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Quantitative Nanomechanics

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Nanomechanics are important for product qualities, including bioinspired techniques, when combined with 3D-microscopy and AFM (atomic force microscopy). Thus, nano-indentation and nano-scratching become able to explain the extraordinary cracking resistance of Macadamia hard-shells (breaking force 4 N!) in comparison with other nutshells. Applications are improved constructions of domes, not reflecting surfaces, non-wetting surfaces by dropping but wetting within water, super compliant and super elastic materials. Hardness and modulus are replaced by all including penetration resistance k (µN nm$^{-3/2}$) and normalized work of indentation or scratching. Quantitative nano-mechanic data are obtained from indentation loading curves, according to normal force $F_N = k\, h^{3/2}$ or indentation work $W_{ind} = 0.4\, k\, h^{5/2}$, where h is indentation depth. These exponents on h are now also physically founded. Linear correlation coefficients are >0.999 and often >0.9999. All kinds of hard and soft materials obey the same equations independent of their indentation mechanism. This was also demonstrated with hundreds of analyzed loading curves from all around the world, unfortunately against the opposing textbook claims. Nano-scratching goes with lateral force $F_L = K\, F_N^{3/2}$ and scratch-work $W_{scr} = K \cdot F_N^{3/2} L$, where K (µN$^{-1/2}$) is the friction coefficient and L the scratch length.

The penetration resistance (k) analysis reveals that mathematically exact 80% of the applied work is used for the penetration and 20% for all other processes. Furthermore, it recognizes initial surface-effects, gradients, and other peculiarities. The high precision of the k-values allows for studies of crystallographic anisotropies (different faces, or different orientations) and adhesion energies. Importantly, k changes sharply upon any pressure induced phase transformations, as seen by two linear branches in the linear presentation, the detection of which is of highest technical importance. Even energies and activation energies of phase transformations are obtained from indentation loading curves. These tools avoid iterations, fittings, or simulations. Common mechanical parameters that rely on an erroneous exponent 2 instead of 3/2 on h require urgent correction, because penetration h goes with $F_N^{2/3}$ (not with $F_N^{1/2}$), and unrealistic mechanical property data deny the state-of-the-art, which is dangerous (for example failing medical transplants, turbine blades, etc.).

Keywords: loading curves; nanoindentation; physical deduction; penetration resistance; phase transformation energy; activation energy