them during the process of coating layer deposition.

2. Method of determination of residual stresses in multi-layer coatings

In some cases, necessity arises to determine residual stresses in multi-layer coatings. Using of well-known calculation methods in determination of residual stresses in multi-layer coatings for specific cases causes difficulties connected with cumbersome calculations. In this study, method of determination of residual stresses in multi-layer coatings produced by plasma gas-thermal deposition is suggested.

IOP Conf. Series: Materials Science and Engineering **511** (2019) 012005 doi:10.1088/1757-899X/511/1/012005

Let us consider the *N*-layer thin coating with thickness α_N with different moduli of elasticity E_i of layers, but with the same Poisson ratios μ_i. Let us assume that the layer of thickness η has been etched and further etching is taking place in the layer m. We apply stresses σ to the liberated surface (Figure 1) that existed in the etched layer of thickness η before its removal. Bending moment arises under these stresses, it can be determined from the following expression:

$$M(\eta) = -\int_{k-\eta-\delta(\eta)}^{h-\delta(\eta)} \sigma(z) z dz = \int_0^{\eta} \sigma(\xi)\left[\xi + \delta(\xi) - h\right] d\xi, \quad (1)$$

in this expression, transition to the variable ξ has been done according to the formula

$$\xi = h - \delta(\eta) - z;$$

$$\delta(\eta) = \frac{\int_0^{h-\eta} E(z_z) z_1 dz_1}{\int_0^{h-\eta} E(z_z) dz_1}.$$

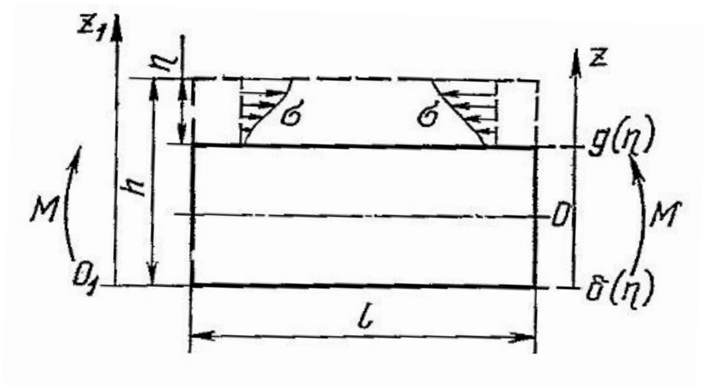

Figure 1. Scheme of determination of residual stresses after removal of the material of thickness η.

Bending moment $M(\eta)$ results in deflection (Figure 2) determined from the relation:

$$f(\eta) = \frac{l^2 M(\eta)}{2 I_E(\eta)}; \quad (2)$$

$$I_E(\eta) = \int_0^{h-\eta} E(z_1)\left[z_1 - \delta(\mu)\right]^2 dz_1,$$

where $I_E(\eta)$ – moment of inertia of the plate cross section in relation to its width.

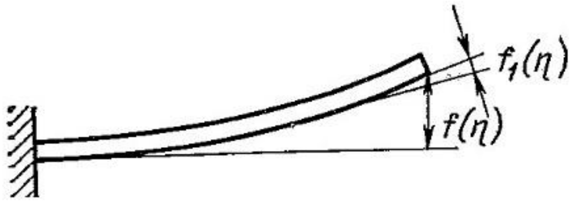

Figure 2. Scheme of deformation measurement.

IOP Conf. Series: Materials Science and Engineering **511** (2019) 012005 doi:10.1088/1757-899X/511/1/012005

Using (1-2), we get integral equation:

$$\frac{2f(\eta)I_E(\eta)}{l^2}=\int_0^{\eta}\sigma(\xi)\left[\xi+\delta(\eta)-h\right]d\xi\,. \tag{3}$$

Differentiating twice the equation (3) and taking into account that $\left[\dfrac{\eta+\delta(\eta)-h}{\delta'(\eta)}\right]'_{\eta}=-1$, we get

$$\frac{d\sigma}{d\eta}=\frac{2}{l^2}\frac{\left\{\dfrac{\left[f(\eta)I(\eta)\right]'_{\eta}}{\delta'(\eta)}\right\}'_{\eta}}{\dfrac{\eta+\delta(\eta)-h}{\delta'(\eta)}}\,. \tag{4}$$

Assume that etching is taking place in the layer m, i.e. $h-a_m<\eta<h-a_{m-1}$.

Integrating (4), we get

$$\sigma(\eta)=\sigma(h-a_m)+\frac{2}{l^2}\int_{h-a_m}^{\eta}\frac{\left\{\dfrac{\left[f(\xi)I_E(\xi)\right]'_{\xi}}{\delta'(\xi)}\right\}'_{\xi}}{\dfrac{\xi+\delta(\xi)-h}{\delta'(\xi)}}d\xi\,. \tag{5}$$

Taking the integral in parts twice in the equation (5) and determining $\sigma(h-a_m)$ after single differentiation of (3) we get

$$\sigma(\eta)=-\frac{2}{l^2}\left\{\frac{\left[f(\eta)I_E(\eta)\right]'_{\eta}}{\eta+\delta(\eta)-h}-f(\eta)I_E(\eta)\frac{\delta'(\eta)}{\left[\eta+\delta(\eta)-h\right]^2}-\right.$$
$$\left.-\int_{h-a_m}^{\eta}f(\xi)I_E(\xi)\frac{\delta'(\xi)}{\left[\xi+\delta(\xi)-h\right]^3}d\xi\right\}-$$
$$-\left[\frac{2}{l^2}f(\eta)I_E(\eta)\frac{\delta'(\eta)}{\left[\eta+\delta(\eta)-h\right]^2}+\frac{\delta'(\eta)}{\eta+\delta(\eta)-h}\int_0^{\eta}\sigma(\xi)d\xi\right]\Bigg|_{\eta=h-a_m}\,. \tag{6}$$

Formula (6) is right for a thin bar $\sigma=\sigma_x>>\sigma_y$. For an isotropic plate or a thin coating the derivation is the same, but the equation members from the first to the forth of the right part of the equation (6) are to be divided by $1-\mu$.

For the case $N=1$ equation (6) becomes (single layer plate):

$$\sigma(\eta)=-\frac{2}{l^2}\left\{\frac{\left[f(\eta)I_E(\eta)\right]'_{\eta}}{\eta+\delta(\eta)-h}-f(\eta)I_E(\eta)\frac{\delta'(\eta)}{\left[\eta+\delta(\eta)-h\right]^2}-\right.$$

$$-\int_{h}^{\eta} f(\xi) I_E(\xi) \frac{\delta'(\xi)}{\left[\xi+\delta(\xi)-h\right]^3} d\xi \Bigg\}. \tag{7}$$

For the case $N = 2$ when $h - a_1 < \eta \le h$ equation (6) becomes:

$$\sigma(\eta) = -\frac{2}{l^2} \left\{ \frac{\left[f(\eta) I_E(\eta)\right]'_\eta}{\eta+\delta(\eta)-h} - f(\eta) I_E(\eta) \frac{\delta'(\eta)}{\left[\eta+\delta(\eta)-h\right]^2} - \right.$$

$$\left. -\int_{h-a_1}^{\eta} f(\xi) I_E(\xi) \frac{\delta'(\xi)}{\left[\xi+\delta(\xi)-h\right]^3} d\xi \right\} -$$

$$-\left[\frac{2}{l^2} f(\eta) I_E(\eta) \frac{\delta'(\eta)}{\left[\eta+\delta(\eta)-h\right]^2} + \frac{\delta'(\eta)}{\eta+\delta(\eta)-h} \int_0^{\eta} \sigma(\xi) d\xi \right]_{\eta=h-a_1}. \tag{8}$$

3. Results and discussion

This procedure has been used to determine residual stresses in the deposited layer NiCr80-20 + CaF_2 and the sublayer NiCr80-20 (Figure 3). Streaks of heat-resistant alloy 80 x 10 x 3 mm were used as substrate-samples. Deposition was carried by argon-hydrogen plasma at modernized installation UPU-8M using portable plasmatron of own design. Argon consumption was 3 m^3/h, hydrogen consumption 0.45 m^3/h, deposition distance 100 mm, rate of the burner travel 0.1 m/s, scanning pitch 7.5 mm. Before deposition, the samples were sand blasted.

When determining residual stresses, sample's deflection was measured during continuous electropolishing. For uniform electropolishing, special etchant, a cathode made of stainless steel, a barretter for keeping direct current, an automatic mixer for balancing of etching temperature, and special oil for impregnation of porous samples were used.

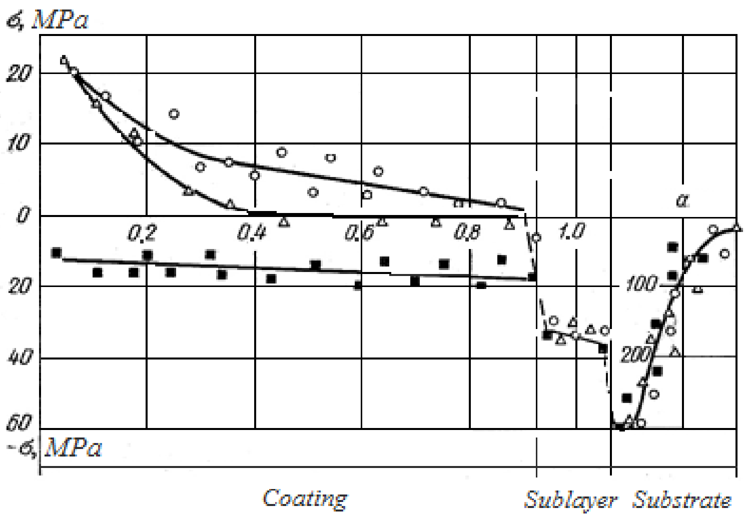

Figure 3. Distribution of residual stresses in the deposited layer, the sublayer and the substrate under the arc current: ■ 265 A; Δ 400A; ○ 535 A; – – – residual stresses in the transitional layers coating-sublayer, sublayer - substrate.

4. Conclusions

Performed work has allowed to develop method of determination of residual stresses in multi-layer plates, to determine residual stresses in three-layer plasma coatings, and to evaluate effect of plasma arc power on the distribution pattern in the coating, the sublayer, and the substrate. Study results of residual stresses are shown in the Figure 3.

Acknowledgments

The reported study was funded by the Ministry of Education and Science of the Russian Federation according to the research project No.11.2744.2017.

References

[1] Barvinok V A 2005 *Plasma in Technology: Reliability and Resource* (Moscow: Nauka i technologii Publishers)
[2] Barvinok V A 1990 *Strained state and properties of plasma coatings control* (Moscow: Mashinostroyeniye)
[3] Bobrov G V, Ilin A A and Spektor V S 2014 *Theory and technology of inorganic coatings formation* (Moscow: Alfa-M)
[4] Bobrov G V and Ilyin A A 2004 *The Application of inorganic coatings* (Moscow: Intermet-Inzhiniring)
[5] Ilyushchenko A F, Shevtsov A I and Okovity V A 2011 *The processes and modeling of thermal spray coatings formation* (Minsk: Belarus nauka)
[6] Puzryakov A F 2003 *Theoretical bases of plasma spraying technology* (Moscow: Bauman University Publishers)
[7] Kudinov V V, Pekshev P Yu and Belashchenko V E 1990 *Plasma coating application* (Moscow: Nauka)
[8] Kravchenko I N, Puzryakov A F, Gladkov V Yu, Pankratova E V and Glinskih M A 2011 *Repair. Recovery. Modernization* **10** 6-11
[9] Bondareva G I 2011 *Bulletin of mechanical engineering* **9** 32-35
[10] Kartsev S V and Shirshov V S 2012 Engineering technology **5** 37-38
[11] Kravchenko I N, Moskal O Ya, Pankratova E V and Shiyan A V 2012 *Repair. Recovery. Modernization* **10** 44-50
[12] Pankratova E V, Kravchenko I N and Moskal O Ya 2012 *Repair. Recovery. Modernization* **11** 34-40
[13] Kravchenko I N, Kolomeychenko A V, Pupavtsev I E, Puzryakov A A and Solovev R Y 2017 *Welding International* **31(10)** 809-813
[14] Mutter M, Mauer G, Mücke R, Guillon O and Vaßen R 2017 *Surface and Coatings Technology* **318** 157-169
[15] Nayebpashaee N, Seyedein S H, Aboutalebi M R, Sarpoolaky H and Hadavi S M M 2016 *Surface and Coatings Technology* **291** 103-114
[16] Croom B P, Bumgardner C and Li X 2016 *Extreme Mechanics Letter* **7** 126-135
[17] Capek J, Pala Z and Kovarik O 2015 *IOP Conference Series: Materials Science and Engineering* **82(1)** 012112
[18] Yang L, Yang F, Long Y, Zhao X and Xiao P 2014 *Surface and Coatings Technology* **251** 98-105