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Modelling the limits of coating toughness in brittle coated systems

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ABSTRACT

As the accuracy and applicability of existing indentation models to assess coating toughness can be affected by many factors (such as fracture mechanisms, crack type, coating thickness, cracking size etc), it is uncertain to what extent the values obtained are quantitatively correct. Therefore, an estimation of the limits of coating toughness is very useful. In this paper, a limits model is proposed to assess coating toughness based on numerical and phenomenological analysis. This approach provides universal expressions for the lower and upper bounds of fracture dissipated energy for indentation performed under load control and displacement control. It has shown that the lower bound determined in this study is also a good estimation of the coating toughness.

1. Introduction

Nanoindentation is a well-established method to assess the mechanical properties of thin coatings including hardness [1–4], elastic modulus [1–4], toughness [5–8] and the adhesion between the coating and its substrate [7–10]. The coatings may not be available in bulk form (or with suitable thickness) which makes the conventional indentation method not applicable. They can also be highly stressed and the coating/substrate interface may fail prior to the coating. Various cracking pattern can occur in different coated systems. All these make it difficult to accurately assess the fracture properties of thin coatings. In such cases it is important to obtain the limits of coating toughness based on a convenient test.

CN_x coatings with novel properties have attracted the interest of many researchers for nearly a decade [11–17]. Amorphous CN_x coatings are applied to hard disks or magnetic recording heads for their good tribological properties. One of the most successful of these is the "fullerene-like" CN_x, which possesses high hardness and very significant elastic recovery [13–14]. The coating fracture and interfacial failure are main reasons to limit their application. Although fracture is extensive in CN_x coated systems at relatively high indentation load but there are few reliable assessments of coating toughness.

In this paper, we present a model to determine the upper and lower bounds for coating toughness based on the original idea by Toonder et al. [18]. In order to further assess the viability of this approach, several existing models were used as comparisons when estimating the toughness of CN_x coatings on various substrates.

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2. Analysis of energy based models

In this section, energy based models to assess coating toughness based on analysing the nanoindentation load–displacement curve are briefly reviewed, followed by the detailed discussion of the original toughness bound model and the model developed here.

2.1. Brief review of the existing energy models

Li et al. [5] proposed that the fracture dissipated energy is the difference of integrated area between the extrapolated loading curve and the measured loading curve when the presence of a plateau in the load–displacement curve is caused by through-thickness cracking. However, this method ignores the change in elastic–plastic response in the coated system before and after fracture which can be essential as remarked by Wu et al. [19] and Gao et al. [20]. Toonder et al. [18] also argue that this difference is not the actual energy dissipated by fracture. Later, Malzbender and de With [21] developed another method by analysing the discontinuities in the plot of irreversible work (W_{irr}) against the applied load (P) during indentation. The energy dissipated by delamination or chipping can be obtained by extrapolating the W_{irr}–P plot at the corresponding transitions. This method requires a lot of experiments in a wide load range to obtain the toughness for one sample and the influence of substrate deformation is significant. To circumvent this problem, another method was proposed by Chen and Bull based on the analysis of total work vs. displacement [6]. As complex factors will affect the accuracy and applicability of the existing toughness assessment methods based on indentation tests, Toonder et al. [18] originally present a concise universal expression to determine the limits of fracture dissipated energy. However, the assumptions on which this model is based conflict with each other, which is discussed in the following section.

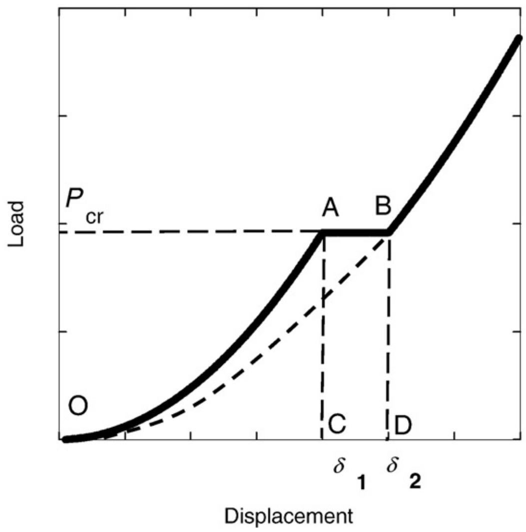

Fig. 1. Schematic of the original bound method under load control [20]. The areas OAB and ACDB are regarded as the lower and upper limits of fracture dissipated energy, respectively.

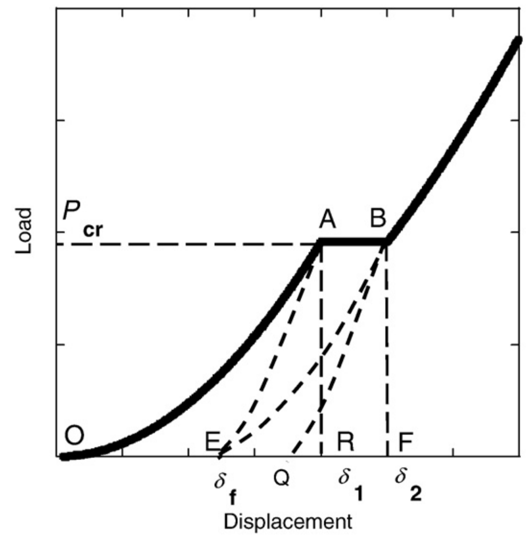

Fig. 3. Schematic of the bound model presented in this study in the case of fracture induced plateau in a P–δ curve for load control. The area ABQE is the maximum energy to be dissipated by fracture, while, the areas ABE and ABFE are the lower and upper limits of area ABQE, respectively.

2.2. Original bound model

In the original toughness bound model, it is assumed the load (P) scales with displacement squared (δ^2) in the loading curve before and after cracking [18]. The fully elastic unloading behaviour (i.e. final depth $\delta_f=0$) in the coated system before and after crack events is assumed to determine the lower bound (i.e. area OAB in Fig. 1), meanwhile, the fully plastic behaviour (i.e. $\delta_f=\delta_m$, where δ_m is the maximum depth) is assumed to determine the upper bound (i.e. area ABDC in Fig. 1) for fracture dissipated energy, U, under load control. Thus [18],

$$\frac{2}{3}P_{cr}(\delta_2-\delta_1)\le U\le P_{cr}(\delta_2-\delta_1),\ \text{for load control} \tag{1}$$

where P_{cr} is the critical load for a through-thickness crack induced plateau, and δ_1, δ_2 are the indentation penetration before and after the fracture event (see Fig. 1.), respectively.

With the same assumptions, the upper limit for fracture dissipated energy, U, (i.e. area OST in Fig. 2) is obtained for displacement control.

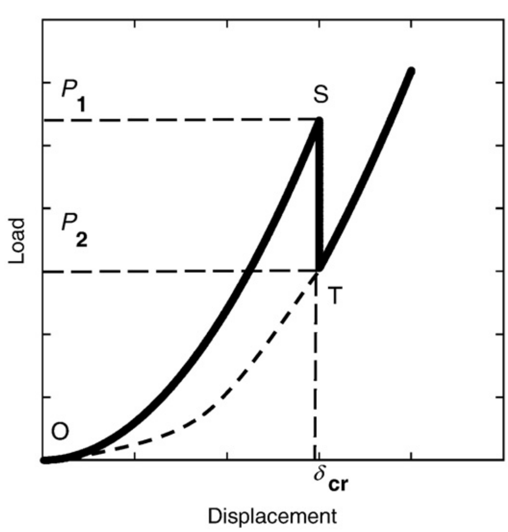

Fig. 2. Schematic of the original bound method under displacement control [20]. The area OST is regarded as the upper bound of fracture dissipated energy.

Unlike in load control, this method is unable to provide the lower limit of the fracture toughness for displacement control.

$$U\le\frac{1}{3}\delta_{cr}(P_2-P_1),\ \text{for displacement control} \tag{2}$$

In fact the presence of plastic deformation leads to non-zero final depth. It is not reasonable to regard the area OAB (see Fig. 1) as the lower bound of fracture dissipated energy. Actually, the area OAB is the upper bound of fracture dissipated energy under the assumption of fully elastic behaviour. It is also incorrect to treat the area enclosed by ABDC (see Fig. 1) as the maximum irreversible work of the indentation, because the area ABDC is the work done by indenter which can be elastic or plastic and may include other factors (such as the energy dissipated by heat). Fundamentally, both the area OAB and the area ABDC are the maximum available energy that could be dissipated by fracture for two totally different extreme materials (i.e. super elastic and infinitely soft materials) and it is not realistic for both to be used simultaneously for a given material.

For a displacement control test, the area OST in Fig. 2 is the maximum elastic strain energy available to be dissipated by fracture only for super elastic materials as mentioned previously. However, the well-developed fracture occurs at relatively high indentation load where plastic deformation has possibly occurred even for traditional brittle materials. This will cause residual depth associated with the unloading curve. Therefore, it is necessary to derive a more general expression to determine the limits for the fracture dissipated energy.

2.3. Alternative bound model

In this section, an alternative model is proposed based on a more reliable analysis of the unloading curves at the points where the crack induced excursion starts and ends. This method gives the lower and upper bound of fracture dissipated energy for both load control and displacement control indentation tests. Actually, the real lower bound is very difficult to obtain as it requires no other dissipation mechanisms during indentation except fracture. The lower and upper bounds discussed here are thus the lower and upper limits of maximum energy available to be dissipated by fracture.