EFFECT OF SLIDING AND HAMMERING CONTACT FOR CRACK GENERATION AND FRACTURE TOUGHNESS IN SCRATCH TEST

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Received: 2 August 2019; Accepted for publication: 13 January 2020

Abstract. Scratch test is one of widely used, fast, and effective methods to obtain the critical loads that are related to adhesion properties of coating. The contact situation in a scratch tester is the combination of the hammering and sliding contact. Due to the increasing load of the stylus over an elastic-plastic zone, the surface defect will occur and lead to the creation of some first visible angular cracks in the coating. As a result, this phenomenon will affect to the crack generation and failure mechanism. A three-dimensional finite element model (FEM) for describing the stress-strain behavior under stylus loading was built to illustrate the effect of contact forces for the fracture mechanism.

Keywords: scratch test, coating layer, fracture mechanism, elasto-plastic behavior, Abaqus.

Classification numbers: 2.5.3, 2.10.1, 5.4.6.

1. INTRODUCTION

In recent years, surface coatings have attracted a lot of research regarding the material surface quality control. The scratch test is the tribological contact test which include the effect of hammering and sliding with two surfaces loading again each other in relative motion. This phenomenon consists a very complex system link to the contact behavior between the stylus and coating surface of the test sample. During the test, the interaction of stylus and coated surface show solid relation with the test condition which can be used to describe the friction and wear behavior in coated tribology [1].

Coating materials such as TiN, TiC, Al₂O₃ and more recently diamond, diamond like carbon (DLC) and MoS₂ and their combinations as multilayers and dopants have been used with great success [2]. In the best cases, these very thin coating has decreased the coefficient of friction and wear rate by one or two orders of magnitude [2]. A tribological contact with two loaded surfaces in relative motion was carried out at macrolevel, the component level [2]. One problem is that even the parameters used to describe friction and wear behavior in coated tribological contact are not clear due to the dynamic effect. However, the mechanism of the coated surface, which will lead to failure or fracture performance is more certain.
Therefore, this study focusses on studying the mechanism of changing surface quality during the test by using finite element method. A 3D FEM model has been developed using Abaqus/Explicit for investigating the stress-strain illustration during the force applying procedure under dynamic effect. The model will combine two kind of load: hammering and sliding to check the effect of contact with the coated surface and discuss the related tribological mechanisms.

2. MATERIALS AND METHODS

2.1. Scratch test model

The scratch test was first suggested for coating adhesion measurements by Perry, Steinmann and Hintermann and Valli [1]. The method is today widely used by the coating industry and coating development laboratories, as well as in research for evaluating the tribological properties of coatings. There are two main components of the scratch test: pulling diamond stylus over the coated sample surface.

![Figure 1. Model of scratch test.](image)

The loading and response condition of the material have been divided into three phases to illustrate the involved contact and deformation mechanism [3]. The material loading and response can be divided into three phases: ploughing, interface sliding and pulling a free-standing coating is showed in Figure 2. The deformation mechanism of surface cracks can be classified into five kinds: angular cracks, parallel cracks, transverse semi-circular cracks, coating chipping, coating spalling, and coating breakthrough as shown in Figure 3 [2].

When the diamond stylus sliding over the surface of the test sample with the increasing vertical load, there will be the stress concentration field at the contact position [3]. As a result, it will slowly lead to the formation of cracks in the coating surface [2]. The crack formation also consists of angular cracks, parallel cracks, transverse semi-circular crack, coating chipping, coating spalling and coating breakthrough [4].
Figure 2. Schematic illustration of the stylus drawn along the coated sample. The material loading and response can be divided into three phases: ploughing, interface sliding and pulling a free-standing coating.

Figure 3. The surface cracks generated in a scratch test track can be classified as (a) angular cracks, (b) parallel cracks, (c) transverse semi-circular cracks, (d) coating chipping, (e) coating spalling, and (f) coating breakthrough.

2.2. FEM model for scratch test illustration

A three-dimensional finite element model was built to check and investigate the stress and strain stage in the coated TiN surface with the effect of elastic modulus 210 GPa, yield strength 3100 MPa, Poisson’s ratio 0.3 and the friction coefficient 0.1 during loading time, using elastic-perfectly-plasticity [5-7]. It requires a material constitutive model that can represent the complicated material response at large strains, and a modelling method that can comprehensively resolve several physics, i.e., tribology, material deformation and damage, indenter statics and dynamics [6-8]. A preload of 5 N was used and the maximum load was 50 N with 0.1 mm of scratch length. The model was built with Abaqus/Explicit, which include two parts: stylus and coated TiN object. For the stylus, because it has a higher Young’s modulus compare with the TiN object, so it was considered as a discrete rigid and the coated TiN is the deformable part. After analyzing the convergence behavior of the contact interactions of the model, the kinematic formulation was present the finite strain deformation description. The contact event was defined by choosing two interacted surfaces of two parts. The contact property includes both tangential behavior with penalty friction formulation using friction coefficient 0.1 and normal behavior using hard contact [7]. Furthermore, the contact formulation for the sliding effect was finite sliding due to large local deformations and the distance the tip travels during the experiment. For the element model, the TiN object using C3D8R – an 8-node linear brick, reduced integration, hourglass control [8]. The mesh size divide into two part depend on the contact position 0.0006 mm for the contact zone and global size is 0.001 mm [8]. 3D FEM model of scratch test is shown in Figure 4.
3. RESULTS AND DISCUSSION

3.1. Results

The analysis of the simulated scratches and the variation features of the hammering load
and sliding distance of the model and find out consequences of the coated surface [9]. The Fig. 5 and Fig. 6 are topographical stress-field maps where each color corresponds to a certain stress level range at the surface and at the intersection shown in the figure. The watch angel is similar to that in Fig. 2 but the spherical tip is invisible in order to display the stresses. The stress fields result in elastic and plastic deformations that change the surface’s shape. The stress distribution also shows the original of possible crack initiation and crack propagation in the coating surface.

During sliding contact time, with the increasing of stylus normal load, the conformal cracking the phenomenon which micro cracks form while coating try to conform the grooves, open away from the direction of the scratch. The Figures 7 and 8 show the change of the width and depth of the scratch during the contact.

**Figure 7.** The width of groove over sliding distance from FEM results.

During the increasing of sliding distance, the scratch’s width also increase due to the effect of surface pile-up. The normal force of stylus increases by the time and lead to the increasing of material piled-up The way that pile-up evolves during the course of sliding indentation strongly depends on relative amounts of elastic and plastic deformation. In this case the simulation result of plastic deformation shows the distribution of the pile-up material along the scratching distance, the volume increasing along with the depth of the stylus.

**Figure 8.** The depth of groove over sliding distance from FEM results.

In front of the stylus, there were also the material pile-up and at the back it was skin-in material. These two kind of material represent the stress at the sraactching surface. In Fig. 6, the
stress values show the continuous distribution of compressive stress and tensile stress occur at two side of the stylus: compressive in front of stylus and tensile for the opposite side. Finite element simulations revealed that pile-up and sink-in during sliding indentation of elastic–plastic materials depend on the relative amount of elastic and plastic deformation which is affected by the normal force of the stylus or sliding distance. The volume of Pile-up and Sink-in material correlate with relative amount of Compressive and Tensile Stress along the scratch distance.

For the coating definition, the angular crack result in a state of plastic deformation within the surface due to the high stress of elastic-perfectly-plastic model. The shape and angular variation of stresses result from the prevailing state of deformation, i.e. at locations of tensile stress minima the deformations attain their maximum values along with the von Mises stress. By observing the strain distribution on the coated surface, the crack density can be illustrated.

Cracking is modelled to occur within the applied first principal stress-field such that a field of specific length through coating cracks is formed with a given cracking density in the direction of the stylus movement. With the increasing of two factor: sliding distance and stylus load, the angular crack density also increases on the coated surface.

When the diamond stylus sliding over the surface of the test sample with the increasing vertical load, there will be the stress concentration field at the contact position. As a result, it will slowly lead to the formation of cracks in the coating surface. The crack formation also consists of angular cracks, parallel cracks, transverse semi-circular crack, coating chipping, coating spalling and coating breakthrough. At sufficient stress, cracks initiate preferentially at defect sites in the coating and/or coating-substrate interface. Propagation of such cracks lead to coating failure. In figure 6, the stress fields result in elastic and plastic deformations that change the surface’s shape. The stress distribution also shows the original of possible crack initiation and crack propagation in the coating surface. During sliding contact time, with the increasing of stylus normal load, the conformal cracking the phenomenon which micro cracks form while coating try to conform the grooves, open away from the direction of the scratch.

For the fracture toughness, the grooves can be considered as a factor to prove the effect of scratching. The density of the grooves appear on the surface along the scratch will stand for the fracture toughness of the material. More and more grooves will lead to the micro at the surface and reduce the fracture toughness of the material, especially the coating surface. As a result, the groove density can represent the surface quality and the fracture toughness. The fracture toughness of the coating will in future work be calculated more clearly.

It is interesting to compare the simulation result with the experimental results collected from the scratch test. The stress in Fig. 5 corresponds to the surface loading condition in the test. For the comparison, the results also compare with the references [3] and [10]. It is shown that the results and the shape are similar.

4. CONCLUSIONS

A FEM model for the scratch test contact system was created and applied to draw out the stresses and strains incorporating elastic and plastic behavior in a contact geometry of the scratch test. With increasing load, a new stress-field with a tetra-armed star shape grows around the contact area. At the tail arms, stress concentrations are amplified at 1–2 times the contact length from the edge of the contact at the border of the scratch groove. The magnitude of these stress concentrations is of the same level as within the contact area. After about 0.03 mm of sliding in the scratch test, a peak area of maximum principal stress is generated in the back-tail
region at the border of the scratch groove, creating the first visible angular cracks in the coating with this material-coating combination.

By observing the deformation and the plastic deformation distribution over contact area, the effect of two main factors in scratch test: sliding distance and hammering load of stylus to the surface quality was investigated. The coating procedure is the combination of hammering loading and sliding loading that will lead to the damage feature occur in the coated surface and form micro cracks along the direction of the scratch. As a result, the quality of coated surface will be reduced and occur defects which is the main reason for a lot of failure modes started from the outer surface of materials.

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