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Material specific nanoscratch ploughing friction coefficient

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ABSTRACT

In nanoscratch testing it is observed that the normal and tangential forces do not increase linearly. This behavior results in ploughing friction coefficients that vary with nanoindenter penetration depth. Lafaye and Troyon conducted research on ductile materials that concluded this is due to the nanoindenter not having an ideally sharp tip, but rather a blunt spherical one. The friction coefficient model, applied to brittle materials in this research, uses a previously published analytical friction coefficient model as its foundation, and extends it to include material-specific characteristics that effect friction coefficient behavior. Through the comparison between experiment and modeling, material characteristics such as pileup and nanoindenter contact area were found to aid in properly describing the friction coefficient of brittle materials.

1. Introduction

Nanoscratch testing has become popular as a nanomechanical testing method and is able to characterize material behavior such as adhesion strength [1], wear [2], and failure modes [3]. The nanoscratch testing method is capable of being applied to many areas of research due to the customization of input parameters such as scratch length, velocity, force profile and many others. One common research application of the nanoscratch test is to model a single asperity contact for tribological research.

With the introduction of advanced ceramics into many areas of research, such as medicine, aerospace, and superconductors, demands for the manufacturing of ceramic materials has risen. For the manufacturer, this results in the desire to efficiently and economically produce precise ceramic parts with less imperfections. This requires the manufacturer to know the magnitude of the grinding forces required to best produce ceramic parts. As a result, the friction characteristics between abrasive grinding asperities and ceramic materials must be known.

Lafaye et al. [4] have developed an analytical model that gives the ability to evaluate the ploughing friction coefficient of an elastic contact for a conical nanoindenter with a blunt spherical tip. The model is formed from a simple ratio which makes for an elegant predictive model. The approach is to use the ratio between tangential S_t and normal S_n cross sectional nanoindenter-material contact areas to determine the ploughing friction coefficient. S_t is the tangential (normal to $y-z$ plane, parallel to nanoscratch direction, Fig. 1) and S_n is the normal (normal to $x-y$ plane, Fig. 1) cross sectional contact areas between the nanoindenter and material. Lafaye et al.'s [4] model has three contact regimes that depend upon the contact radius a and the elastic recovery parameter of the material ω (regimes two and three are depicted in Fig. 1):

1. At low indenter depths when contact is between the material and spherical tip; when the contact radius a is less than the spherical tip transition radius a_0 ($a < a_0$)
2. At higher indenter depths when the contact is between the material and conical portion of the indenter, $a > a_0$, and the material is behaving elastically such that the elastic rear contact radius a_r is greater than or equal to a_0 ($a_r \geq a_0$)
3. At higher indenter depths when the contact is between the material and conical portion of the indenter, $a > a_0$, and the material is behaving plastically such that $a_r \leq a_0$

The term "elastic recovery" is in reference to the material wrapping around the tip and sides of the nanoindenter during a nanoscratch event. The elastic recovery parameter was first introduced by Bucaille et al. [5] when studying the influence of rheology during a nanoscratch test. Fig. 1 shows that higher elastic recovery (higher ω) results in more material wrapping around the nanoindenter. The evaluation of the normal cross sectional area S_n is identical for all three regimes due to the symmetric nature of the conical nanoindenter [4].

$$S_n = \frac{a^2}{2}(\pi + 2\omega + sin(2\omega)) \tag{1}$$

On the other hand, the evaluation of the tangential cross sectional contact area S_t is more complex due to ω determining if the spherical

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Nomenclature

ν	Poisson's ratio
ω	Elastic recovery parameter [0, $\pi/2$]
ω_0	Rear angle in the spherical extremity of the nanoindenter tip
ρ	Fictive radius of indenter spherical tip
ρ_0	Fictive radius of indenter spherical tip evaluated at a_0
σ_0	Yield stress
θ	Conical indenter half-angle
a	Material-indenter contact radius
a_0	Maximum material-indenter contact radius of spherical tip
A_c	Material-indenter contact area
a_f	Plastic material-indenter contact radius
A_p	Pileup-indenter contact area
a_r	Elastic rear material-indenter contact radius
$A_{p,b}$	Base pileup cross sectional area
c	Half-crack size
D	Indentation diagonal length
E	Elastic modulus
f_A	Material-indenter contact area normalization factor
$f_{p,h}$	Pileup height proportionality constant
$f_{p,w}$	Pileup width proportionality constant
H	Hardness
h	Indenter depth
h_p	Pileup height
h_{DBT}	Ductile-to-brittle transition depth
K_c	Fracture toughness
R	Indenter spherical tip radius
r_p	Pileup full-width
$S_{n,d}$	Normal-projected pileup-indenter displaced-material area
$S_{n,p}$	Normal-projected pileup-indenter contact area
S_n	Normal-projected material-indenter contact area
$S_{t,d}$	Tangential-projected pileup-indenter displaced-material area
$S_{t,p}$	Tangential-projected pileup-indenter contact area
S_t	Tangential-projected material-indenter contact area
V_p	Pileup volume
w_p	Pileup contact-width
X	Rheological factor

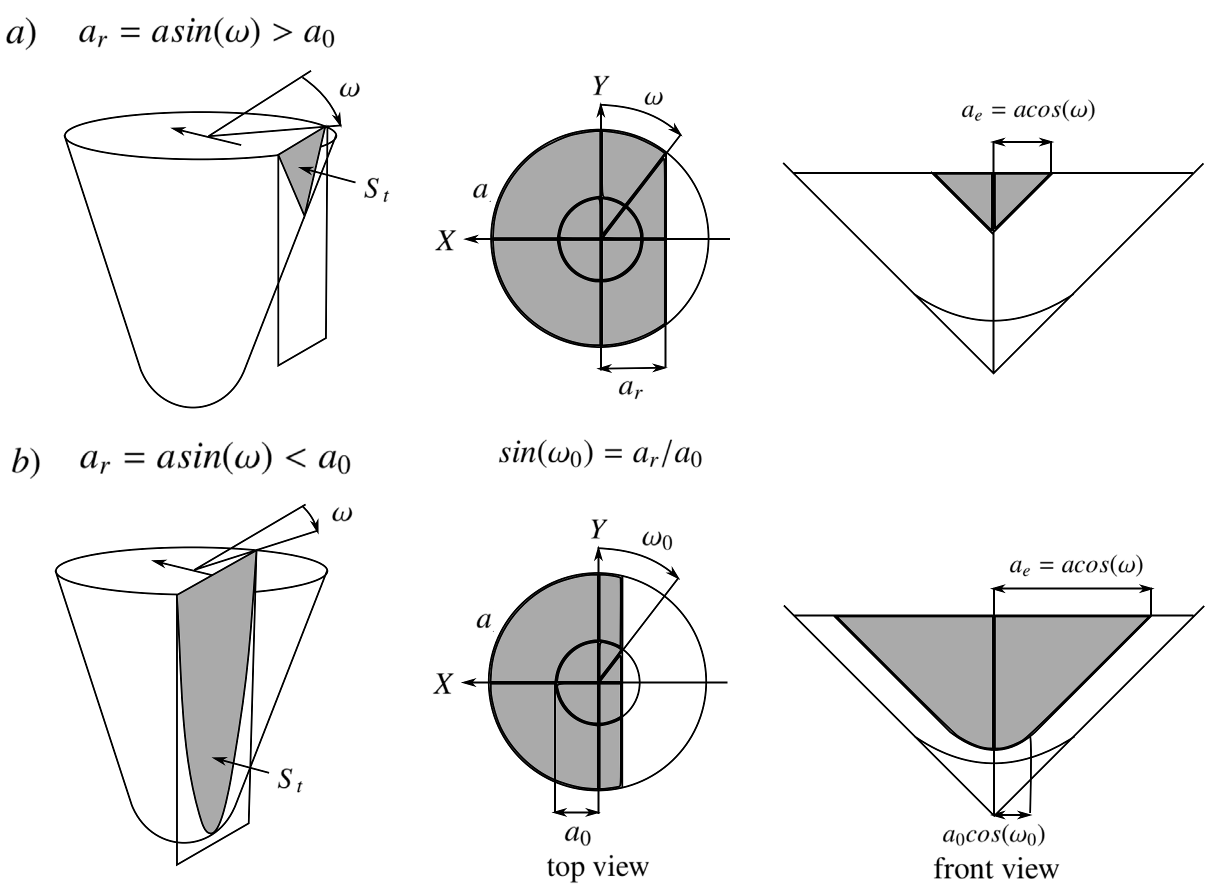

Fig. 1. Different views of the cross sectional areas of contact, reproduced with guidance from Lafaye and Troyon [6].

and/or conical areas make up the cross section. Additional parameters arise due to this complex geometry: the fictive radius of the spherical tip ρ (radius of circle made by S_t cross section), fictive radius evaluated at the spherical tip transition radius ρ_0, rear angle in the spherical extremity of the nanoindenter tip ω_0, and conical nanoindenter half-angle θ.

- For spherical contact, $a < a_0$ [4].

$$S_t = \rho^2 sin^{-1}(acos(\omega)/\rho) - acos(\omega)\sqrt{\rho^2 - a^2cos^2(\omega)} \quad (2)$$

- For conical contact, $a > a_0$ & $a_r > a_0$ [4].

$$S_t = \frac{a^2cos(\omega)(1 - sin(\omega))}{tan(\theta)} \quad (3)$$

- For spherical/conical contact, $a > a_0$ & $a_r < a_0$ [4].