Instrumented Indentation Technique

(Tensile strength, Residual stress)

2014. 04. 29.

Jong hyoung Kim

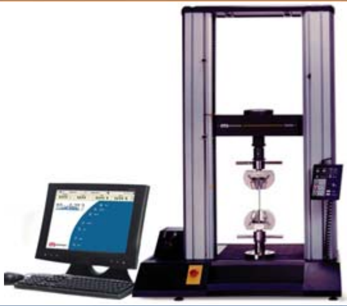
1. Instrumented Indentation Technique

2. Strength

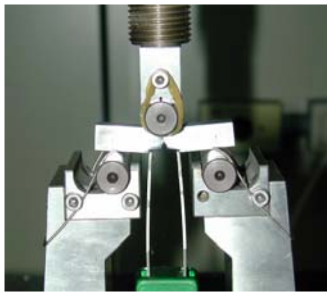
3. Residual Stress

Mechanical Testing Methods

Uniaxial tensile test



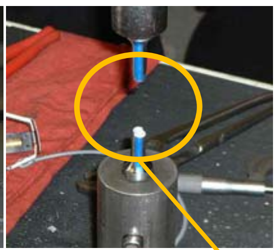
CTOD test

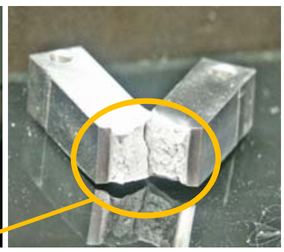


Impact test

X-ray diffraction

Limitation (1) - Destructive



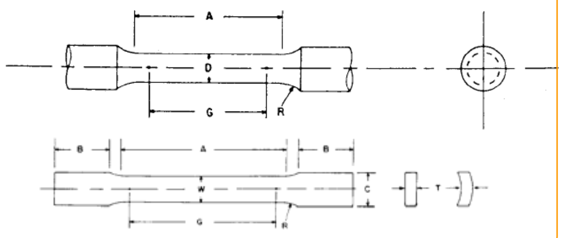


Destructive !!!

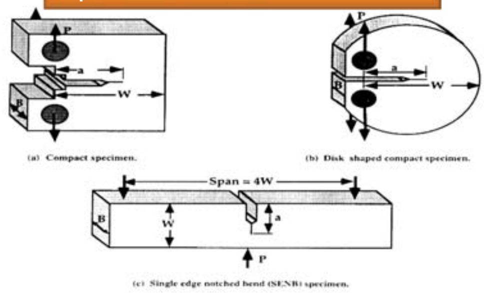
Not applicable in-field

Limitation (2) – Large Scale

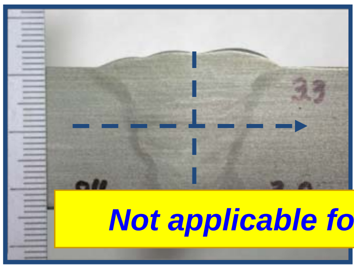
Specimens for tensile test

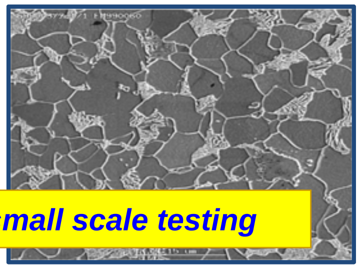


Specimens for fracture test



Large scale testing!!!





Not applicable for small scale testing

Conventional Non-destructive Tests

Crack type damage

Non-destructive (In-field)

- **Macrography**
- **Radioactive**
- **Ultrasonic**
- **Magnetic particle**
- **Eddy current**
- **Acoustic emission**

etc.

Quantitative information of crack size

Micro-structural degradation

Non-destructive (In-field)

- **Replica**
- **Electrical resistance**
- **Electric polarization**

etc.

Issues

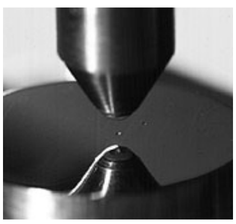
Inaccurate (need empirical reference)

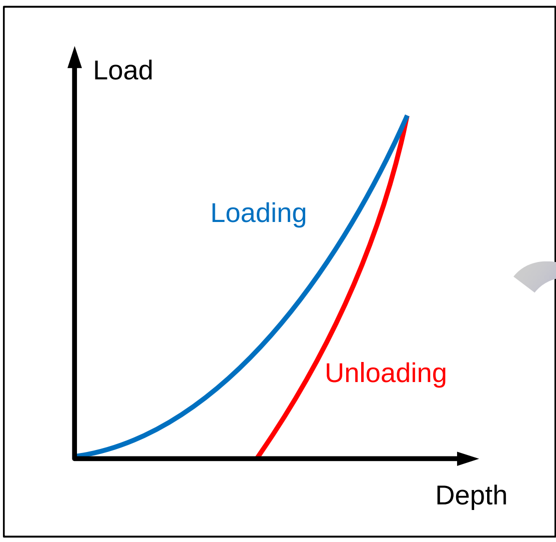
Need for non-destructive In-field testing technique

What is IIT?

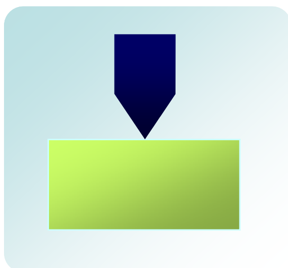
Instrumented Indentation Test (1)

A novel method to characterize mechanical properties





Indentation load-depth curve



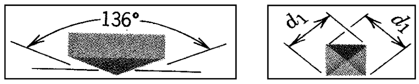
Hardness
Elastic modulus
Tensile properties
Residual stress
Fracture toughness

Instrumented Indentation Test (2)

Conventional Hardness Test

Hardness

Vickers



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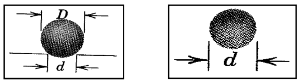
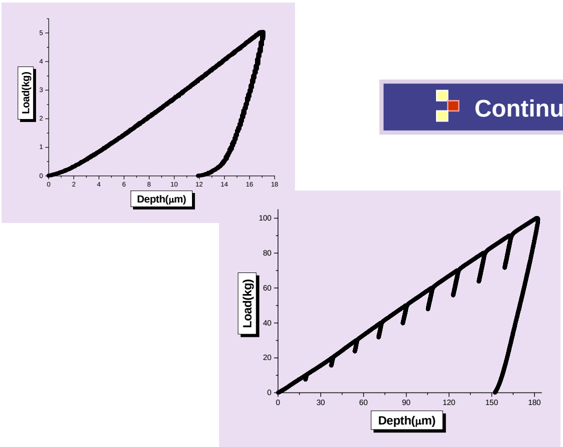




Continuous Indentation Test

- Flow curve
- Yield Strength
- Tensile Strength
- Work Hardening Exp.
- Fracture Toughness
- Residual Stress

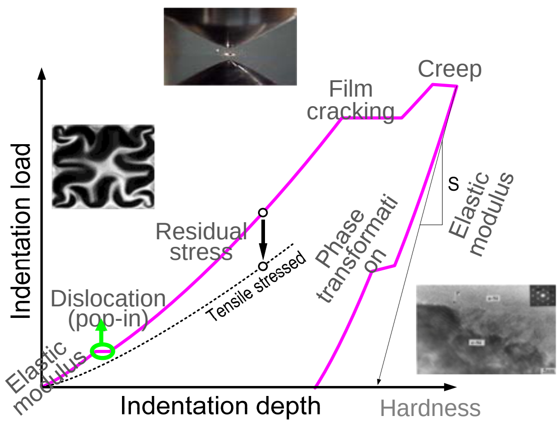
Instrumented Indentation Test (3)

Advanced Indentation

Instrumented indentation
Continuous indentation
Depth-sensing indentation
Innovative indentation

Indentation load-depth curve

" fingerprint of material like DNA "



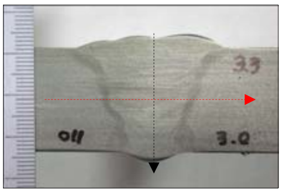
Merits of IIT

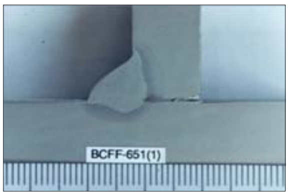
Measurement local properties
Easy sample preparation
Simple procedure
Non-destructive testing
Applied to in-service system
In-situ evaluation

In-field & Nondestructive Test

In-situ & In-field system

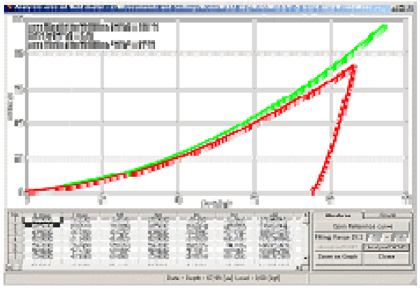
Non-destructive & Local test





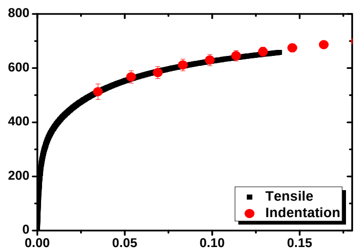
Simple & Fast

Convenient



Various Properties

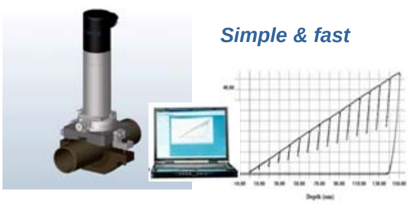
Tensile property



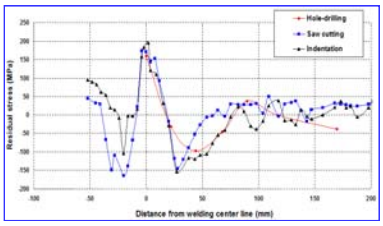
Uniaxial tensile test

Instrumented Indentation

Simple & fast



Residual stress



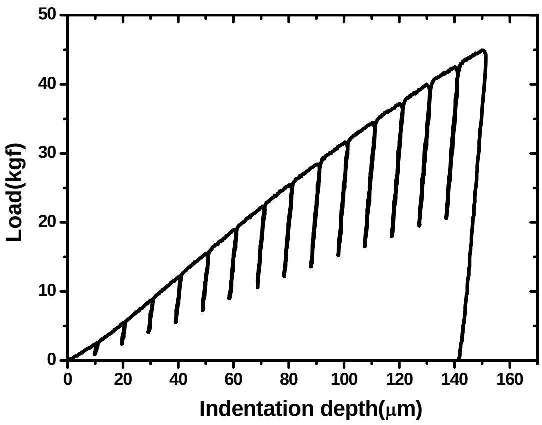
Hole drilling
Saw cutting
X-ray diffraction

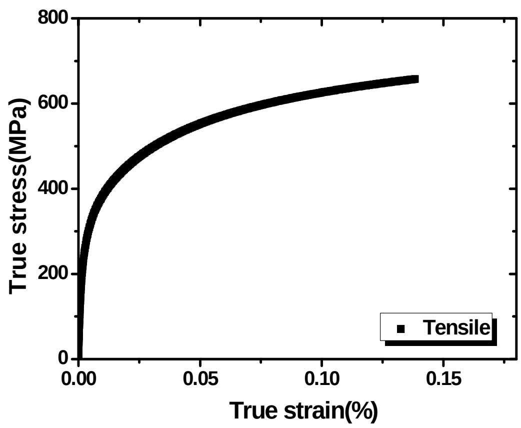
Strength

Evaluation of Strength using IIT

Can you imagine this?

Indentation curve ➡ **Tensile curve**

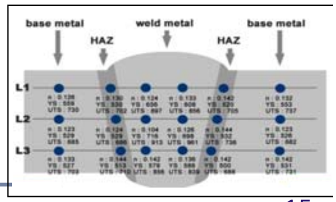




In ISO Documents

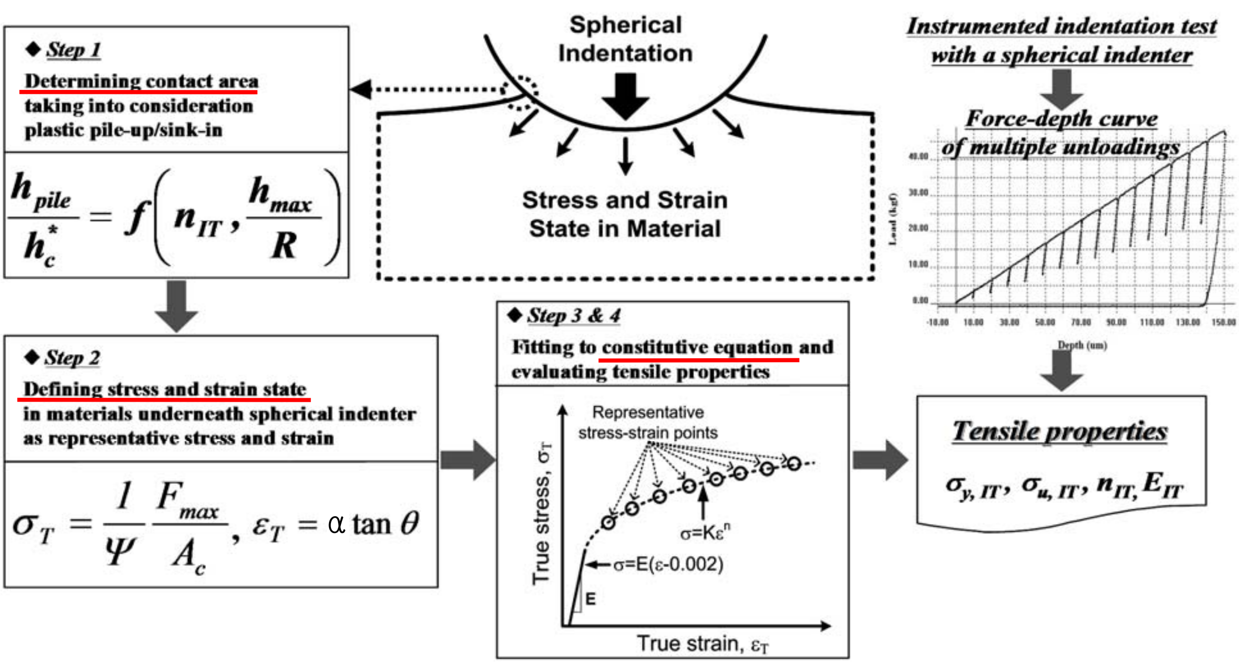
(ISO/TR29381, 2008)

	Tensile Test	IIT
Property Characterized	Bulk (average)	Local (surface)
Testing Nature	Destructive	Non-destructive
Sample Preparation	Machining	Surface polishing
Potential Examples	Laboratory (conventional) Large volume	In-field Small volume



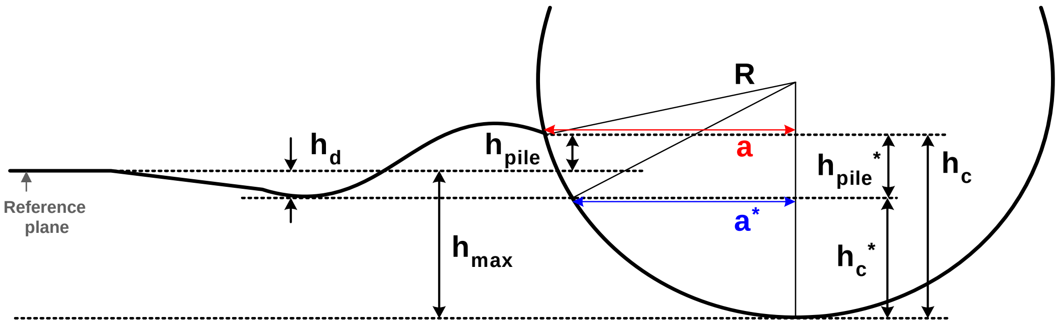
Algorithm for Strength Evaluation

[ISO/TR 29381, 2008]



Step 1_Determination of Contact Area

Plastic pile-up & elastic deflection



Pile-up

h_{pile}

Plastic deformation
+
Elastic deflection

Elastic deflection

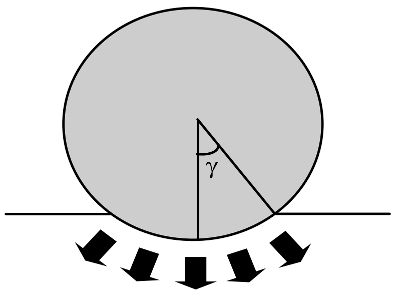
$-h_d$

Plastic pile-up

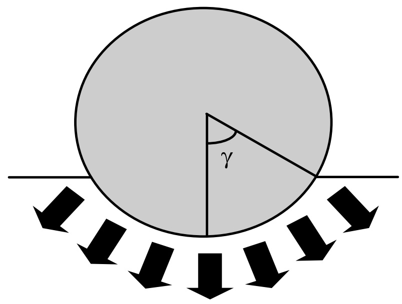
$+h^*_{pile}$

$$h_c = h_{max} - h_d + h^*_{pile}$$

Step 2_Representation of Stress & Strain



Indentation depth increases

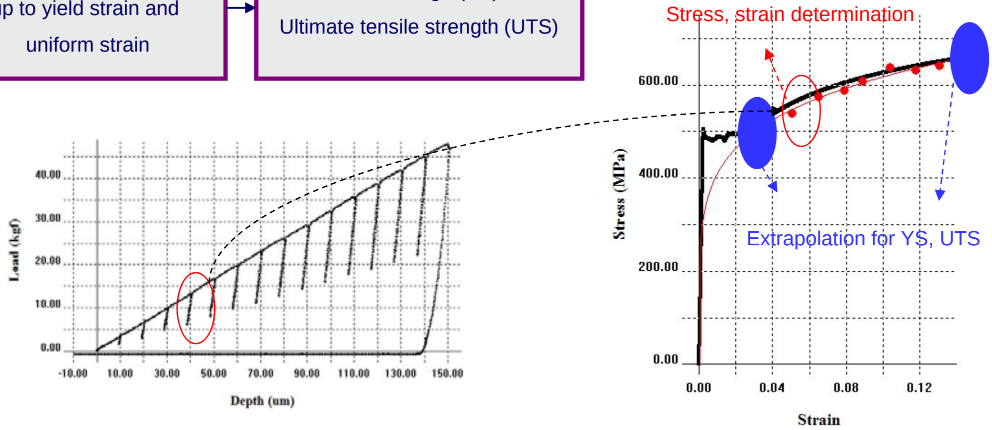


Stress and strain increase

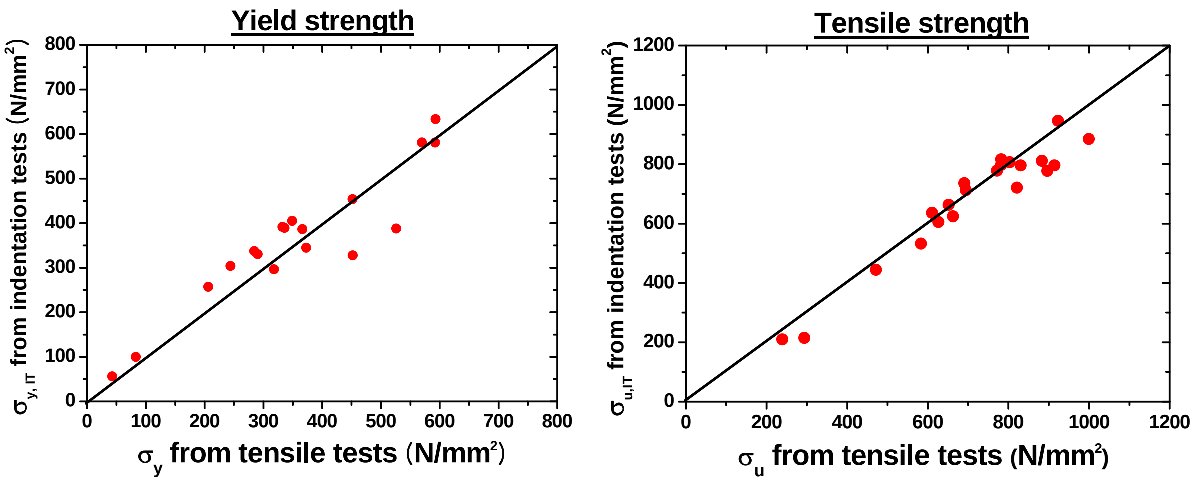
Representative Stress Definition	Representative Strain Definition
$\sigma = \frac{1}{\psi}\frac{L_{max}}{\pi a_c^2}$ **Ψ=3** for metallic material (by D. Tabor)	$\varepsilon = f(a_c / R)$ - Power-law hardening material **: 0.14tanγ** - Linear hardening material **: 0.3sinγ**

Flow Chart for Tensile Curve Derivation Using IIT

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



Results



Good agreement with results from tensile test

International Standardization Works (ISO)

TECHNICAL REPORT

ISO/TR 29381

First edition
2008-10-15

Metallic materials — Measurement of mechanical properties by an instrumented indentation test — Indentation tensile properties

Matériaux métalliques — Mesure des caractéristiques mécaniques par un essai de pénétration instrumenté — Caractéristiques de traction par indentation

Reference number
ISO/TR 29381:2008(E)

Annex A
(informative)

Measurement of residual stress by instrumented indentation test

A.1 General

This annex describes a method for evaluating residual stress in the test piece by an instrumented indentation test using Vickers and spherical indenters to measure test force and indentation depth.

This method for measuring residual stress non-destructively enables in-service components and laboratory materials of small volume suitable for indentation to be assessed usefully.

This method can be applied by the instrumented indentation test using only a Vickers indenter when the local true stress-strain curves caused by inhomogeneity of the test specimen are not changed, and can be applied by the instrumented indentation test using both Vickers and spherical indenters when those curves are changed.

A.2 Symbols and designations for measuring residual stress

See Table A.1.

Table A.1 — Symbols and designations for measuring residual stress

Symbol	Designation	Unit
T	Tensile residual stress state (used as subscript)	—
C	Compressive residual stress state (used as subscript)	—
0	Stress-free state (used as subscript)	—
s	The state including residual stress (used as subscript)	—
F	Test force	N
F_T	Test force under tensile residual stress	N
F_C	Test force under compressive residual stress	N
h	Indentation depth under applied test force	mm
h_m	A given indentation depth to determine force difference	mm
A	Contact area	mm^2
σ_{res}	Residual stress	N/mm^2
$\sigma_{x,d}$	Shear deviatoric stress component applied along the indentation test direction	N/mm^2
p	Ratio of residual stresses along one direction to those along the normal direction	—
Ψ	Ratio of average contact pressure to true stress (the plastic constraint factor)	—

 25

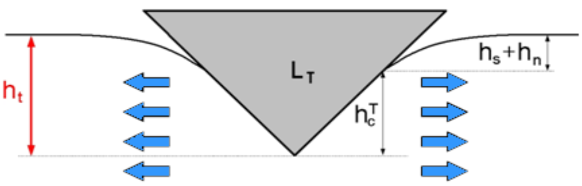
Residual Stress

Merits of IIT

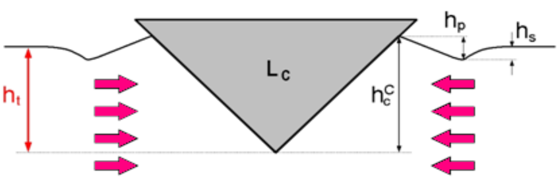
	Method	Merit	Limitation
Mechanical Methods	Hole-Drilling	- Quantitative & mechanical analysis	- Destructive
	Saw-Cutting		
Physical Methods	X-Ray Diffraction	- Non-destructive	- Only crystalline materials - Sensitive to environment
	Neutron Diffraction		

	Merit	
IIT	- **Quantitative & mechanical analysis** - **Non-destructive, can be used in field**	- **Any materials possible** - **Microstructure not influenced**

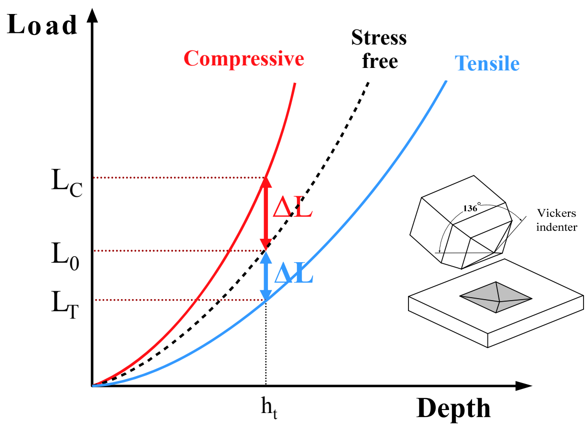
Basic Principle



Tensile stress



Compressive stress



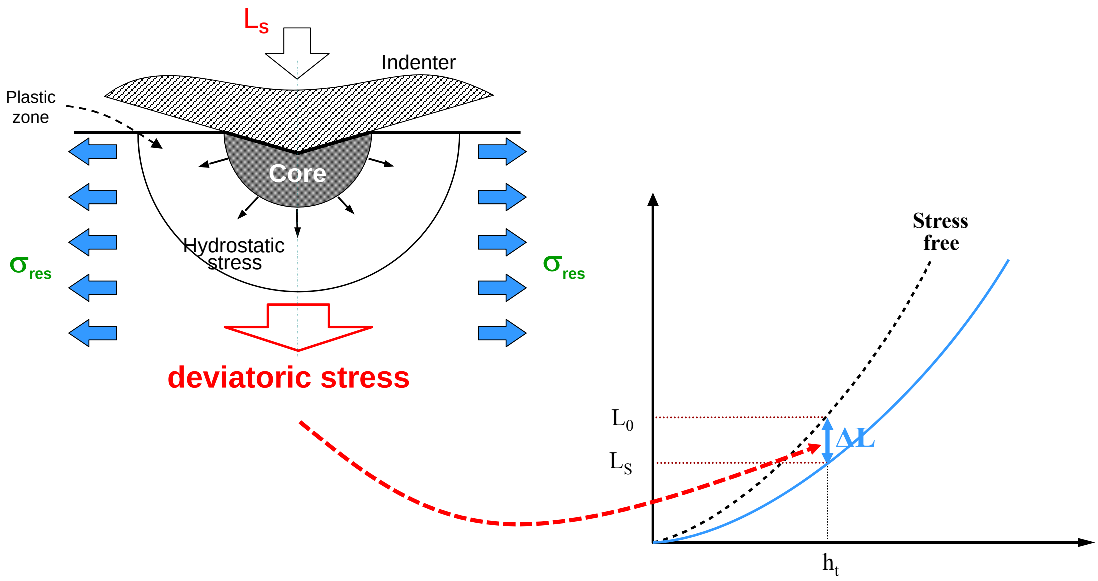
Indentation Load-Depth Curves

$$\Delta L = L_S - L_0$$

$(L_S = L_T \text{ or } L_C)$

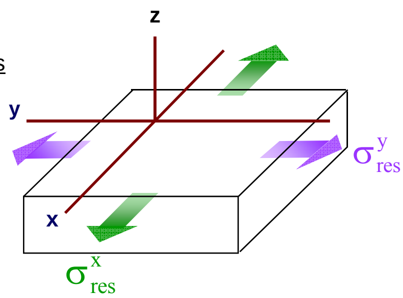
Stress Interaction

Indentation Load : L_S ⟷ Residual Stress : σ_{res}



Stress Tensor

Non-equibiaxial residual stress



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

Evaluation of Residual Stress by IIT

Residual Stress ⟷ **Indentation Load**

Deviatoric stress along Z direction : Indentation stress :

$$\frac{(1+p)}{3}\sigma_{res}^{x} = \sigma_{int}\left(=\frac{1}{\Psi}\frac{\Delta L}{A_S}\right)$$

where , Ψ = constraint factor (3.0)

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

$$\sigma_{res}^{x} = \frac{3}{(1+p)}\frac{1}{\Psi}\frac{\Delta L}{A_S} \qquad \left(p = \frac{\sigma_{res}^{y}}{\sigma_{res}^{x}}\ ,\quad \mathbf{A_S} = \text{Contact Area}\right)$$

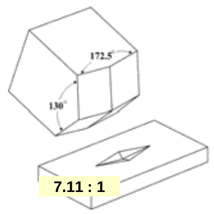
$$\boldsymbol{\sigma_{res}^{x} \propto \Delta L}$$

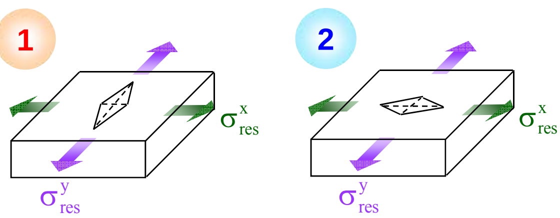
Directionality using Knoop Indenter

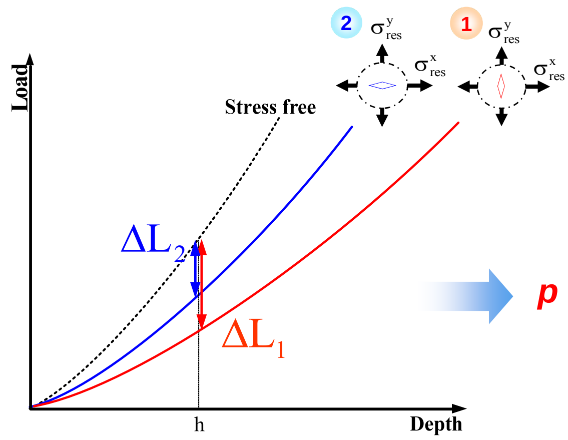
$$\sigma_{res}^{x} = \frac{3}{(1+p)}\frac{1}{\Psi}\frac{\Delta L}{A_S}$$

$$p = \frac{\sigma_{res}^{y}}{\sigma_{res}^{x}}$$ **(Stress Directionality)**

Knoop Indenter

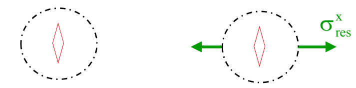






Determination of Conversion Factors

Stress-free Uni-axial stress

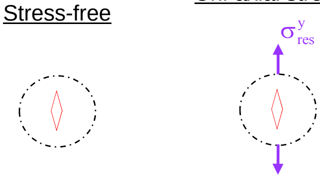


Comparison of indentation curves

$$\Delta L \approx \alpha_{\perp} \sigma^x_{res}$$

conversion factor
in **normal** direction

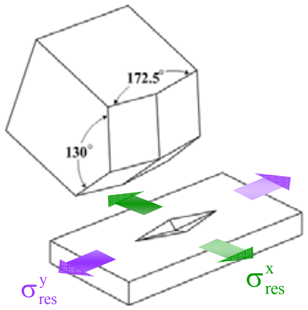
Stress-free Uni-axial stress



Comparison of indentation curves

$$\Delta L \approx \alpha_{//} \sigma^y_{res}$$

conversion factor
in **parallel** direction

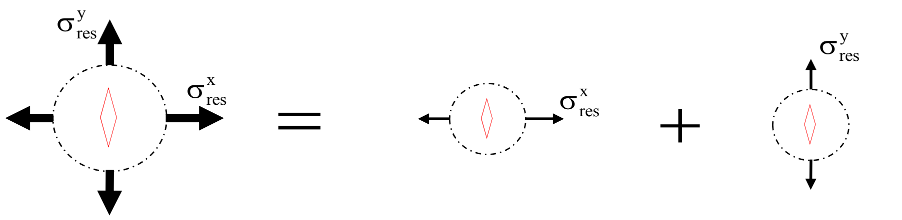


$\alpha_{\perp}$, $\alpha_{//}$ are conversion factors that are depth variables relating the residual stress to the indentation load difference

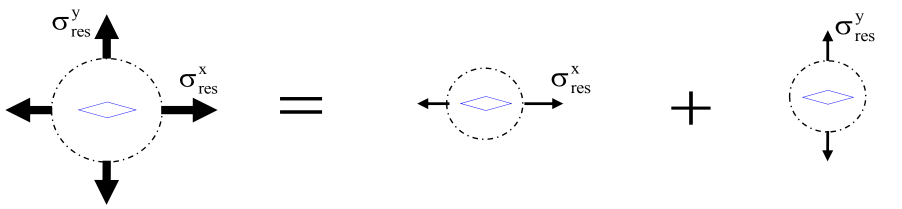
It can be proved that the ratio of conversion factors is constant.

$$\frac{\alpha_{//}}{\alpha_{\perp}} \approx 0.34$$ (from experiments)

Direct Summation



$$\Delta L_1 = \alpha_{\perp}\sigma^x_{res} + \alpha_{//}\sigma^y_{res}$$



$$\Delta L_2 = \alpha_{//}\sigma^x_{res} + \alpha_{\perp}\sigma^y_{res}$$

Knoop Indentation Modeling

$$\frac{\Delta L_2}{\Delta L_1} = \frac{\alpha_{//}\,\sigma^x_{res} + \alpha_{\perp}\,\sigma^y_{res}}{\alpha_{\perp}\,\sigma^x_{res} + \alpha_{//}\,\sigma^y_{res}}$$

$$\frac{\dfrac{\alpha_{//}}{\alpha_{\perp}} + \dfrac{\sigma^y_{res}}{\sigma^x_{res}}}{1 + \dfrac{\alpha_{//}\,\sigma^y_{res}}{\alpha_{\perp}\,\sigma^x_{res}}} = \frac{\dfrac{\alpha_{//}}{\alpha_{\perp}} + p}{1 + \dfrac{\alpha_{//}}{\alpha_{\perp}}p}$$

$$\frac{\Delta L_2}{\Delta L_1} = \frac{\dfrac{\alpha_{//}}{\alpha_{\perp}} + p}{1 + \dfrac{\alpha_{//}}{\alpha_{\perp}}p}$$

$$p = \frac{\sigma^y_{res}}{\sigma^x_{res}} = \frac{\dfrac{\Delta L_2}{\Delta L_1} - 0.34}{1 - 0.34\dfrac{\Delta L_2}{\Delta L_1}}$$

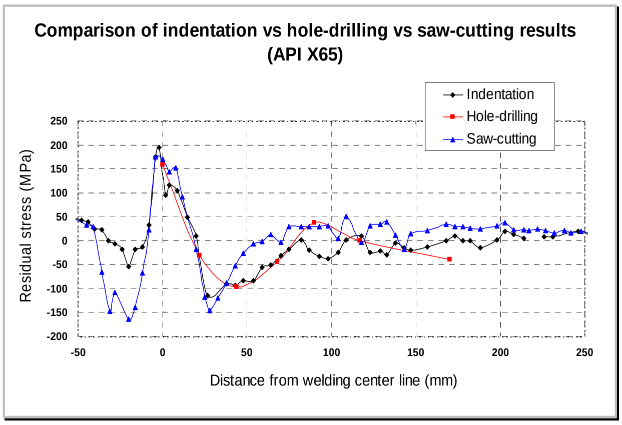
$$\frac{\alpha_{//}}{\alpha_{\perp}} \approx 0.34$$

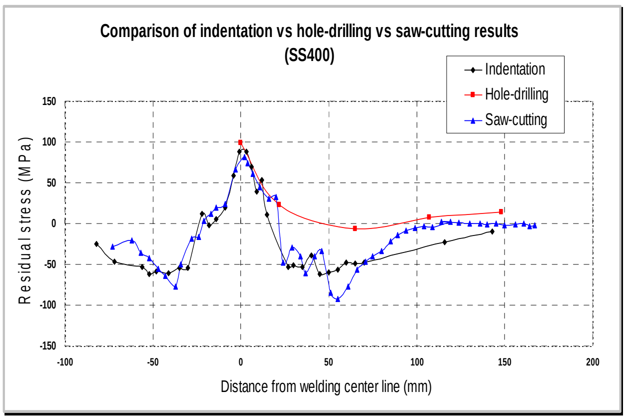
Experimental data

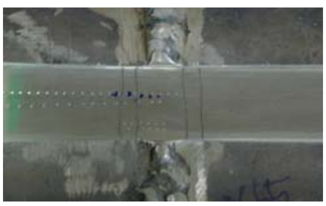
Experimental Verification

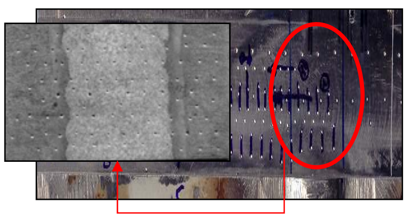
API X65

SS400










Thank You
for Your Attention