FRACTURE TOUGHNESS MEASUREMENT OF THIN SURFACE COATINGS

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The generation of stresses in a thin hard TiN coating were demonstrated when a loaded counterface slides over a coated surface by applying three-dimensional finite element analysis. A methodology was developed which unifies local experimental measurements to fracture mechanical assessment by using a numerical model calibrated on the basis of experimental findings. A novel method for calculating the fracture toughness of the coating substrate system in a scratch test was formulated. A patent has been applied for the test method.

INTRODUCTION

There has been an increasing interest in the use of coatings on mechanical components, on tools in the production industry, on disc drives in the computer industry, on precision instruments, and on medical implants. New coating deposition techniques developed over the last two decades offer a wide variety of possibilities to tailor surfaces with many different materials and structures. In particular, chemical vapor deposition (CVD) and physical vapor deposition (PVD) techniques have made it possible to deposit thin coatings one micrometer thick in a temperature range from very high temperatures (about 1000?C) down to room temperature. [1,2].

Coating materials such as TiN, TiC, Al_2O_3 and more recently diamond, diamond-like carbon (DLC) and MoS_2 and their combinations have been used with great success. Nonetheless, the exploitation of the full potential offered by these new techniques requires a more systematic approach.

The current paper describes a methodology which unifies local experimental measurements to fracture mechanical assessment by using a numerical model calibrated on the basis of experimental findings. This provides one with a possibility to derive the fracture toughness of the coating by using a simple and inexpensive scratch test, providing a completely new view into understanding and characterizing the phenomena of contact and wear in thin coatings. The results of such an analysis can be applied e.g. in development and characterization of coatings and their performance, materials selection for tribological applications and in designing components for wear critical applications. The results of the current work are addressed in more detail in [3].

NUMERICAL - FINITE ELEMENT ANALYSIS

The scratch test, shown schematically in Fig. 1, was discretized with a three-dimensional finite element model of the coating, substrate and stylus. The TiN coating thickness was 2 ?m over a tool steel substrate in an infinite half-space. A topographical first principal stress field of the experiment after 1100 ?m of sliding is presented in Fig. 2 and after 2300 ?m in Fig. 3. The distance from the beginning of the sliding correlates directly to the applied loading.

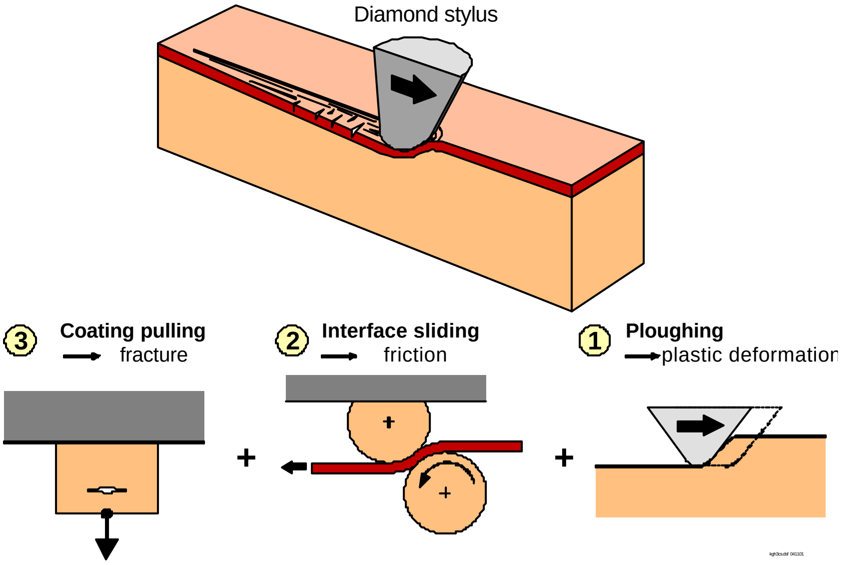

Fig. 1. Schematic illustration of the stylus drawn along the coated sample. The material loading and response can be divided into three phases: ploughing, interface sliding and pulling a free-standing coatin

During the test at increasing load a stress field grows around the contact area. At the tail arms, stress concentrations are amplified at a distance of 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. This situation corresponds to Fig. 2.

As the test progresses, the stress concentrations at the tail travel to the plane of symmetry and increase in magnitude considerably faster than within the contact area, and become the dominating tensile stress as the contact conditions change to ploughing mode. This is presented in Fig. 3.

The results of Fig. 2 can be linked to formation of angular cracks, while those of Fig. 3 to straight transverse cracks in the scratch groove, both cracks and peak stresses occurring outside the contact zone. The synthesis between numerical analyses and experiments enables identification of conditions and micromechanisms leading to certain types of crack patterns, and as such, provide a basis for fracture mechanical analysis.

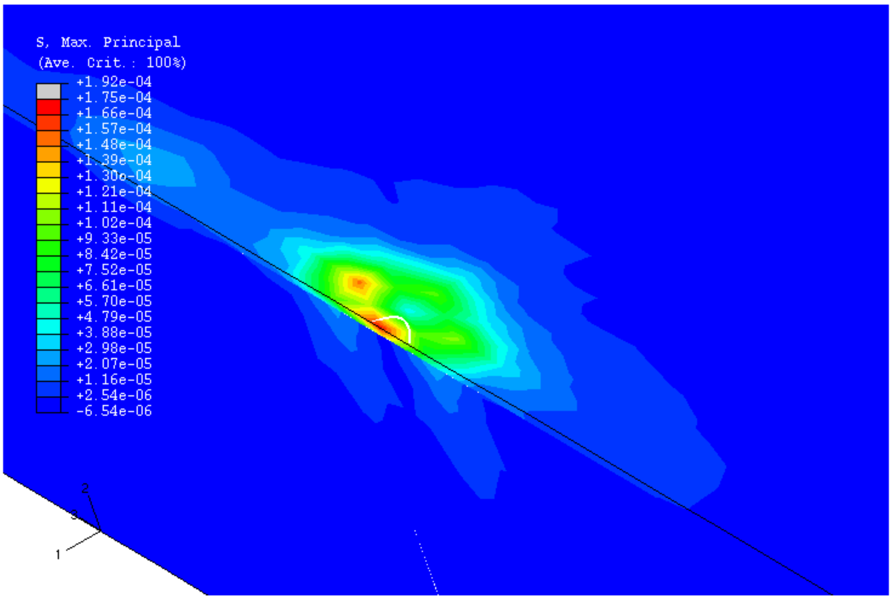

Fig. 2. Topographical first principal stress field map showing stresses on the coating surface and symmetry plane at 1100 ?m. The contact zone is shown by the white curve. Stylus movement in direction of negative 3 axis.

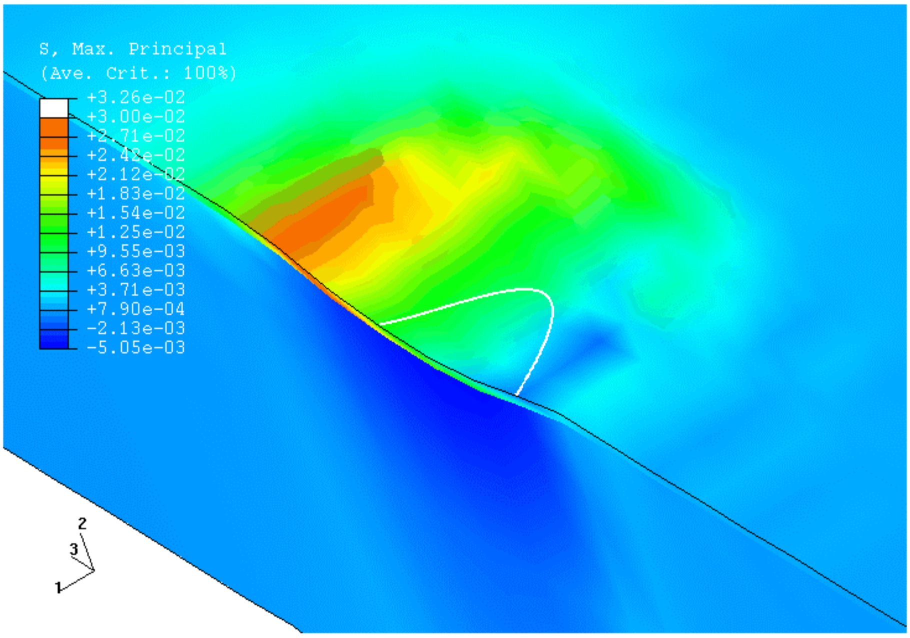

Fig. 3. Topographical first principal stress field map showing stresses on the coating surface and symmetry plane at 2300 ?m. The contact zone is shown by the white curve. Stylus movement in direction of negative 3 axis.

FRACTURE MECHANICAL ANALYSIS

Cracking was modeled to occur within the applied first principal stress field such that a set of specific length through coating cracks is formed with a given cracking density in the direction of stylus movement. Crack dimensions, particularly the crack density, are used as input to the K evaluation throughout the experiment. The solutions for the stress intensity factor are given as $K ? ?_1\sqrt{b} ? f (a,b)$, where $?_1$ is the first principal stress, b crack spacing and $f (a,b)$ a non-dimensional function dependent on crack length, a, and crack spacing/density.

The assessment is simplified by the fact that the non-dimensional function approaches unity for very dense crack fields, such as in the current case. The results of Fig. 4 display fracture toughness both for straight and angular cracks giving mean, upper and lower bound values. The lower and upper bound values comprise scatter effects from crack size, crack angle, finite element discretization, estimated crack coupling effects etc. These effects are highlighted for the smaller angular cracks, introducing a higher scatter band than for the larger, straight cracks.

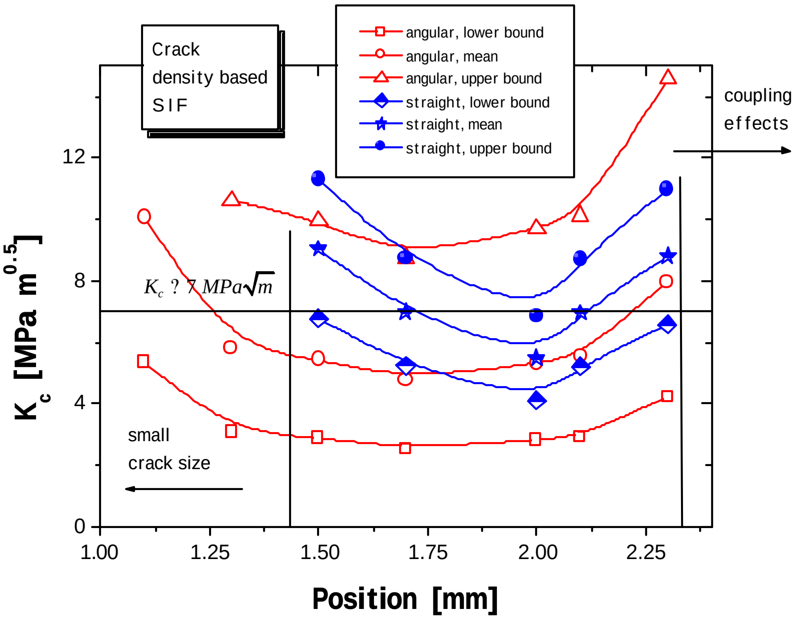

Fig. 4. Results of the fracture toughness evaluation for straight and angular cracks.

At the beginning of the test, the smaller crack size and its relation to dimensions characteristic of numerical modeling are interpreted to increase scatter and uncertainty. In part this is related to use of stress values, since current values are surface values, and initially the coating through thickness stresses have not stabilized to pure membrane type of loading. Overall, it can be stated that best estimate of fracture toughness for the TiN coating is approximately 7 MPa.m$^{0.5}$.

CONCLUSIONS

Finite element and fracture mechanical analysis methods were applied to investigate experimental scratch test results and applied to a 2 ?m TiN coating on steel substrate. Based on this the following conclusions can be drawn:

1. The created model describes the stresses and strains incorporating elastic and plastic behavior and finite deformations in a contact geometry of a sphere sliding on a coated surface.

2. In determining the critical fracture toughness scatter is introduced from identification of crack density and orientation. The fact that in the other end of the experiment damage related coupling is neglected by the finite element analysis, limiting the scope for larger cracks, introduces a range from approximately 1 mm to 2.5 mm best suited for fracture toughness evaluation.

3. For determining the fracture toughness of 2 ?m thick TiN coatings on a steel substrate, a suitable crack field turned out to be the transversal tensile cracks in the scratch groove. Computations provided the best estimates for K_c when the cracks had not grown through the whole groove. For the studied case the fracture toughness of the TiN coating was measured to be K_c =7 MPa ?m$^{0.5}$.

4. The approach is generic in nature and enables characterization of fracture toughness of coatings in general as well as evaluation of coating substrate system performance. The methodology and its results can be applied to structural integrity and design problems by use of fracture mechanics.

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