# Evaluation of material properties using IIT

**2018. 04. 18.**

**원종호**

# Contents

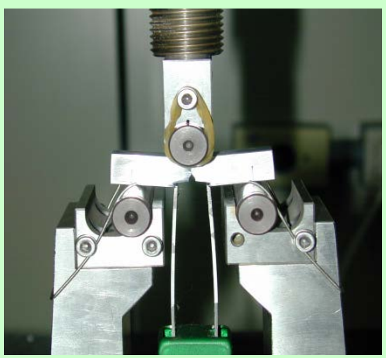
- **What is IIT?**

- **Evaluation of materials properties**
  - **Strength**
  - **Residual stress**
  - **Fracture toughness**

## Deformation

$\sigma_{YS}$, UTS, n, $E$, · · ·

## Fracture



$K_{IC}$, $J_{IC}$, $\delta_{IC}$, · · ·

**Destructive**


**How can I measure the mechanical properties?**

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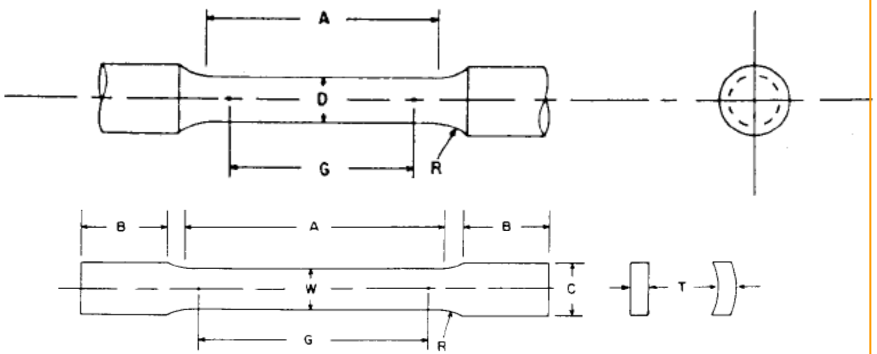
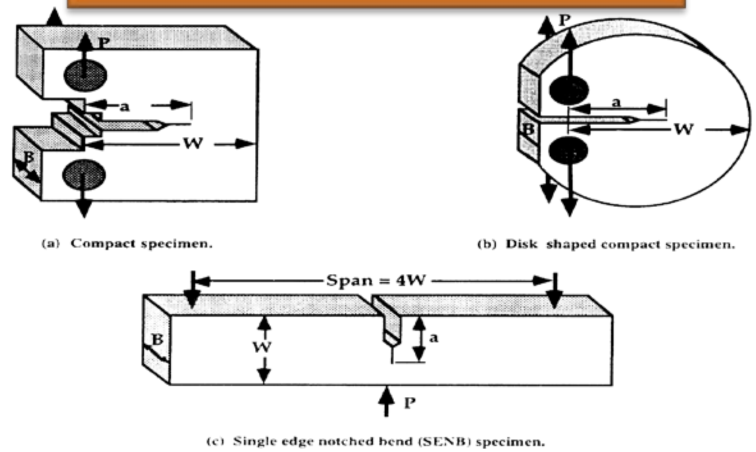
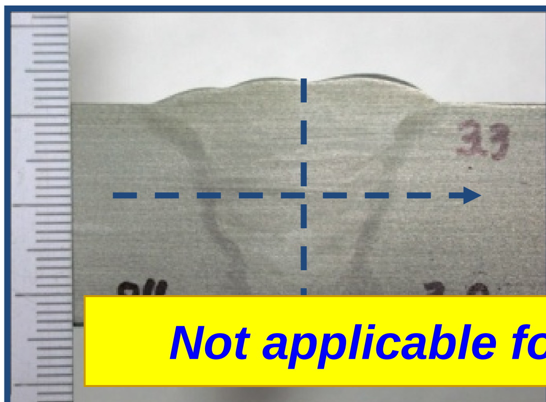
## Specimens for tensile test

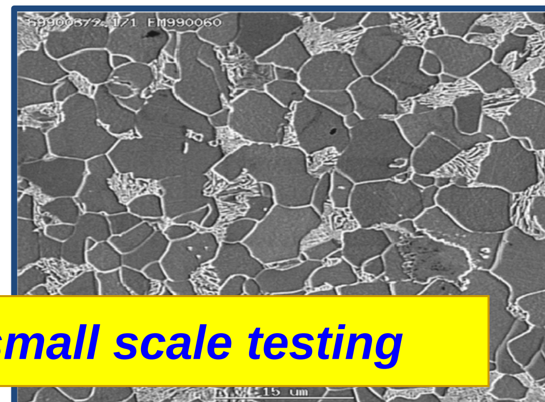



## Specimens for fracture test




# Large scale testing!!!





**Not applicable for small scale testing**

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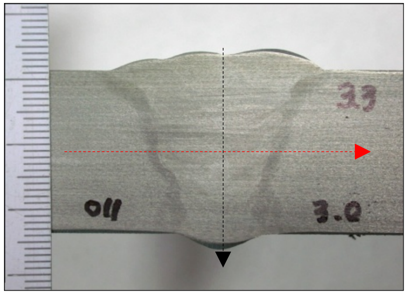
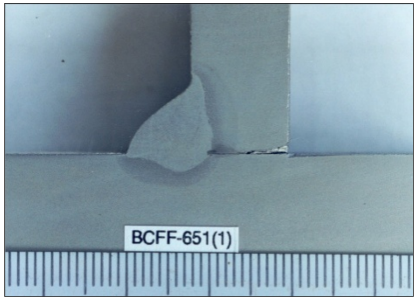
*In-situ & In-field System*

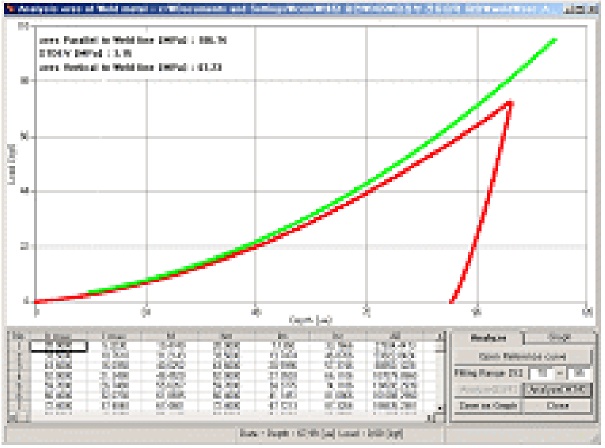
*Non-destructive & Local test*





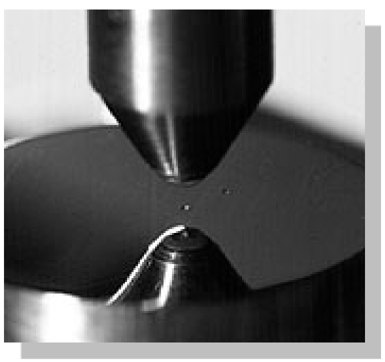

*Simple & fast*

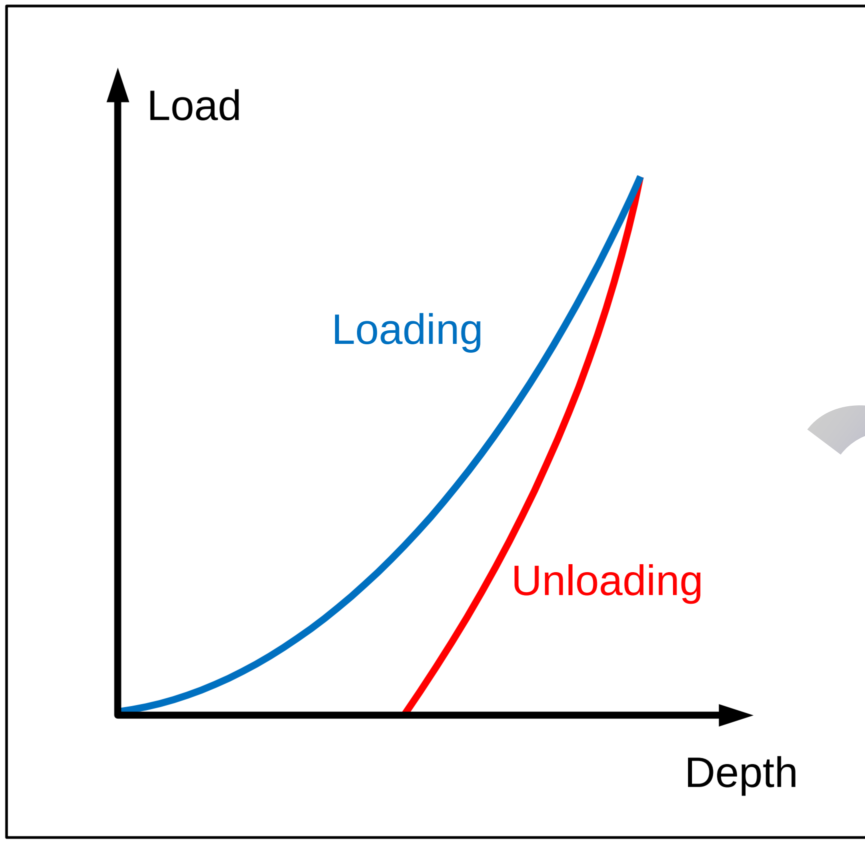
*Convenient*



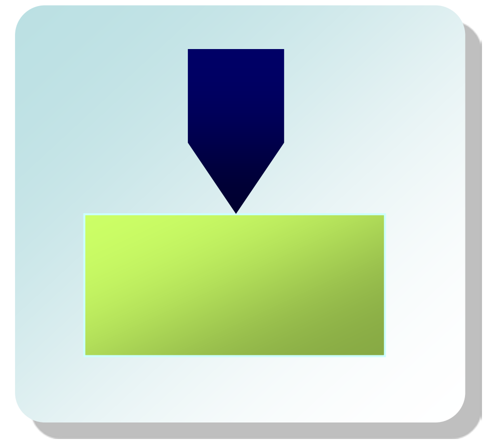
# Instrumented Indentation test

## A novel method to characterize mechanical properties






Indentation load-depth curve



*Hardness*
*Elastic modulus*
*Tensile properties*
*Residual stress*
*Fracture toughness*

# Research history

**Brinell (1900):** defining as the ratio of the load to the surface area,

$$B.H.N.=\frac{2L}{\pi D^2\left\{1-\sqrt{1-(d/D)^2}\right\}}$$

- *L: applied load*
- *d: diameter of residual impression*
- *D: diameter of the ball indenter*

**Meyer (1908):** defining as the ratio of the load to the projected area,

$$p_m=\frac{4L}{\pi d^2}=\frac{4A}{\pi}\left(\frac{d}{D}\right)^{m-2}$$

- *A: material constant*
- *m: Meyer index (≈ n+2)*

**O'Neill (1944):** expressing *d/D* as the indentation strain, plotting $p_m$ against *d/D*

**Tabor (1950):** representing the uniaxial stress and strain,

$$\sigma_r=\frac{p_m}{\psi},\ \ \varepsilon_r=0.2\frac{d}{D}$$

- *$\sigma_r$, $\varepsilon_r$: representative stress, strain*
- ***ψ: plastic constraint factor (≈2.8-3.0)***

# Strength

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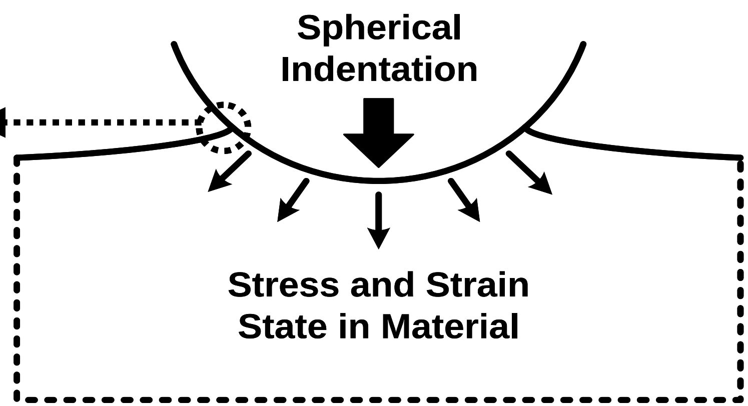
◆ ***Step 1***

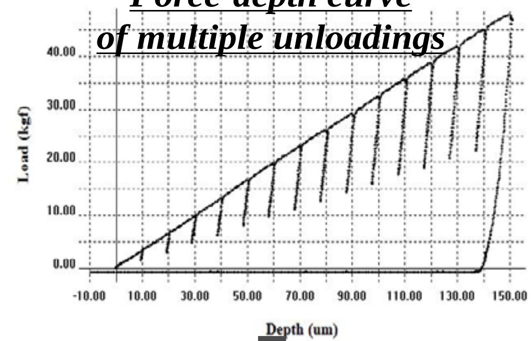
**Determining contact area taking into consideration plastic pile-up/sink-in**

$$\frac{h_{pile}}{h_c^*} = f\left(n_{IT}, \frac{h_{max}}{R}\right)$$




***Instrumented indentation test with a spherical indenter***

***Force-depth curve of multiple unloadings***



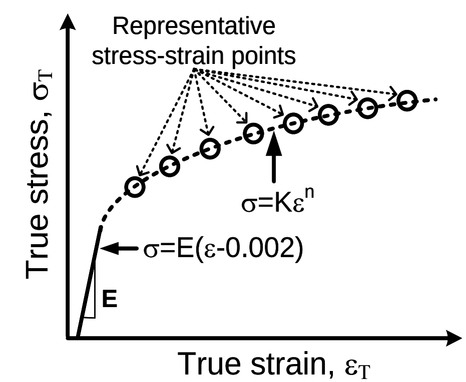

◆ ***Step 2***

**Defining stress and strain state in materials underneath spherical indenter as representative stress and strain**

$$\sigma_T = \frac{1}{\Psi}\frac{F_{max}}{A_c}, \quad \varepsilon_T = \xi \tan\theta$$

◆ ***Step 3 & 4***

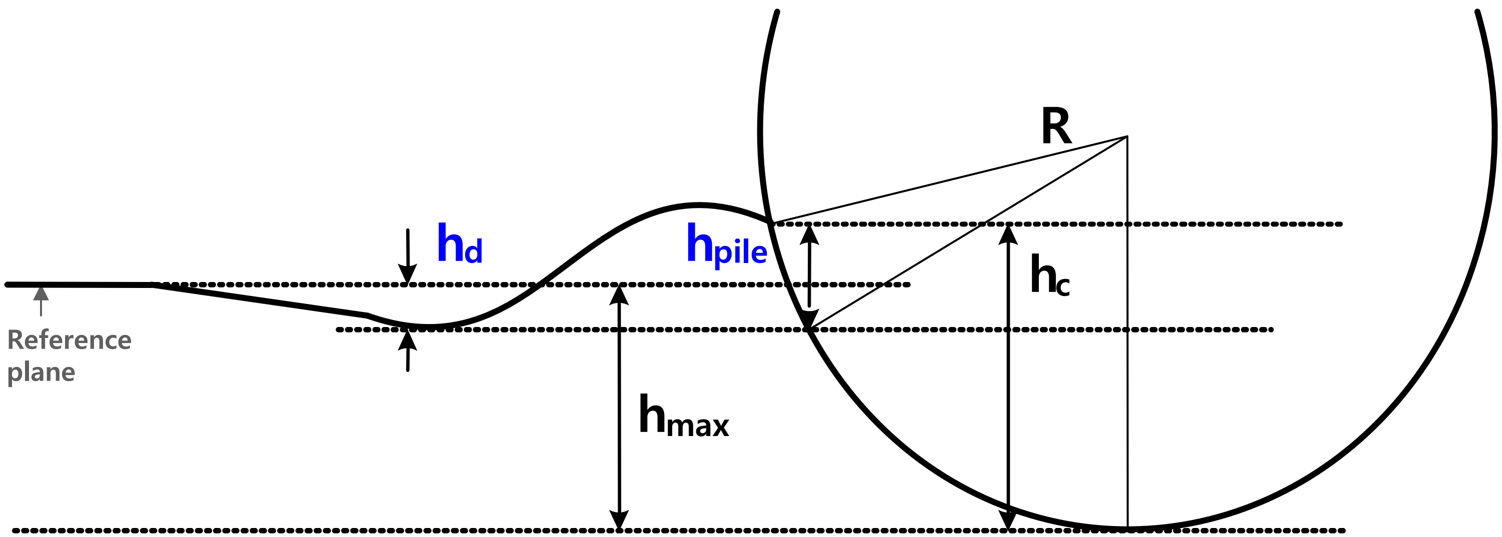
**Fitting to constitutive equation and evaluating tensile properties**




***Tensile properties***

$\sigma_{y,IT}$, $\sigma_{u,IT}$, $n_{IT}$, $E_{IT}$

-W.C. Oliver & G.M. Pharr *J. Mater. Res.* (1992)
-S.H. Kim *et al*, *Mater. Sci. Eng. A* (2006)




**Elastic deflection**

$-h_d$

**Plastic pile-up/sink-in**

$+h_{pile}$

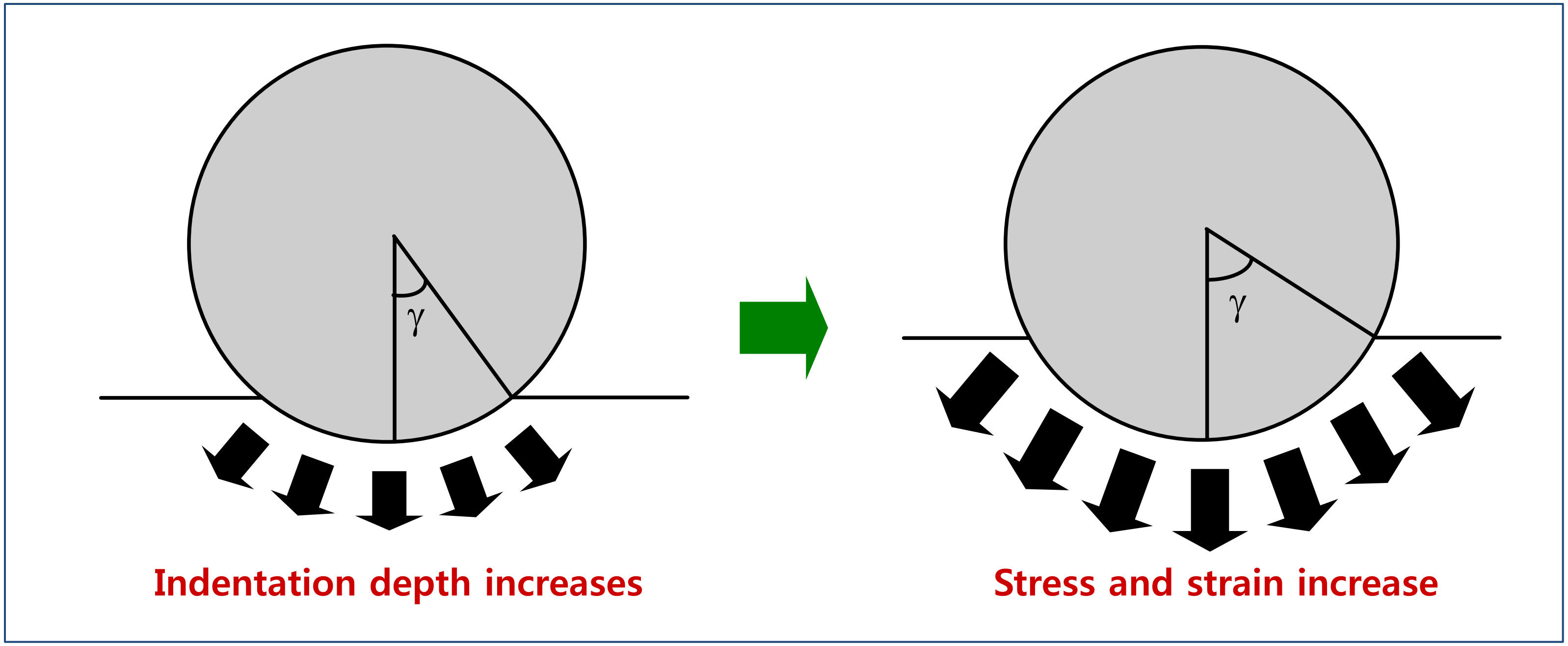
$$h_c = h_{max} - h_d + h_{pile}$$

$$h_d = \varepsilon \frac{L_{max}}{S} \qquad h_{pile} = f(n, \frac{h_{max}}{R})$$

# Representation



-D.Tabor, *The Hardness of Metals* (1951)
-J.H. Ahn *et al*, *JMR* (2000)




## Representative Stress Definition

$$\frac{P_m}{\sigma_R} = \Psi \qquad P_m = \frac{L_{max}}{\pi a_c^2}$$

Ψ: Constraint Factor
(about 3)

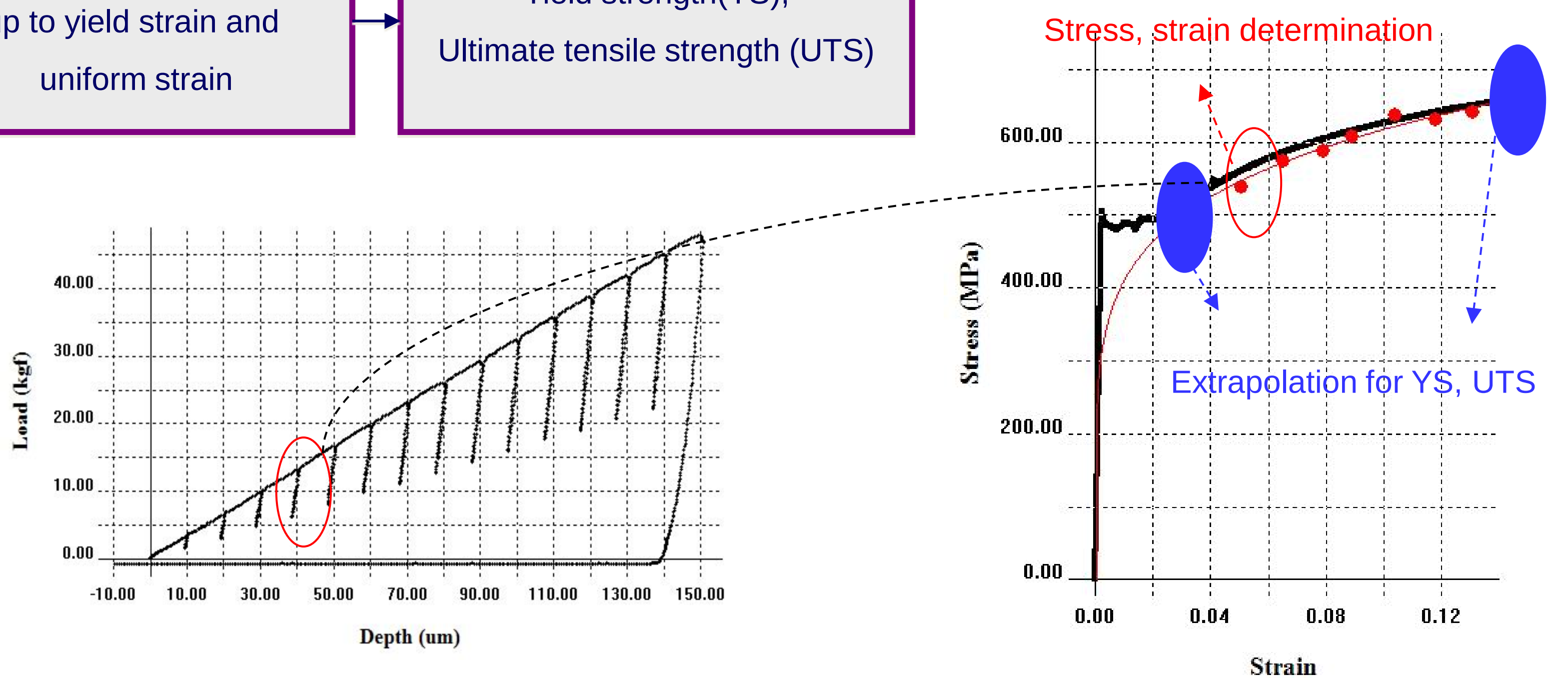
## Representative Strain Definition

$$\varepsilon_R = \frac{\alpha}{\sqrt{1-(a_c/R)^2}}\frac{a_c}{R} = \alpha \tan\gamma$$

# Representation

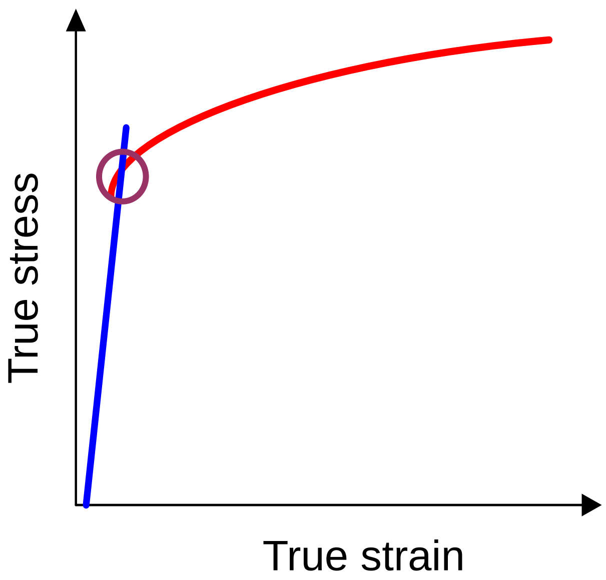


1. Continuous indentation test →
2. Load, depth data at each unloading step (15th) →
3. Stress, strain determination at each step (15 points) →
4. Flow curve fitting from stress-strain points (K, n determination) →
5. Extrapolation of flow curve up to yield strain and uniform strain →
6. Yield strength(YS), Ultimate tensile strength (UTS)



**Yield strength**

$$K\varepsilon_y^n = E(\varepsilon_y - 0.002)$$




**Tensile strength**

$$L = \sigma A$$

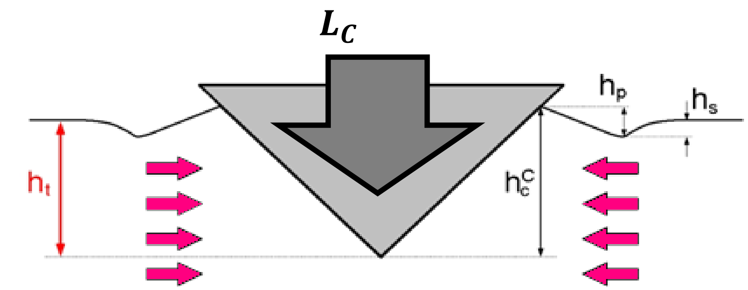
$$\frac{dl}{l} = -\frac{dA}{A} = d\varepsilon \qquad -\frac{dA}{A} = \frac{d\sigma}{\sigma}$$

$$\frac{d\sigma}{d\varepsilon} = \sigma$$

$$\varepsilon_u = n$$

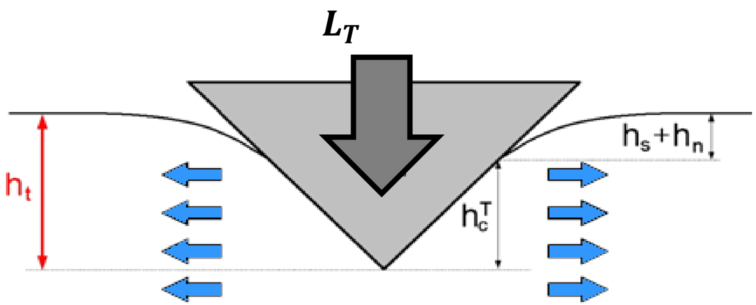
# Residual stress

**Condition : same indentation depth**



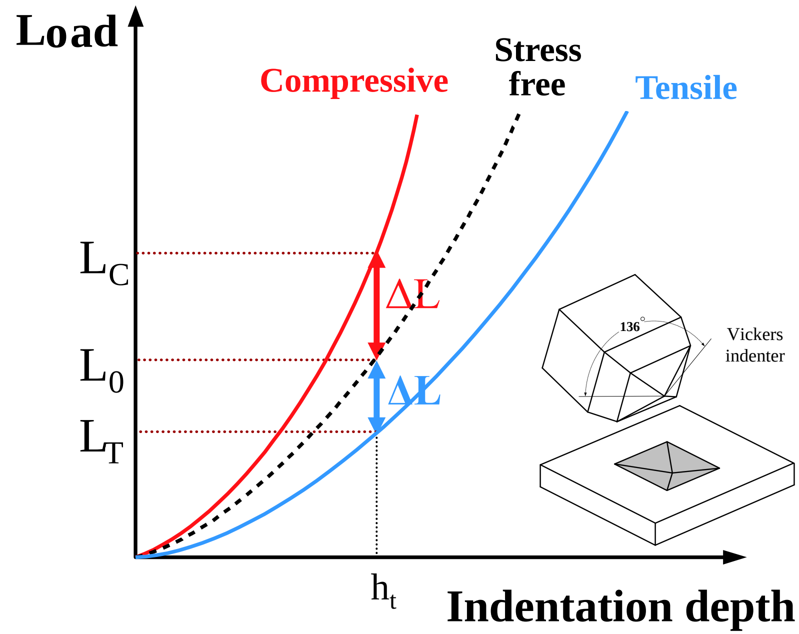

**Compressive stress**

: High load is needed to reach to the same indentation depth.




**Tensile stress**

: Less load is needed to reach to the same indentation depth.

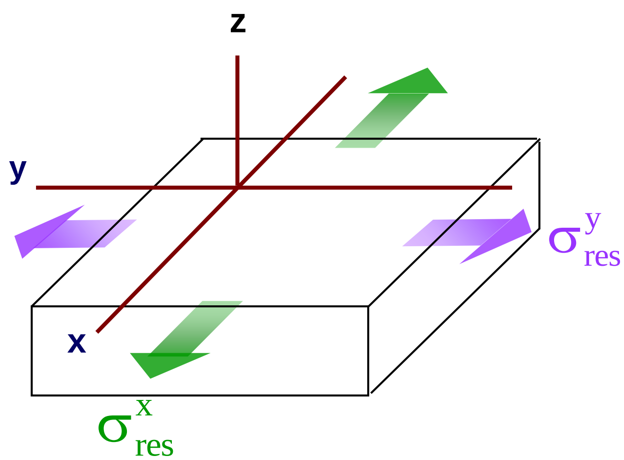



**Indentation Load-Depth Curves**

$$\Delta L = L_S - L_0$$

$L_T$ or $L_C$

Non-equibiaxial residual stress state




**Stress Ratio : $p = \dfrac{\sigma^{y}_{res}}{\sigma^{x}_{res}}$**

$$\begin{pmatrix} \sigma^{x}_{res} & 0 & 0 \\ 0 & \sigma^{y}_{res} & 0 \\ 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} \sigma^{x}_{res} & 0 & 0 \\ 0 & p\sigma^{x}_{res} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$= \begin{pmatrix} \frac{(1+p)}{3}\sigma^{x}_{res} & 0 & 0 \\ 0 & \frac{(1+p)}{3}\sigma^{x}_{res} & 0 \\ 0 & 0 & \frac{(1+p)}{3}\sigma^{x}_{res} \end{pmatrix} + \begin{pmatrix} \frac{(2-p)}{3}\sigma^{x}_{res} & 0 & 0 \\ 0 & \frac{(2p-1)}{3}\sigma^{x}_{res} & 0 \\ 0 & 0 & -\frac{(1+p)}{3}\sigma^{x}_{res} \end{pmatrix}$$

hydrostatic stress

deviatoric stress

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**Residual Stress** ⟷ **Indentation Load**

Deviatoric stress along Z direction :

$$\frac{(1+p)}{3}\sigma^{x}_{res}$$

$$=$$

Indentation stress :

$$\sigma_{int}\left(=\frac{1}{\Psi}\frac{\Delta L}{A_S}\right)$$

where , $\Psi$ = constraint factor (3.0)

$$\left[\frac{(1+p)}{3}\sigma^{x}_{res}=\frac{1}{\Psi}\frac{\Delta L}{A_S}\right]$$

$$\sigma^{x}_{res}=\frac{3}{(1+p)}\frac{1}{\Psi}\frac{\Delta L}{A_S}$$

$$\left(p=\frac{\sigma^{y}_{res}}{\sigma^{x}_{res}},\quad A_S=\text{Contact Area}\right)$$

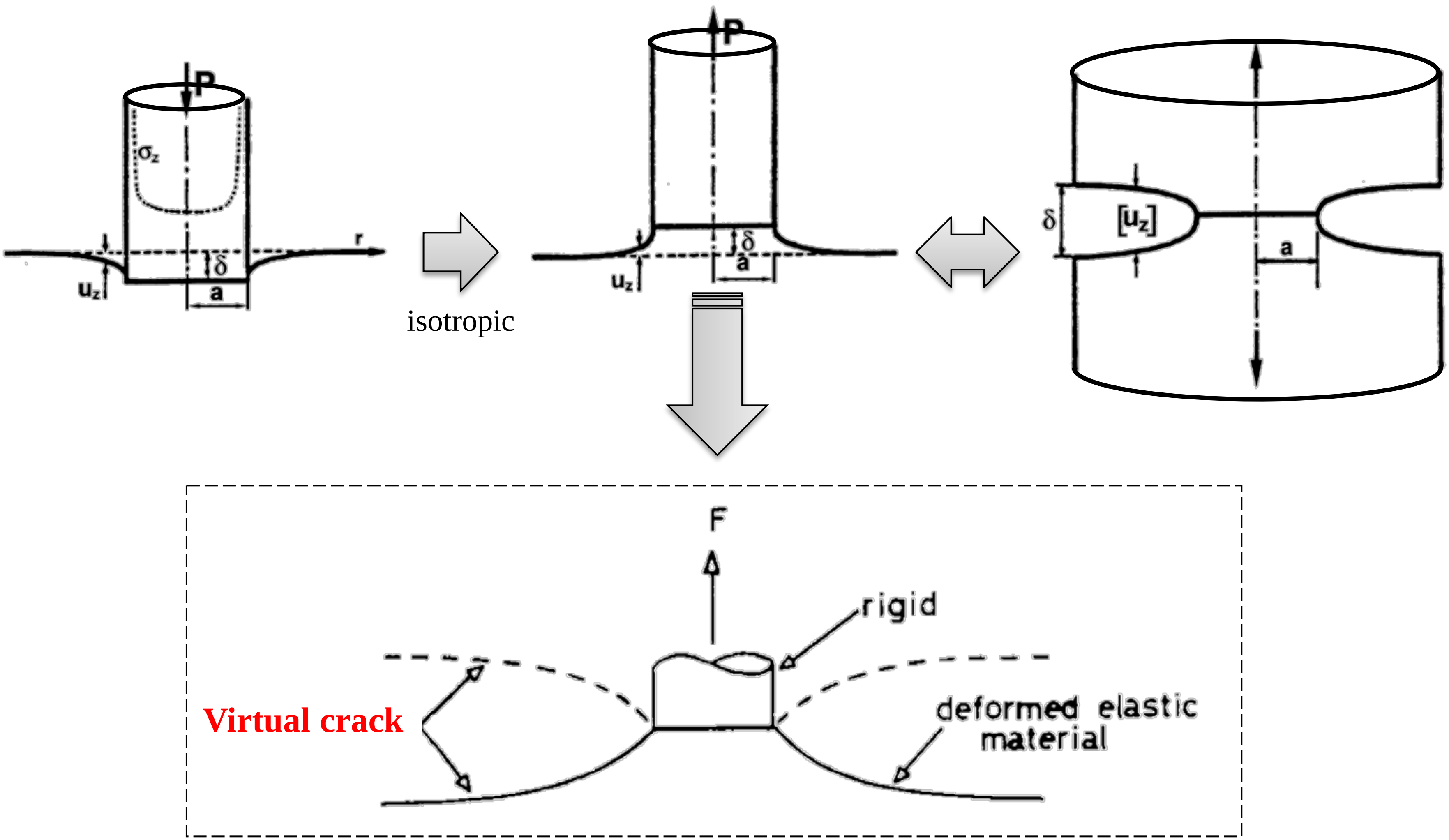
$$\boldsymbol{\sigma^{x}_{res}\propto\Delta L}$$

# Fracture toughness

# Approach



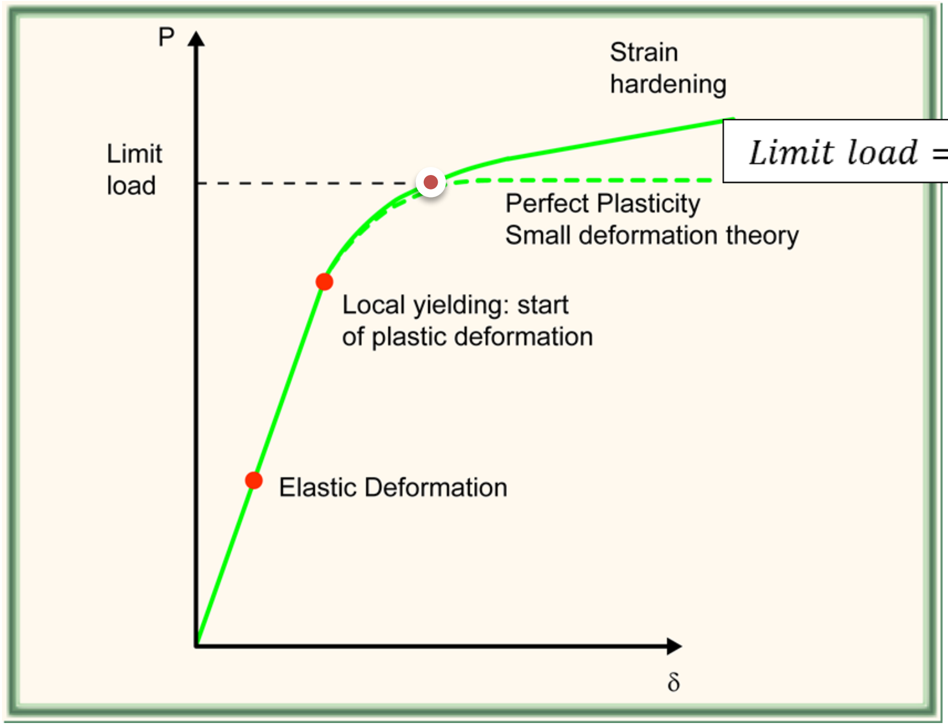
* How to correlate **flat punch indentation** with **crack tip behavior in CRB test**



* Scibetta (1999)

"**Maximum load** can be evaluated by **limit load** in case of cracked round bar geometry"

* **Limit load**



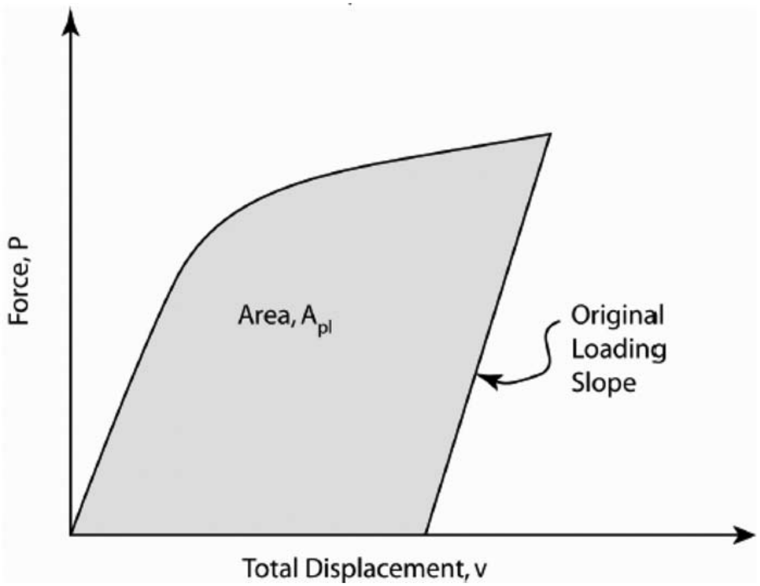

$$Limit\ load = f(geometry, \sigma_{YS})$$

* For cracked round bar geometry

$$P_L = \pi b^2 \sigma_{YS} \begin{cases} 3.285 & for \quad \frac{a}{R} > 0.65 \\ \frac{R}{b} & for \quad \frac{a}{R} < 0.65 \end{cases}$$

Von mises yield criterion
a : crack length
b : ligament radius
R : specimen radius

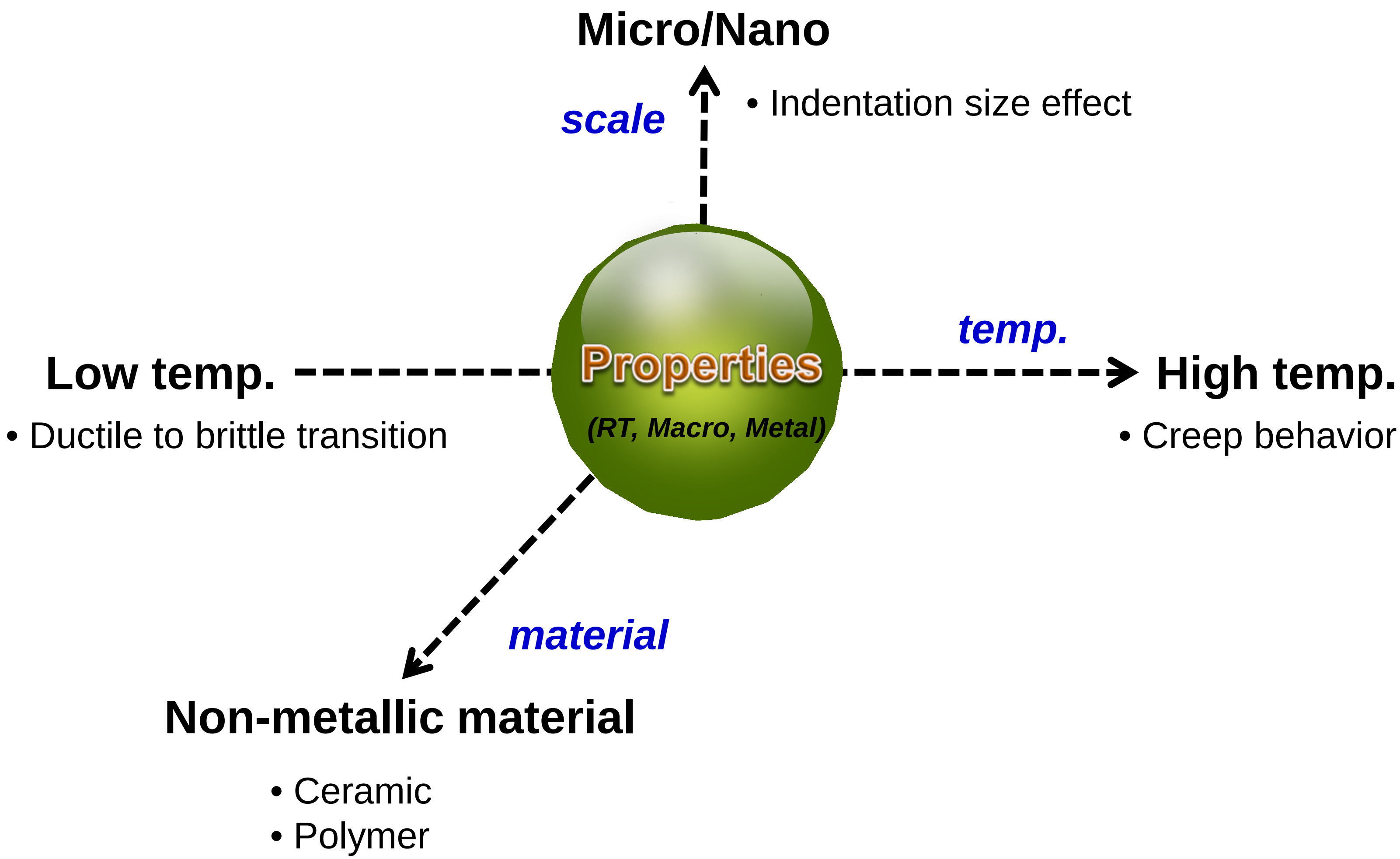
* J-integral formula from fracture mechanics

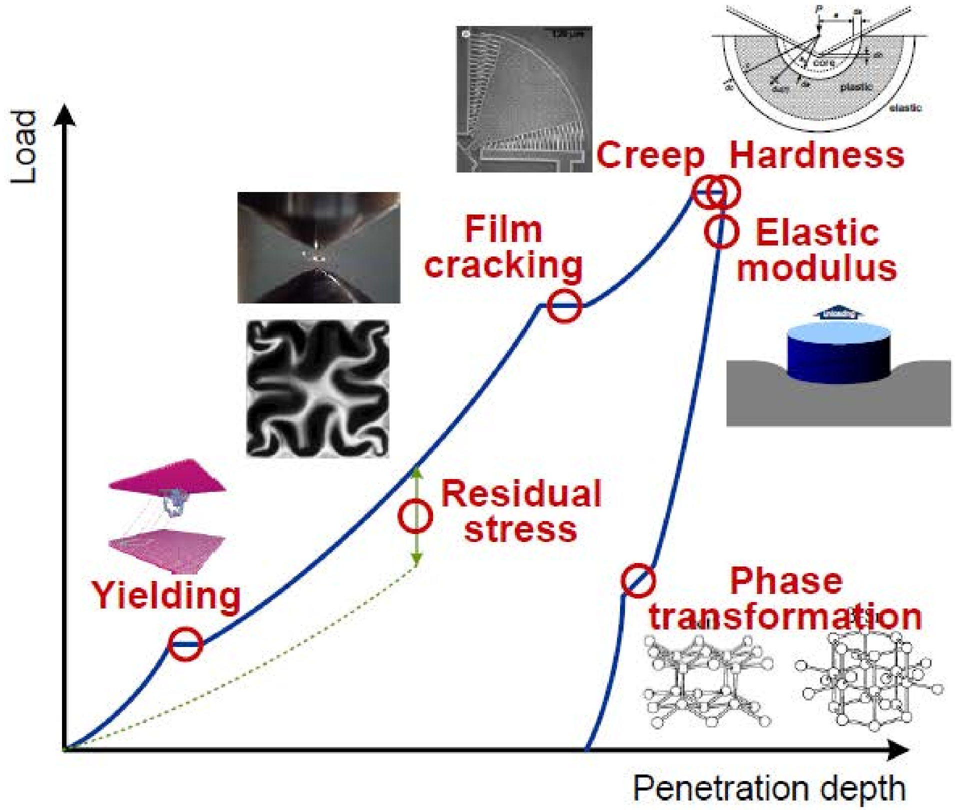


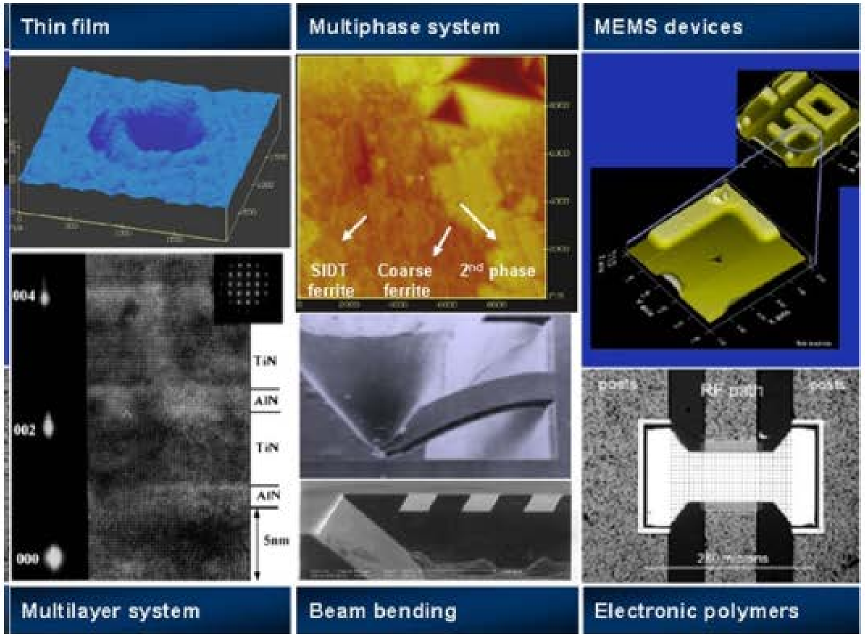

$$J_{IC} = J_e + J_p = \frac{(1-\nu^2)K_I^2}{E} + \eta_{pl}\frac{A_{pl}}{\pi a^2}$$

$A_{pl}$: area under force versus displacement record
$\eta_{pl}$: factor for specimen geometry and crack size
$\pi a^2$: ligament area

$$K_{JC} = \sqrt{\frac{J_{IC} \cdot E}{(1-\upsilon^2)}}$$

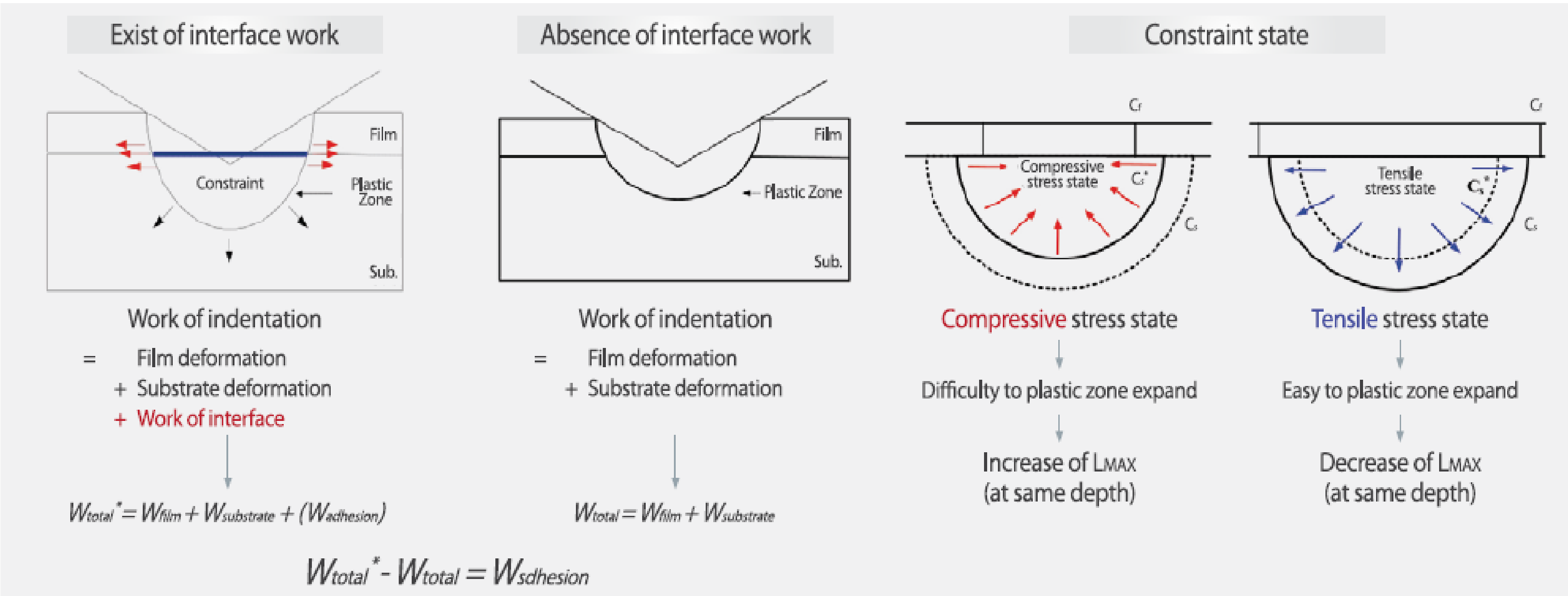

Micro/Nano
scale
• Indentation size effect
Low temp.
• Ductile to brittle transition
Properties
(RT, Macro, Metal)
temp.
High temp.
• Creep behavior
material
Non-metallic material
• Ceramic
• Polymer




**Accurate measurement at nano-scale without specific sample preparations**

# Adhesion concept



# Thank You for Your Attention