Mechanics Research Communications 66 (2015) 27–33

Contents lists available at ScienceDirect

Mechanics Research Communications

journal homepage: www.elsevier.com/locate/mechrescom

Modeling segmentation cracking of a brittle coating due to underneath periodic eigenstrains

Xuejun Chen*, Xiuping Wang, Haiwen Wang

Department of Applied Mechanics, University of Science and Technology Beijing, 30 Xueyuan Road, Beijing 100083, China

ARTICLE INFO

Article history:
Received 28 August 2013
Received in revised form 19 March 2015
Accepted 29 March 2015
Available online 4 April 2015

Keywords:
Eigenstrain
Segmentation cracking
Dimensional analysis
Finite element method

ABSTRACT

The formation mechanism for a segmented Cr coating by the hybrid technique of laser pre-quenching steel substrate plus post-electroplating was investigated. The discrete laser quenched zones (LQZs) were modeled as multiple inclusions with prescribed eigenstrains. The stress field was determined to account for the onset of segmentation cracking. Also addressed was segmentation crack growth through the evaluation of the stress intensity factor (SIF). The computations were implemented by using the finite element (FE) method. The dependence of a wide range of dimensionless variables of interest on both the stress field and SIF was assessed through a detailed parametric study.

1. Introduction

In a broad area of technological application, protective coatings have been widely used to enhance a certain mechanical properties [1]. The coating-substrate material counterpart can fulfill lots of performance requirements (e.g. thermal, corrosion and wear resistance), which otherwise cannot be sufficiently met by homogeneous materials. However, depositing a coating onto a substrate means bonding dissimilar materials and thus may cause damage problems such as cracking and interfacial debonding [1–4]. The latter scenario, in most cases the consequence of the former, is believed to be most undesirable since it usually results in the final removal of coating [2,3].

The focus on retaining the integrity of the coating-substrate system has stimulated a large amount of research [1–7]. The purpose of these investigations primarily involved two aspects. One is to improve the resistance of crack growth (toughness of coating) and the other is to reduce the driving force for crack propagation. It is well known that there exists strain mismatch across the interface between the coating and substrate due to the differences in properties of individual material [1]. In efforts to alleviate this mismatch, various kinds of coating has been designed such as duplex coating, multilayer coating as well as functionally gradient coating [5–7]. Recently, in contrast to the above mentioned design idea of an intact coating, the segmented coating has been developed by different research groups to improve the durability of coating [8–15]. In this new concept design, multiple segmentation cracks were intentionally generated within the coating with penetration depth comparable to the coating thickness. Both experimental observations [13,14] and theoretical predictions [16,17] demonstrated that the segmented coating could withstand more thermal cycles prior to failure than the intact coating. Actually, attention has been paid to this beneficial effect of segmentation cracks in early 1980s by Ruckle [18], who observed the enhancement of thermal shock resistance to delamination for plasma sprayed TiC coatings. The similar effectiveness was also validated in pre-cracked Thermal Barrier Coatings (TBCs) [9–12], which was supposedly attributed to its better strain tolerance.

Recently a segmented Cr coating has been formed with the combined aid of laser pre-quenching treatment and post-electroplating [8,13,14,15]. With this hybrid technique applied, the 30CrNi2MoVA alloy steel substrate was at first pre-quenched by Nd:YAG laser irradiation in a discrete manner. Then the Cr coating was deposited onto the discrete quenched steel substrate via conventional electroplating. Fig. 1a [15] shows the micrograph of the cross-section of an as-deposited Cr coating-steel substrate system, where individual laser quenched zone (LQZ) is indicated in a crescent shape. The LQZs are well known to experience phase transformation and maintain a majority of martensitic phases. It should be noted that both the size and spacing of the formed LQZs can be controlled by adjusting the hybrid processing parameters. The details of chemical composition of substrate material, the conditions for both Cr electroplating and laser quenching can be found in Ref. [13]. Interestingly, when the as-deposited specimen undergoes the required

* Corresponding author. Tel.: +86 10 62332901.
E-mail address: chenxuejun@ustb.edu.cn (X. Chen).

http://dx.doi.org/10.1016/j.mechrescom.2015.03.010

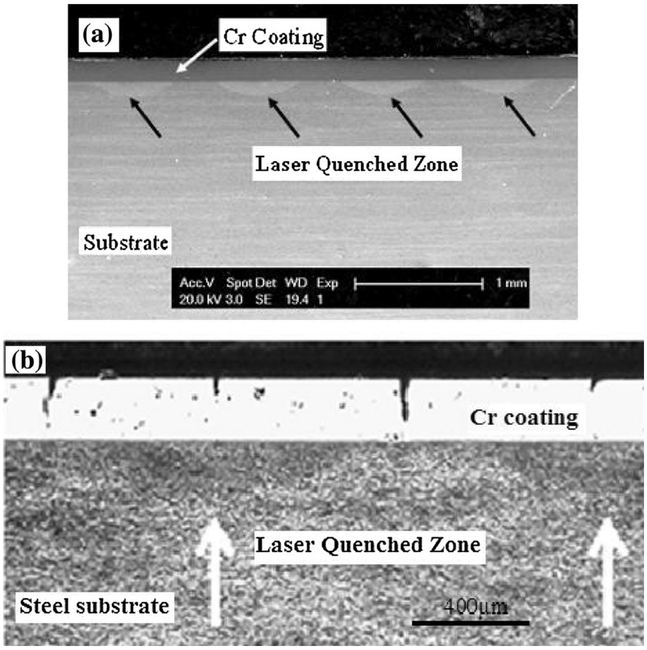

Fig. 1. The profile of: (a) Cr-steel system processed by the hybrid technique of laser pre-quenching substrate plus post-electroplating and (b) a typical segmented coating in which the dark black LQZs are marked by the white arrows [15].

tempering at about 400 °C for dehydrogenation, the cracking of Cr coating is observed to take place mostly at fixed locations, i.e., the central cross-sections between two adjacent LQZs. A periodic array of such cracks result in the formation of a segmented coating, a typical example of which is illustrated in Fig. 1b [15]. In characterizing the multiple segmentation cracks, the crack density is commonly used, which is referred to as the number of cracks per unit length in the longitudinal direction [11,12,16,17]. In this sense, the segmentation cracks with narrower spacing are of higher density.

Motivated by the favorable effect of a segmented coating, we try in this work to understand the formation mechanism for such periodic segmentation cracks based on the above experimental results. Section 2 is devoted to establishing the computational model with the effect of LQZs taken into account. The FE solution procedure is also detailed herein. Section 3 has identified the main dimensionless quantities affecting the stress field and SIF by using dimensional analysis. In Section 4, the numerical results for the stress field and SIF are obtained in graphical forms and sensitivity analysis is carried out to illustrate the effects of various dimensionless parameters on both of them. Finally, main conclusions from the present investigation are drawn in Section 5.

2. Computational model

The geometry to be considered is an as-deposited coating-substrate system as illustrated in Fig. 2. The coating layer #2 of thickness h is perfectly bonded to the substrate layer #1 of infinite thickness and both layers extend infinitely in the horizontal direction. An array of LQZs is assumed to be uniformly distributed with a spacing l and each profile is approximated by a hatched semicircle of radius r. The material of each layer is assumed to be homogeneous, isotropic, and linear-elastic, for which Hooke's law is valid. The Young's modulus and Poisson's ratio are denoted by the symbols E_i and μ_i, with the subscripts $i = 1, 2$ referring to the substrate and coating, respectively. The LQZs are modeled as inclusions [19], whose elasticity constants are considered to be the same as those of unquenched substrate. Periodicity can be invoked for analyzing the coating-substrate configuration. Thus we only need to consider

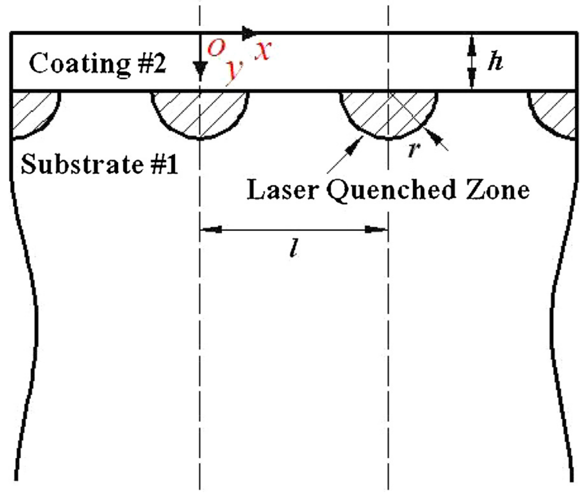

Fig. 2. Model schematic of an as-deposited coating-substrate system.

a typical section as shown in Fig. 3a, which is extracted from the region between the dashed lines in Fig. 2 and is repeated periodically. Herein, the rectangular coordinate system is chosen such that the x-axis coincides with the surface of coating and y-axis vertically downward along the left edge.

Upon being tempered, the LQZs will experience volumetric shrinkage, the degree of which depends on many factors, for example, carbon content, temperature, etc. As a first approximation, it is equivalent to an overall negative eigenstrain embedded into each LQZ, which is denoted here as a uniform eigenstrain ε_0. Due to constraints imposed by both the surrounding unquenched substrate and coating, the appearance of such eigenstrain will certainly generate a particular stress field in the system of coating and substrate and hence cause the initiation of segmentation cracks. It should be noted that other initial stresses, such as those developed during pre-quenching and subsequent coating electroplating, are neglected in this work. In order to investigate the driving force for the segmentation cracking, modeled in Fig. 3b is an edge crack of depth h_c, which is situated at the central cross-sections between two adjacent LQZs. Our analysis is limited to segmentation cracking behavior within the coating, thus the crack depth of interest only covers the range $0 < h_c < h$.

For simplicity, the coating-substrate system in question is modeled as a plane strain problem within the paper plane. At the same time, it is dealt with as a quasi-static problem without taking inertial effect into account. We solve such a complex boundary value problem via FEM through commercial package ANSYS [20]. As for finite element model, the thickness of substrate d is chosen to be $d \gg h$ ($d = 30\,h$). Eight-node solid plane strain elements are used and the symmetrical boundary condition is exerted on both sides of the typical section (see Fig. 3). Careful element meshing is necessary to assure a reasonable aspect ratio of the elements, and in particular, element refinements should be done in the vicinity of the crack tip. Since segmentation cracks are situated at the central cross-sections between two adjacent LQZs, the fracture behavior is in pure mode I due to symmetry. In order to pick up the square root singularity nature of the crack-tip strain field with high accuracy, the quarter points and singular elements are adopted near the crack tip. The SIF, K_I, is extracted from the FE solution of displacement of the quarter point as [21]

$$K_I = \frac{E^* u_x^q}{4} \sqrt{\frac{2\pi}{r_q}}, \qquad (1)$$