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Interface delamination study of diamond-coated carbide tools considering coating fractures

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ABSTRACT

Interface delimitation is one of the major failure modes of diamond-coated carbide tools in machining. On the other hand, diamond coatings are prone of cracking easily due to its brittleness, which may affect interface delaminations. To study any influence between the two failure modes, micro-scratch testing on diamond-coated carbide tools was conducted and finite element (FE) modeling was developed to simulate the scratching process. In scratch testing, normal and tangential forces as well as acoustic emission signals were recorded to detect coating delaminations and crack initiations. Scratched samples were also observed by optical microscopy to determine the corresponding critical load of delaminations and cracking initiations. In the FE scratch simulation, a cohesive-zone interface and the extended finite element method (XFEM) were applied to investigate delamination and coating fracture behaviors, respectively. The cohesive elements were based on a bilinear traction – separation model and XFEM was implemented to model cracking behavior in a diamond coating with a damage criterion of the maximum principal stress.

The major findings are summarized as follows. The coating fracture energy has a negligible effect on the critical load for interface delaminations, and similarly, the interface fracture energy has no effect on the critical load for coating cracking, indicating that the two failure modes are mostly uncoupled for the testing range in this study. From the experiments and simulations, it is estimated that the coating fracture energy of the samples tested in this research is in the range of 120 to 140 J/m^2, and the diamond-carbide interface fracture energy is from 77 to 192 J/m^2. Moreover, increasing the coating Young's modulus will increase the critical load for coating delaminations, but decrease the critical load of coating cracking.

1. Introduction

Hard coatings such as chemical vapor deposited (CVD) diamond films on tungsten carbide cutting tools (typically, cobalt cemented, noted as WC–Co) has attracted significant interest for advanced tooling in machining due to their high hardness and strength, low friction coefficient, chemical stability, etc. [1]. Much research has been devoted to studying the wear mechanism of CVD diamond coated tools. Oles et al. [2] reported that abrasive wear on the tool flank face is a common wear mechanism of CVD diamond coated tools. However, the life of CVD diamond-coated tools in machining is dominantly limited by coating interface delaminations [3] or coating fractures [4]. The major obstacle for cost-effective applications of CVD diamond-coated tools is the insufficient adhesion between the diamond coating and the carbide substrate, which results in coating delaminations during cutting. For CVD diamond-coated WC–Co tools, Polini [5] concluded that the presence of Co in carbide tools leads to a non-diamond carbon layer formation at the substrate surface, resulting in a weak interface adhesion. On the other hand, diamond is very brittle and coating cracking due to local fractures may induce catastrophic tool failures. Thus, it is desired to quantitatively characterize the interface adhesion of diamond-coated tools and further to know how coating fractures may affect interface delaminations.

Several experimental methods have been applied to examine the coating–substrate adhesion [6]. One of widely adopted techniques is scratch testing, which is a useful technique for obtaining comparative values of the adhesion strength for hard coatings on a compliant substrate [7]. Considering that the coating–substrate interface failure is adhesive, the adhesion strength is a measure when a critical load is reached at which the coating–substrate interface delaminates [8]. In addition, scratch testing may also be used to identify coating cracking. von Stebut et al. [9] observed that there is a clear correlation between high-energy acoustic emission (AE) pulses and coating cracking failures. Similarly, the same argument of the critical load for interface delaminations can be applied for coating cracking; i.e., the corresponding critical load when the cracking failure occurs could be a measurement of the coating fracture strength.

In scratch testing, a spherical indenter tip slides over a coating surface to cause a groove under an incremental normal load. The detailed

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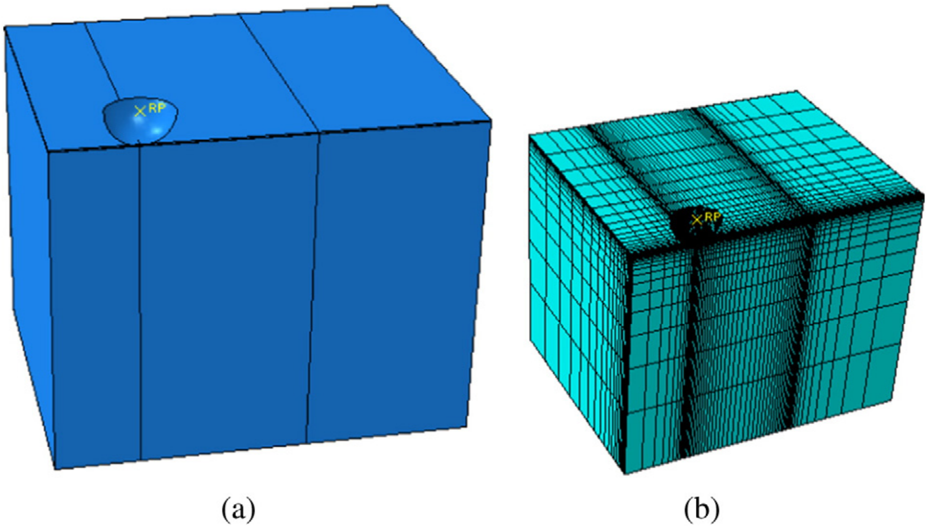

Fig. 1. (a) Assembly of coating, substrate, and indenter in the FE model, and (b) meshes of the FE model for scratch simulations of CVD diamond-coated cutting inserts.

description of scratch testing can be found from an earlier study [10]. During a scratch test, tangential forces, penetration depths and acoustic emission signals can be monitored and the morphology of the scratch track can be observed simultaneously or afterwards. For coating adhesion evaluations, the normal load that causes the coating to detach from the substrate can be considered as the critical load for coating delaminations [11]. On the other hand, while a hard coating, e.g., diamond in this study, can withstand compressive stresses induced by the indenter to a certain extent, a brittle diamond film may fracture if a high tensile or shear stress field is developed [12]. Coating cracking failure occurs when the mechanical work of the brittle failure in the coating is equal to the energy release rate from coating cracks. When the mean compressive stress over an area in the coating exceeds a critical value, the coating cracking failure that first occurs may be detectable by high-energy AE pulses [7].

Though scratch testing may offer critical load information for coating cracking and interface delaminations, it may not shed light of the interactions between the two modes by using only limited sets of experiments. On the other hand, numerical studies of scratch process modeling and simulations may be useful to investigate coating cracking and interface delaminations together. Simulations of a scratch process have been investigated before. Several challenges associated with scratch simulations include the interface behavior modeling, coating brittle failures, and possible interactions between the two, etc. In a previous study about diamond-coated tools [10], a three-dimensional (3D) finite element (FE) simulation was developed to investigate coating delaminations alone when a rigid indenter slides on a diamond-coated carbide substrate. In that study, the cohesive zone concept, a bi-linear constitutive law, was applied to model the interface behavior [13]. However, the coating fracture phenomenon which may influence diamond coating delaminations was not considered. To better understand the adhesion of diamond-coated carbide tools, it is essential to investigate interface delamination by simultaneously considering the coating fracture phenomenon. Cracking behavior analysis of hard coatings such as CVD diamond is a challenging task too. Recently, the extended finite element (XFEM) method in ABAQUS software using enriched elements has been applied for cracking analysis. XFEM was first introduced by Belytschko and Black [14]. It is an extension of the conventional finite element method based on the concept of partition of unity by Melenk and Babuska [15], which allows local enrichment functions to be incorporated into a finite element approximation. XFEM can be used for the estimation of multiple crack propagation in indentation simulations, with or without pre-cracks defined, and it is independently defined from the existence of any predefined crack or its propagation path without alternating the finite element mesh. XFEM has been used to model some applied mechanics problems after its development. For example, quasi static crack propagations in 2D and 3D by using XFEM were introduced by Daux et al. [16]. In addition, Combescure's group [17]

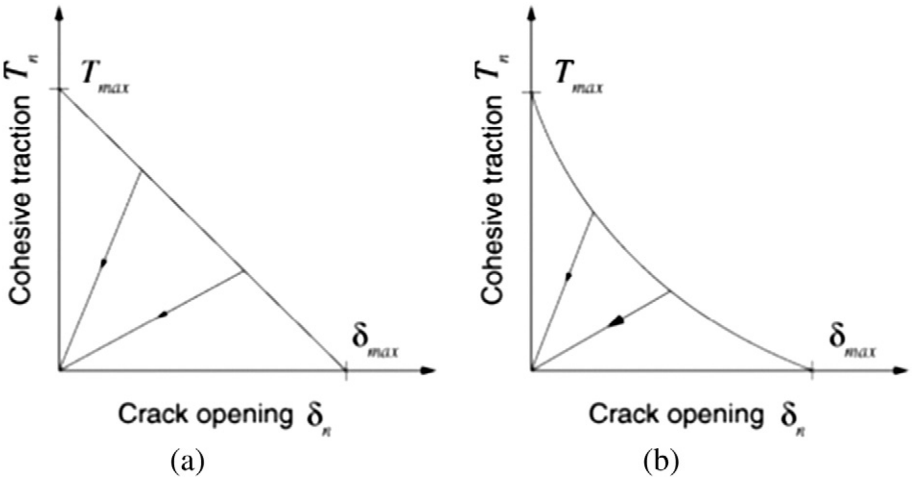

Fig. 2. Traction–separation response examples for XFEM: (a) linear and (b) nonlinear [22].