2023.9.21
Web in Saitama

JSTP-KMUTT Tube Forming Seminar

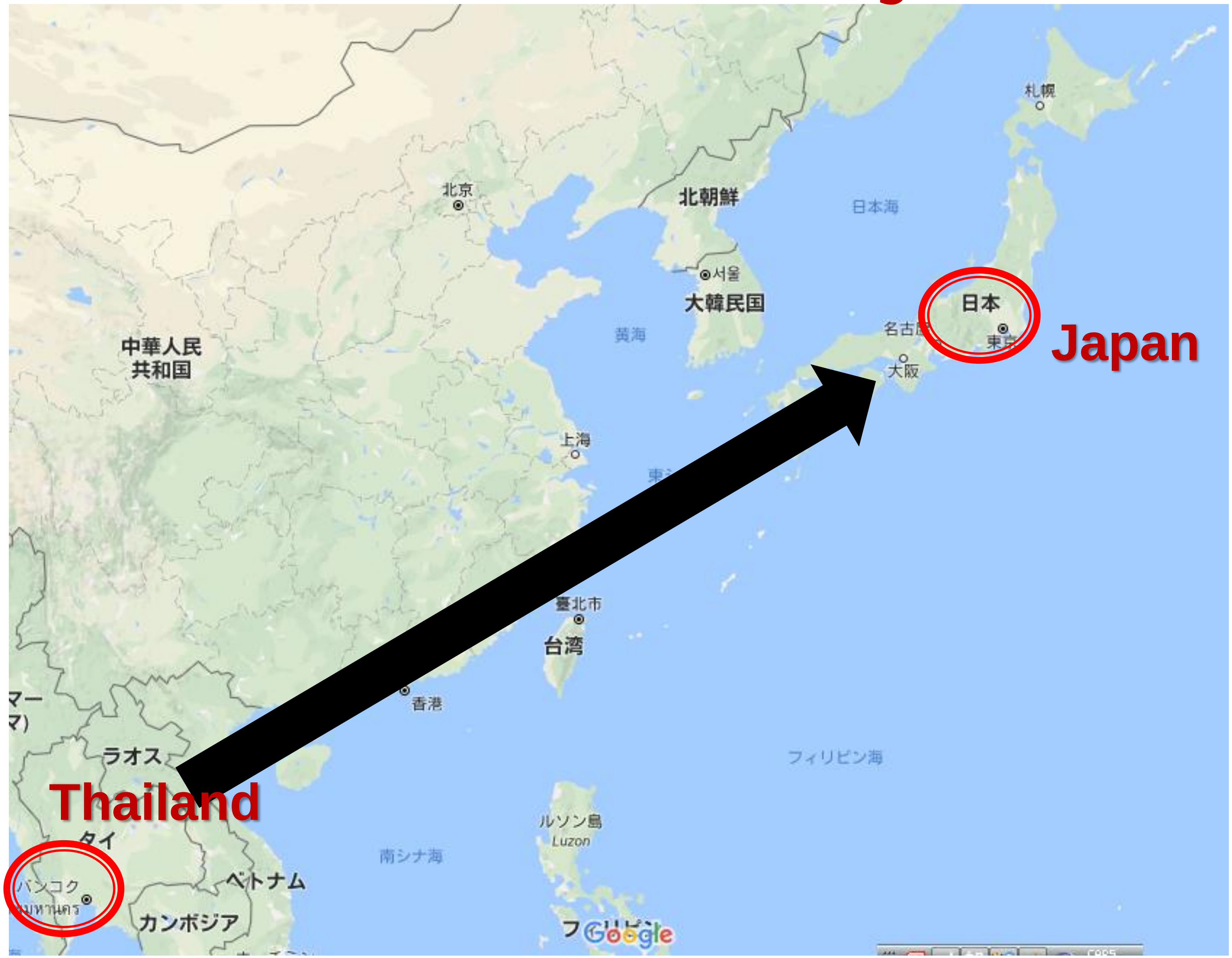
Bending Technology for Tubes and Profiles

Saitama University
Material Forming Lab.
内海能亜　UTSUMI　Noah

Saitama University and Saitama prefecture ?

(埼玉大学+埼玉？)

・Saitama university（埼玉大学）



·Saitama Univ. http://www.saitama-u.ac.jp/index.html

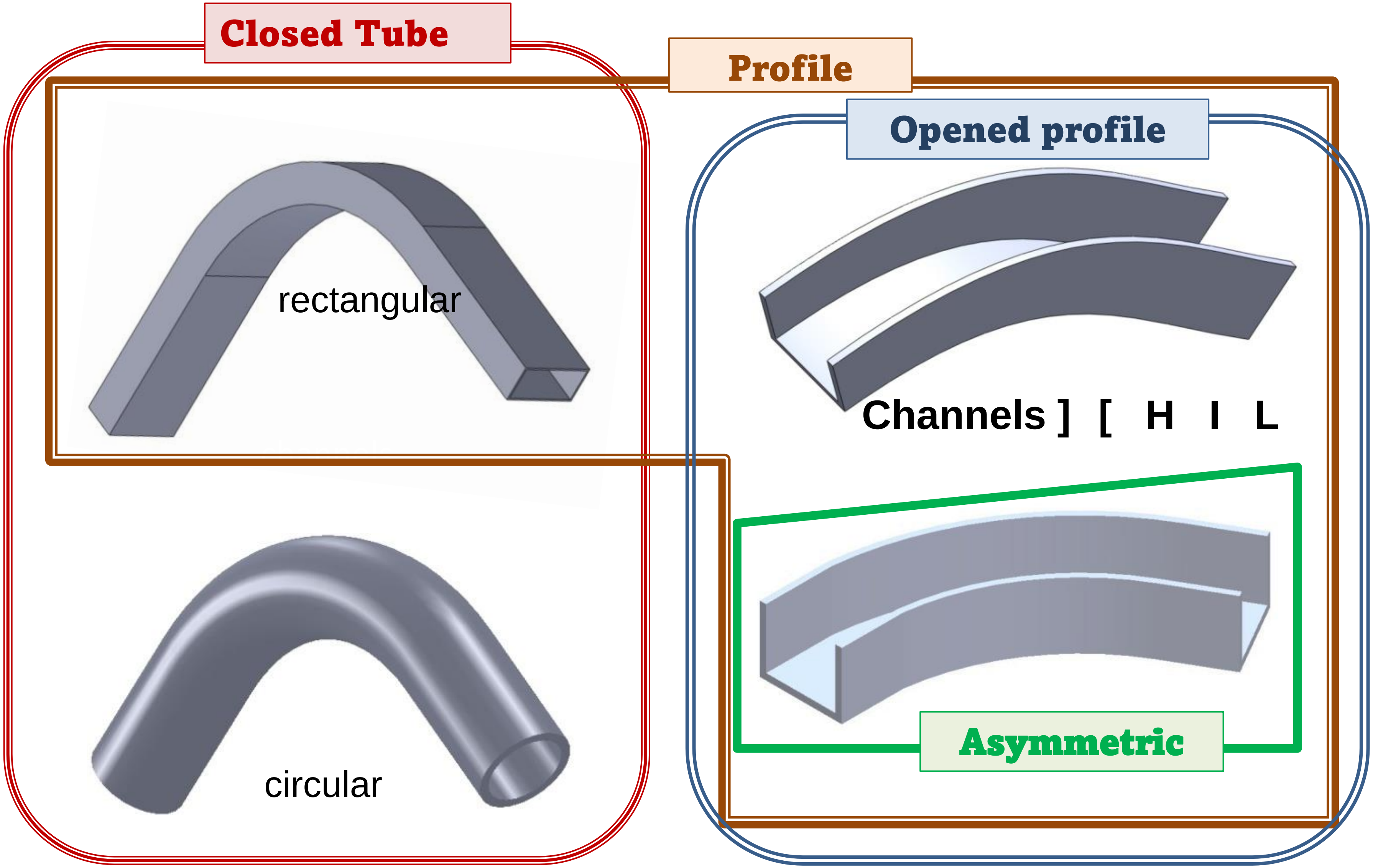
Specialties and Places of Interest

our university

Basic of Bending

1. Classification of cross-sectional shapes

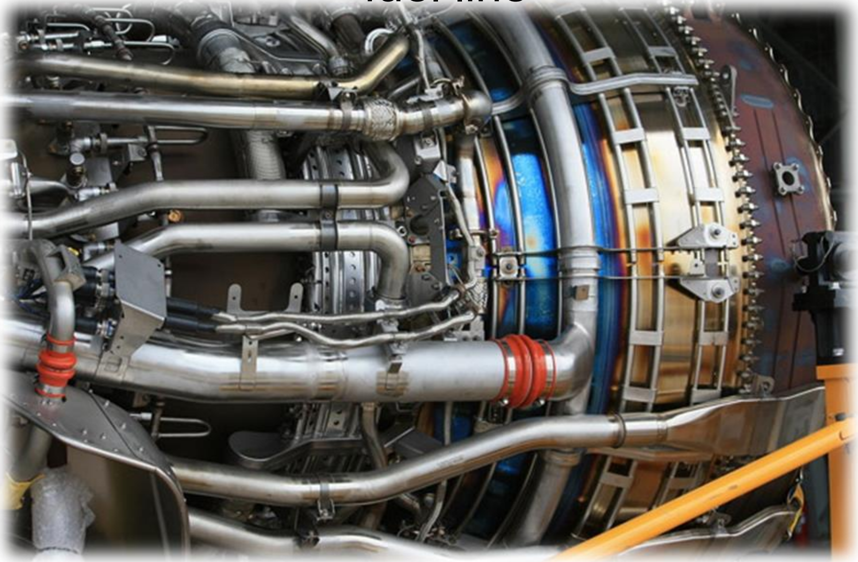
page 39 of the Textbook



2. Products of Tubes and profiles

Pipes


pipe line

fuel line


radiator pipe



water pipe

Products around us

health equipment

Body frame or member will survive,

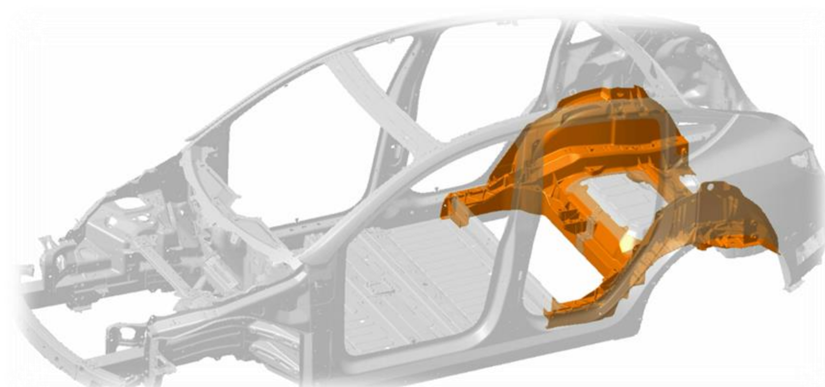
but Vehicle exhaust pipes・・・・

structural components

musical instruments

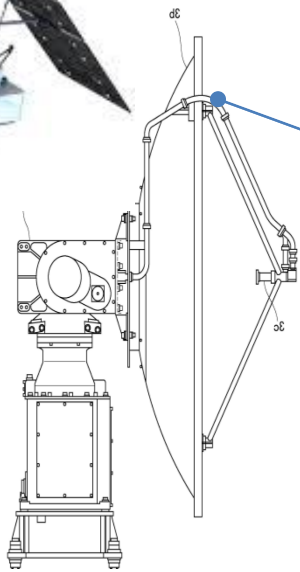
EV Threat

Benders' jobs down?



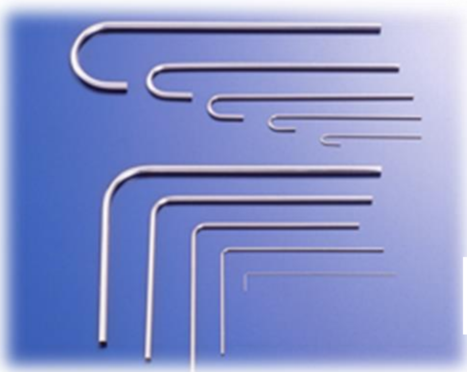
[Tesla Model Y giga-press aluminum casting (sae.org)]

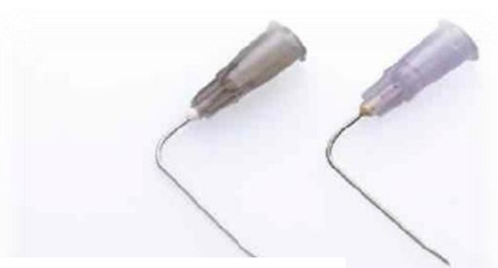
Specialty Products



waveguides

Bourdon tubes

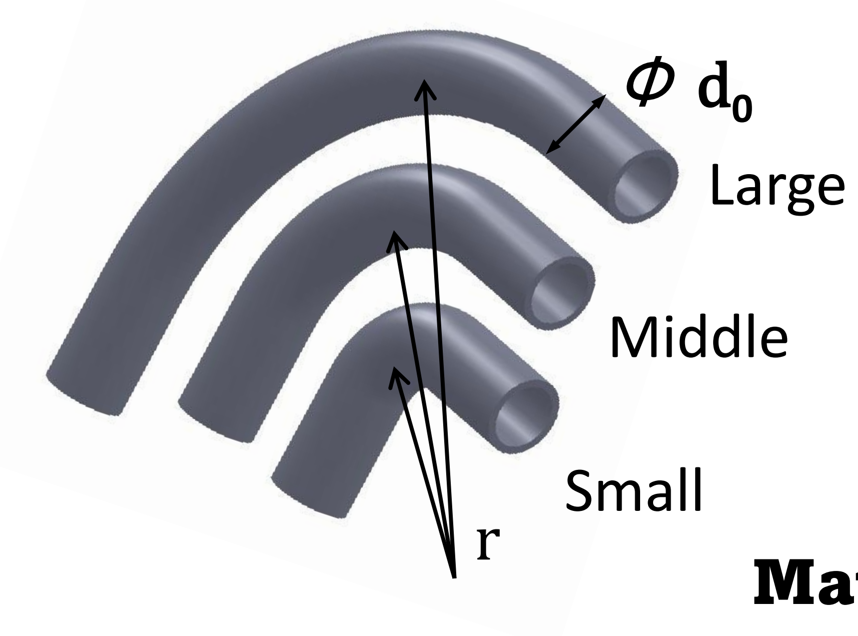


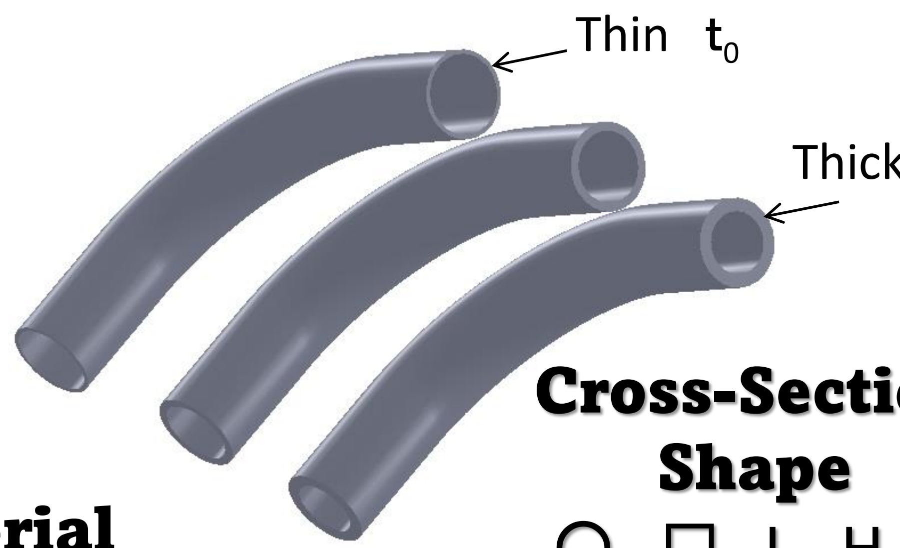


medical devices

Key Factors for Bending technol.

Bending Radius r/d_0, Thickness Ratio t_0/d_0





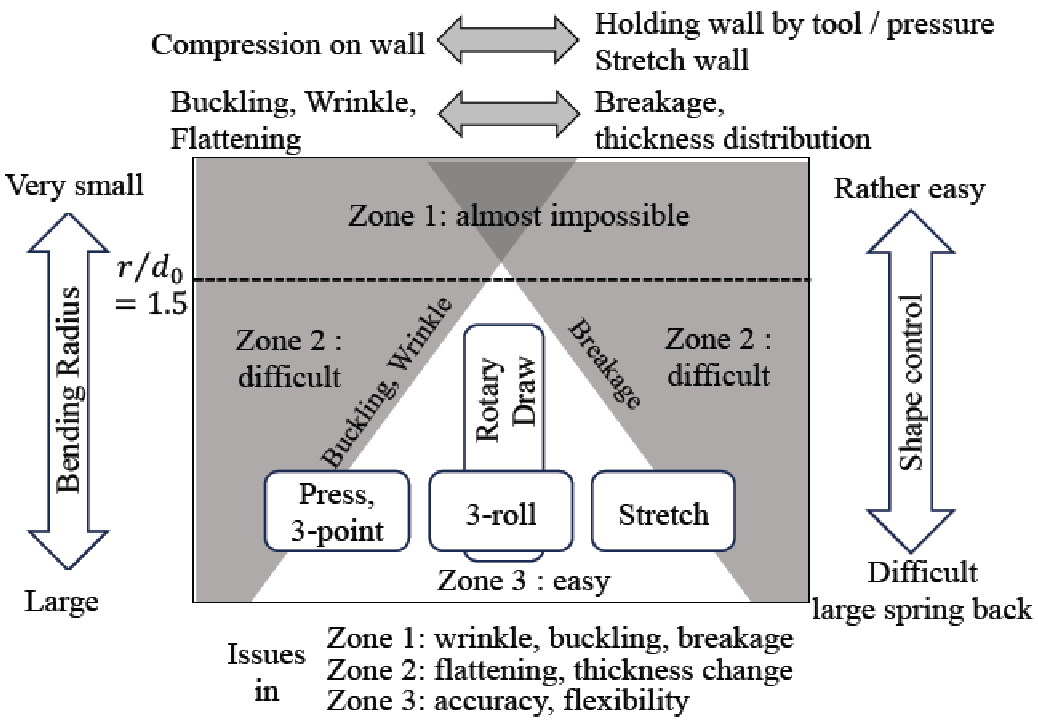
Material

Cross-Section Shape

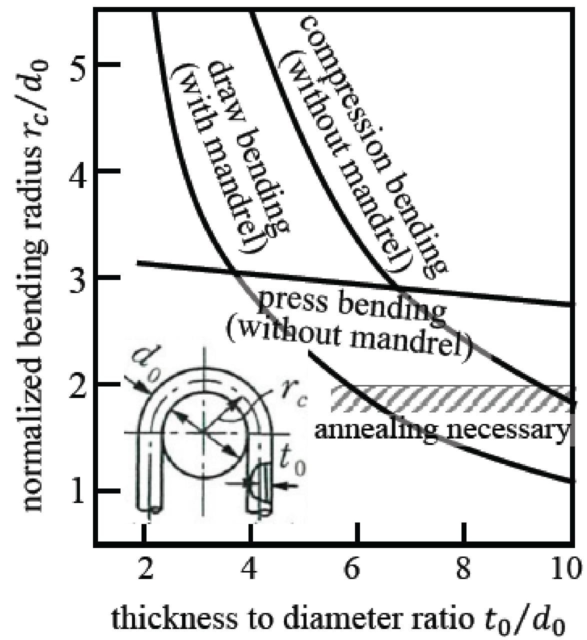
○ □ L H]

･Mass or Flexible products

Preparation for bending **p40**



(a) bending radius and defects



(b) standard forming limits

Fig. 3.1 process window of bending

Until now, we have used elementary analysis and numerical analysis to predict processing forces (moments) and deformations, etc.

Now a days, simulation (FEA) is used to predict (reaction force, moment, wall thickness, stress, displacement, deformation, material handling etc.)

3. Bending method *p*41

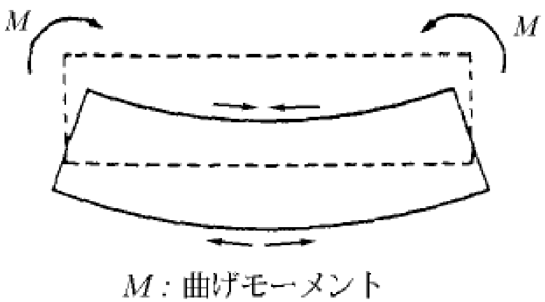
Table 3.1 Classification and comparison of bending methods

Classification	Summary	Typical bending method
Bending method	Apply bending moment	Press, Rotary draw, Compression, Stretch
	Apply strain difference between outer and inner	Hamburg, Eccentric plug
	Apply shear strain	Shear
Bending temperature	Cold	Rotary draw, Stretch, Flexible penetration
	Hot	Hamburg, High frequency induction heating, Quench
Axial load	Tension	Press, Rotary draw, Stretch
	Compression	Roll, Flexible penetration, Hamburg, Quench

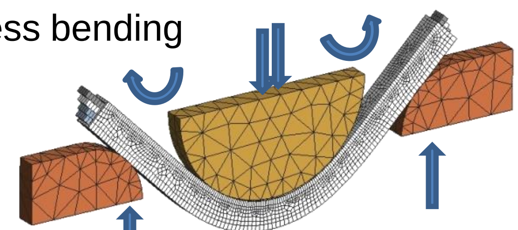
Tightness of bending		Typical bending method
Minimum bending radius (r/d_0)	Large ($r/d_0 > 6$)	Roll, Quench
	Medium	Press, Rotary draw, Compression, Stretch, Penetration
	Small (possible $r/d_0 < 1$)	Shear, Hot press, Hot penetration
Limit bending angle	$\leq 90°$	Shear, High frequency induction heating
	$\geq 360°$	Flexible penetration, Hamburg, Roll

Principles of Processing

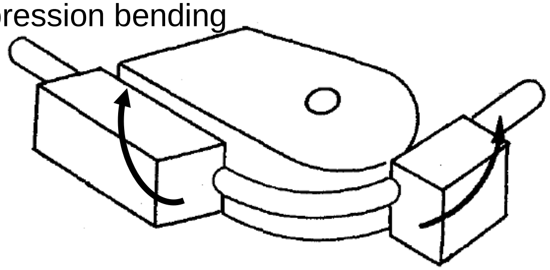
・Bending moment



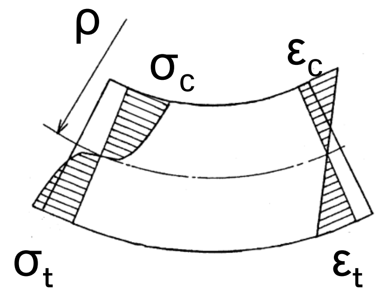
Press bending



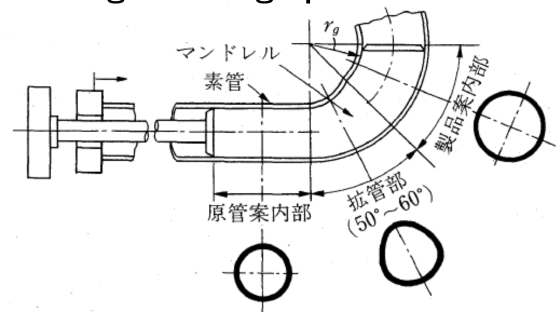
Compression bending



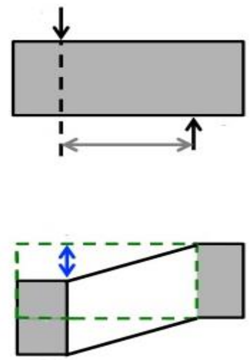
・Strain difference between outside and inside



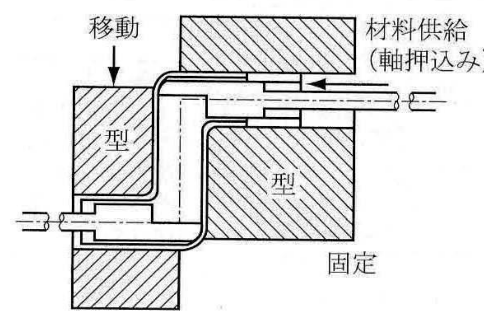
Hamburg bending p59



・Shear strain



Shear bending p61



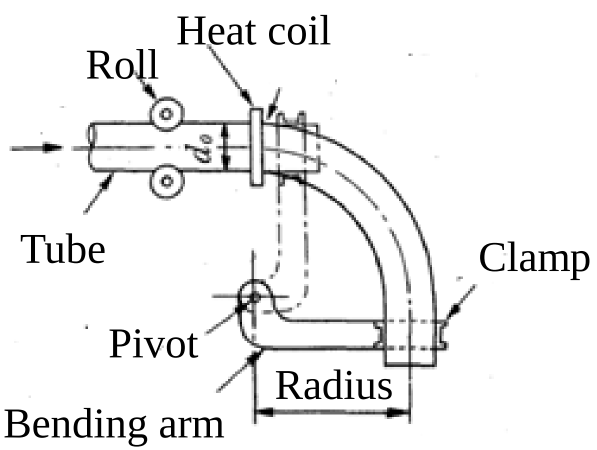
Working temperature

・Hot

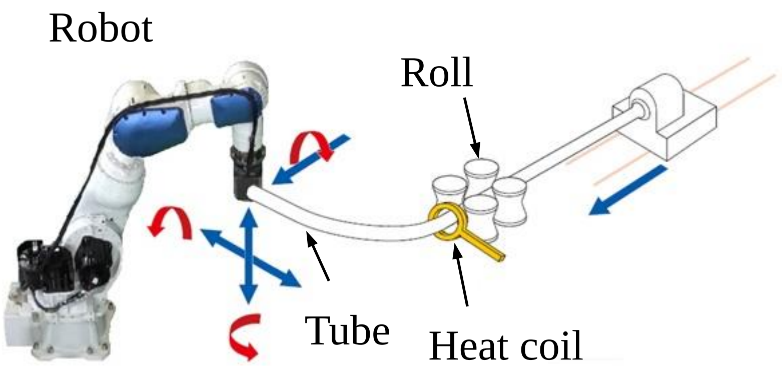
・Cold

Die less, 3D bending

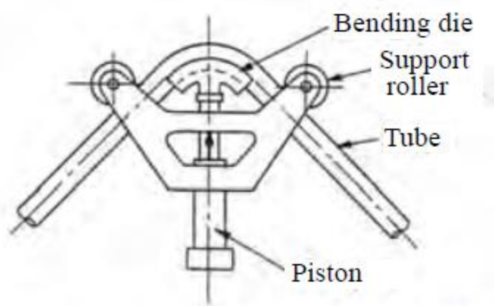
p63



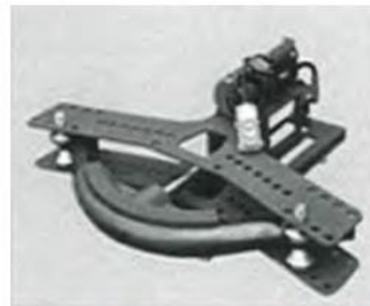
・Variable bending, Continuous bending p65

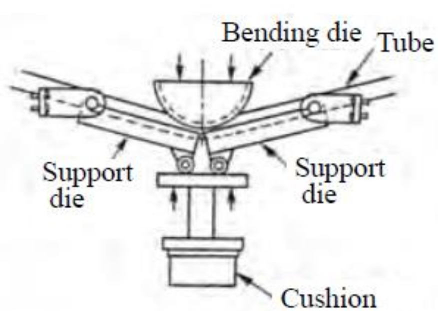


Press bending (Cold) p42



(a) Support roller type (for field work)

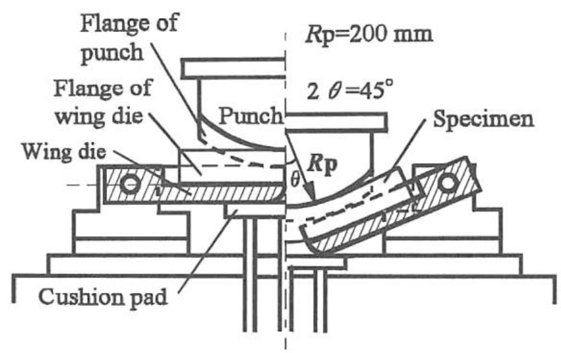

(b) Support roller type pipe bender †



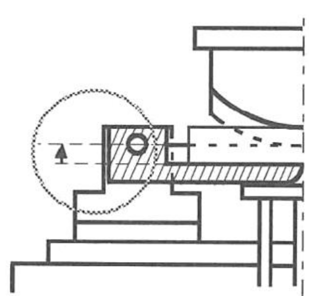
(c) Support die type


(d) Press type pipe bender [8]

Fig. 3.2 Press bending



(a) Standard wing die


(b) High supported wing die

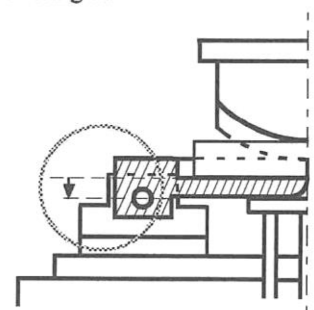
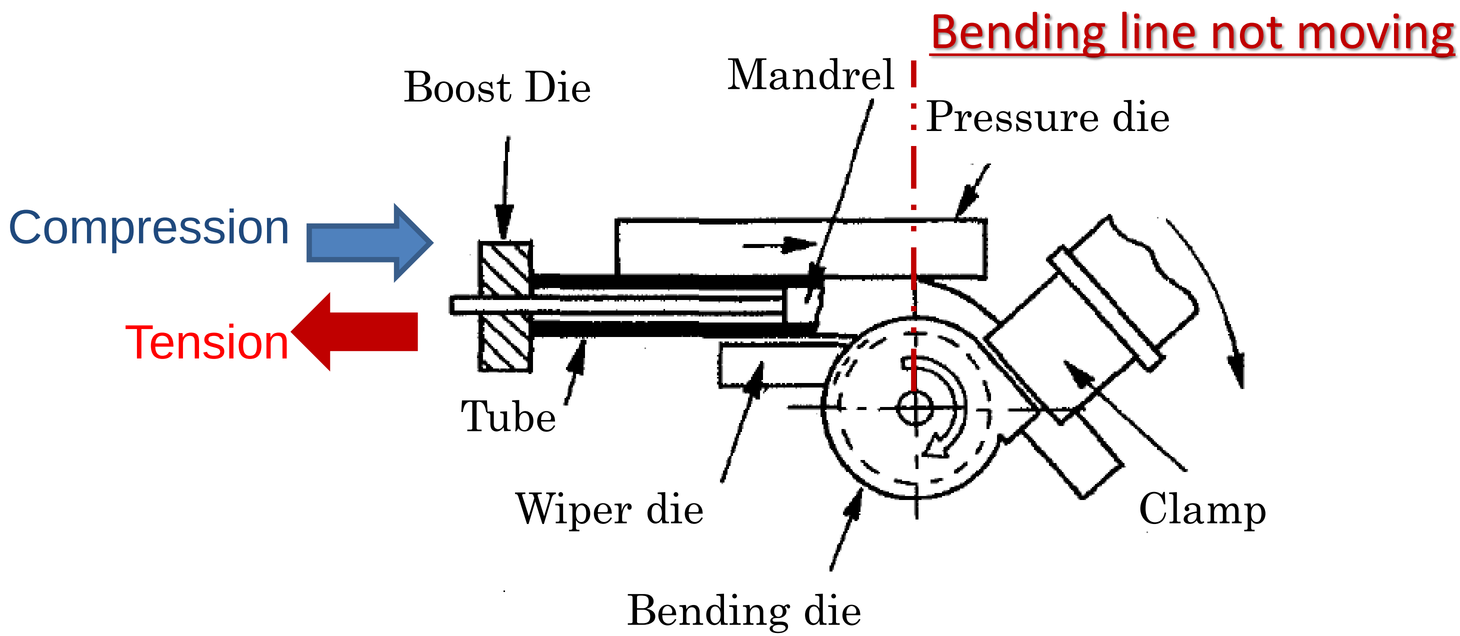

(c) Low supported wing die

Fig.1 Schematic illustration of wing-type dies used.

Hasegawa, 51th Sokaren, 2000, 105

Rotary draw bending p44



Basic tools
・Clamp
・Pressure die
・Bending die

Option tools
・Mandrel
・Force to axis directions
・Wiper

Characteristic Rotary Bending

SANGO : Bent double walled product P45

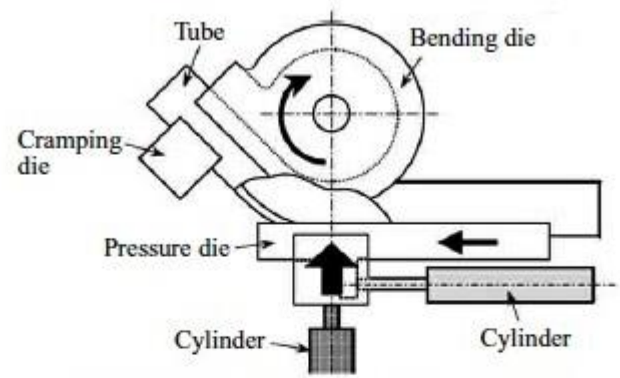
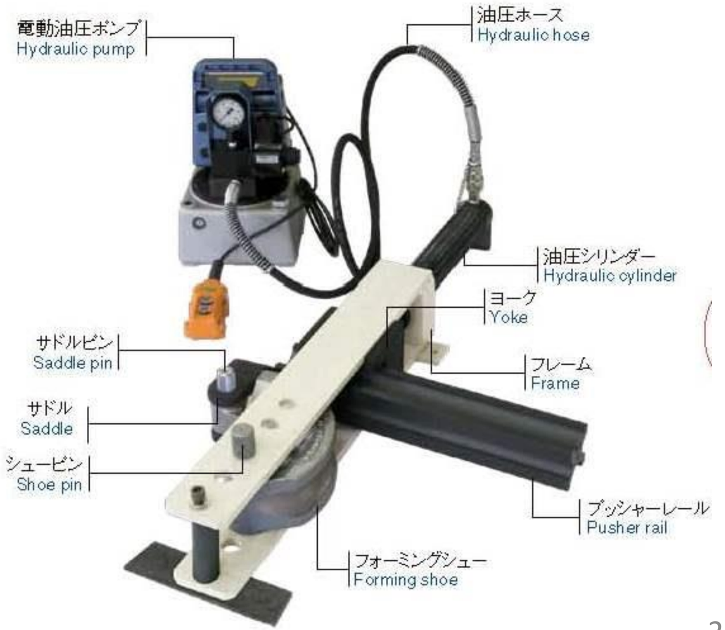


Fig.7 Schematic diagram of PRB method

Push Rotary Bending P46



P46

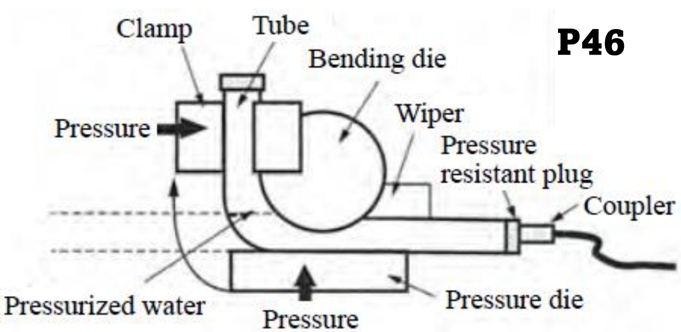
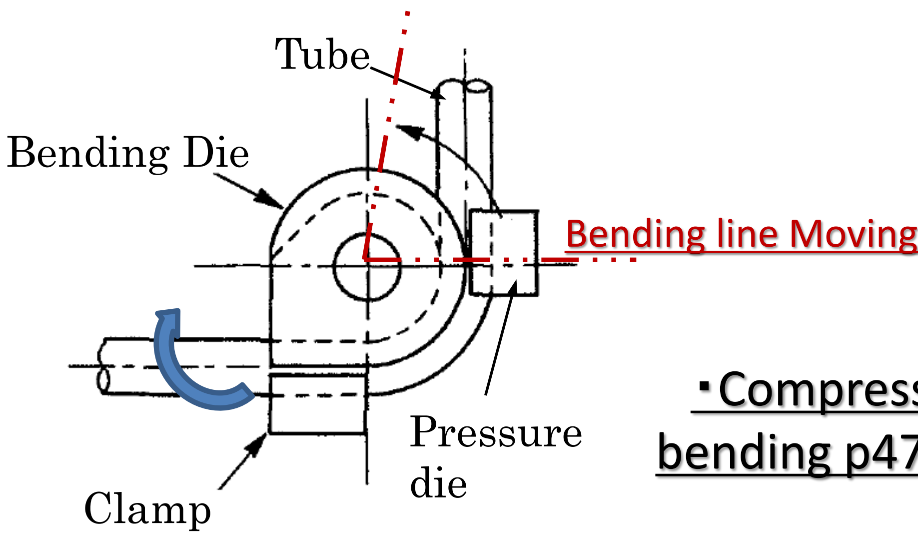
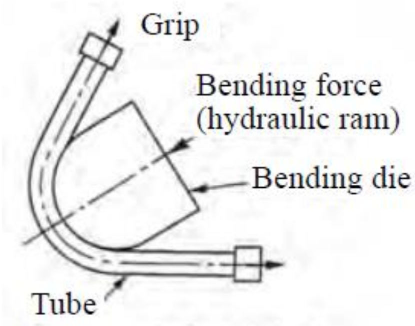


Fig. 3.12 Hydro-bend method

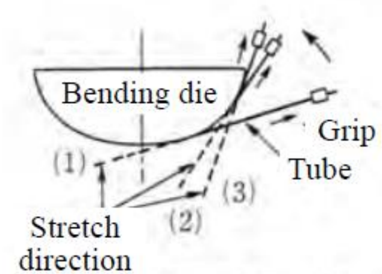
Other, Bending with moment(cold)



・Compression bending p47

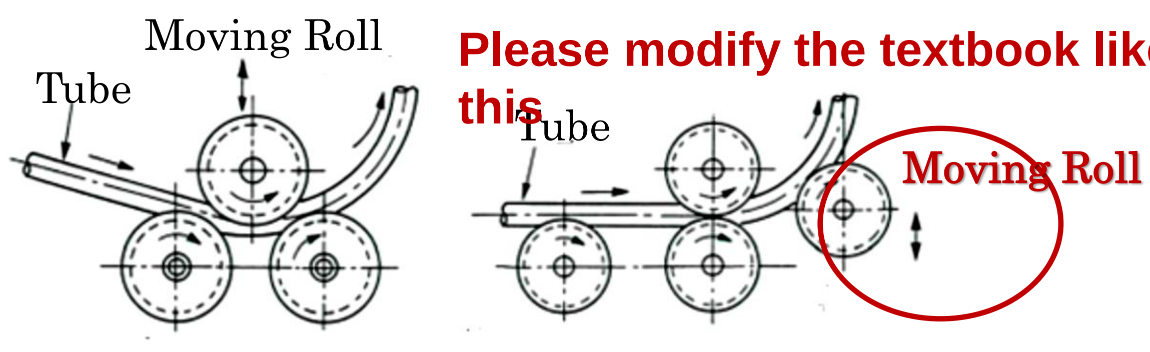


(a) fixed on both ends method



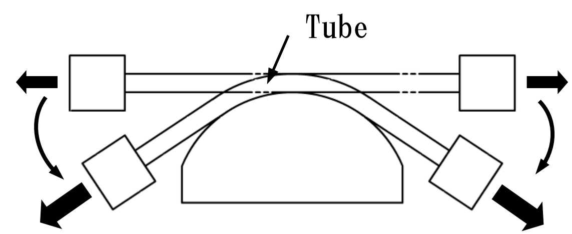
(b) tension winding method

Please modify the textbook like this



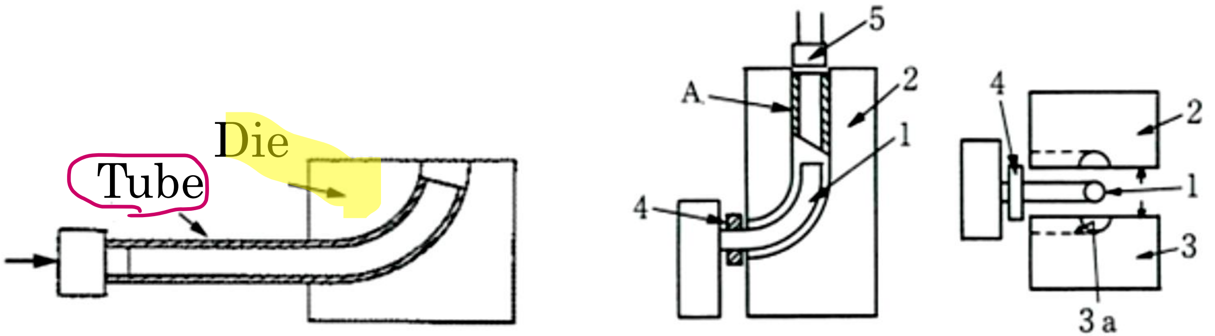
(a) 3 roll (b) 4 roll

・Roll bending p47



・Stretch Bending p48

Push-through bending(Penetration Bending) with Die p48,49



(a) Basic Type (b) Improvement Type

1:Mandrel, 2 3:Outer die, 4:Ring, 5:Punch, A:Tube

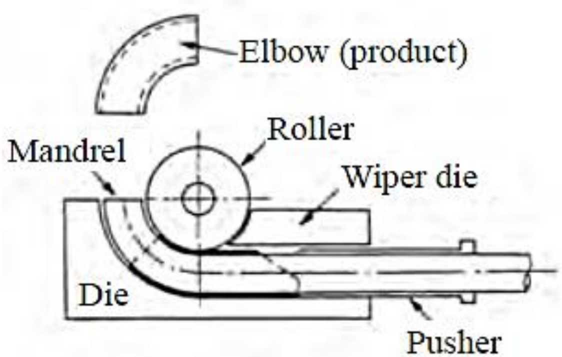
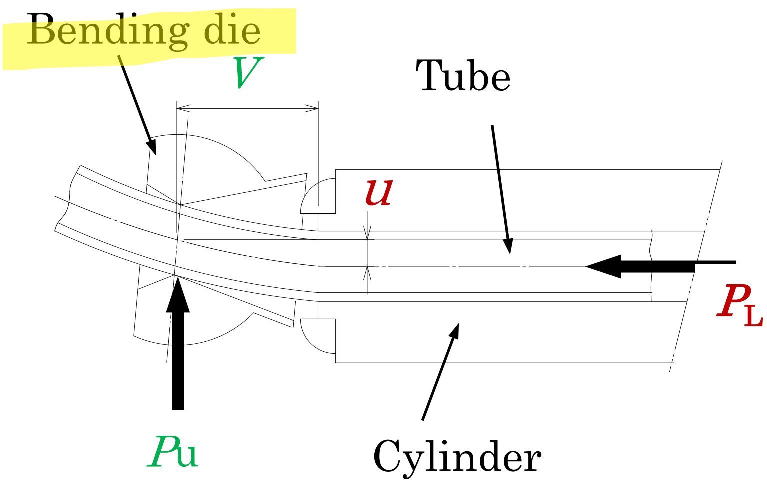


Fig. 3.17 Elbow forming by penetration bending

Fig. 3.18 Example of produced elbow

Flexible Penetration Bending p49



Nissin HP

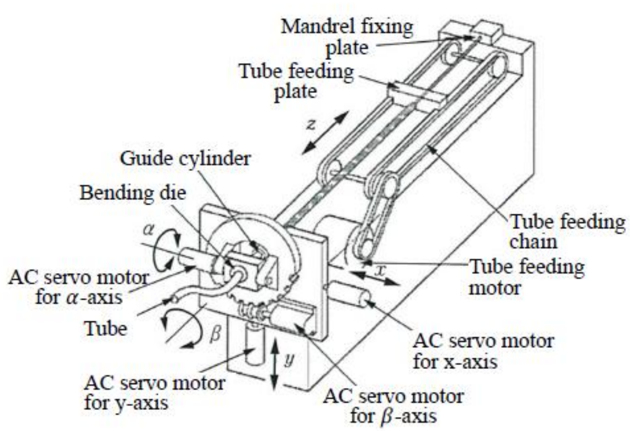
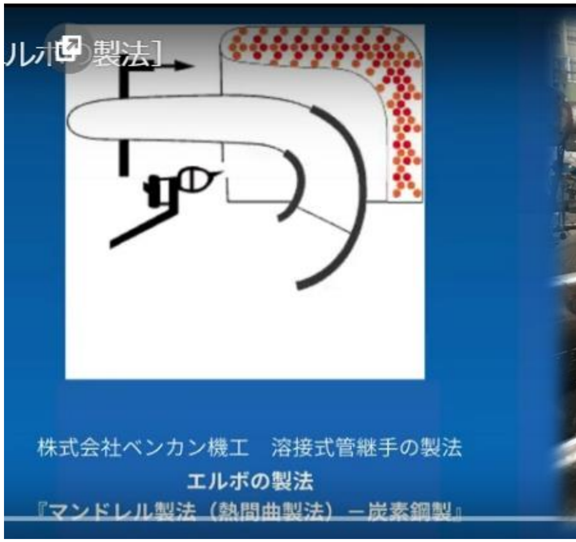
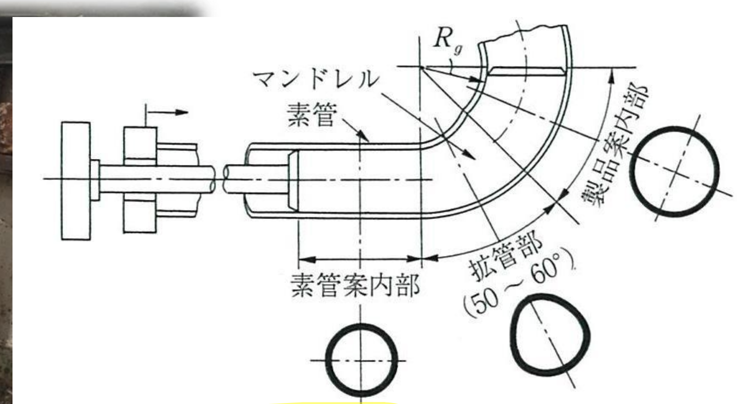


Fig. 3.20 MOS bending machine [20]

Fig. 3.21 Example by MOS bending

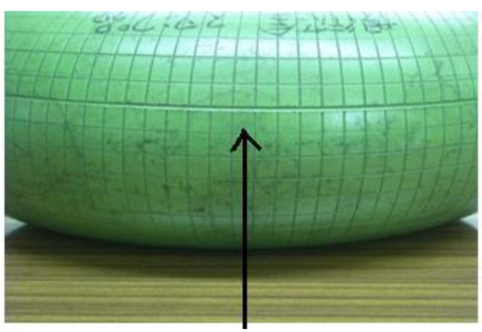
Hot bending (Expand tube)



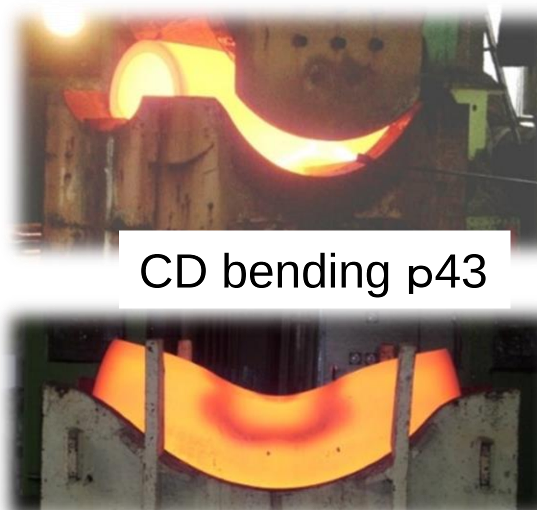


Hamburg p50

Benkankikoh by HP



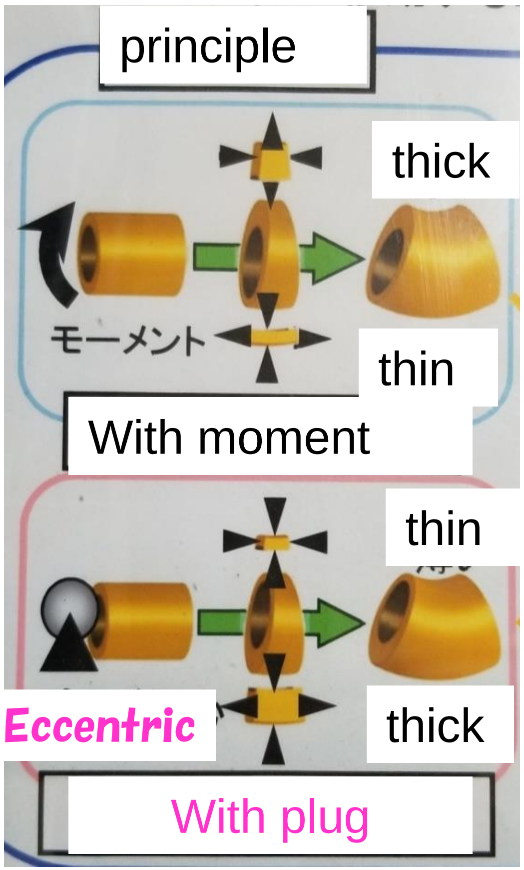
No strain change after bending

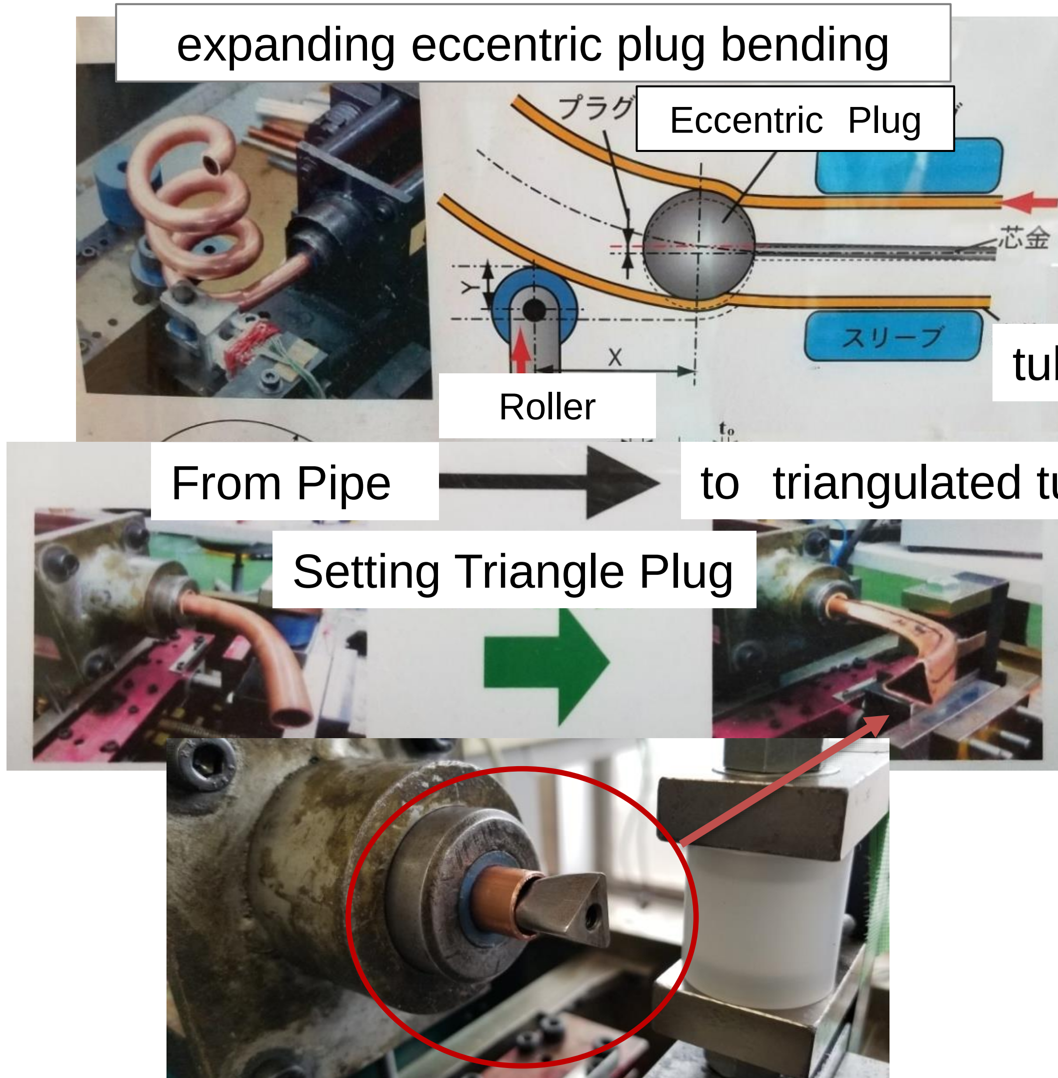


CD bending p43

Eccentric Plug Bending (Expand tube)

p52





Shear bending p53

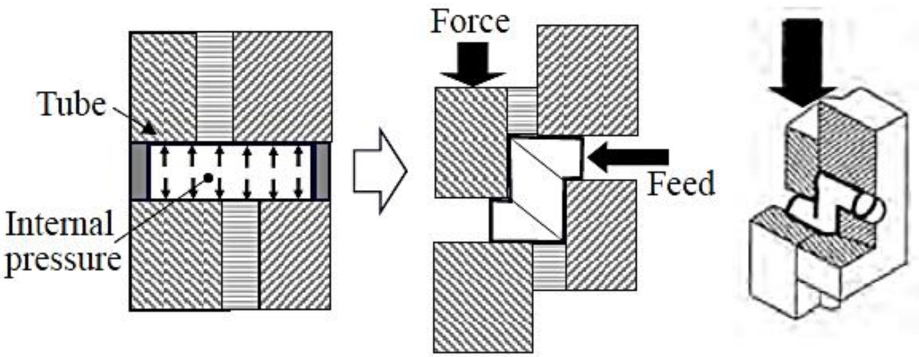


Fig. 3.26 Principle of shear bending

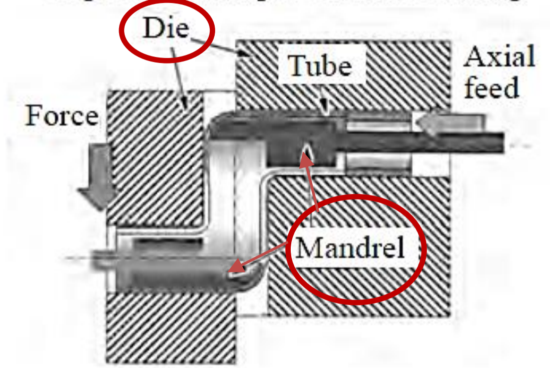
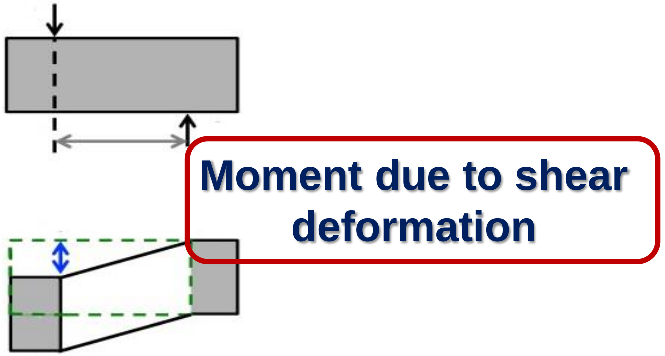
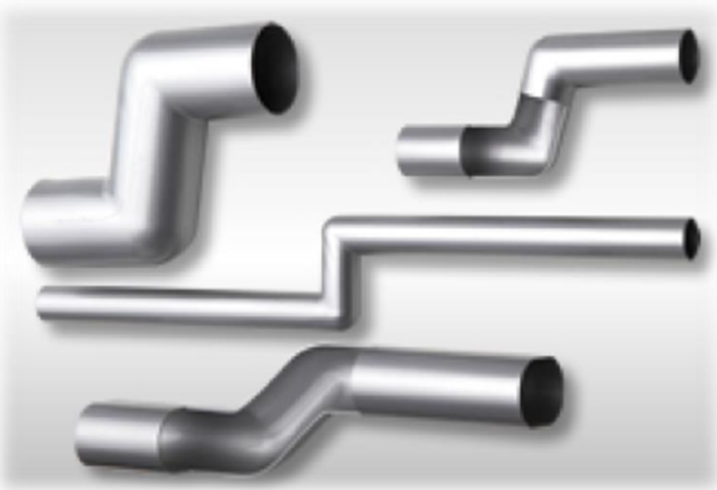


Fig. 3.27 Shear bend using mandrel [30]



Sango by HP



Bending of Shapes and profiles p57

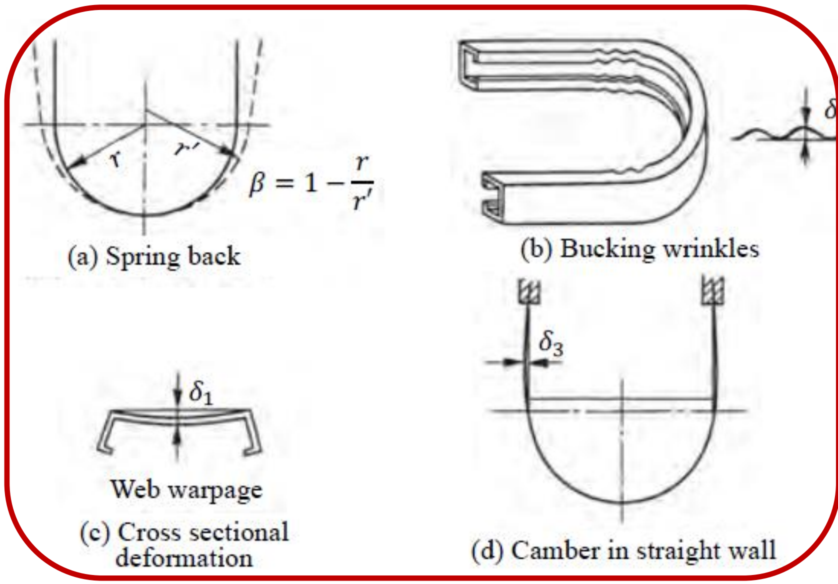


Fig. 3.34 Forming defects in bending of profiles

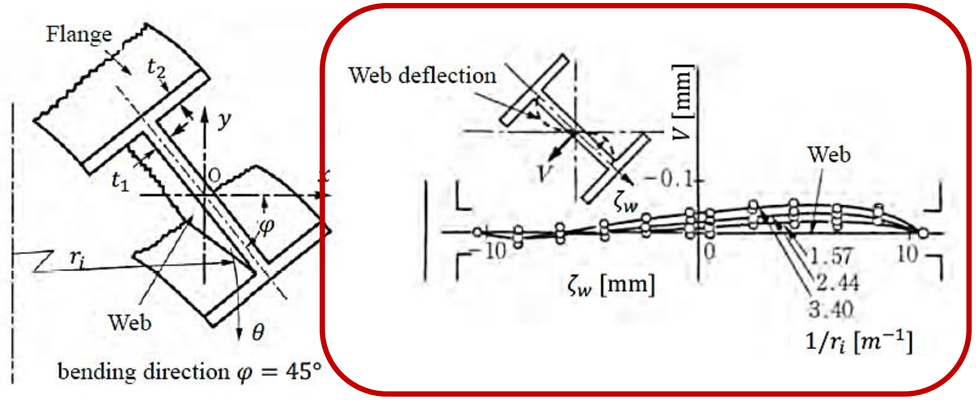


Fig. 3.36 Deformation of web in asymmetric bending of H-shaped beam [40]

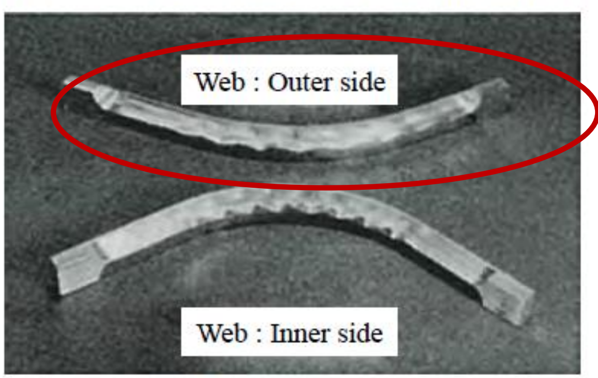
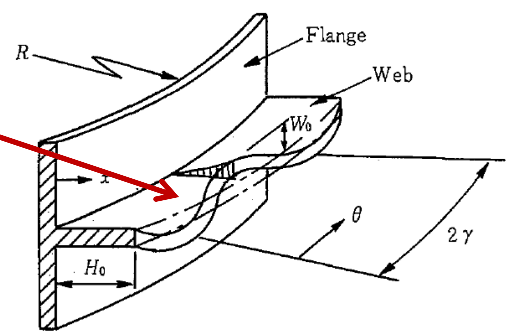


Fig. 3.35 Buckling example in bending of profiles



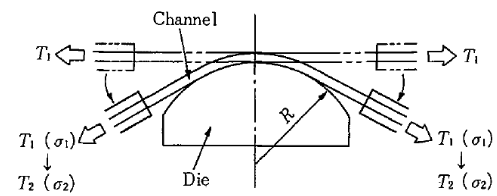
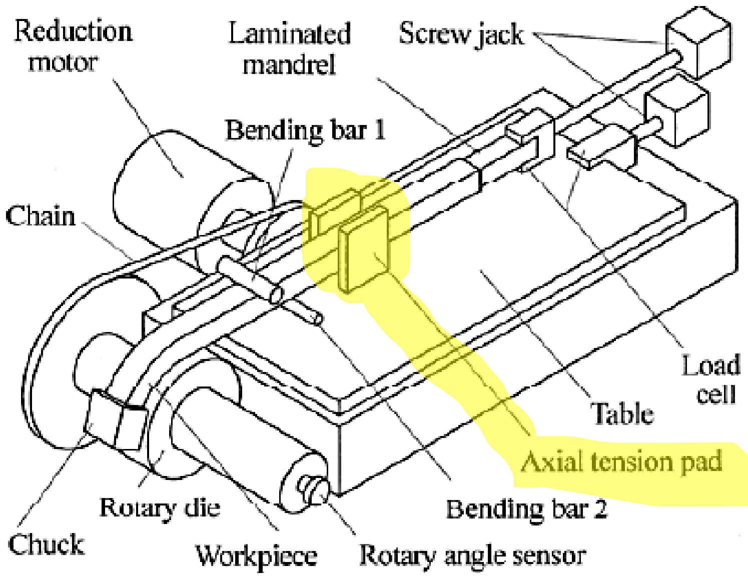
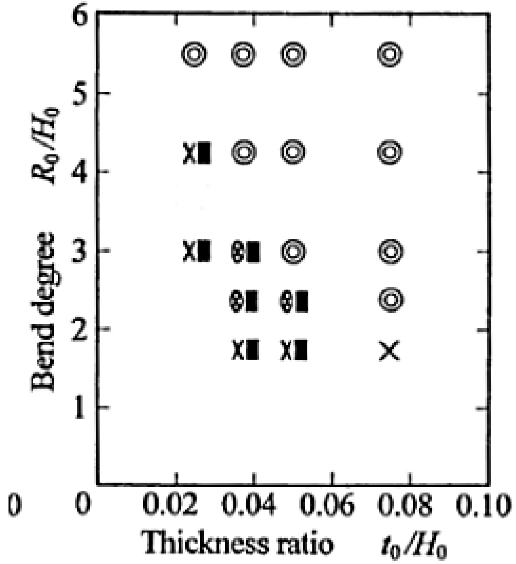


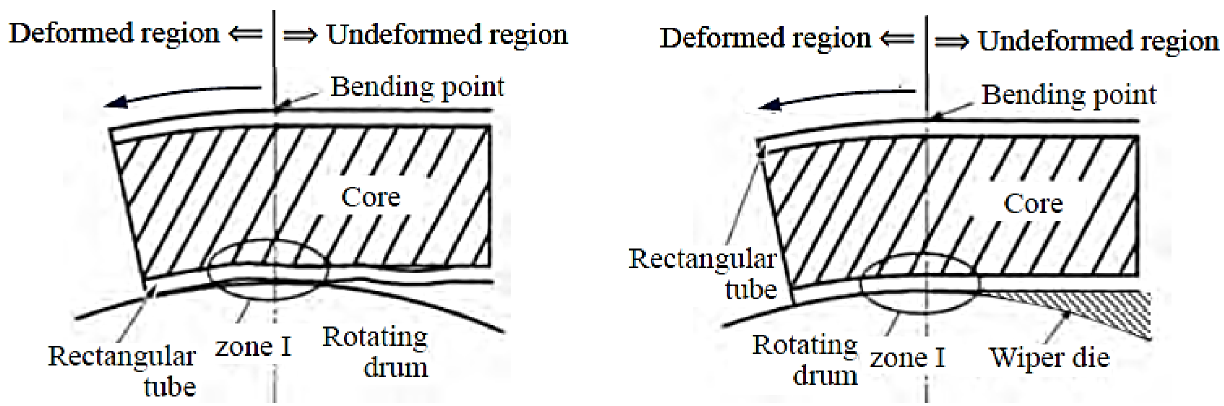
Fig. 2 Schematic drawing of stretch bending method.

JSTP:30-336(1989)p26

Bending of Square tube p60, 61







(a) without wiper die

(b) with wiper die

Fig. 3.39 Effect of wiper die

Asymmetric channel p61

r_0

Torsion occurs when shear center is shifted

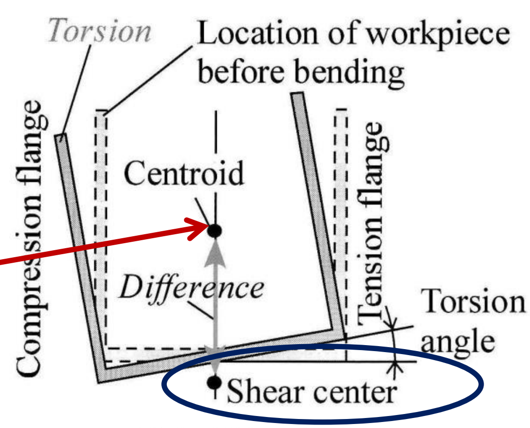
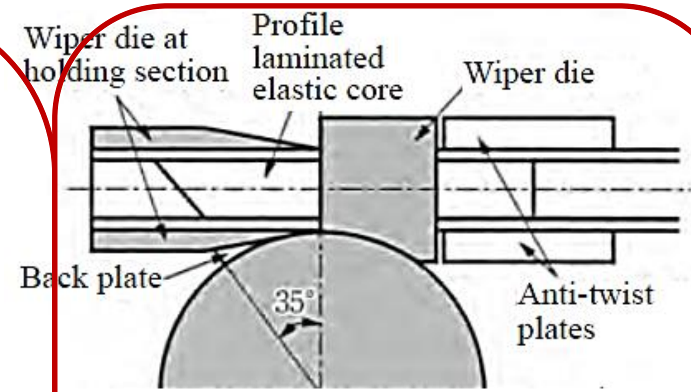
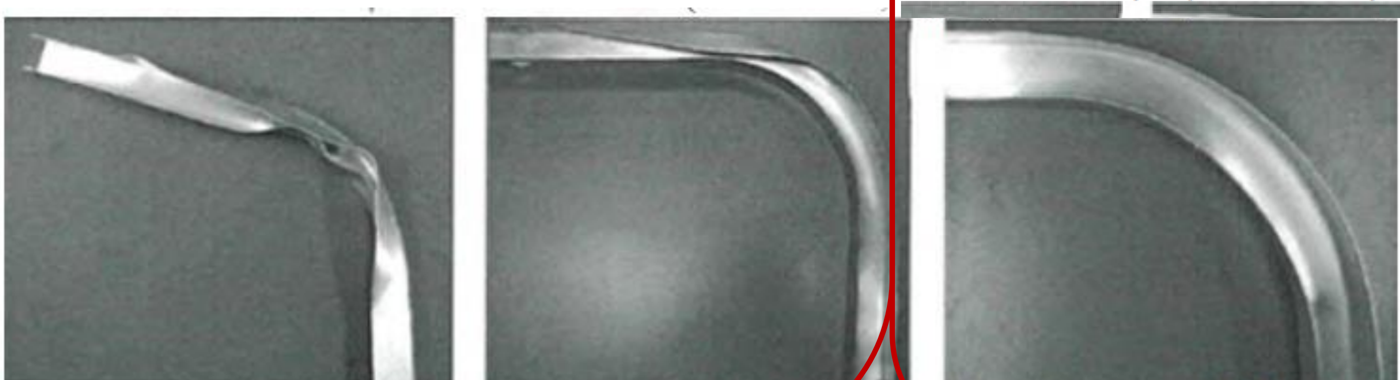


Fig.1-4-5 Schematic of torsion

Okude : doctoral thesis2013



(A 6061S-O, $t_0/h_0 = 0.038$, $t_0 = 1.5\ mm$)



(a) without core and jigs

(b) with core and wiper die

(c) with core and dedicated jigs, applying axial load

Fig. 3.41 Bent examples of asymmetric channel profiles [44],[45]

Stretch bending for profiles p62

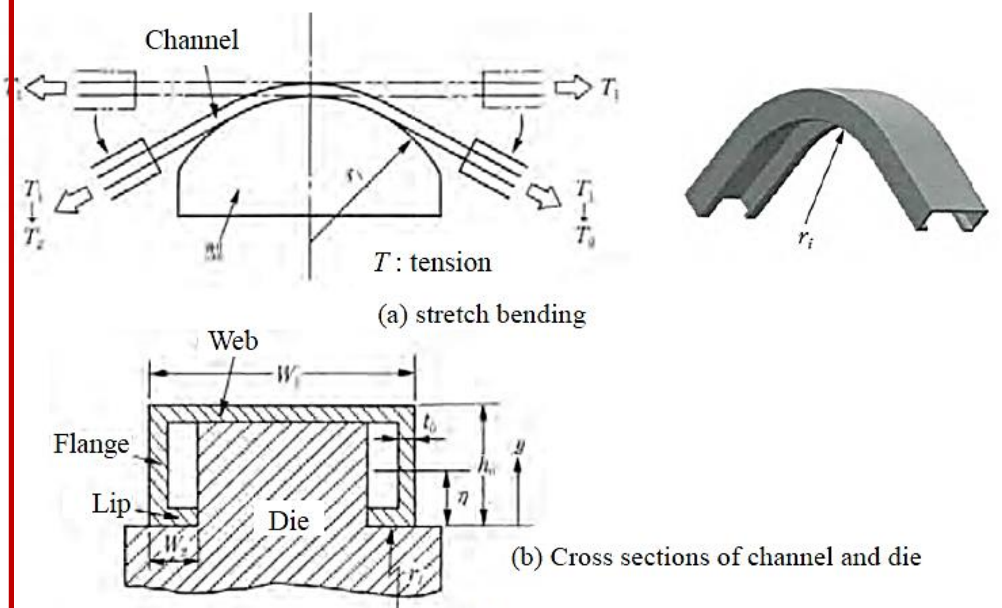


Fig. 3.42 Stretch bending of channel

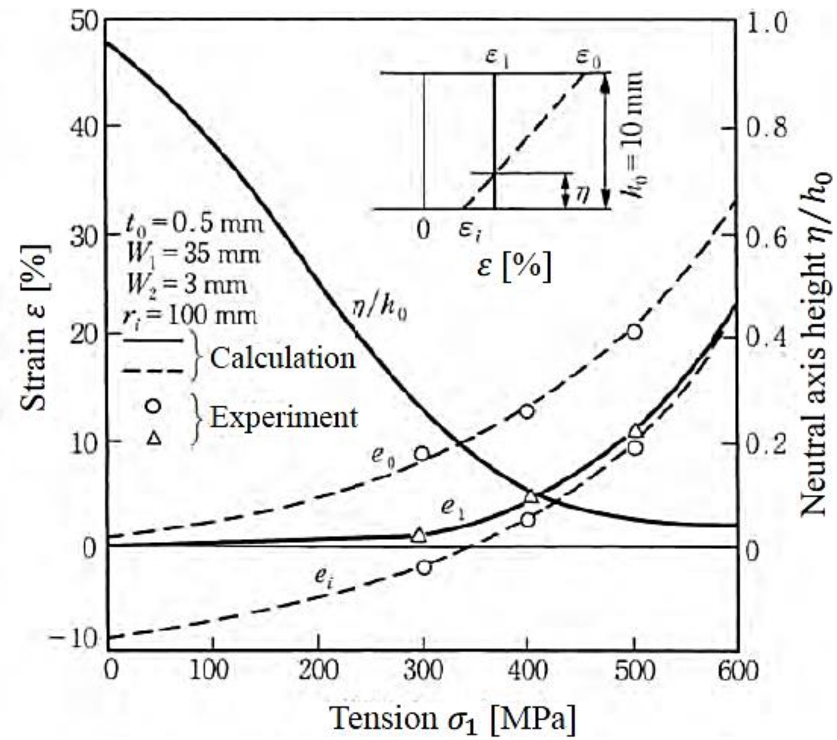


Fig. 3.43 Relation of tension, neutral axis height, and strain [46]

・Neutral axis moves to compression side in Stretch Bending move

・Be careful of necking or breaking on the tension side.

High Tension⇒
No wrnkling, Low springback

Rolling bending p64

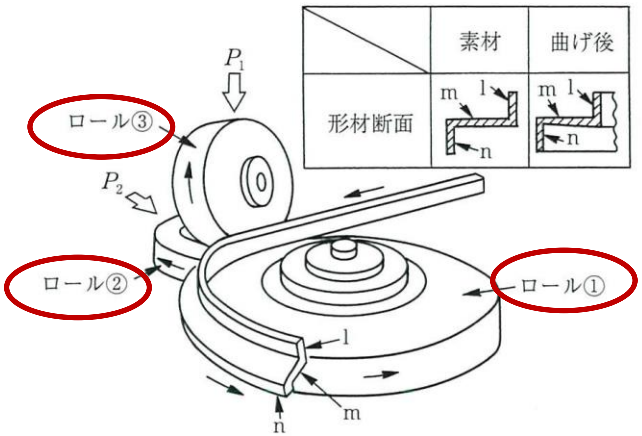


図 3.45 くさび形ロールによる圧延曲げ[48)]

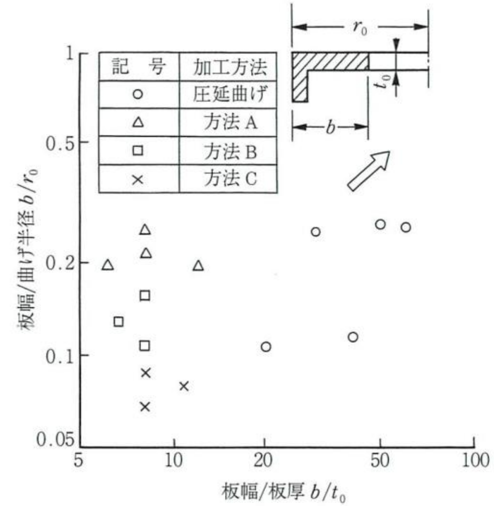
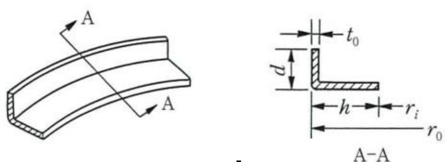
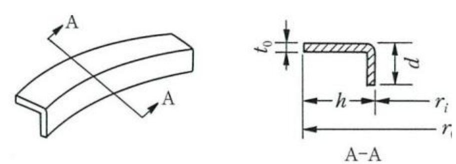


図 3.47 圧延曲げとほかの方法の加工限界[48)]

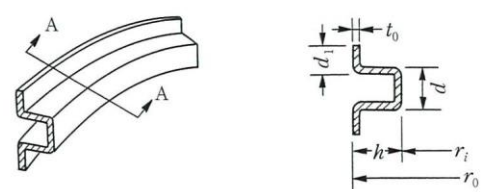
Working limit p65-68

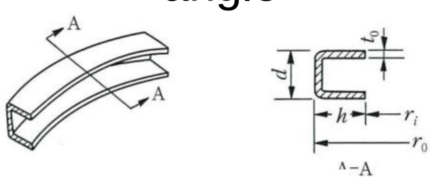


angle

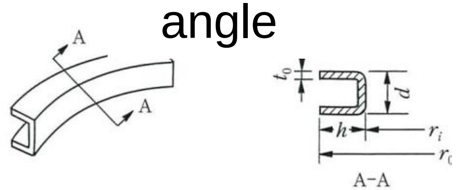


angle





Channel **Inner**



Channel **Outer**

Hat

50)

Let's take a look p68

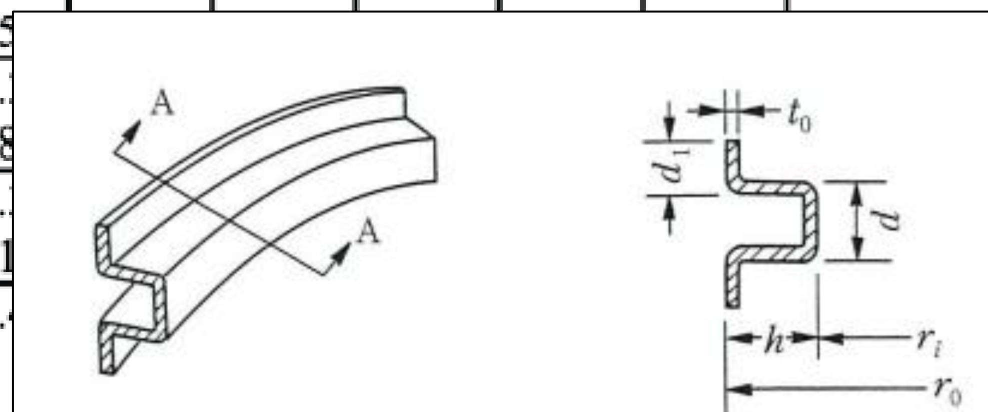
$t_0=1, h=10, r_0=53.4$

Table 3.4 Forming limit of stretch (outward) bending of hat section [50]

Let's take a look at p68

$t_0=1, h=10, r_0=53.4$

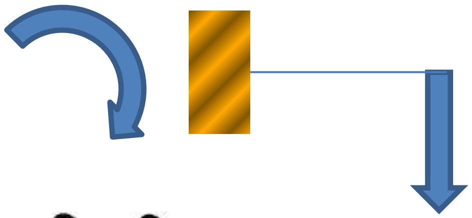
Material	Temp. [°C]	Fracture limit h/r_0						
		h/t_0						
			3	5	8	10	15	20
2024 T-3	R.T.	h/r_0 r_0/t_0	.23 13.3	.21 24	.19 41.3	.19 53.4	.17 86.4	.16 128
Ti-8-1-1	R.T.	h/r_0 r_0/t_0	.17 17.3	.16 31.3	.15 55	.14 72.5	.13 115	.12 174
TZM Moly	R.T.	h/r_0 r_0/t_0	.19 15.5	.18	.17	.16	.14	.13
Cb-752	R.T.	h/r_0 r_0/t_0	 11.8					
PH 15-7 Mo	260	h/r_0 r_0/t_0	 10.1					
	R.T.	h/r_0						



3.3 Working force p69

・Selection of processing machines

Tension, compression, shear, moment, torsion



・Bending moment

force × distance

For selecting a machine

For durability of Tools

・Selection of tools and jigs (Reaction force)

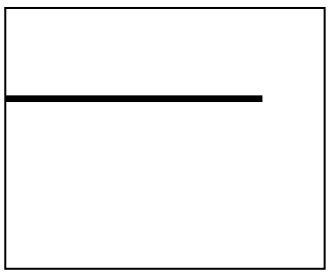
$$M_0 = \int_A \sigma y \, dA$$

Material*Radius*Area

The fully plastic bending moments p69

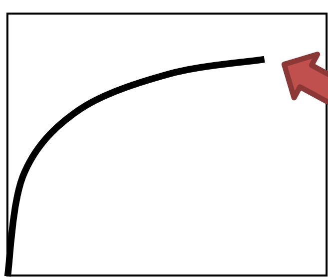
Rigid Perfectly Plastic Materials

σ



ε

Work Hardening Materials



$$M_0 = \frac{1}{6}\left(d_o^3 - d_i^3\right)\sigma_s$$

The fully plastic bending moment, M_0, neglecting cross-sectional flattening and uneven thickness in the bending of a circular tube, is given by the following equation.

Here, σ_s represents the yield stress of the material, d_o is the outer diameter of the tube, and d_i is the inner diameter. In the case of thin-walled tubes, considering the average diameter d_m and wall thickness t_0, the fully plastic bending moment, M_0, is given by equation (3.5).

$$M_0 = d_m^2\, t_0\, \sigma_s \qquad (3.5)$$

Similarly, for thin-walled square tubes with side length a and wall thickness t_0, the equation (3.6) applies.

$$M_0 = \frac{3}{2}a^2\, t_0\, \sigma_s \qquad (3.6)$$

Assuming the material follows the power hardening rule $\sigma = C\varepsilon^n$, and neglecting the cross-sectional flattening, the bending moment M of a circular tube can be determined using the following equation.

$$M = \frac{1}{4}C\left(\frac{d_o}{2r_c}\right)^n \cdot d_0^3\left\{1 - \left(\frac{d_i}{d_o}\right)^{n+3}\right\} \cdot \mathrm{B}\left(\frac{n+2}{2}, \frac{3}{2}\right) \qquad (3.7)$$

Here, d_o is the outer diameter of the tube, d_i is the inner diameter, and r_c is the bending radius of the tube's central axis. The beta function B{(n+2)/2, 3/2} is shown in **Figure 3.52** [53].

p70

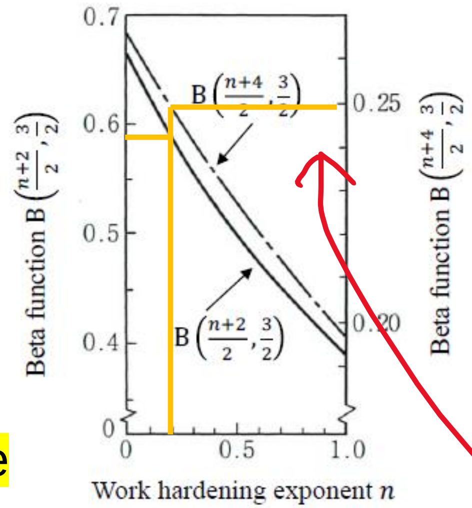


Fig. 3.52 Beta function diagram [54]

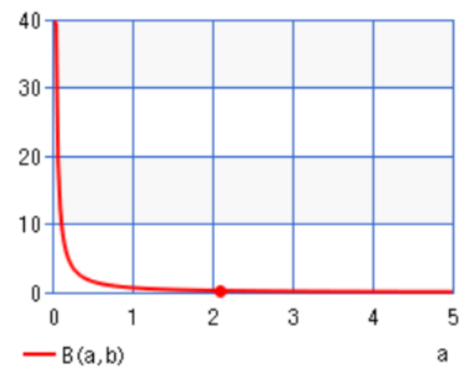
Example
n=0.2

https://keisan.casio.jp

The beta function

|数

を計算します。



a 2.1

b 1.5

計 算 | クリア | 保存・呼出 | 印刷 | 22桁

ベータ関数	計算値
B(a,b)	0.2495071248545138039584

3.3.3 Work Hardening Materials (Considering Flattening) [54]
Assuming the material follows the power hardening rule $\sigma = C\varepsilon^n$ and consideri cross-sectional flattening, the bending moment can be expressed by the follo equation, which corrects the bending moment M without considering flattening. He represents the flattening ratio. D_f can be determined using the experimental for (3.11) mentioned later. The beta function B{(n+4)/2, 3/2} is shown in Figure 3.52 [

$$M_r = M(1-\xi D_f)$$

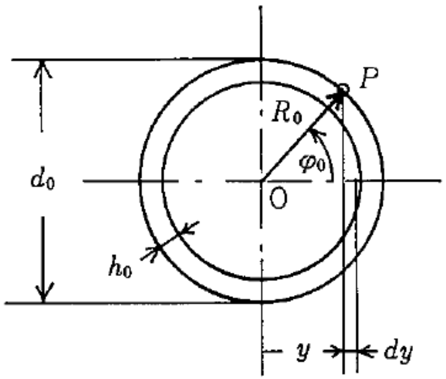
$$\xi = \frac{1}{2}\left\{(n+7) - 2(n+5)\frac{B\left(\frac{n+4}{2},\frac{3}{2}\right)}{B\left(\frac{n+2}{2},\frac{3}{2}\right)}\right\} \quad (3.8)$$

0.25

0.59

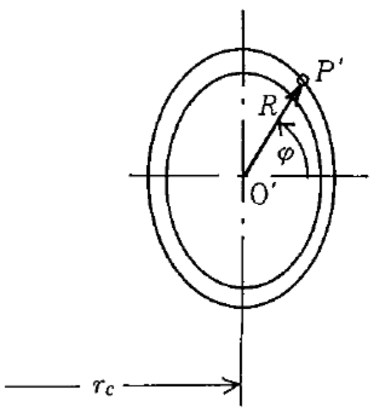
Figure 3.53 show the experimental results of bending pure aluminum tubes comp with the calculated results using equations (3.7) and (3.8). The calculated results n the experimental data in the range of small curvatures, but as the curvature increase consideration of flattening deviates slightly from the experimental values, although the difference is small [54].

p71



(a)

Flattening in bending



(b)

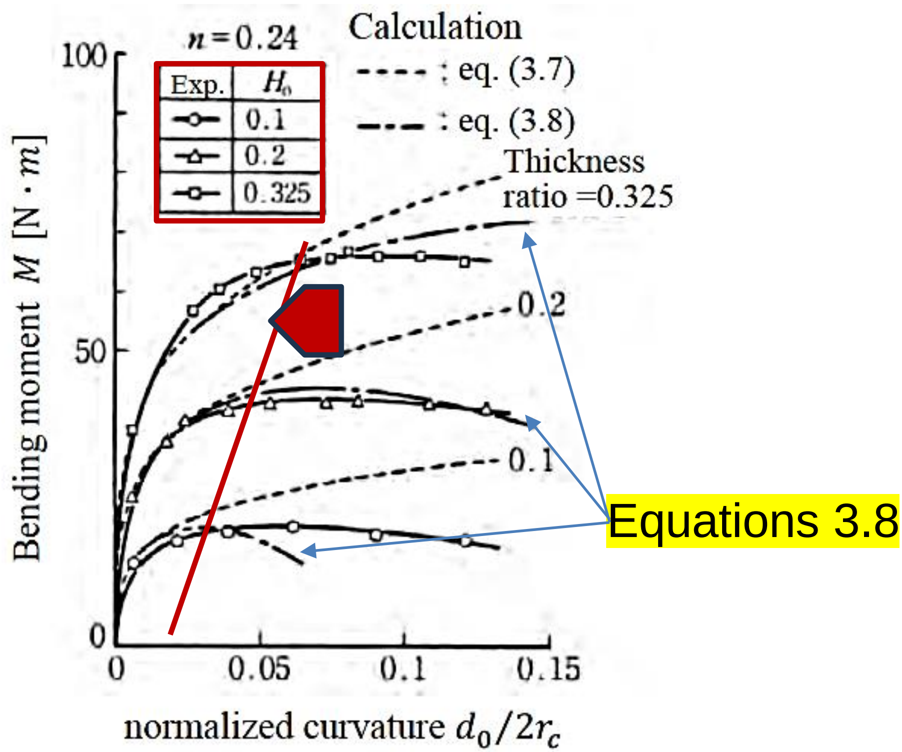
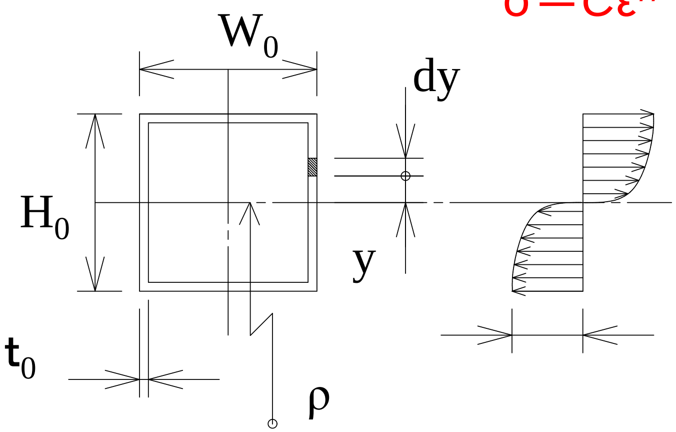


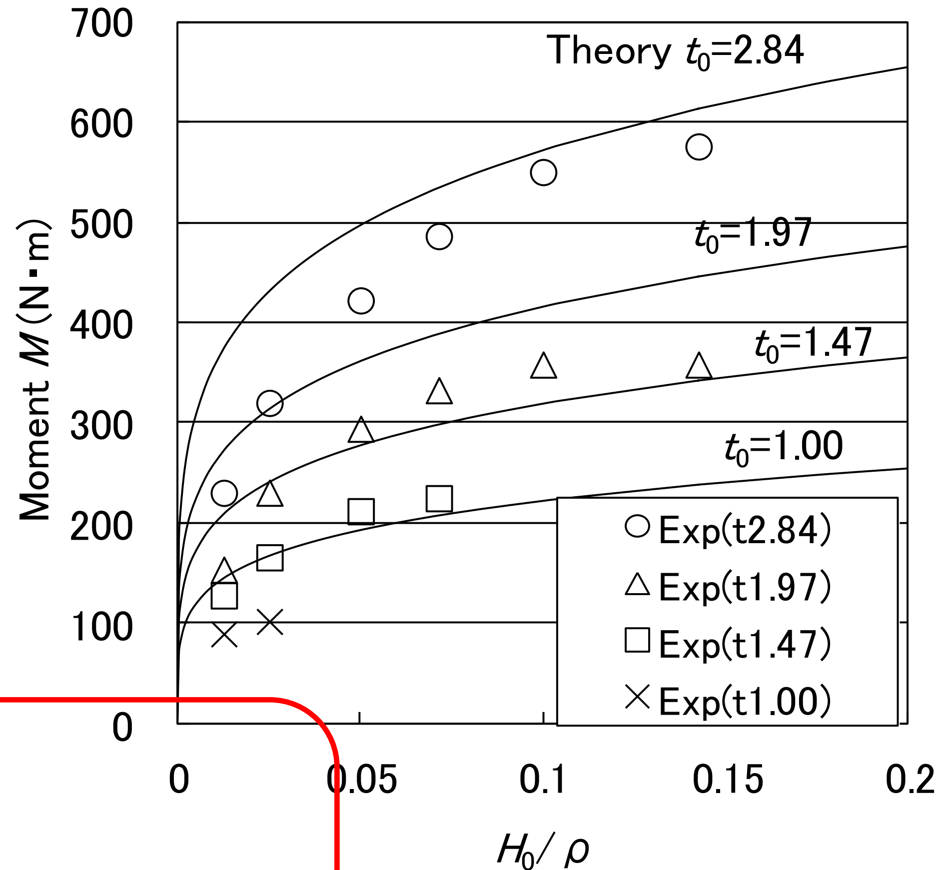
Fig. 3.53 Bending moment and curvature ($H_0 = 2\,t_0/d_0$) [54]

Utsumi: Doctoral thesis 2001, p157–159

$$P = \int_A \sigma \cdot \mathrm{dA}, \quad M = \int_A \sigma \cdot y \cdot \mathrm{dA}$$

$\sigma = C\varepsilon^n$





$$M = \frac{C}{\rho^n (n+2)} \times \left[\frac{t_0 \cdot H_0^{\,n+2}}{2^n} + 2\left(H_0 - 2t_0\right)\left\{ \left(\frac{H_0}{2}\right)^{n+2} - \left(\frac{H_0}{2} - t_0\right)^{n+2} \right\} \right]$$

Square tube$W0 = H0 = 40$

Saitama University

Empirical Formula for Bending Moment in Rotary Bending p71

The following empirical formula for bending moment in rotary bending has been proposed.

$$M = \mu Z \sigma_B \sqrt[3]{d_o / r_c} \qquad (3.9)$$

Here, M represents the bending moment [N·mm], d_o is the outer diameter of the tube [mm], d_i is the inner diameter of the tube [mm], r_c is the bending radius of the tube's central axis [mm], and σ_B is the tensile strength [MPa]. Z takes the following values based on the wall thickness t_0:

It was missing .... Please add

For $t_0 > 0.06\ d_o$: $Z = 0.1(d_o{}^4 - d_i{}^4) / d_o$ [mm^3]

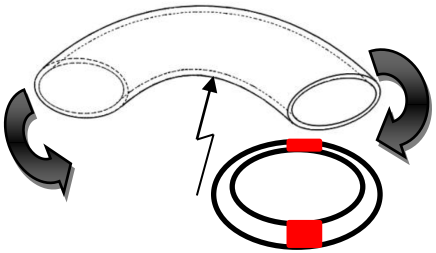
For $t_0 < 0.06\ d_o$ (thin-walled tube) : $Z = 0.8\ t_0(d_o - t_0)^2$ [mm^3]

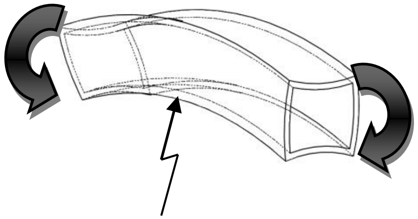
μ takes the following values based on the mandrel:

- μ = 1.0: No mandrel
- μ = 2.0: Hemispherical mandrel, good lubrication
- μ = 3.0: Floating mandrel, good lubrication
- μ = 5~8: Mandrel used, poor lubrication.

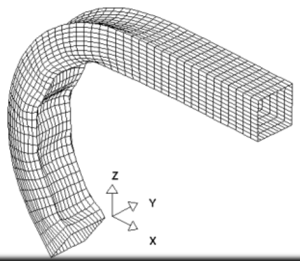
Undesirable phenomena p72

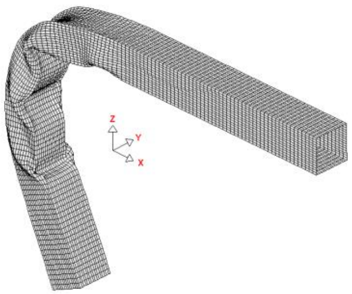
/Deformation of cross-section
⇒Flattening, thickness deviation



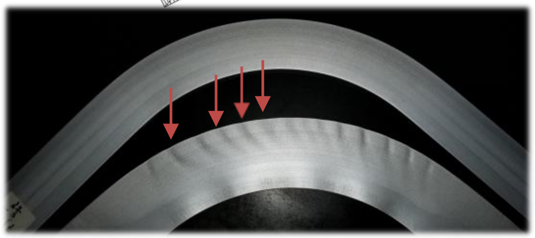


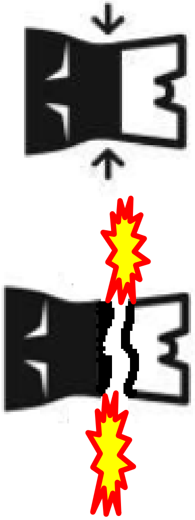
/Buckling
⇒Wrinkling, Folding





/Breaking
⇒splitting, necking





/Springback

/Initial failure, Distortion, Outward falling, Inward falling・・・・

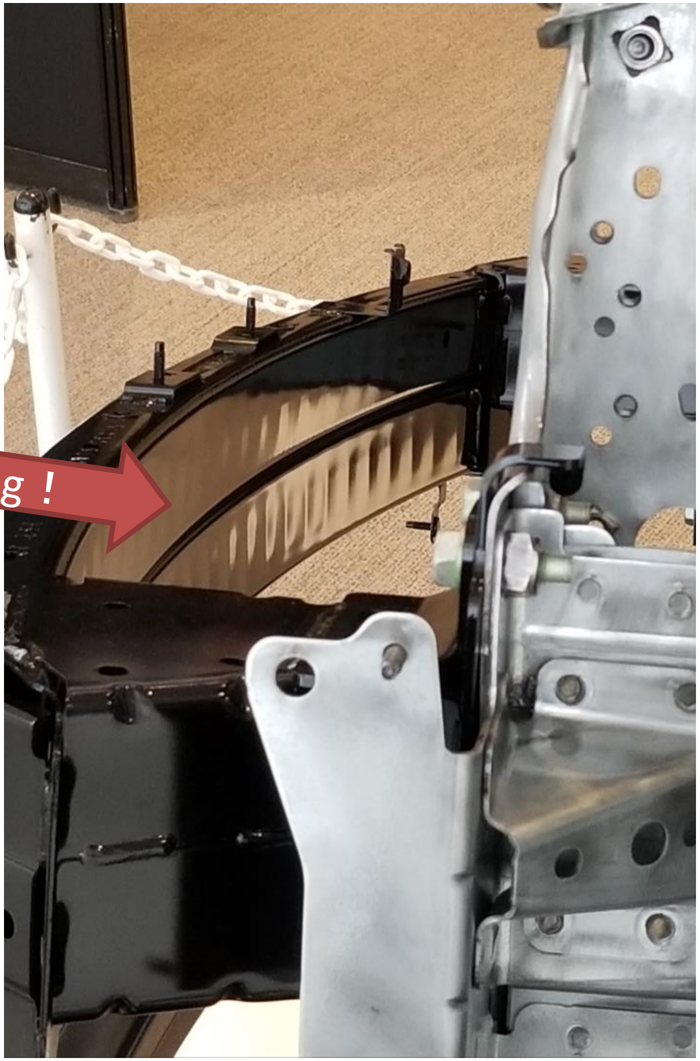
Automotive Engineering Exposition in YOKOHAMA

White body Exhibition

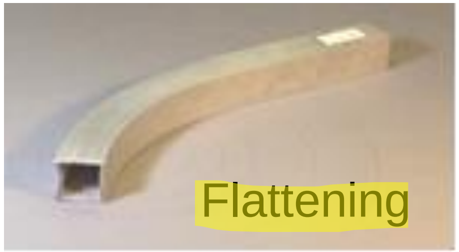
OUTLANDER SOLIO QASHQAI

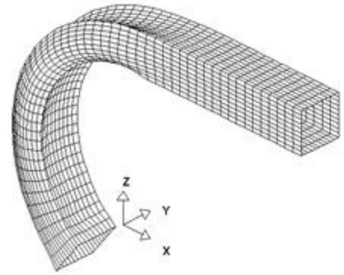
Inner of the frame bumper

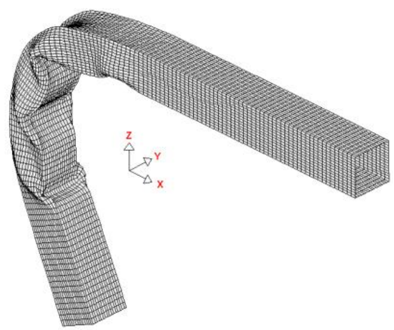
here ! wrinkling !



Specific Defective Phenomena







Al-Mg-Si

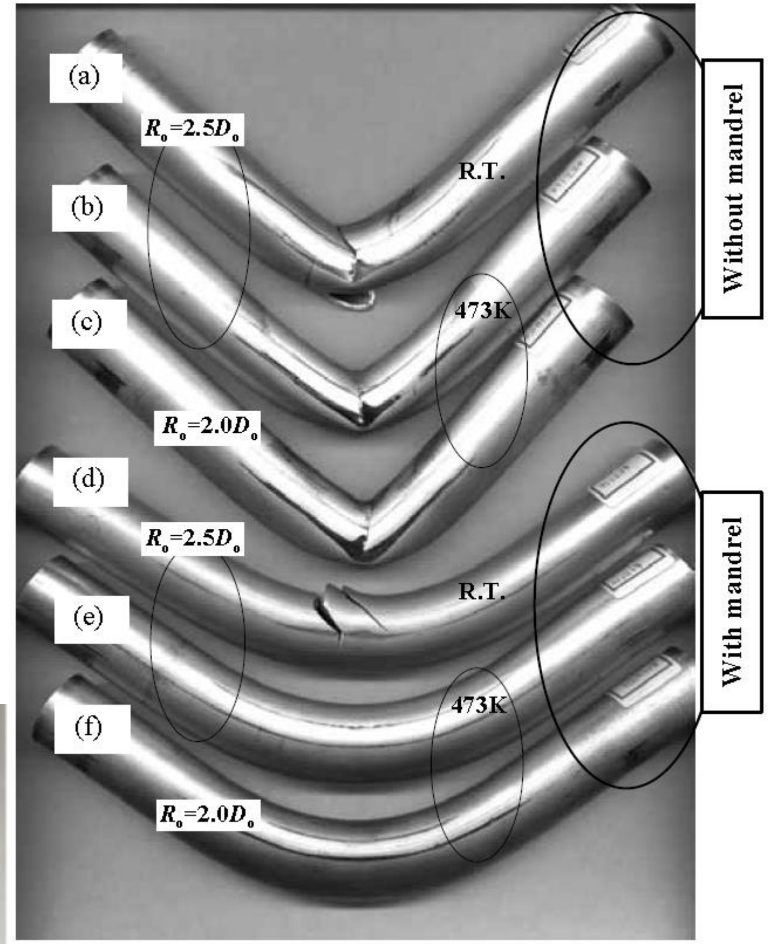
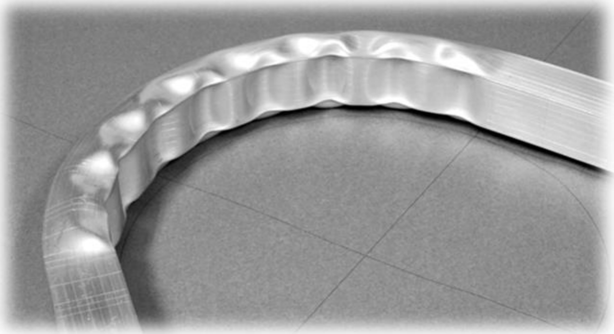


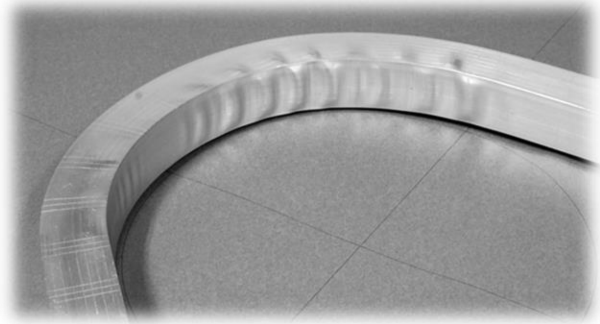
Fig.3 Appearance of bent AZ31 tubes

Mg-Al-Zn (compression side)

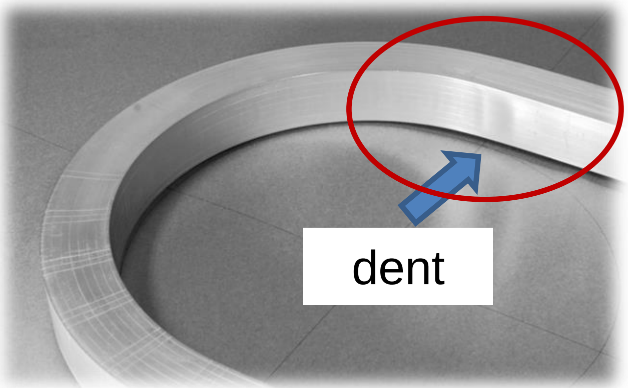
Effect of bending with axial force



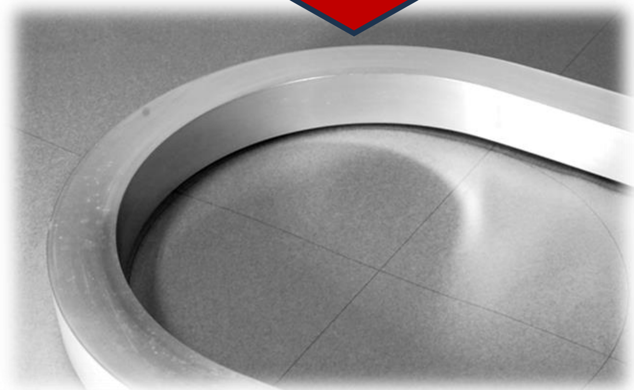
(1) Without any restraining tool



(2) Laminated elastic mandrel



(3)Laminated elastic mandrel and small axial tension



(4) Laminated elastic mandrel and optimum axial tension

A6063S-O, t_0=1.5, t_0/H_0=0.038, R_0/H_0=4.3

JSTP, 52-604(2011)572-576

$$\frac{1}{r_1} - \frac{1}{r_2} = \frac{M}{EI}$$

Springback p73-75

Conditions with small springback

- Stretch bending or draw bending
- Small Bending Radius
- Short Mandrel Position
- Short Distance between pressure die and bending point
- Small Proof Stress

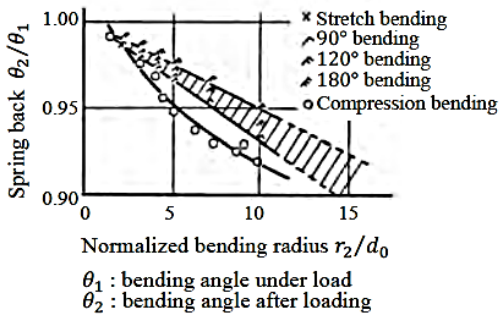


Fig.3.55 Spring back in various bending methods[60]

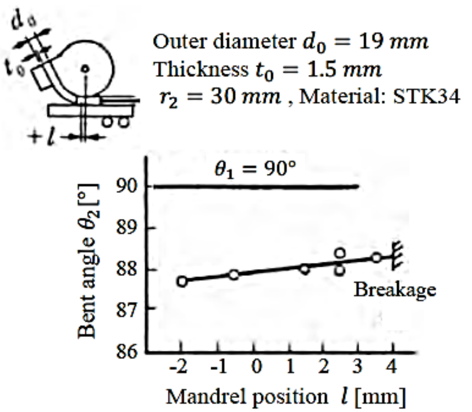
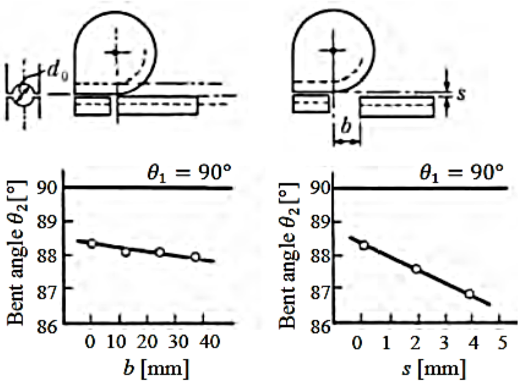


Fig.3.56 Spring back and mandrel position [61]



Outer diameter $d_0 = 19\ mm$, Thickness $t_0 = 1.5\ mm$
$r_2 = 33\ mm$, Material: STK34

Fig. 3.57 Spring back control by pressure die

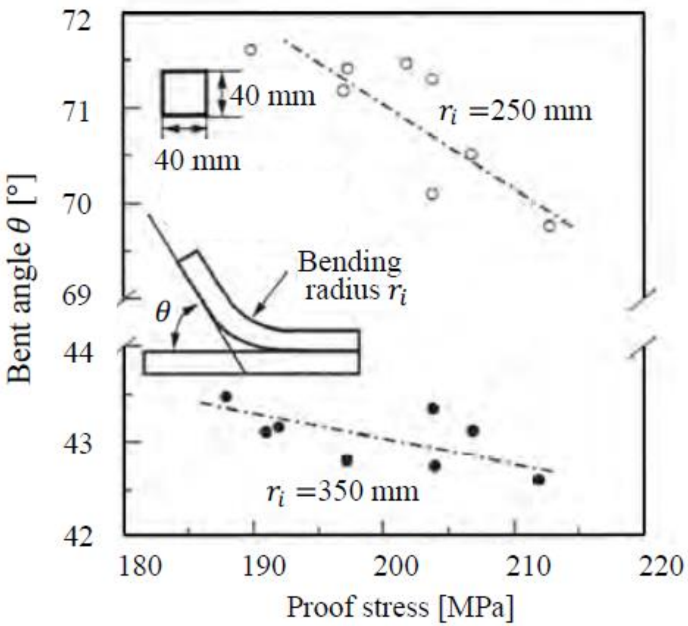
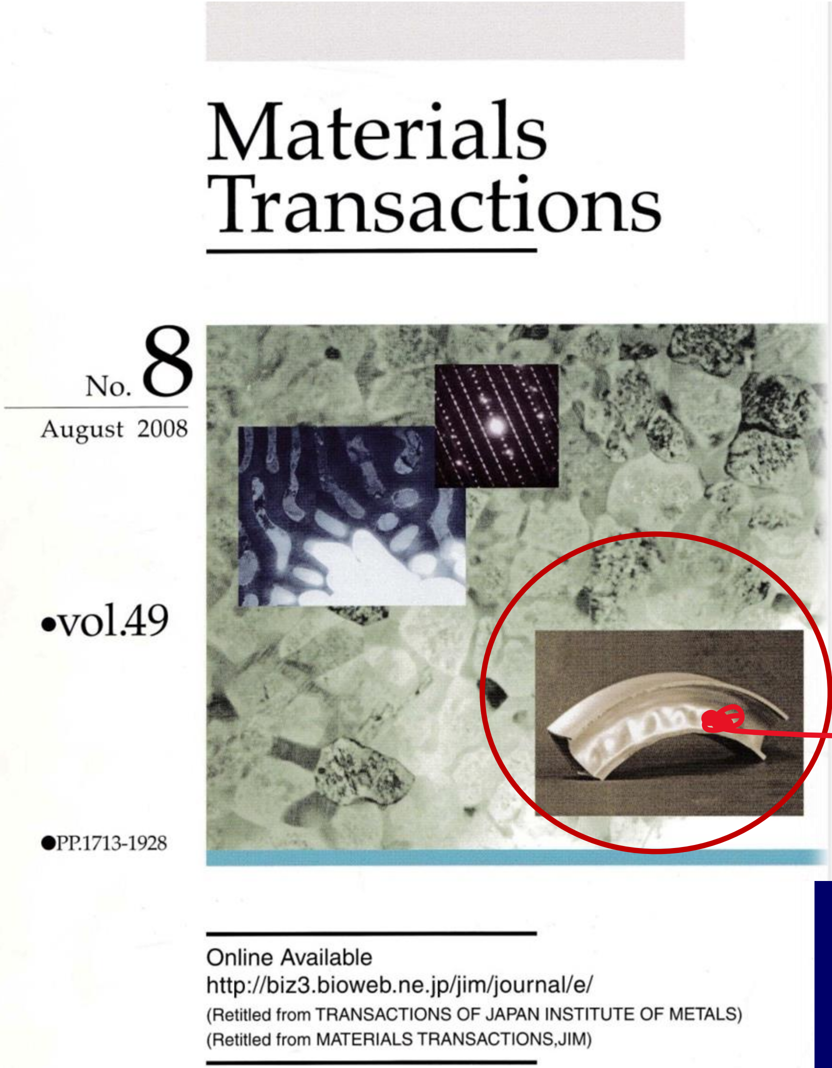
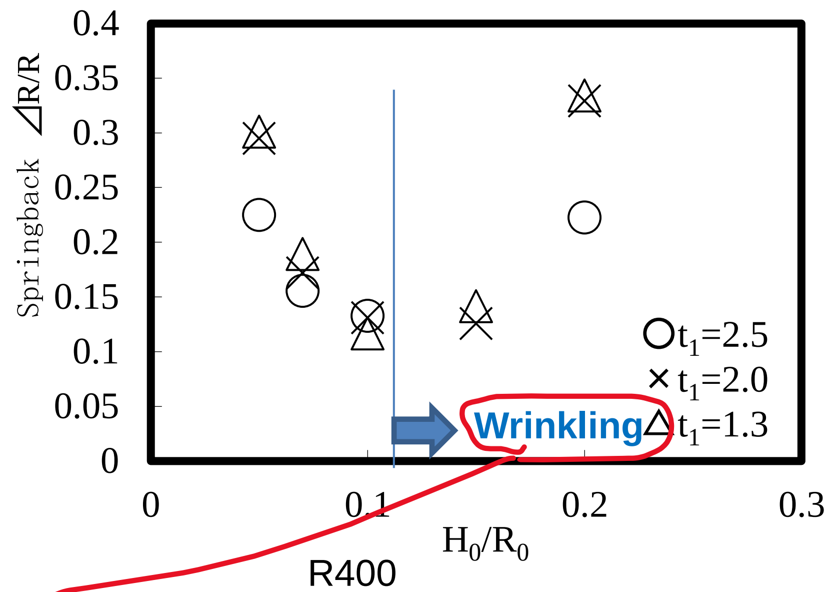


Fig. 3.58 Proof stress and bent angle. [65]

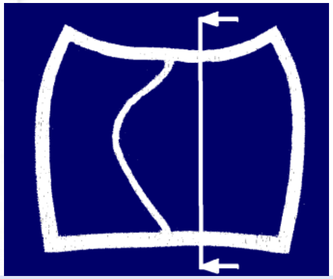
Springback increases when wrinkles appear





A6063-T5 Square tube with rib

40×40, t_0=2.5



3.5 Bending Die・Tool

Rotary draw bending
p75

Axial force

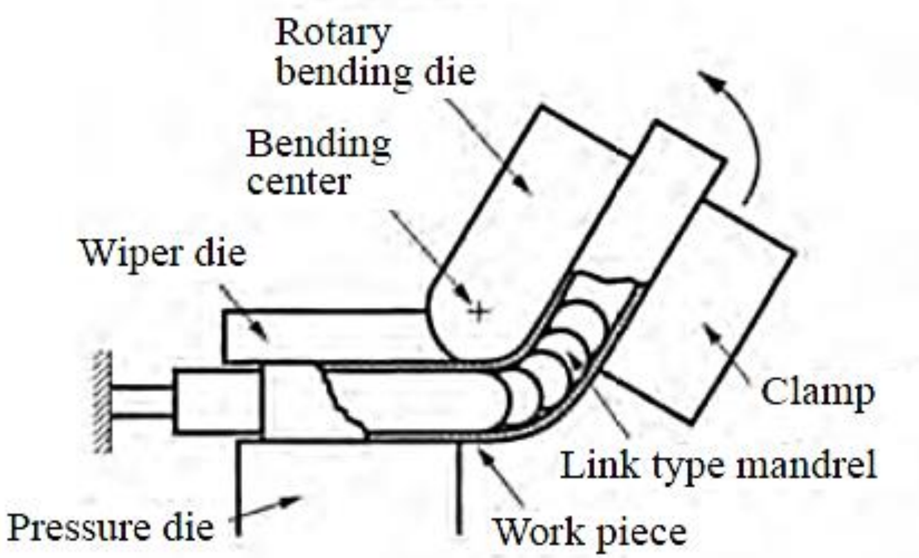


Fig. 3.59 Arrangement of tools in draw bending

Basic tools
・Clamp
・Pressure die
・Bending die

Option tools
・Mandrel
・Axial force
・Wiper

Die-less bending p76

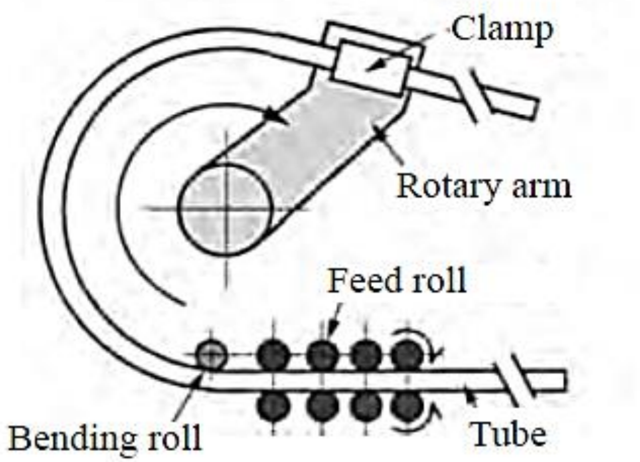


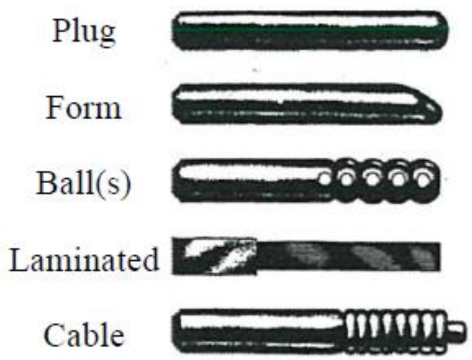
Fig. 3.60 Schematic of die-less U-bending [67]

Basic tools
・Clamp
・Rotary Arm
・Bending Roller guide

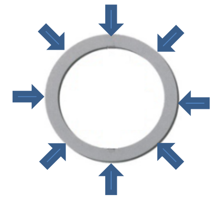
$r/d_0 = 14$ to 30
The curvature can be freely adjusted.

Mandrel and others p77

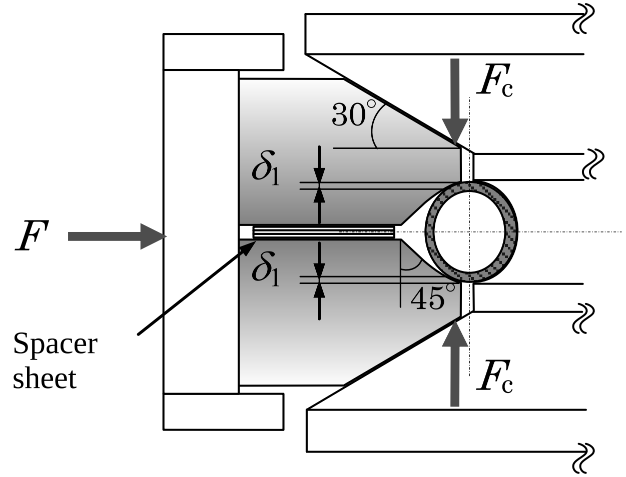
How to constrain from inside of a pipe



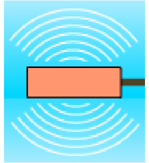
(a) Mandrels

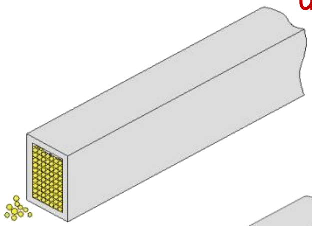


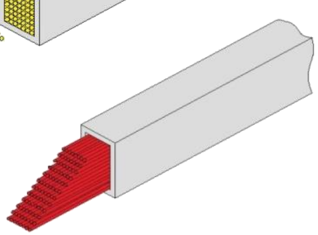
How to constrain from out of a pipe



grain, wire, low melting point ally, sand, ice, liquid,
ultrasonic vibration







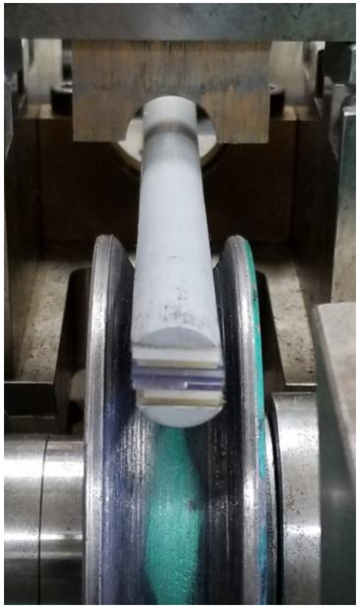
Euler

Restraint condtion

$$Pcr = \frac{n\pi^2}{l^2} EI$$

Wiper die

Homemade Mandrel



Effect of mandrels p77-78

Table 3.5　Selection criteria for mandrel of rotary draw bending

Outer diameter [mm]	Thickness [mm]														
	0.406	0.508	0.635	0.711	0.889	1.067	1.245	1.473	1.651	1.829	1.981	2.108	2.413	2.769	3.048
15.88	1	1	1	1	1	F	F	F	F	–	–	–	–	–	–
19.05	1	1	1	1	1	1	1	F	F	–	–	–	–	–	–
22.23	1	1	1	1	1	1	1	F	F	F	–	–	–	–	–
25.40	2	2	2	2	1	1	1	F	F	F	F	–	–	–	–
31.75	3	3	2	2	2	2	2	2	2	1	1	F	F	F	F
38.10	3	3	2	2	2	2	2	2	2	2	2	1	1	F	F
44.45	4	4	3	3	3	3	3	3	3	2	2	2	1	1	F
50.80	4	4	3	3	3	3	3	3	3	2	2	2	2	1	1
57.15	4	4	4	4	3	3	3	3	3	2	2	2	2	2	1
63.5	4	4	4	4	3	3	3	3	3	2	2	2	2	2	2
76.2	4	4	4	4	3	3	3	3	3	2	2	2	2	2	2
88.9	5	5	5	5	4	4	4	3	3	2	2	2	2	2	2
101.6	5	5	5	5	4	4	4	3	3	2	2	2	2	2	2
114.3	6	6	5	5	4	4	4	3	3	3	3	3	2	2	2
127.0	6	6	6	6	5	5	5	4	4	4	4	4	3	3	3
139.7	6	6	6	6	5	5	5	4	4	4	4	4	3	3	3
152.4	6	6	6	6	6	6	5	5	5	4	4	4	4	3	3

Form mandrel : F,　Ball mandrel : (number) = number of balls

Cable mandrel : 2×(number)+1= number of cables,　in lower left box 2×(number)+2= number of cables

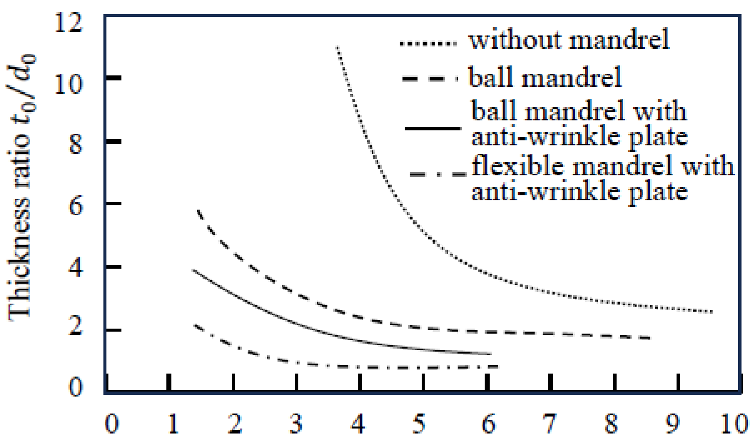


Fig. 3.63　Forming limit of rotary draw bending

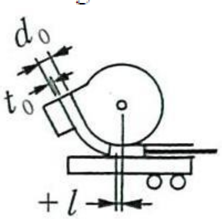


Table 3.6　Protrusion amount of mandrel and bendability　[68]

Protrusion amount of mandrel	without mandrel	~ 0.2 mm	0.5 mm	1.5 mm
Maximum thickness reduction rate		21 %	22 %	32 %
Flattening rate	51 %	21 %	18 %	13 %
Outlook	outer: dent inner: wrinkle	good	good	deformation by mandrel at end of bend

Manderl・・・・

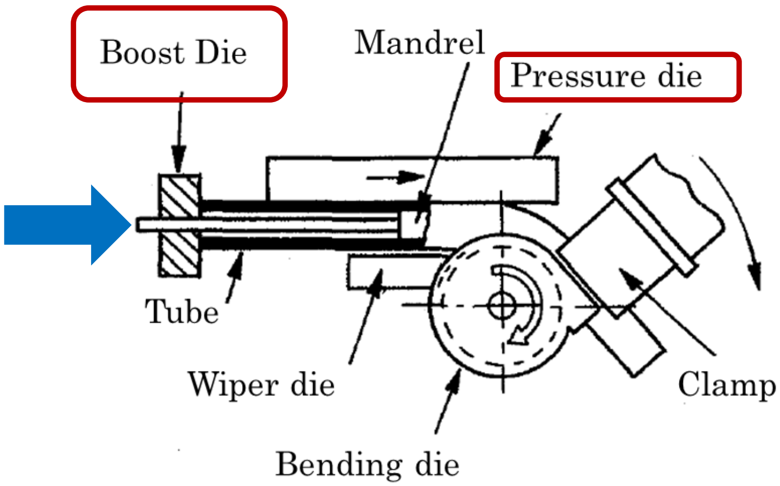
・is effective in flattening and Folding

・is also effective for wrinkling, but has no intrinsic effect.

Pressure die・・・・

・is effective in deformation of cross-section and thickness deviation.

Other tools p78-79



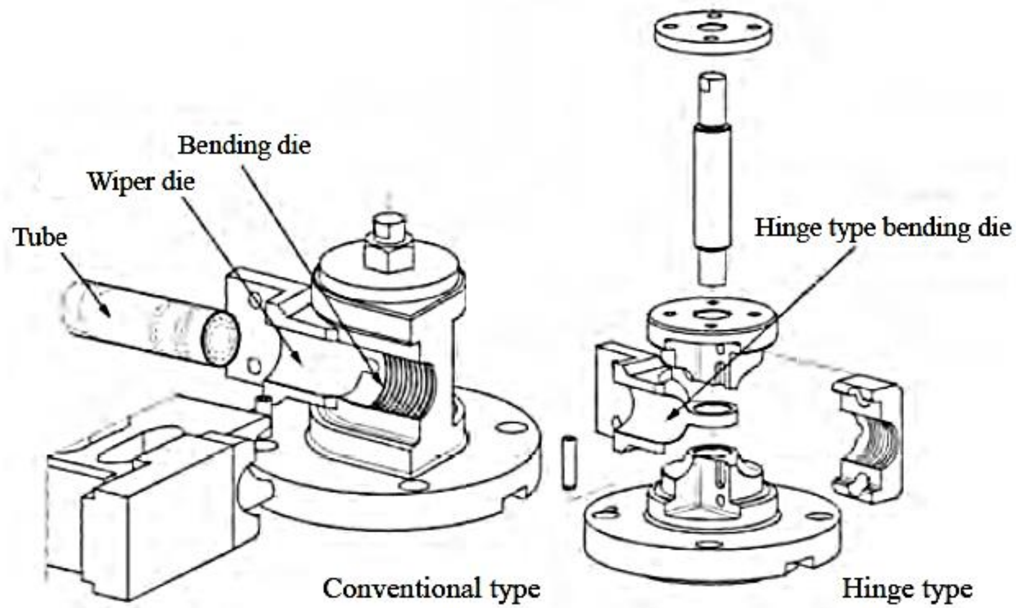
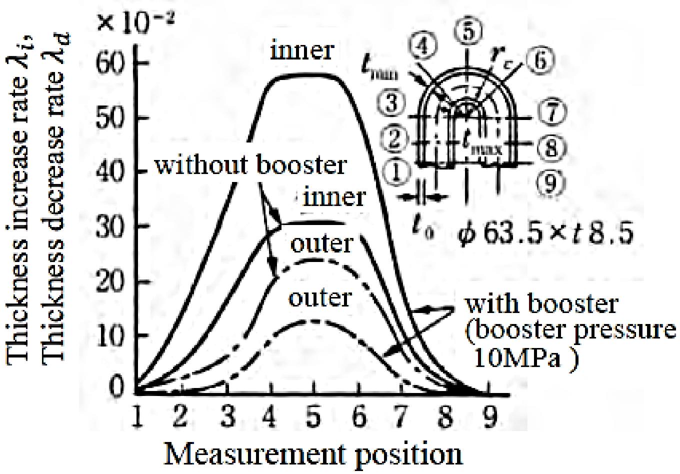


Fig. 3.65 Conventional and Hinge type bending dies. [73]



$$\lambda_i = \frac{t_{max} - t_0}{t_0}$$

$$\lambda_d = \frac{t_0 - t_{min}}{t_0}$$

Fig. 3.64 Effect on booster die on thickness deviation [72]

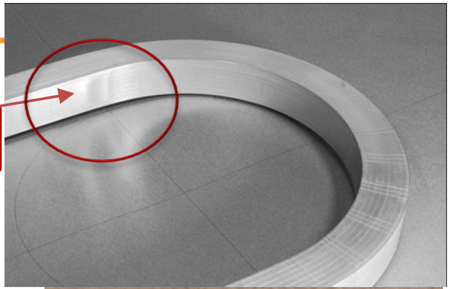
Common Wiper・・・

・is effective in initial dent.

Hinge Type・・・

・can extend a tool life.

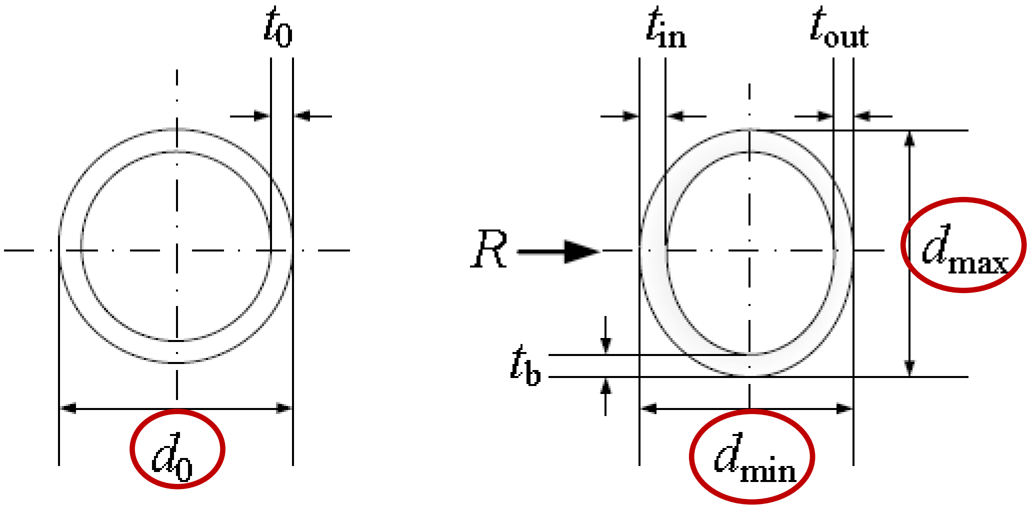
・is an easy tool change.



3.6 Forming limits

Flattening ratio

$$D_f = (d_{max} - d_{min}) / d_0$$



(a)Before bending (b)After bending

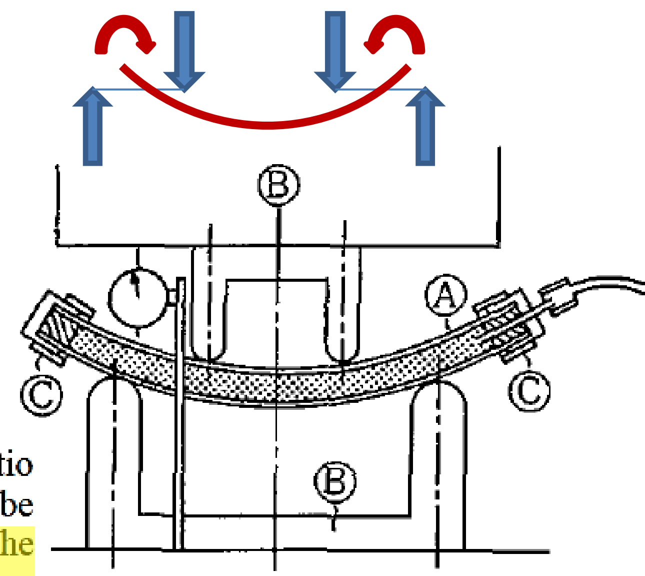
JSTP:49-572（2008）p896

Flattening ratio in pure bending p79

$$D_f = A \cdot \left(\frac{d_o}{2r_c}\right)^B \qquad (3.11)$$

Table 3.7 Constant A, B in equation (3.11) for flattening [3]

Material	A	B
A 1100	$\frac{0.07}{(H_0 - 0.05)^{2.67}}$	$\frac{1.4}{(H_0 - 0.05)^{0.167}}$
A 5056	$\frac{0.03}{(H_0 - 0.17)^{3.73}}$	$\frac{0.07}{(H_0 - 0.012)^{0.267}}$
Pure Copper	$\frac{0.08}{(H_0 + 0.4)^{9.51}}$	$\frac{0.07}{(H_0 - 0.08)^{0.042}}$

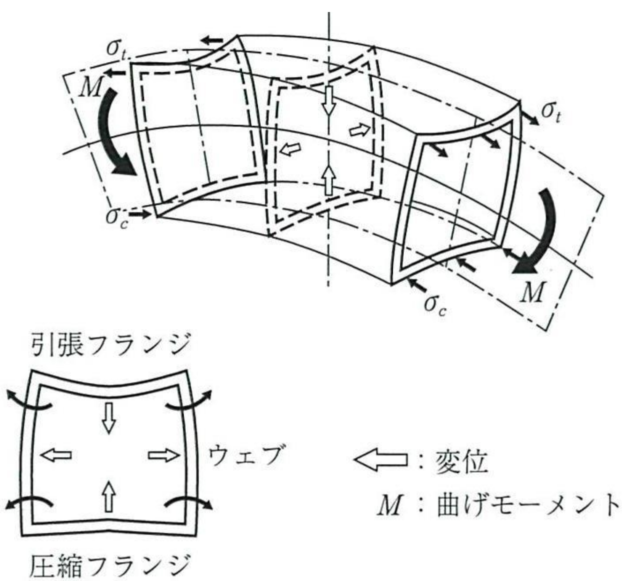


where r_c is the bending radius, A and B are constants determined by the thickness ratio $H_0 = 2t_0 / d_0$ and various materials as shown in **Table 3.7**. From equation (3.11), it can be observed that the flatness ratio increases as the thickness becomes thinner and the bending radius becomes smaller.

Flattening Force p96

$$P_{tn} = P_{cn} = t_0 W_0 C \left(\frac{h_0}{2 r_c} \right)^n d\theta \qquad (3.12)$$

In the equation, P_{tn} and P_{cn} represent the tension and compression components of flattening forces for a small angle $d\theta$, r_c is the curvature radius, h_0 is the height of the square tube, W_0 is the width, t_0 is the thickness, n is the work hardening exponent, and C is the plastic coefficient. Equation (3.12) indicates that as the bending progresses and the curvature radius r_c becomes smaller, the flattening force increase, leading to greater flattening.



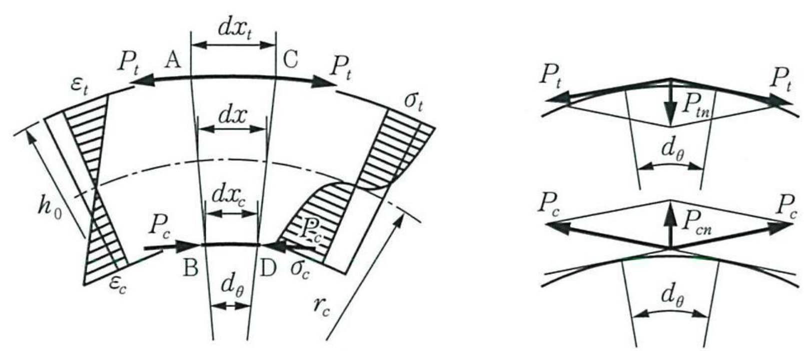
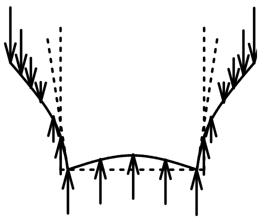
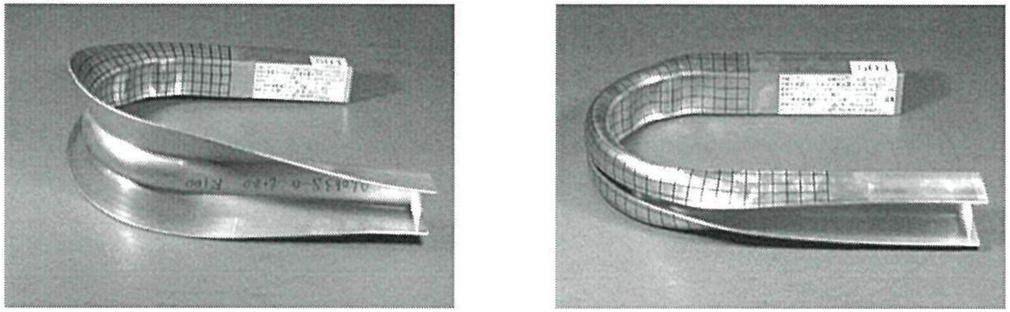


図 3.66　角管のへん平変形 [56)]

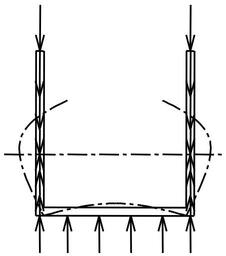
Deformation of Channel p81

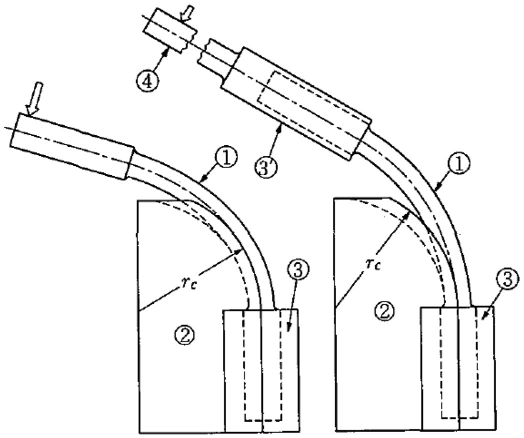




(a) outward (b) inward

Fig. 3.67 Web deformation in bending of channel section [74]





(a) (b)

Thickness deviation

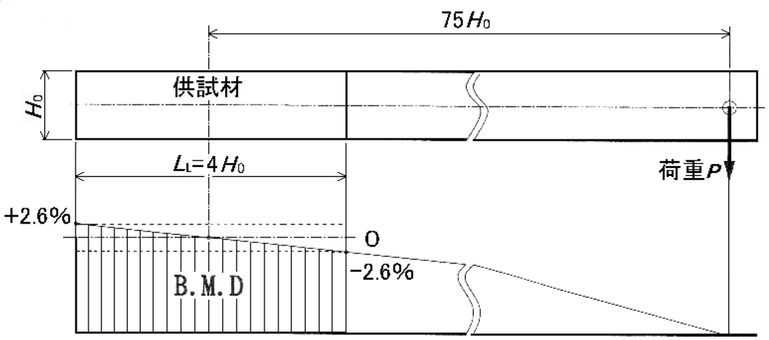
$$\lambda_t = (t_{max} - t_{min}) / t_0$$

$$\lambda_t = C \cdot \log_{10}\left(\frac{d_0}{2r_c}\right) + D$$

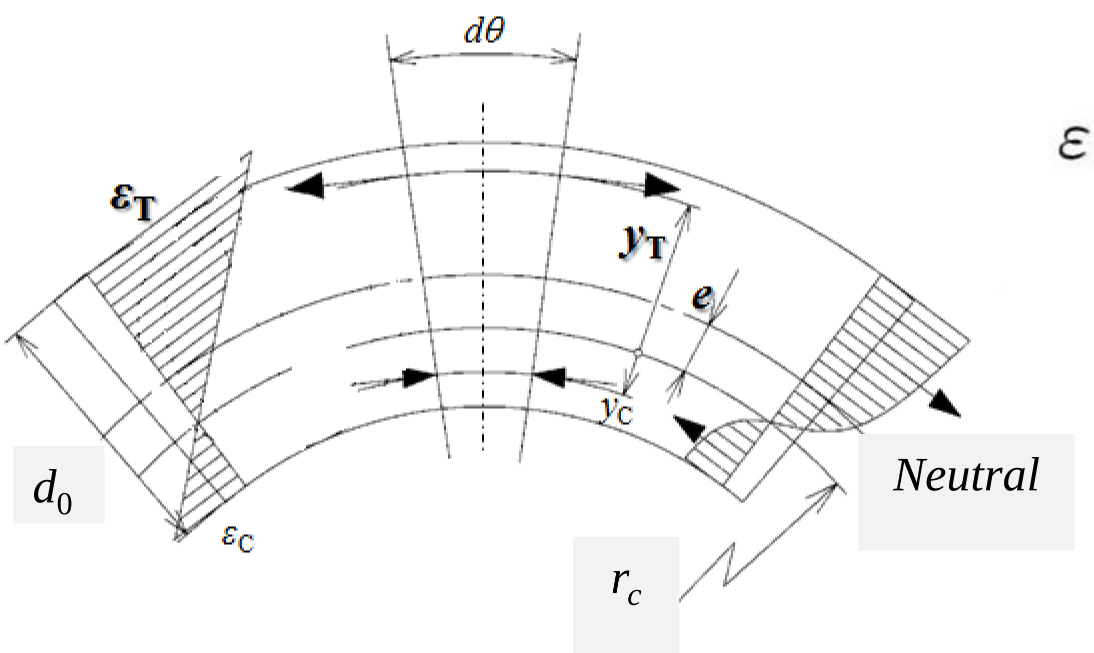
$H_0 = 2t_0/d_0$

Table 3.8 Constant C, D in equation (3.13) for thickness deviation [3]

Material	C	D
A 1100	$0.092\ H_0^{-0.324}$	$0.158\ H_0^{-0.324}$
A 5056	$0.26\ H_0^{0.35}$	$0.30\ H_0^{0.11}$
Pure Copper	$0.31\ H_0^{0.43}$	$0.37 H_0^{0.26}$



Splitting limit ***p*82**



$$\varepsilon_0 = \frac{0.5\,d_0 + e}{r_c - e}$$

Simplified form

$(e = 0)$

$$\varepsilon_0 = d_0 / 2 r_c$$

Ex.

If the limit of elongation is **20%**

pipe diameter : d_0=20mm

$r_0 = d_0/2\varepsilon_{Tmax} = 20/(2 \times 0.20) =$ **50mm bending radius**

Folding limit *p*82

$$\frac{r_m}{r_b} = 4.8\,H_m^{\,2.0} \cdot n^{-(0.3\,H_m^{\,-0.21})}$$

Wrinkling limit *p*83

$$\frac{r_m}{r_w} = K \cdot H_m^{\,2.0} \cdot n^{-0.46}$$

Wrinkling limit are determined by restraint condition, material, inertia, buckling length.

Forming limits of Pipe and Square tube　*p* 84-85

Table 3.11　Minimum bending radius of rotary bending for steel tube　[78]

Outer diameter [mm]	Thickness [mm]	Minimum bending radius r_0/d_0 with mandrel, Bending angle 90°	with mandrel, Bending angle 180°	w/o mandrel, Bending angle 90°	w/o mandrel, Bending angle 180°
9.53	0.71	2	2.3	3.3	6.7
	0.81	2	2.3	3.3	4.7
	0.89	1.7	2.0	3.0	4.7
	1.25	1.5	2.0	2.7	4.0
12.70	0.81	2	2.25	3.0	4.0
	0.89	1.8	2.0	3.0	4.0
	1.25	1.5	1.8	2.8	3.5
	1.65	1,5	1.8	2.5	3.5
15.88	0.89	1.6	2.0	3.2	4.0
	1.25	1.4	2.0	2.8	4.0
	1.65	1.2	1.8	2.4	3.6
19.05	0.89	1.8	2.0	3.0	4.0
	1.25	1.7	1.8	3.0	4.0
	1.65	1.5	1.7	2.7	3.3
	2.12	1.3	1.5	2.7	3.3
22.23	0.89	1.9	2.0	2.9	4.0
	1.25	1.6	1.9	2.9	3.7
	1.65	1.4	1.8	2.6	3.7
	2.12	1.3	1.6	2.6	3.4
	1.25	1.6	1.9	3.0	4.5

Outer diameter [mm]	Thickness [mm]	Minimum bending radius r_0/d_0 with mandrel, Bending angle 90°	with mandrel, Bending angle 180°	w/o mandrel, Bending angle 90°	w/o mandrel, Bending angle 180°
50.80	2.12	1.75	1.9	3.0	4.25
	2.77	1.7	1.8	3.0	4.0
	3.05	1.6	1.75	2.9	4.0
57.15	1.25	1.9	2.1	4.4	5.3
	1.65	1.8	1.9	3.1	4.2
	2.12	1.8	1.9	3.0	4.2
	2.77	1.7	1.8	3.0	4.0
	3.05	1.7	1.8	2.9	4.0
	1.65	1.8	1.9	3.2	4.0

Table 3.10　Minimum bending radius of rotary bending for square welded steel tube　[50]

Side length \ Thickness	2.11	1.65	1.24	0.89
12.7	41.28	44.45	47.63	50.0
19.05	50.8	50.8	63.5	76.2
25.4	76.2	76.2	88.9	101.6
28.58	76.2	76.2	88.9	101.6
31.75	88.9	88.9	101.6	—
38.10	114.3	114.3	127.0	—
44.45	152.4	165.1	177.8	—

$12.7 \times 1.8 \fallingdotseq 23$　　$\fallingdotseq 38$

3.7 Forming example *p86*

（SUS316）

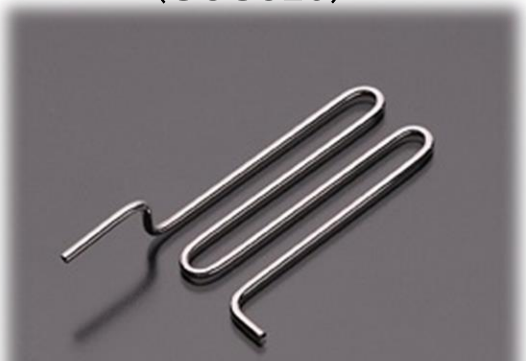


Fig. 3.69 Three dimensional bending of small diameter tube †1

Al-Mg-Si

Fig. 3.70 Three dimensional bending of small rectangular tube †2

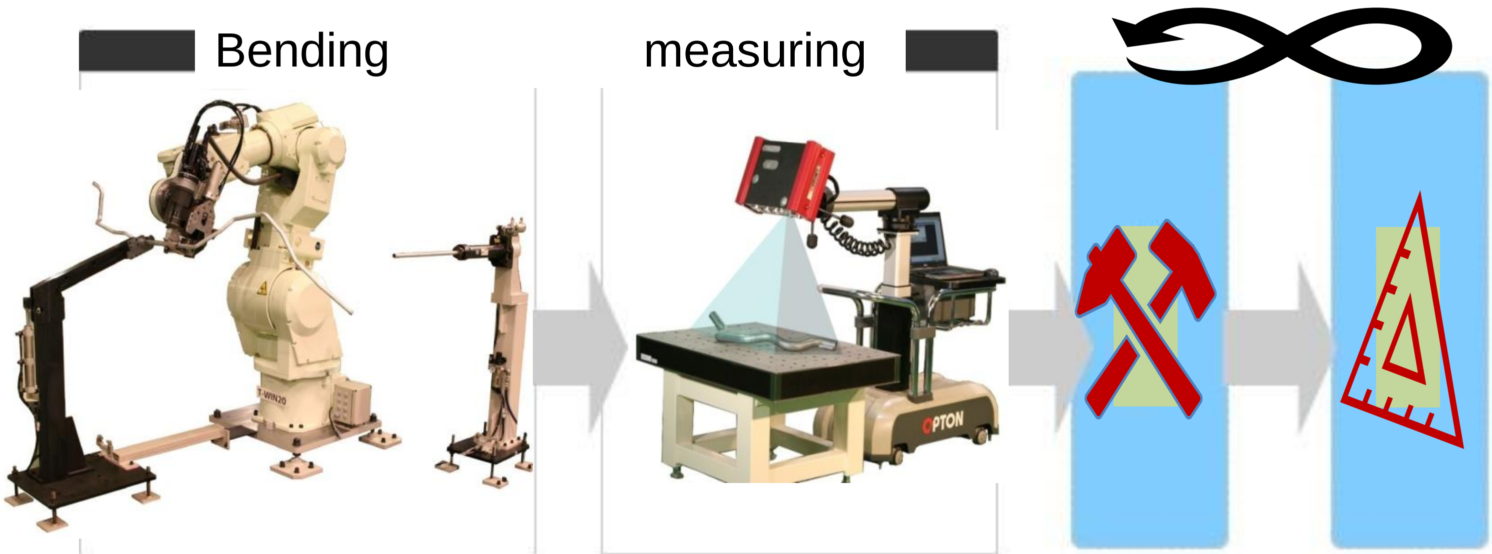
780MPa, ERW

Photo 3 Automotive part applied PRB method and 780 MPa class ERW tube

Small diameter tube of SUS, Aluminum alloy extrusions and ERW high-strength steel tube are applied for lightweight and high rigidity, mainly in medical, aerospace and automotive industry.

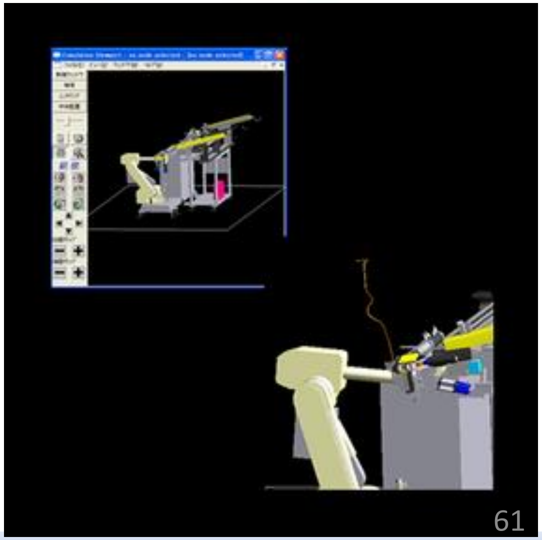
R50, A6063-O
20×10×0.5mm, Rotary Draw bending
⇒Waveguide for a Satellite

Robots and measuring systems p86



Simulation⇒
Material handling, Interference Checking

Opton by HP



Summarize

- Method

⇒draw bending, flexible bending, shear bending

- Mandrel

⇒Flattening

- Restraint from outside

⇒cross-sectional shape accuracy

- Axial tension force

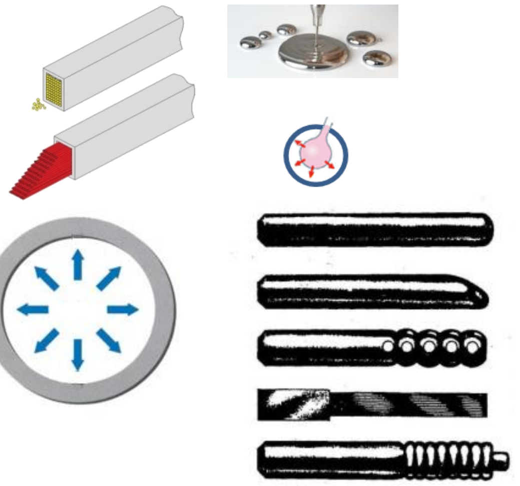
⇒Constraint buckling

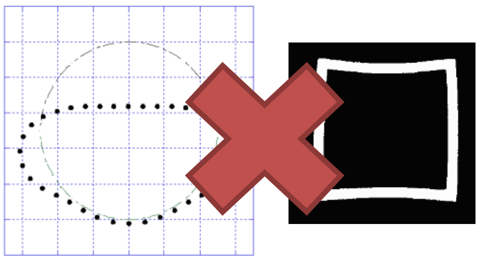
⇒Decrease springback

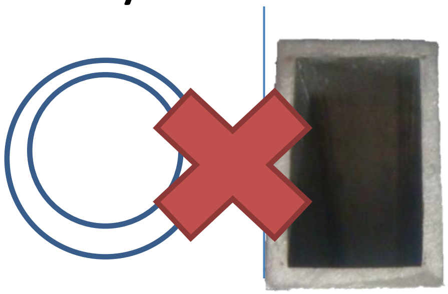
- Axial compression

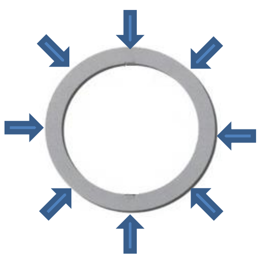
⇒Reduced thinning,

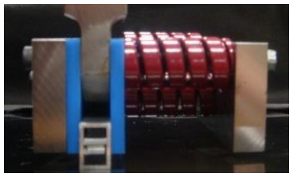
necking, splitting

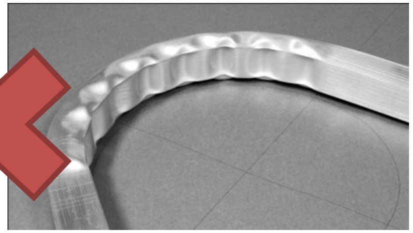


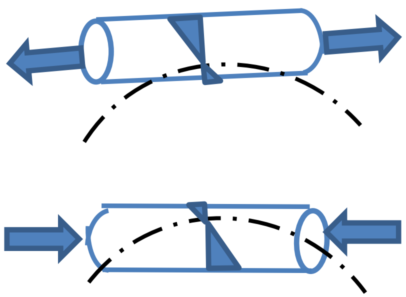












Thank you for your attention.