64th Advanced Materials Congress World Fellow Summit,
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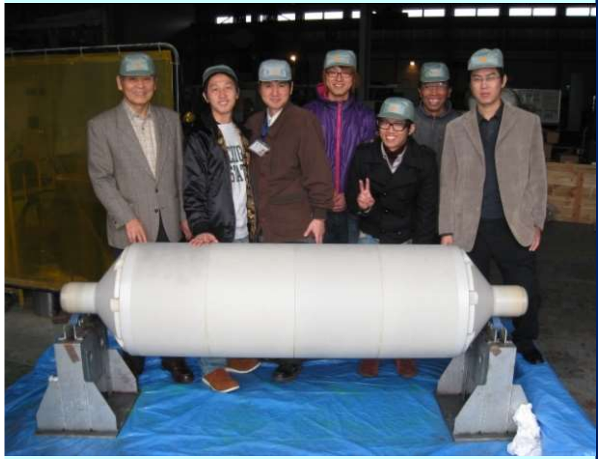

Study on Application of Lage Ceramics Structures to the Steel Manufacturing Industry

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Nao-Aki NODA Resume

Noda, Nao-Aki was born on December 25, 1956 in Bisai-city, Japan.

Education: B in Engring Kyushu Institute of Technology, 1979; M in Engring 1981

（九州工業大学卒論修論指導：Y.Murakami村上敬宜先生）;

Ph.D in Engring, Kyushu University, 1984 （九州大学博論指導：H.Nisitani西谷弘信先生）

Career: Assistant professor Kyushu Institute of Technology, Kitakyushu, Japan, 1984-1987.

Visiting Scholar Lehigh (Pennsylvania) University, 1985-1986（受入教授：Fazil Erdogan先生）.

Associate professor Kyushu Institute of Technology, Kitakyushu, Japan, 1987—2003,

Professor, 2003-2022, <u>Professor emeritus Kyushu Inst. Tech. 2022.</u>

<u>Honorary professor, 2024 Indian Institute of Technology, Guwahati.</u>

Awards:

Japan Society of Automotive Engineers, Technical Paper Award, 2025 （日本自動車技術会賞論文賞）

JSMS Branch Distinguished Service Award, 2023 （日本材料学会支部功労賞）

JSME Materials and Mechanics Division Achievement Award, 2022 (日本機械学会材料力学部門賞業績賞)

JCOM Award for Scientific Papers, Japan Society of Materials Science, 2020 (日本材料学会複合材料部門賞論文賞)

Japan Society for Technology of Plasticity JSTP Education Award, 2020 (日本塑性加工学会賞教育賞)

Japan Society for Design Engineering Best Paper Award, 2020 (日本設計工学会論文賞)

JSME Materials and Mechanics Division Contribution Award, 2017 (日本機械学会材料力学部門賞貢献賞)

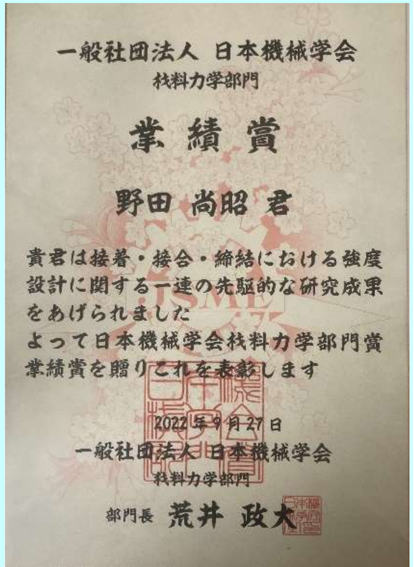
Fellow of JSAE, 2015 (自動車技術会fellow称号）

Fellow of JSME, 2012 （日本機械学会fellow称号）

The Materials Process Technology Center Award 2010（素形材産業技術賞）

JSMS Award for Academic Contribution, 2010 （日本材料学会学術貢献賞）

JSTP Medal for Outstanding Paper, 2008（日本塑性加工学会論文賞）



Concurrent/Guest Professorship:

Northeastern University, 2018 (東北大学兼職教授）

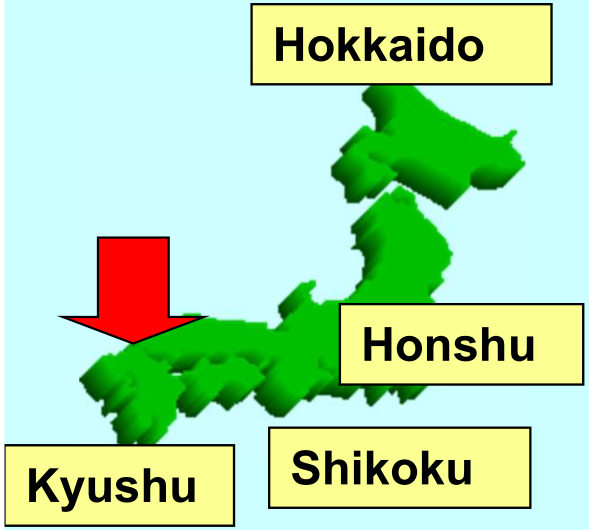
Henan University of Science and Technology, 2010（河南科技大学 兼職教授）

Shandong University, China, 2008 （山東大学 客座教授）

East China Jiaotong University, China, 2003 （華東交通大学 兼職教授）

Shandong University of Technology, China, 1996 （山東工業大学 客座教授）

Kyushu Institute of Technology



The Location of Kyutech in Kitakyushu

Location and Size

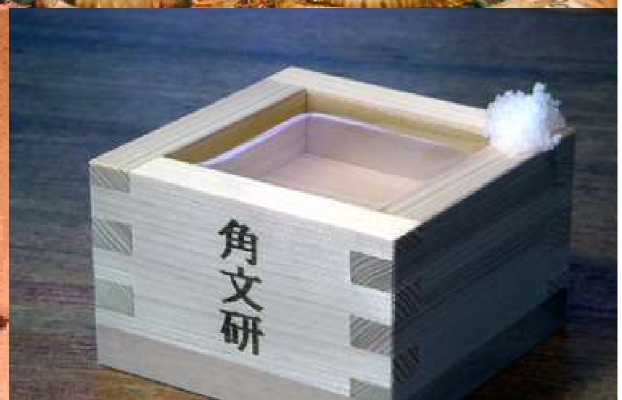
・Northern most city in Kyushu, Japan / a large city of 1 million people

Flights

・2 hours from **Hong Kong** (direct)
・4 hours from **Beijing** (via Shanghai)
・2 hours from **Shanghai** (direct)
・1.5 hours from **Seoul** (direct)
・3.5 hours from **Singapore** (direct)
・11 hours from **Amsterdam** (direct)
・12 hours from **Los Angeles**
(via Narita / Seoul)

→Fukuoka Airport
→Hakata station
→Kokura station

Delicious Food and Drink Found in Kitakyushu



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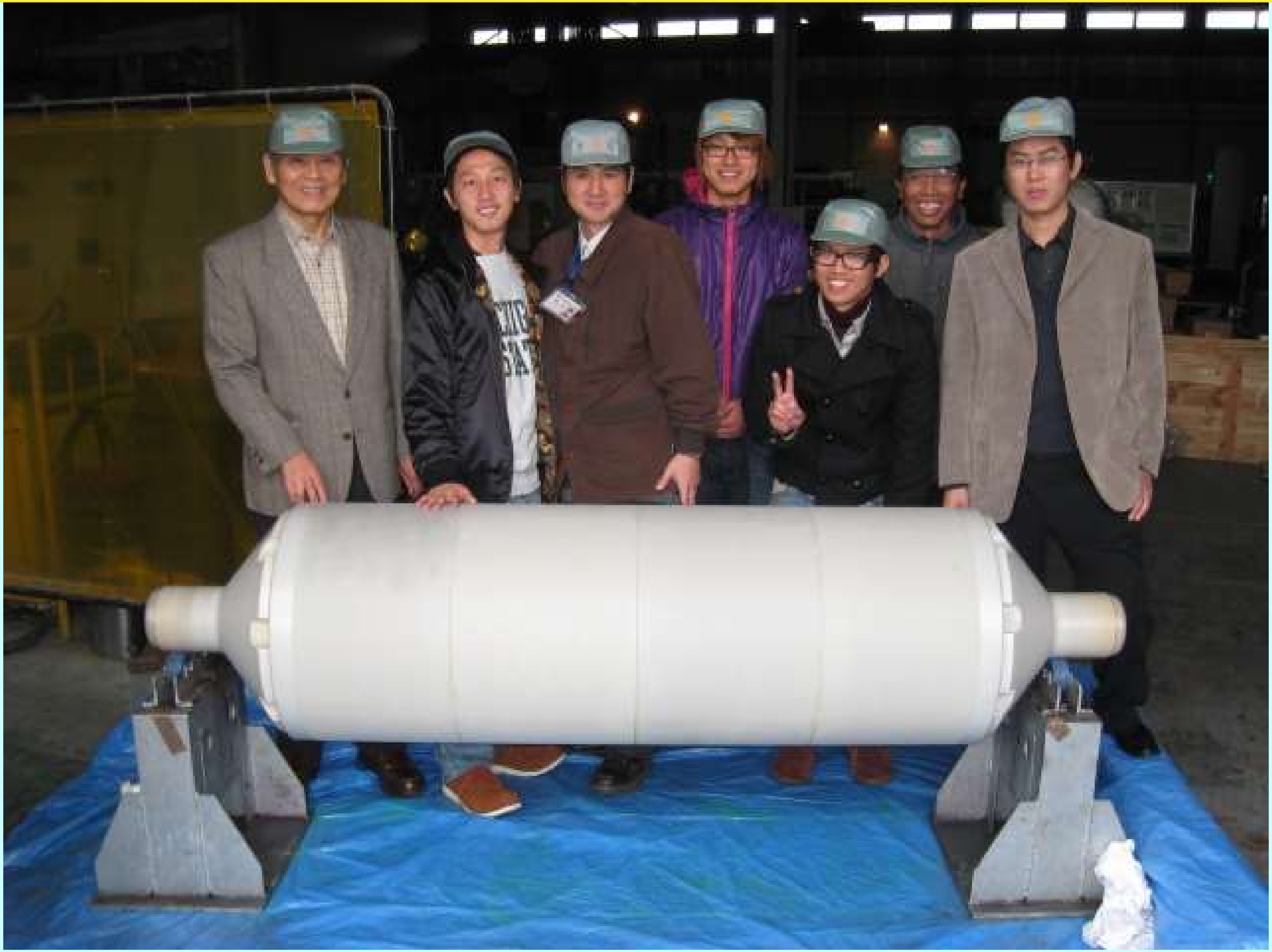
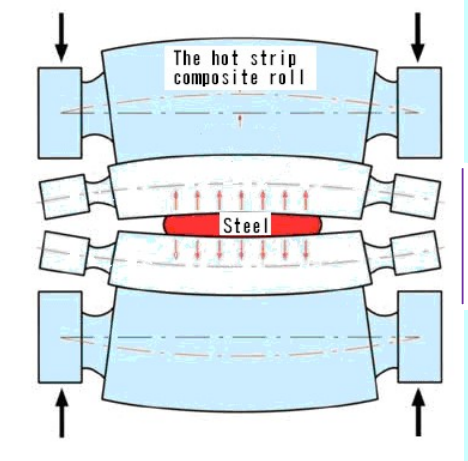
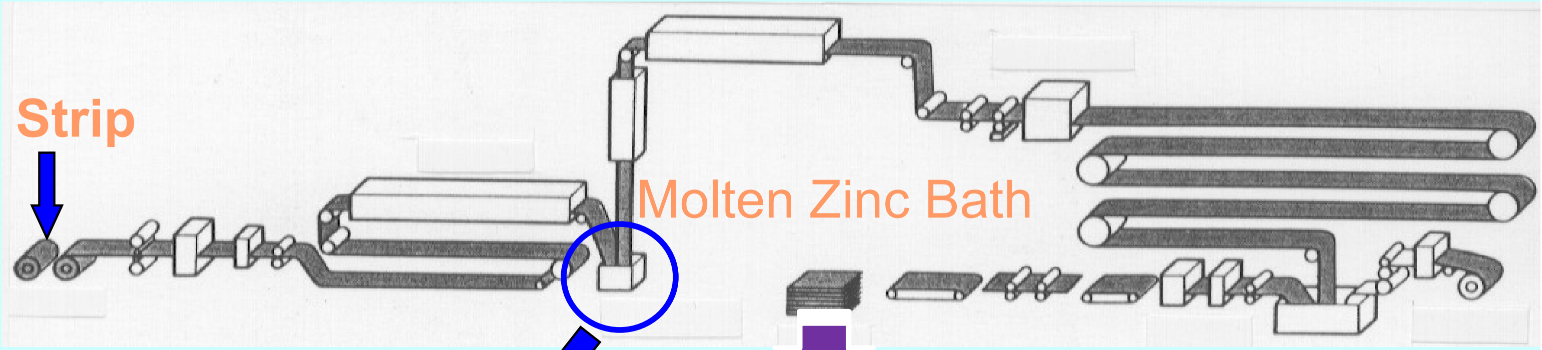
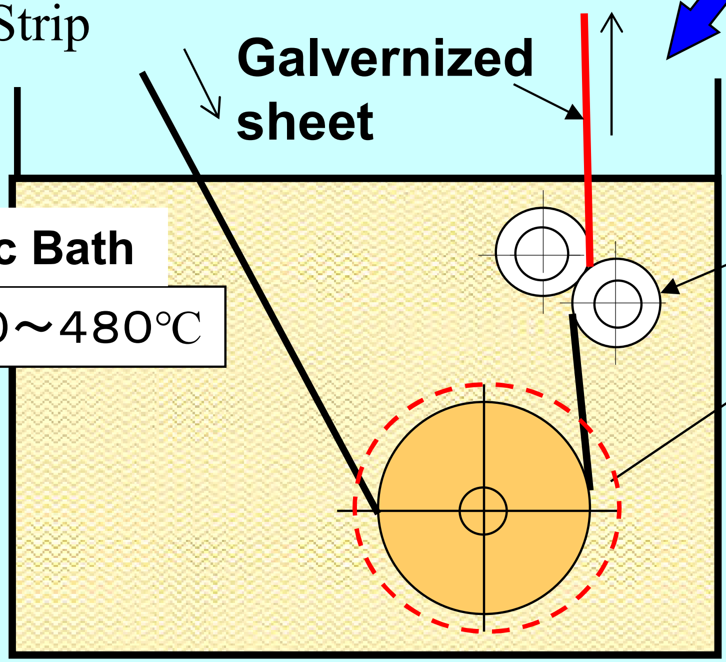


CGL=Continuous Galvanizing Line





Galvernized Sheet



Support Roll

Sink Roll

D：528～800mm
L：1300～2200mm

Used for Changing the direction of Strip

Key points in METI Funded Project

(METI=Ministry of Economy, Trade and Industry)

(1) Development of high toughness, high thermal conductivity special silicon nitride (completed)

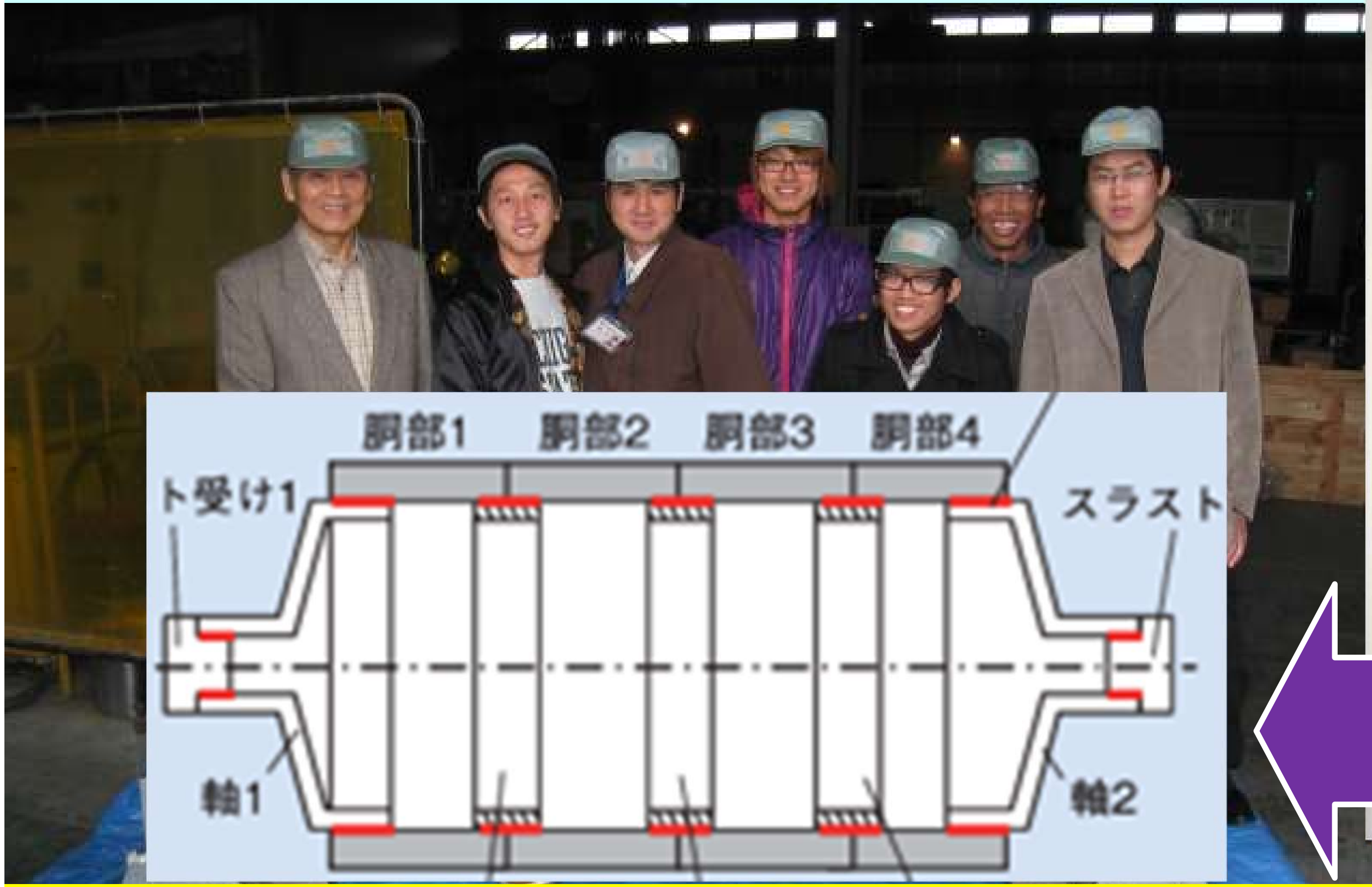
(2) Accurate thermal stress and bonding stress analysis

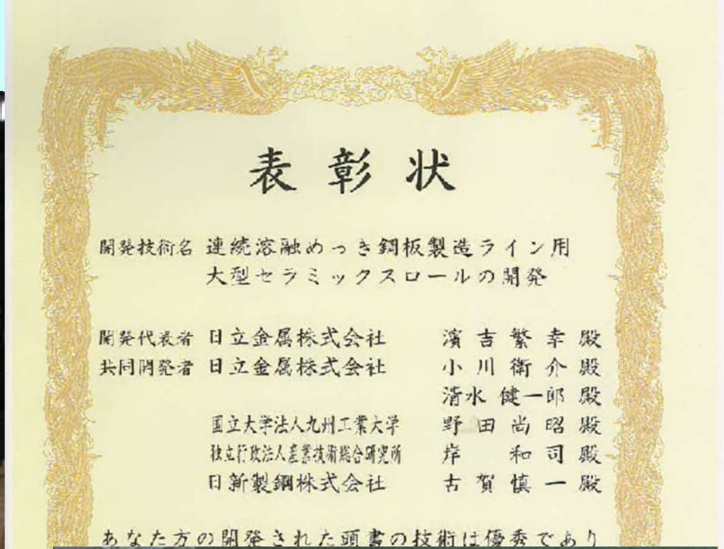
(3) Ceramic bonding technology based on structural analysis

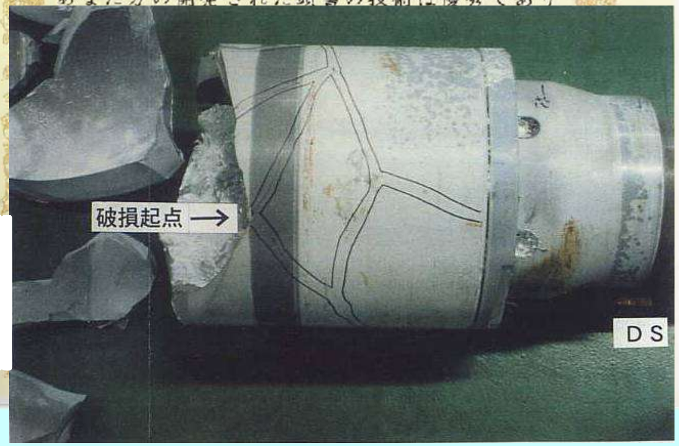
(4) Ultra-precise machining technology for large ceramics

"Ceramics Roll Used in Molten Metal Bath to produce Galvanized Steel Sheet (2008-2009)"

METI Funded Project
(METI=Ministry of Economy, Trade and Industry)

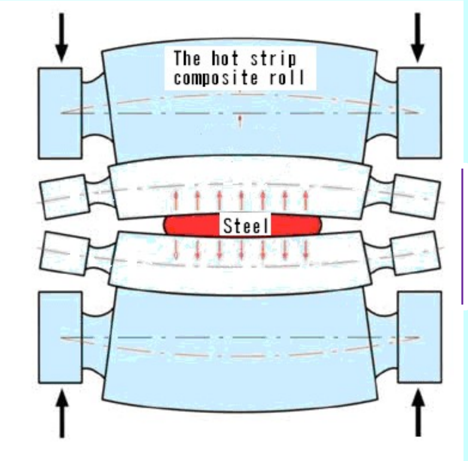


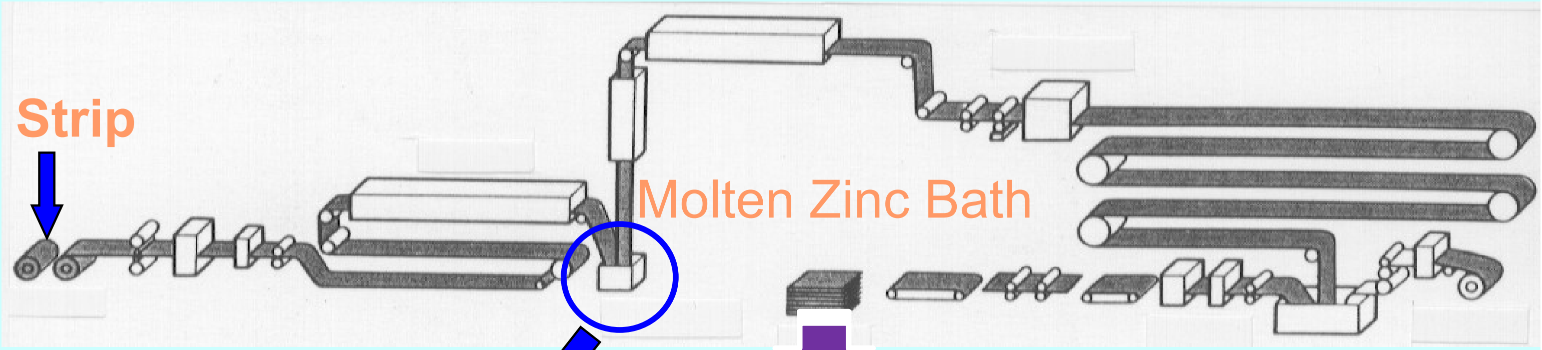




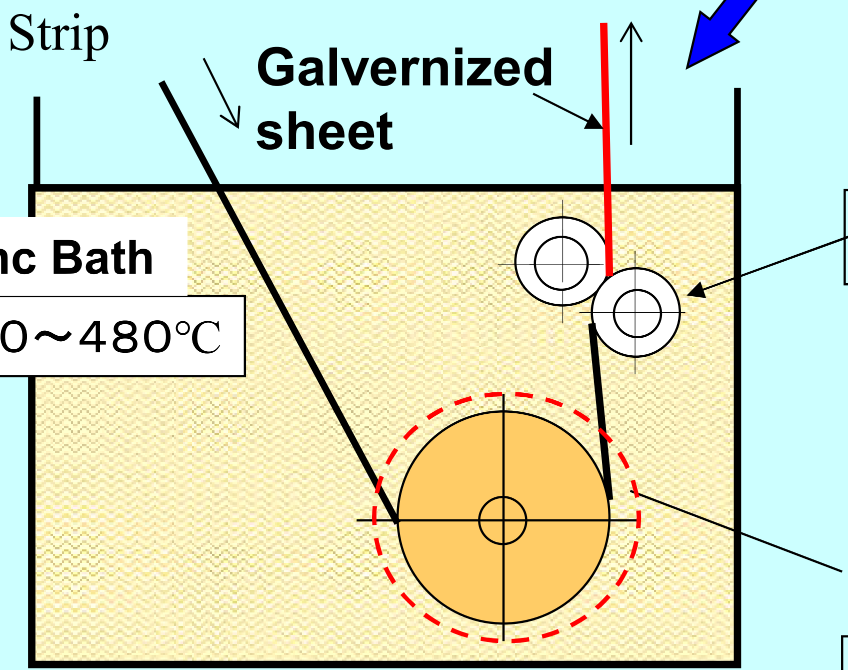
“All Ceramics Roll Used in Molten Metal Bath to produce Galvanized Steel Sheet (2008-2009)”

CGL=Continuous Galvanizing Line





Galvernized Sheet



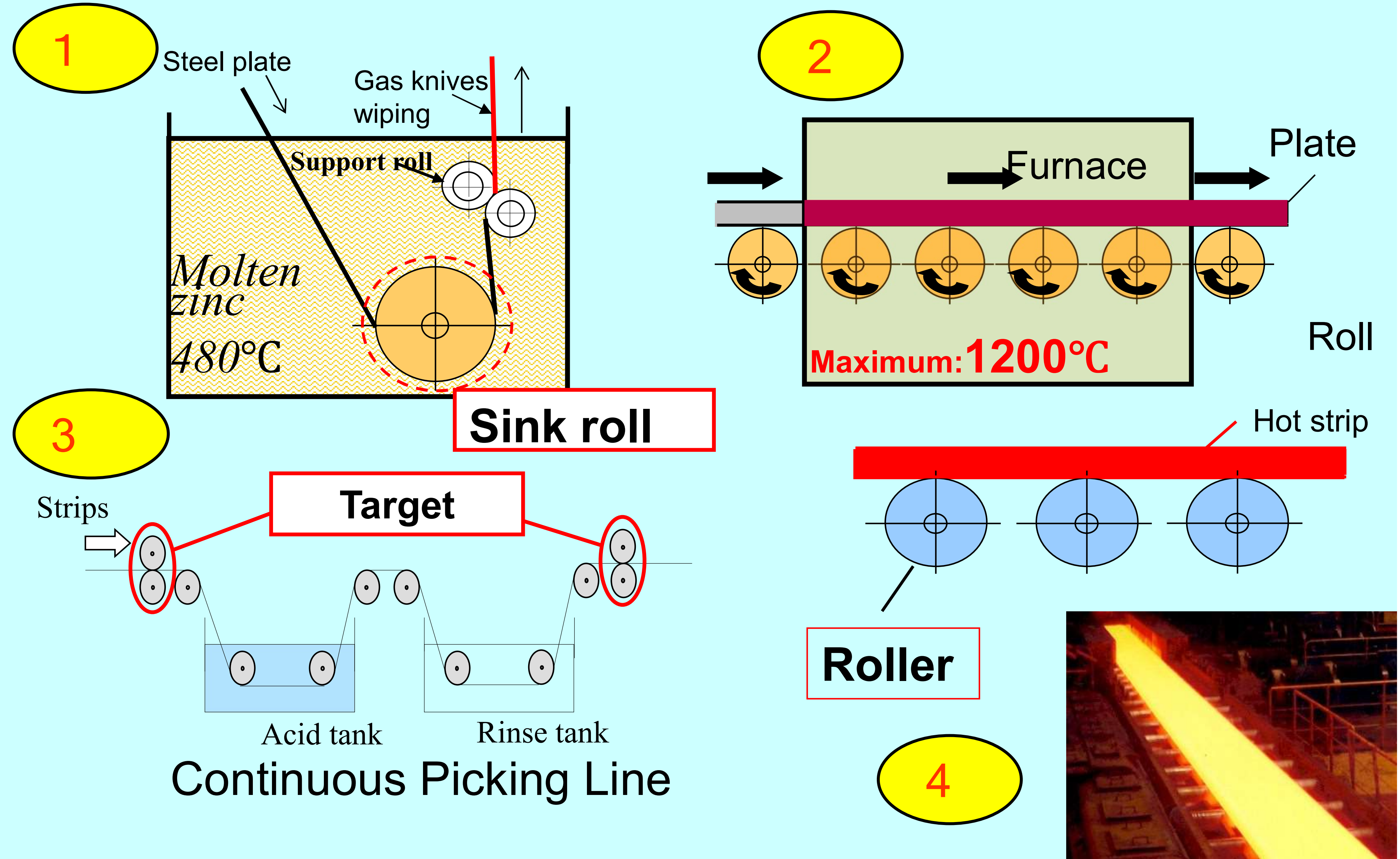
Support Roll

D：～215mm
L：1300～2200mm

Sink Roll

D：528～800mm
L：1300～2200mm

Application of ceramics rolls to steel manufacturing industries



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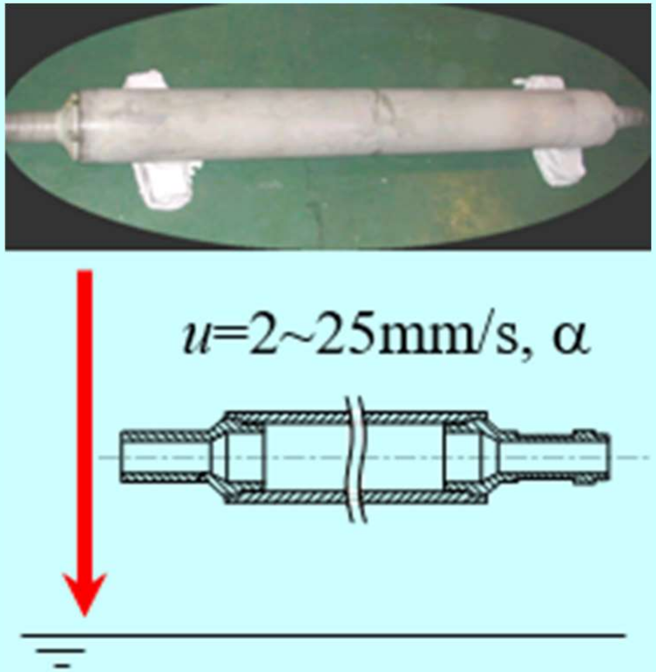
Thermal Stress for All-Ceramic Support Rolls Used in Molten Metal



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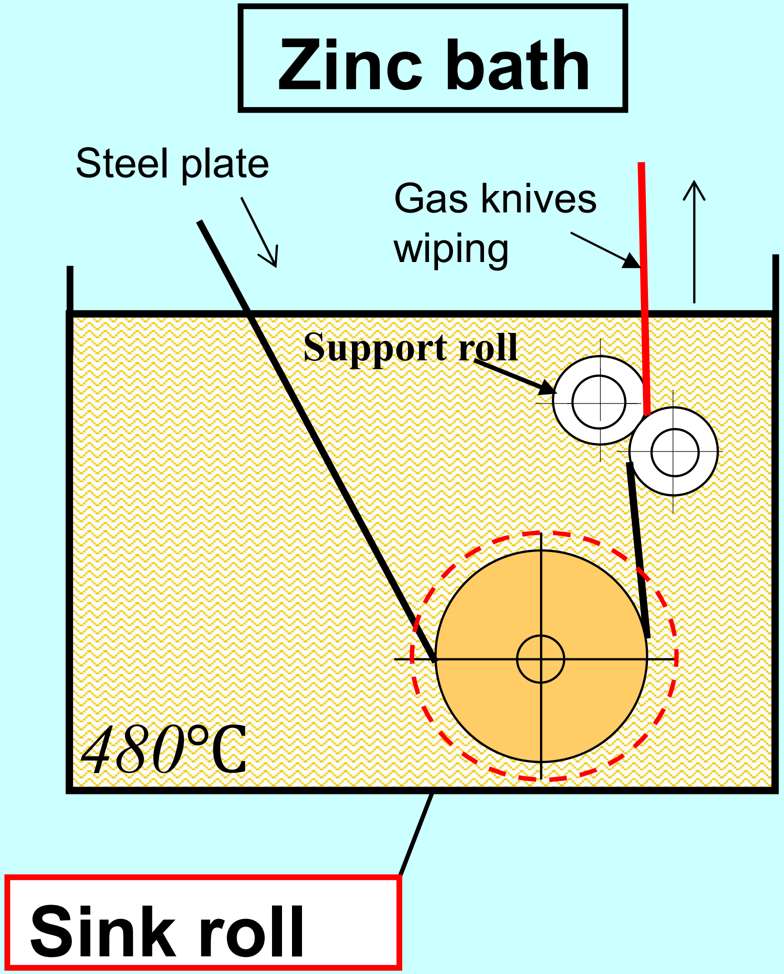
Background



In the molten zinc bath, the strip changes direction by the sink roll

Sink rolls and the support rolls are usually made of stainless steel

Corrosion and abrasion arise on the roll surface and causing the deterioration of quality of plating.

High temperature resistance, high abrasion resistance and high corrosion resistance

All Ceramic Roll

Ceramics (Silicon Nitride) vs. Steel

	Ceramics	Steel
Young's moduls [GPa]	300	210
Poisson's ratio	0.28	0.3
Tensile strength [MPa]	**500**	600
Fracture toughness [MPa·$m^{1/2}$]	**7**	100
Fatigue stre[illegible] [MPa]	[illegible]	300
Mass density [kg/m^3]	3200	7800
Thermal conductivity [W/m[illegible]	62.5(393K)	25
Thermal expansion coefficient [1/K]	3.0×10^{-6}	$\mathbf{14.5\times10^{-6}}$
Specific heat [J/kg·K]	680	477
Emissivity	0.4	0.4

Almost same as steel

Much small than steel

About 5 times larger than ceramics

Sialon vs. Special Silicon Nitride

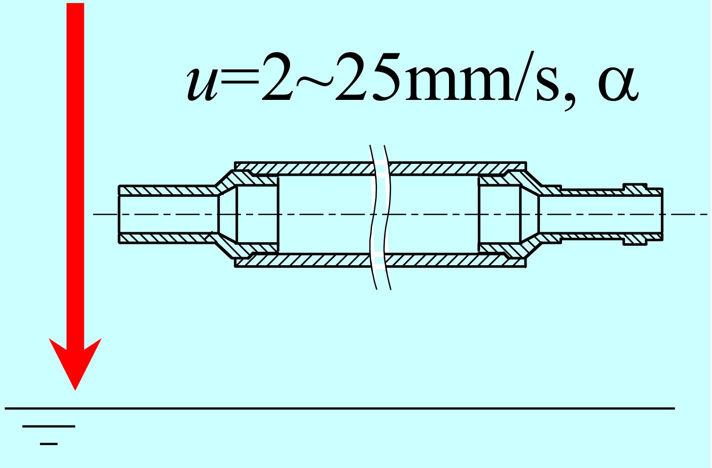
SiAlON ceramics are based on the elements Si, Al, O and N.

Table 2 Mechanical properties of ceramics

Physical property (Dimension)	Sialon	Silicon nitride
Thermal conductivity {W/m·K}	17	65
Specific heat {J/kg·K}	650	680
Coefficient of linear expansion {1/K}	3.0×10^{-6}	3.0×10^{-6}
Young's modulus {GPa (kgf/mm^2)}	294 (29979)	300 (30591)
Specific weight	3.26	3.20
Poisson's ratio	0.27	0.30
4 point bending strength {MPa (kgf/mm^2)}	1050 (10296)	880 (8630)
Fracture toughness {MN/m$^{3/2}$}	7.5	7.7

3.8 times difference

u=2~25mm/s, α

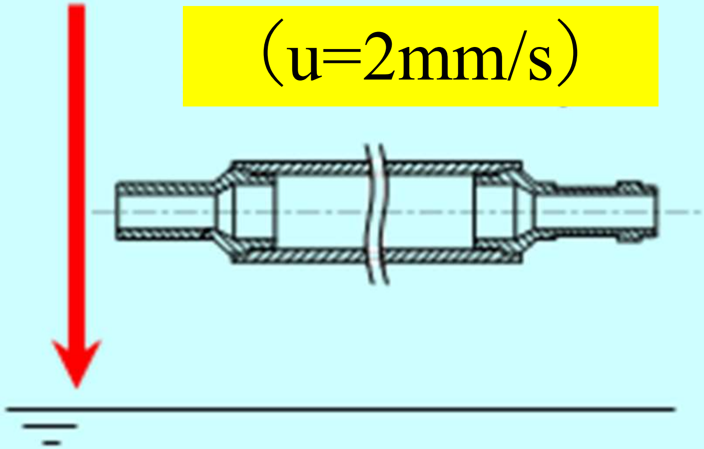


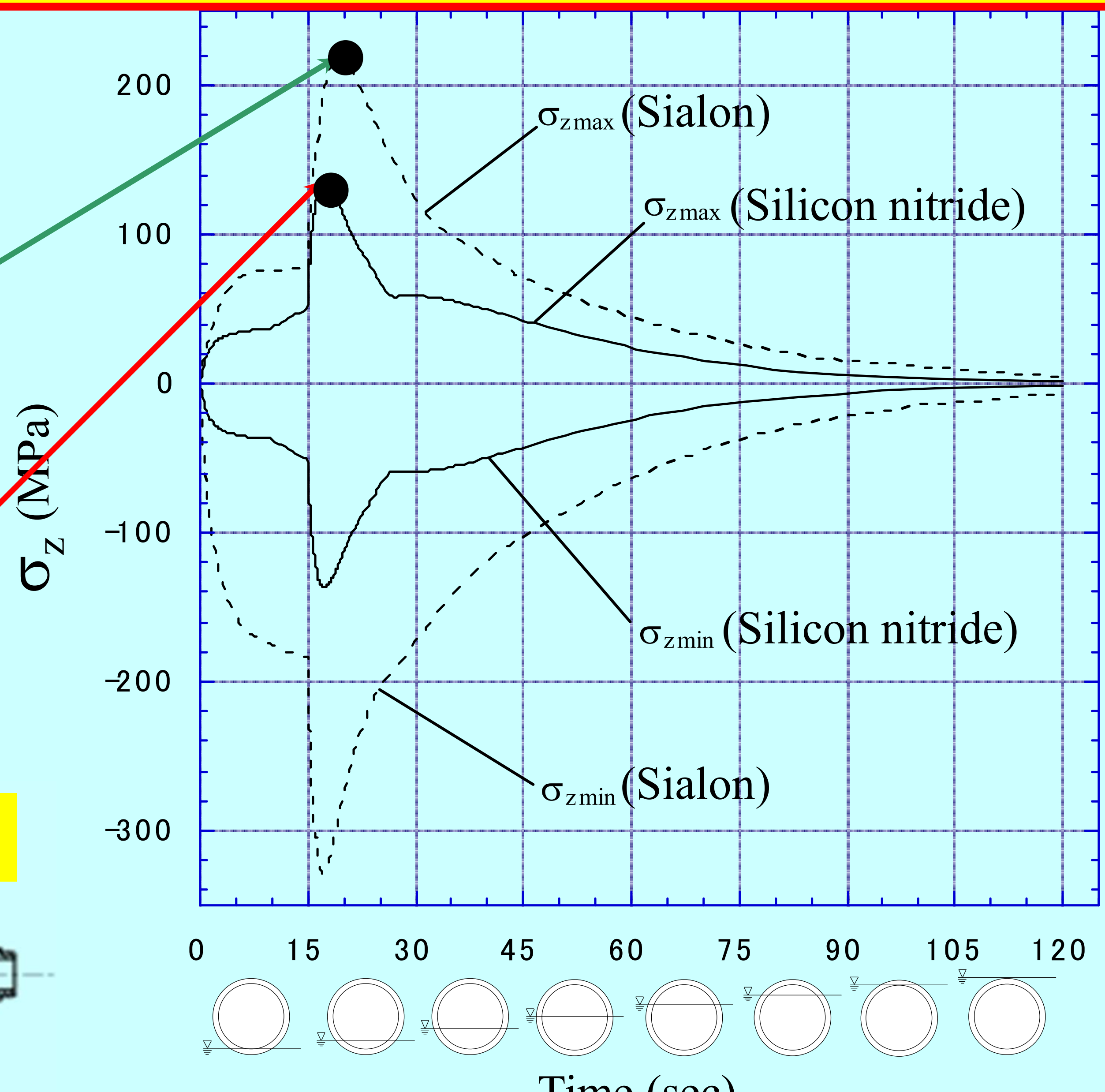
Special Silicon Nitride reduces the thermal stress of Sialon by 40％. SiAlON ceramics are based on the elements Si, Al, O, N.

At 19sec
Maximum tensile stress=219 MPa

At 17sec
Maximum tensile stress=136 MPa

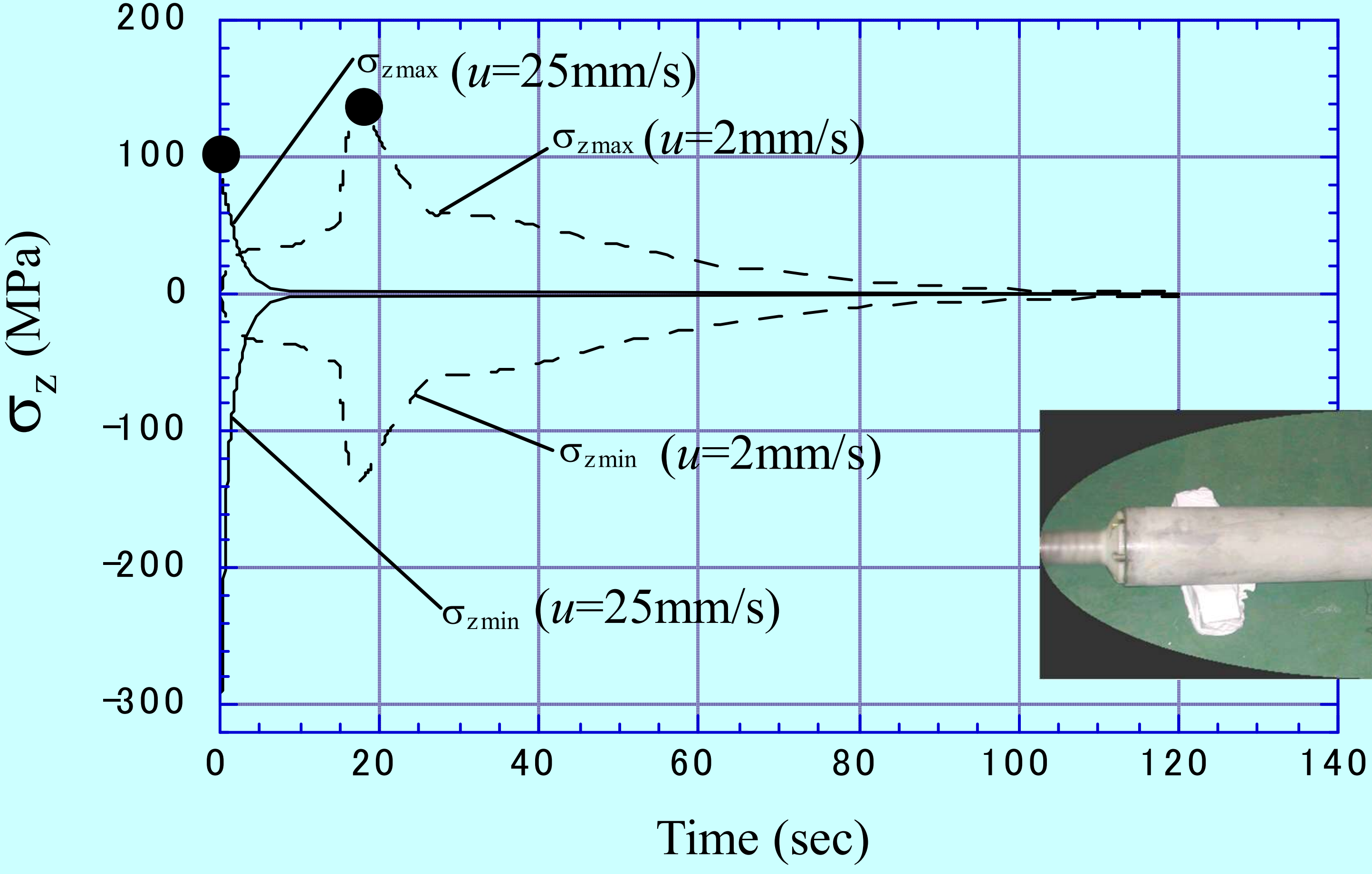
(u=2mm/s)





σ_z vs. time relation (u=2mm/s)

Dipping fast （ u=2mm/s ） is better than Dipping slowly （u=25mm/s）



σ_z vs. time relation (u=25mm/s or u=2mm/s)

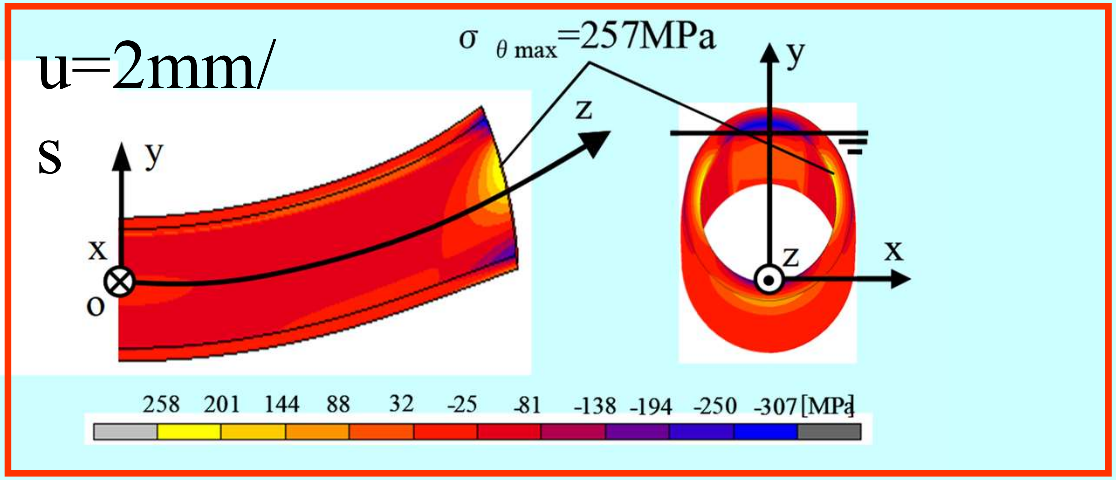
Why is Dipping Fast Better for Horizontal Dipping?

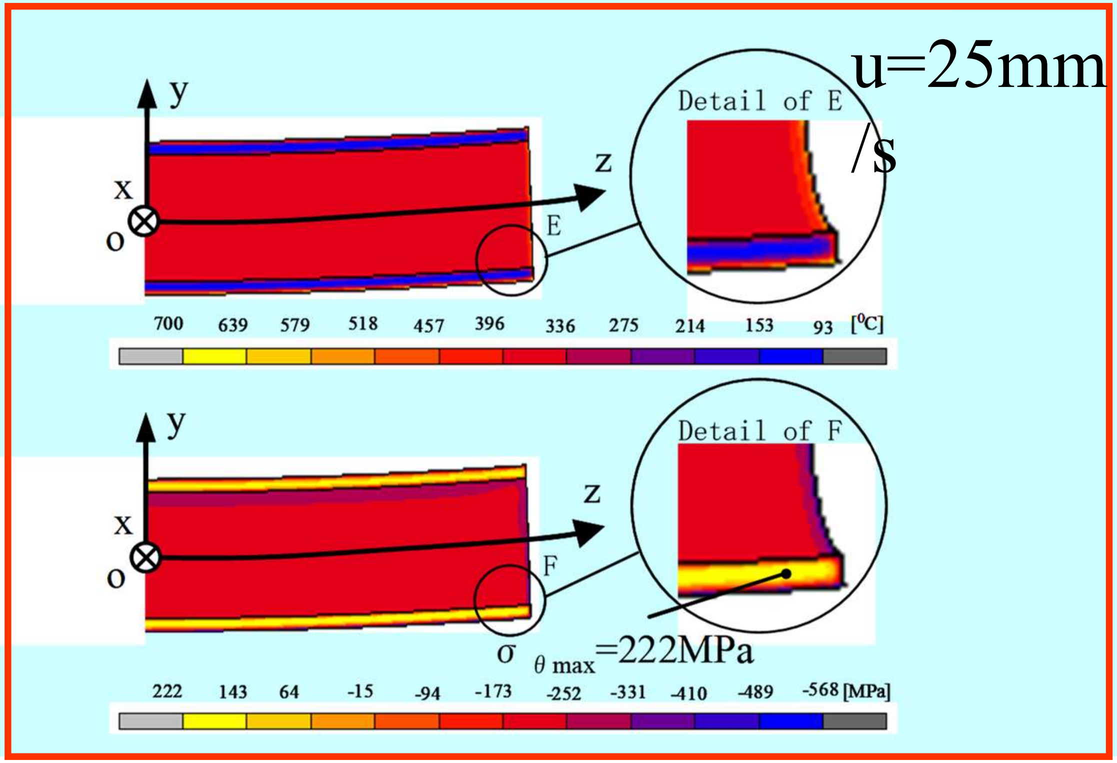
u=2mm/s

σ_θ =258MPa

u=25mm/s

σ_θ =222MPa





Dipping Fast (u=25mm/s) is better than dipping slowly (u=2mm/s).

This is due to large deformation occurs for dipping slowly.

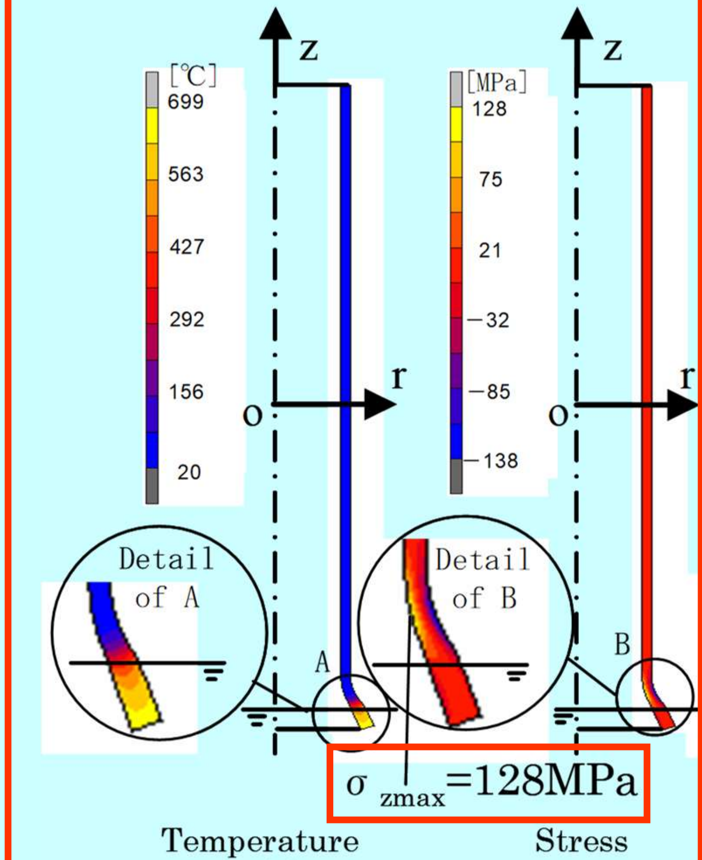
On the other hand for dipping fast the deformation is almost axi-symmetric.

Temperature, stresses and displacement when maximum stress is reached (u=2mm/s at time t=75s and u=25mm/s at

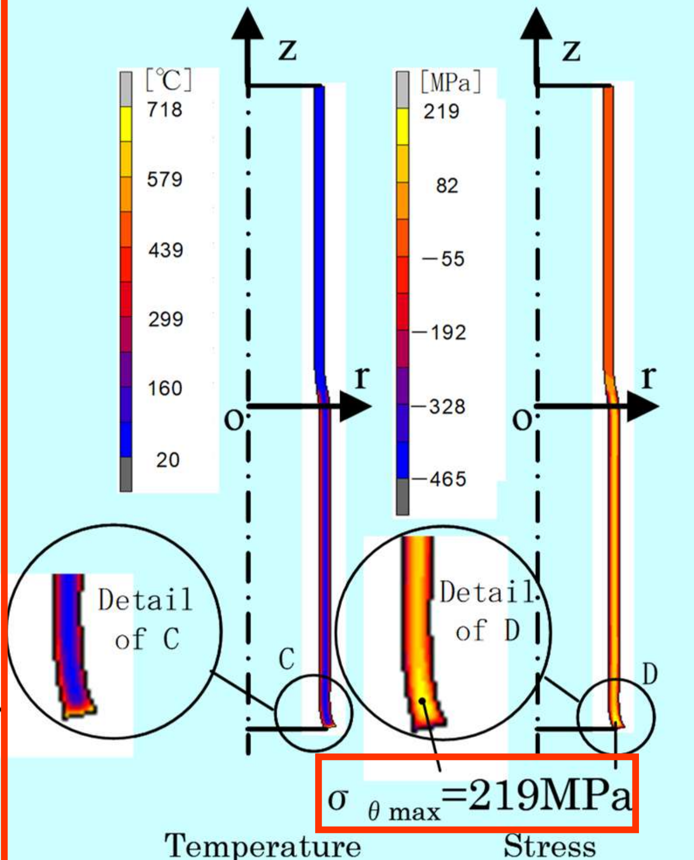
In vertical dipping, dipping fast(u=2mm/s)is not better.

u=2mm/ < u=25mm/s

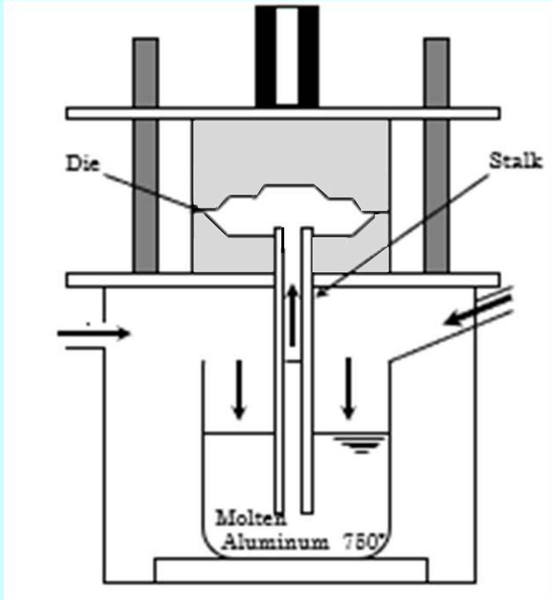
σ_z =128MPa σ_θ =219MPa



(a) u=2mm/s



(b) u=25mm/s



Low Pressure Die Casting Machine

- Cylinder head
- Piston
- Brake drum
- Light automotive wheels

Temperature, stresses and displacement when maximum stress appears (u=2mm/s at time t=20.5s and u=25mm/s at time t=1.3s, displacement $u_r \times 50$)

Key points in METI Funded Project

(METI=Ministry of Economy, Trade and Industry)

(1) Development of high toughness, high thermal conductivity <u>special silicon nitride </u>(completed)

(2) Accurate thermal stress and bonding stress analysis

(3) <u>Ceramic bonding technology </u>based on structural analysis

(4) <u>Ultra-precise machining technology</u> for large ceramics

"Ceramics Roll Used in Molten Metal Bath to produce Galvanized Steel Sheet (2008-2009)"

Proposed structure of support and sink rolls

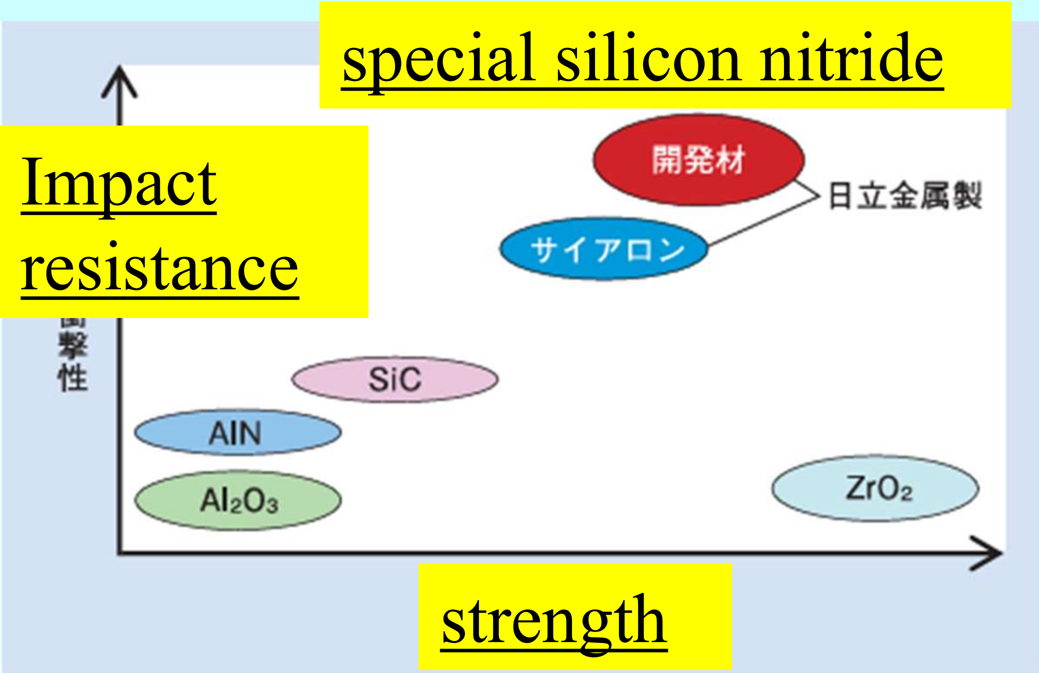


図 4　開発材の位置づけ
Fig. 4 Characteristic comparison with other ceramics

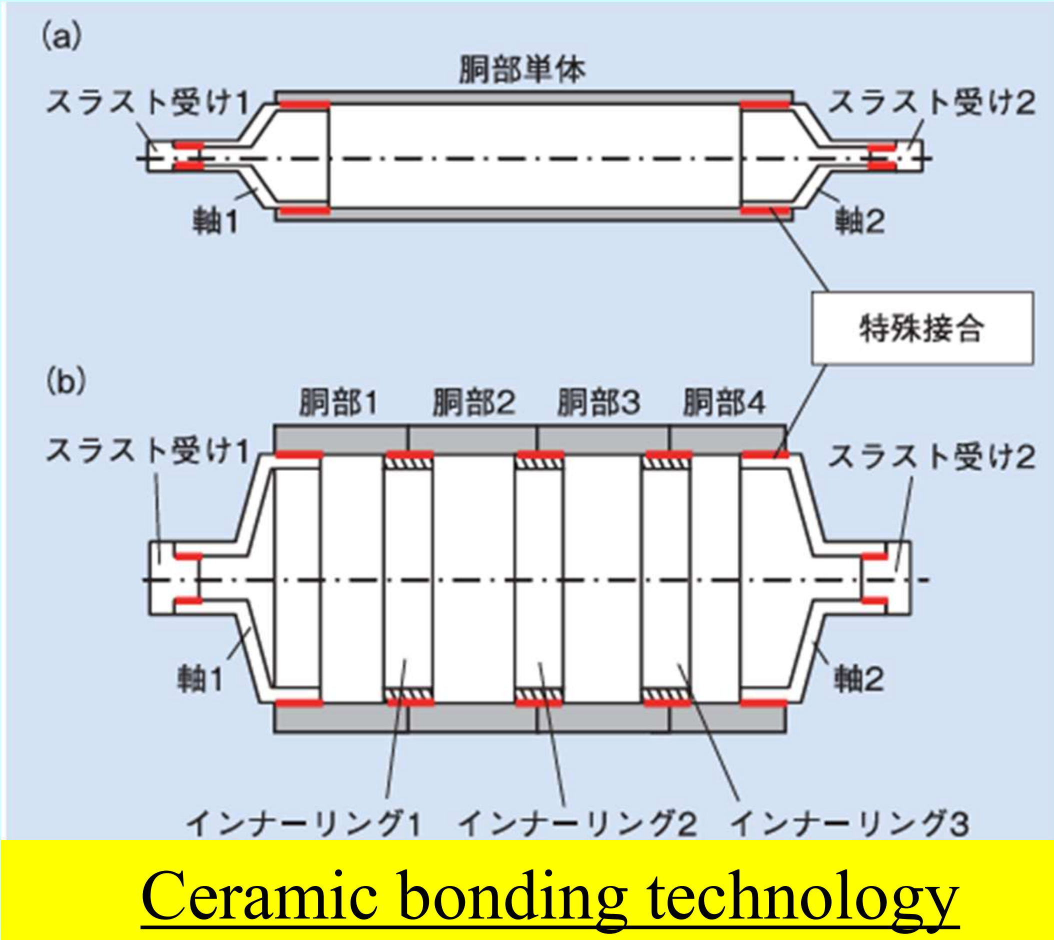


図 6　構造の概略図（a）サポートロール　（b）シンクロール
Fig. 6 Structure of pot rolls (a) Support roll (b) Sink roll

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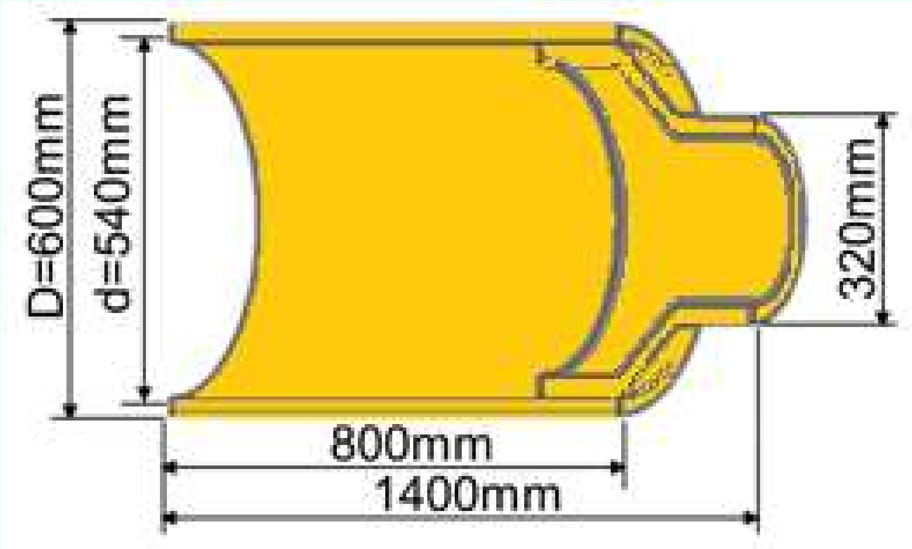

Thermal Stress for All-Ceramic Sink Rolls Used in Molten Metal

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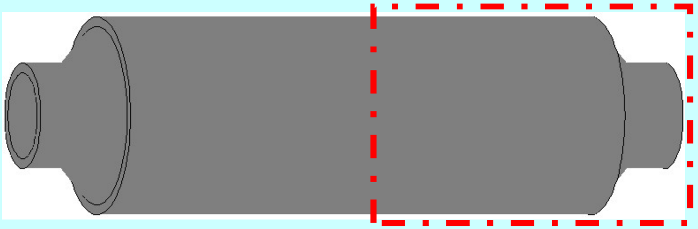
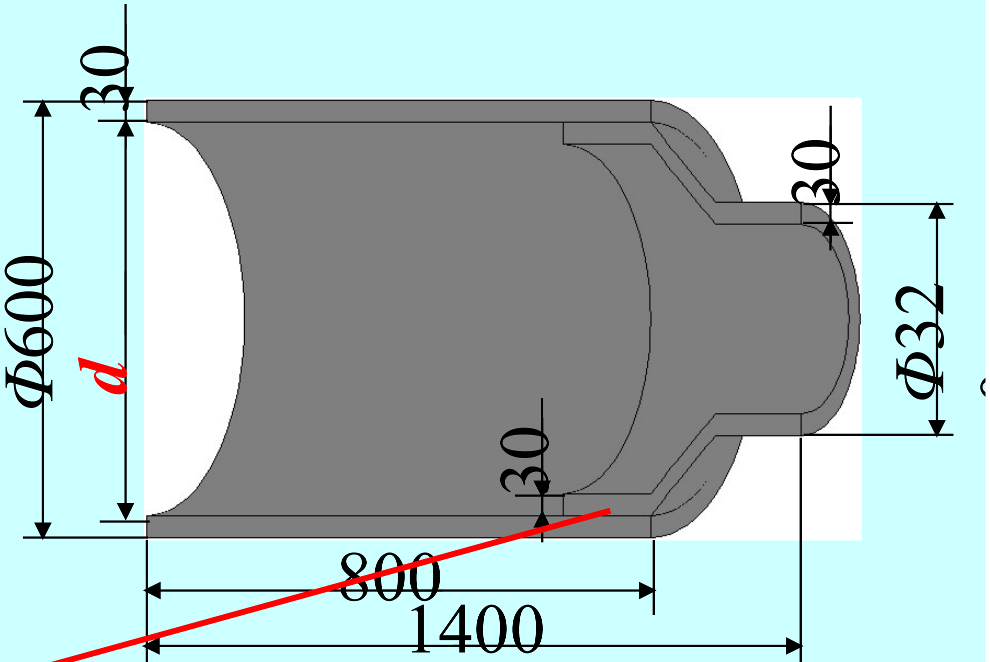
Analytical model



Real Roll



1/4 Cylindrical model (mm)

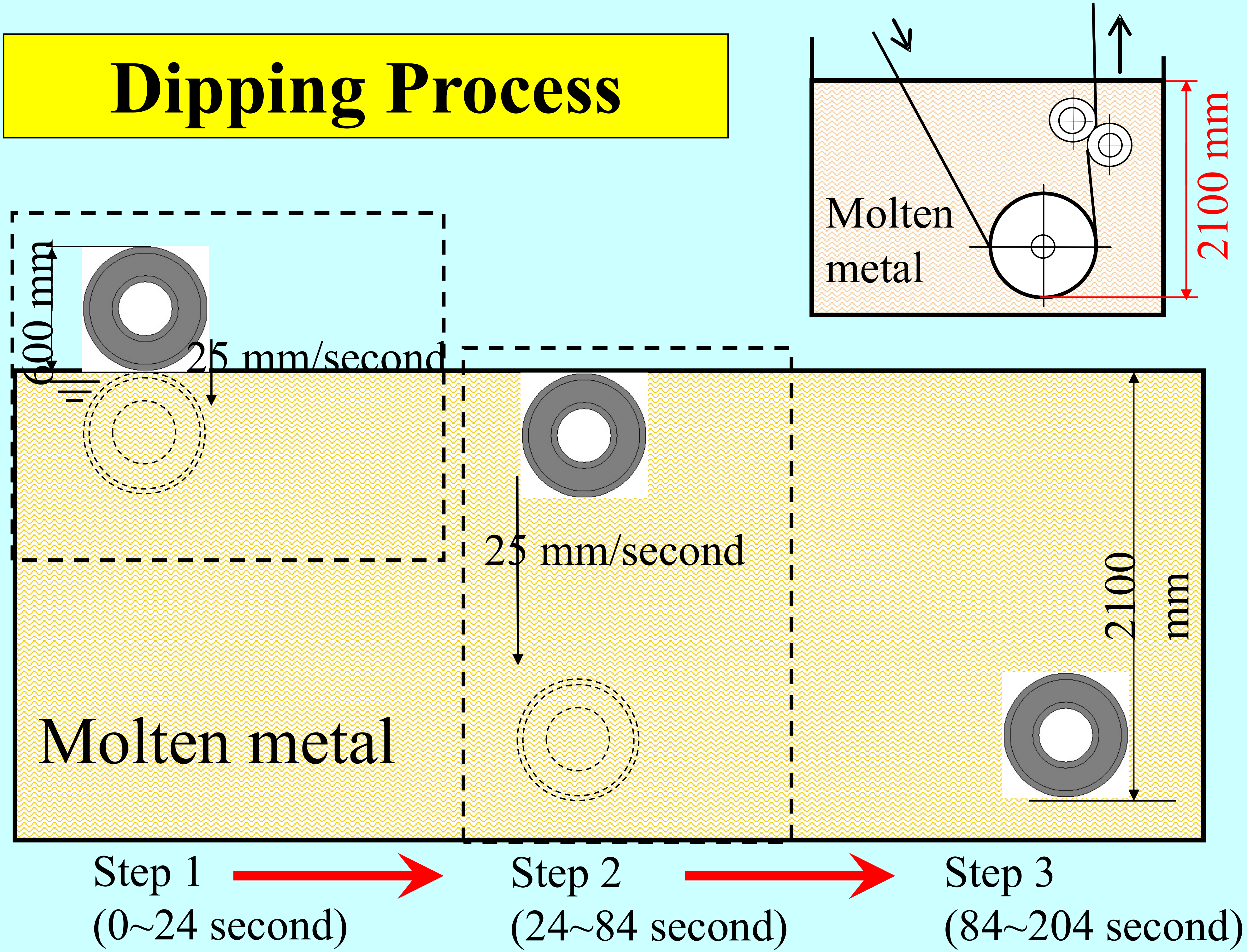
Shrink fitting

Definition of Shrink fitting

$$\frac{\delta}{d} = \frac{\text{Diameter difference}}{\text{Inside diameter of the sleeve}}$$

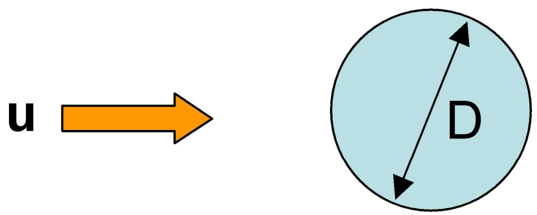
For Ceramic roll $\delta/d = 0.1 \times 10^{-3} \sim 0.4 \times 10^{-3}$

Dipping Process



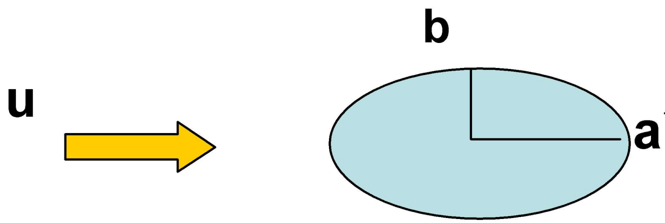
Models for Analysis of HTC in Molten Metal Flow
(HTC =Heat Transfer Coefficient)

u=2mm/s，25mm/s



Circle

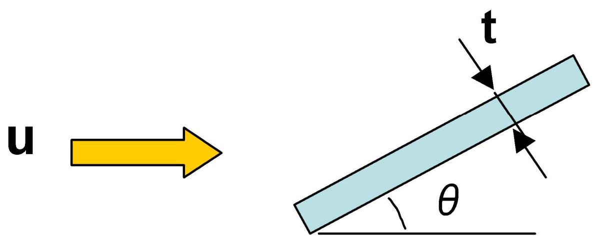
D=170～540mm



Ellipse

a/b=1/2

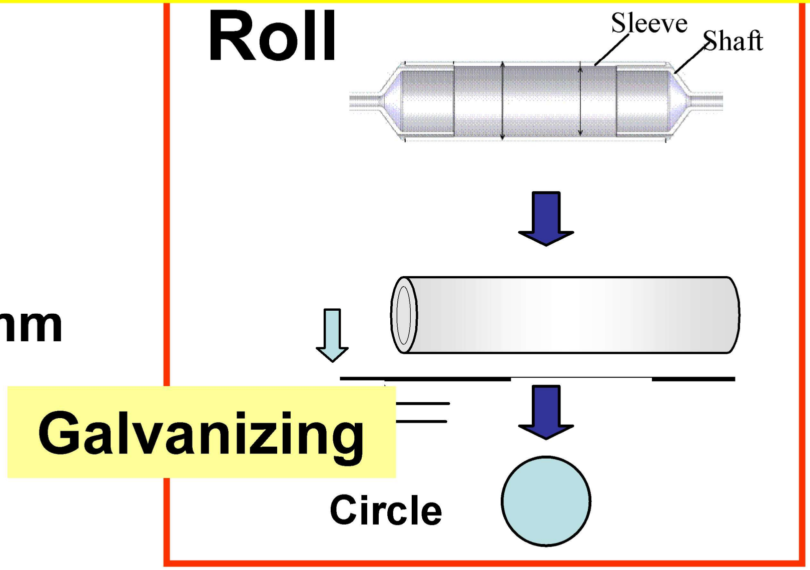
～ 1/32.5

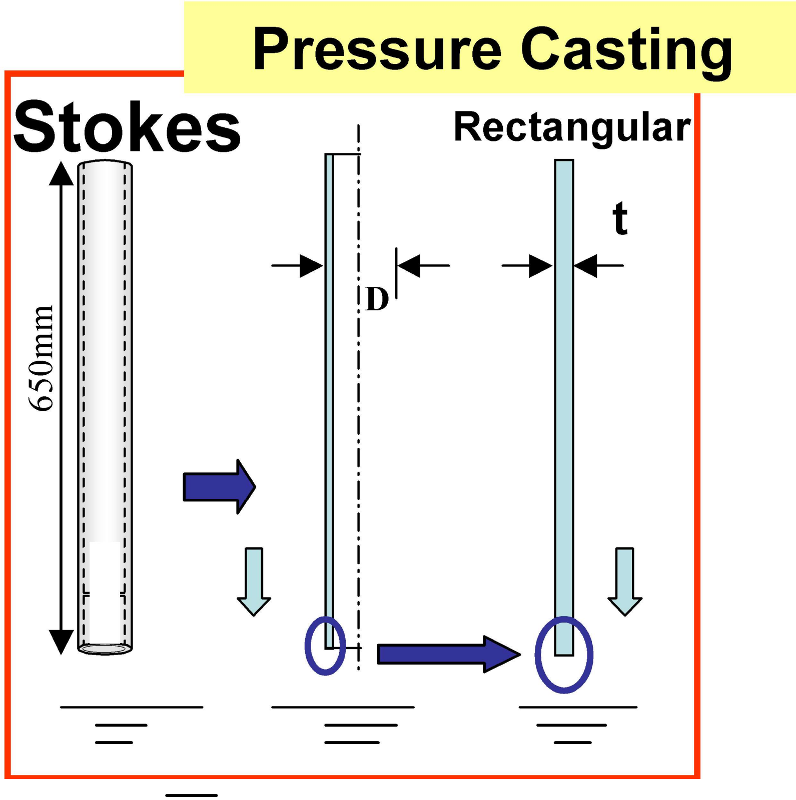


Rectangular

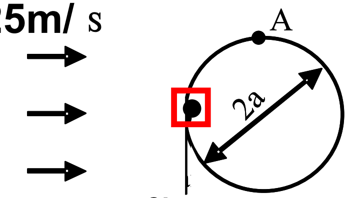
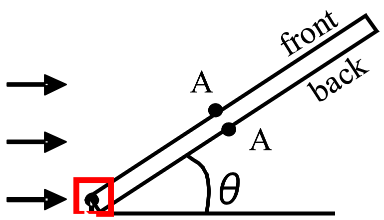
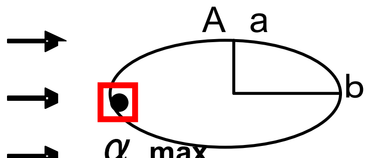
t=10～30mm

θ =0° ,45° ,90°



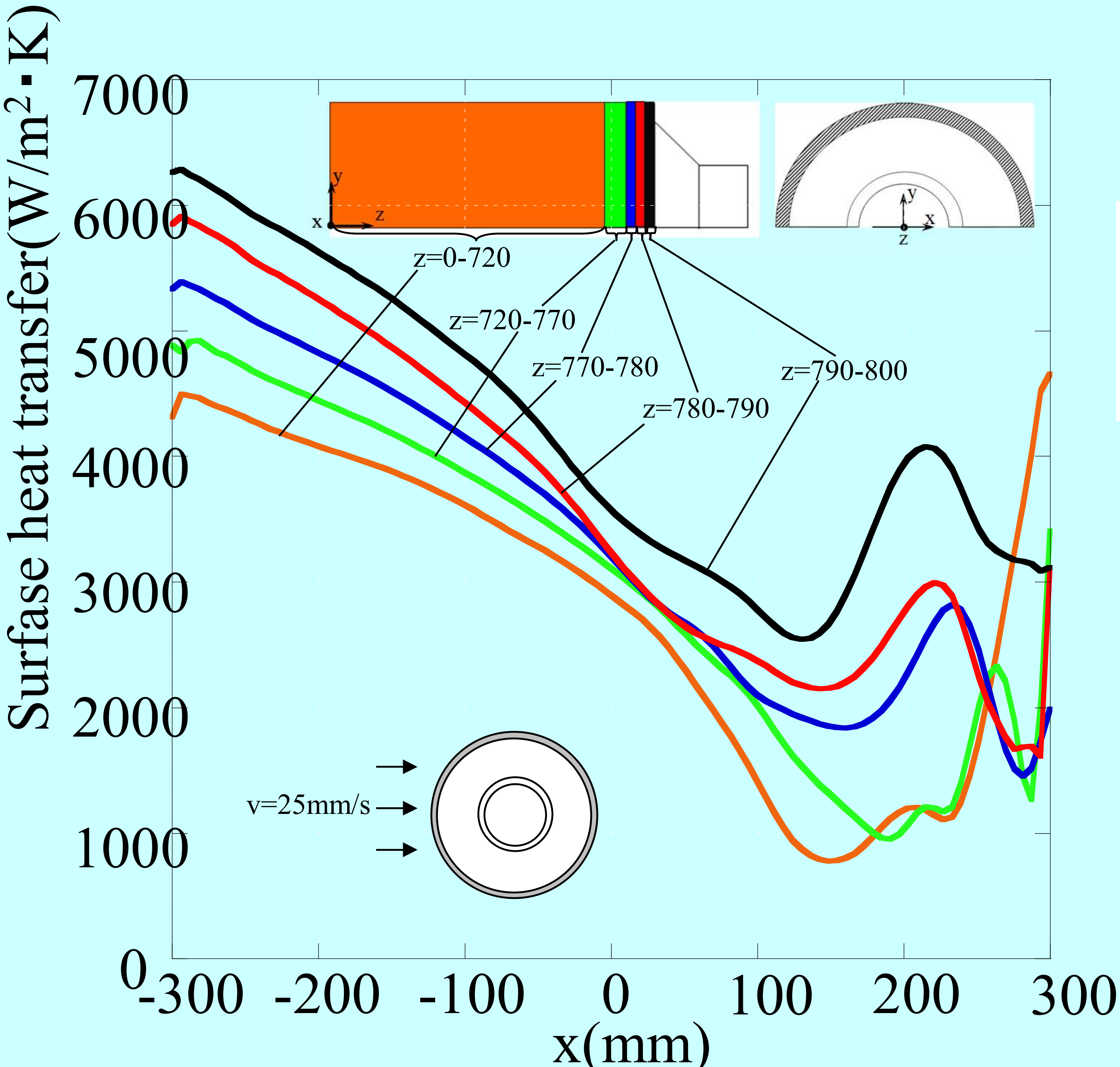


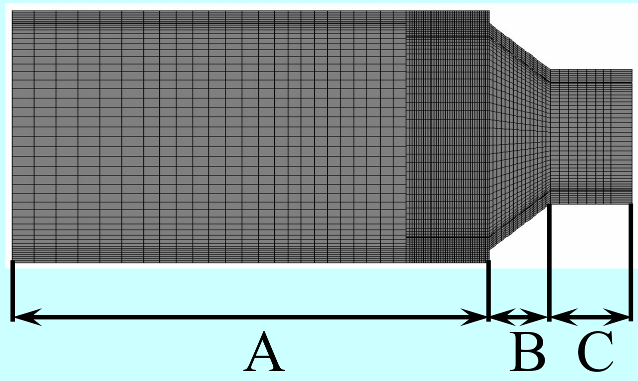
Results and Discussion

Model	Dimension		α max	α A	α min	α max / α min
u =25m/ s  Zinc	2a=20mm		$\boxed{24.1}$	14.6	4.72	$\boxed{5.1}$
	170mm		8.38	5.63	1.62	5.2
	:540mm		5.21	3.07	1.02	5.1
 Al	θ =0 （a=10）		$\boxed{17.5}$	2.45	1.88	$\boxed{9.6}$
	θ =45	front	10.6	3.24	3.05	3.5
		back	2.15	1.41	0.84	2.6
	:90	front	4.85	3.52	3.51	1.4
		back	2.85	1.36	1.35	2.1
 Zinc	a/b=1/2， ρ 5 （a=10）		$\boxed{30.3}$	9.55	4.53	6.7
	1/32.5		$\boxed{39.9}$	2.08	1.61	25.8

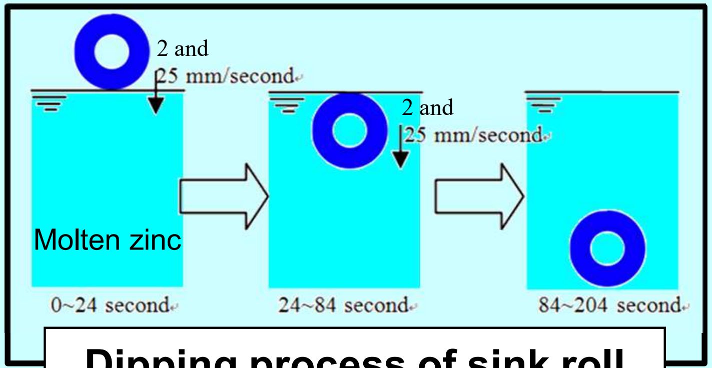
＊ 2 a= 2 ρ= 1 0 : α max = 3 0 . 4

Heat transfer coefficient (Part A)



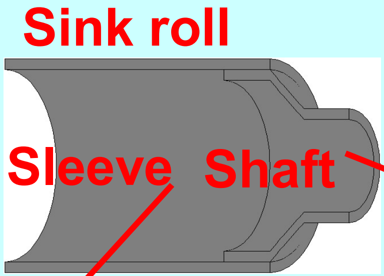


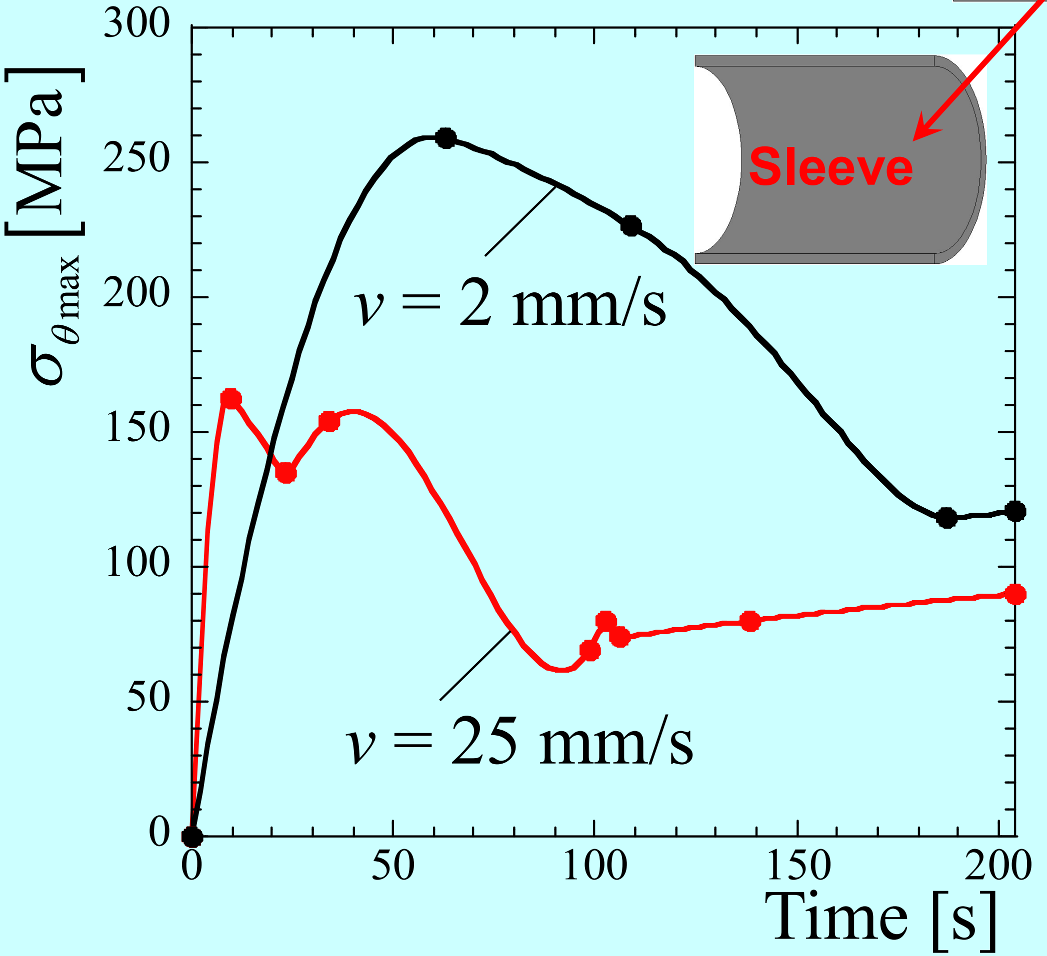
Thermal stress of the sleeve and shaft

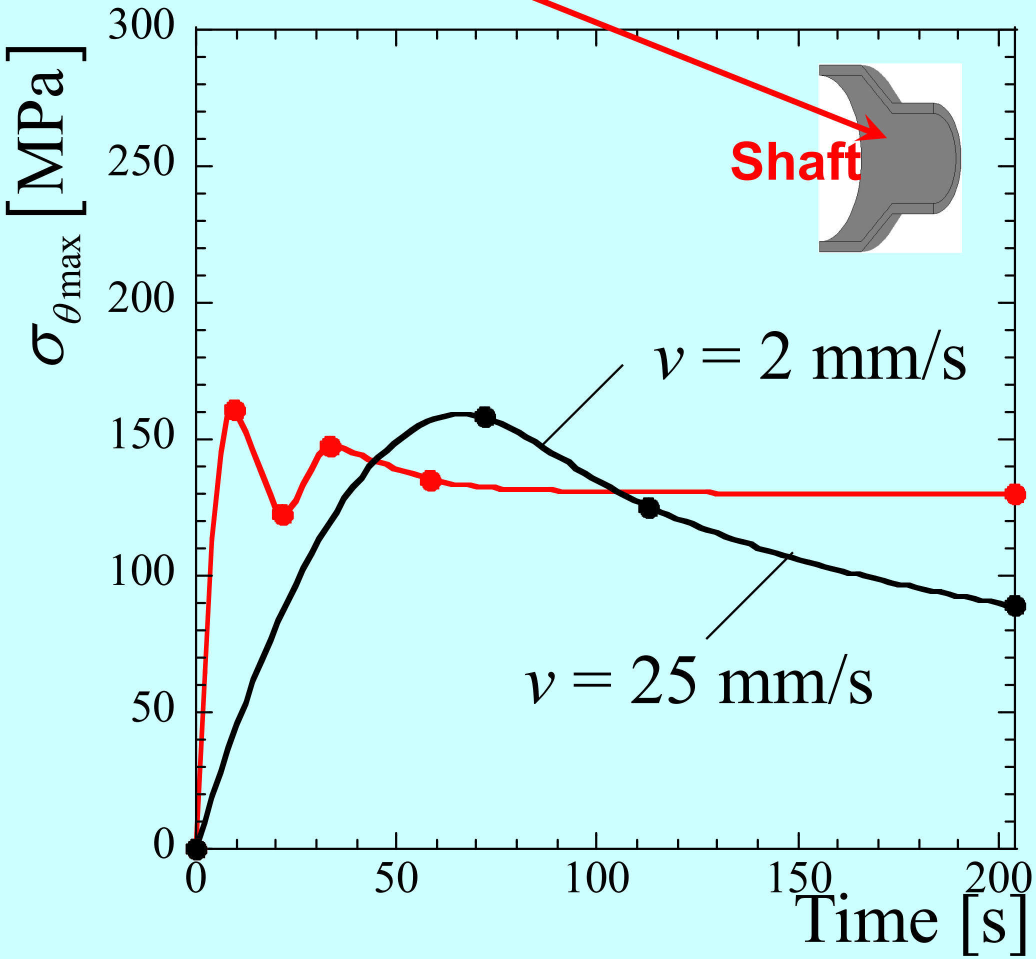


Dipping process of sink roll

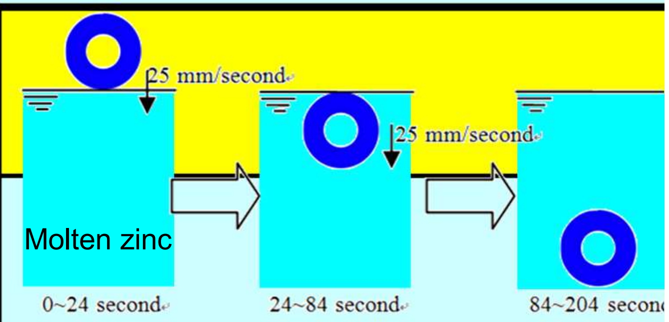
v = 2 mm/s
and
v = 25 mm/s





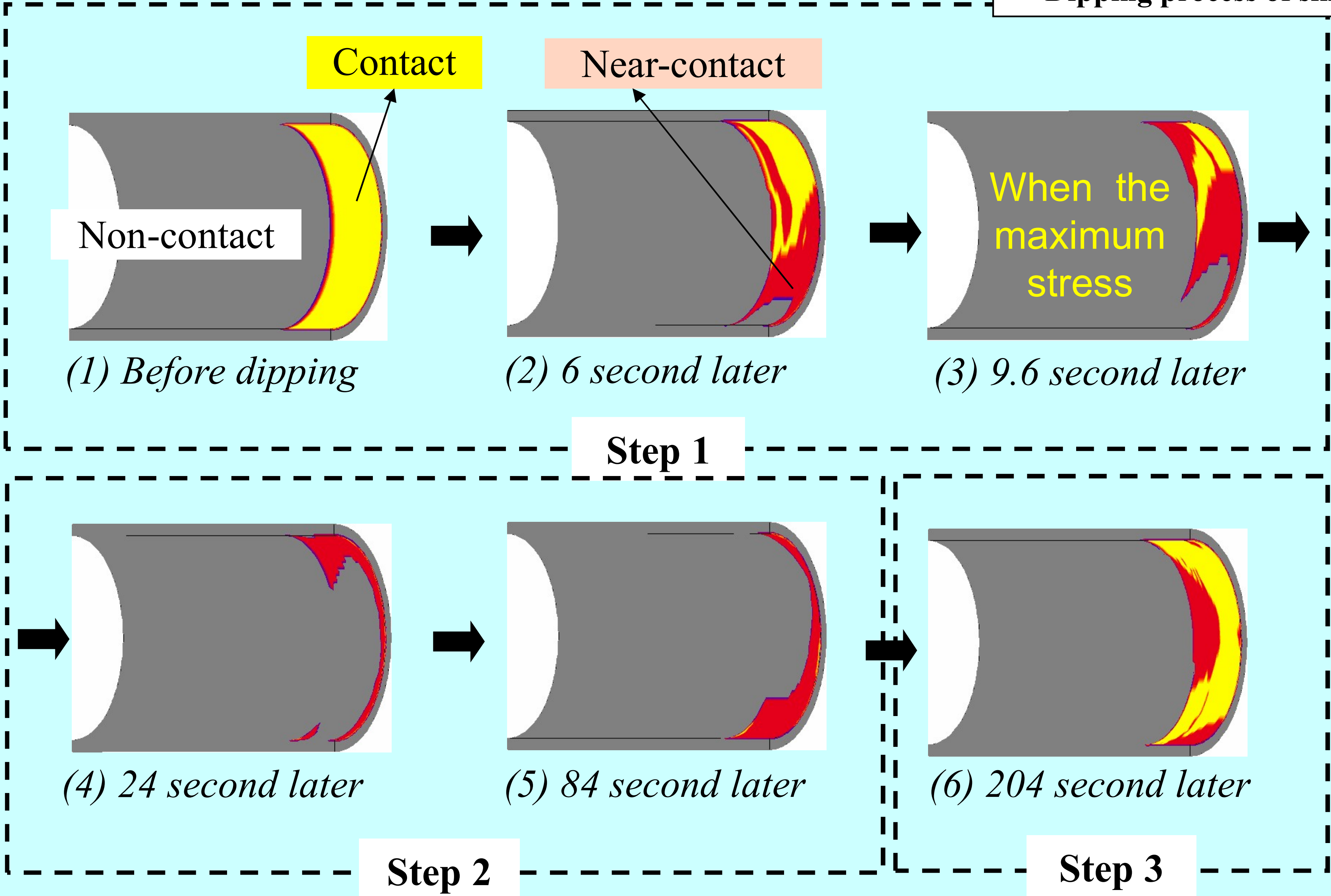


Contact Status



Dipping process of sink roll

Contact status during dipping



Thermal Stress: Conclusions

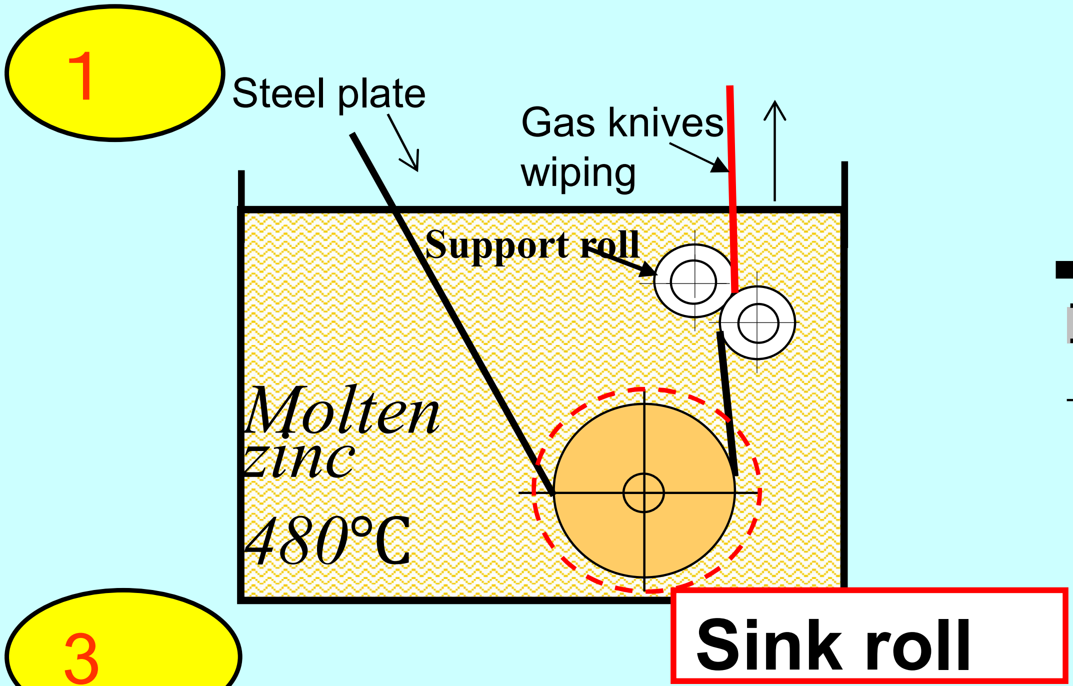
(1) Maximum tensile stresses of the sleeve and the shaft are smaller than the tensile strength of ceramics.

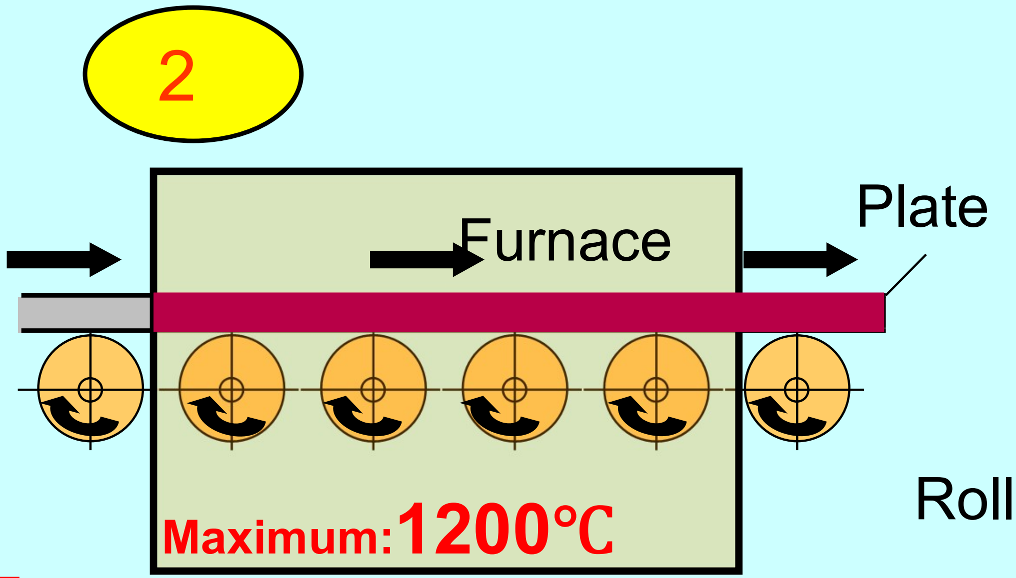
Sleeve : $\sigma_{\theta max} = 162.7\ MPa < \sigma_a = \sigma_B / S = 500/(1.5) \approx 333.3\ MPa$

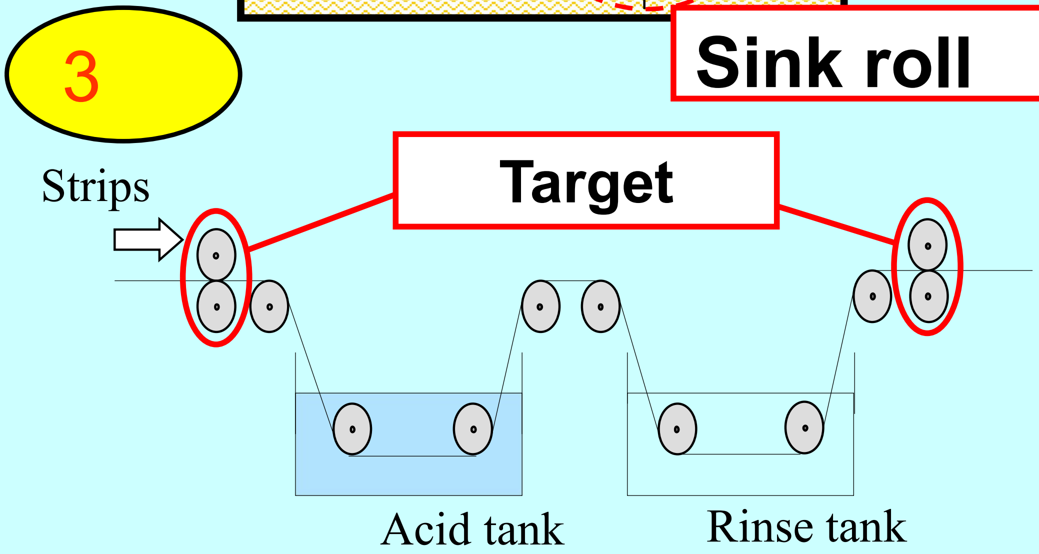
Shaft : $\sigma_{\theta max} = 160.5\ MPa < \sigma_a = \sigma_B / S = 500/(1.5) \approx 333.3\ MPa$

(2) The separation appears temporarily during dipping. However, the contact status is recovered after 204s at the operating position.

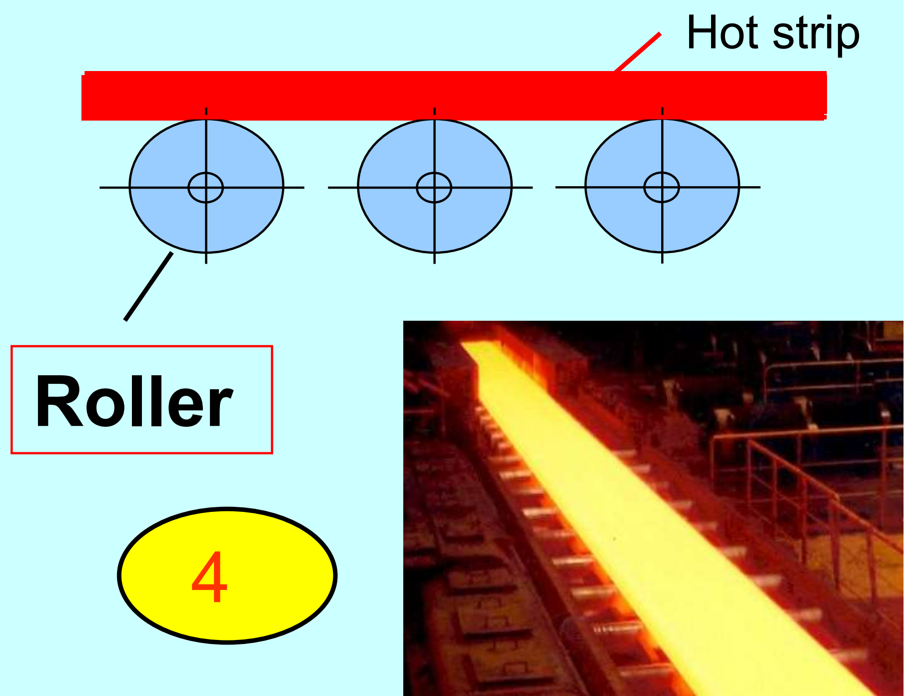
Application of ceramics rolls to steel manufacturing industries

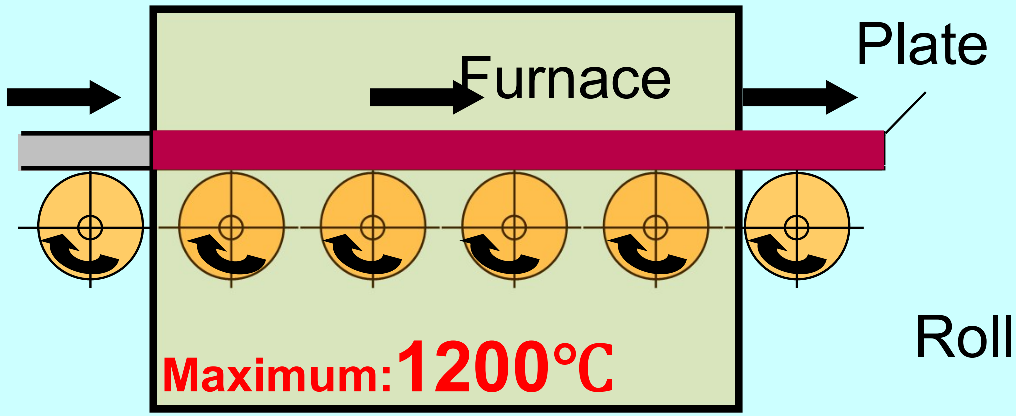


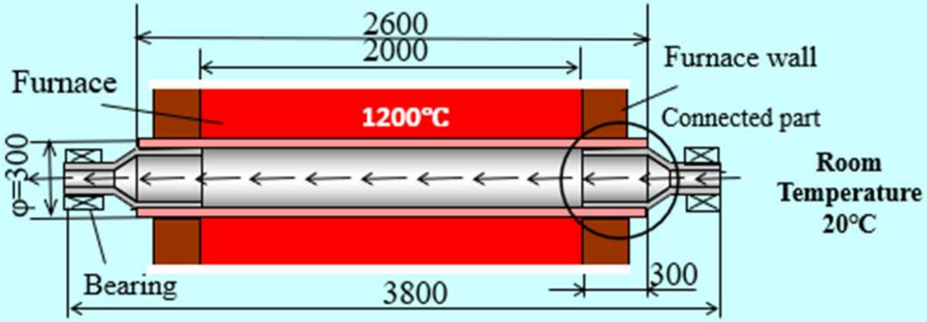




Continuous Picking Line







Thermal Stress of Hearth Rolls in Furnace

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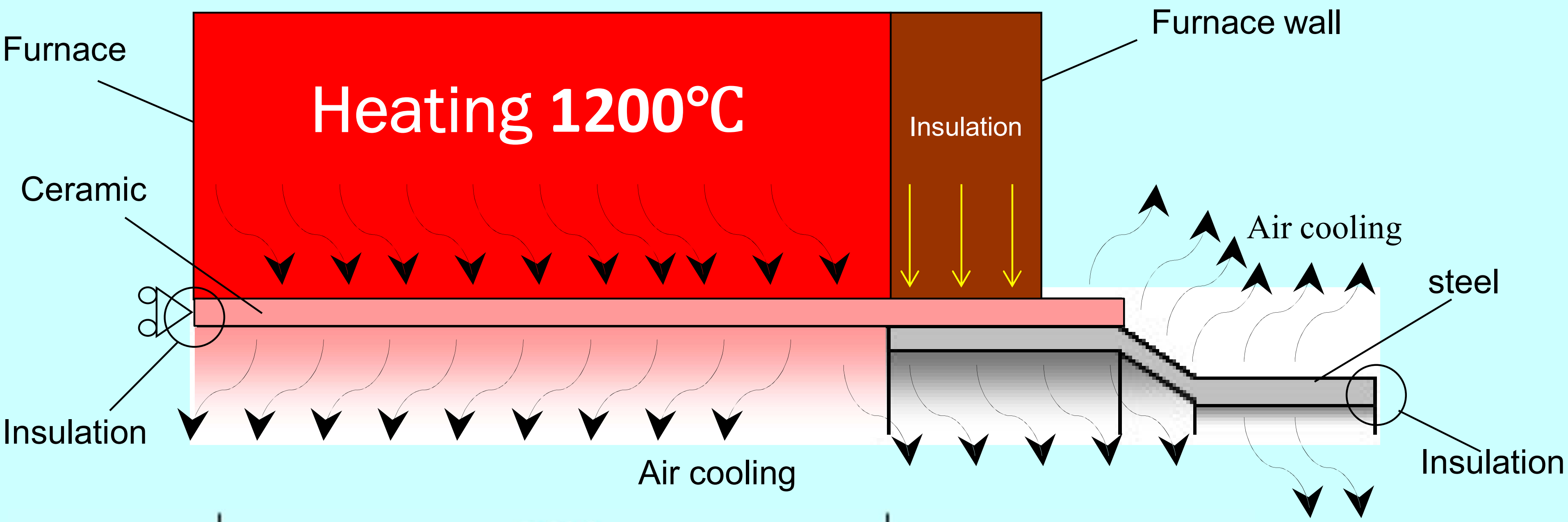
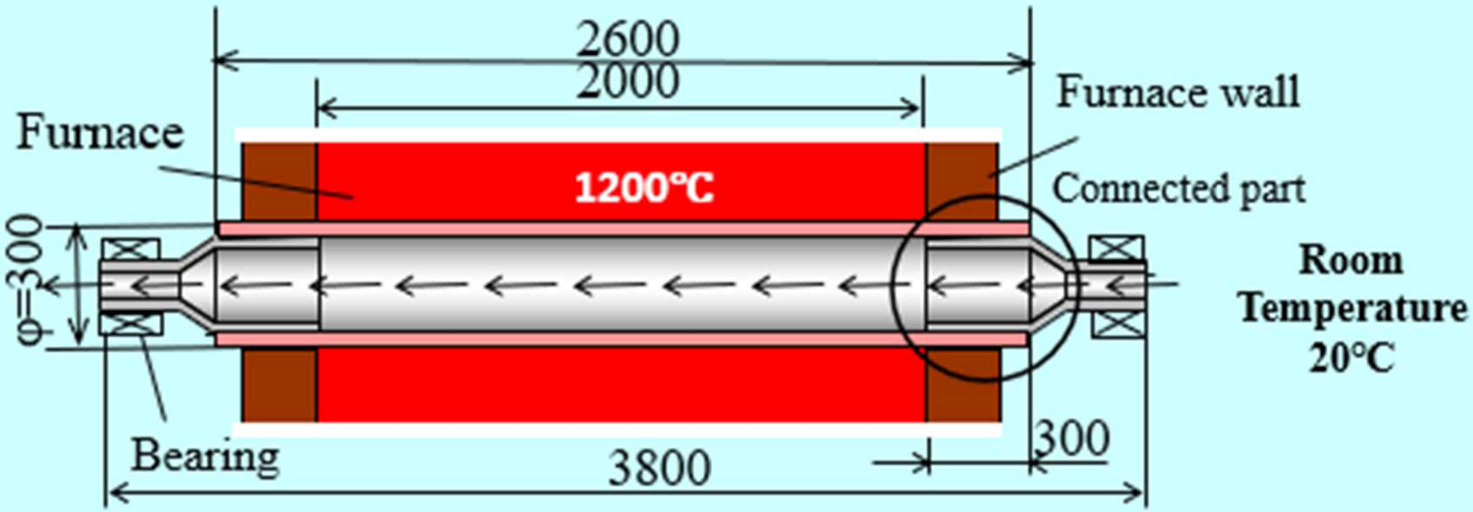
Boundary Condition of Hearth Roll

Thermal Boundary Conditions





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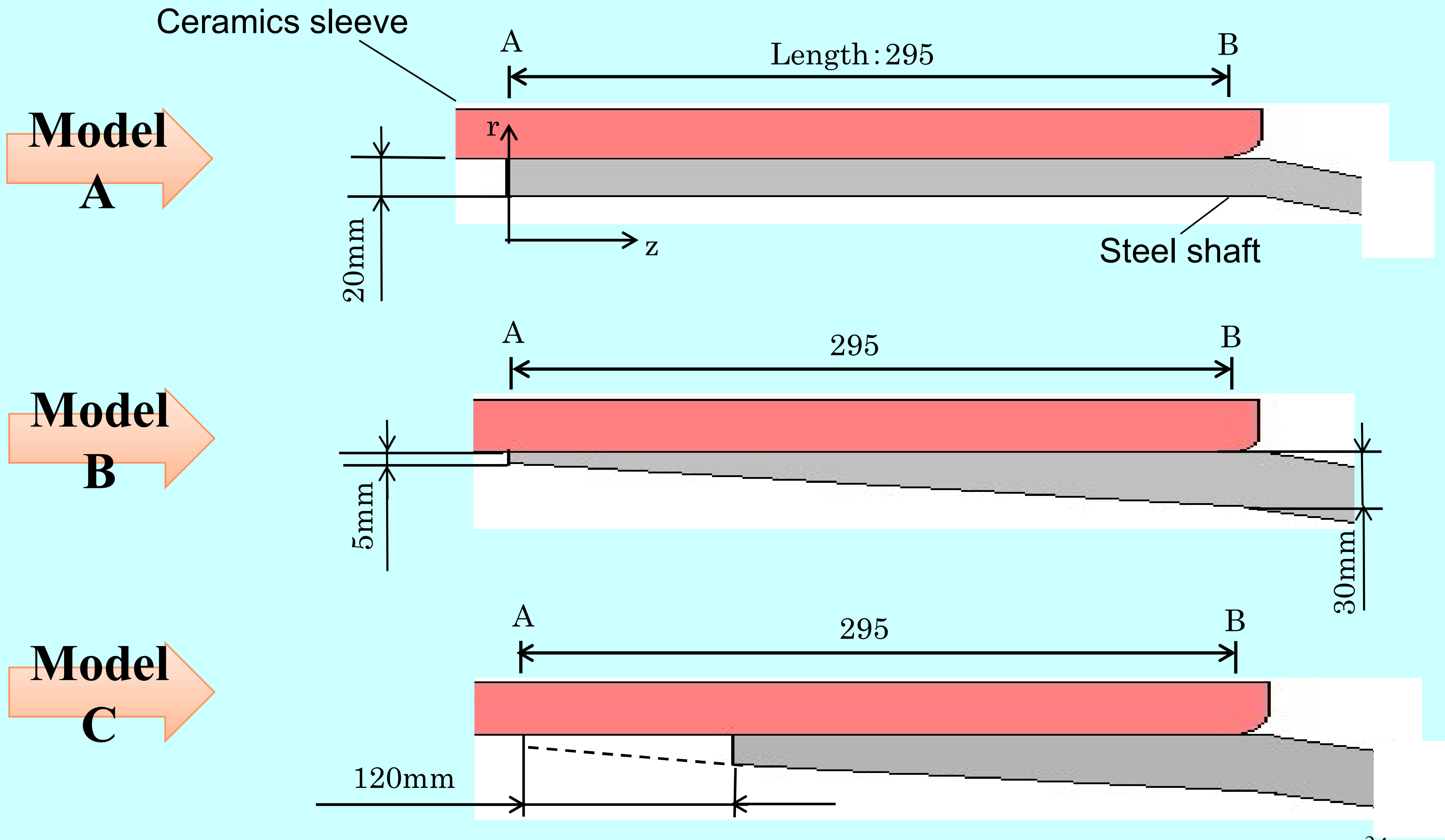
Connected Portion of Hearth Roll

Three Types of Shaft Models



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Ceramics (Silicon Nitride) vs. Steel

	Ceramics	Steel
Young's moduls [GPa]	300	210
Poisson's ratio	0.28	0.3
Tensile strength [MPa]	**500**	600
Fracture toughness [$MPa \cdot m^{1/2}$]	**7**	100
Fatigue stre [MPa]		300
Mass density [kg/m^3]	3200	7800
Thermal conductivity [W/m	62.5(393K)	25
Thermal expansion coefficient [1/K]	3.0×10^{-6}	$\mathbf{14.5 \times 10^{-6}}$
Specific heat [J/kg·K]	680	477
Emissivity	0.4	0.4

Almost same as steel

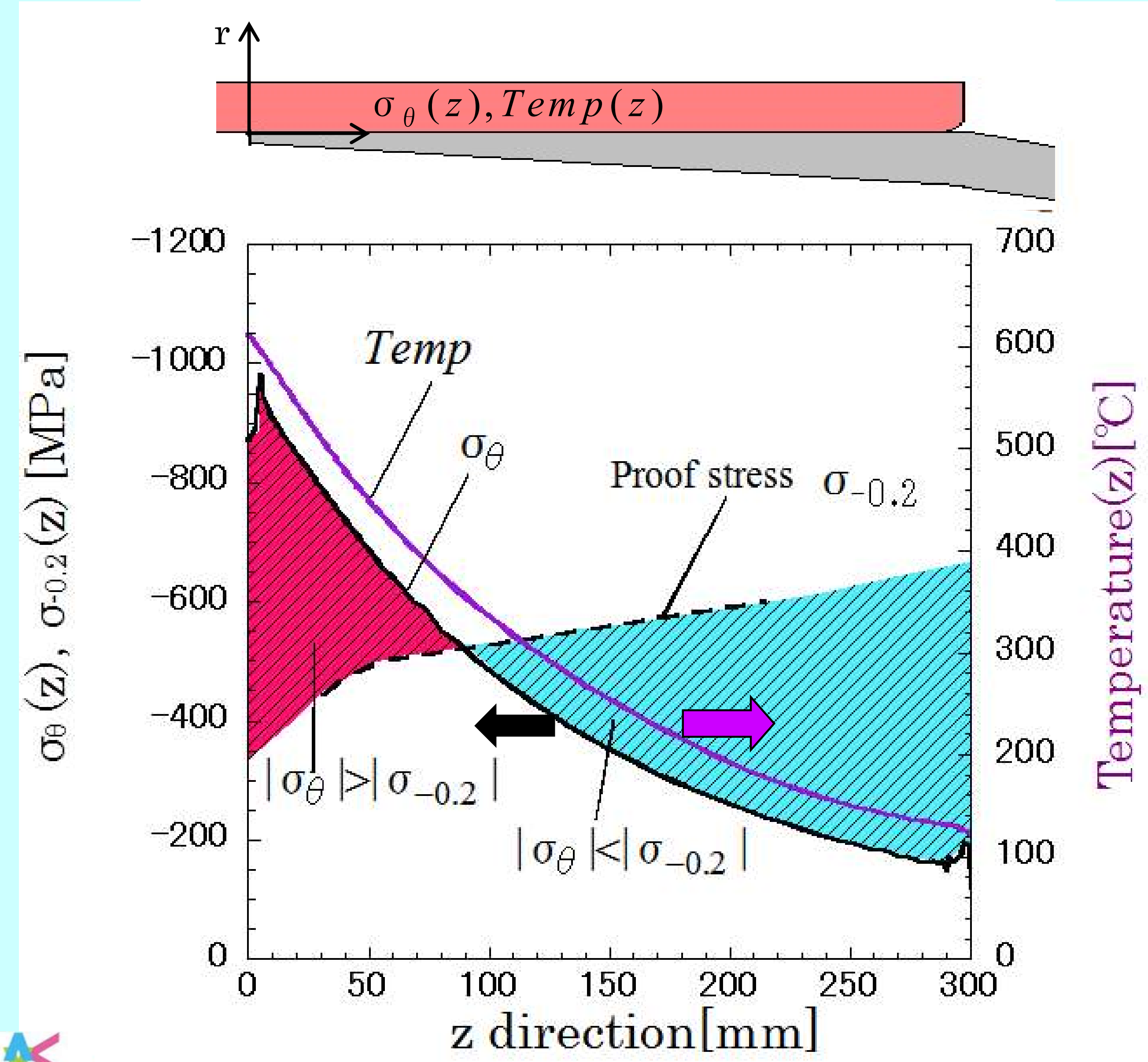
Much small than steel

About 5 times larger than ceramics

Shrink Fitted Portion of Hearth Roll

Model B

Steel Shaft



The stress is LARGER than 0.2% proof stress ($\sigma_{0.2}$)

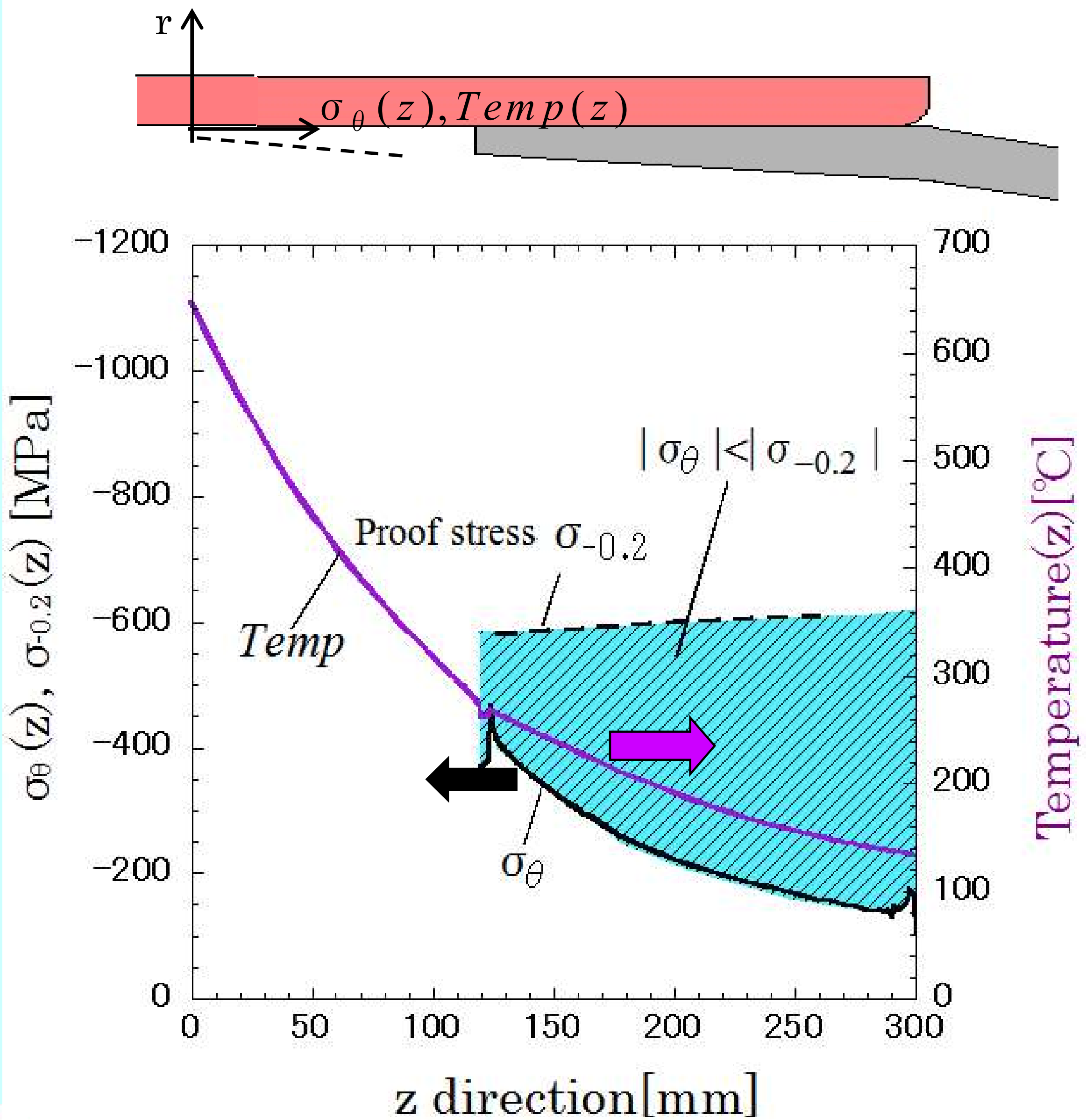
Plastic deformation occurs

Not Safe

Shrink Fitted Portion of Hearth Roll

Model C

Steel Shaft



The stress is SMALLER than 0.2% proof stress ($\sigma_{0.2}$)

↓

Plastic deformation does not occur

↓

Safe

Study on Application of Ceramics Structures to Steel Manufacturing Industries

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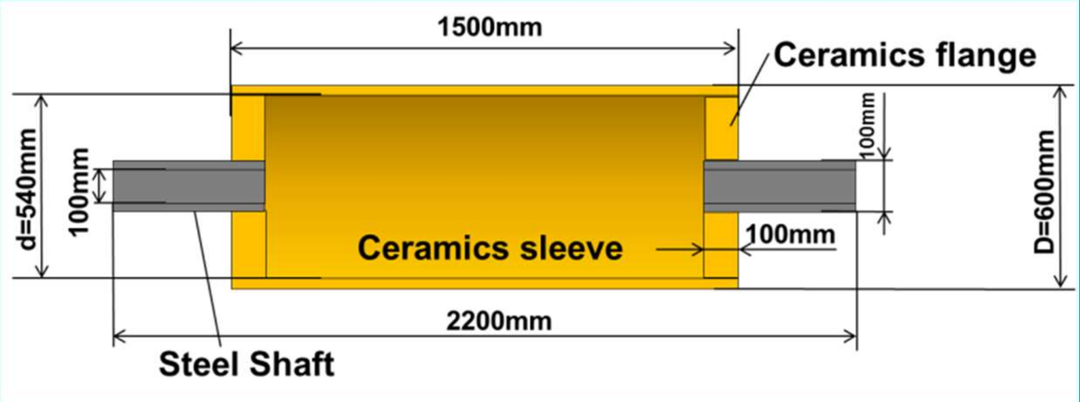

Mechanical Stress of Ceramic Rolls in CPL

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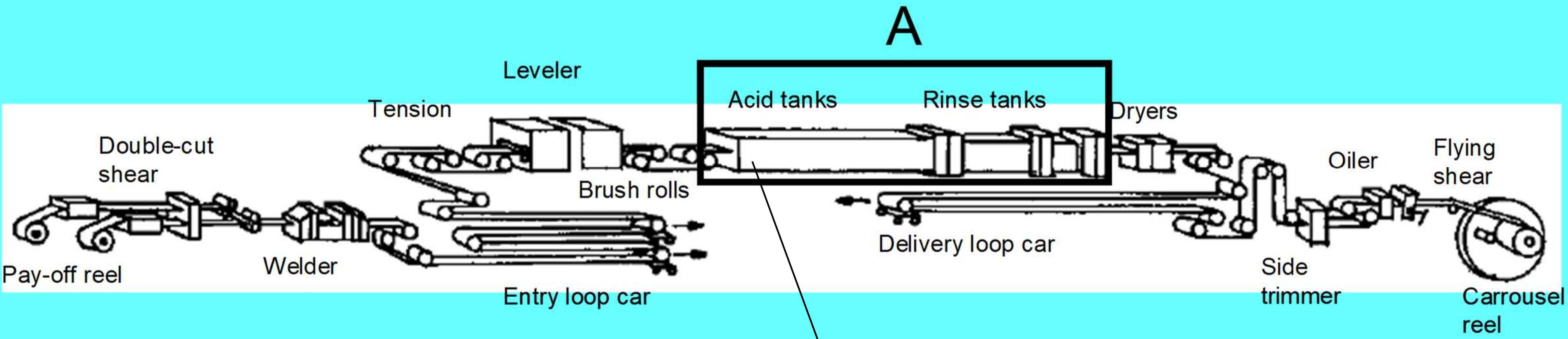
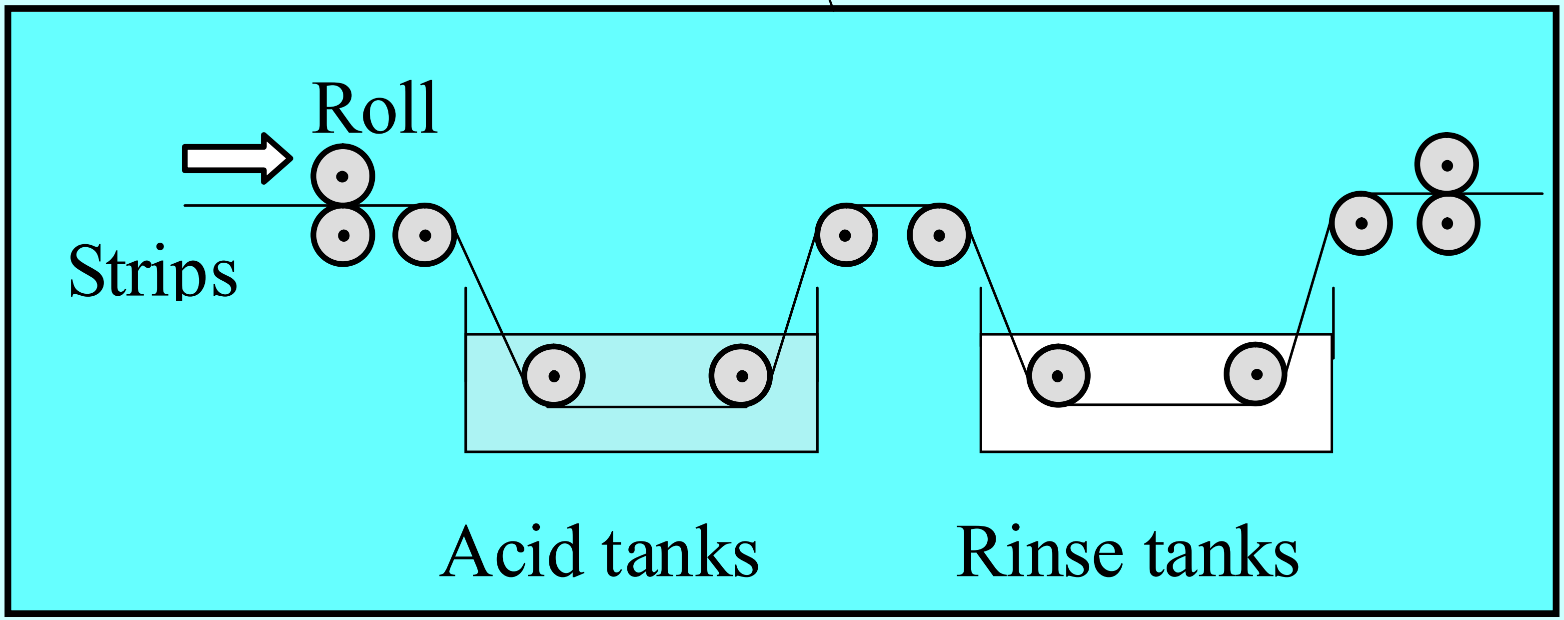
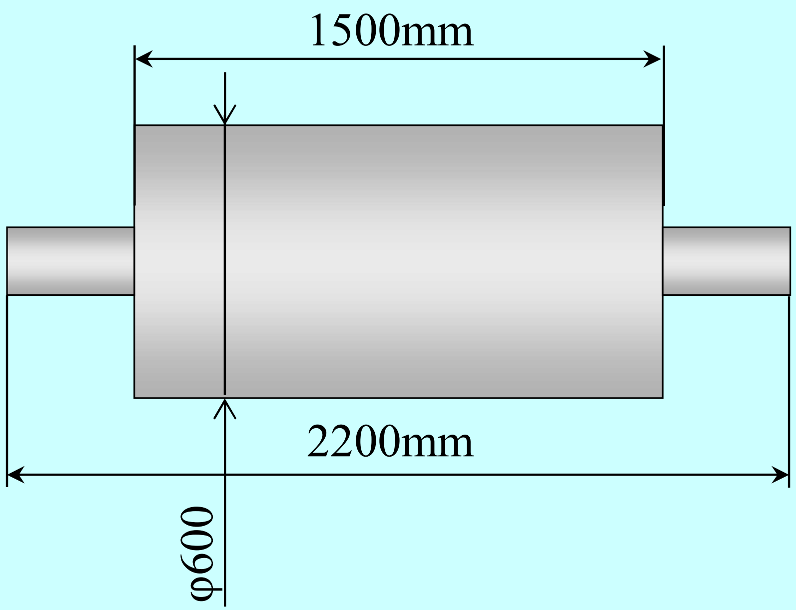
CPL=Continuous Picking Line

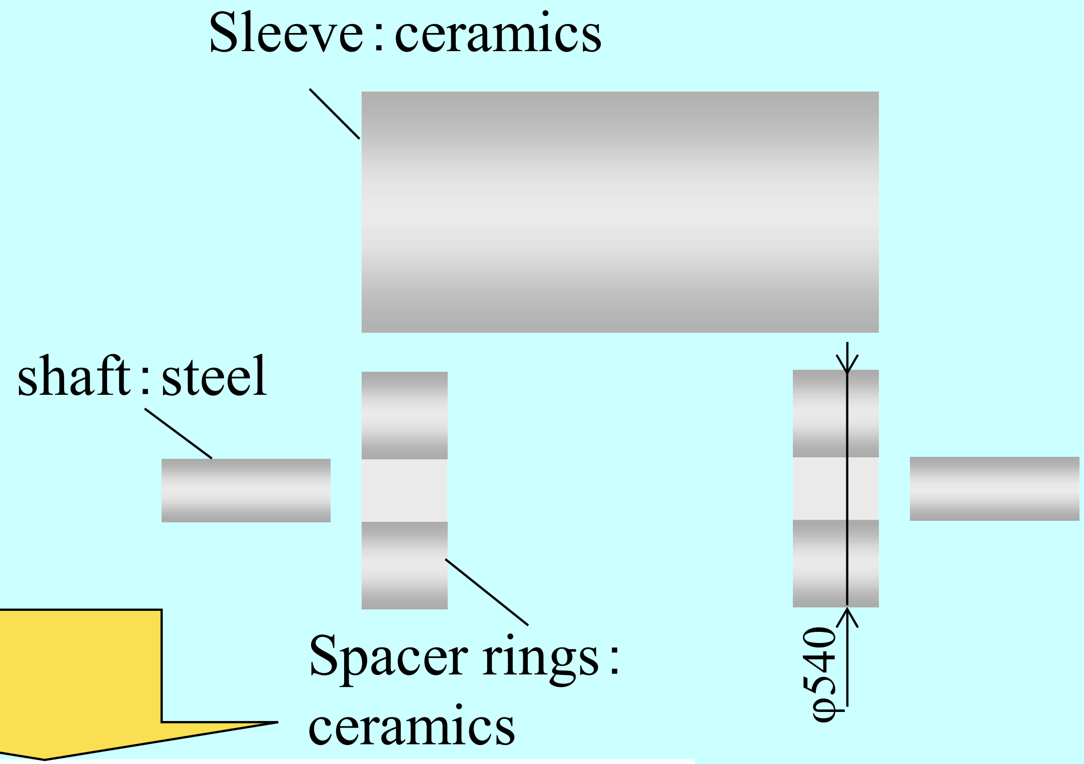
CPL is a steel processing facility that removes oxide scale from hot-rolled steel using a continuous pickling process.

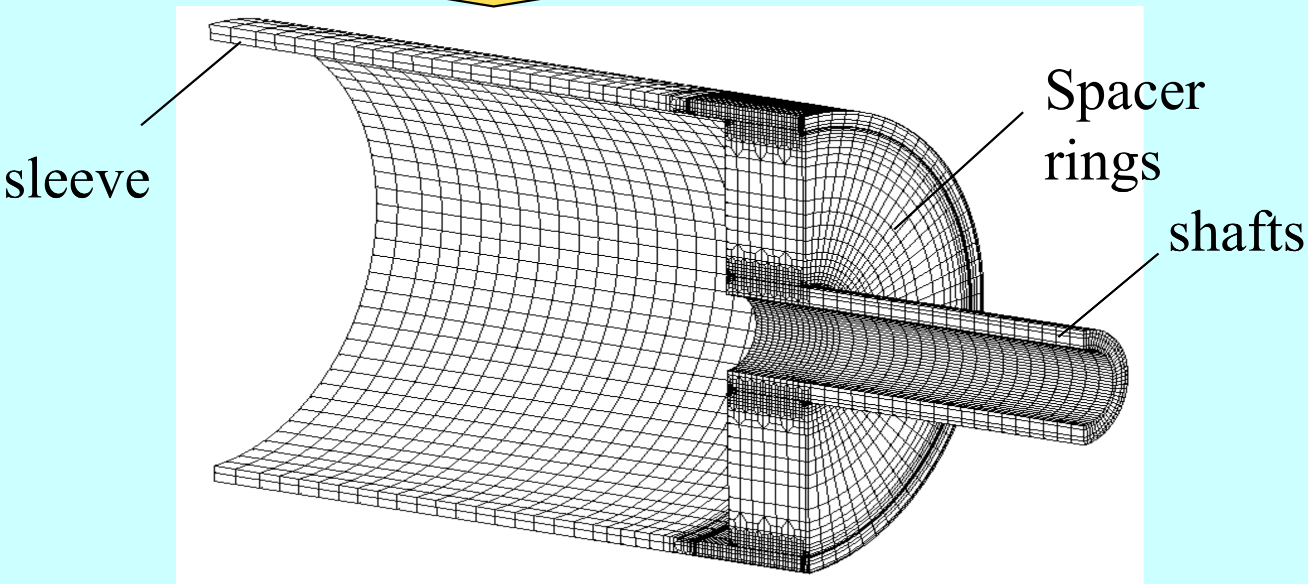




Analytical model



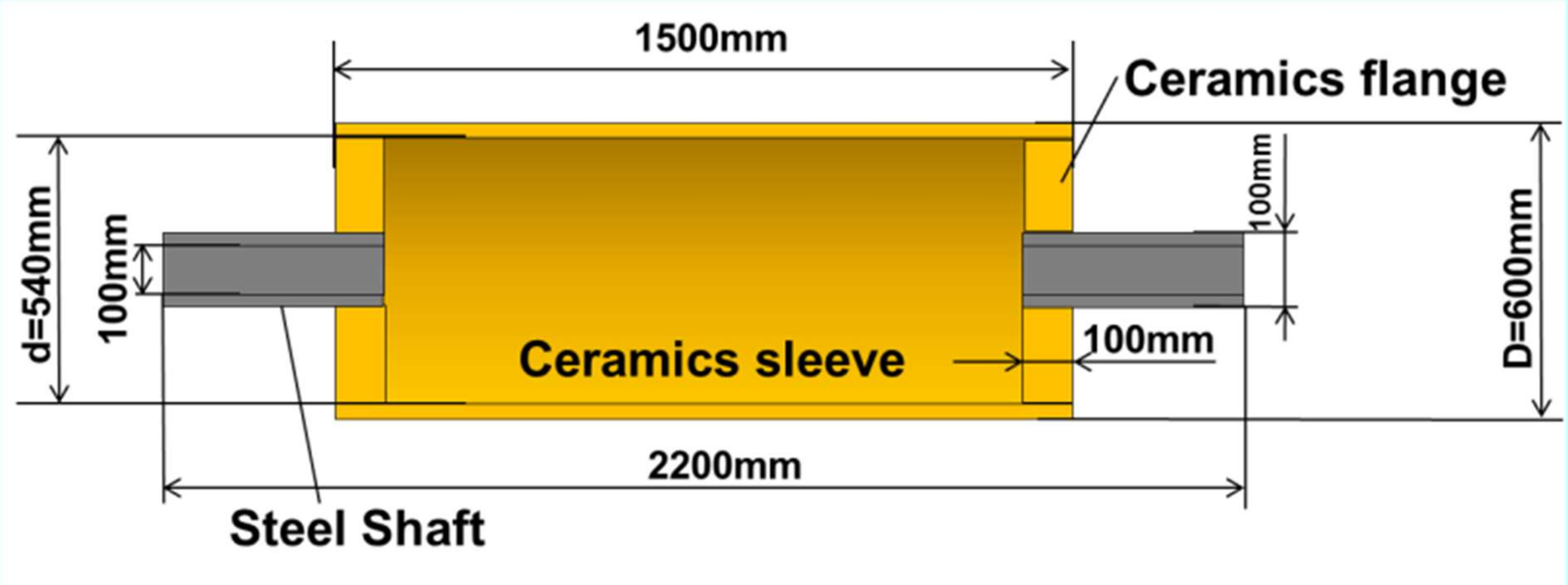




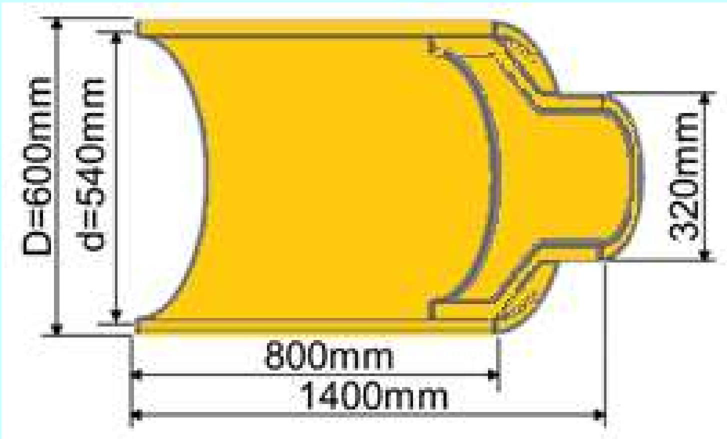
- Hexahedron
- Number of elements is 32070
- Number of nodes is 35687

Pickling Roll in CPL vs. Sink Roll in CGL

Picking roll D=600mm



Sink roll
D=600mm



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Fatigue stre[illegible] [MPa]	[illegible]	300
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Thermal conductivity [W/m[illegible]	62.5(393K)	25
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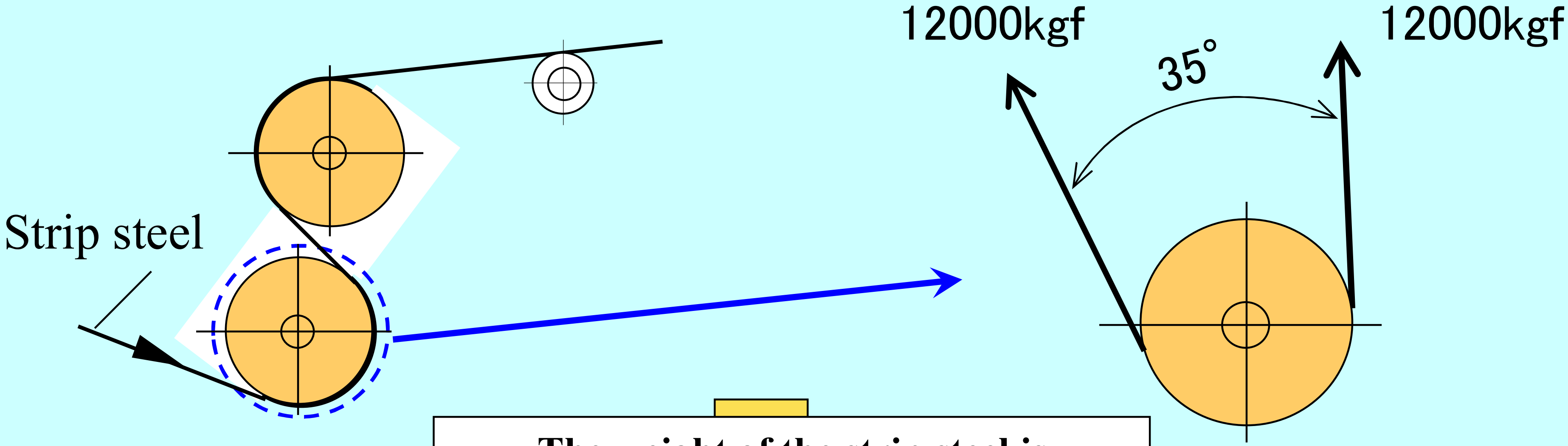
Specific heat [J/kg·K]	680	477
Emissivity	0.4	0.4

Almost same as steel

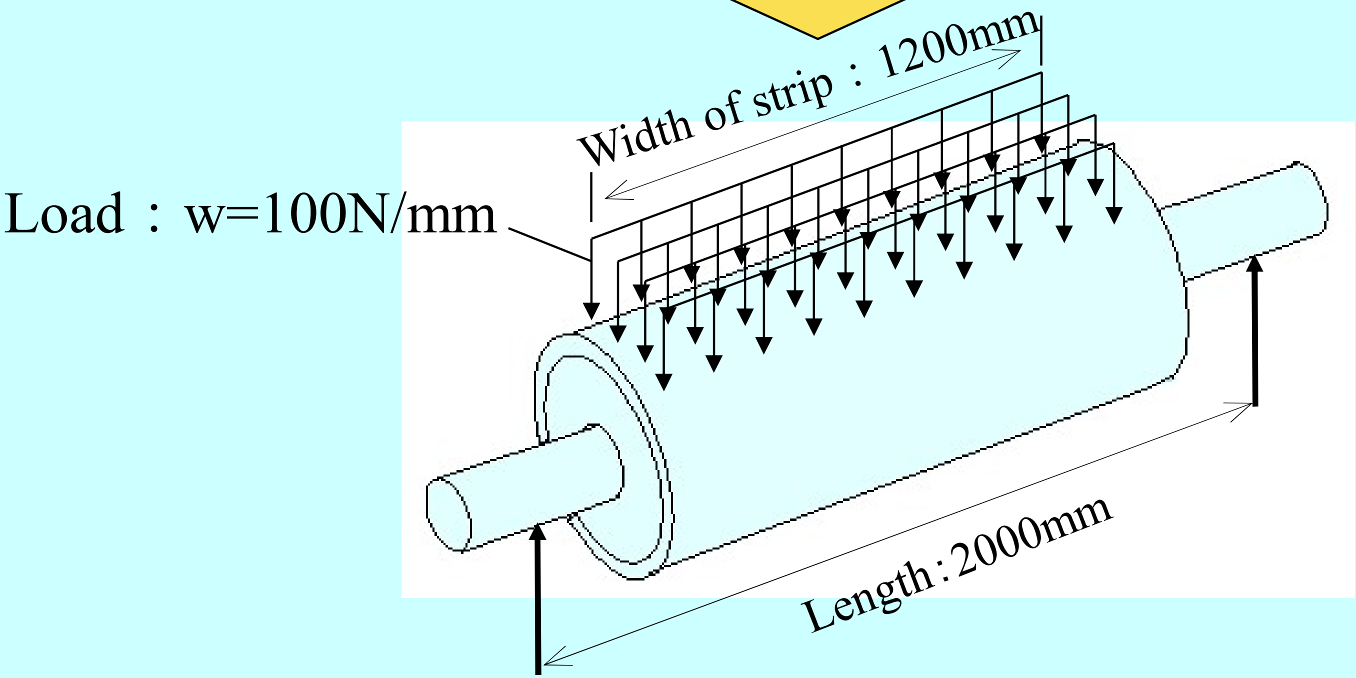
Much small than steel

About 5 times larger than ceramics

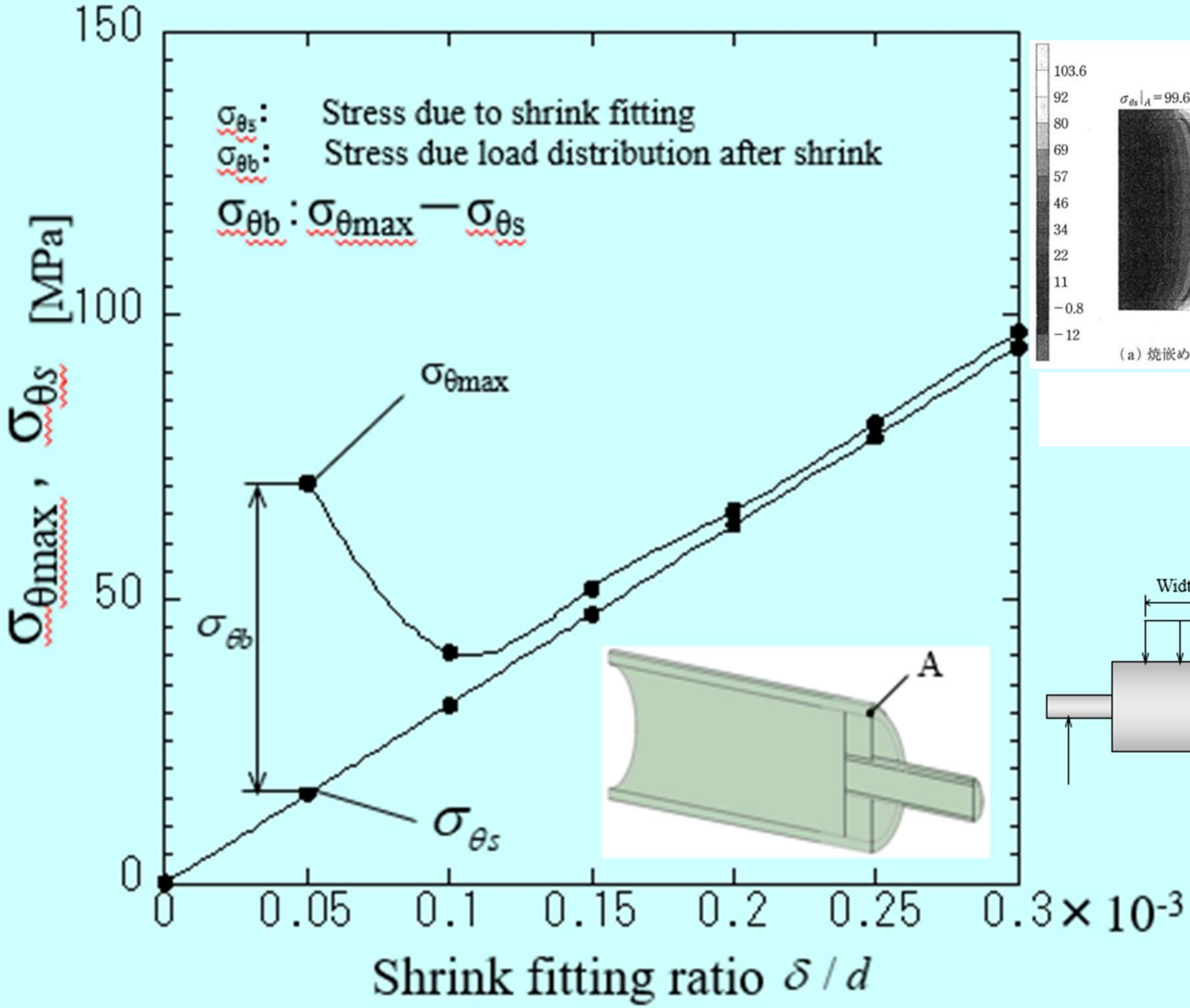
Boundary Condition

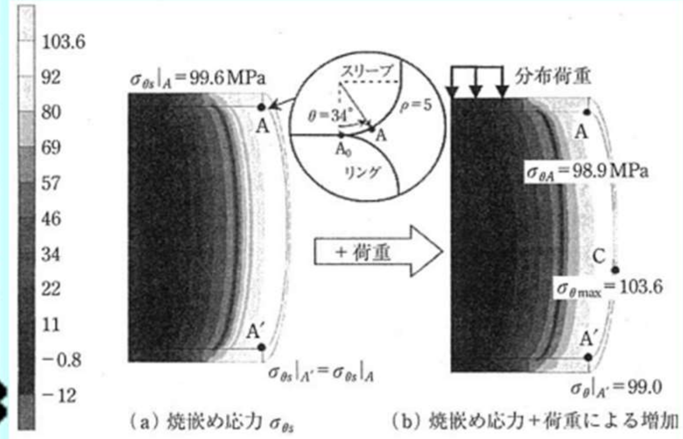


The weight of the strip steel is expressed by the distribution load.

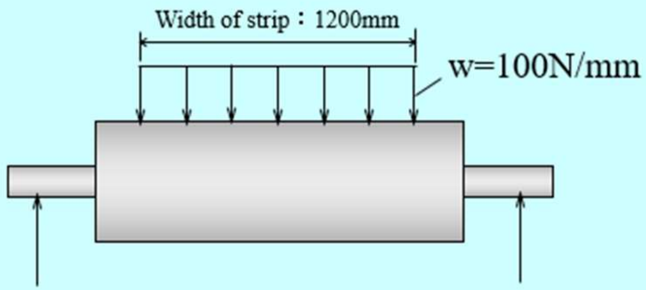


The maximum Tensile Stress vs. Shrink Fitting Ratio (Thickness of sleeve h=30mm, w=100N/mm)



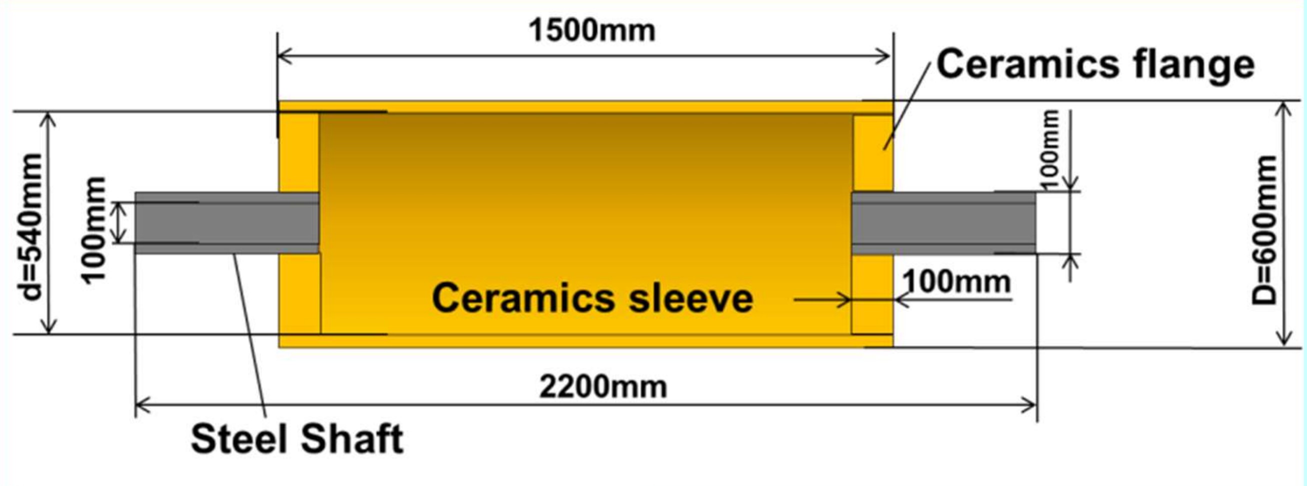


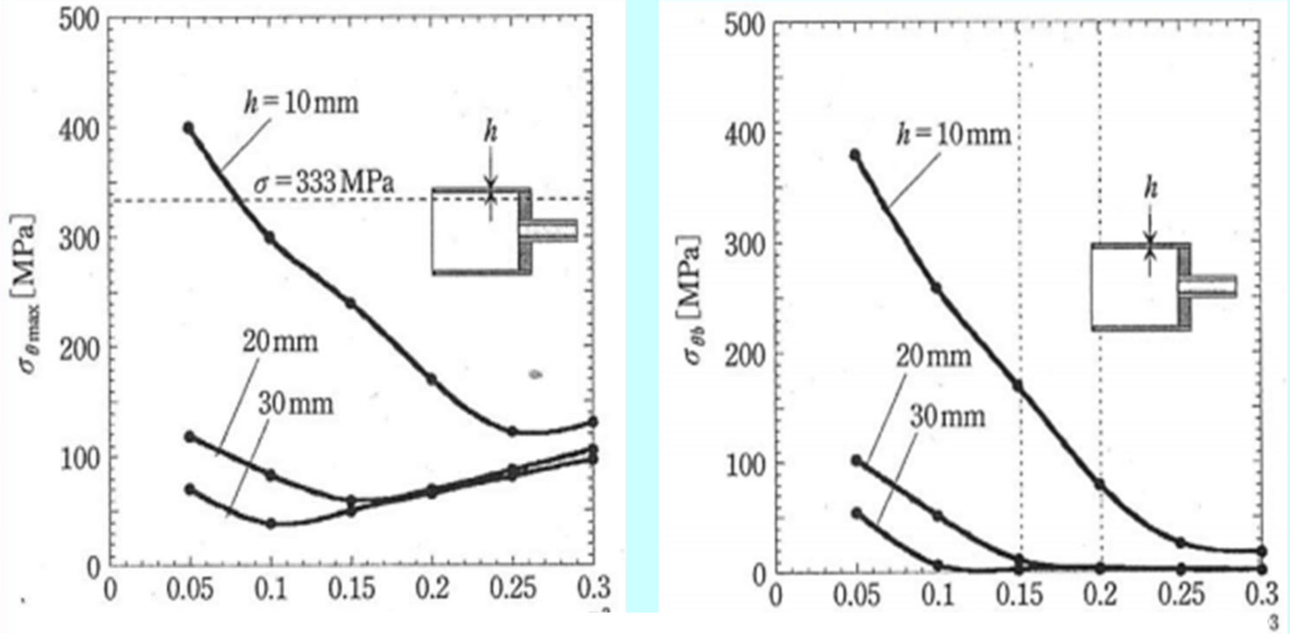
$$\sigma_{\theta \max} = \sigma_{\theta s} + \sigma_{\theta b}$$



Static Strength Analysis for Picking Roll

Picking roll

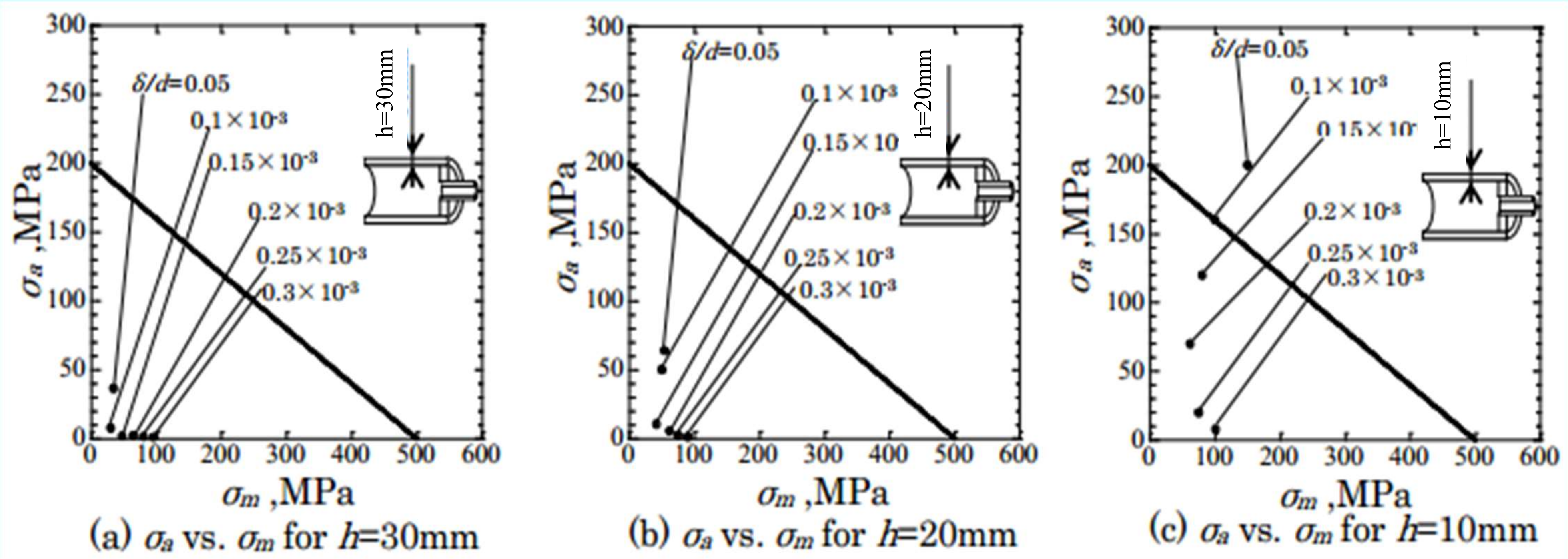




(a) $\sigma_{\theta\max}$ vs. δ/d (b) $\sigma_{\theta b}$ vs. δ/d ($\sigma_{\theta\max} = \sigma_{\theta s} + \sigma_{\theta b}$)

$\sigma_{\theta\max}$, $\sigma_{\theta b}$ vs. δ/d when h=30mm ($\sigma_{\theta\max} = \sigma_{\theta s} + \sigma_{\theta b}$)

Fatigue Strength for Picking Roll



Stress amplitude vs. mean stress diagram when *h* = 10mm, 20mm, 30mm

Conclusions: Pickling Roll

(1) The maximum tensile stress appears at the inner surface of the sleeve at the right end as σθmax. The maximum tensile stress after applying load distribution is 96.60MPa appearing at point B when $\delta/d=0.3\times10^{-3}$.

Sleeve: $\sigma_{\theta \max}$ =96.6 MPa < σ_B=500 MPa

⇓

Safety factor=5.1

(2) For small values of δ/d, the maximum stress σθmax becomes larger because large contact forces may appear between the sleeve and space rings. Appropriately large values of δ/d may reduce σθmax effectively. <u>In other words, σθmax has a minimum value at a certain value of δ/d.</u>

(3) Fatigue strength analysis is very important for ceramics rolls subjected to load distribution. Fatigue strength can be decreased by reducing the shrink fitting ratio

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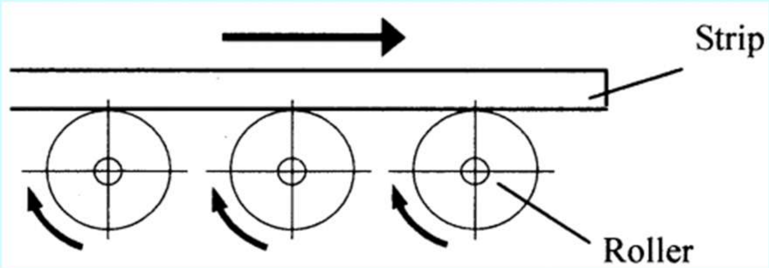

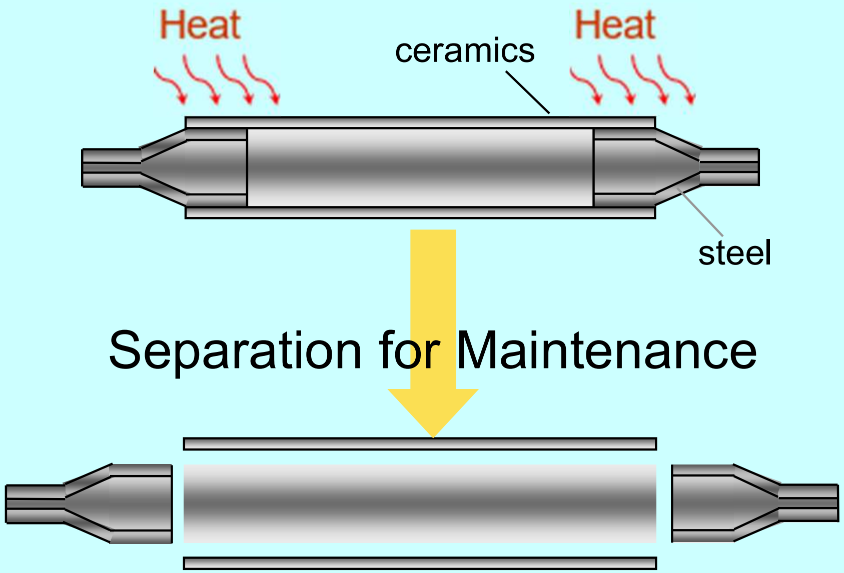

Heating Separation for Ceramic Rolls in Conveying Line

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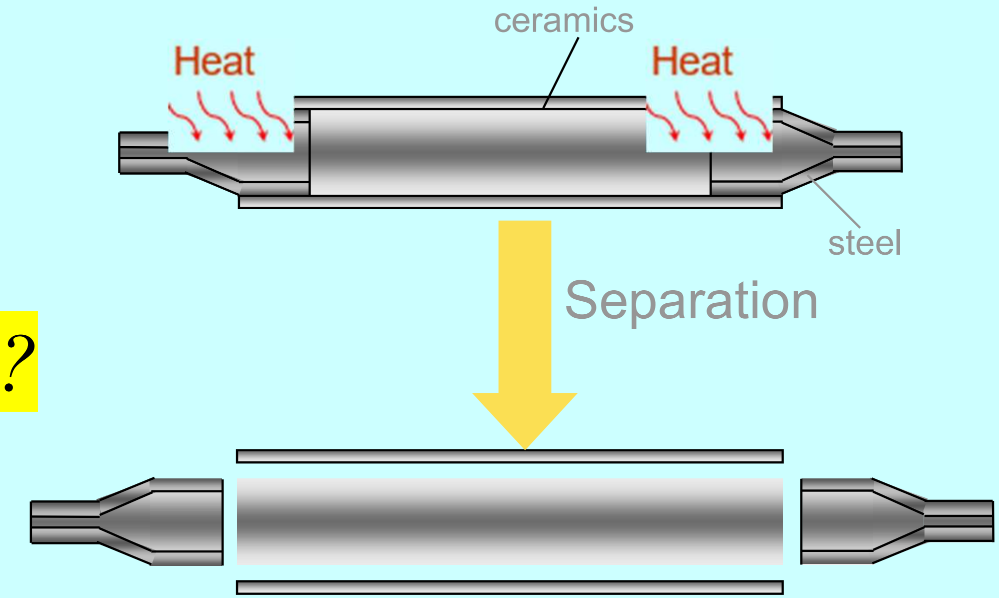
Heating Separation possible？

♦ In Ceramics-Steel rolls, wear and deterioration are easy induced on the steel shaft

⇒ It is necessary to exchange the shaft sometimes for reconstruction.

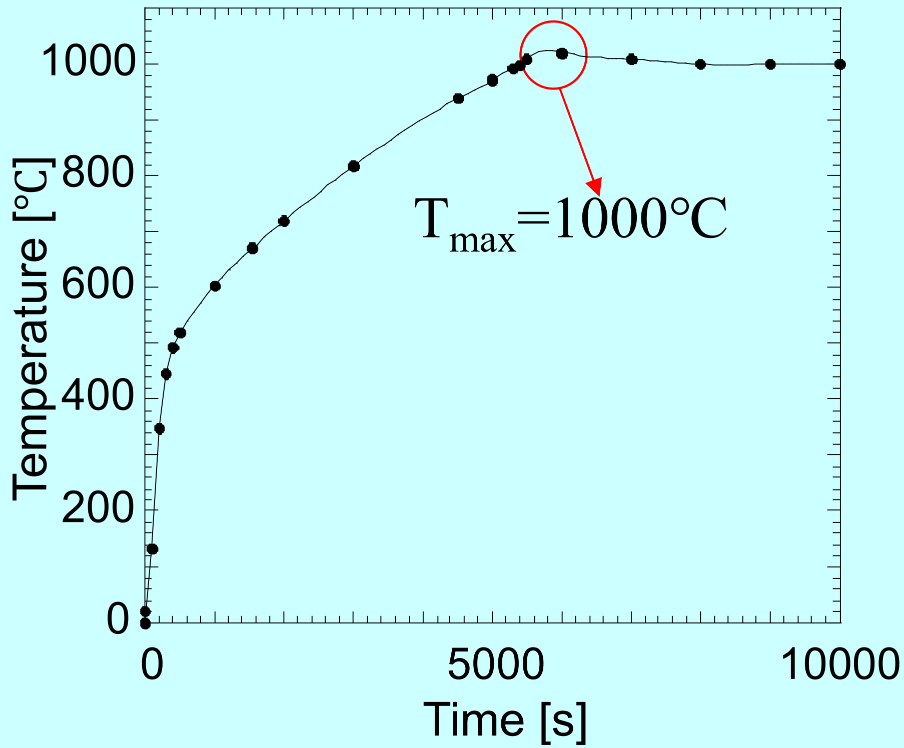


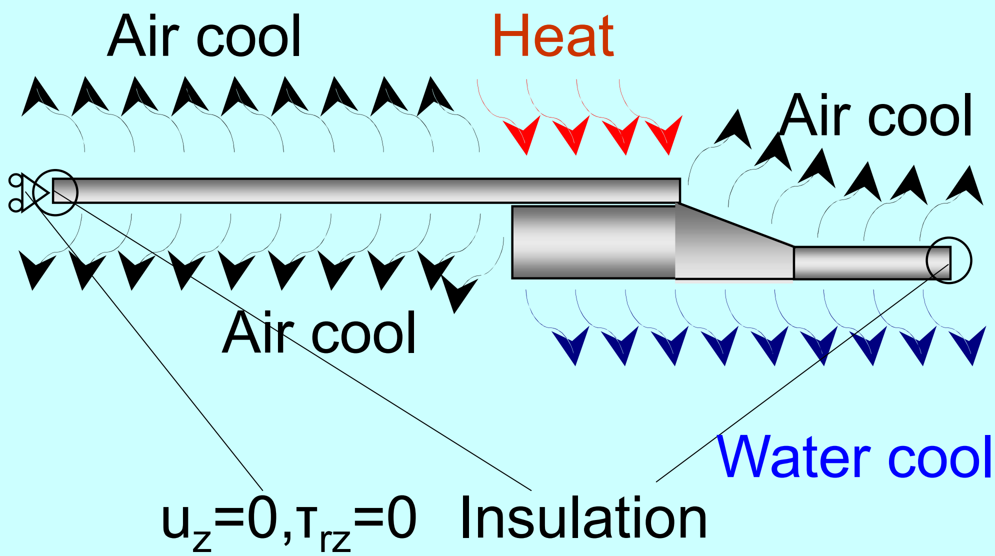
Purpose

① *Separation can be realized ?*

② *The appropriate conditions to make separation easily?*

Analysis conditions



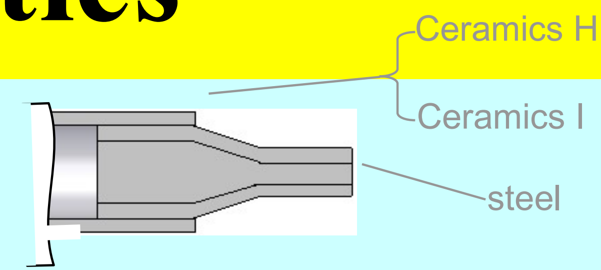


Thermal parameters in details

$$
\begin{cases}
\text{Heating} \begin{cases} \text{Radiation: } \varepsilon = 0.4 \\ \text{Convection: } \alpha = 50\,\mathrm{W/m^2 \cdot K \cdot s} \end{cases} \\
\text{Water Cooling: } \alpha = 1.163 \times 10^4\,\mathrm{W/m^2 \cdot K \cdot s} \\
\text{Air Cooling: } \alpha = 50\,\mathrm{W/m^2 \cdot K \cdot s}
\end{cases}
$$

- Forced convection for heating and water cooling
- Natural convection for air cooling

Material properties



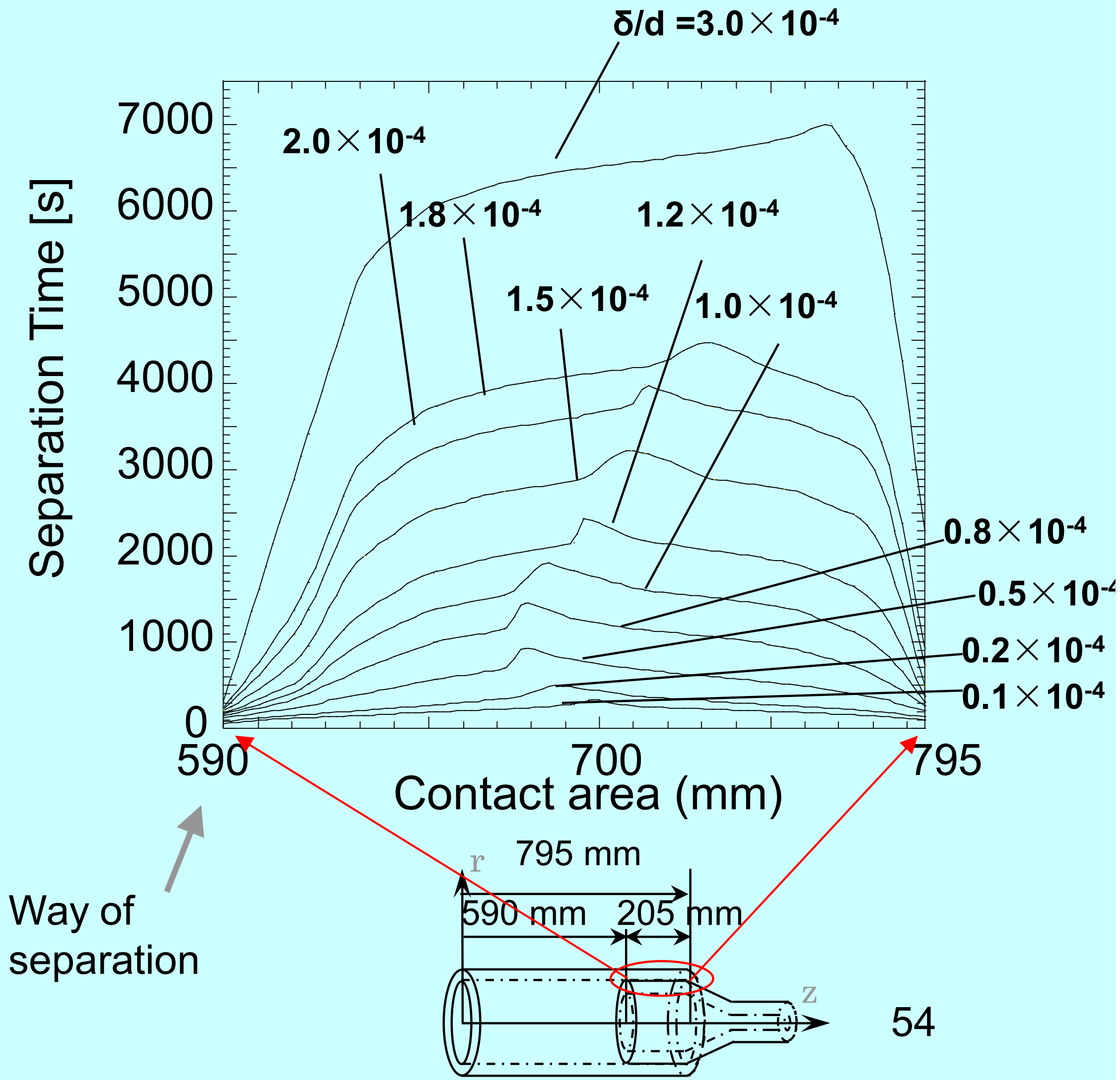
	Ceramics H	Ceramics I	Steel
Young's modulus [MPa]	300	294	210
Poisson's ratio	0.28	0.27	0.3
Tensile strength [MPa]	500	500	600
Mass density [kg/m^3]	3200	3260	7800
Thermal conductivity [W/m·K]	62.5(393K) 12.5(1273K)	17(393K) 3.2(1273K)	25
Thermal expansion Coefficient [1/K]	3.0×10^{-6}	3.0×10^{-6}	1.45×10^{-5}
Specific heat [J/kg·K]	680	650	477
Emissivity	0.4	0.4	0.4

Large δ/d→Large Separation Time

δ/d

Separation starts from both ends

Last separation is at the center



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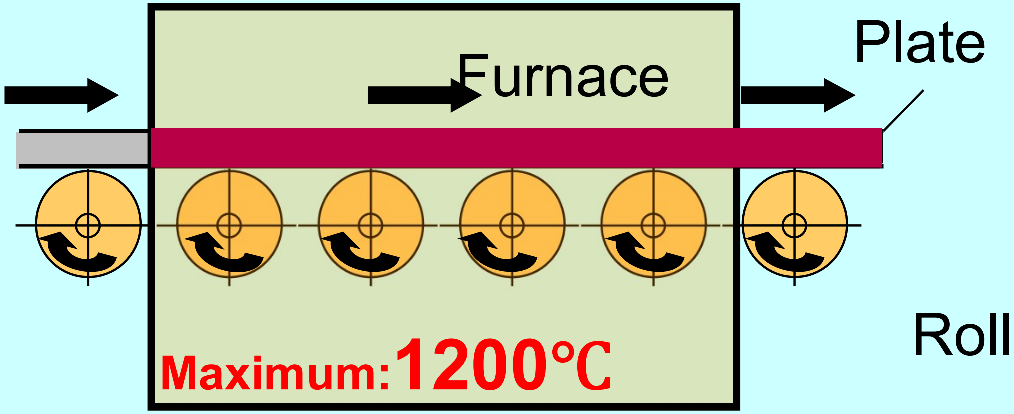
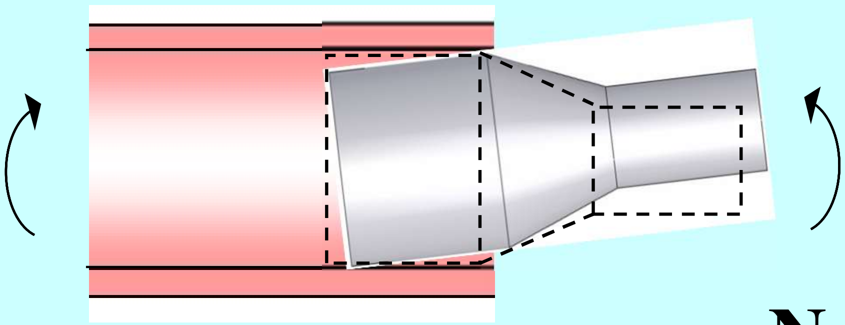
64th Advanced Materials Congress World Fellow Summit, Port of Helsinki, Finland, 1115-1135, 27 May (Tue), 2025.



Coming out of the Shaf of Hearth Roll in Furnace



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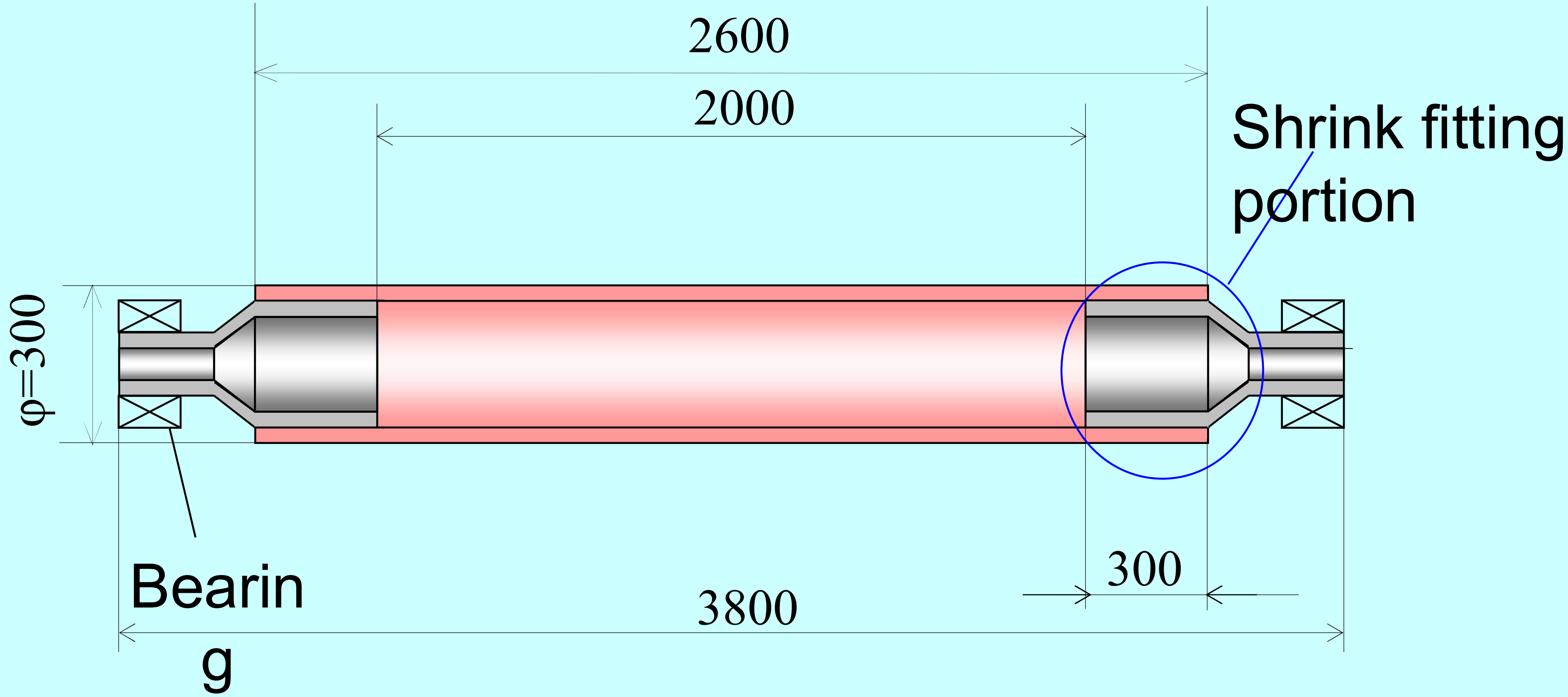
Dimensions of Hearth Roll

Analysis Condition



In this rsearch, analysis of coming out was carried out under room temperature

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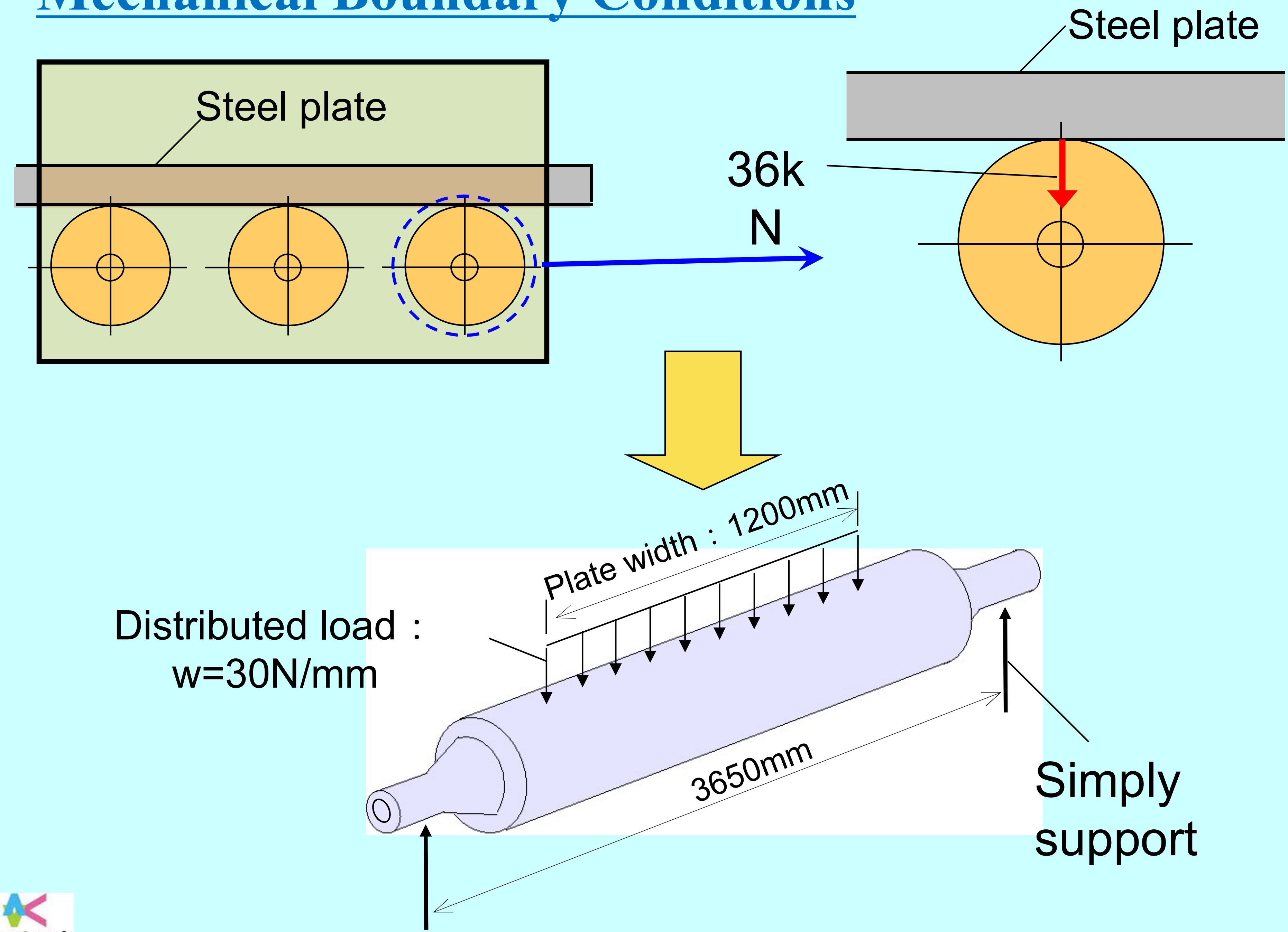
Boundary Conditions of Hearth Roll

Mechanical Boundary Conditions



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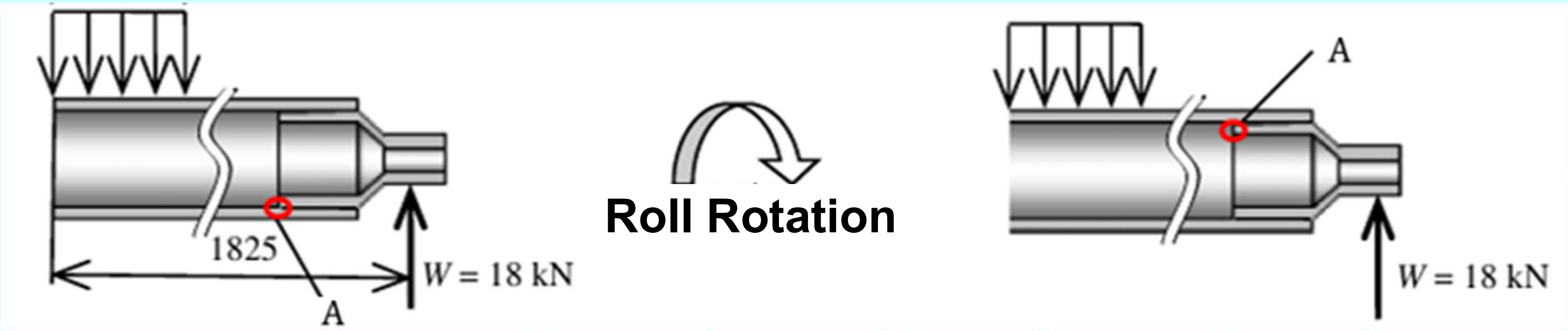
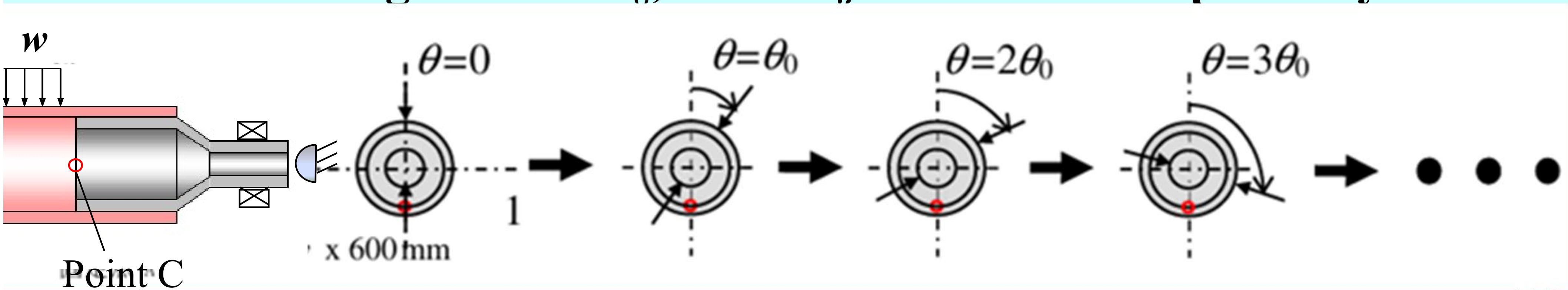
"Load Shifting Method" to realize coming out of the shaft

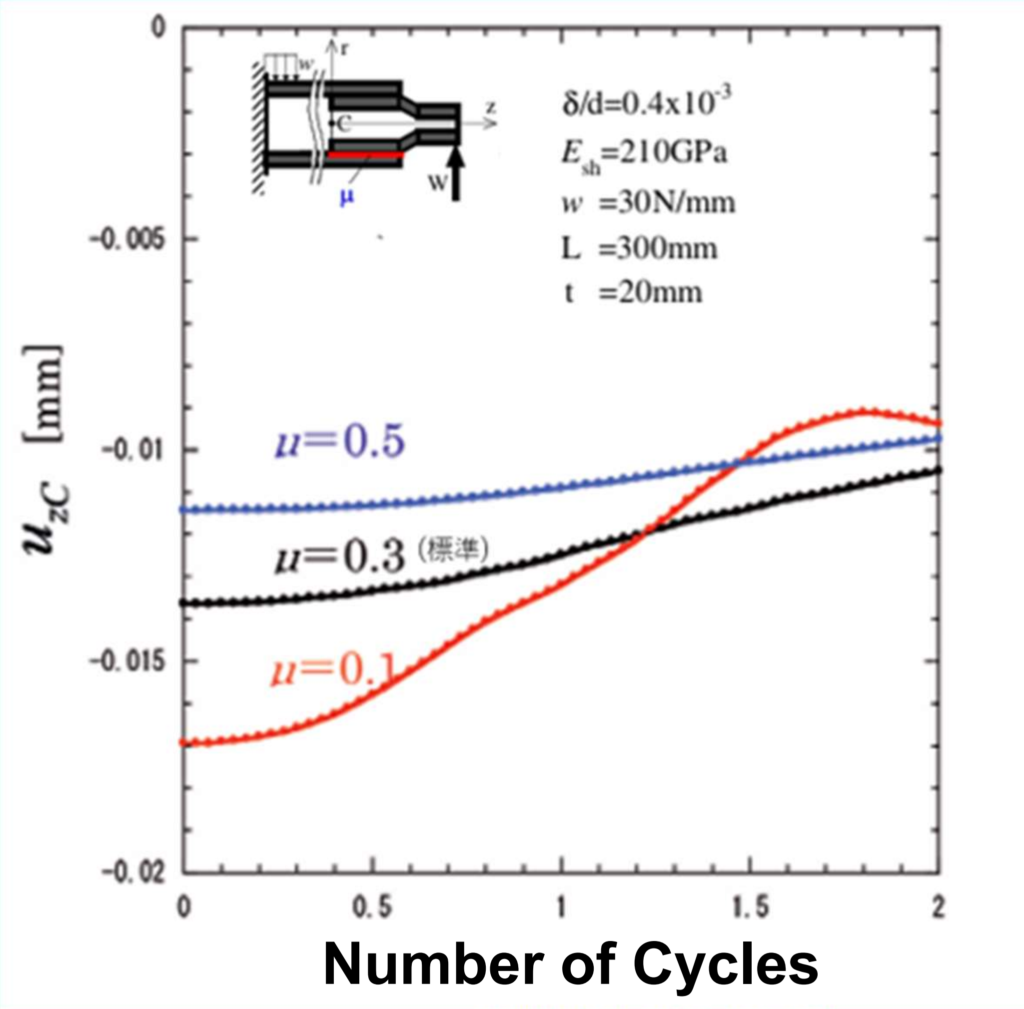


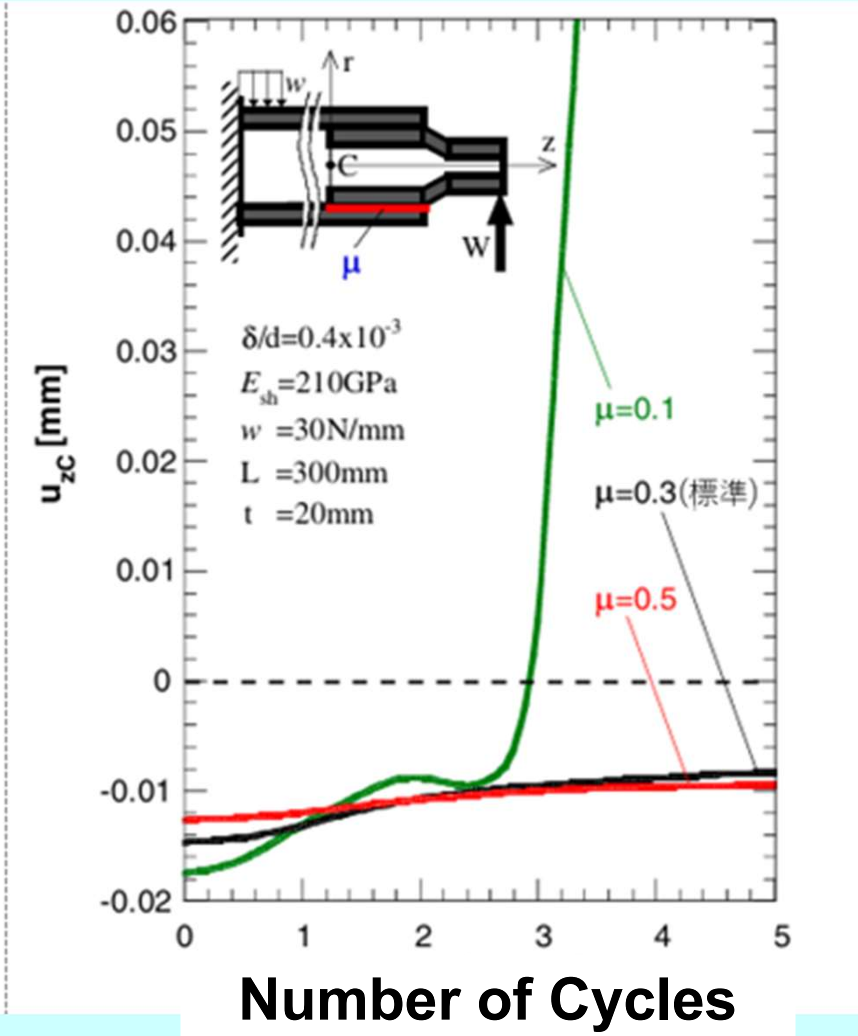
Load shifting method θ_0, when $\theta_0 = 12^\circ$, 30 steps = 1 cycle



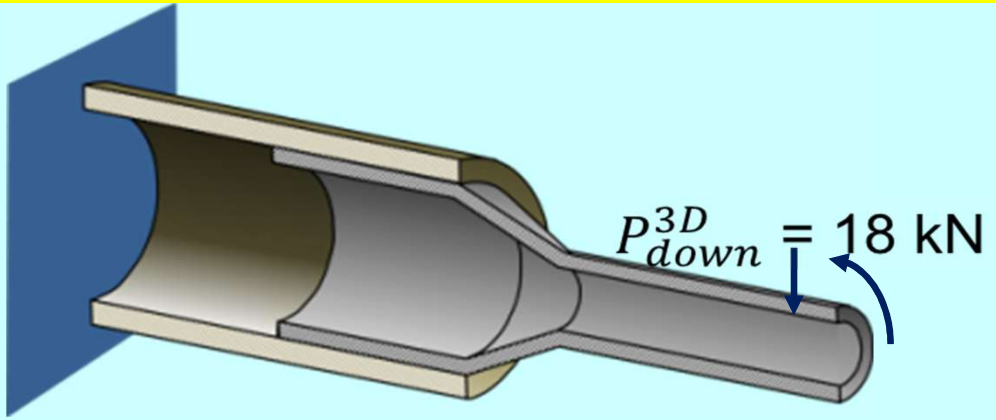
Effect of the Friction Coefficient

($\theta_0 = 12°$, $\delta/d=0.4\times10^{-3}$)



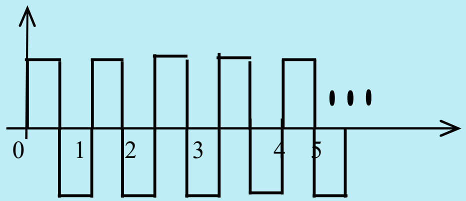


2D alternate load model

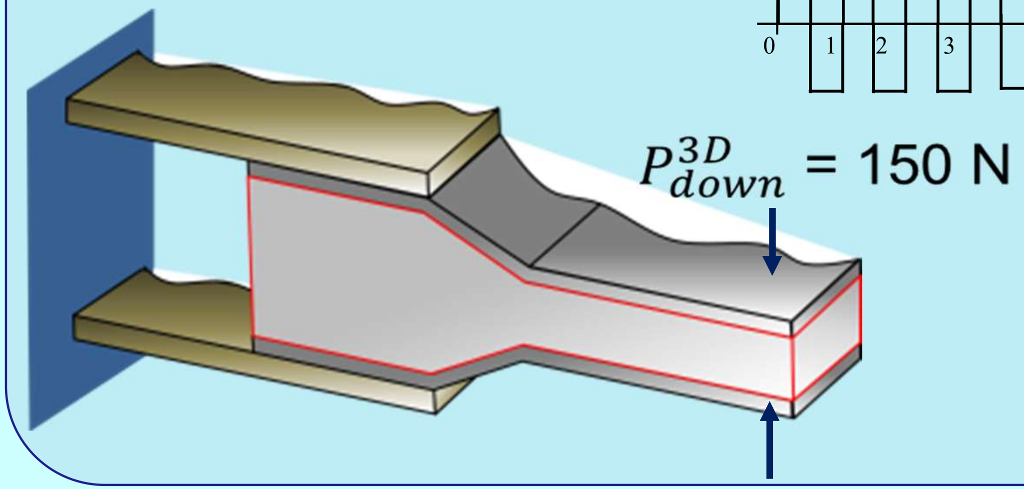


3D

Simplified to



2D

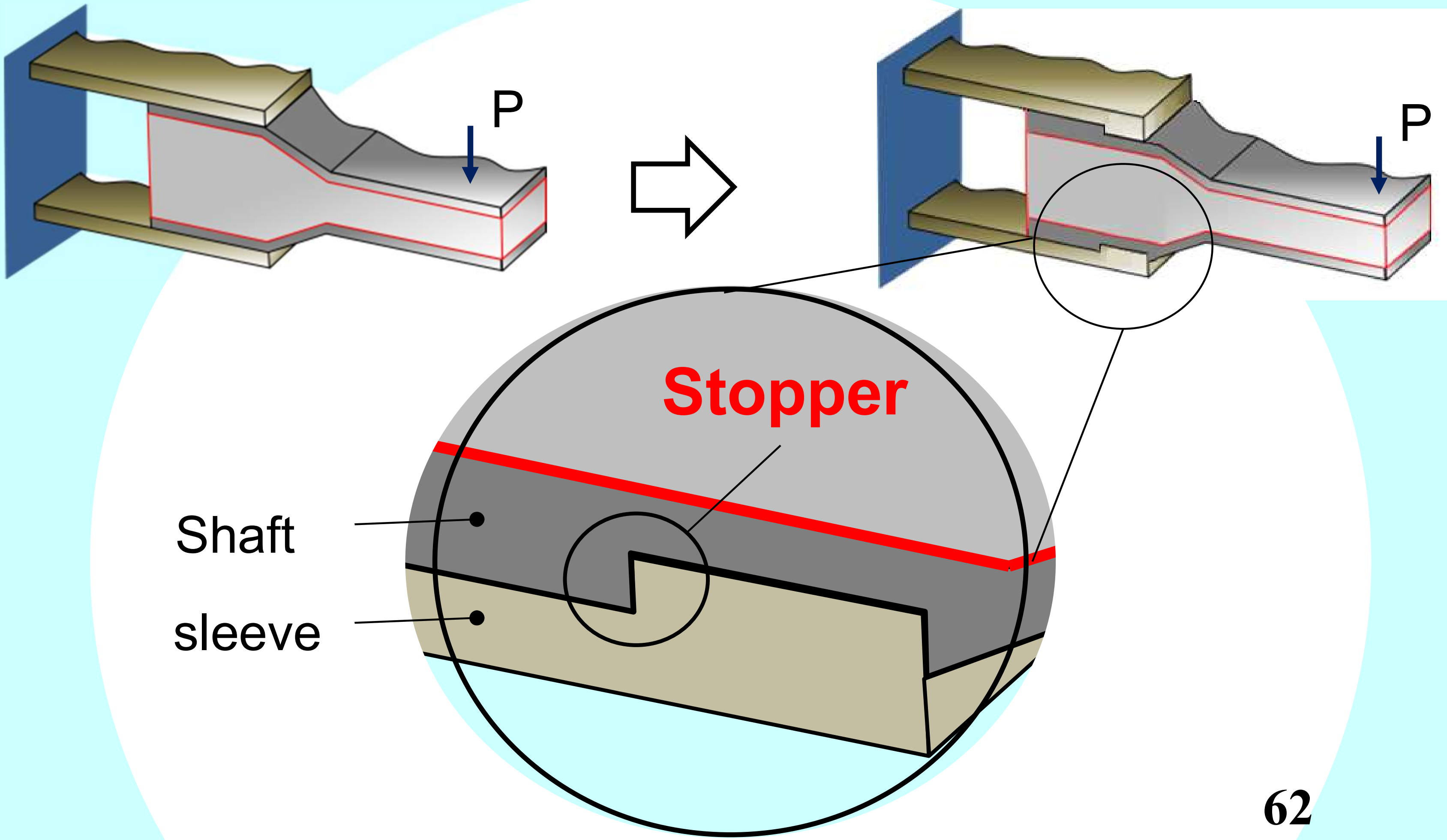


Alternate load Cycle $N_s \geq 40$

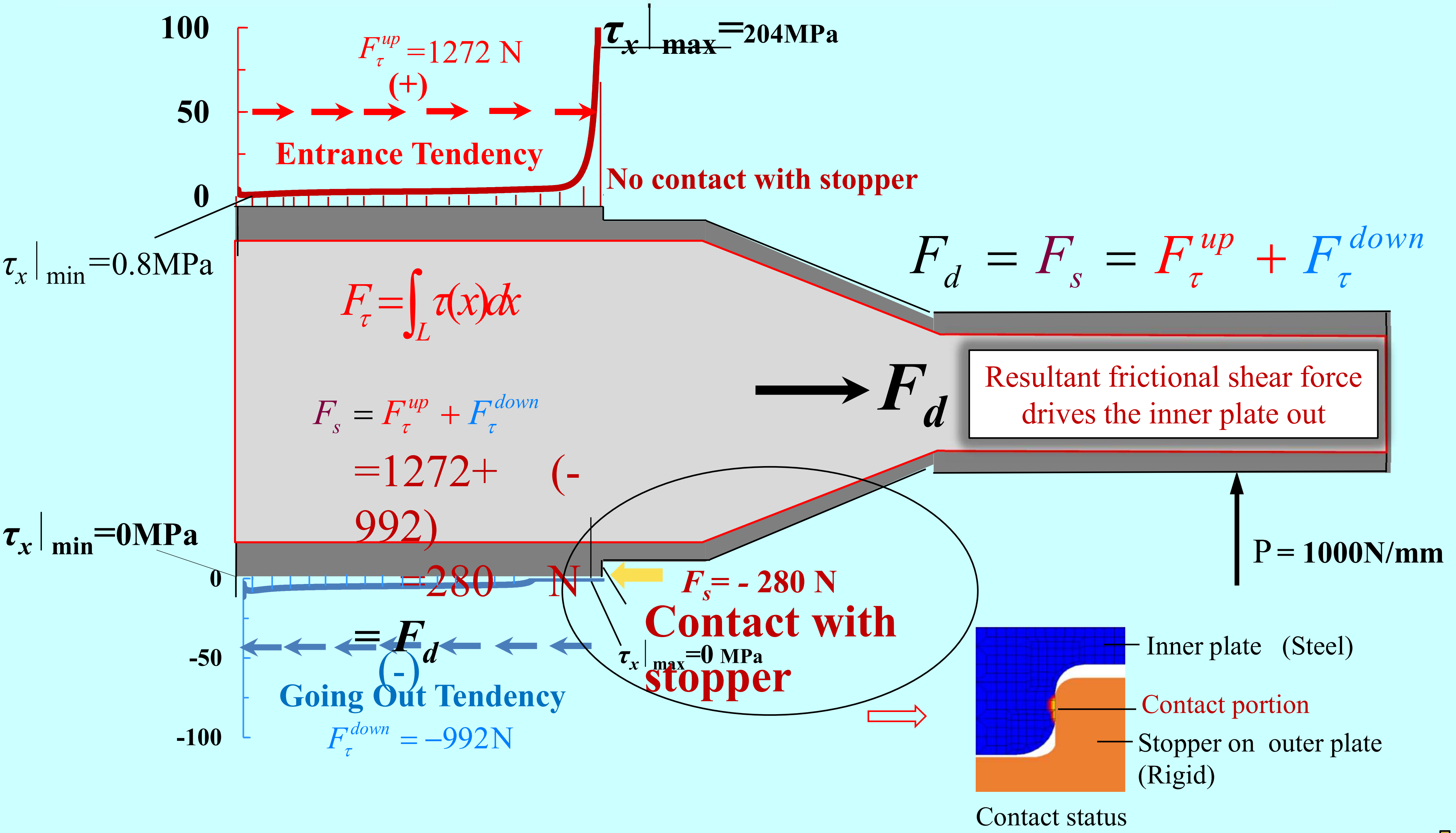
Time saving
Easy to judge & analyze

2D alternate load model with stopper

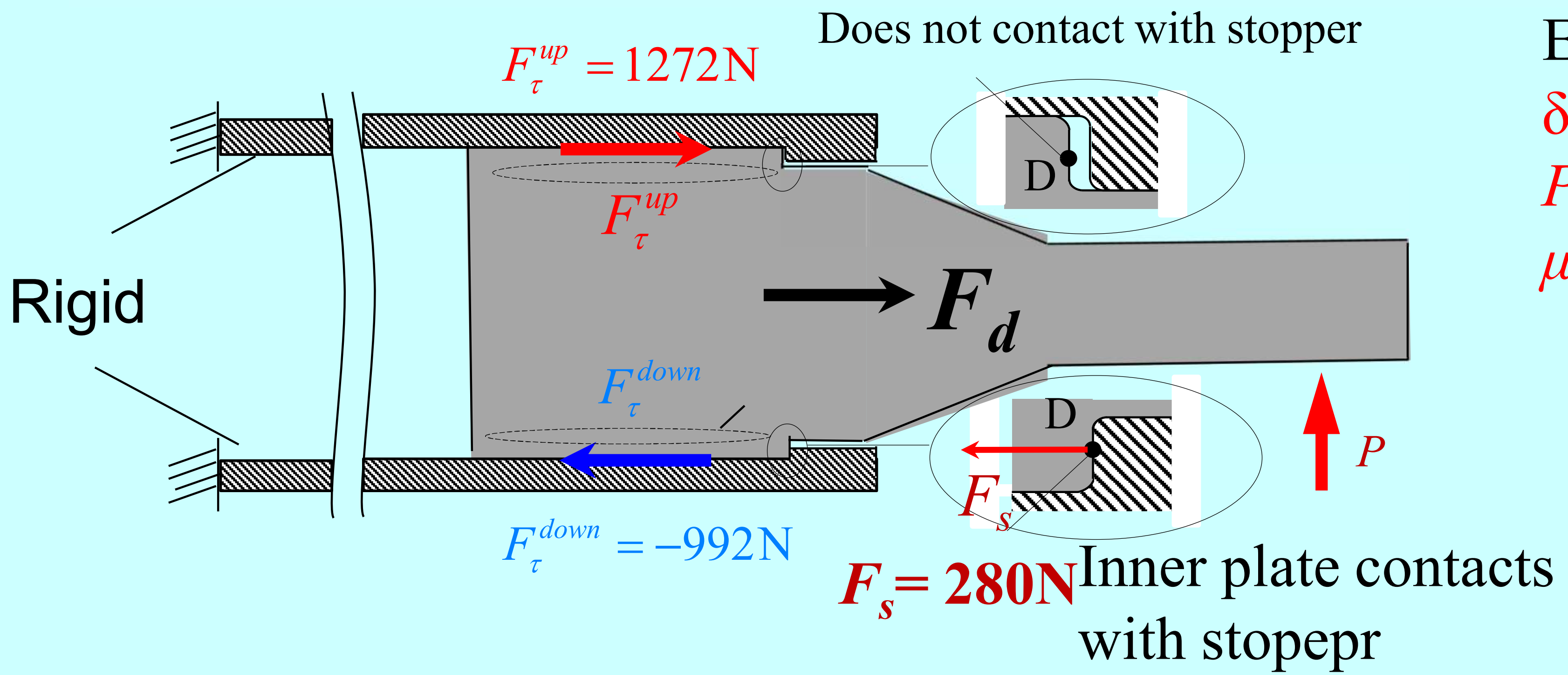
- To find out the generation mechanism of the driving out force.
- To evaluate the driving out force.



Diving out force F_d



Diving out force F_d

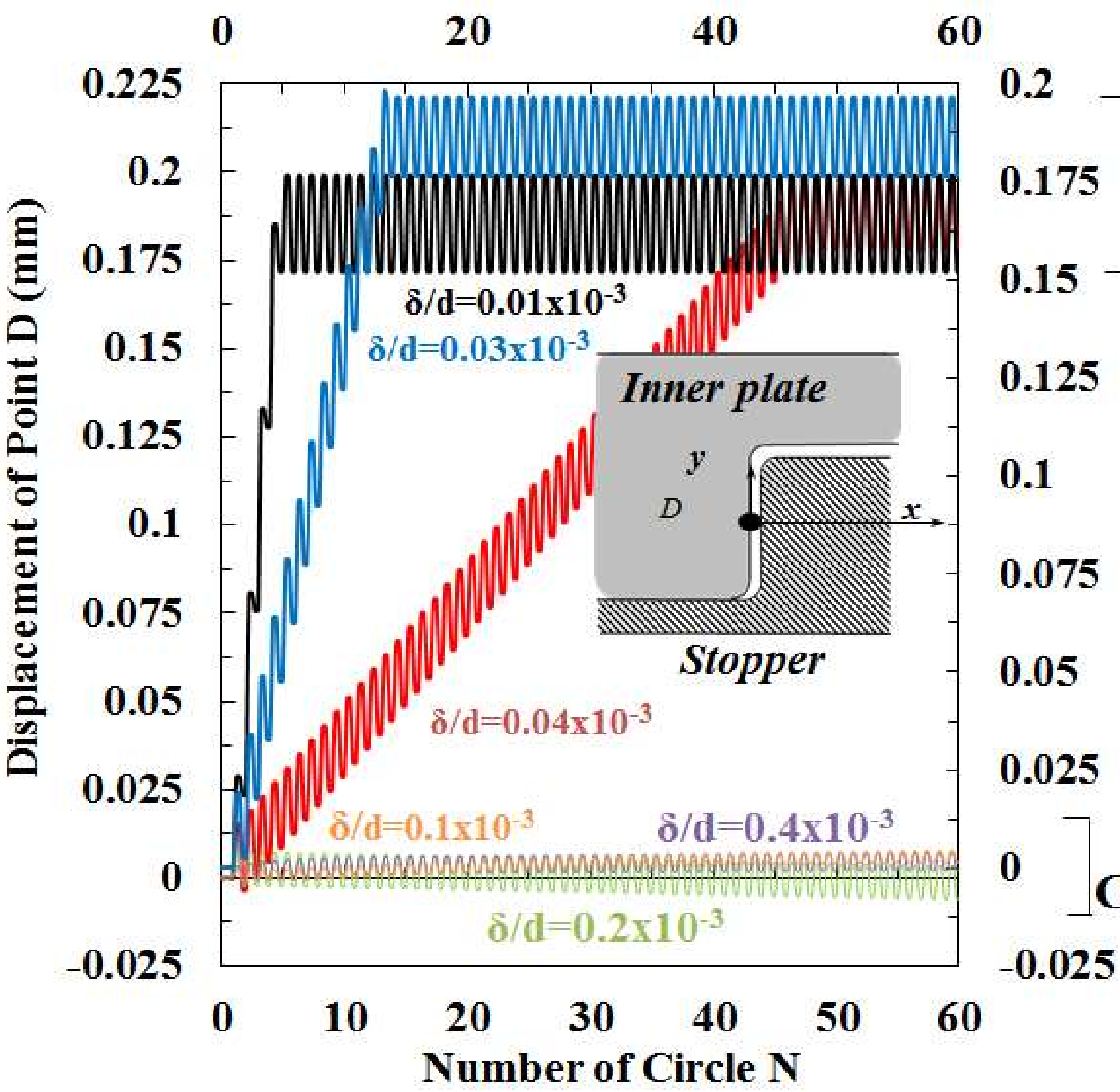


Example:
$\delta/d = 0.2 \times 10^{-3}$
$P = 1000\text{N}$
$\mu = 0.3$

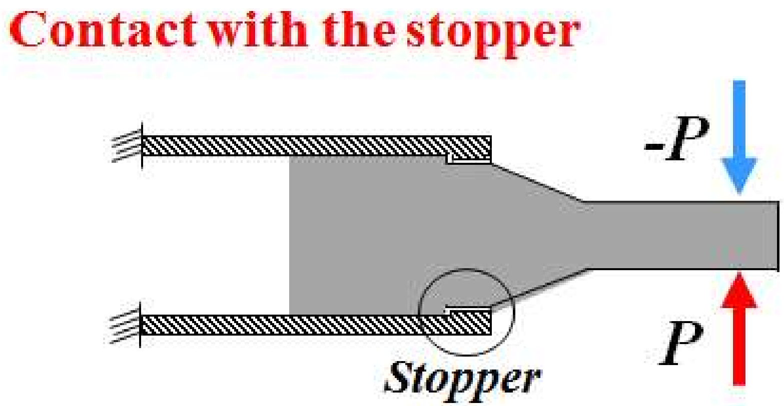
$$F_d = F_s = F_\tau^{up} + F_\tau^{down}$$

$$\boxed{F_\tau^{up} + F_\tau^{down} > 0 \ \text{(Coming out)}}$$

Simulation of coming out



Effect of δ/d

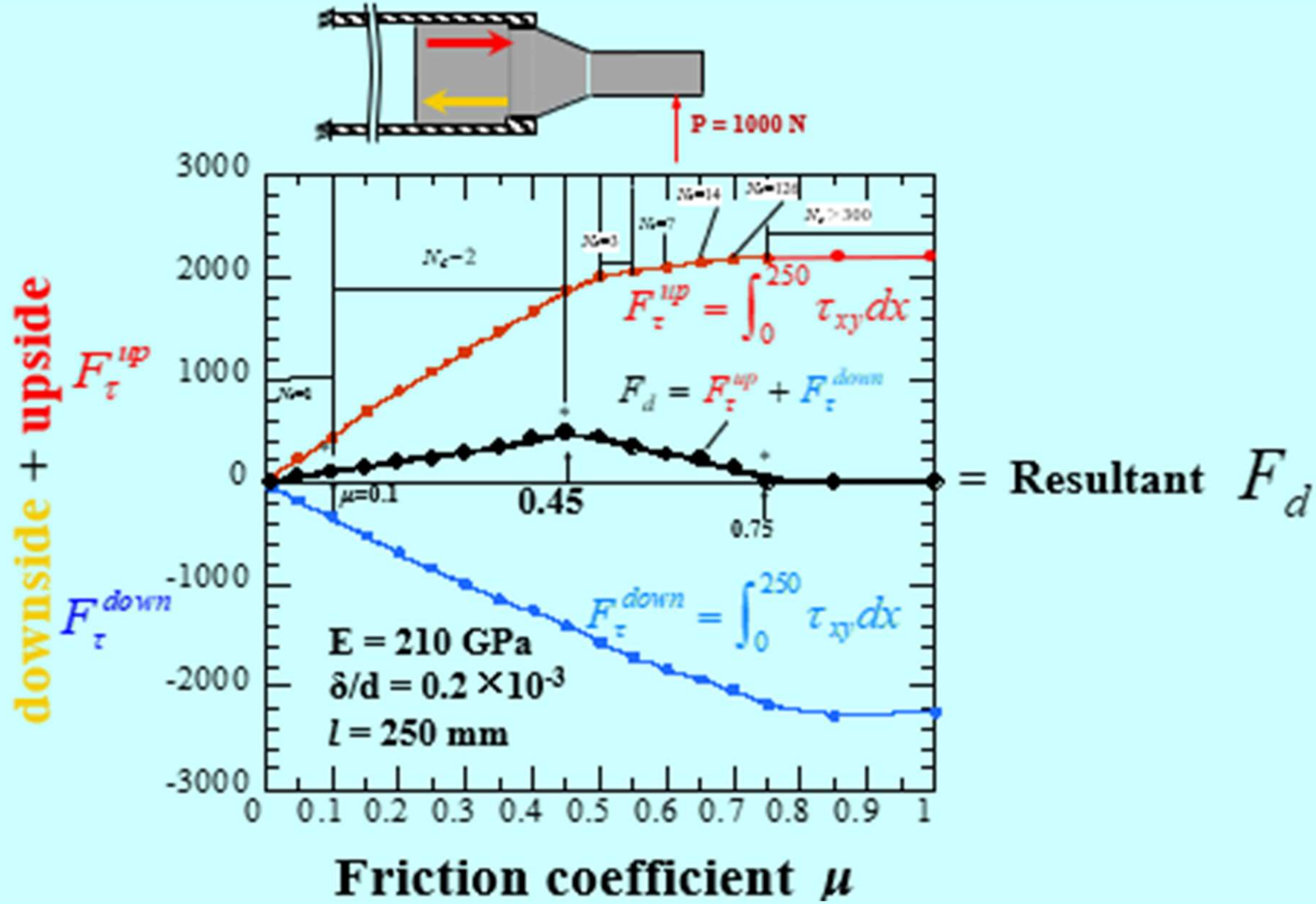


$\delta/d = 0.01 \sim 0.4 \times 10^{-3}$

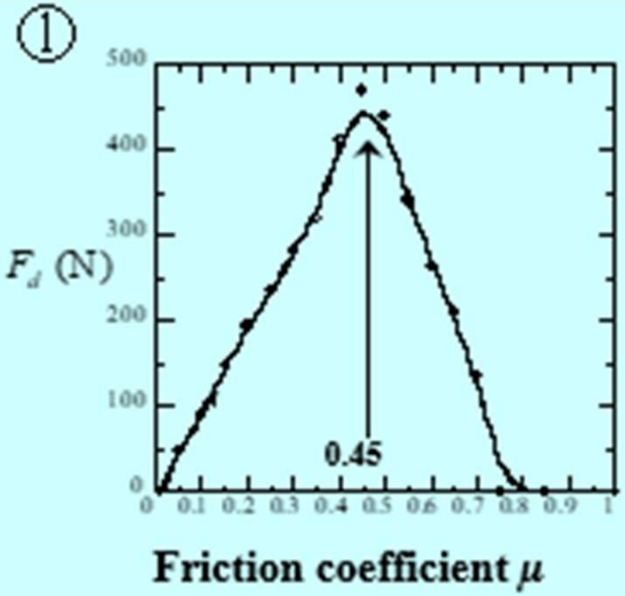
P = 150N (Constant)

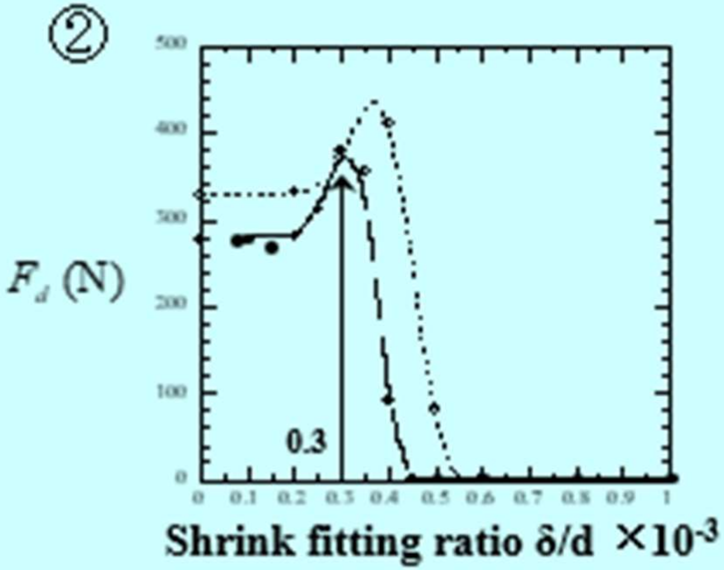
μ = 0.3 (Constant)

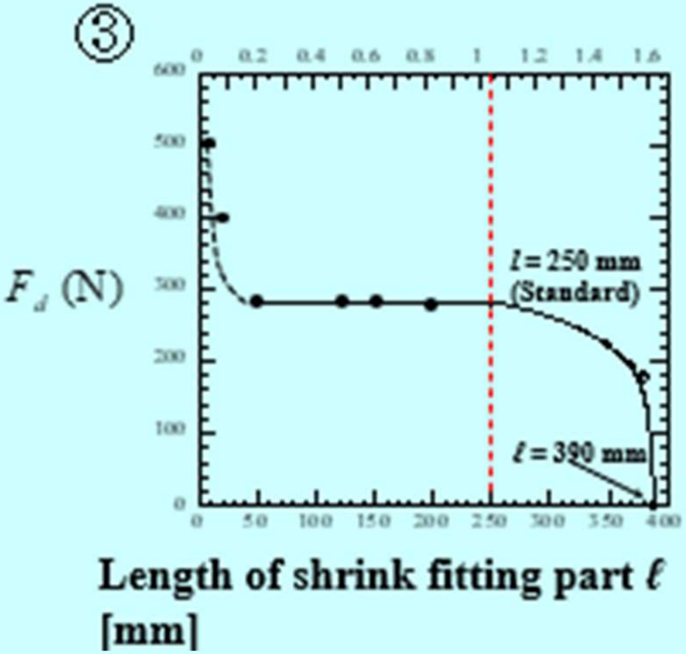
Effect of Friction coefficient μ on the Driving out force F_d

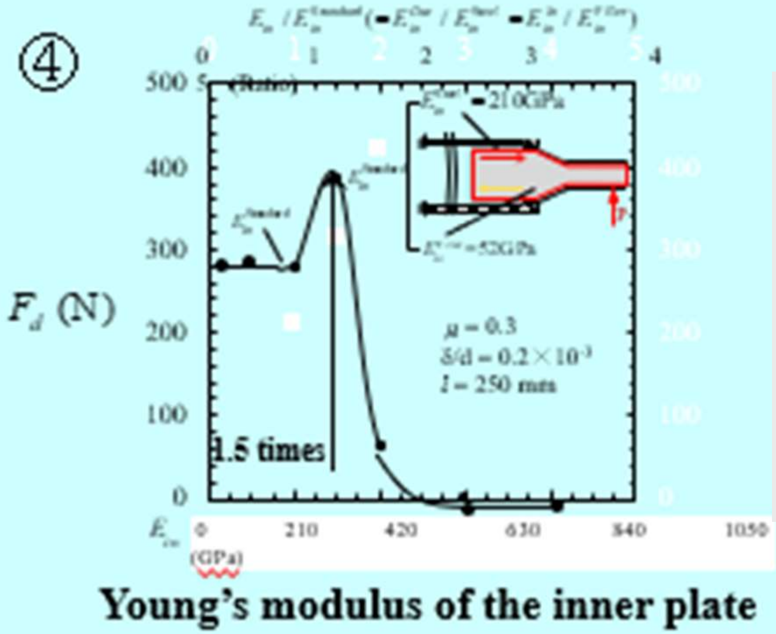


Effects of Several Design Factors on the Driving out Force









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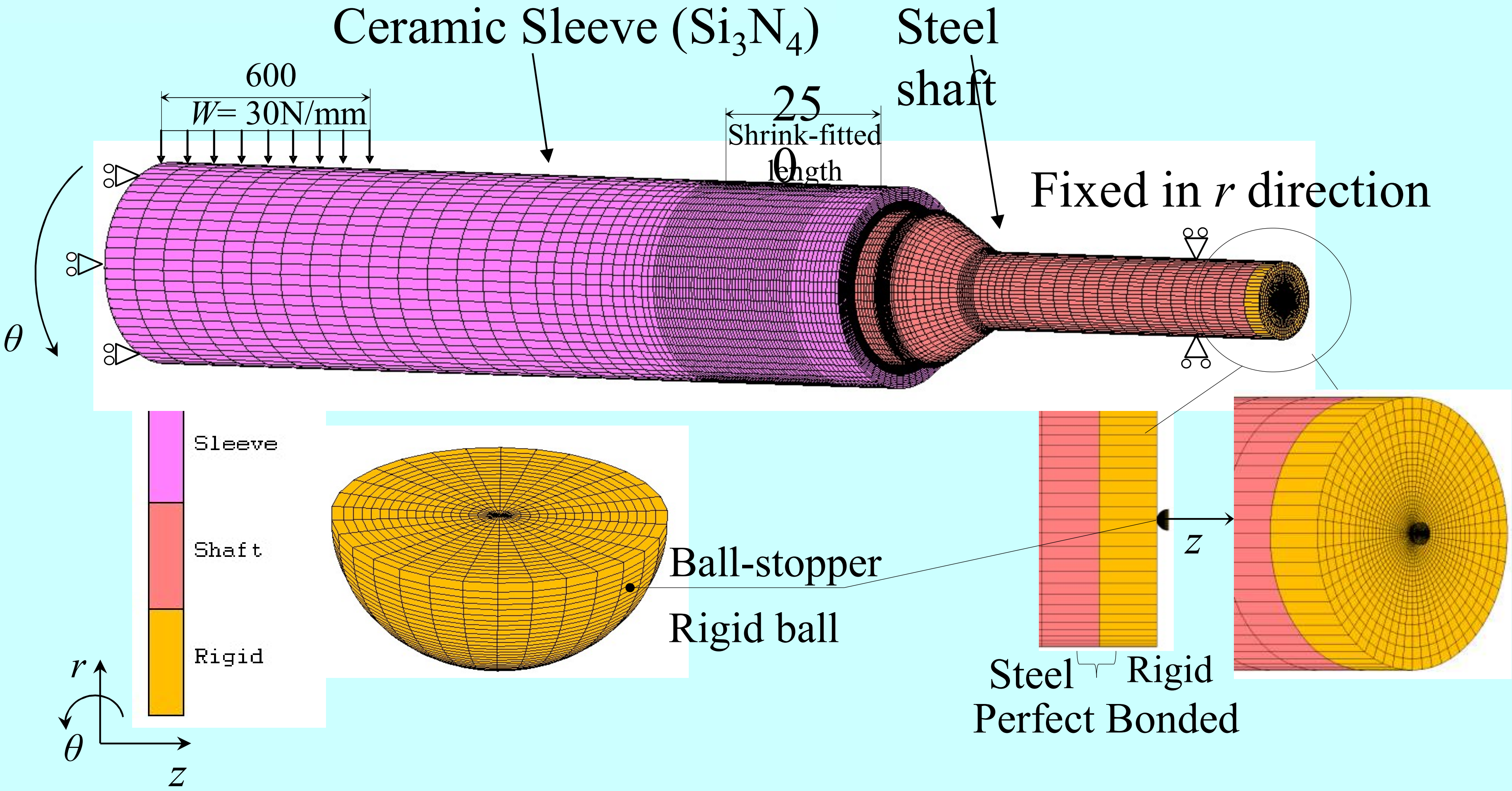
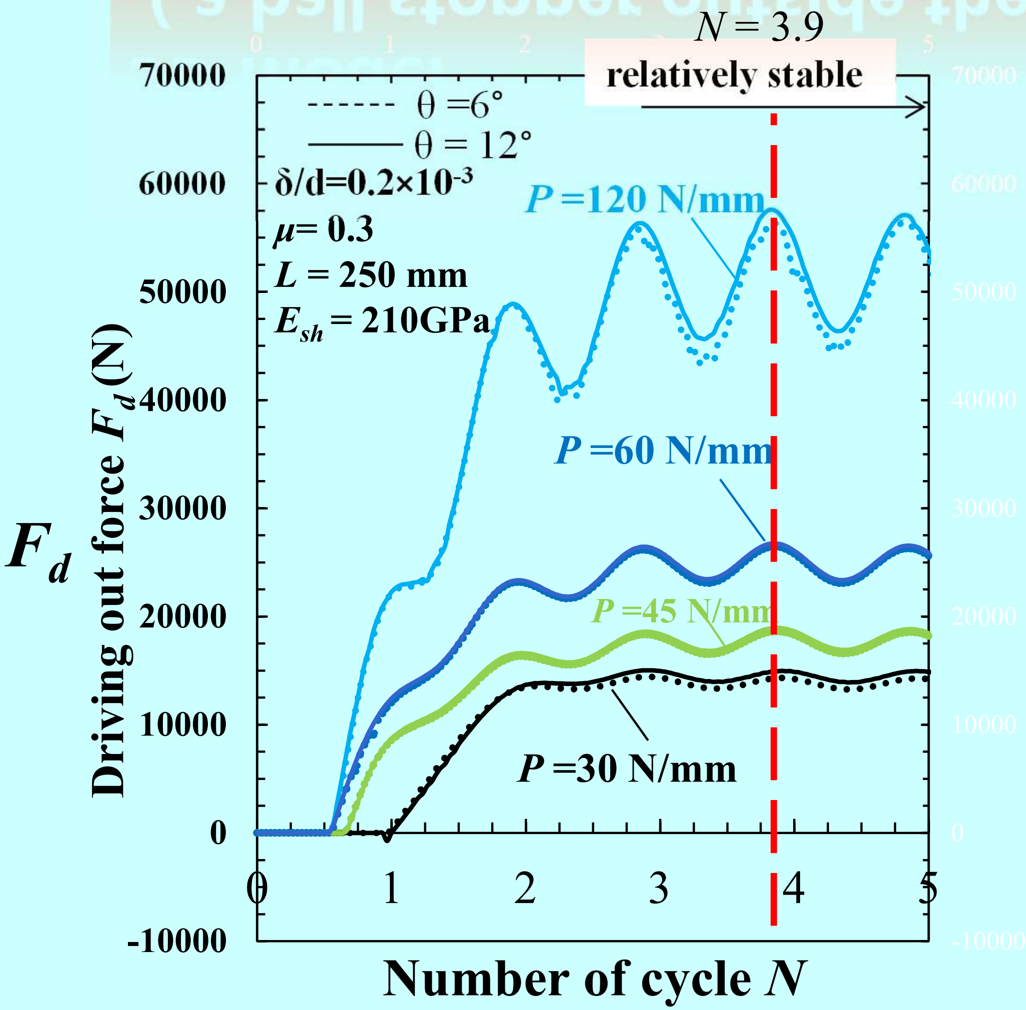
Driving Out Force in 3D model

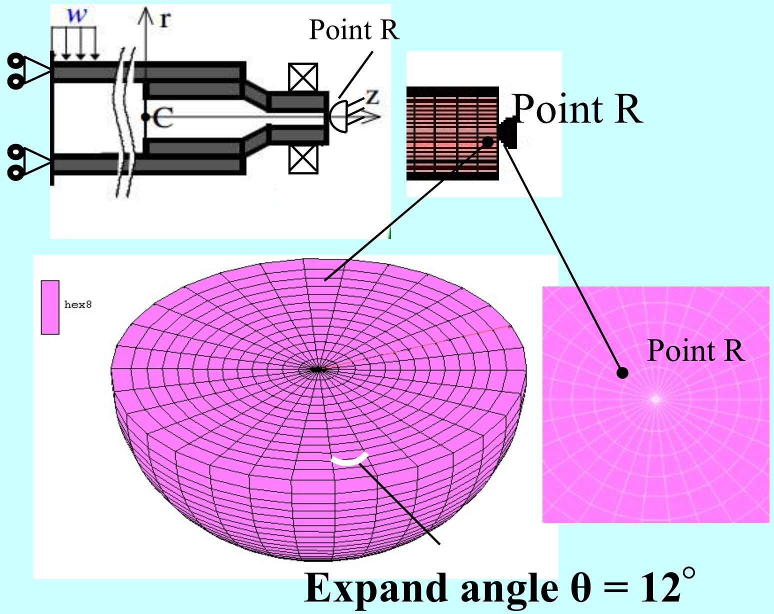


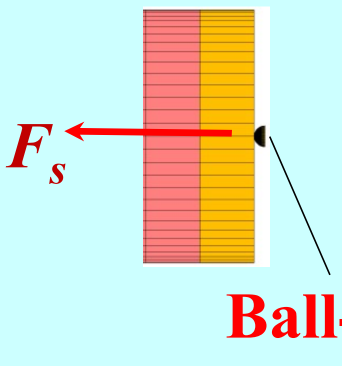
New FEM model (half) with the Ball-stopper (3D)

Driving out Force in 3D model



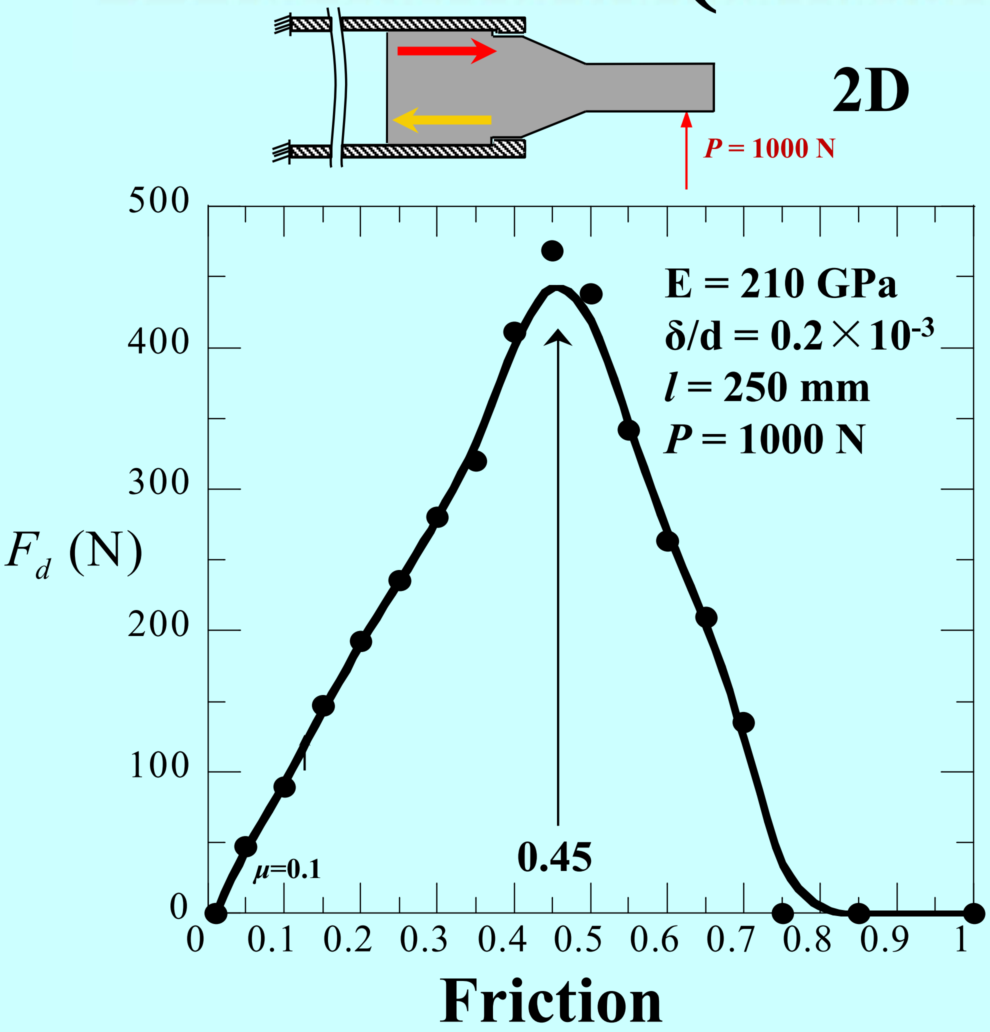
$N = 1$ is equivalent to the roller rotates 1 circle

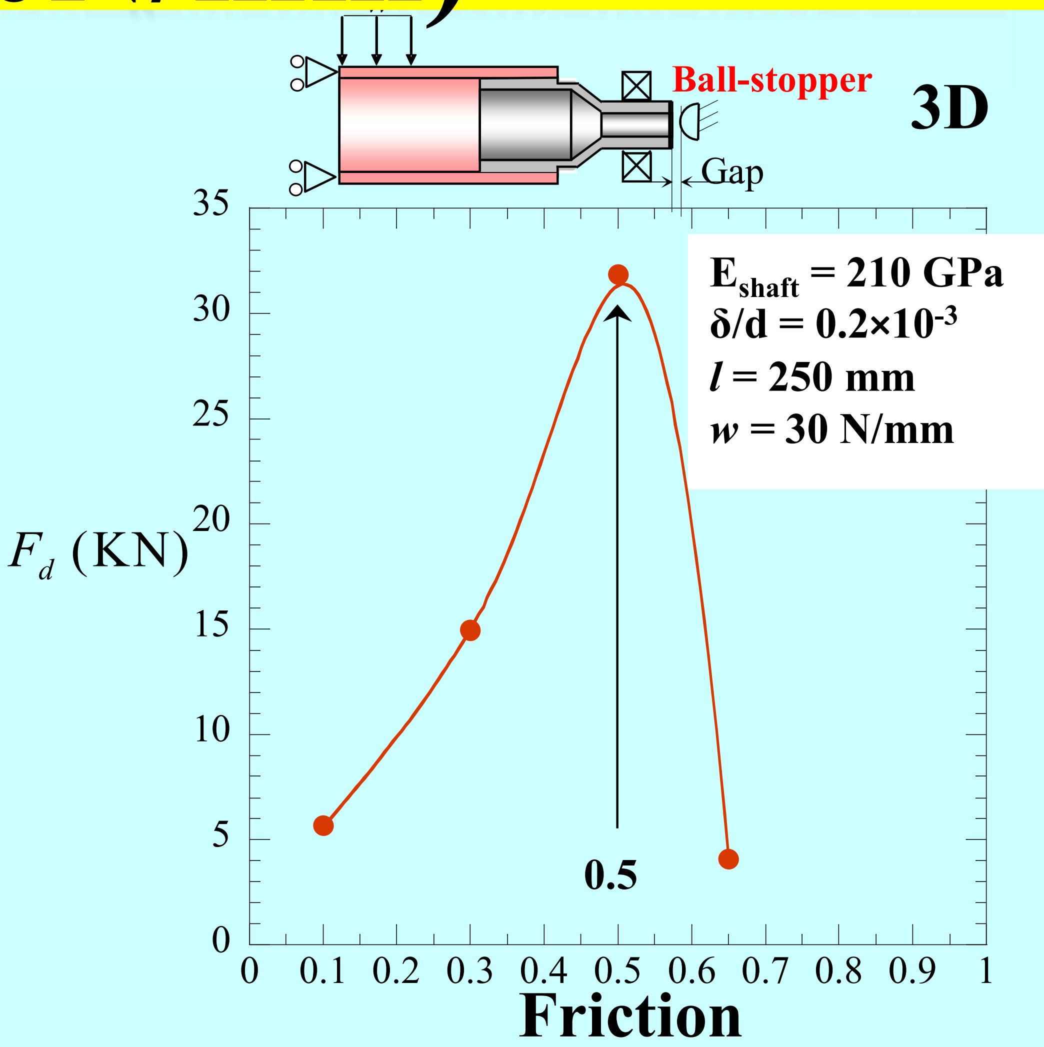




$$F_d = F_s \, (F_s \text{ after stable })$$

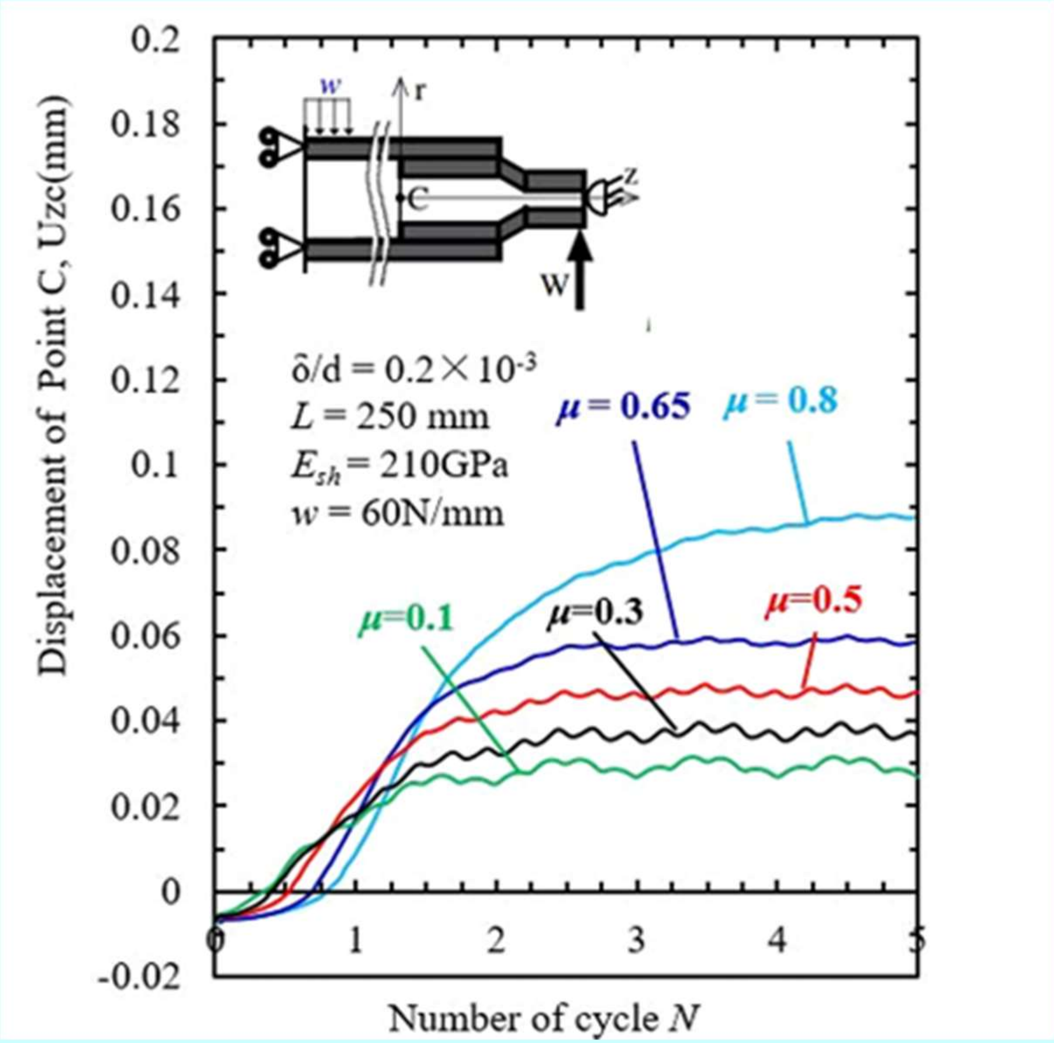
2D model vs. 3D model (w=30N/mm)





Similar tendencies are obtained from 2D model and 3D model

Driving Force in 3D model (w=60N/mm)



Conclusions: Coming out Analysis

1. The 3D driving out force F_d^{3D} is in the range of F_d^{3D}=26.3kN~35kN. when $\mu = 0.3$, $\delta/d = 0.1 \times 10^{-3}$~$\delta/d = 0.4 \times 10^{-3}$, L = 150~350mm, $E_{sh} = 150$~400GPa.

2. The effects of the design factors such as friction coefficient μ, engagement length L, and shrink fit ratio δ/d on the driving out force are investigated.

Contributors

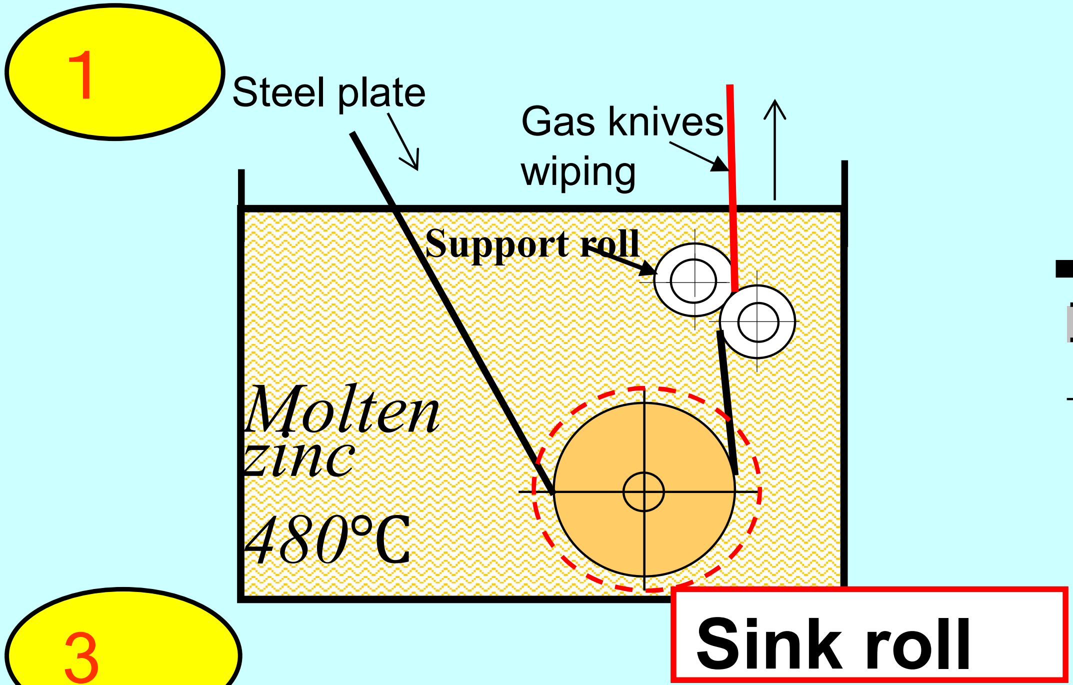
1) Thermal Stress Analysis for Ceramics Rolls with Shrink Fitting System Dipped into Molten Metal (Dr Hendra, Dr D.Suryadi)

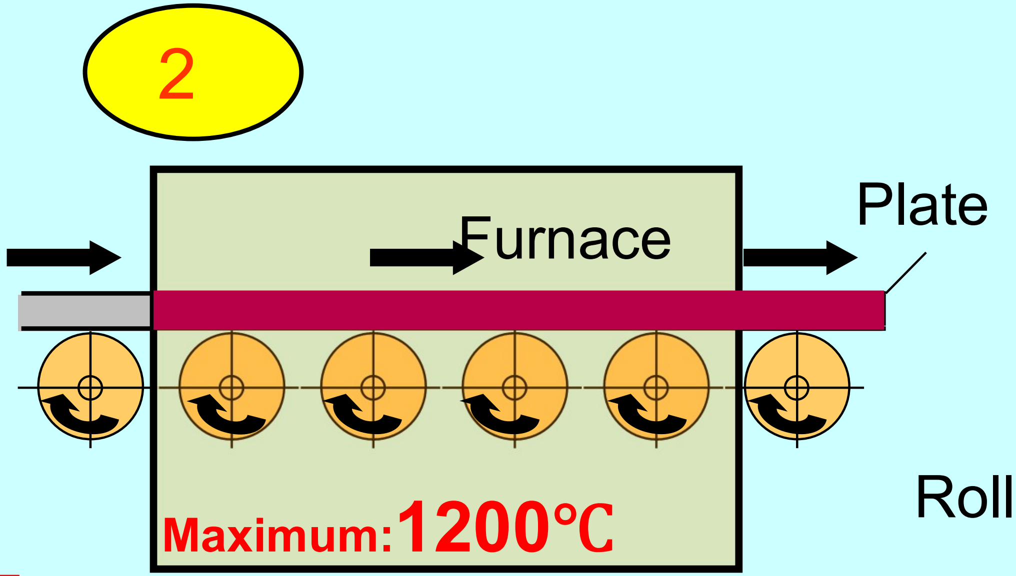
2) Static Strength and Fatigue Strength Analysis for Shrink Fitting System Used for Ceramics Rolls in the Continuous Pickling Line (Dr H.Sakai)

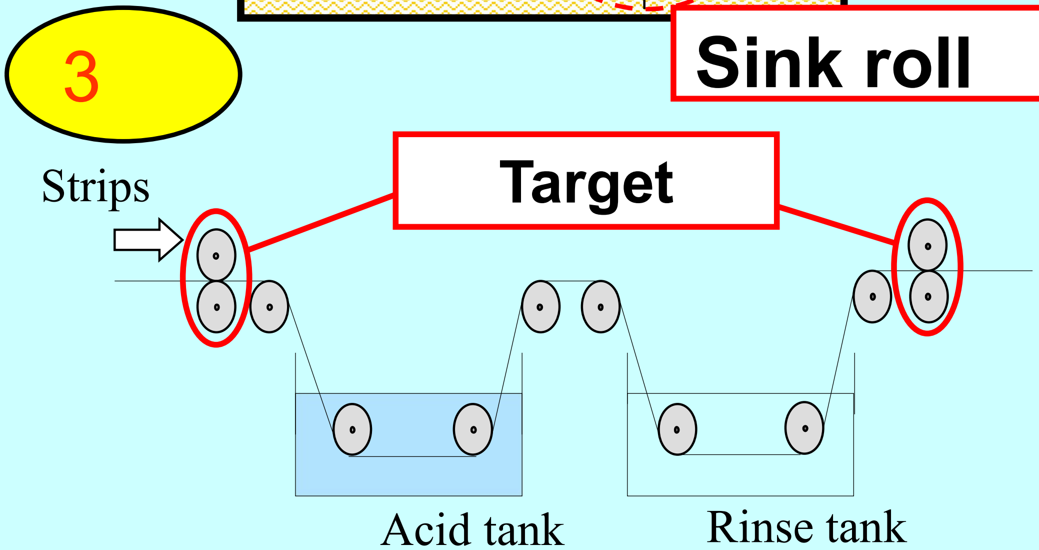
3) Analysis of Separation Conditions for Shrink Fitting System Used for Ceramics Conveying Rollers (Dr W.Li)

4) Analysis of Coming out of the Shaft due to Small Shrink Fitting Ratio (Dr G.Zhang)

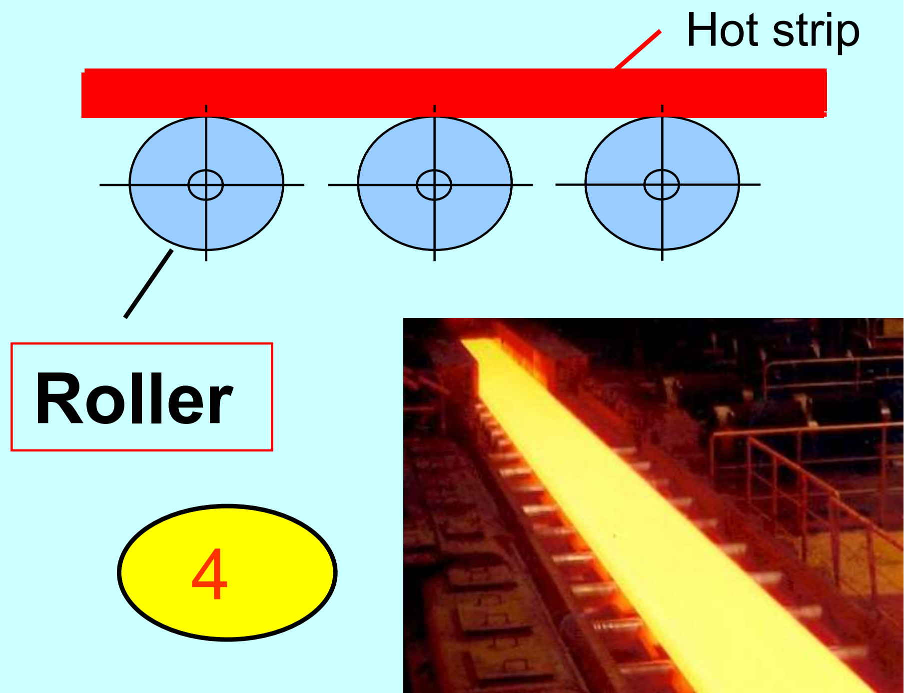
Application of ceramics rolls to steel manufacturing industries







Continuous Picking Line



Thank you for your attention

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