Engineering Fracture Mechanics 158 (2016) 23–38

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Rebuttal: Shallow and deep scratch tests as powerful alternatives to assess the fracture properties of quasi-brittle materials

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ARTICLE INFO

Article history:
Received 3 September 2015
Received in revised form 20 January 2016
Accepted 1 February 2016
Available online 8 February 2016

Keywords:
Scratch tests
Fracture toughness
Size Effect Law
Ductile-to-brittle transition

ABSTRACT

We recall the principles of Dimensional Analysis. We do not violate the principle of geometrical similarity: the Size Effect Law can be applied to dissimilar specimens when the energy release function is known. By considering a two-dimensional and a three-dimensional similitude case, we can predict the fracture toughness using scratch tests. Finally, we recall our Scratch Fracture Mechanics model that was validated via an exhaustive campaign of numerical simulations. In sum, whether deep or shallow, the ductile-to-brittle transition in scratch tests is governed by the out-of-plane width and the width-to-depth ratio.

1. Introduction

Scratch tests consist in pushing a hard probe across the surface of a weaker materials. Scratch tests date from the Hellenistic area where they were employed to classify minerals according to their hardness. Later in the 1820s, the German mineralogist Fried Mohs built the Moh's scale that formalized this classification of materials. Nowadays, scratch tests are pervasive in a wide range of scientific and industrial applications including strength of rocks [12,48], damage of polymer [19,20,38], abrasion of metal [1] and cohesion and adhesion of thin films and coatings [7,24,32].

Five years ago, we introduced a novel application for scratch tests: a means to measure the fracture resistance of materials [6,5,4]. Using advanced theoretical models, comprehensive finite element simulations and controlled desktop scratch test experiments, we formulated a robust method to estimate the fracture toughness. In turn, this launched a controversy that has spanned several publications [2,40,41].

The goal of this communication is to set the scientific community at rest. Despite Lin and Zhou's ill-founded claims, scratch tests represent a powerful means to evaluate the fracture toughness. We show that their main objection, that a tridimensional formulation of the Size Effect Law for scratch test would always point to nonlinear Fracture Mechanics, is unwarranted. In return, we address the question of geometrical self-similitude as well as the effect of friction.

This paper is organized as follows. First, we perform scratch test assays on paraffin wax and record the observed failure mechanisms. Second, we employ Dimensional Analysis to examine the concept of geometrical self-similitude. Finally, the experimental data obtained on cement and rock is used to investigate the validity of our theoretical derivations.

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http://dx.doi.org/10.1016/j.engfracmech.2016.02.010
0013-7944/

Nomenclature

a	crack length
α	width-to-depth ratio
B^w	Size Effect Law coefficient
$\widetilde{B}$	Size Effect Law coefficient
c_f	fracture process zone
d	penetration depth
D_0^w	Size Effect Law transitional length
$\widetilde{D}_0$	Size Effect Law transitional length
E	Young's modulus
F_T	scratch horizontal force
F_V	scratch vertical force
F_{eq}	scratch Equivalent force
$\overline{F_{eq}}$	average scratch equivalent force
f	dimensional physical function
$\mathcal{F}$	dimensionless physical function
f'_t	ultimate tensile strength
g^w	energy release rate function
$\tilde{g}$	energy release rate function
K_c	fracture toughness
L_n	generic structural parameter
ln	natural logarithm function
μ_i	interface friction coefficient
M	Size Effect Law empirical coefficients
ν	Poisson's ratio
N	Size Effect Law empirical coefficients
Π_i	generic dimensionless parameter
q_i	generic physical variable
σ_0	tensile yield strength
σ_N	ultimate nominal strength
$\overline{\sigma_N}$	average ultimate nominal strength
$\widetilde{\sigma}_N$	ultimate nominal strength
θ	blade back-rake angle
w	blade width

2. Scratch test experiments

2.1. Experimental set-up

In order to investigate the occurrence of fracture processes during scratch testing (cf. Fig. 1(b) and (c)), we built a macroscopic scratch testing equipment. Fig. 1(a) displays a digital photograph of our apparatus. In the experiments, a rotatory stepper motor NEMA 34 (3) drives a round rail linear motion assembly (4) supporting a ball-bearing carriage (6). The carriage holds the specimen which is then pushed again a steel blade (7) at a constant speed and depth of penetration. The forces generated are recorded using two 2000-lb strain gauge load transducers (8), whereas the displacement is independently measured with a linear position transducer (5). The penetration depth is accurately set via a linear ball-bearing translation stage actuated by a 1-μm resolution differential micrometer. Furthermore, the overall compliance is kept below 0.05 mm/N by means of a 3-D T-slotted aluminum extrusion frame (2) holding the scratching tool and mounted on a high-performance vibration isolation table (1). Finally, the Laboratory Virtual Instrument Engineering Workbench (LabVIEW) [39] is employed for motion control and data collection.

2.2. Fracture processes

We carried out macroscopic scratch tests using paraffin wax as a model material. The specimens were prepared by casting a melted blend of paraffin wax and wax additives into 3.5 in. × 4 in. × 2 in. aluminum molds and cooling for 24 h at room temperature. The specimens were then tested at a constant depth of $d = 2$ mm using a blade of width $w = 3.5$ in. at a prescribed constant horizontal speed of $V = 1.7$ mm/s. In order to visualize the failure macro-mechanisms, a Nikon D800 DSLR camera was employed at an acquisition rate of 50 frames per second. Fig. 2 displays a succession of images captured during the test corresponding to 0.56 s time period.