Residual Stress Evaluation Instrumented Indentation Testing

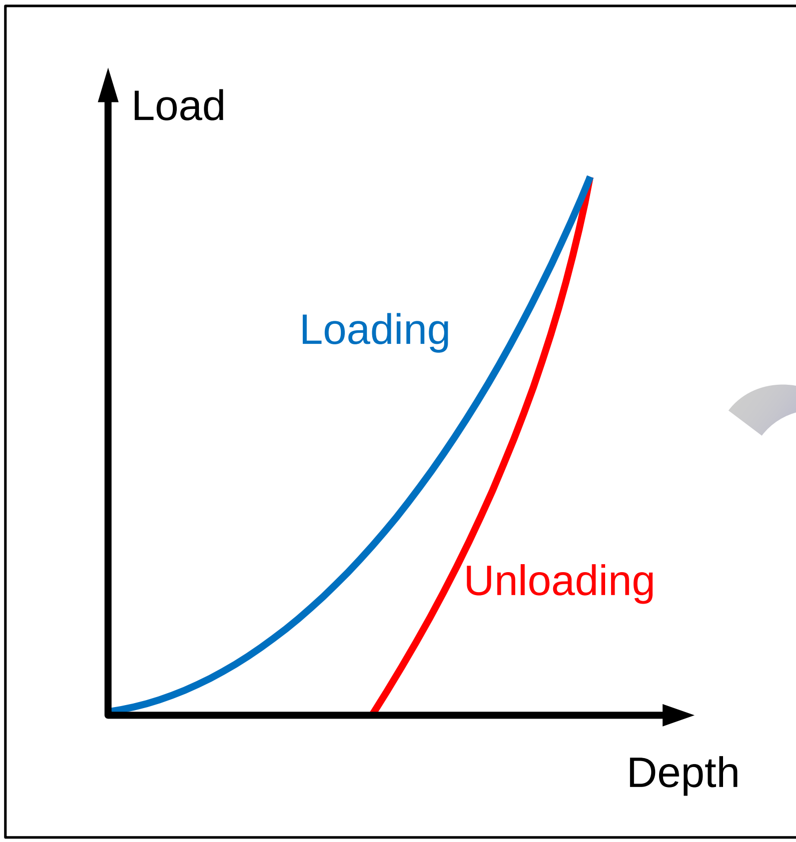
2018. 03. 26.

Jun Sang Lee

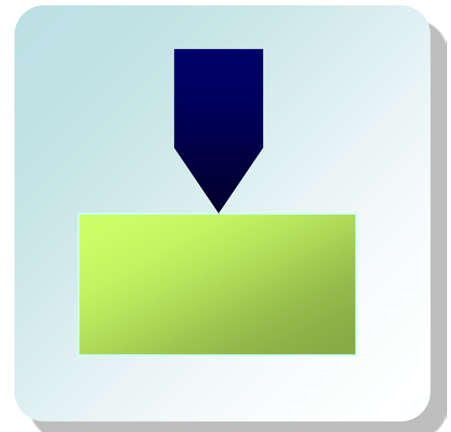
Contents

Instrumented Indentation Test

A novel method to characterize mechanical properties



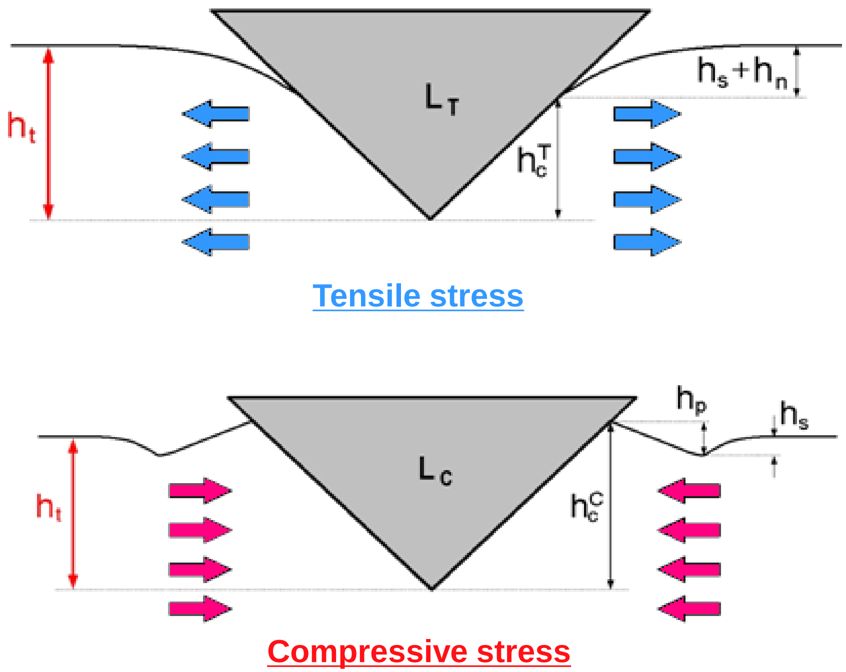
Indentation load-depth curve

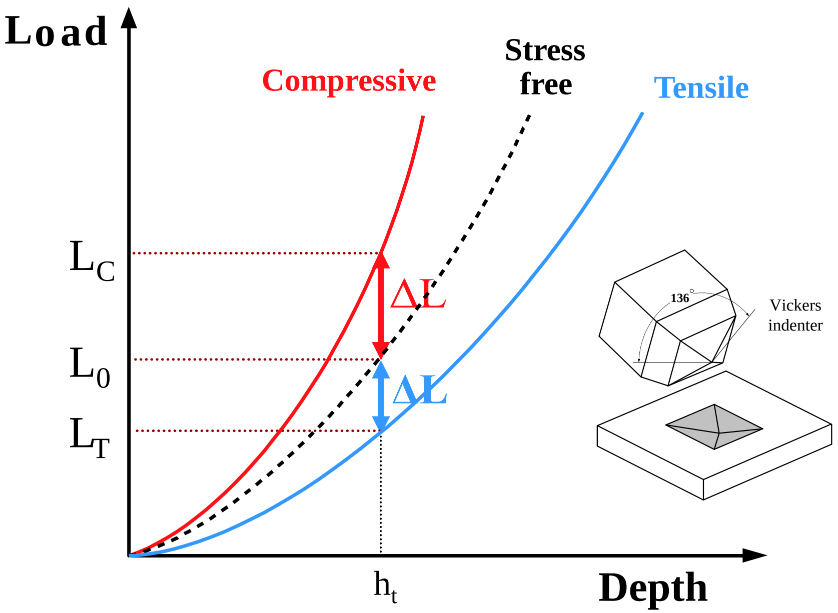


Hardness
Elastic modulus
Tensile properties
Residual stress
Fracture toughness

"fingerprint of material"

Basic Principle



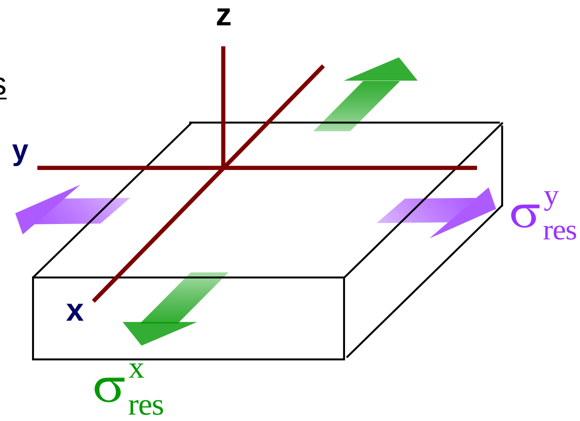


Indentation Load-Depth Curves

$$\Delta L = L_S - L_0$$

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

Stress Tensor



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

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

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

hydrostatic stress

deviatoric stress

Material Reliability & Forensic Safety Lab.

Residual Stress Evaluation 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)

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

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

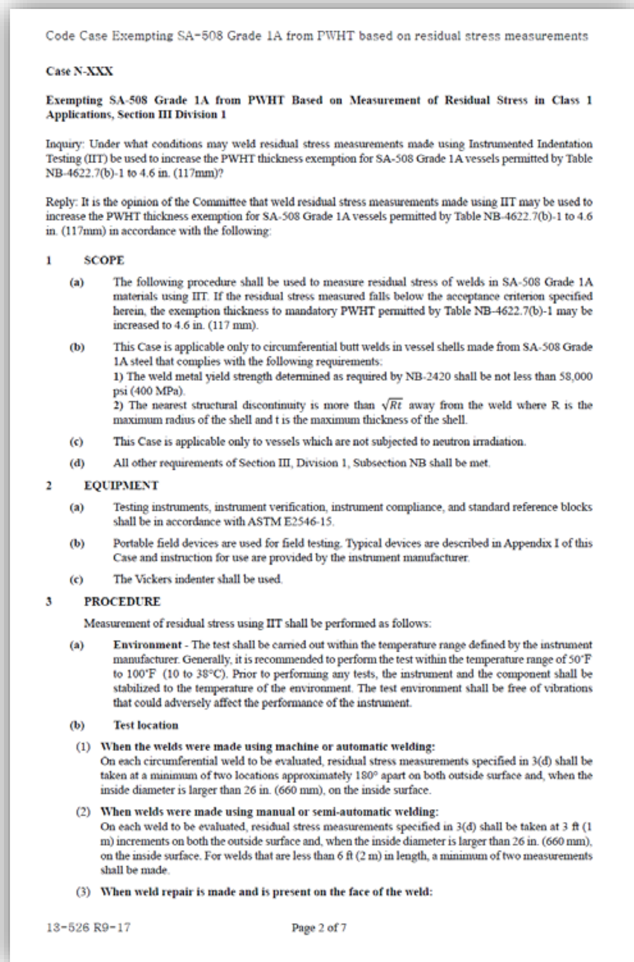
$$\left(p = \frac{\sigma_{res}^{y}}{\sigma_{res}^{x}} \;,\quad \mathbf{A_S} = \text{Contact Area}\right)$$

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

Code Case N-881

<Code Case N-881>

Exempting SA-508 Grade 1A from PWHT Based on Measurement of Residual Stress in Class 1 Applications



Code Case Exempting SA-508 Grade 1A from PWHT based on residual stress measurements

Case N-XXX

Exempting SA-508 Grade 1A from PWHT Based on Measurement of Residual Stress in Class 1 Applications, Section III Division 1

Inquiry: Under what conditions may weld residual stress measurements made using Instrumented Indentation Testing (IIT) be used to increase the PWHT thickness exemption for SA-508 Grade 1A vessels permitted by Table NB-4622.7(b)-1 to 4.6 in. (117mm)?

Reply: It is the opinion of the Committee that weld residual stress measurements made using IIT may be used to increase the PWHT thickness exemption for SA-508 Grade 1A vessels permitted by Table NB-4622.7(b)-1 to 4.6 in. (117mm) in accordance with the following:

1 SCOPE

(a) The following procedure shall be used to measure residual stress of welds in SA-508 Grade 1A materials using IIT. If the residual stress measured falls below the acceptance criterion specified herein, the exemption thickness to mandatory PWHT permitted by Table NB-4622.7(b)-1 may be increased to 4.6 in. (117 mm).

(b) This Case is applicable only to circumferential butt welds in vessel shells made from SA-508 Grade 1A steel that complies with the following requirements:
1) The weld metal yield strength determined as required by NB-2420 shall be not less than 58,000 psi (400 MPa).
2) The nearest structural discontinuity is more than $\sqrt{Rt}$ away from the weld where R is the maximum radius of the shell and t is the maximum thickness of the shell.

(c) This Case is applicable only to vessels which are not subjected to neutron irradiation.

(d) All other requirements of Section III, Division 1, Subsection NB shall be met.

2 EQUIPMENT

(a) Testing instruments, instrument verification, instrument compliance, and standard reference blocks shall be in accordance with ASTM E2546-15.

(b) Portable field devices are used for field testing. Typical devices are described in Appendix I of this Case and instruction for use are provided by the instrument manufacturer.

(c) The Vickers indenter shall be used.

3 PROCEDURE

Measurement of residual stress using IIT shall be performed as follows:

(a) **Environment** - The test shall be carried out within the temperature range defined by the instrument manufacturer. Generally, it is recommended to perform the test within the temperature range of 50°F to 100°F (10 to 38°C). Prior to performing any tests, the instrument and the component shall be stabilized to the temperature of the environment. The test environment shall be free of vibrations that could adversely affect the performance of the instrument.

(b) **Test location**

(1) **When the welds were made using machine or automatic welding:**
On each circumferential weld to be evaluated, residual stress measurements specified in 3(d) shall be taken at a minimum of two locations approximately 180° apart on both outside surface and, when the inside diameter is larger than 26 in. (660 mm), on the inside surface.

(2) **When welds were made using manual or semi-automatic welding:**
On each weld to be evaluated, residual stress measurements specified in 3(d) shall be taken at 3 ft (1 m) increments on both the outside surface and, when the inside diameter is larger than 26 in. (660 mm), on the inside surface. For welds that are less than 6 ft (2 m) in length, a minimum of two measurements shall be made.

(3) **When weld repair is made and is present on the face of the weld:**

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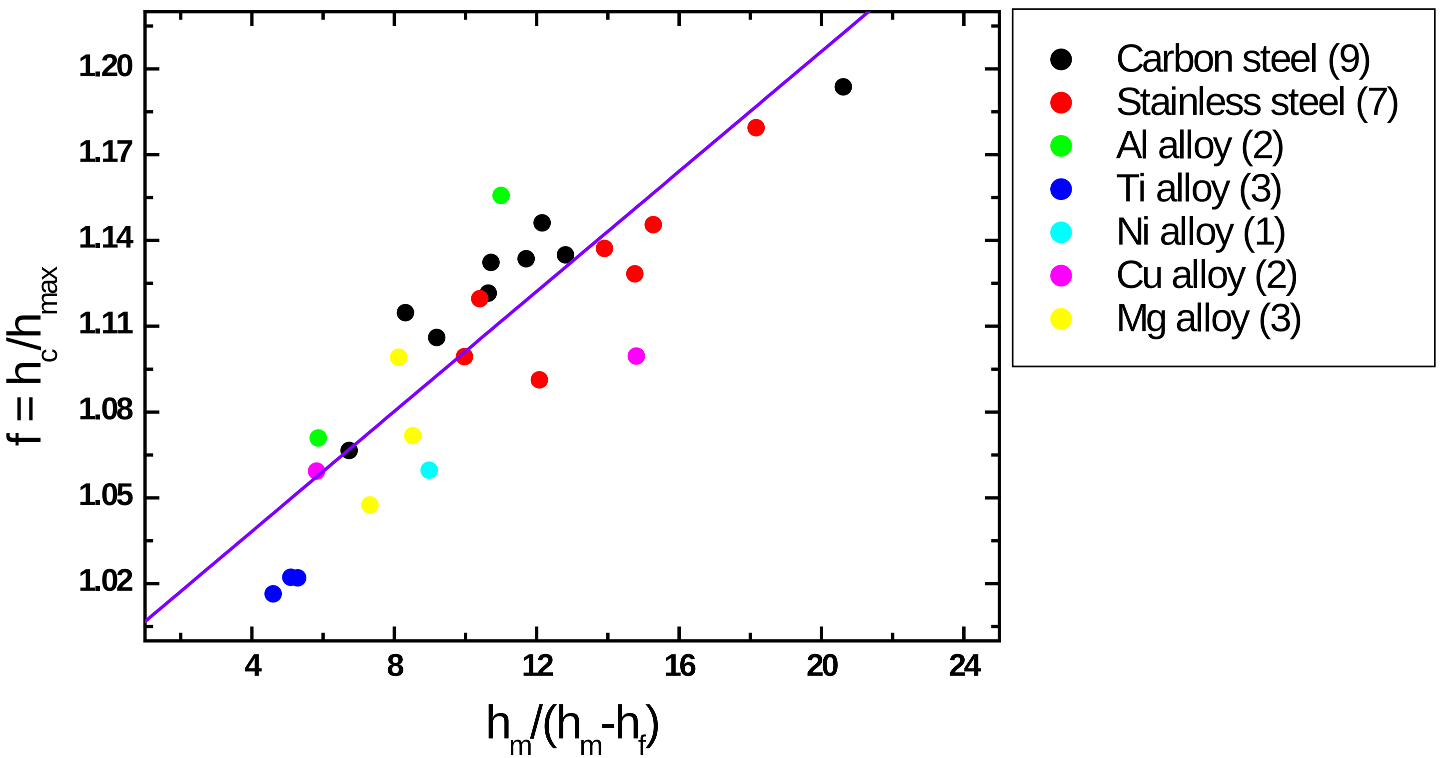
- **Work period : 2013.03 ~ 2017.12**
- **Session : Section III**
  Construction of Nuclear Facility Component
- **ASME Code Case N-881 – Approved in 2017**

Contents

Contact area equation for sharp indenter

- S.K. Kang *et al.*, *J. Mater. Res.* (2010)

For 27 metallic materials



$$f = \frac{h_c}{h_{max}} = 9.90 \times 10^{-3} \frac{h_{max}}{h_{max} - h_f} + 1.00$$

f-function Model

- **Assumption**

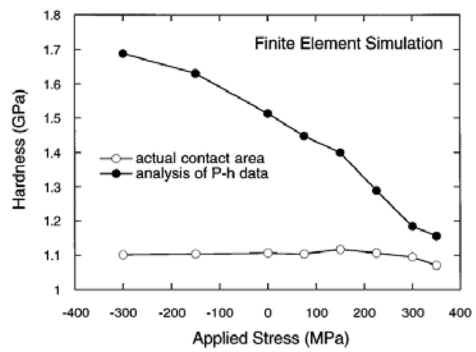
$$H^{t}_{v,0} = H^{t}_{v,s}$$ *[Swadener, Pharr, 2001]*

• A_c, h_c are invariant to residual stress.

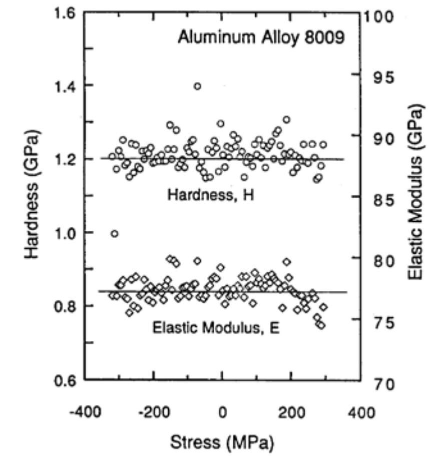
• $h_{max} - h_f$ is invariant to residual stress.

• $h^{0}_{max,t}$ is obtained using f-function.

[A. Bolshakov et al., J. Mater, Res (1996)]



[T.Y. Tsui et al., J. Mater, Res (1996)]



- **Equation**

A_c → h_c → h^{0}_{max} → k → S-F curve

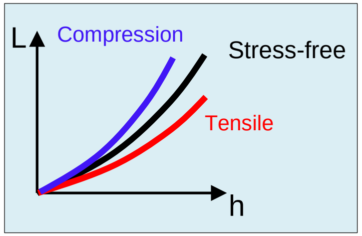
$A_c = 24.5 h_c^2$

$f - function$ (h_c & $h_{max} - h_f$ relation)

$$\frac{h_c}{h_{max}} = 0.99 \times 10^{-2} \frac{h_{max}}{h_{max} - h_f} + 1.00$$

Kick's law

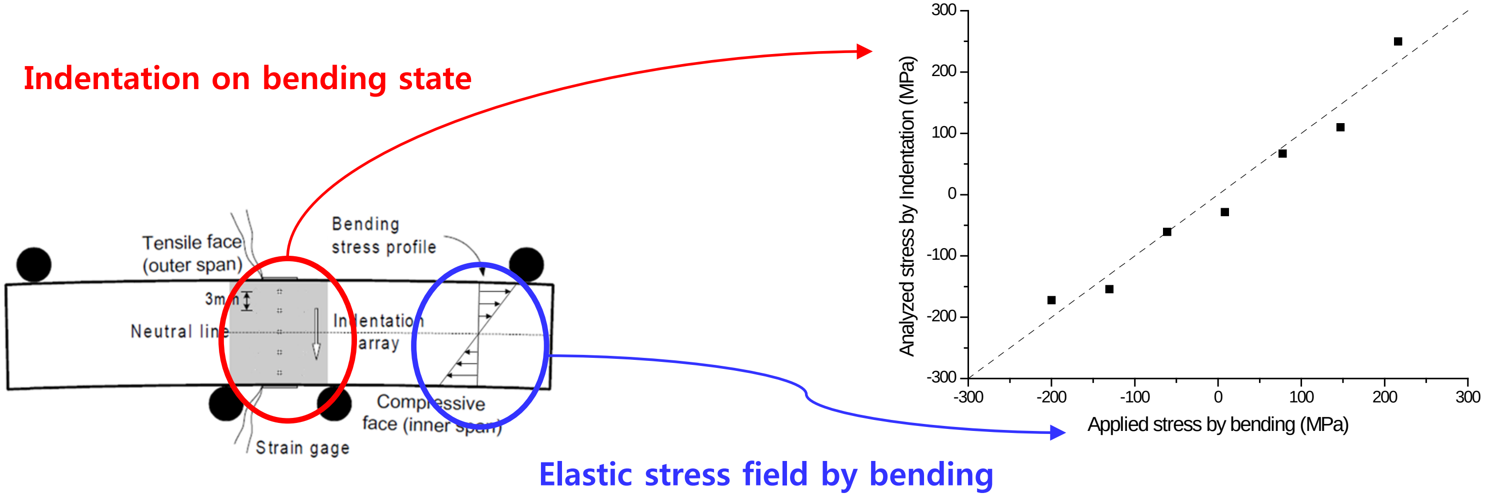
$L = kh^2$



Verification Test

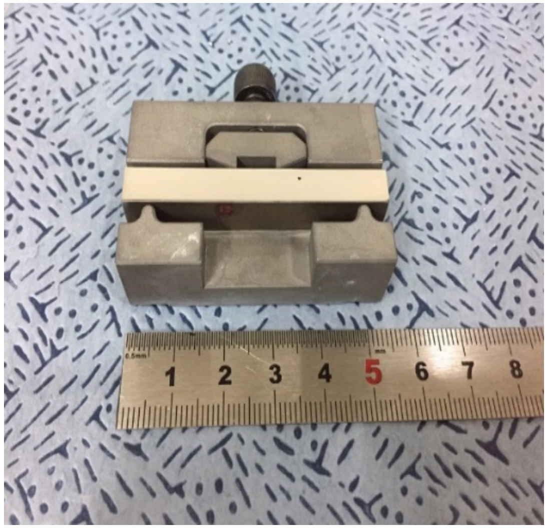
Applied Stress Specimen

- Material : SA-508 Grade 1A
- Test Equipment : Indentation AIS 3000, FRONTICS
- Test Condition : 50 kgf load condition



Invariant Parameter Analysis in Nano Scale

Position	1	2	3	4	5	6
Stress(Mpa)	-135.602	-61.4133	12.775	86.96333	161.1517	235.34

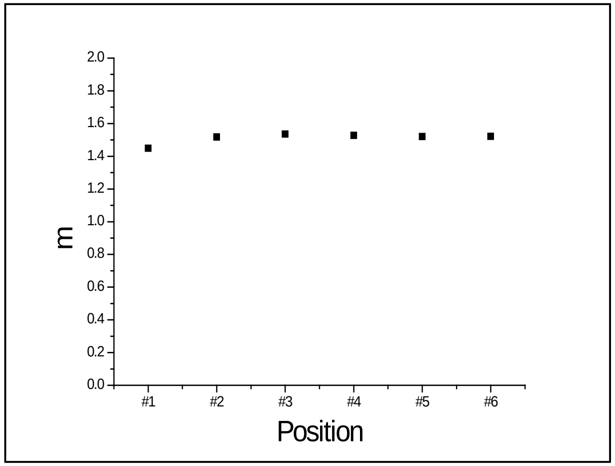


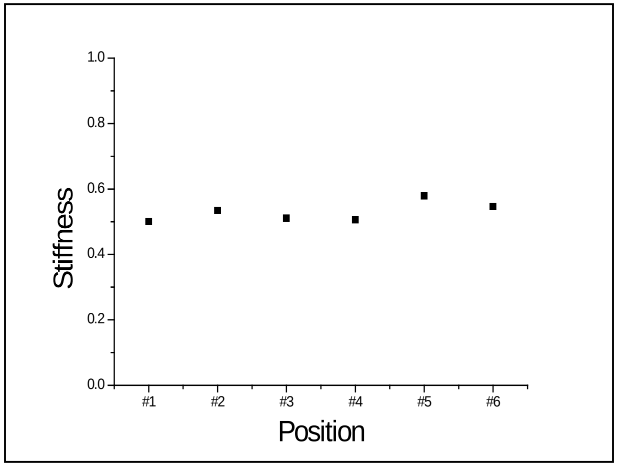
Test Condition

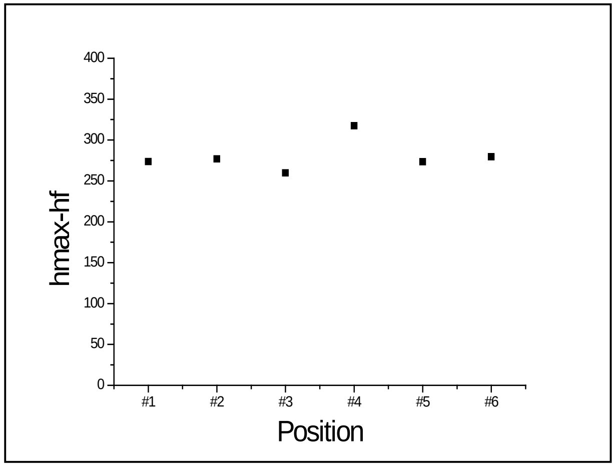
Target Material : SUS316(Bulk)

Specimen Treatment : Heat treatment for stress relaxation

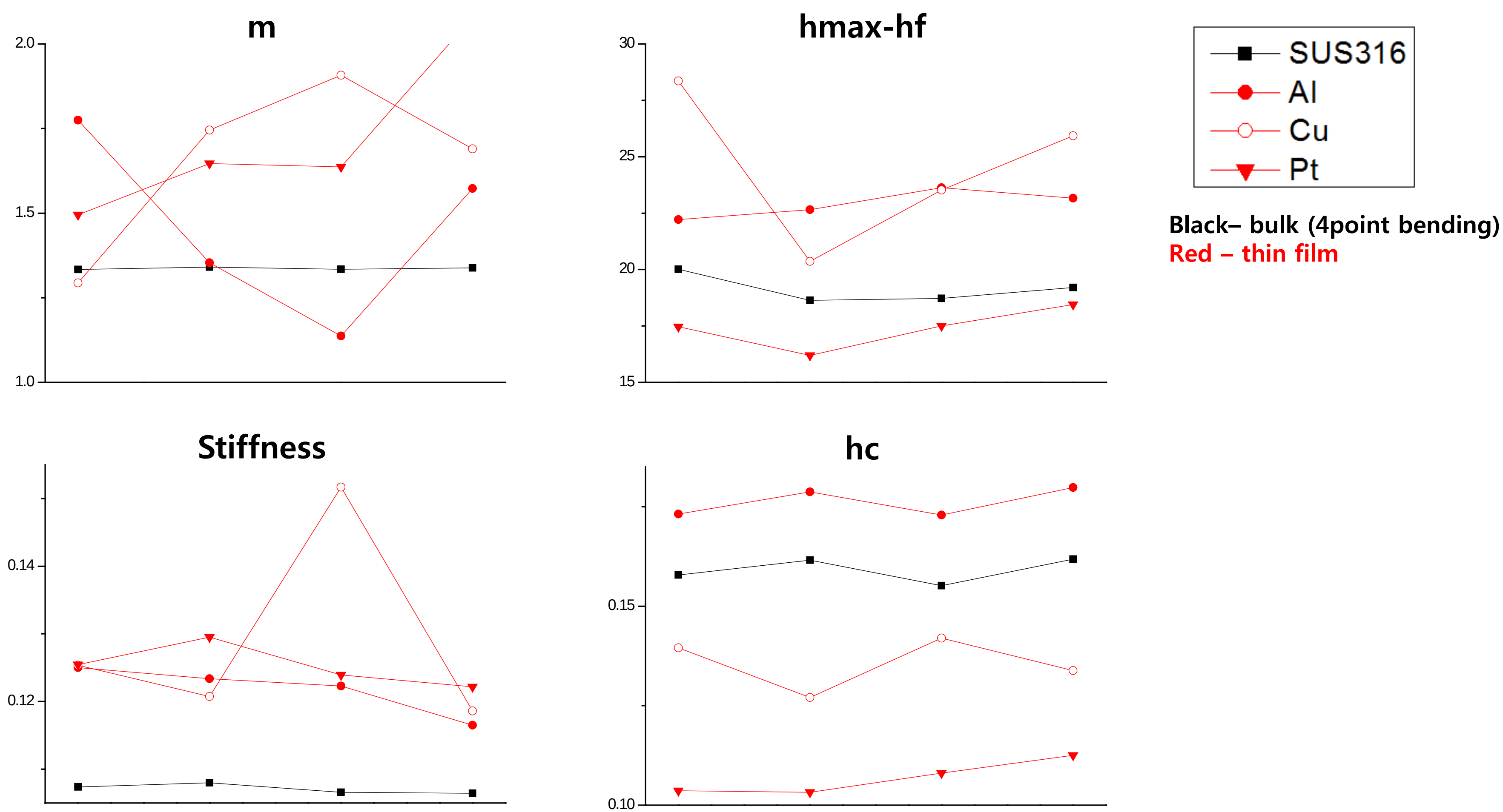
Maximum Load : 60mN





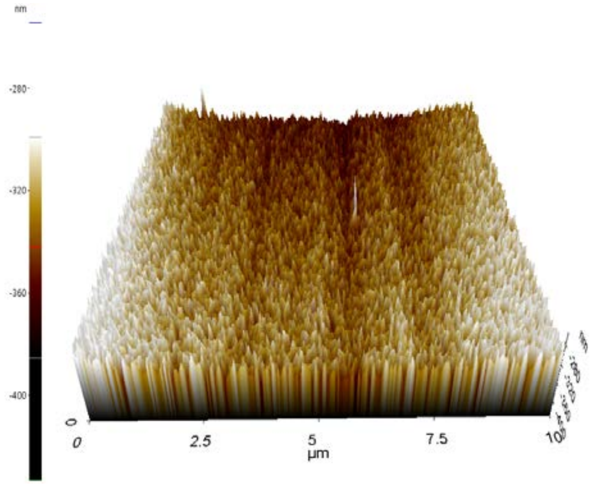


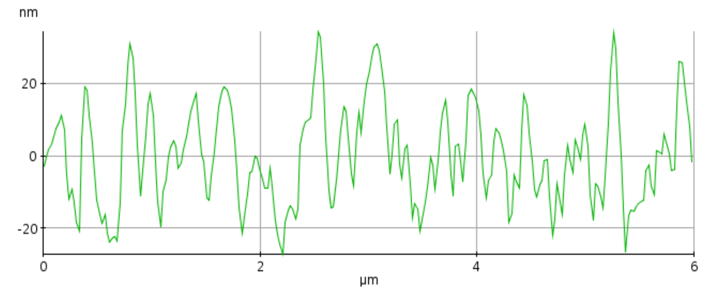
Comparing Invariant Parameters (Bulk vs Thin film)

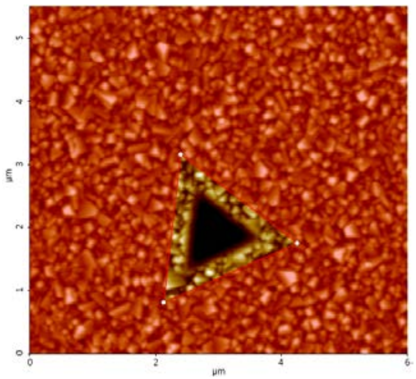


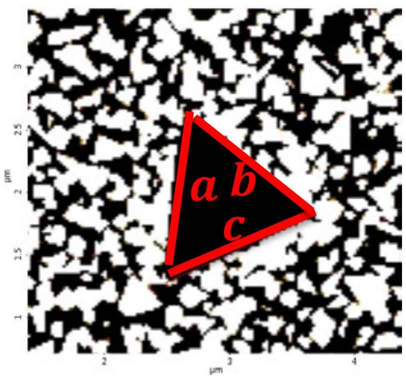
Invariant parameters of thin film have greater deviation than bulk metal
(∵inhomogeneous deposition & roughness effect)
⇒ hmax-hf, hc have less deviation than m.

Contact Area Mesurement









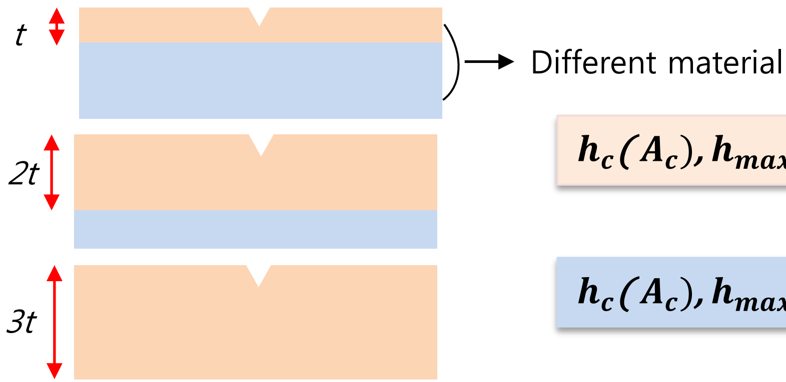
$$S = \sqrt{s(s-a)(s-b)(s-c)} \qquad \left(s = \frac{a+b+c}{2} \right)$$

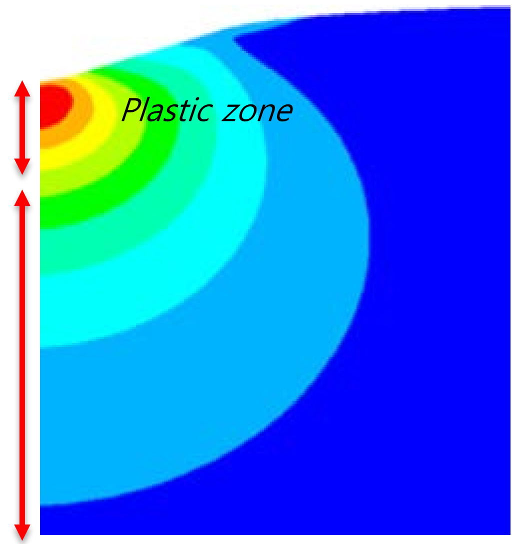
- AFM resolution limit degrades accuracy of indentation area

Substrate Effect

- Thin film with various deposition depth

- Check the change of curve depending on $\frac{h_{max}}{t}$ with same load condition

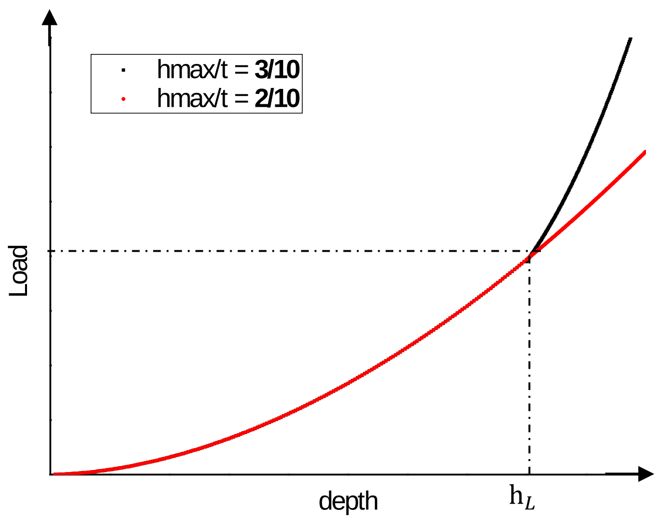


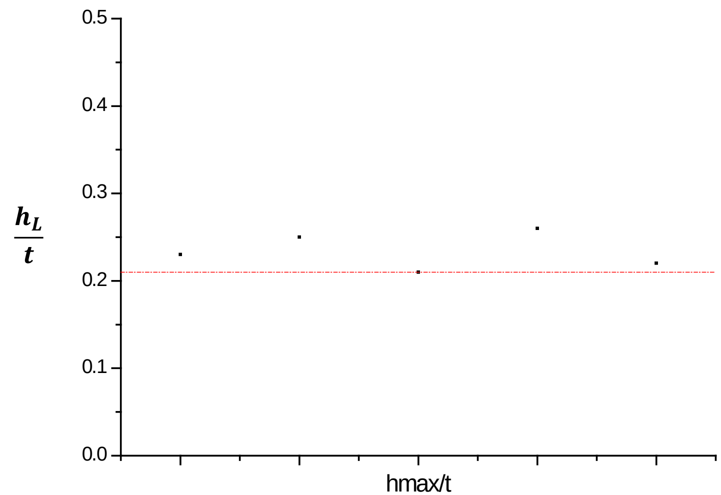


$h_c(A_c), h_{max} - h_f$ → h_{max}

Estimation

$h_c(A_c), h_{max} - h_f$ → h_{max}





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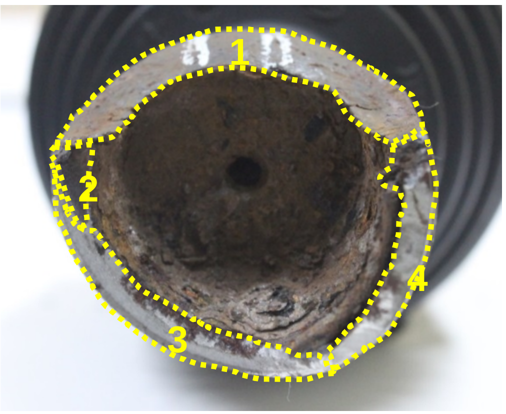
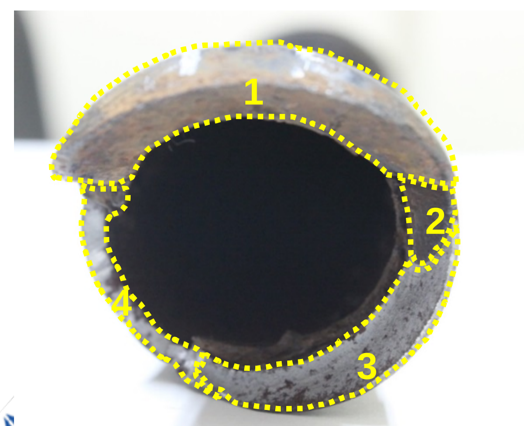
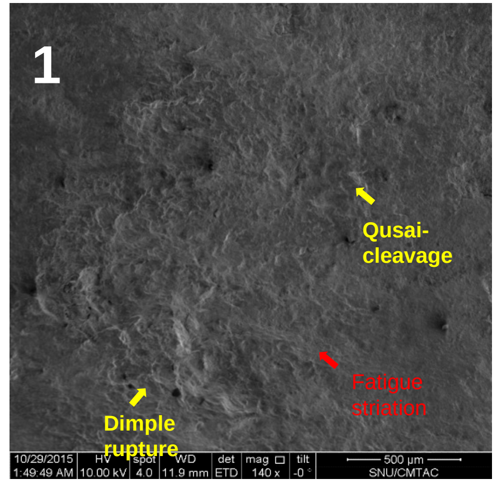
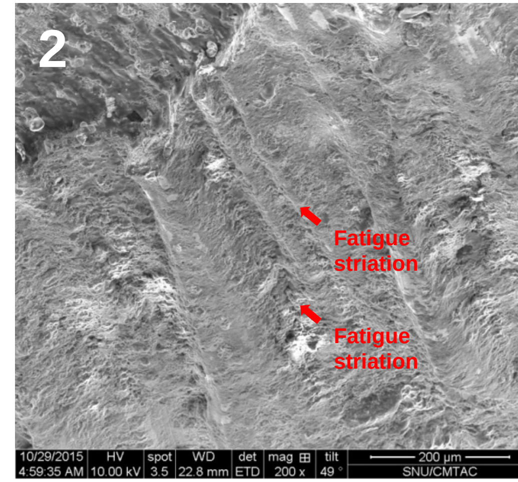
4. LTT Welding Integrity Evaluation

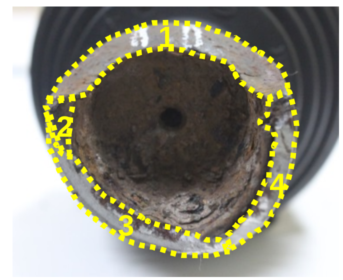
Fracture Analysis

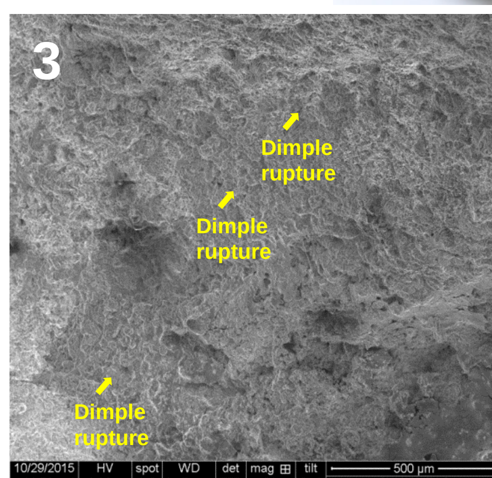


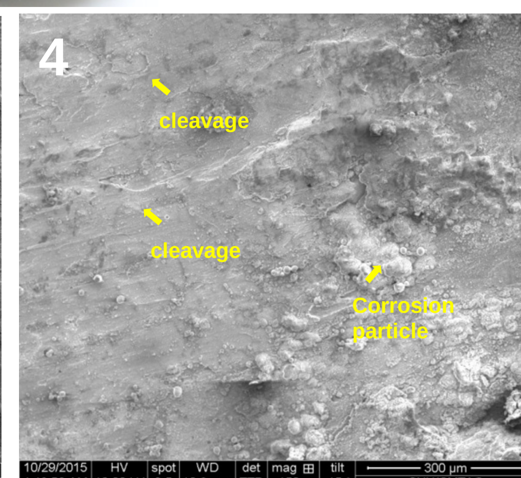










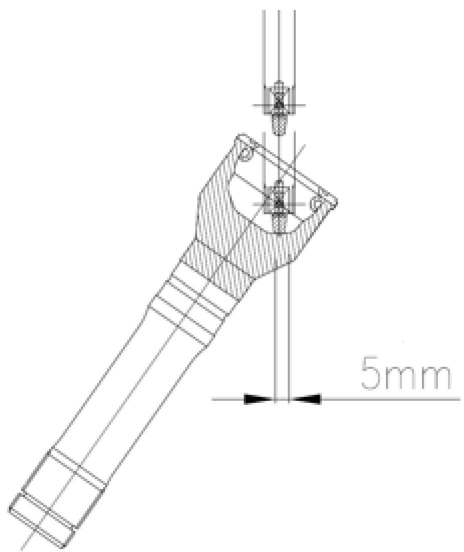


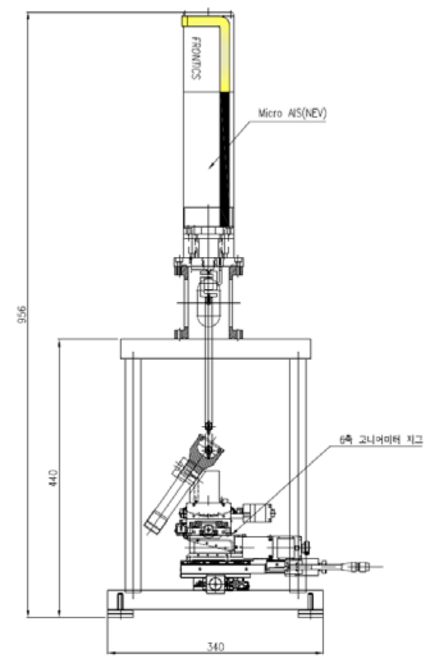
Issue 1 Resolution: Evaluation for inner slope part

- 6 axis jig

- Insturmented Indentatiton test on the slope of the inner part of drive shafts
- The inner shape of the drive shaft is different for each part

- Results





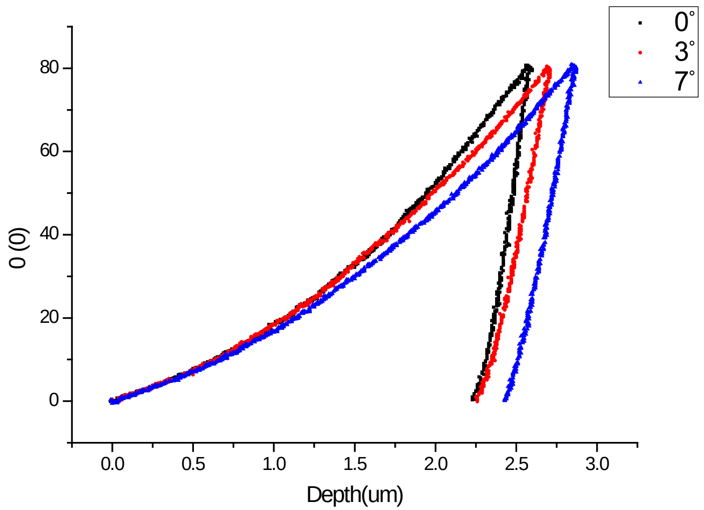
→ Manufacture jig for Micro-AIS with adjustable angle

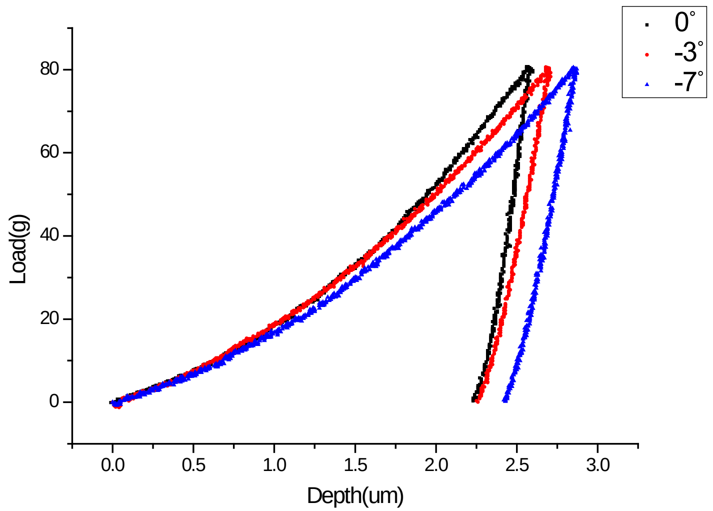
Issue 2 Resolution : Optimal test angle

- Optimal test angle setting

- For correct data indentation direction should be perpendicular to the surface of specimen.
- Symmetrical curve were generated according to the test angle change with reference curve (perpendicular direction)

- Results



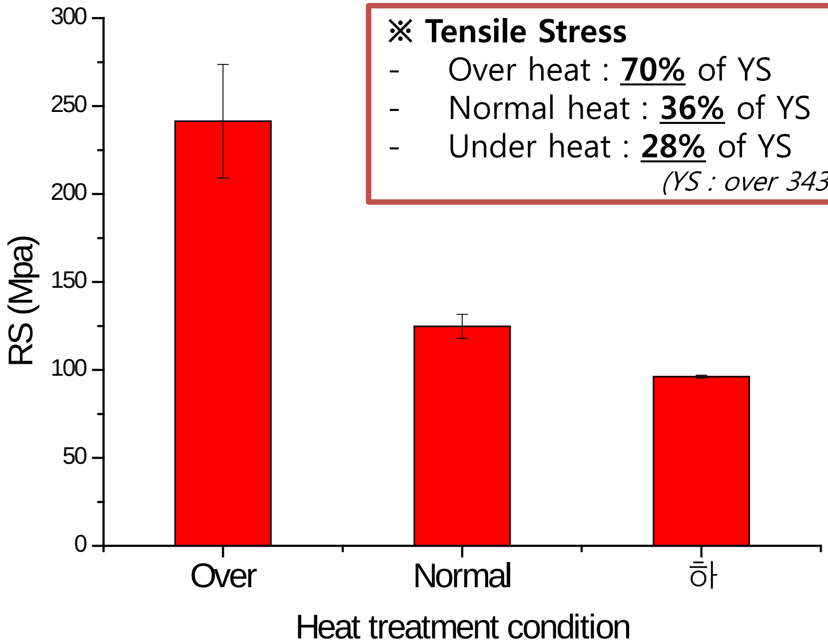


- Maximum indentation depth increases with test angle

→ Determine the optimal test angle condition for each specimen

Residual Stress Results

- Evaluation Results



※ **Tensile Stress**
- Over heat : **70%** of YS
- Normal heat : **36%** of YS
- Under heat : **28%** of YS

(YS : over 343 MPa)

Sample		RS (MPa)
Heat treatment	#	
Over heat	1	305.98
	2	234.09
	3	238.66
	4	186.67
	Ave	**241.35**
Normal heat	1	126.42
	2	122.82
	3	136,65
	4	112.80
	Ave	**124.67**
Under heat	1	80.61
	2	104.41
	3	102.11
	4	97.68
	Ave	**96.20**

Tensile residual stress increases as out surface heat treatment condition.

(→ For accurate analysis, applied stress information during operation should be added)

Evaluation of Failure Sensitivity of Drive Shaft

$$K_{Ir} = RS(\pi a / 1000)^{0.5} F_m$$

RS : residual stress
a : Depth of crack (assume as 2mm)

$$F_m = 1.10 + (a/t)(0.15241 + 16.772(a\theta/\pi t)0.855 - 14.944(a\theta/\pi t))$$

$$f_2 = A_2 \cdot \frac{K_{Ir}}{K_{IC}}$$

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LTT(Low Transformation Temperature) Welding

- **Definition**

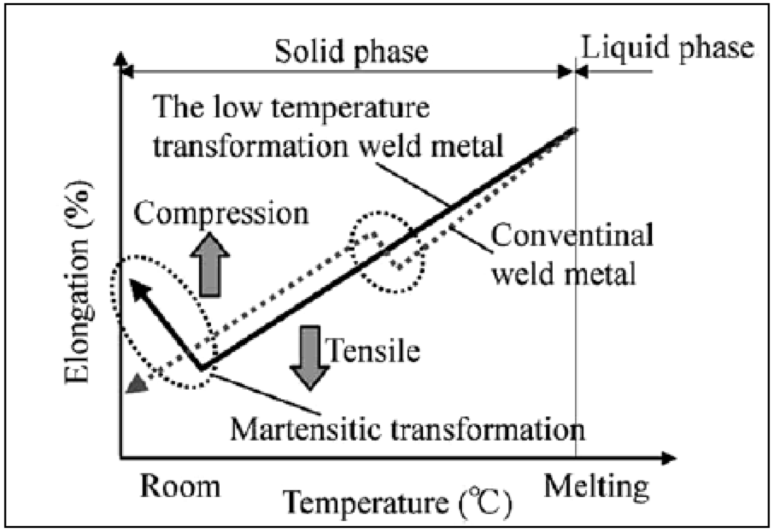
  The novel welding method with relatively low temperature martensitic transformation of welding filler

- **Purpose**

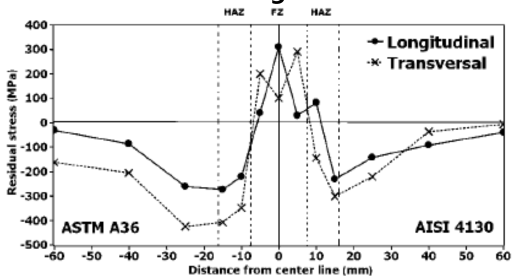
  Reducing tensile residual stress or inducing compressive residual stress in weld material

- **Basic Principle**

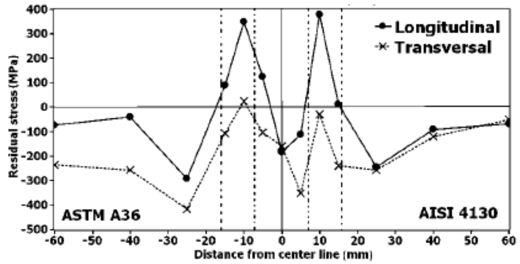
Strain by Phase Transformation → Compressive Residual stress/strain



(a) Conventional welding



(b) LTT welding



(Application of low Ms temperature consumable to dissimilar welded joint, 2014)

C/S welding & LTT welding

- **C/S (Carbon steel) welding & LTT welding**

[C/S welding]

[LTT welding]

Angular Distortion

Vickers Hardness

YS, UTS

CVN test

Residual Stress

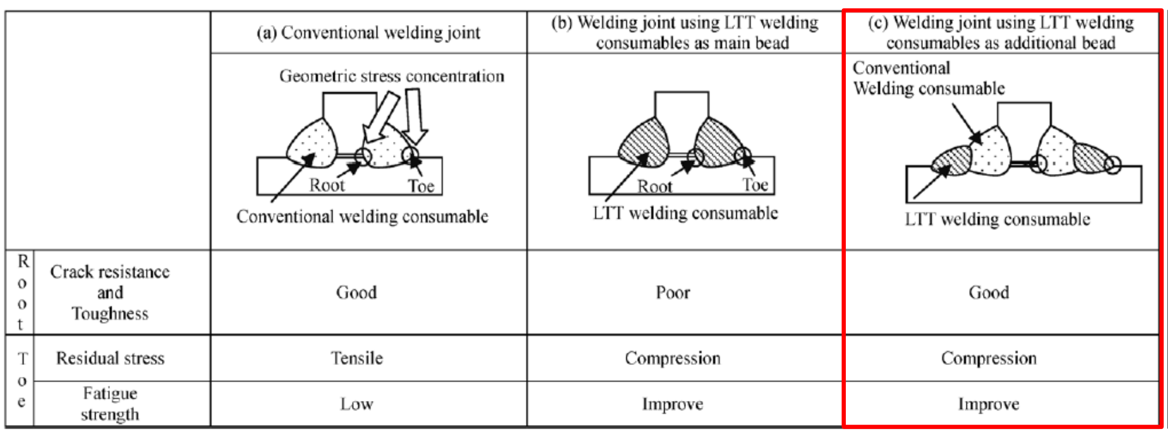
Validation of LTT welding by comparing convational welding

C/S welding & LTT welding

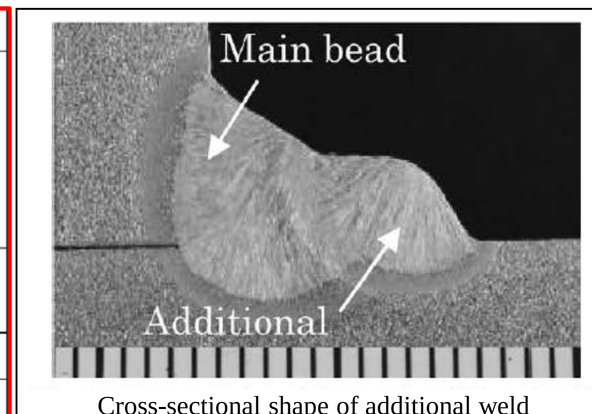
- **C/S (Carbon steel) welding & LTT welding**
  (Base Metal : A516 70N)

	Weld material	Type	Welding	
1	TGC-50 (C/S)	Bead on plate	TIGW	-
2	GSCO12 (Ni- LTT)			-
3	K-71T (C/S)	Butt Joint	FCAW	-
4	K-71T (C/S)			PWHT
5	MX-4AD (Mn- LTT)			-
6	MX-4AD & K-71T			Partial

Partial LTT Welding



		(a) Conventional welding joint	(b) Welding joint using LTT welding consumables as main bead	(c) Welding joint using LTT welding consumables as additional bead
		Geometric stress concentration; Root; Toe; Conventional welding consumable	Root; Toe; LTT welding consumable	Conventional Welding consumable; LTT welding consumable
Root	Crack resistance and Toughness	Good	Poor	Good
Toe	Residual stress	Tensile	Compression	Compression
	Fatigue strength	Low	Improve	Improve



Cross-sectional shape of additional weld

* Welding Process and Consumables Aimed at Improving Fatigue Strength of Joints, Minoru MIYATA, 2016 (KOBELCO)

Summary

- **Weld region results**

Welding Method	C/S	Ni- LTT	Mn- LTT	Partial LTT
Angular distortion (°)	3.43	2.64	-	-
Residual stress (MPa)	150.8	-323.2	-381.2	**-333.8**
Vickers Hardness (HV)	227.5	386.9	228.4	**287.3**
Absorbed energy (J)	255.3	45.0	53.3	**146.9**
Yield strength (MPa)	356.7	919.6	673.5	
Tensile strength (MPa)	741.6	1106.0	743.3	

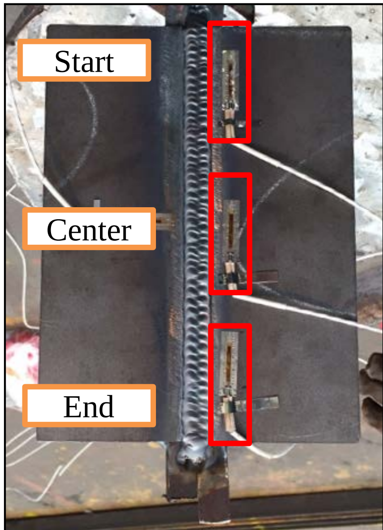
Welding Integrity (Angular distortion, Residual stress)

Mechanical Properties (Vickers Hardness, Absorbed energy, Yield strength, Tensile strength)

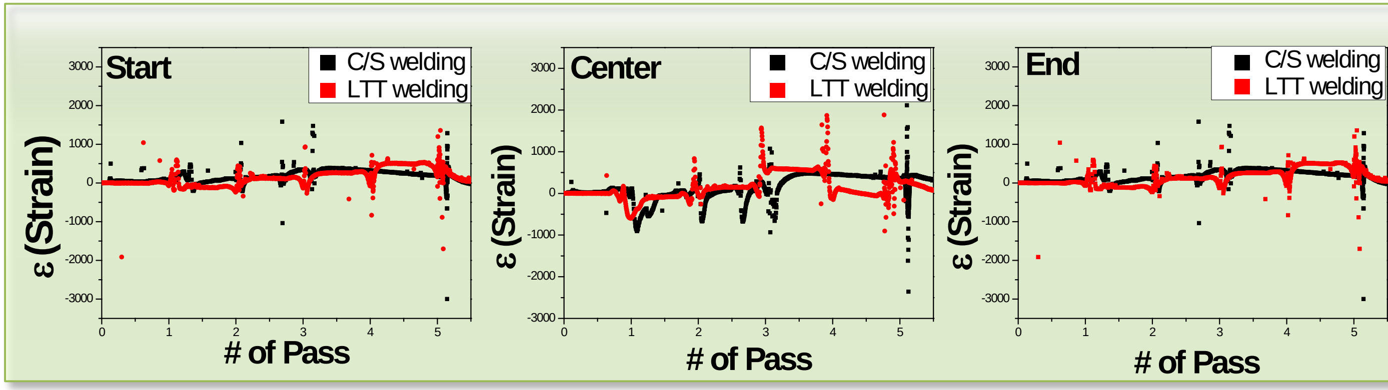
- **LTT welding has excellent welding integrity.**
  (WRS reduction : Mn-LTT > Partial LTT > Ni-LTT)
- **Relatively poor mechanical properties (Hardness & Absorbed E) compared with conventional welding**
- **Partial LTT welding shows excellent properties and integrity both.**

Construction of Strain D/B for Welding Processes

- **Measure strain rate during welding using strain gauge**



[Using strain gauge]



[5 Pass welding]

Measure Welding Strain

- **Purpose : Investigate the effect of phase transformation of martensite to residual stress**

Thermal Expansion

Martensic Transformation

→ *Strain* → *Stress* → *Stress by phase transformation*

Expect thermal stress

High tep. Tesnsile test

(E, Thermal Coefficient, YS, TS..)

Measure residual stress due to martensic transformation
by comparing with conventional welding