Applied Mechanics and Materials Vol 470 (2014) pp 146-149 *Online: 2013-12-13*

doi:10.4028/www.scientific.net/AMM.470.146

Research on fracture behavior of a Cr coating/original steel substrate material under thermal fatigue loading

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Keywords: Crack density; Cr coating/original steel substrate system; Thermal fatigue loading.

Abstract. The facture behavior of a chromium (Cr) coating/ original steel substrate material was investigated in this work. The results presented in this work show the crack density of the Cr coating on the substrate increases with the increase of the thermal fatigue times, and the failure process and modes of the Cr coating /original steel substrate system can be described as follows: Firstly, the micro-cracks of the coating grew and interconnected as the thermal fatigue time increased. Secondly, the "pocket" cracking at the coating and the substrate interface occurred, and the main cracks of the coating formed. Finally, the spallation or (and) collapse of the coating occurred.

Introduction

Chromium coatings have been widely used on engineering parts and composites such as piston rings, work rolls and aircraft landing gear etc. due to their high hardness, excellent wear and corrosion resistance, high melting point and low coefficient of friction [1]. However, under the severe service conditions such as thermal fatigue loading, gas erosion and severe stressing, cracking is usually caused at the coating or the substrate/chromium interface, which will result in the spallation of the chromium coatings from the substrate [2, 3]. The spallation of the coating from the substrate means the failure of the coating-substrate system to a certain extent. In these severe service conditions, the thermal fatigue loading is often considered to be the dominating factor that causes the engineering parts or composites failure, and the fracture behaviors and failure mechanisms of coatings under this loading have been the subject of considerable research [4, 5]. However, the failure process and modes of this material system under thermal fatigue loading is still lacking. In this work, the fracture behaviors under thermal fatigue loading of a Cr coating on the original steel substrate system are investigated, and the failure process and modes of this material system are revealed and described.

Experimental procedure and results

The substrate material was 30CrNi2MoV (AISI 3034) steel (main chemical ingredients: 0.28C, 0.7Cr, 2.27Ni, 0.20 Mo, 0.21V, all in wt. %). The Cr coatings composed of low-contraction (LC) and high-contraction (HC) Cr were prepared by the commercial electroplating processing of the practical chromium-coated parts. The LC-Cr layer about 20μm thick was pre-deposited as an interlayer with the commercial plating bath of chromic acid (250 gl^{-1}) and sulfuric acid (2.5 gl^{-1}), at a temperature of 85 °C and a current density of 60 A/dm^2. The HC-Cr plate approximately 110μm thick was deposited

at a lower bath temperature and a lower current density. The dimension of the specimens is designed to be 6mm×5mm×5mm.

In this work, the number of specimens of the Cr coating / original steel substrate is 8. The representative optical microscope of the cross section of the specimen is shown in Fig.1.

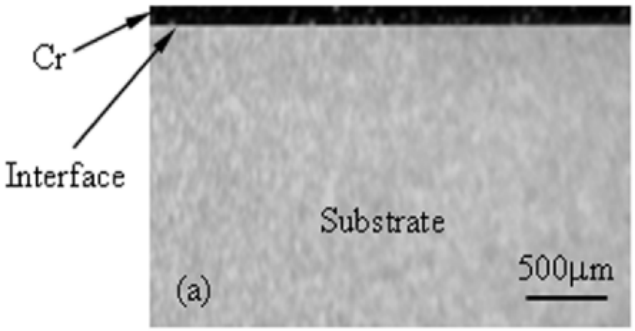

Fig. 1. The optical photo of the cross section of the Cr coating /original steel substrate

In this experiment, all the specimens were heated simultaneously in an electromagnetic oven at $650C^0$ with a heating rate of approximately $200C^0$/min. The experiment setup is shown in Fig.2. After the temperature of the specimens remained $650C^0$, they were quickly removed from the induction oven, and quenched with water at temperature of $12C^0$. The heated and quenched process repeated.

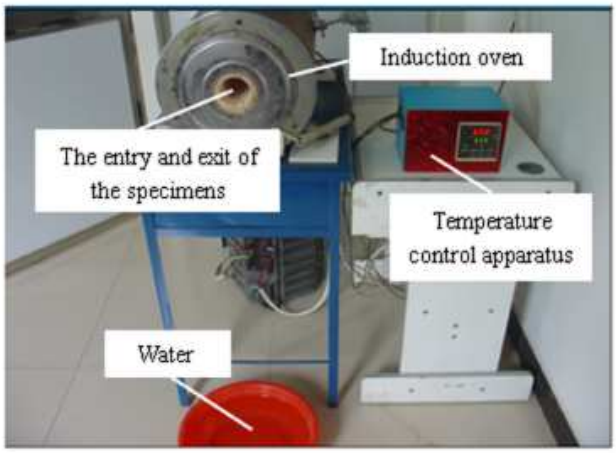

Fig. 2. The experiment setup.

Generally, failure in coatings is associated with the build-up of stress mainly due to the thermal expansion mismatch. During thermal cycling, when the specimens were taken out from the high temperature oven and quickly quenched in water, very large stress developed in the coating due to the difference of thermal expansion coefficients between the coating and the substrate, which can be given by the following expression:

$$\sigma_C = \frac{E_C \Delta\alpha}{1-\nu_C}\Delta T \tag{1}$$

Where σ_C is the stress developed in the coating, E_C and ν_C are Young's modulus and Poisson ratio of the coating respectively, $\Delta\alpha$ is the difference in coefficients of thermal expansion between the coating and the substrate, and ΔT is the change in temperatures.

After the thermal cycle times reached the designed number, the specimens were taken out. Then, they were mechanically ground and polished. The representative optical microscopes of the cross section of the specimens after 100, 200, 400, 650, 800, 1300 cycles are shown in Figs.3 (A), (B), (C), (D), (E), (F), respectively.

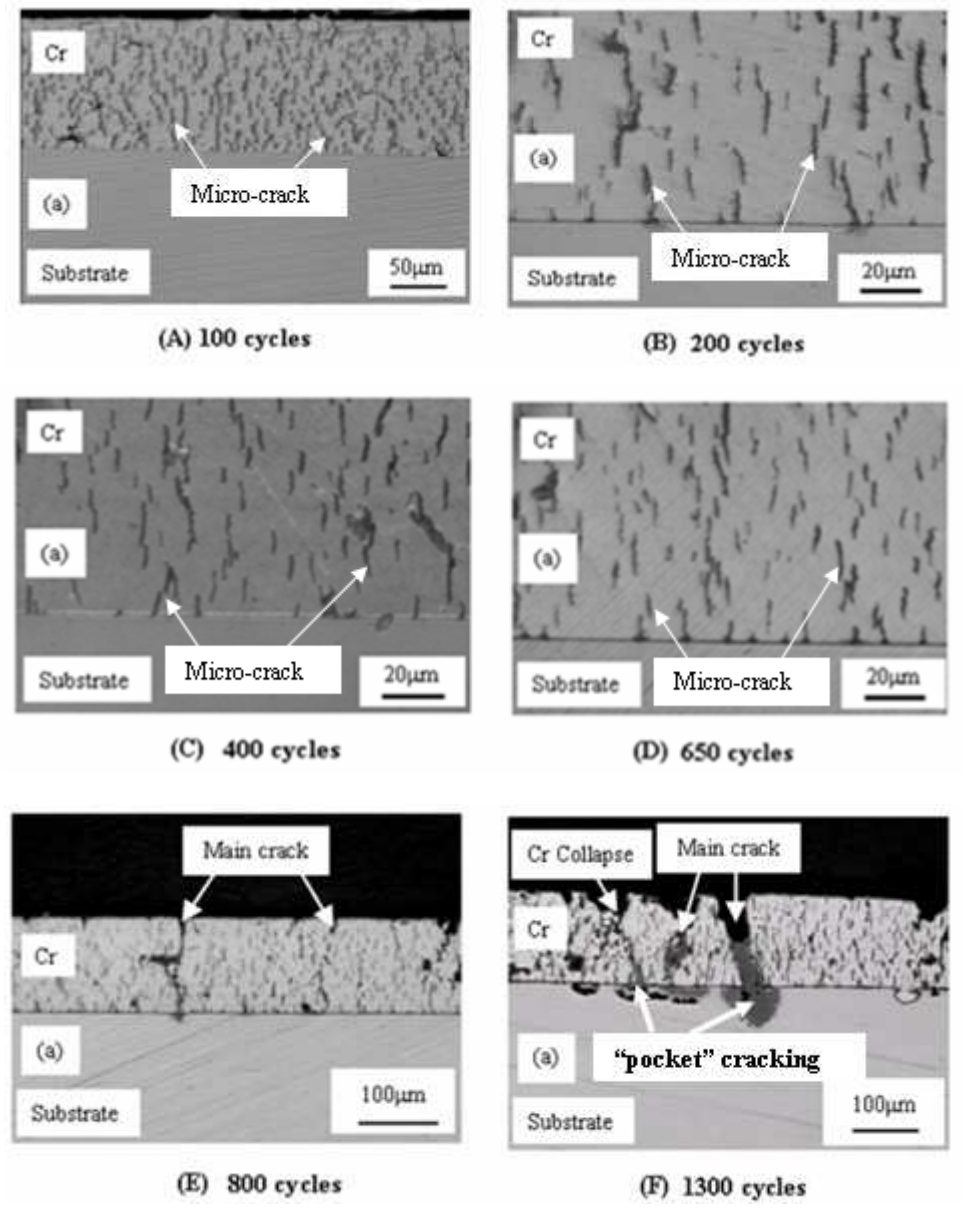

Fig. 3. The representative optical microscopes of the cross section of the specimens after 100, 200, 400, 650, 800, 1300 cycles shown in (A), (B), (C), (D), (E), (F), respectively.

Characterization of the crack density

The crack density is often defined as the number of the cracks per unit distance [6, 7]. It was found that the cracking of the coating initiated at critical strain, and then the number of the cracks of the coating per unit axial distance increased with the increase of the tensile strain [6, 7]. At another critical strain, the crack density (the number of the cracks) of the coating became saturated, i.e. the number of cracks per unit axial distance became a constant after this critical strain [6, 7]. Although the number of the cracks remained constant after the critical strain, the crack length or (and) width would increase with the increase of the tensile strain in order to accommodate the applied strain [6, 7]. So, a more suitable parameter to characterize the crack density should be presented. In this work, a novel parameter involving the number of the cracks, the crack length and the crack width for characterization of the crack density of the coating is presented as

$$\varepsilon_C = \frac{\sum_{i=1}^{N} L_{Ci} \times B_{Ci}}{A} \tag{2}$$

Where ε_C is the crack density of the coating, A is the area of the coating, N is the number of the cracks of the coating, L_{Ci} is the crack length, and B_{Ci} is the average crack width. All the parameters can be measured using the optical microscope.

The average crack density of the Cr coating corresponding to the thermal fatigue times is calculated from Eq. (2), and the variation law of the crack density vs. the thermal fatigue times is shown in Fig.4

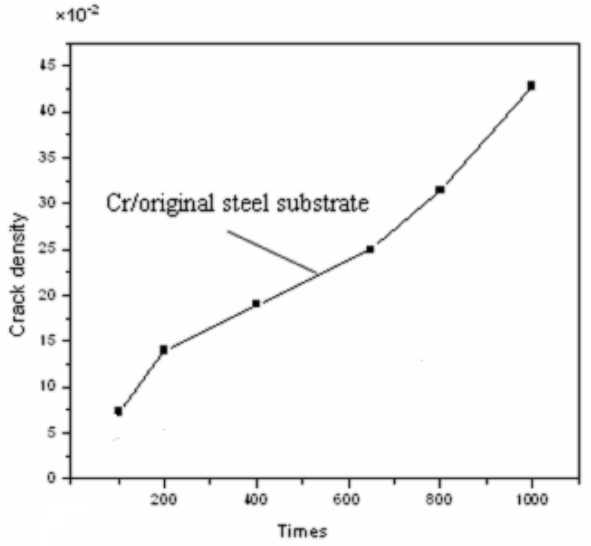

Fig.4. The variation of the crack density of the coating vs. the thermal fatigue times

Discussions and results

From Figs.3 (A-E), it can be seen that the failure process and modes of the coating can be described as follows: Firstly, the micro-cracks of the coatings grew and interconnected as the thermal fatigue time increased. Secondly, the "pocket" cracking at the coating and the substrate interface occurred, and the main cracks of the coating formed. Finally, the spallation or (and) collapse of the coating occurred. From Fig.4, it can be seen that the crack density of Cr coating on the original steel substrate increases with increasing the thermal fatigue times.

Acknowledgements

The authors gratefully acknowledge the financial support of the Innovative Science Foundation of Academy of Armored Force Engineering (Grant No. 2011CJ025), the financial support of the National Natural Science Foundation of China (Grant No. 51171026, 51102283, 51075398).

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10.4028/www.scientific.net/AMM.470

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