On the relationship between indentation hardness and modulus, and the damage resistance of biological materials.

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Nanoindentation has become the primary method for determining the mechanical properties of biological materials. However, most of our understanding of the measured parameters derives from ‘classic’ engineering materials such as metals. While elastic properties - characterised by a ‘modulus’ - are well understood, plastic properties - characterised by a ‘hardness’ - have been more elusive. What is the relevance and functional meaning of indentation hardness, \( H_I \)?

Indentation hardness is defined as the mean contact pressure:

\[
H_I = \frac{P}{A}
\]

Three examples where this matters

(1) Changes in elastic properties affect indentation hardness

(II) High indentation hardness does not imply high resistance to irreversible deformation per se

(III) Unusually low elasticity index may signify functional adaptation

~ Biological materials achieve high toughness via hydration and composite design, at the cost of being more susceptible to quasi-plastic deformation

Conclusions

~ Indentation hardness is an elastic-plastic hybrid property
~ Resistance to irreversible deformation depends on the ratio between indentation hardness and modulus
~ High toughness leads to dominance of quasi-plastic deformation

What are the structural features which allow quasi-plastic deformation in biological materials?

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Equation (1), constant

Indentation hardness is directly proportional to indentation modulus

Indentation hardness is not an accurate measure for resistance to irreversible deformation in biological materials

A lumped parameter model for indentation

Two limiting cases

Normalised characteristic indentation dimensions, \( H_I \)

Brittleness index, \( B_I \)

Normalised load, \( P / E \)

Load, \( P \)

Displacement, \( h \)

Contact area

Deformation completely reversible \( H_I = E \)

Deformation completely irreversible \( H_I = R_e \)

Resistance to irreversible deformation depends on the ratio between indentation hardness and modulus

Inelastic deformation can occur via brittle fracture (cracking) or yielding (quasi-plastic deformation). Combined with the critical strain energy release rate, \( G \), indentation hardness can serve as a brittleness index.

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~ High indentation hardness does not imply high resistance to irreversible deformation per se

~ Biological materials achieve high toughness via hydration and composite design, at the cost of being more susceptible to quasi-plastic deformation

Contact area

Normalised characteristic indentation dimensions, \( H_I \)

Brittleness index, \( B_I \)

Normalised load, \( P / E \)

Load, \( P \)

Displacement, \( h \)

Effect of indentation hardness on indentation modulus, \( E \)

Indentation hardness

Resistance to irreversible deformation

Indentation modulus, \( H_I \)