Basic 3
Micro-Fabrication Methodology
– Machining with machine tools –

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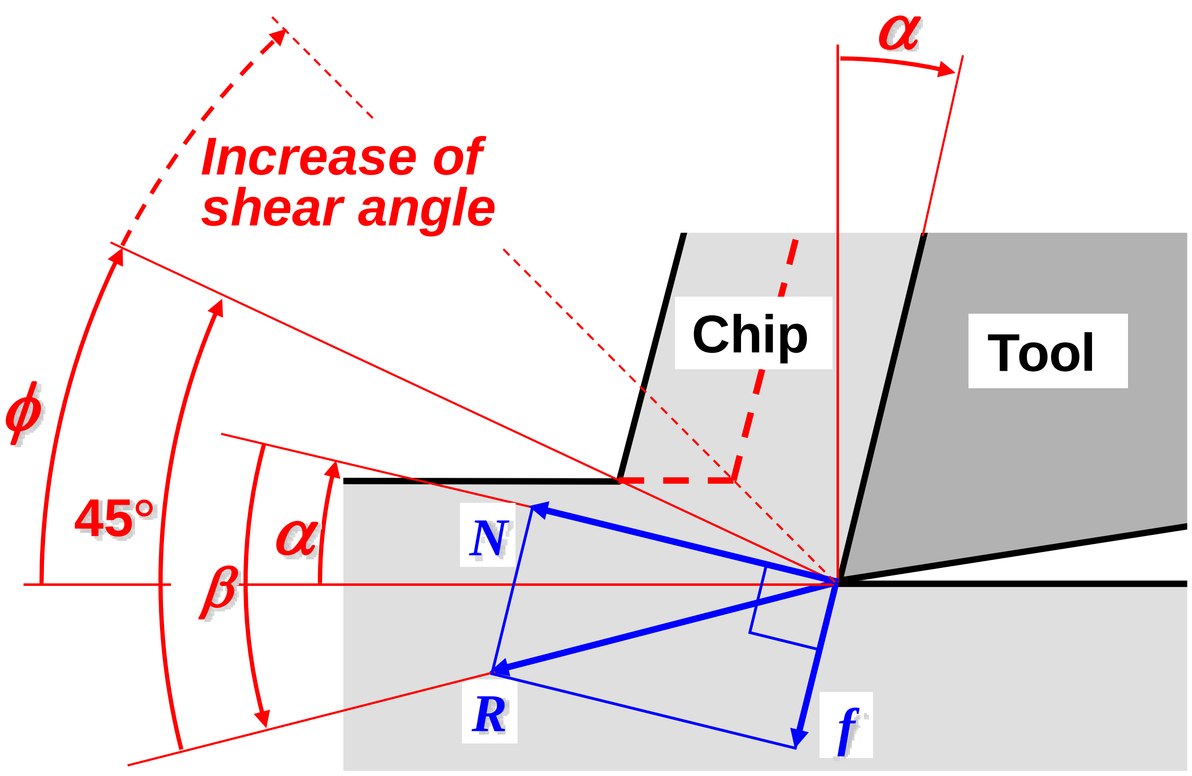
Contents;
- *Oblique cutting mechanics*
- *Chatter vibration in ball end milling process*
- *Ultraprecision/micro elliptical vibration cutting*

Oblique cutting mechanics

- Eiji Shamoto and Yusuf Altintas: Prediction of Shear Angle in Oblique Cutting with Maximum Shear Stress and Minimum Energy Principles, Trans. ASME Journal of Manufacturing Science and Engineering, Vol.121 (1999) pp.399-407
- Eiji Shamoto: Study on Three Dimensional Cutting Mechanics (1st Report)- Comprehension and Vector Formulation of Oblique Cutting Process, J. of JSPE, Vol.68, No.3, (2002) pp.408-414

Orthogonal Cutting Mechanics



* Increase of rake angle
* Decrease of friction

Why ?

* Low force,
* Low power,
* Small damage,
etc.

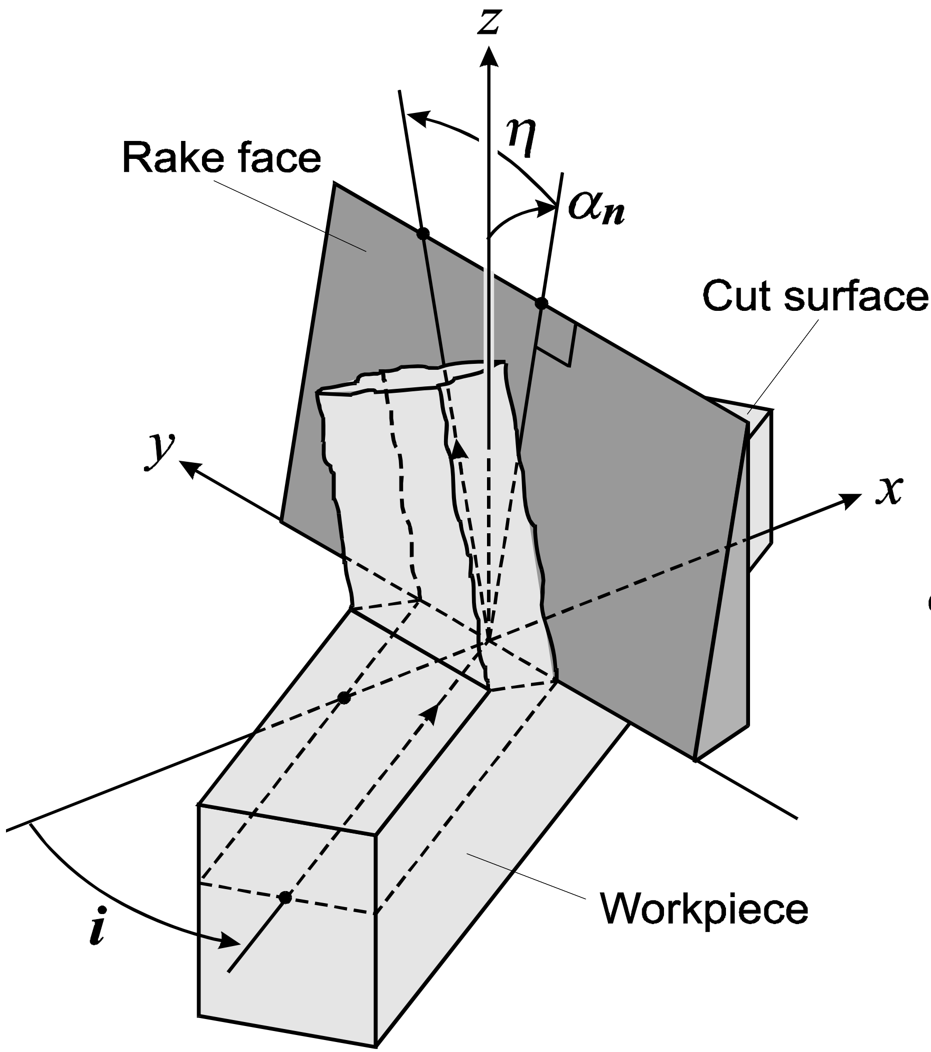
- ***Maximum shear stress*** **principle**
  Krystof (1939), Lee & Shaffer (1951)

$$\phi = 45° - \beta + \alpha$$

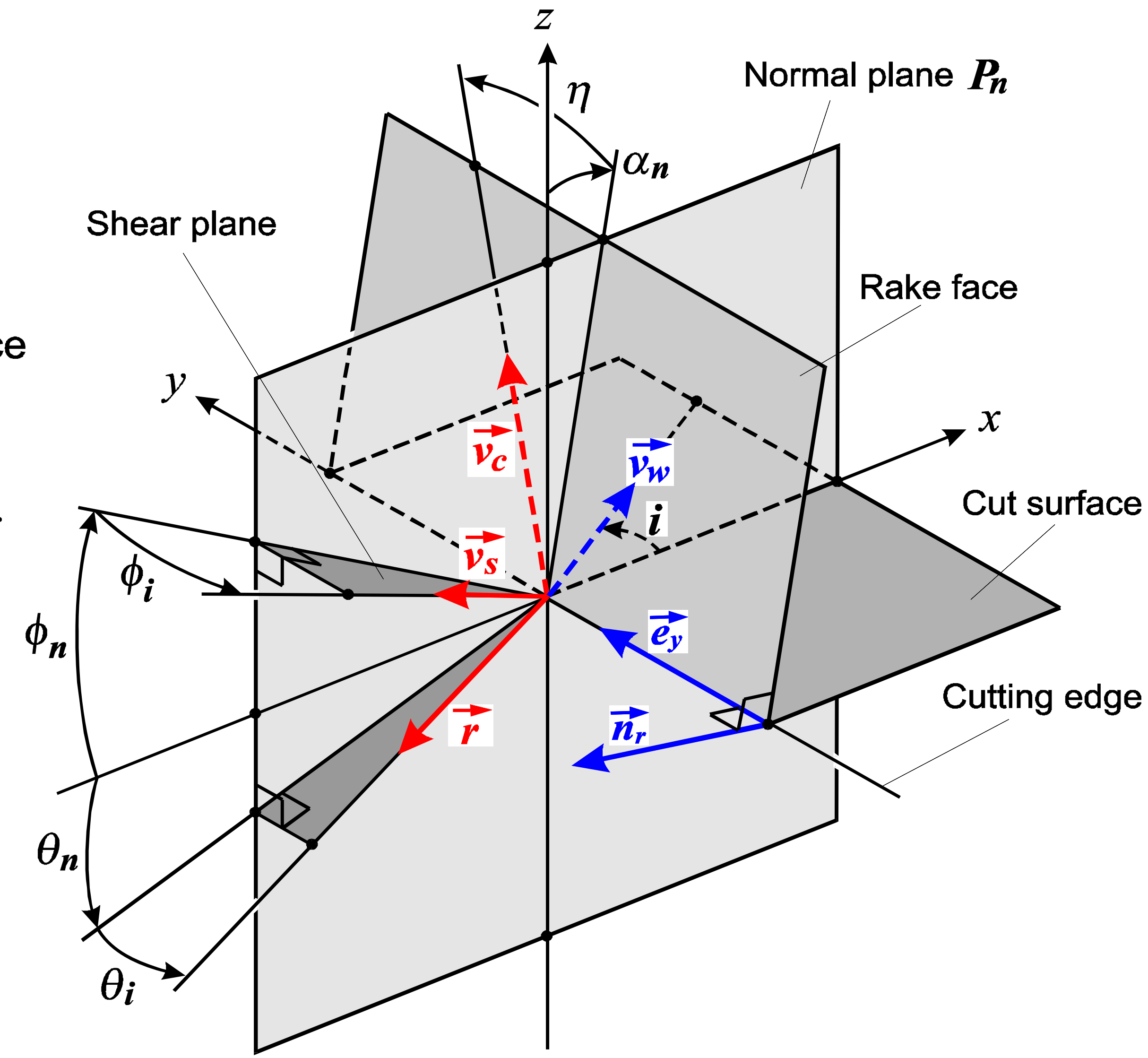
- ***Minimum energy*** **principle**
  Merchant (1945)

$$\phi = 45° - \beta \times 2 + \alpha \times 2$$

Oblique Cutting Process and Parameters



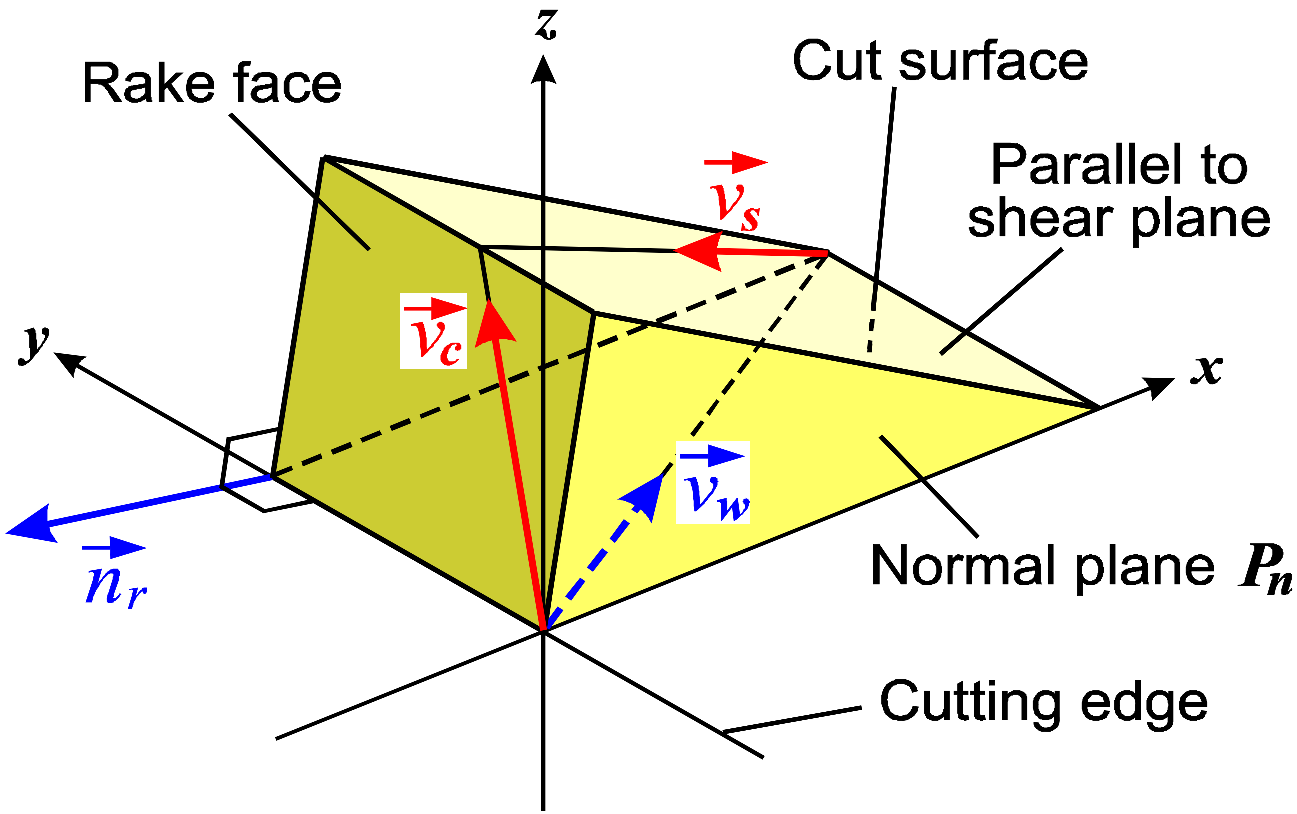
Oblique cutting process



Oblique cutting parameters

Unknown vectors: v_s, v_c, r

Velocity Relation (Merchant, 1944)



Shear direction $\vec{v}_s$ →

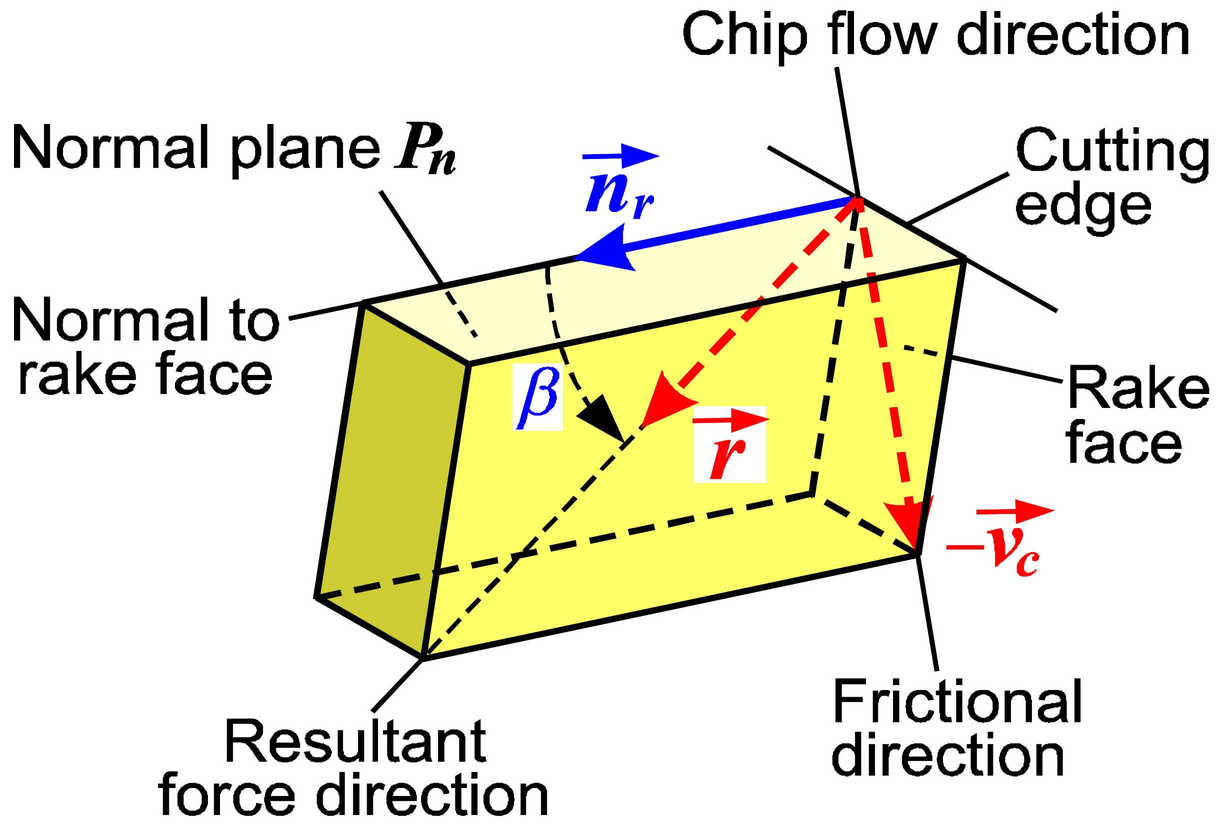
$$\vec{v}_{tmp} = (\vec{v}_s \cdot \vec{n}_r)\,\vec{v}_w - (\vec{v}_w \cdot \vec{n}_r)\,\vec{v}_s$$

$$\vec{v}_c = \vec{v}_{tmp} \big/ \left|\vec{v}_{tmp}\right| \qquad \textbf{(1)}$$

→ **Chip flow direction** $\vec{v}_c$

Knowns $\vec{v}_w$ ↑ $\vec{n}_r$ ↑

Force Relation (Stabler, 1951)



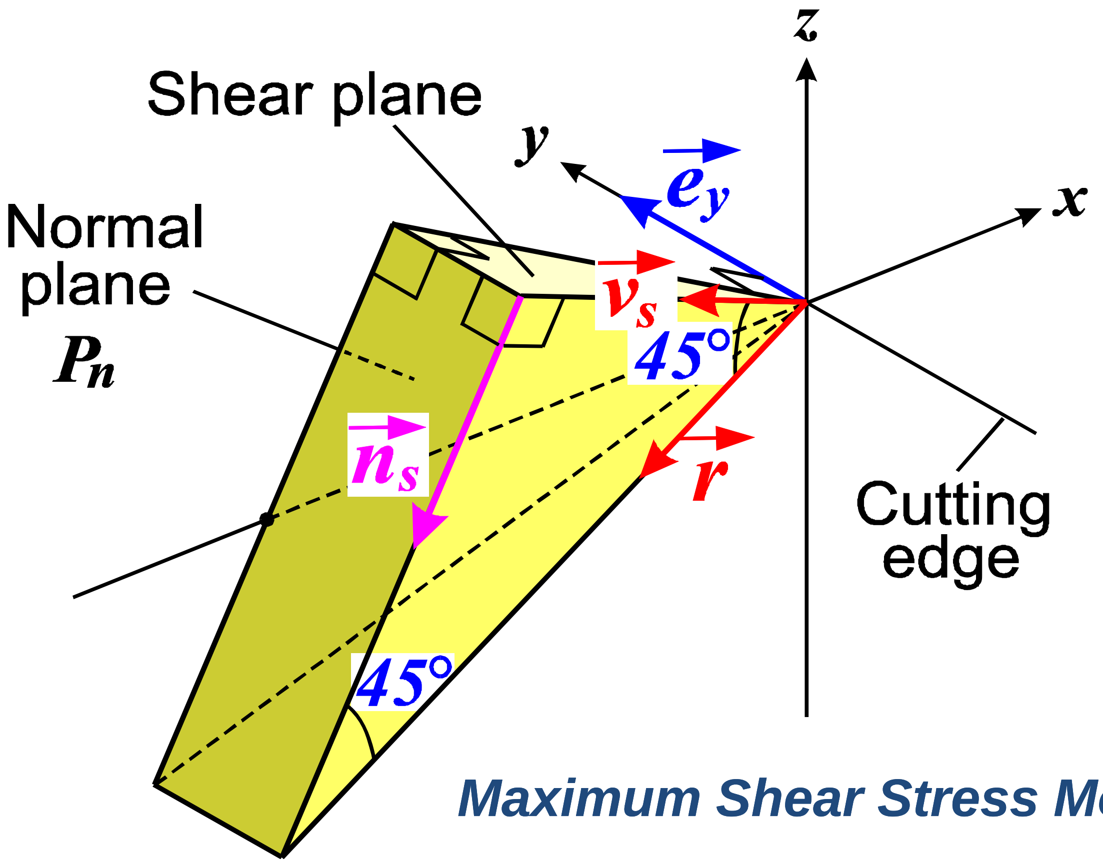
Chip flow direction → $\vec{v}_c$

$$\vec{r} = \vec{n}_r \cos\beta - \vec{v}_c \sin\beta \quad (2)$$

→ Resultant force direction $\vec{r}$

Knowns $\vec{n}_r$ β

Proposed Methods to Predict Shear Direction



Maximum Shear Stress Model

Resultant force direction $\vec{r}$ →

1. Maximum shear stress

$$\vec{r} = (\vec{v}_s + \vec{n}_s)\cos 45° \quad \textbf{(3)}$$

where $\vec{n}_s = (\vec{v}_s \times \vec{e}_y) / |\vec{v}_s \times \vec{e}_y|$

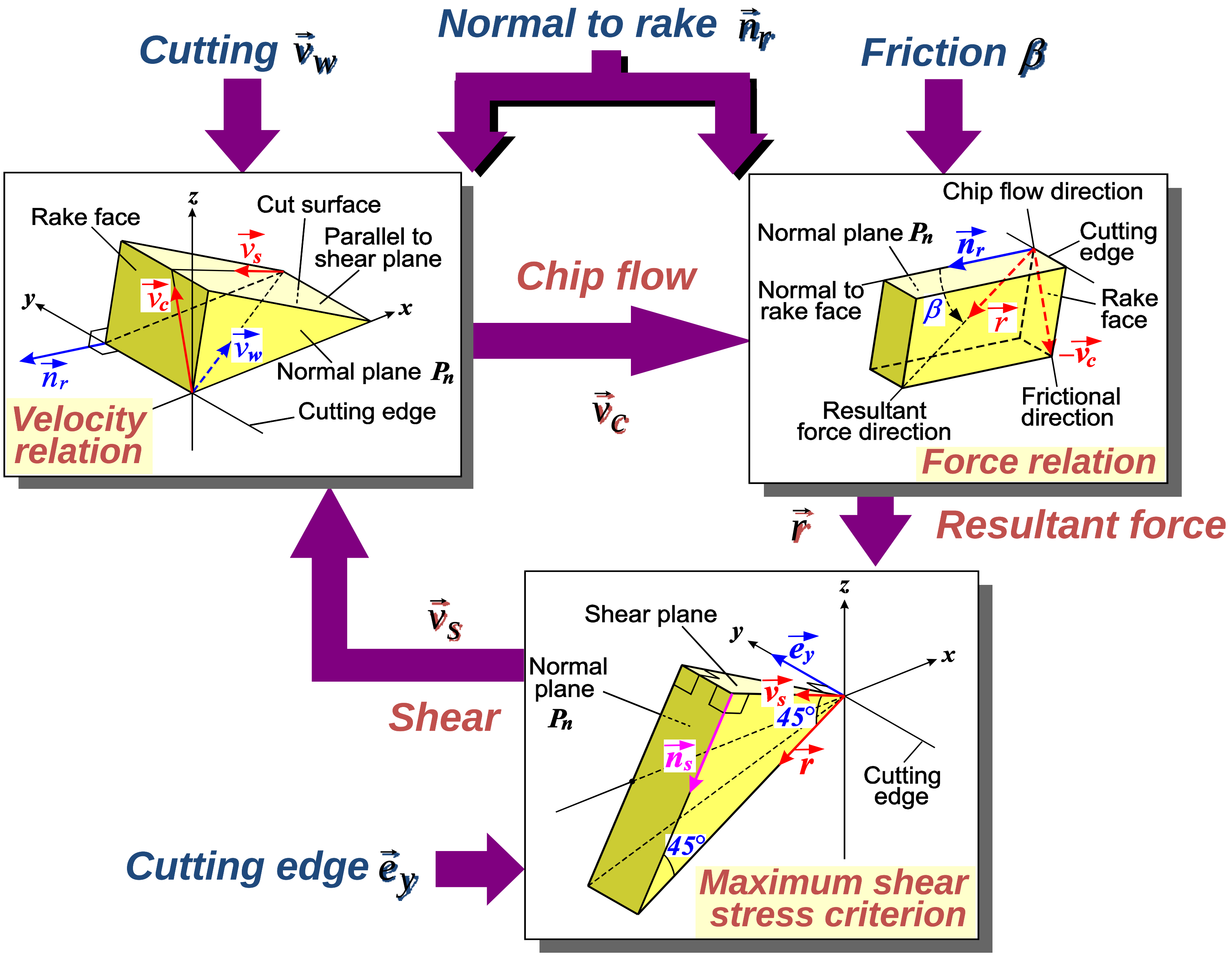
2. Minimum energy

$$dU(\vec{v}_s) = 0 \quad \textbf{(4)}$$

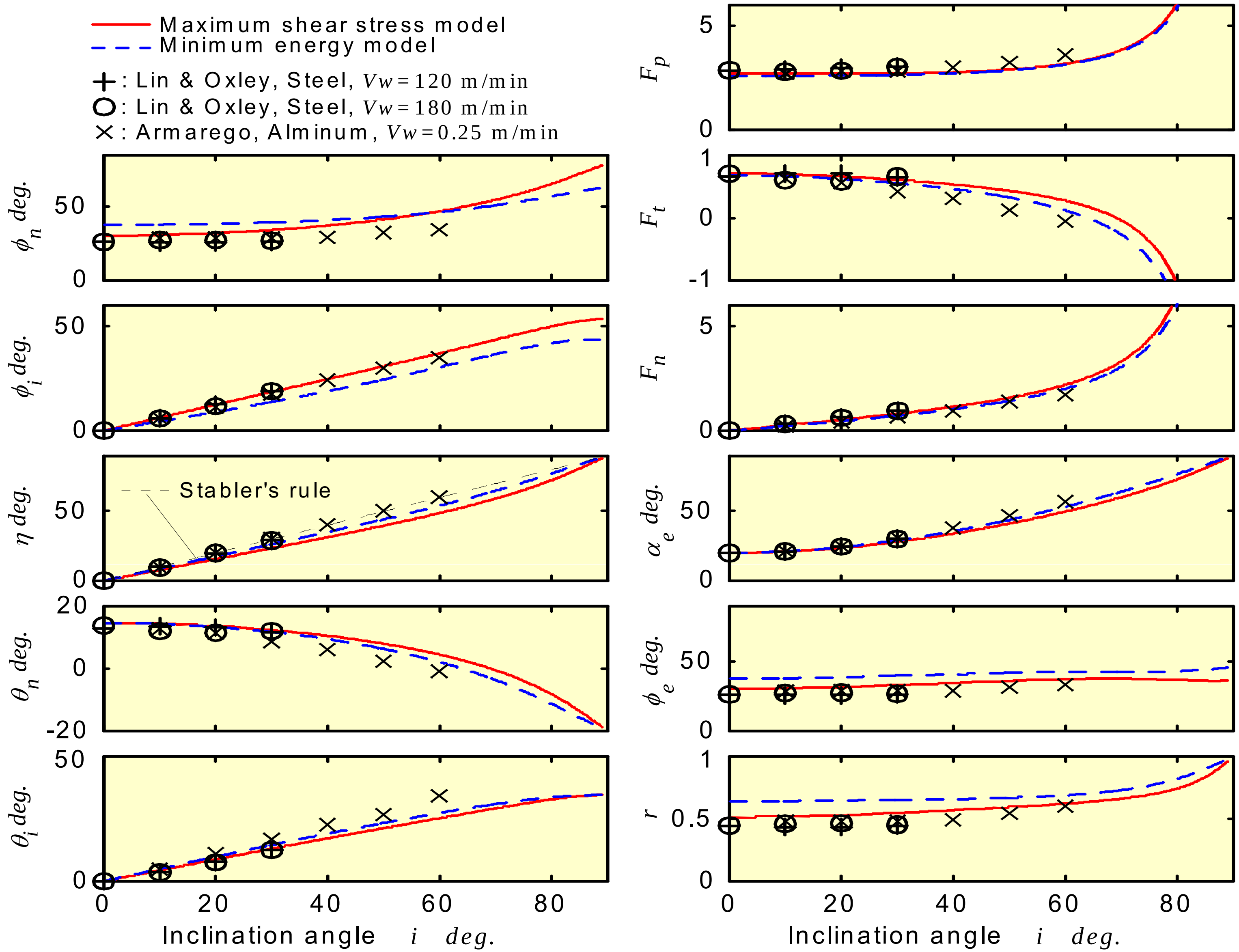
→ **Shear direction** $\vec{v}_s$

$\vec{e}_y$ ↑ **Known**

Relations among Parameters in Oblique Cutting

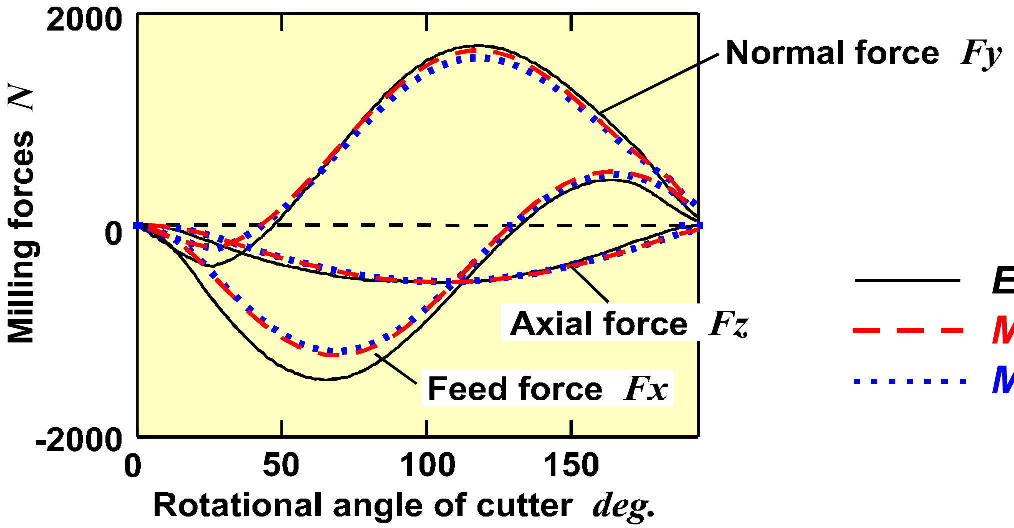


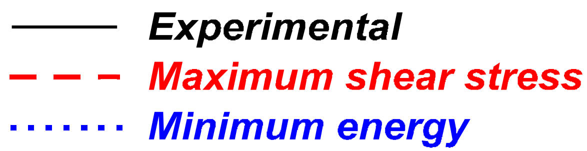
Results of Oblique Cutting Simulations



α_n=20°, β=34.6°. Lin & Oxley's data: S1214 Steel, β=32.5-35.5°, h=0.5mm, b=5mm, Vw=120,180m/min.
Armarego's data: 60655-T6 Aluminum, β=33.5-40°, h=0.06-0.32mm, b=6.25mm, Vw=0.25m/min

Experimental and Simulated Milling Forces

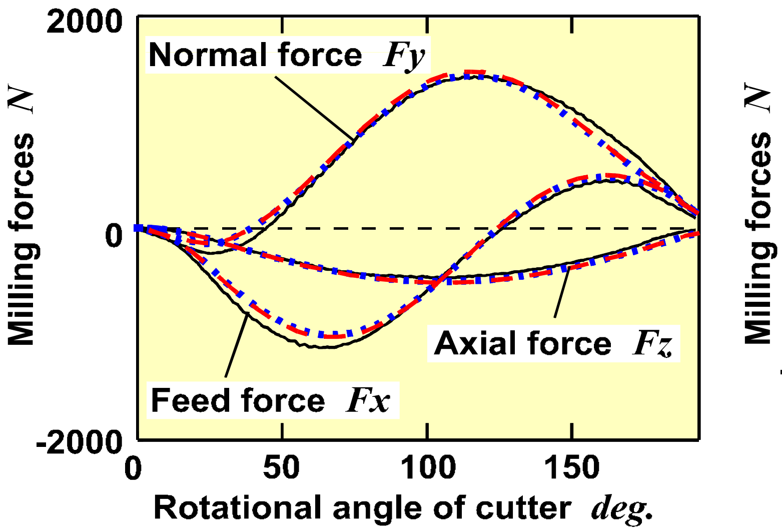




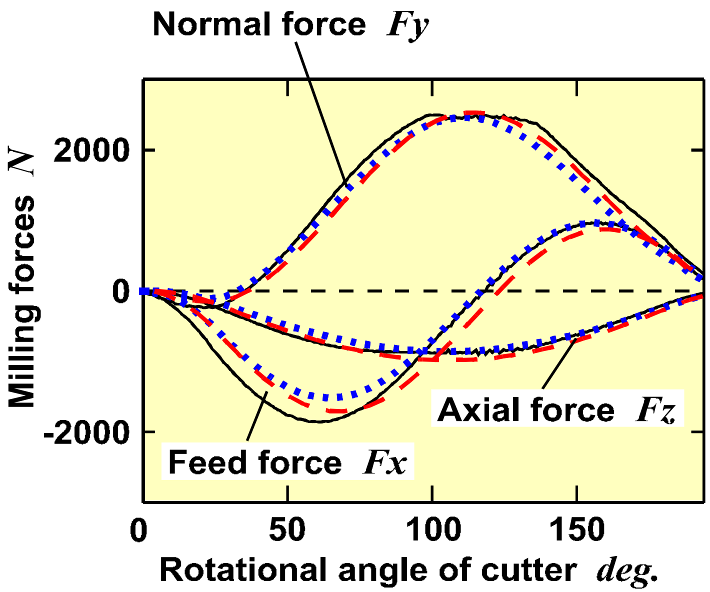
a) Rake angle: α_n=0 deg.,
Feed rate: 0.1016 mm/tooth.

[Conditions]

Single flute slotting, Work: Ti6Al4V, Axial depth: 7.62mm, Speed: 30m/min, Helix: 30 deg., ϕ19.05mm, τ=613Mpa, β=19.1+0.29α_n(deg.)



b) Rake angle: α_n=5 deg.,
Feed rate: 0.1016 mm/tooth.

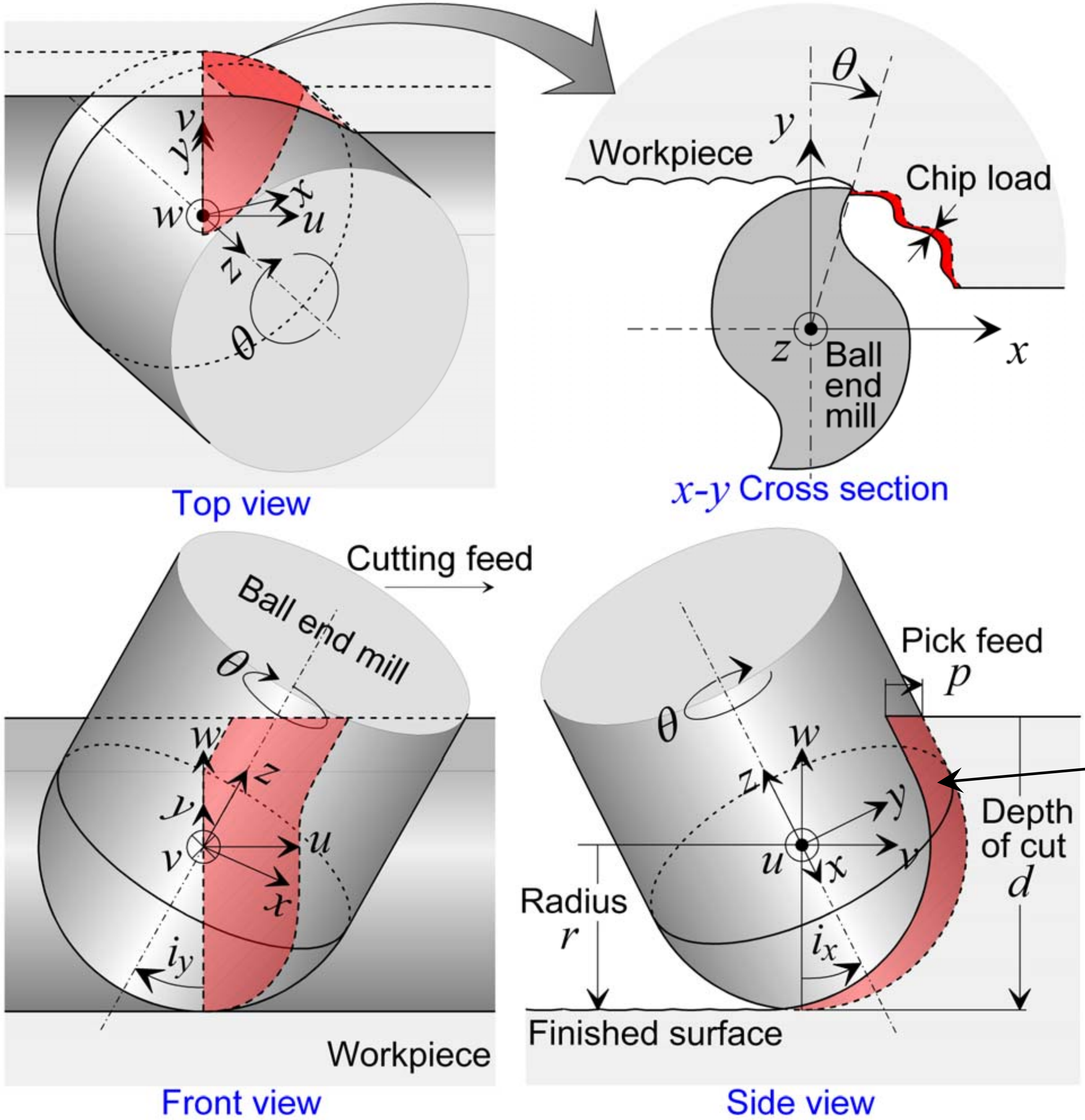


c) Rake angle: α_n=12 deg.,
Feed rate: 0.2032 mm/tooth.

Chatter vibration in ball end milling process

- E. Shamoto and K. Akazawa, Analytical prediction of chatter stability in ball end milling with tool inclination, CIRP Annals – Manufacturing Technology, Vol.58/1 (2009) pp.351-354
- Y. Altintas, E. Shamoto, P. Lee and E. Budak, Analytical Prediction of Stability Lobes in Ball End Milling, Trans. ASME J. Manuf. Sci. & Engg., Vol.121 (1999) pp.586-592

Ball End Milling with Tool Inclination



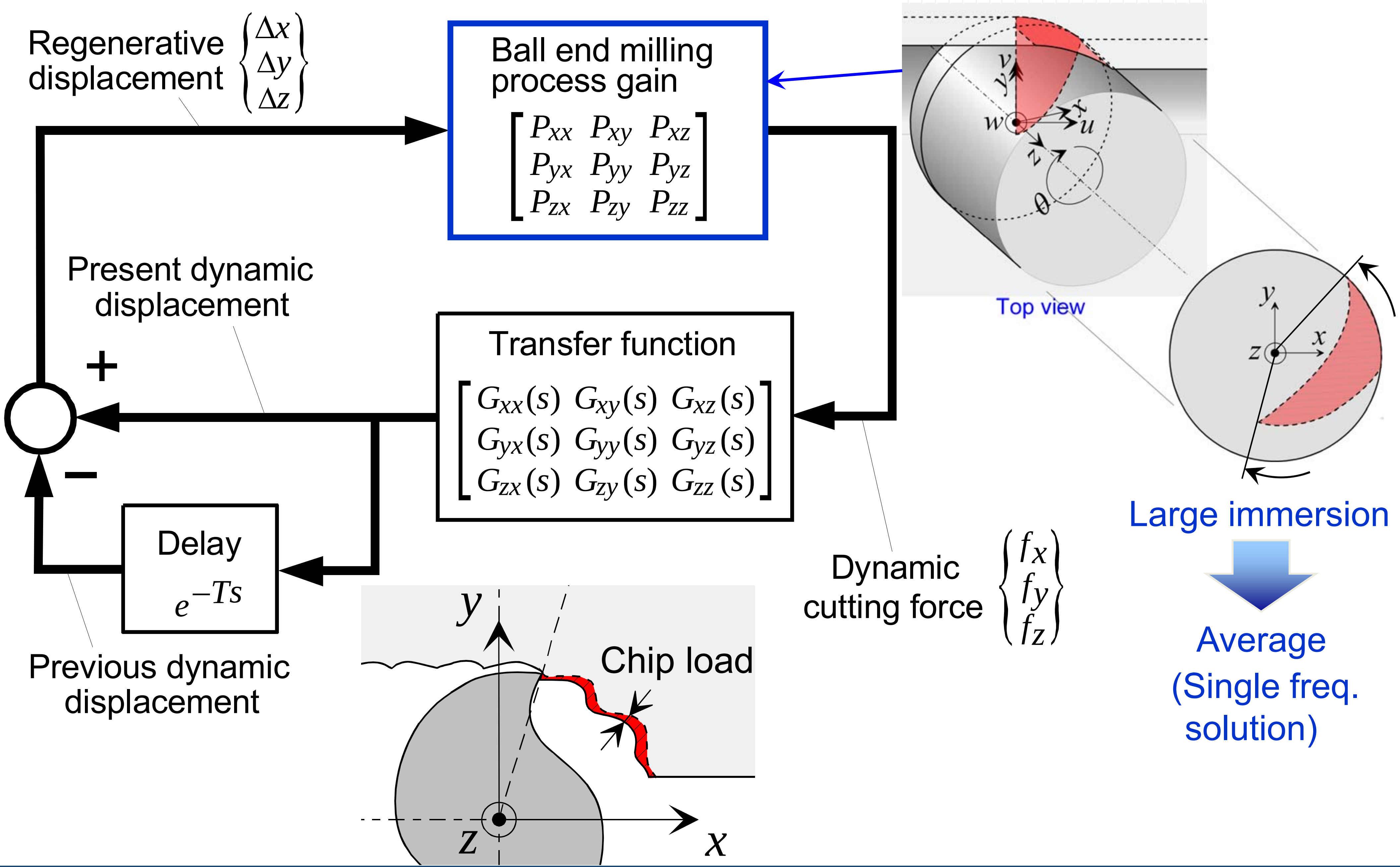
Tool coordinates: xyz
Work coordinates: uvw

Tool inclination:
i_x around x, then
i_y around y

Rotation axis: z
Cutting feed: u
Pick feed: v

Engagement region

Ball End Milling with Self-Excited Chatter Vibration



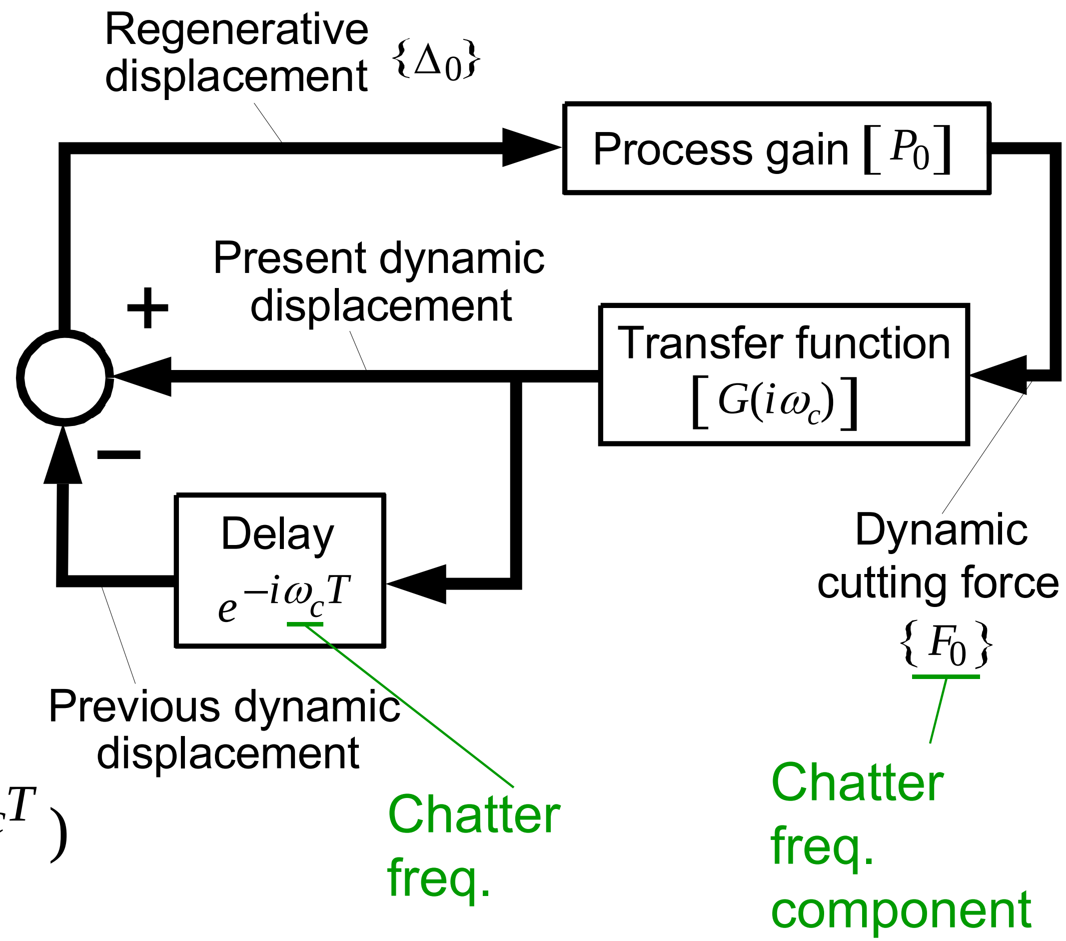
Solution of Chatter Stability

Closed loop relation

$$\{F_0\} = g_m \left(1 - e^{-i\omega_c T}\right)[P_0][G(i\omega_c)]\{F_0\}$$

Gain margin (g_m)

$$\begin{cases} g_m = 1 & \text{Critical} \\ g_m < 1 & \text{Unstable} \\ g_m > 1 & \text{Stable} \end{cases}$$



For non-trivial solutions

$$\det\left[[I] + \lambda[P_0][G(i\omega_c)]\right] = 0$$

where $\lambda = \lambda_r + i\lambda_i = -g_m(1 - e^{-i\omega_c T})$

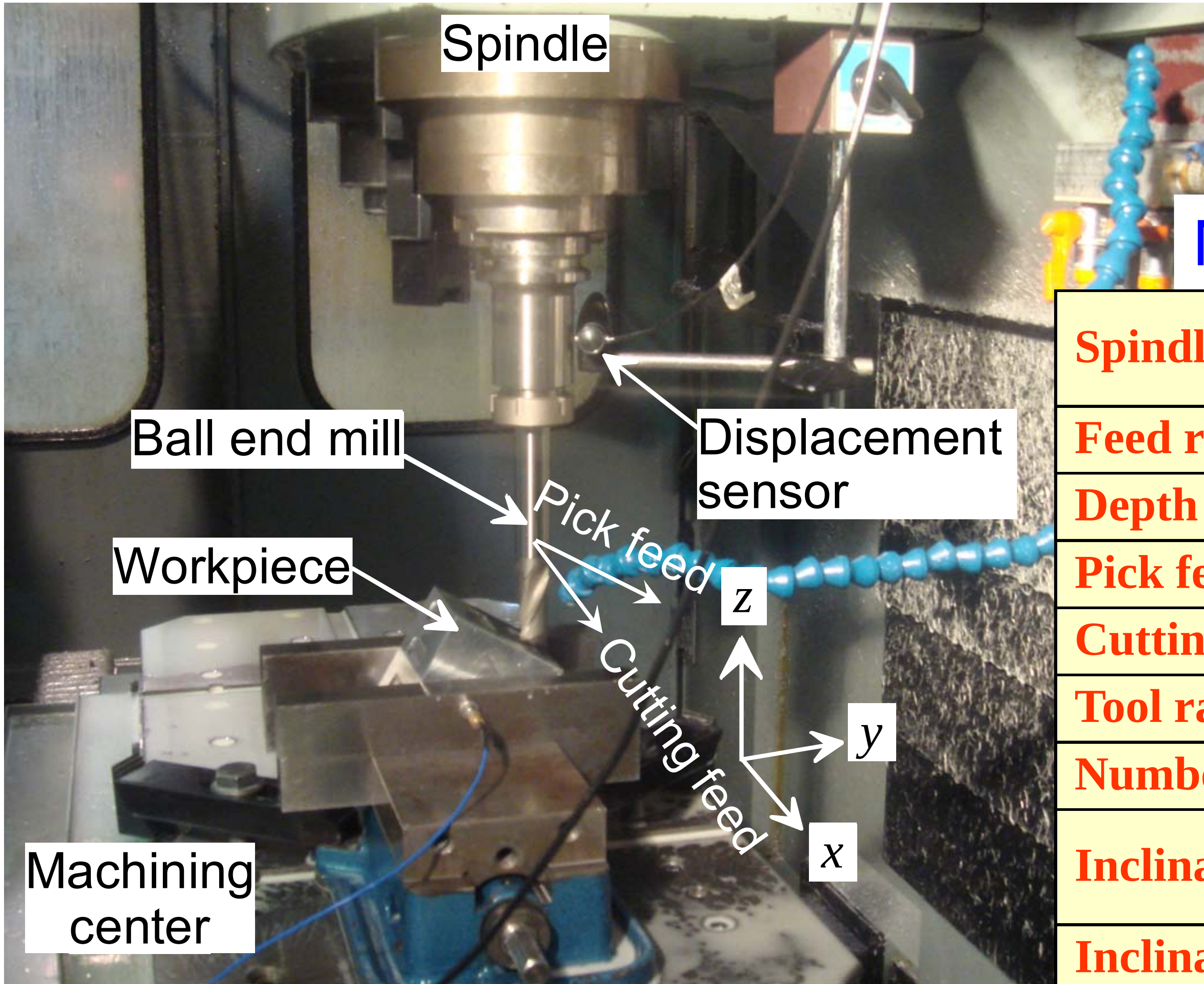
Solution of chatter stability

$$g_m = -\frac{\lambda_r}{2}\left\{1 + \left(\frac{\lambda_i}{\lambda_r}\right)^2\right\}, \quad \varepsilon = \pi - 2\tan^{-1}\frac{\lambda_i}{\lambda_r}, \quad n = \frac{60\omega_c}{n_f(2k\pi + \varepsilon)}$$

Phase shift (ε)

Spindle speed (n)

Experimental Conditions

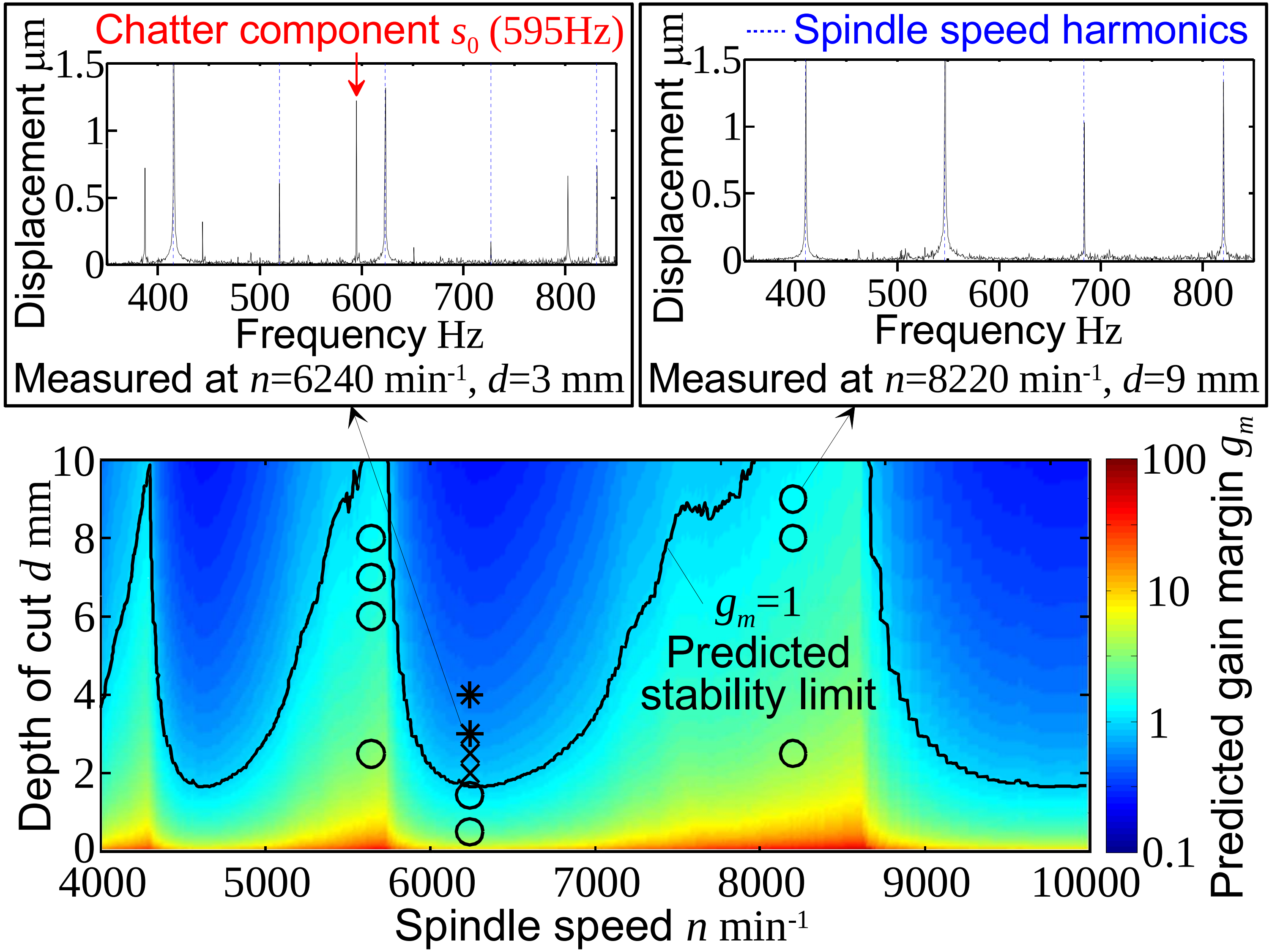


Experimental setup

Machining conditions

Spindle speed n min^{-1}	5640, 6240, 8220
Feed rate mm/tooth	0.01
Depth of cut d mm	0.5 – 5.0
Pick feed p mm	1
Cutting feed dir. f_{dr}	1
Tool radius r mm	10
Number of teeth n_f	2
Inclination angle i_x deg	-60, -30, -10, 0, 10, 30, 45, 60
Inclination angle i_y deg	0
Workpiece	Aluminum alloy (JIS: A5052)

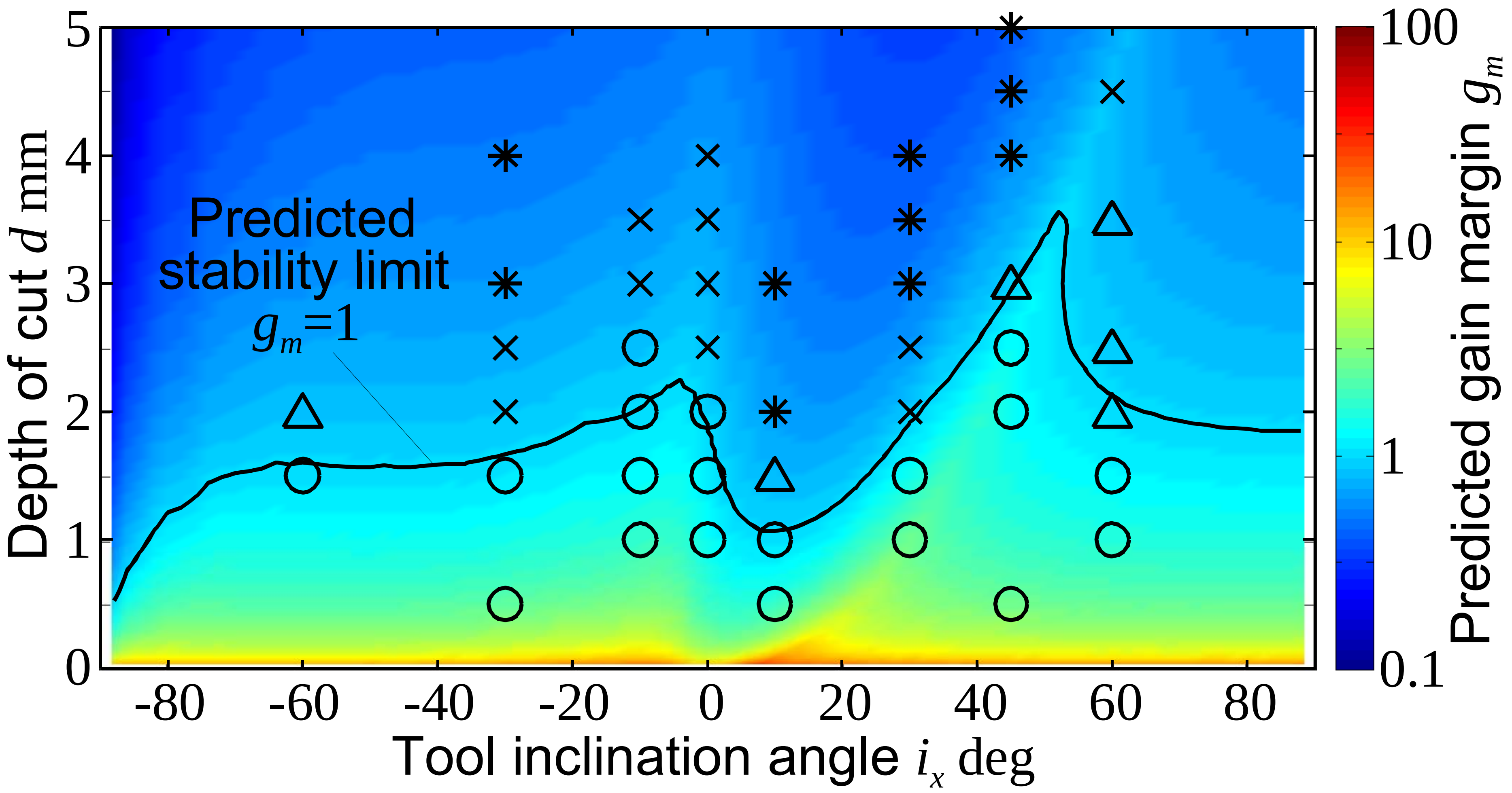
Chatter Stability at Varied Spindle Speed n (i_x =-30 deg)



○: no chatter (s_0≤0.12 μm), △: slight chatter (0.12 μm<s_0≤0.24 μm),

✕: chatter (0.24 μm <s_0≤1.2 μm), ✱: severe chatter (1.2 μm<s_0)

Chatter Stability at Varied Inclination i_x (n=6240 min^{-1})



Workpiece: aluminum alloy (JIS:A5052); Cutter: HSS ball end mill (EBD80820, OSG Corp.), n_f=2, r=10 mm, i_y=0 deg, i_0=30 deg, normal rake angle: 11 deg (roughly constant along ball-ended helical flute); Feed rate: 0.01 mm/tooth; Pick feed p=1 mm; Feed direction f_{dr}=1; Cutting fluid: soluble; Identified material properties: shear strength τ=226 MPa, friction angle β=40.7 deg.

Ultraprecision/micro elliptical vibration cutting

- E. Shamoto and T. Moriwaki: Study on Elliptical Vibration Cutting, Annals of the CIRP, Vol.43/1 (1994) pp.35-38,
- E. Shamoto, et al.: Development of 3 DOF ultrasonic vibration tool for elliptical vibration cutting of sculptured surfaces, Annals of the CIRP, Vol.54/1 (2005) pp.321-324
- N. Suzuki, M. Haritani, J. Yang, R. Hino, E. Shamoto: Elliptical Vibration Cutting of Tungsten Alloy Molds for Optical Glass Parts, Annals of the CIRP, Vol.56/1 (2007) pp.127-130, etc.

1. Elliptical vibration cutting process

2. Ultrasonic elliptical vibration tools

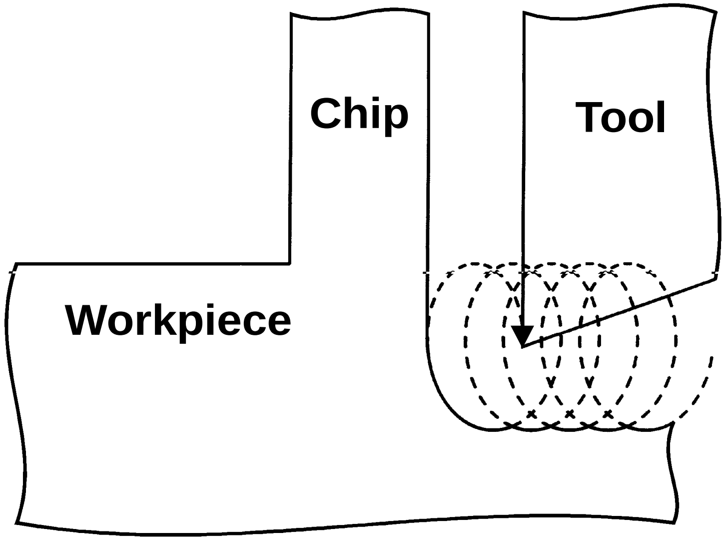
3. Application to ultraprecision micro machining of hard / brittle materials

3-1 Steel

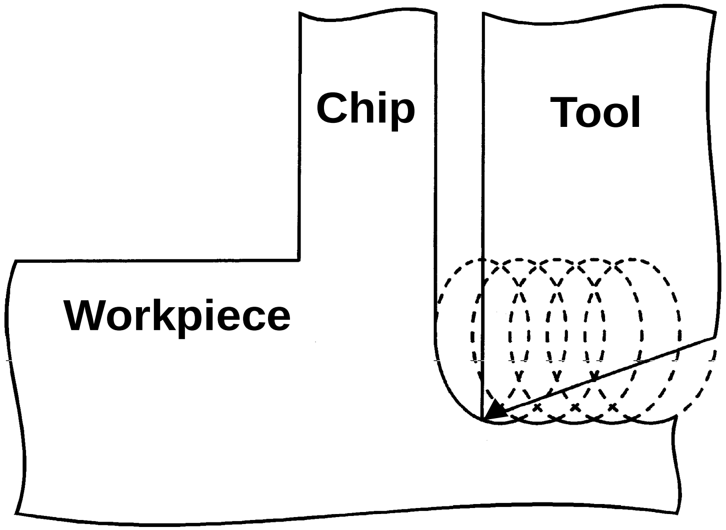
3-2 Calcium fluoride

3-3 Tungsten alloy

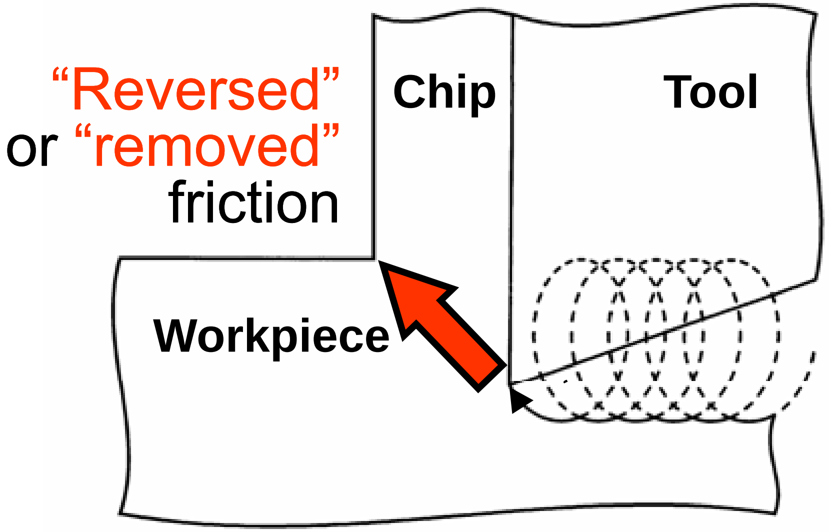
One Cycle of Elliptical Vibration Cutting Process



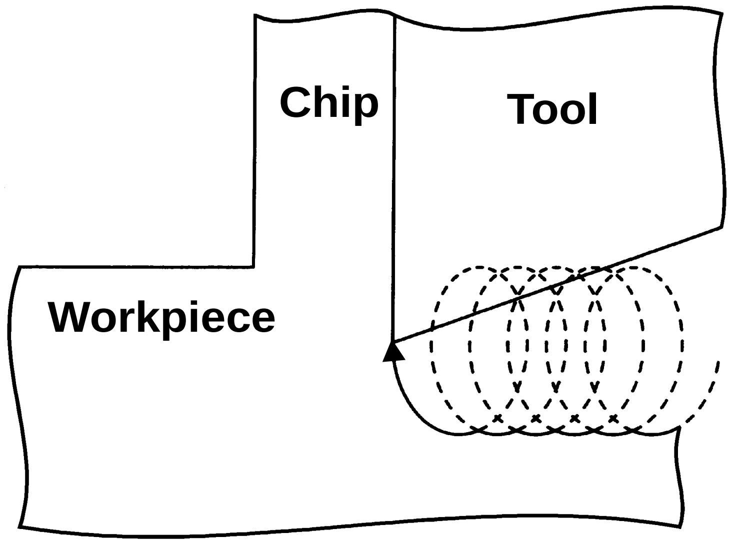
(a) Non cutting



(b) Surface finish



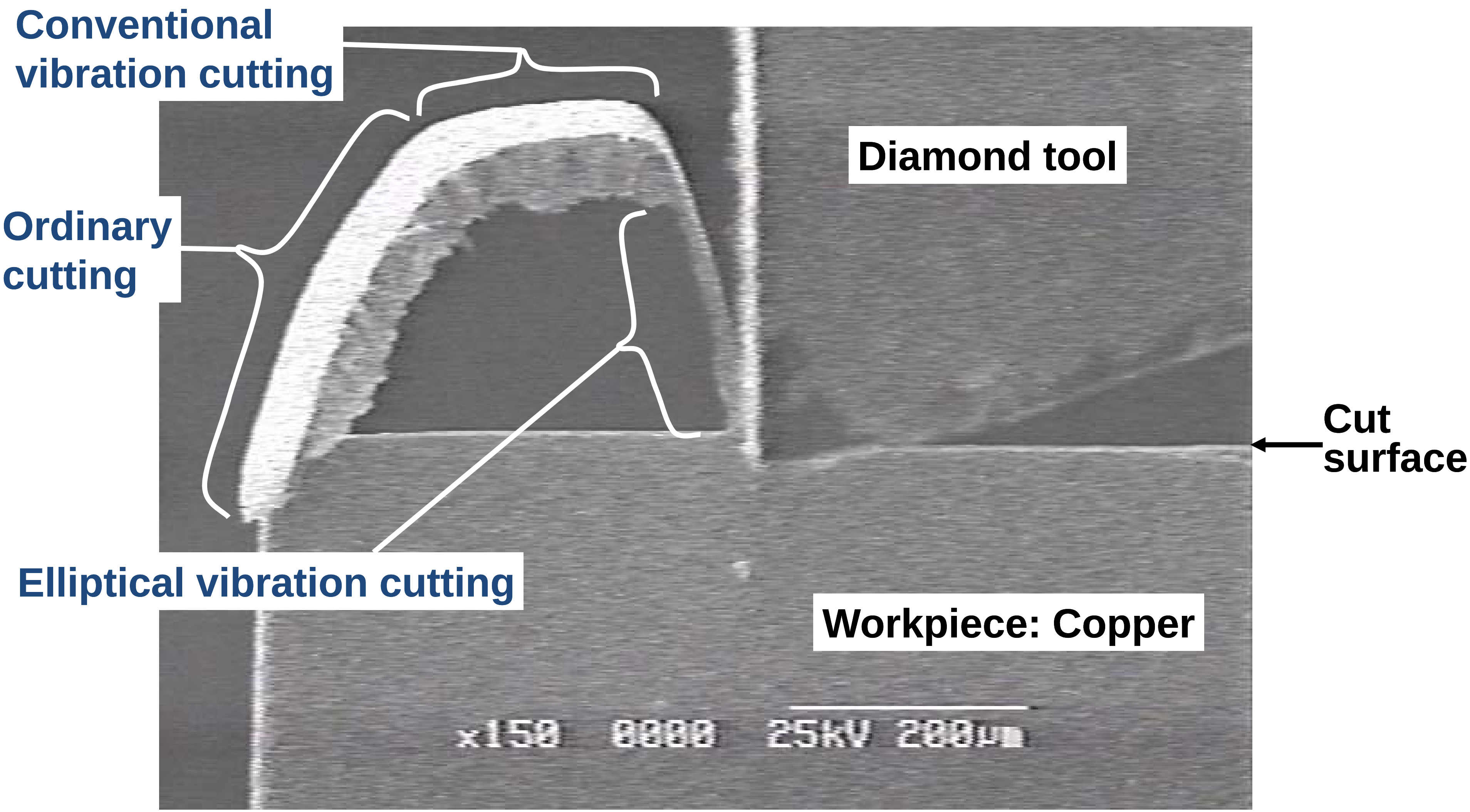
(c) Material removal



(d) End of cutting

Change in Chip Thickness by Applying Elliptical Vibration Cutting

E. Shamoto and T. Moriwaki, 8th ASPE, 1993



Workpiece: copper, rake: 0 deg, cutting speed: 0.26 mm/min, depth of cut: 10 μm, vibration: linear / circular, amp.: 10 $\mu m_{p\text{-}p}$, freq.:1.2 Hz

1. Elliptical vibration cutting process

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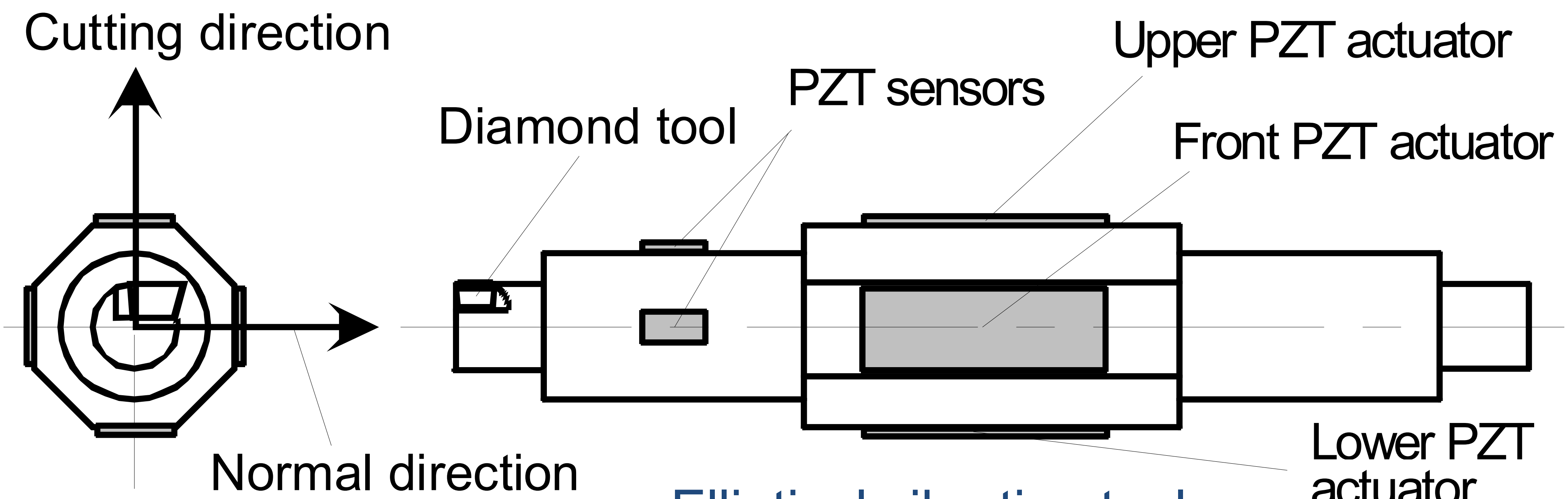
First Prototype of Ultrasonic Elliptical Vibration Tool

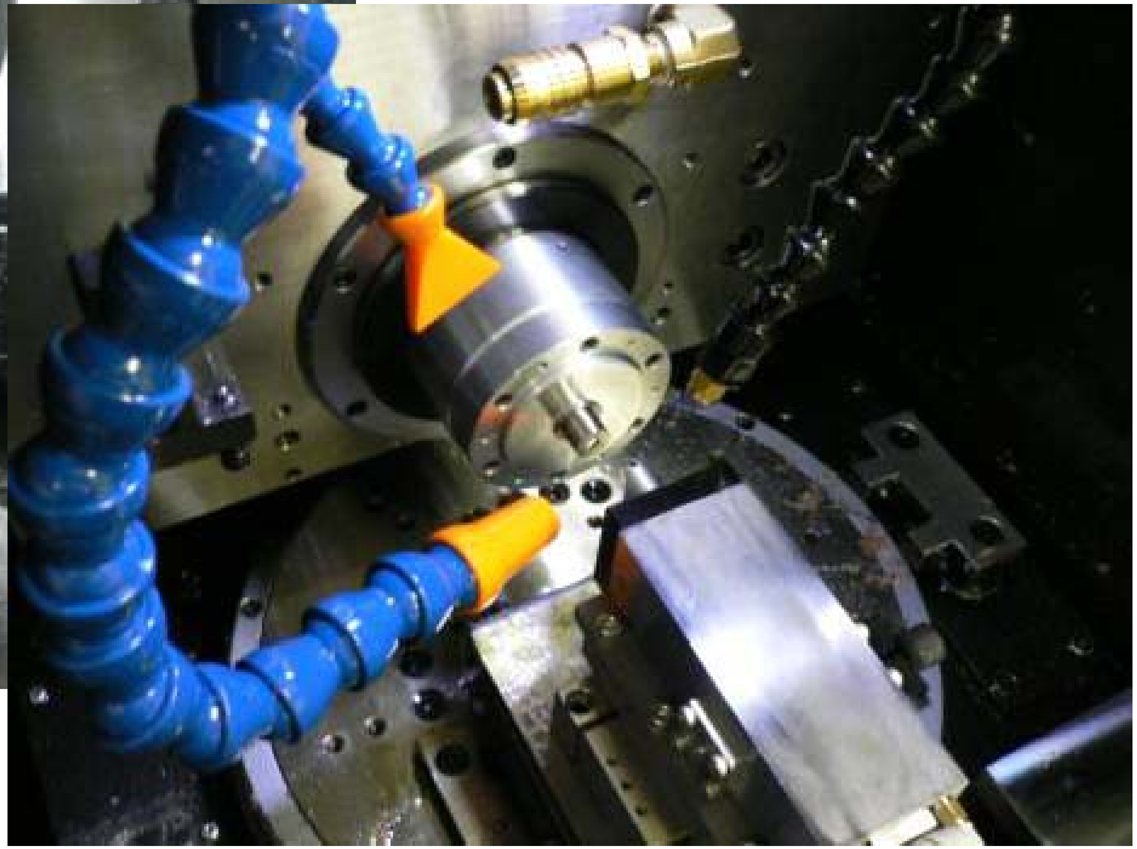


Elliptical vibration tool

Third resonant mode of bending
(20 kHz)

Developed Ultrasonic Elliptical Vibration Tools

First prototype of ultrasonic elliptical vibration tool



Commercial ultrasonic elliptical vibration tool developed by collaborative research with Taga Electric Co., Ltd.

1. Elliptical vibration cutting process

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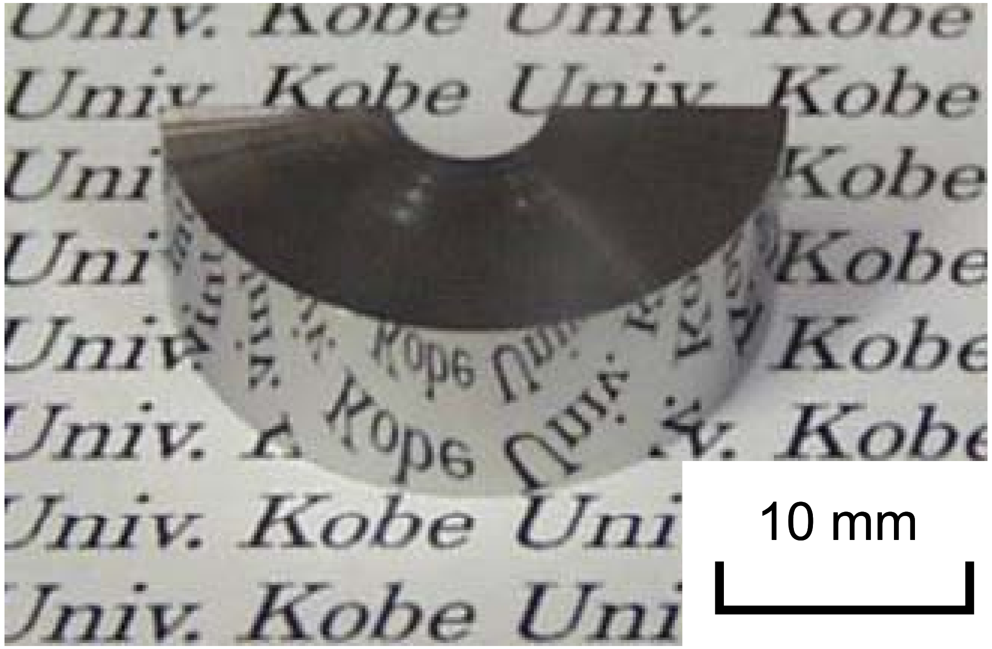
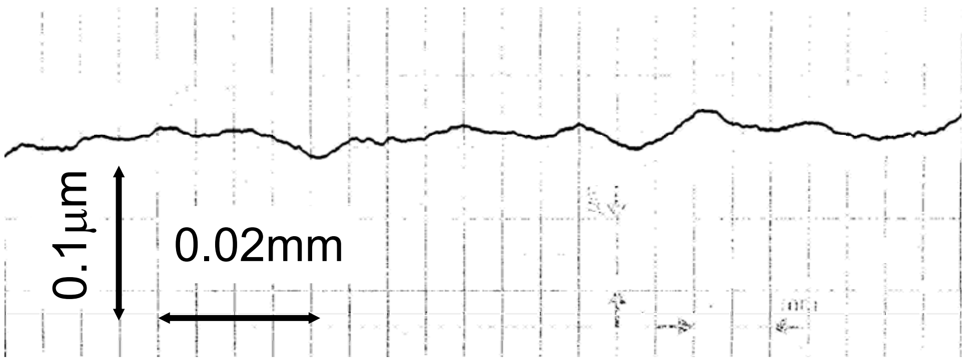
3. Application to ultraprecision micro machining of hard / brittle materials

- 3-1 Steel
- 3-2 Calcium fluoride
- 3-3 Tungsten alloy

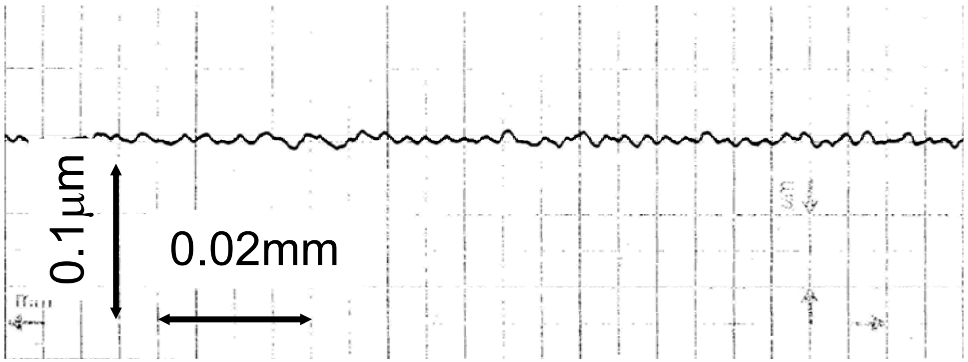
Finished Surface of Hardened Die Steel



(a) Photograph of mirror surface



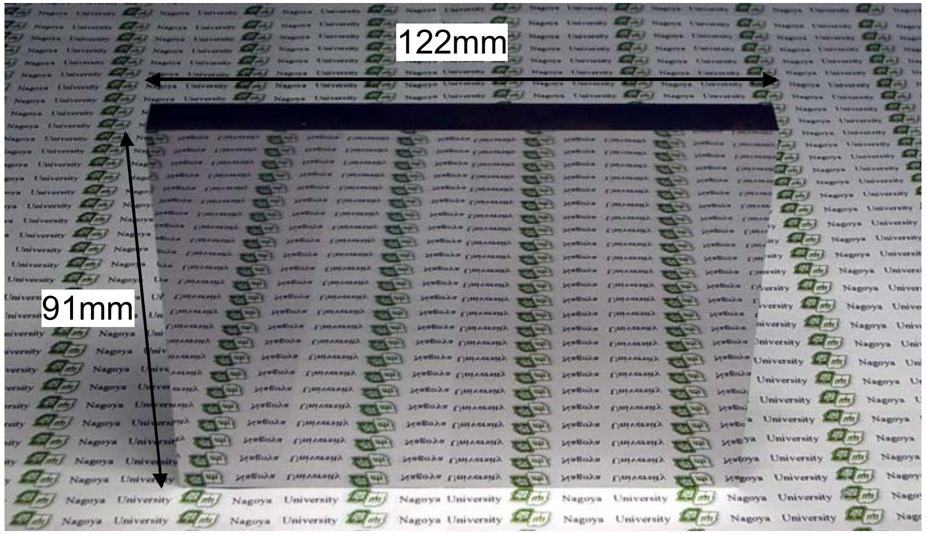
Feed direction



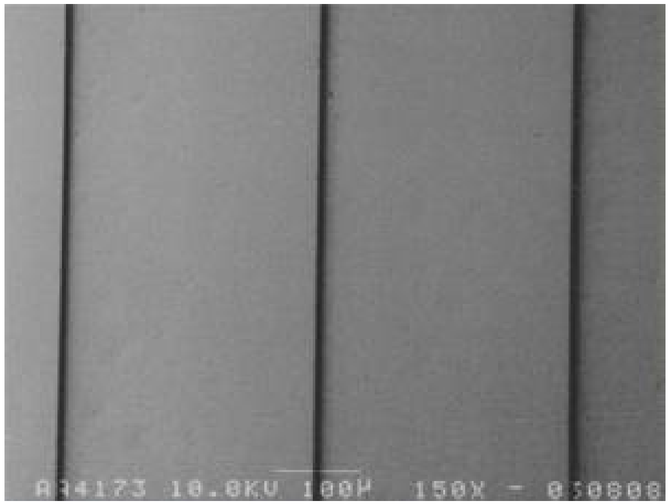
Cutting direction

Workpiece: hardened die steel (JIS: SUS420J2), HRC39. Speed: 3.4 m/min. Feed: 10 μm /rev. Tool: R1 mm.
Vibration: circular, radius 4.25 μm, freq. 21.5 kHz.

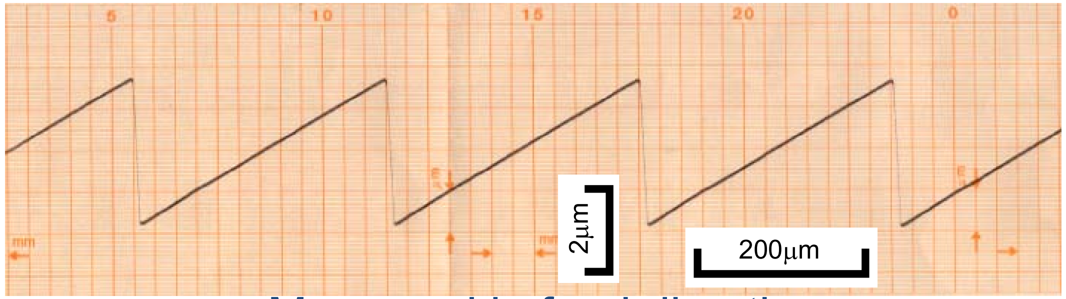
Die for Front Light Panel of LCD Machined by Elliptical Vibration Cutting



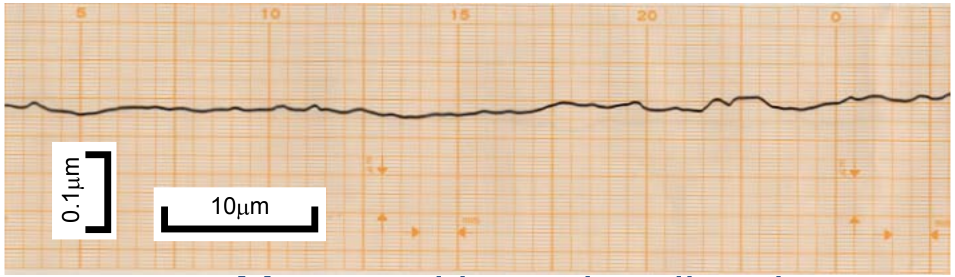
(a) Photograph of Finished surface



(b) SEM photograph of microgrooves



Measured in feed direction



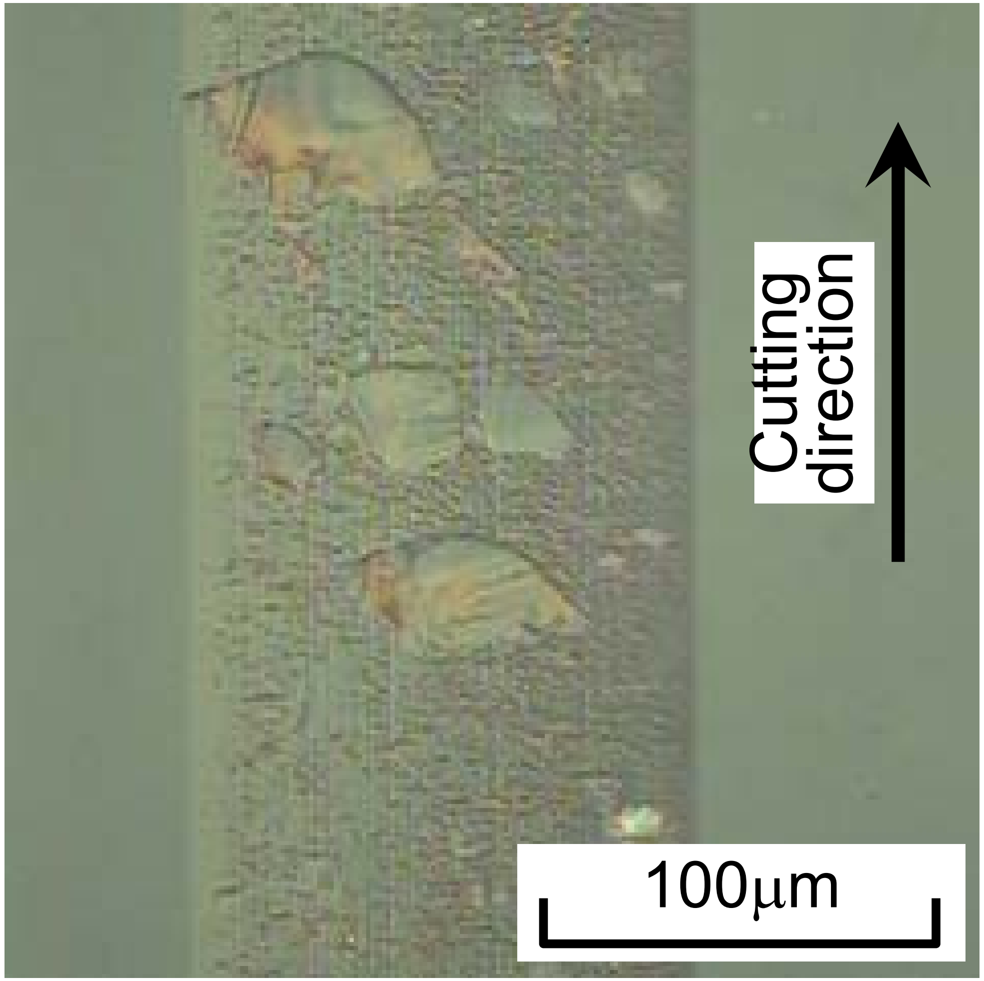
Measured in cutting direction

(c) Profiles of grooved surface

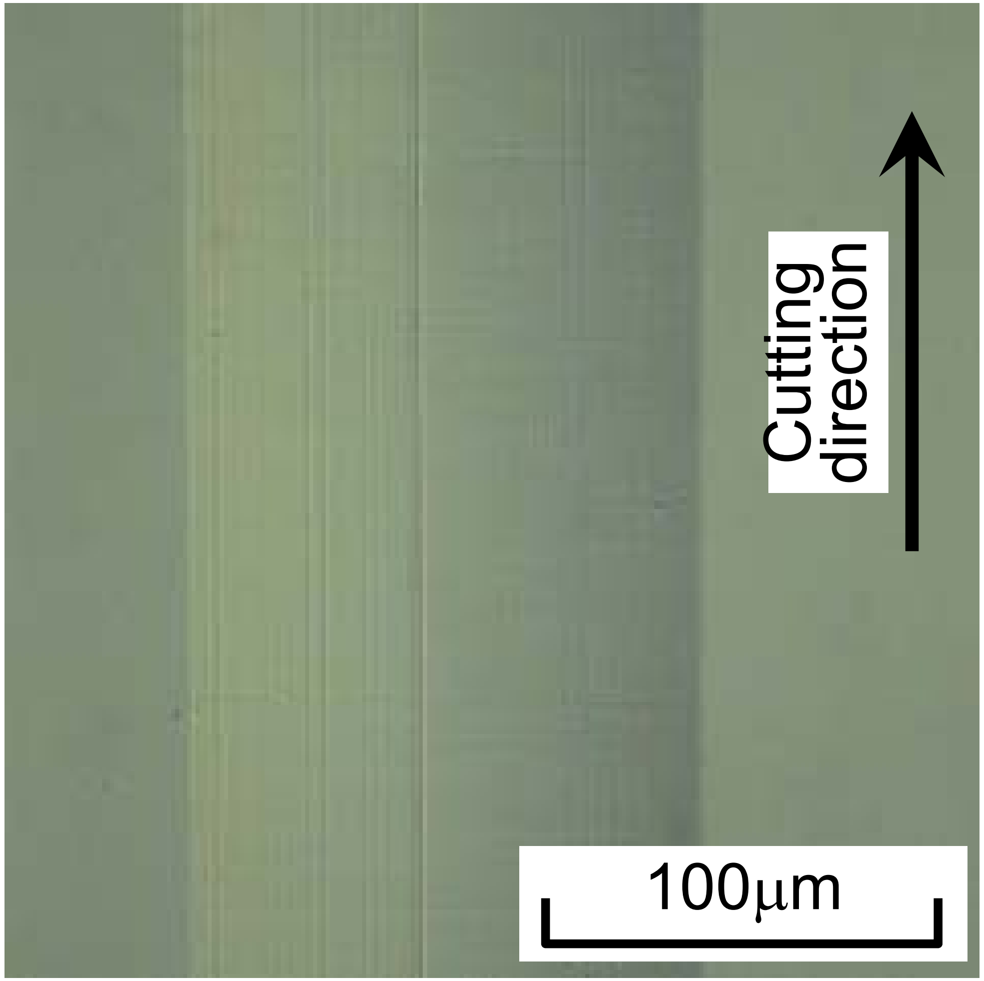
[Conditions] Workpiece: hardened die steel (JIS: SUS420J2), HRC53. Depth: 1 µm. Feed: 300 µm. Speed: 0.25 m/min. Circular vibration. Amp.: 3 µm. Freq.: 19.6 kHz. Tool: V, 107 deg.

[Measured results] Roughness: 0.04 µm Rmax

Micro Grooving of Single Crystal Calcium Fluoride



Ordinary cutting



Elliptical vibration cutting

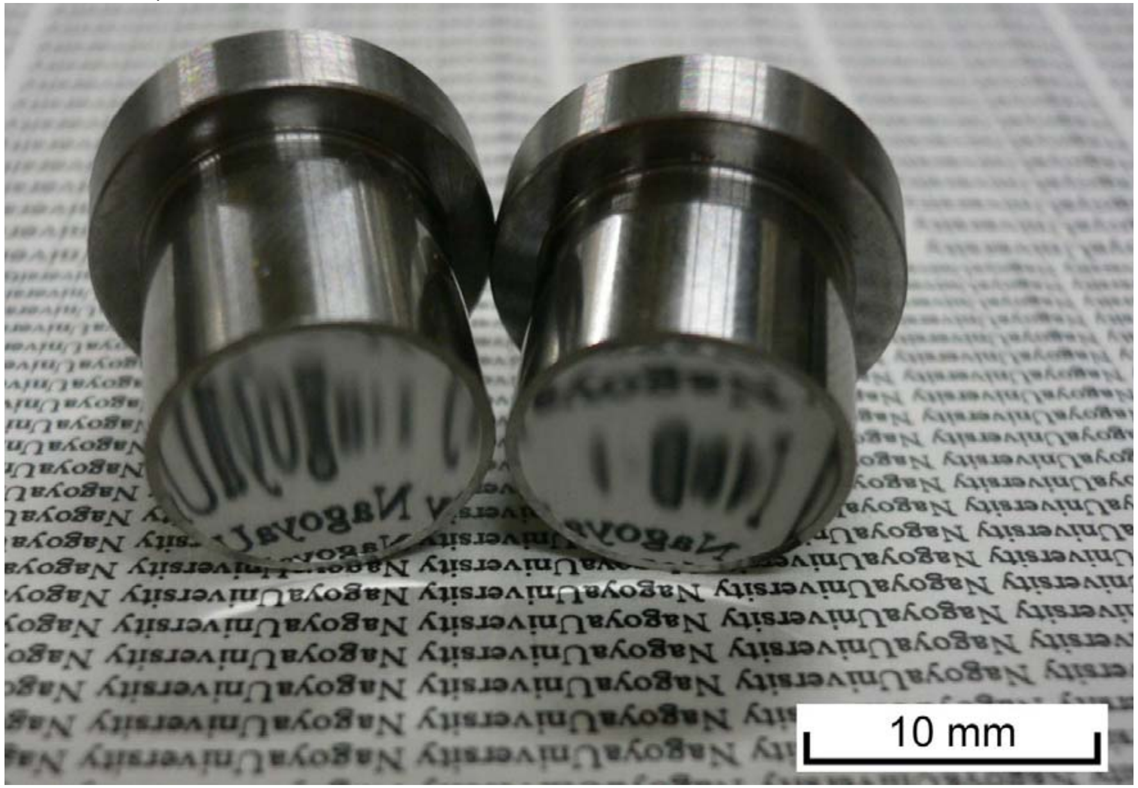
Depth of cut: 2 μm, Cutting speed: 0.37 m/min, Cutting direction: $\langle 0\bar{1}1 \rangle$
Vibration: Circular, Amplitude: 4 μm, Freq.: 19.5 kHz
Tool: Single crystal diamond, Nose radius: 1 mm, Rake: 0°

Ultraprecision Cutting of W Alloy for Optical Glass Molds

Features of W alloy

【Advantage】
- High thermochemical stability up to about 1200℃
- Nonadhesive to glass → molding without coating
- Rough machining by carbide tools
- Low cost

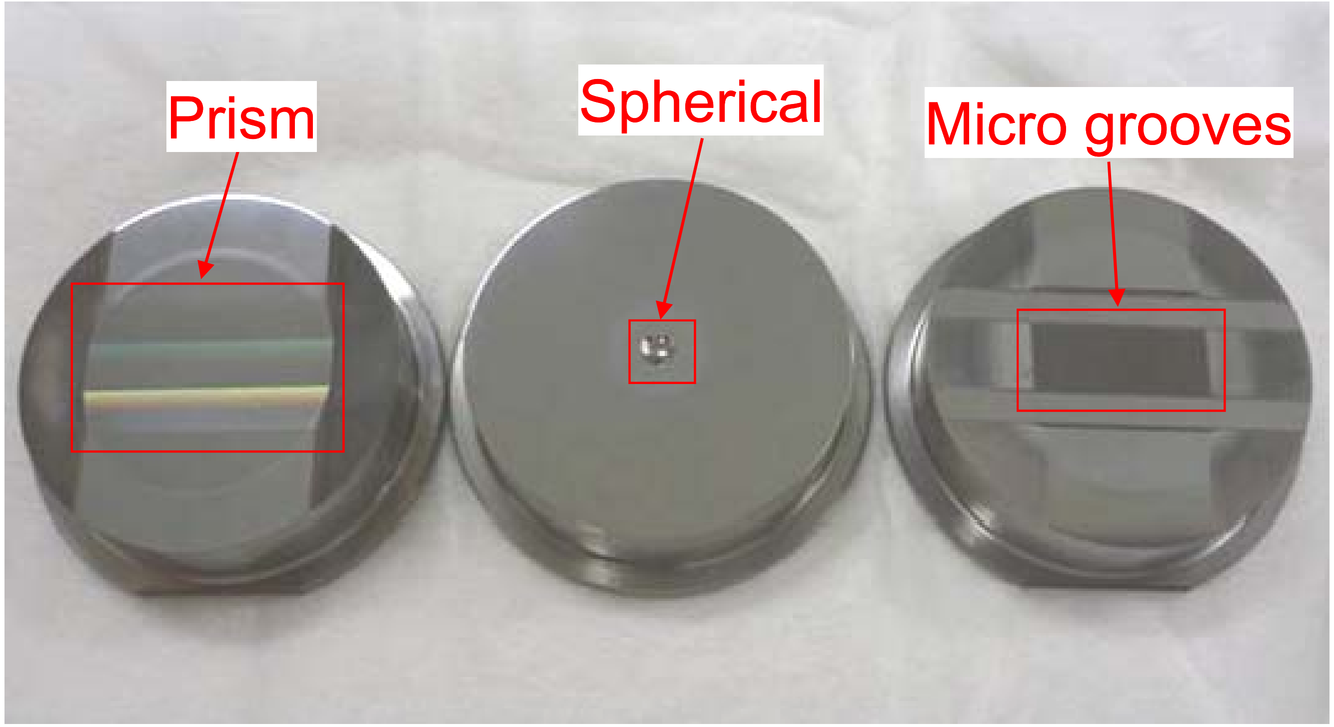
【Disadvantage】
- Difficult to apply diamond cutting due to rapid tool wear, adhesion and brittle fracture.
- Difficult to apply abrasive processes due to loading



W alloy molds finished by elliptical vibration cutting. 0.03-0.04 μm Rmax

Depth of cut: 5 μm, Feed: 5 μm/rev, Rotation: 42 rpm, Vibration: Circular, Amp.: 4 $\mu m_{p\text{-}p}$, Freq.: 38.7 kHz, Tool: Single crystal diamond, Nose radius: 1 mm, Rake: 0 deg, Machined shapes: curvatures of R20 (left), 15 (right), ϕ11 mm

Examples of W Alloy Molds and Molded Glass Parts

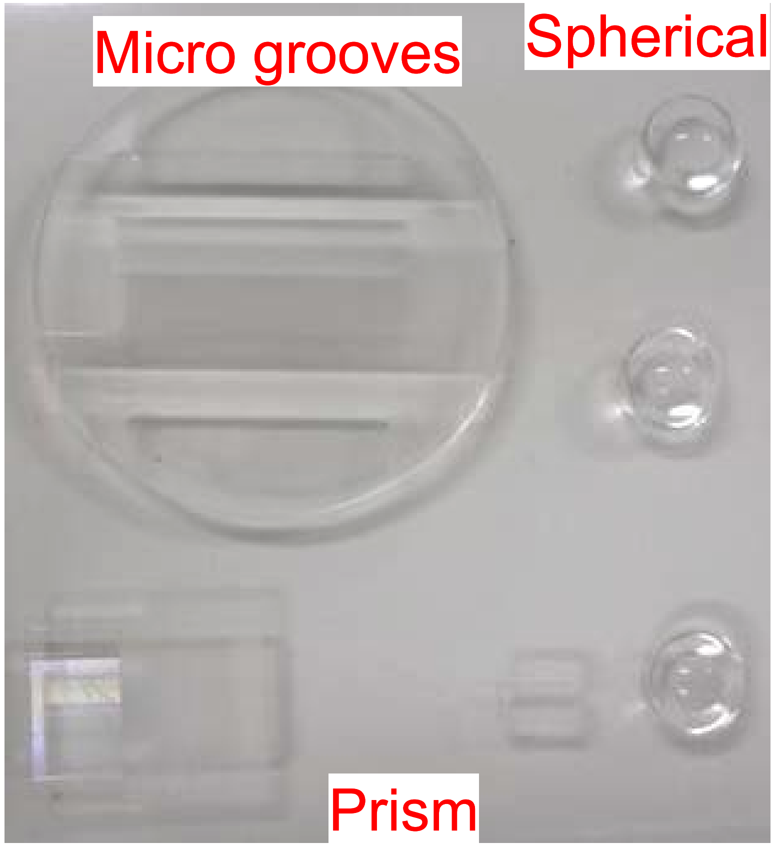


＜Machined molds＞

Left: Mold for prism（13.5×20）

Center: Mold for spherical lens（ϕ3, R2.5, Depth 0.5）

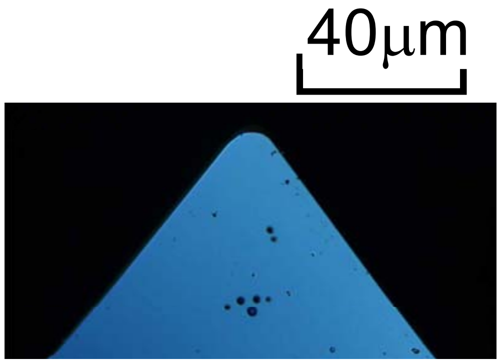
Right: Mold for optical fiber connector



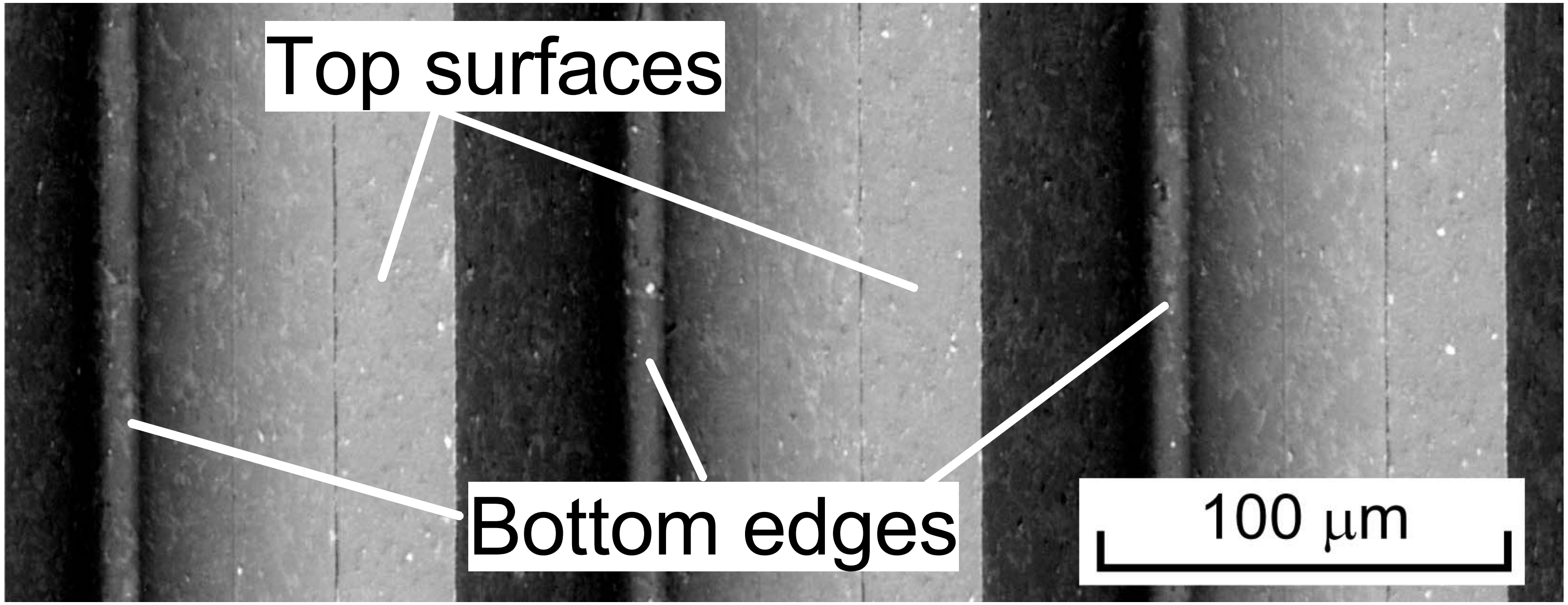
＜Molded parts＞

Optical glass（BK7）

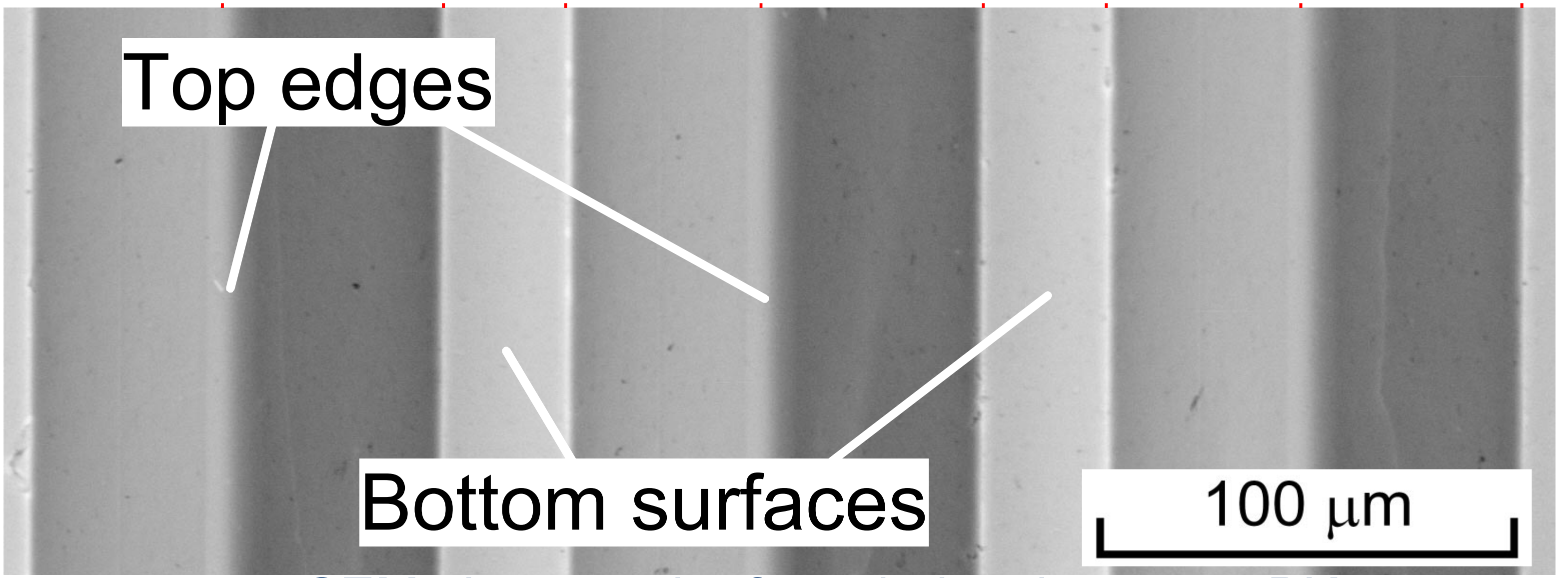
V-Groove Array Mold and Molded Optical Glass



Cutting edge of diamond tool



SEM photograph of tungsten alloy mold



SEM photograph of molded optical glass BK7