CHARACTERIZATION OF THE FRACTURE WORK FOR DUCTILE FILM UNDERGOING THE MICRO-SCRATCH*

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ABSTRACT: The interface adhesion strength (or interface toughness) of a thin film/substrate system is often assessed by the micro-scratch test. For a brittle film material, the interface adhesion strength is easily obtained through measuring the scratch driving forces. However, to measure the interface adhesion strength (or interface toughness) for a metal thin film material (the ductile material) by the micro-scratch test is very difficult, because intense plastic deformation is involved and the problem is a three-dimensional elastic-plastic one. In the present research, using a double-cohesive zone model, the failure characteristics of the thin film/substrate system can be described and further simulated. For a steady-state scratching process, a three-dimensional elastic-plastic finite element method based on the double cohesive zone model is developed and adopted, and the steady-state fracture work of the total system is calculated. The parameter relations between the horizontal driving forces (or energy release rate of the scratching process) and the separation strength of thin film/substrate interface, and the material shear strength, as well as the material parameters are developed. Furthermore, a scratch experiment for the Al/Si film/substrate system is carried out and the failure mechanisms are explored. Finally, the prediction results are applied to a scratch experiment for the Pt/NiO material system given in the literature.

KEY WORDS: micro-scratch test, ductile film, horizontal driving force, double cohesive zone model

1 INTRODUCTION

The micro-scratch test is an important experimental approach for determining the interfacial strength, toughness and adhesion properties for the thin film or coating layer on the substrate interface[1]. Its working principle can be described as follows. On the material or specimen surface along the vertical direction an indentation force is exerted and the indenter tip penetrates inside the material, then the indenter is moved in the horizontal and vertical directions simultaneously according to a fixed proportion. When the indenter tip moves near the film/substrate interface, a region of the thin film or coating layer near the indenter tip will be delaminated along the interface. Through measuring the driving forces, and the scratch depth, as well as the failure geometry, one may obtain the material properties of the thin film or coating layer.
or interface adhesion properties. According to usual experimental observations, there are two main kinds of failure in the scratch tests depending on the material property of the thin film or coating, whether ductile or brittle. One kind of failure can be described as for the ductile film case, a delaminated film strap is formed before the end of the scratch test and the delaminated film strap will be curved into a circular shape. The geometry of the delaminated area is near a rectangle groove shape. Another kind of failure is for a brittle film, a fan shaped damage zone is formed near the indenter tip, inside which the film will be pressed to break up into many small pieces and also delaminated from the substrate. In the present research, our attention will be focused on the metal film/ceramic (or brittle) substrate case. The ductile failure will be simulated and analyzed in detail. Furthermore, a micro-scratch experimental research for the Al/Si system, which is extensively used in the MEMS research area, will be carried out here. The prediction results will be compared with the experimental result of a metal thin film/ceramic substrate system.

On the research of the material surface properties and adhesion work and strength of thin film or coating layer along the substrate interface, many experimental researches based on the scratch methods have been carried out in the past decade. However, theoretical researches (or mechanics analyses) connected with the scratch experiments are very few. This is because any theoretical study must deal with the complicated failure geometry of the scratch test. It is obvious that a three-dimensional elastic-plastic deformation problem must be solved, and a robust theoretical model for describing the scratch failure behavior is needed. Most theoretical researches were based on a simple geometry of the scratch failure strap and a simple mechanical equilibrium to simulate the scratch failure behavior. However, it is difficult to use a simple model to describe the strong influence of plastic deformation on the micro-scratch behavior. It is well known that plastic deformation has a strong shielding effect on the interface cracking. So, in an elastic-plastic failure process, more energy is dissipated than in a pure elastic failure process. Therefore, it is important to develop a reasonable mechanical model for the scratch test simulation.

On the other hand, the failure characteristics of the scratch test for ductile thin film materials are somewhat similar with the thin film peeling problems. Therefore, in the micro-scratch test research, the analytical method for the thin film peeling problem is relevant. It is important to obtain a reasonable relation between the critical driving force and the parameters of the materials and scratch strap geometry.

In the present research, based on the three-dimensional character of failure strap, a new mechanical model describing the interface separation and the thin film shear failure, i.e., a double cohesive zone model will be presented. Using the new model, a relation between the scratch horizontal driving force and the parameters of the materials will be set up and used to predict the scratch work. Moreover, a micro-scratch experiment for the Al/Si film/substrate system, extensively used in the MEMS research area, will be carried out. The present prediction results will be applied to a scratch experiment for the Pt/NiO material system given in the literature, and both results will be compared.

2 FUNDAMENTAL DESCRIPTION AND SIMPLIFICATION

From failure characteristics in ductile film scratching, the scratch test process can be described by Fig.1(a). This process comprises two stages. The first stage is a normal