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Quantitative evaluation of bonding strength for hard coatings by interfacial fatigue strength under cyclic indentation

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ABSTRACT

The adhesion of coating to substrate is an important factor governing the performance and durability of coated engineering components. Existing evaluation methods cannot produce quantitative measurement of bonding strength for strong adherent coating. This paper proposes a novel evaluation method based on the cyclic spherical indentation (CSI) test, which uses successive indentations of a spherical ball onto a coated specimen to induce the detachment of the coatings along the interface. Compared with earlier methods, this method creates only adhesive failures, which only occur during elastic deformation of the substrate, yet it is applicable to coating with strong bonding. The evaluation method creates a curve of shear stress range versus failure cycles for each coating/substrate system. These curves can be used directly to compare the bonding strength of hard coatings.

1. Introduction

Hard coatings are used increasingly in a wide range of mechanical applications to improve the surface properties and increase the components' endurance life. However, the expected performance of the coated products can only be achieved if the adhesion of the coating to the substrate is sufficient, especially for those serving under the harsh conditions. Therefore, it is important to develop a reliable and effective technique for bonding strength measurement besides the bench test.

Many techniques have been developed to characterize the materials response to contact. To use these methods for quantitative adhesion measurement, it is essential that the measurement is focused on only adhesive failure modes [1–3], but unfortunately this cannot be achieved by many of the existing tests. The single indentation method and scratch methods [4,5] create many different failure modes. In addition, the critical load in scratch test is influenced by many intrinsic and extrinsic factors in addition to the adhesion of the coating [6]. Although Finite element method (FEM) can be used to assist various testing methods to help reduce other failure modes, these other failure modes cannot be eliminated [7–13].

The repeated impact method produces fatigue damage, which is close to service conditions. However, it still creates many failure modes, making it hard to quantitatively measure adhesion failure [14,15].

The rolling contact fatigue (RCF) method produces only adhesive failure, and the deformation is elastic, allowing quantitative evaluation [16–19]. One disadvantage of this method is that the maximum stress occurs deep in the substrate so that it is difficult to create large shear stress at coating interface. The restriction to elastic deformation constrains the stress to be small, so that for strong bonding the adhesive failure may not be observable even at the upper limit of number cycles [20].

The contact fatigue method measures fatigue damage through spherical indentation. Like the rolling contact fatigue method, the maximum stress occurs deep in the substrate so that it is difficult to create large shear stress at coating interface. In addition, it produces many other failure modes besides adhesive failure [21].

The cyclic spherical indentation (CSI) method is a variation of contact fatigue method with indenters of much small radius and much higher elastic modulus [22]. The maximum shear stress occurs close to coating interface. This method is capable of producing pure adhesive failure even for strong bonding [22].

In this paper we further demonstrate that CSI creates adhesive failure through elastic deformation. Consequently, the stress responsible for the failure can be accurately obtained. This creates a robust quantitative method for measuring bonding strength for strong bonding.

In Section 2 we highlight our finding for CSI that is essential for the quantitative evaluation method, followed by a description of the

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method. Section 3 describes in detail our experimental setup and findings. Section 4 presents further discussions of properties of the proposed evaluation method.

2. Quantitative measurement of adhesion

In a previous paper [22], we described the CSI method of measuring coating adhesion. The experimental method involves making cyclic indentations on the coated substrate until coating starts to detach. The adhesion is characterized by the curve of load versus number of indentation cycles required to produce start of detachment. In this section, we describe how this can be turned into a method to quantitatively characterize the bonding strength through a stress-cycle curve.

One of the main difficulties of making quantitative measurements in the previous methods is that, in addition to adhesive failures, many other failure modes are produced. Our experiments show that CSI only produce adhesive failures (Subsection 3.2).

Another main difficulty for the existing methods is that the failure occurs with plastic deformations, making it hard to measure and calculate corresponding stress. We observe that with CSI the deformation becomes elastic after only a few cycles of indentation (Subsection 3.4). Combined with earlier observation [22] that for sufficiently low load, the detachment only happens after great number of cycles, it becomes clear that the detachment of the coating only happens when the contact is elastic. This makes it possible to calculate accurately the stress responsible for the detachment.

Experiments show that only the shear stress component is responsible for the detachment (Subsection 3.5), and furthermore it is the stress range, not the maximum stress, that is responsible for the coating detachment (Subsection 3.6). Therefore the bonding strength of coating can be characterized by the shear stress range of each indentation cycle versus the number of indentation cycles required to produce first detachment.

The procedure for quantitative measurement of the bonding strength that we are developing involves a test step that determines the number of cycles required to produce coating detachment under a certain load, and a calculation step to determine the shear stress range produced by the load at the elastic contact.

The test step is the same as in [22] and has been described in detail there. A brief description is as follows: Choose a certain load and that is a few times smaller than that used in the single indentation experiments. The percentage of load is also chosen for unloading to avoid impact. Obtain the number of indentation cycles required to observe under microscope the start of coating detachment. Usually, a number of iterations are required to pinpoint the number of cycles. This dependency of number of cycles on the load was used previously [22] as a means of qualitative characterization. We now add a further calculation procedure to determine the shear stress.

The calculation step makes use of finite element analysis software that is capable of calculating the evolution of the stress and deformation

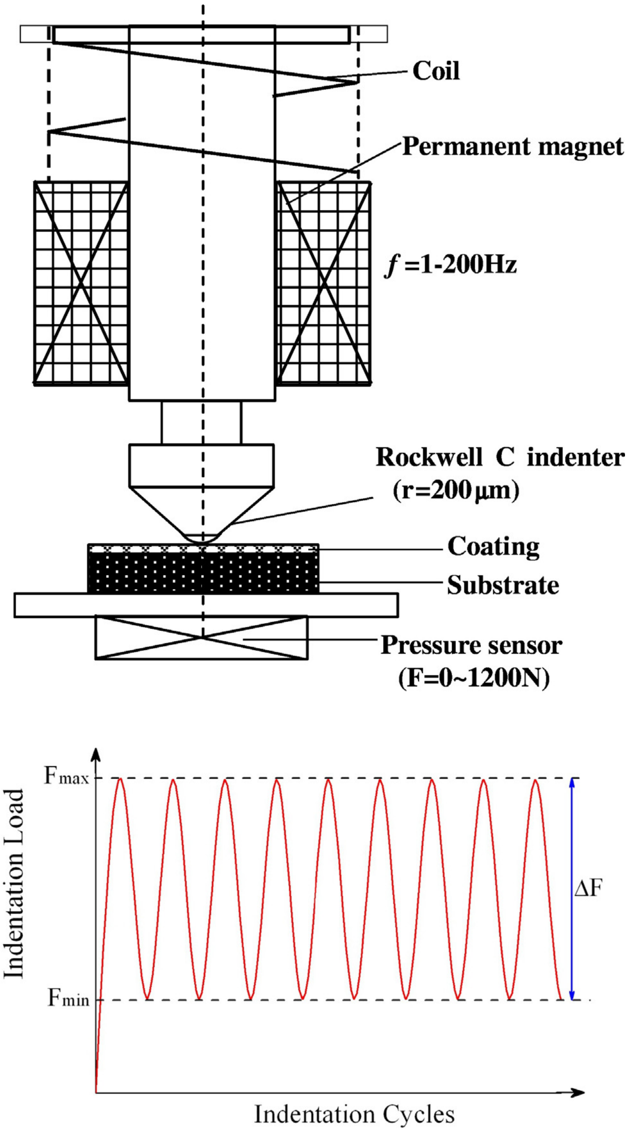

Fig. 1. Sketch of the cyclic spherical indentation tester and the fluctuating load on coating.

under cyclic indentation. We will need the following parameters to describe the coating/substrate model:

Elastic modulus and Poisson's ratio of coating
True stress-strain curve of the substrate material
Thickness of the coating and diameter of indenter
The elastic property of the indenter (considered as rigid in our case)
Number of cycles to calculate

Table 1
Characteristics of the tested coatings.

No.	Coating	Preparation of interface	Thickness/μm	Hardness/GPa	L_c/N	P_c/N
A	TiN	GD (20 min) + Ti (10 min)	1.6	24.5 ± 0.5	>100	>1000
B	TiN	GD (20 min) + Ti (10 min)	3.7	24.7 ± 0.4	>100	>1000
C	TiN	GD (10 min) + Ti (5 min)	3.7	23.8 ± 0.8	90	1000
D	TiN	GD (5 min) + Ti (0 min)	3.7	24.0 ± 0.7	30	400
E	TiN	GD (10 min) + Ti (5 min)	5.8	24.2 ± 0.7	>100	>1000

P_c: critical load that coating delaminates by indentation test.
L_c: critical load that coating delaminates by scratch test.
GD: time for glow discharge cleaning.
Ti: deposition time for Ti interlayer.