The residual stress testing and service life forecasting to the remanufactured component surface coatings

Wang Hai-dou[a], Xu Bin-shi, Zhang Xian-cheng, JiangYi, Piao Zhong-yu, Pu Chun-huan
National Key Lab for Remanufacturing, Beijing, 100072, China
[a] e-mail: wanghaidou@tsinghua.org.cn

Abstract

The analytical models with closed-from solutions based on the force and moment balances were developed to predict the residual stresses in the multilayered coating-based systems and the systems with graded properties and compositions. $NiCr/Cr_2C_3$ wear-resistance coating, which is usually applied for remanufacturing, was sprayed by supersonic plasma spray technique. After relaxation of residual stresses of the thermal spraying coating by cutting, the residual stresses within the cutting side was measured by Moiré interferometry method, and the distribution along the coating thickness was gained. The results showed that residual stresses in the coating were tensile and residual stresses in the substrate were compressive, there was the concentration of residual stress near the interface between the coating and the substrate. The durability of supersonic plasma-sprayed $NiCr/Cr_2C_3$ coatings was evaluated by the rolling contact fatigue tests. The coupling relationship between the contact stress and fatigue life of plasma-sprayed coating was obtained.

Keywords: remanufacturing, surface coating, residual stress, life forecasting

1 Preface

Surface Engineering is today becoming an increasingly important discipline to industry where the performance and lifetime of both tools and products are sought to be improved and extended. For instance, coatings are commonly used in several industrial applications. Both soft and hard coatings can inhibit adhesion between the substrate and the counter face resulting in decreased wear, corrosion, etc.. Generally, the coating properties are strongly influenced by the deposition method and the selected deposition conditions. The following properties are of great interest for coatings: residual stresses, hardness, and plastic properties, elastic modulus, interfacial adhesion strength. The structural integrity technology has been widely used with great success for the design, manufacture and failure prevention of modern constructions such as chemical and petrochemical plants, power generation and energy conversion systems [1]. However, the researches on the structure integrity, especially the thermomechanical integrity are relatively few [2,3].

In this paper, the thermomechanical integrity of the coating-based systems with residual stresses was investigated. Different topics were involved, such as residual stress distribution and redistribution in a coating on a substrate, optimal designing methodologies on the basis of residual stress and structural design of crack and delamination resistances for coatings etc.

2 Error of Stoney's equation

The earliest description of the thermal stresses in a thin coating on a planar substrate was presented by Stoney [4],

$$\sigma_{\mathrm{St}} = -\frac{E_s' t_s^2}{6 t_c} K \qquad (1)$$

a ratio can be obtained,

$$R_{\mathrm{St}} = \frac{\bar{\sigma}_c}{\sigma_{\mathrm{St}}} = \frac{1+\Sigma\eta^3}{1+\eta} \qquad (2)$$

It can be seen that when $\eta \to 0$, $R_{\mathrm{St}} \to 1$. However, for the thick coating on a substrate, Stoney's equation should be corrected by a correction factor R_{St}. The error in using Stoney's equation can be defined as follows,

$$e_{\mathrm{St}} = \frac{\sigma_{\mathrm{St}} - \bar{\sigma}_c}{\bar{\sigma}_c} = \frac{\eta - \Sigma\eta^3}{1+\Sigma\eta^3} \qquad (3)$$

When $\eta \le 0.1$, Stoney's equation is applicable and the error is under 10%, while when $\eta > 0.1$ it is not applicable. When $\eta = 1.0$, the error is about 80% for the softer film (i.e. $\Sigma = 0.1$) and is 60% for the harder film (i.e. $\Sigma = 4.0$). However, when $\Sigma\eta \cong 1$, Stoney's equation again yields good results.

3 Bifurcation behavior for a coating system [5]

Coating systems are prone to deflect due to the presence of the residual stresses. Under sufficiently high magnitudes of stress or strain, coating systems may buckle. Under the equal biaxial stress state, with increasing the curvature sufficiently, a bifurcation point will be reached, at which the curvature increases sharply in one plane and decrease sharply in the plane normal to this. Generally, it is complex to predict the critical curvature K_B for bifurcation and the residual stress necessary to cause bifurcation, σ_B^*. For rectangular geometry, if $\nu_c = \nu_s = \nu$, the critical curvature for bifurcation, and the can be expressed as [6].

For rectangular geometry, if $\nu_c = \nu_s = \nu$, the critical curvature for bifurcation, and the can be expressed as [7]

$$K_B = K_0 \sqrt{12 \frac{2(1+\nu)\Gamma^2 + 5(1+\Gamma^4)}{(1+\nu)(\Sigma\eta+1)^2 \Gamma^4} \left[(\Sigma\eta^2 - 1)^2 + 4\Sigma\eta(1+\eta)^2 \right]} \qquad (4a)$$

$$\sigma_B^* = \pm \frac{E_c' K_B t_c}{6\eta\lambda(1+\eta)} \left(1 + 4\lambda\eta + 6\lambda\eta^2 + 4\lambda\eta^3 + \lambda^2\eta^4\right) - \frac{\nu E_c'}{1+\nu} \Delta\varepsilon \qquad (4b)$$

where $m = b/L$ is the ratio of the width to the length of the substrate, and $K_0 = \frac{t_s}{L^2}$. The critical curvature is dependent on the ratios λ, η, m, and K_0. With increasing m, the critical curvature is reduced. However, the critical curvature is insensitive to the ratios λ and η. When the specimen is narrow, the bifurcation instability will not occur in the specimen. Hence, narrow specimens are often used to measure the curvature along the strip.

If it is assumed that when the average stress in the coating is equal to the critical stress, σ_B^*, the bifurcation behavior occurs, submitting the expression of K, the relationship between σ_B^* and misfit strain $\Delta\varepsilon$ is clear, i.e.

$$\sigma_B^* = E_c'\left(\pm\frac{K_B}{K}\eta - \frac{v}{1+v}\right)\Delta\varepsilon \qquad (5)$$

In this case, when the dimensions and material properties of the substrate and coating are given, the critical misfit strain necessary to cause bifurcation, $\Delta\varepsilon_B$ as a function of width/length ratio of specimen with different ratios Σ and η can be determined, as shown in Fig. 1. It should be noted that only $\Delta\varepsilon_B > 0$ is considered in this paper. This case is important, because when $\Delta\varepsilon_B$ is positive, the resultant residual stress within coating is tensile. When $\Delta\varepsilon_B$ is known, the spraying parameters and the coating thickness can be adjusted to avoid the bifurcation of the coating specimen. With increasing the width/length ratio of specimen, $\Delta\varepsilon_B$ is reduced. While, the critical misfit strain is sensitive to the ratios Σ and η. When the width/length of specimen is given, decreasing the elastic modulus and increasing thickness of the coating can significantly increase the magnitude of $\Delta\varepsilon_B$.

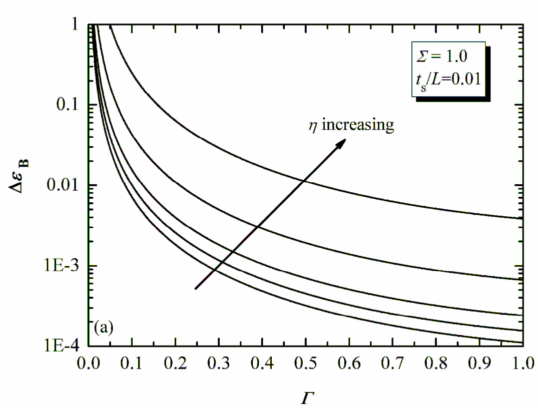

Fig. 1. Predicted relationship between the critical misfit strain causing a bifurcation instability and the specimen width/length ratio with (a) various coating/substrate thickness ratio, η=0.01, 0.05, 0.1, 0.2, 0.3

4 Improving adhesion

One should keep in mind that the average stress-free condition in the coating is not the ultimate criterion of achieving an optimized adhesion. Godoy *et al.* [8] adopt the criterion that the stress at the interface should be zero to improve the adhesion of a coating. In this paper, the criterion is also adopted and the average in-plane normal stress at the interface is given by

$$\frac{\sigma_{c|z=0} + \sigma_{s|z=0}}{2} = 0 \qquad (6)$$

the criterion can be obtained and expressed as

$$\Sigma^2\eta^5 - \Sigma(4\Sigma-1)\eta^4 - \Sigma(1+3\Sigma)\eta^3 + (\Sigma+3)\eta^2 - (\Sigma-4)\eta - 1 = 0 \qquad (7)$$

The relationship between the λ and η can be obtained to achieve an optimized adhesion of a coating, i.e.

$$\Sigma = -\frac{3\eta^2 + 4\eta - 1}{\eta^4 - 4\eta^3 - 3\eta^2} \quad \left(\frac{-2+\sqrt{7}}{3} < \eta < 2+\sqrt{7}\right) \qquad (8)$$

From the above tie-in equation, it can be seen that the correlation between the ratios λ and η should be considered to improve the adhesion of a coating, as seen in Fig. 2. Generally, the ratio Σ should be less than 1 to avoid the premature failure of the coatings. Hence, the criterion mentioned above are well suited the relatively thick coatings. For instance, when $\eta = 0.5$, a harder

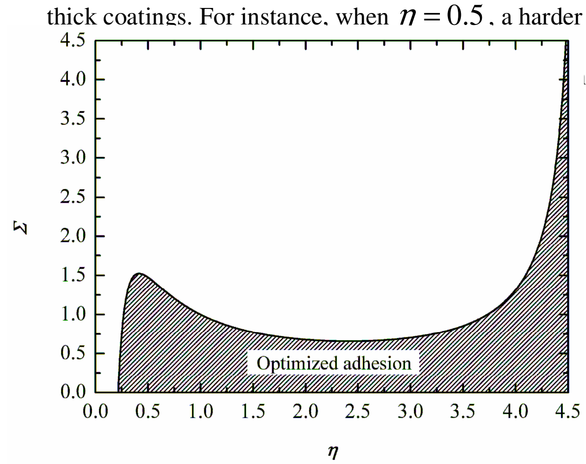

Fig. 2. Predicted relationship between the ratios Σ and η for improving the adhesion of a coating.

Acknowledgements

The paper is sponsored by 863 Project (2007AA04Z408), NSFC (50735006), 973 Project (2007CB607601) and the Foundation (9140C850103080C8510, 2006ZL26).

References

[1] S.T. Tu. High temperature structural integrity, Science press, 2003.

[2] A.G. Evans and J.W. Hutchinson, Thermo-mechanical integrity of thin films and multilayers. *Acta Metall.*, 1995; 43(7): 2507-2530.

[3] X.C. Zhang, B.S. Xu, H.D. Wang and Y. X. Wu, Thermo-mechanical integrity of coatings with residual stresses, in Proceedings of the Fracture Mechanics Symposium 2004, edited by G.C. Sih, S.T. Tu, and Z.D. Wang, Yellow Mountain, Anhui, P.R China, 2004, pp. 225-239.

[4] G.G. Stoney, The tension of metallic films deposited by electrolysis. *Proc. Roy. Soc. London*, 1909; A82: 172-175.

[5] X.C. Zhang, B.S. Xu, H.D. Wang and Y.X. Wu,Underlying mechanisms of the stress generation in surface coatings. *Surf. Coat. Technol.*, 201;15: 6715-6718.

[6] N. J. Salamon and C. B. Masters, Int. J. Solids Structures, 32 (1995) 473.

[7] N. J. Salamon and C. B. Masters, Int. J. Solids Structures, 32 (1995) 473.
[8] C. Godoy, E.A. Souza, M. M. Lima and J.C.A. Batista, Correlation between residual stresses and adhesion of plasma sprayed coatings: effects of a post-annealing treatment. Thin Solid Films, 2002; 420-421: 438-445.