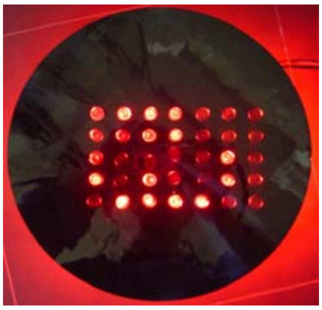
超精密加工技術の基礎とその応用

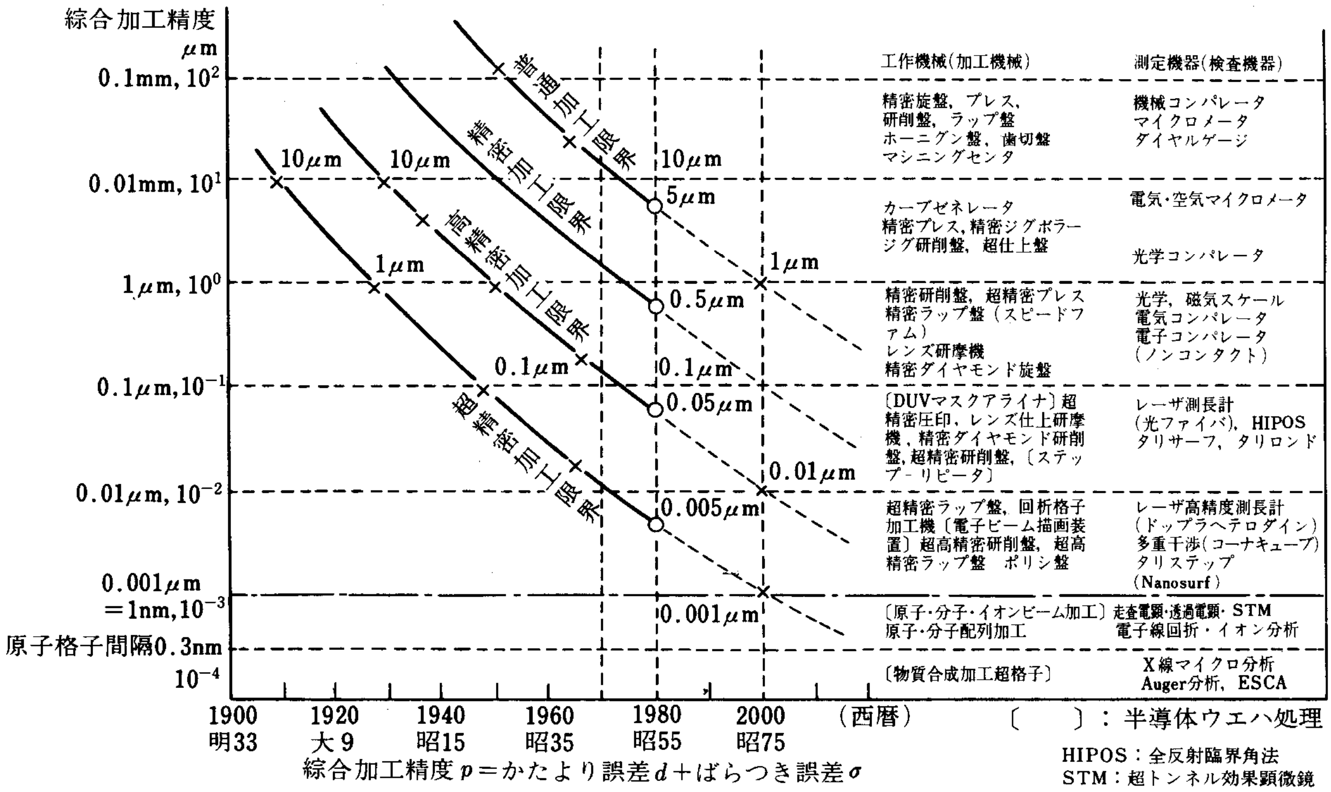
茨城大学・周立波

内容説明

- 超精密加工
  - 究極の加工精度
  - 加工単位と加工方法
- 延性材料の加工
  - 超高速除去加工
  - 超高加速度除去加工（含振動加工）
- 硬脆材料の加工
  - Siウエハの化学・機械複合加工（CMG）
  - 極薄Siウエハの加工
  - サファイアウエハのCMG加工

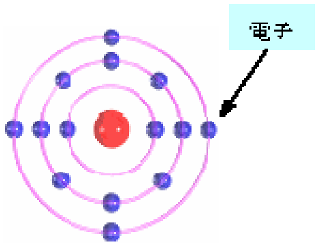


加工精度➔nanotechnology



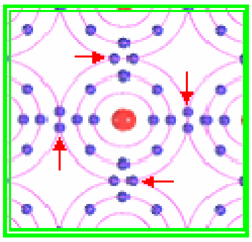
Example: 単結晶Si

シリコンの原子



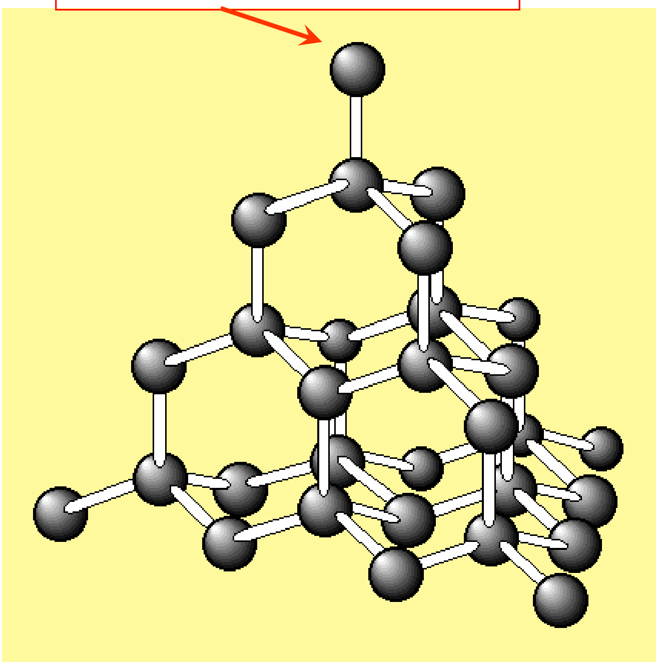
電子の数が14の原子で、最外殻に電子が4個あります。

共有結合



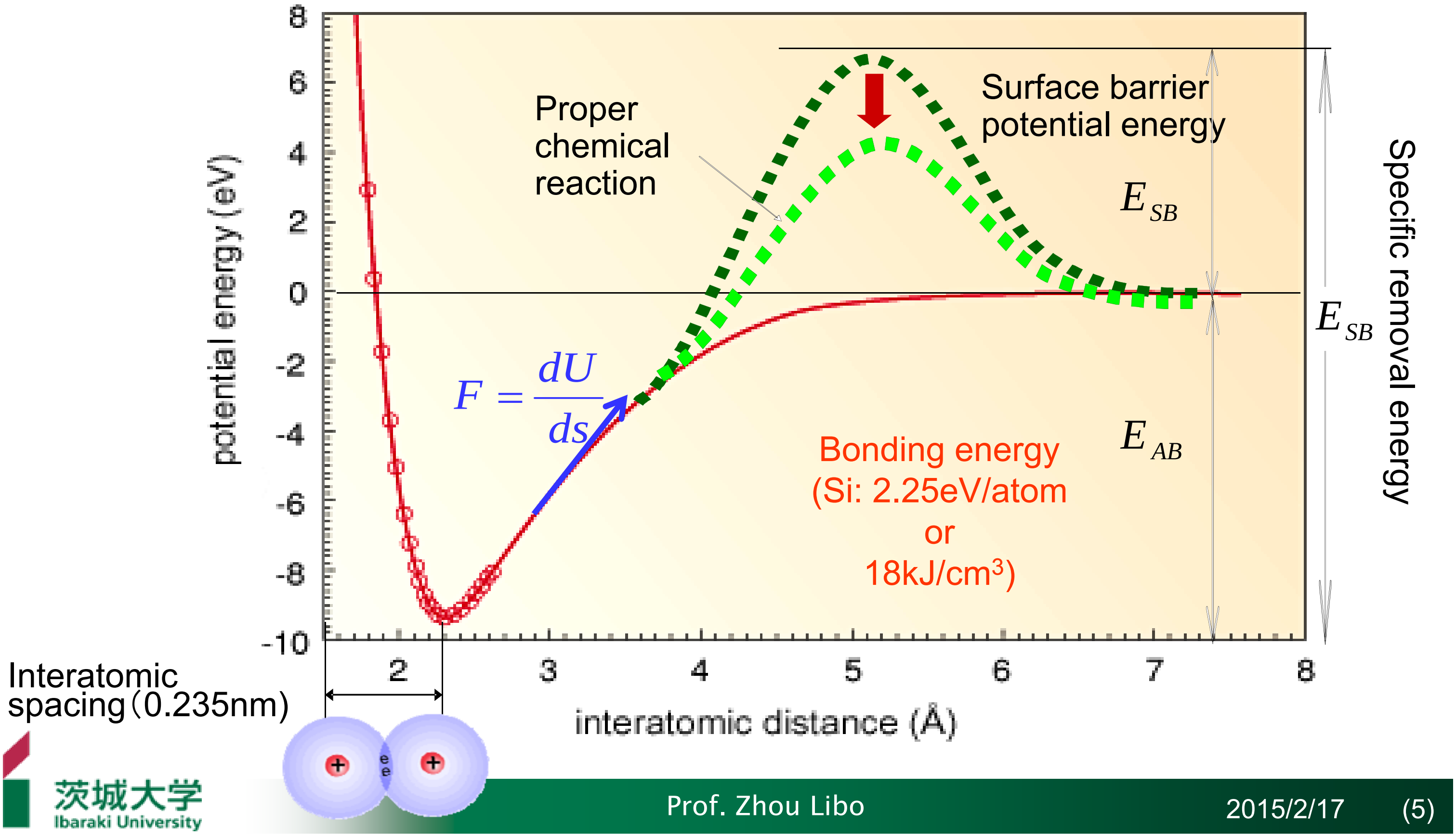
隣の原子の電子を共有して結合します。

この原子を除去する方法は?

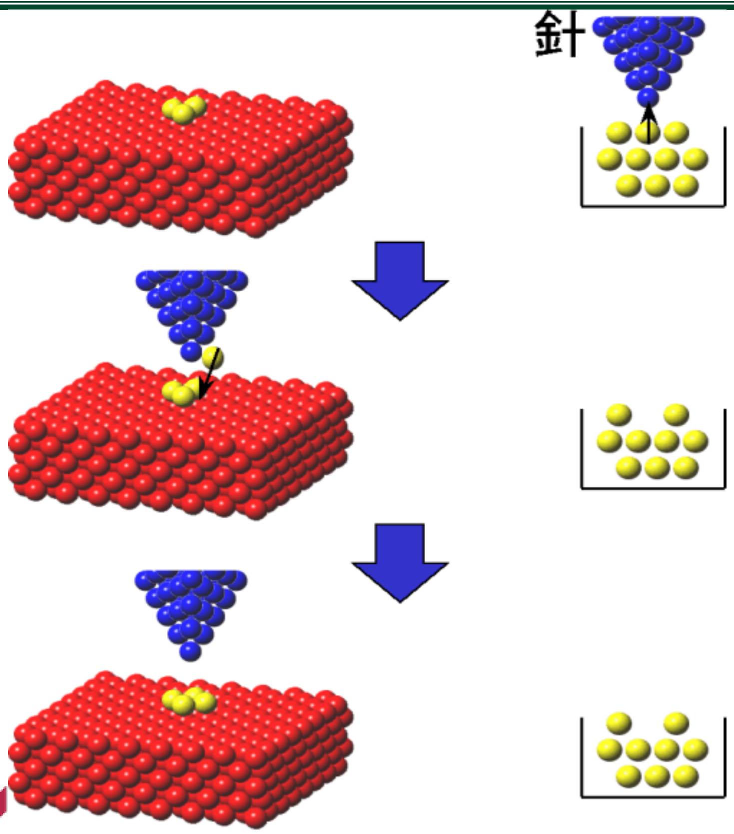


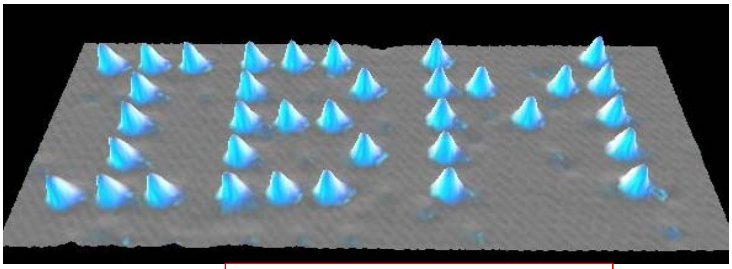
Diamond structure

原子間結合エネルギ

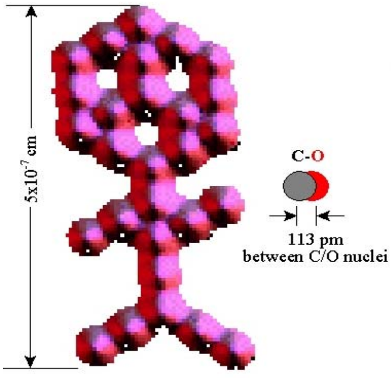


究極の目標:原子レベルの操作

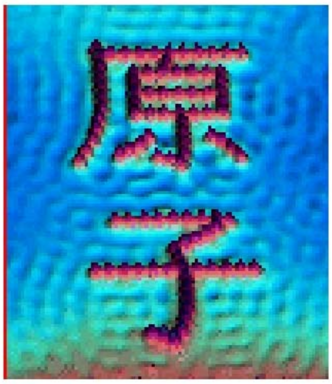




1990年ノーベル物理賞



28 CO molecules alligned on a platinum metal surface using STM to form "Carbon Monoxide Molecule Man".

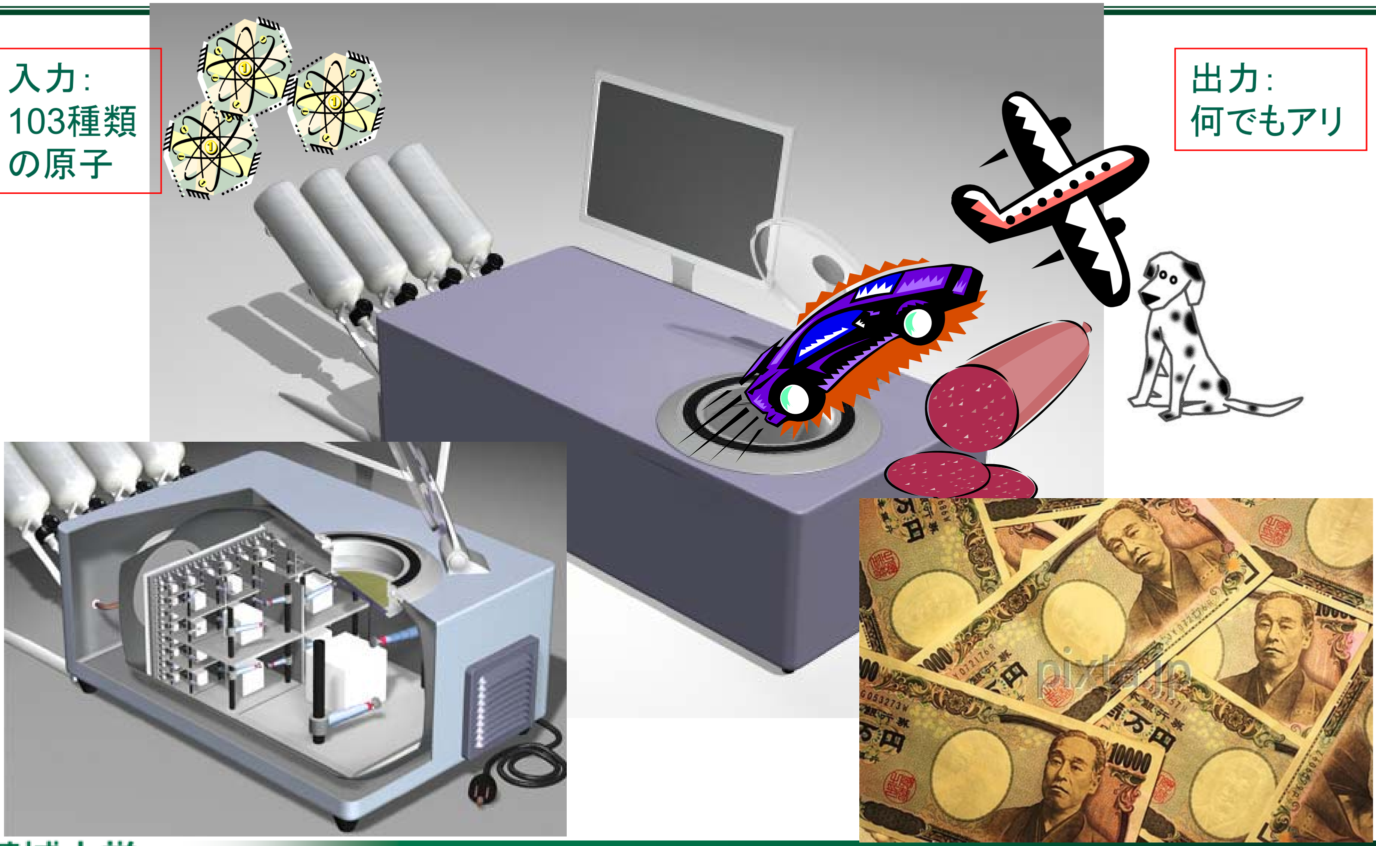


The Kanji characters for "atom" formed with iron atoms on a copper metal surface using STM. The radius of an iron atom is 126 pm.

Drexler’s Assembler

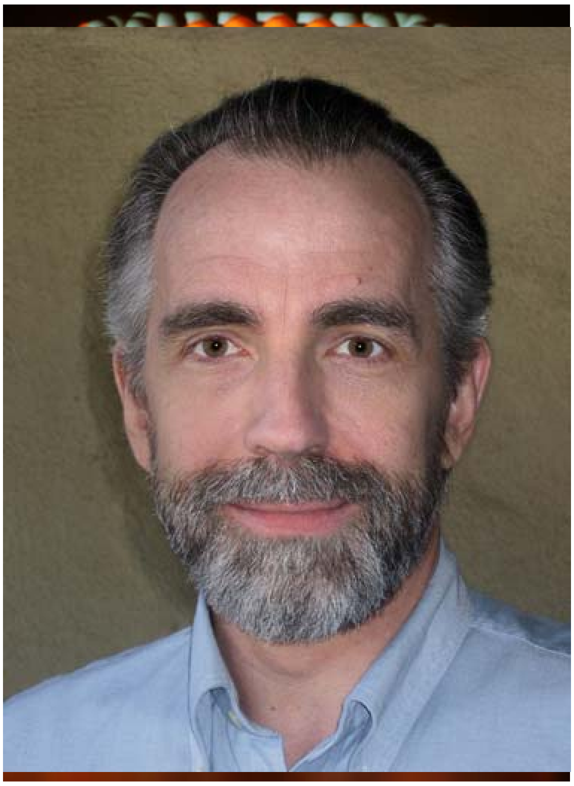
入力：
103種類
の原子

出力：
何でもアリ

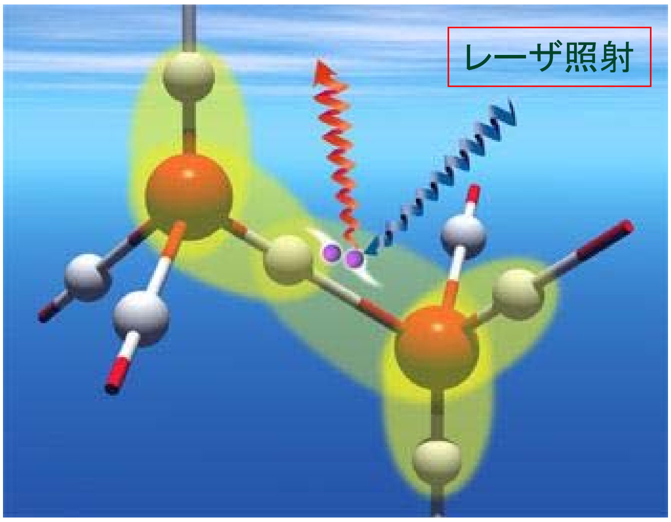


K. Eric Drexler (1955-)

- Massachusetts Institute of Technology, Cambridge, MA
  Ph.D., Molecular Nanotechnology, September 1991
  Dissertation: Molecular Machinery and Manufacturing with Applications to Computation
  Supervisor: Marvin Minsky
- Massachusetts Institute of Technology, Cambridge, MA
  S.M., Engineering, September 1979.
- Massachusetts Institute of Technology, Cambridge, MA
  S.B., Interdisciplinary Science, June 1977



超短パルスレーザ加工

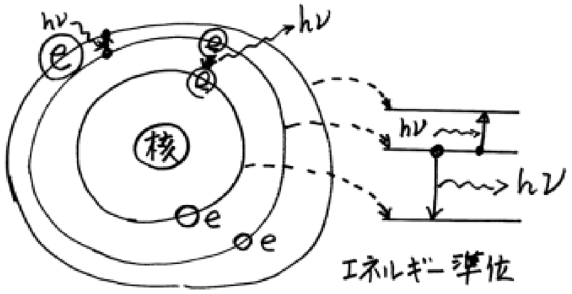


- 原子は電子を介して結合している.
- 電子は原子核から見て決まった位置に存在する.
- 電子が1つの軌道から別の軌道に移るときにエネルギ（光）を吸収したり，放出したりする.

電子軌道間移動に伴うエネルギ

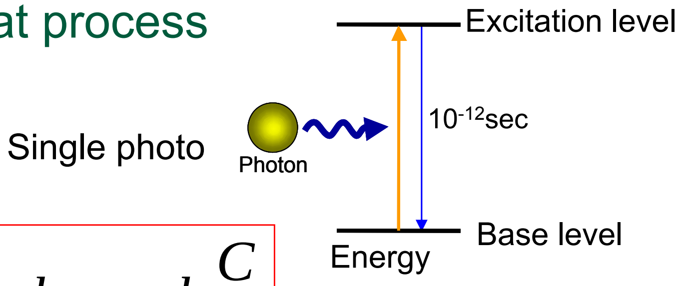
$$\boxed{E = h \cdot \nu = h\frac{C}{\lambda}}$$

- 核の周りに電子が存在する
- 電子の軌道は核から見て決まった位置に存在する
- 電子が1つの軌道から別の軌道に移るときに光を吸収したり放出したりする

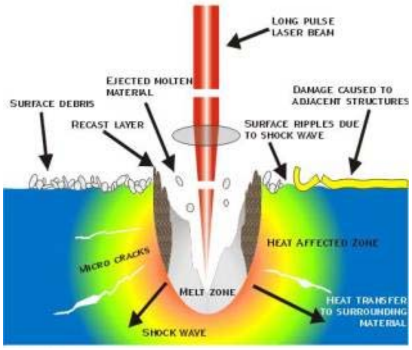


多光子吸収の原理

Heat process

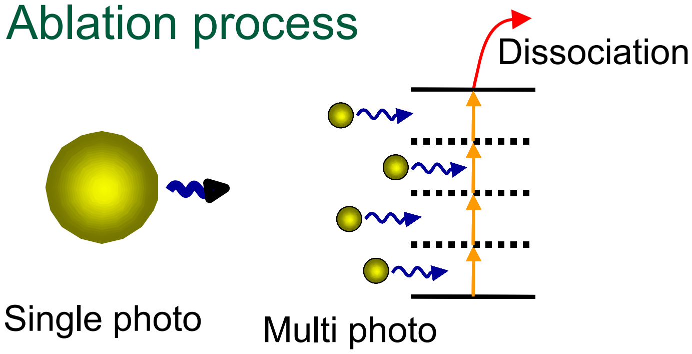


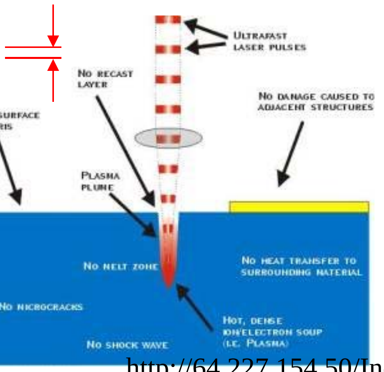
$$\boxed{E = h \cdot \nu = h\frac{C}{\lambda}}$$



Pulse length:
pico(10^{-12}sec) & Femto(10^{-15}sec)

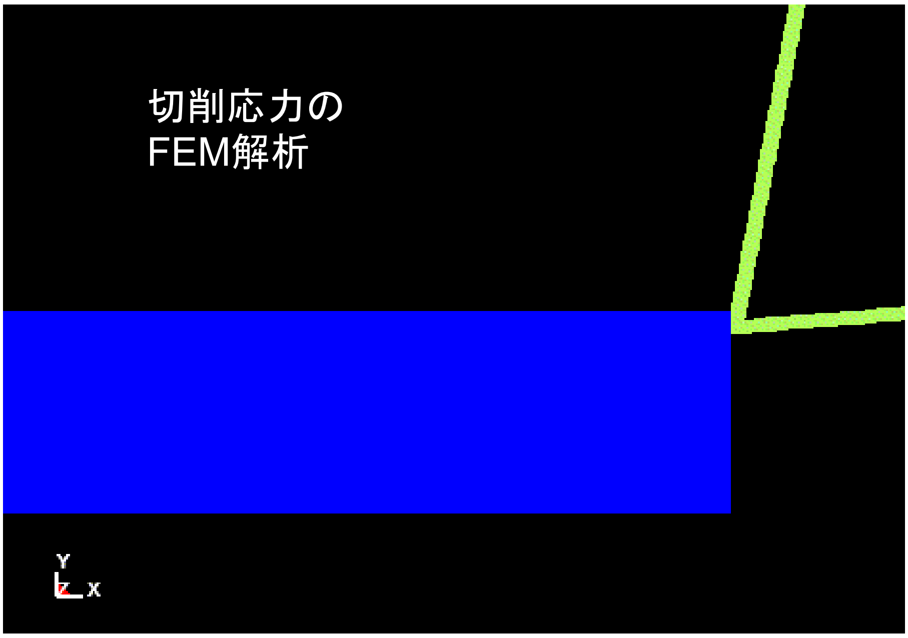
Ablation process





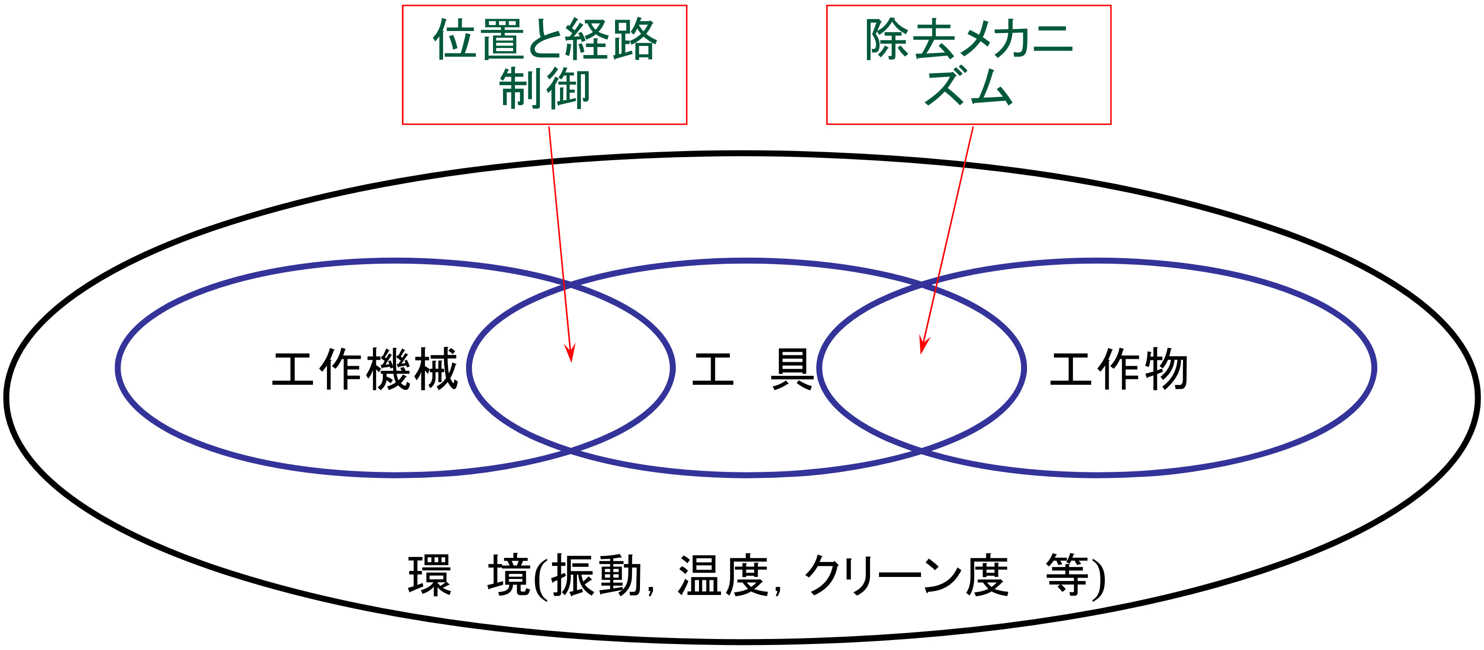
http://64.227.154.50/Index.htm

実際の加工方式



- 材料の除去メカニズムは，石器時代からほとんど変わっていない．

超精密加工の要素技術



位置と経路制御

除去メカニズム

工作機械

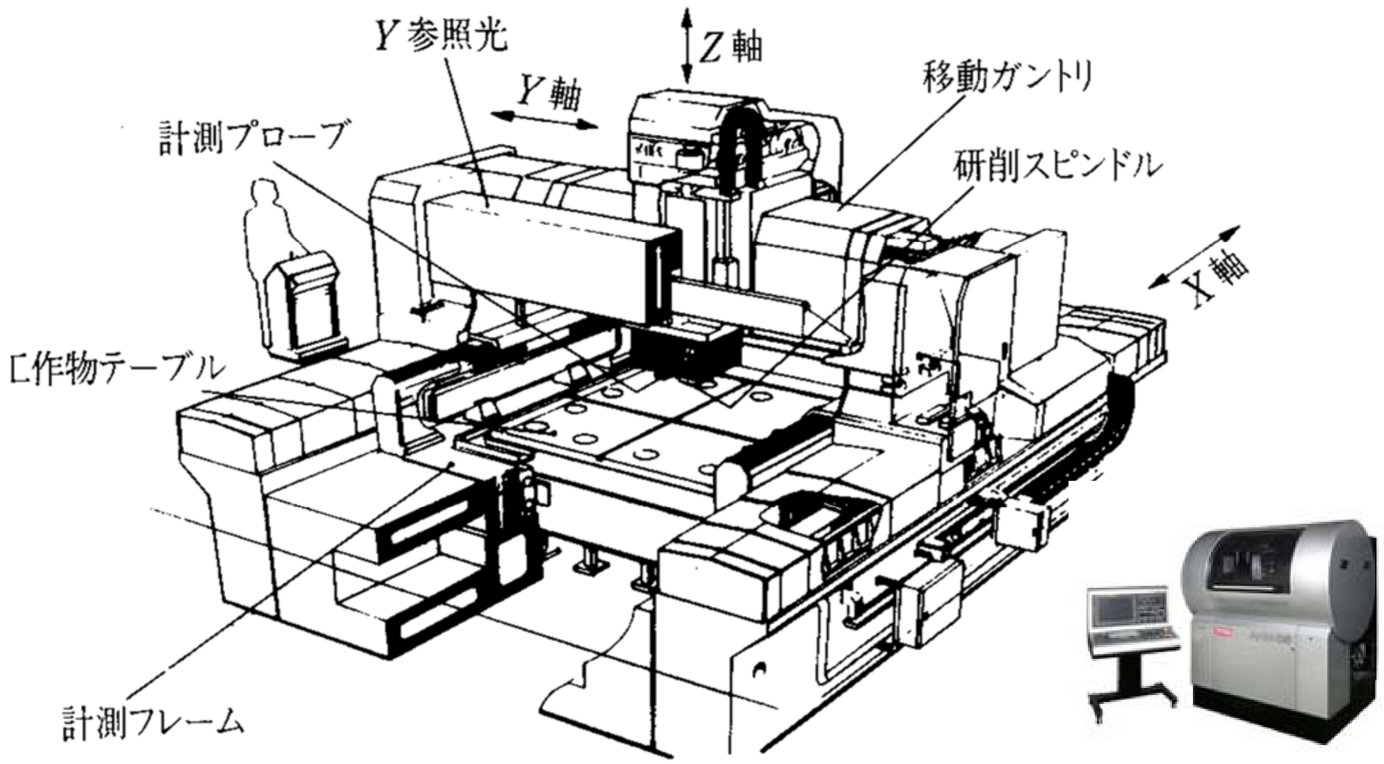
工　具

工作物

環　境(振動，温度，クリーン度　等)

除去加工の3大要素

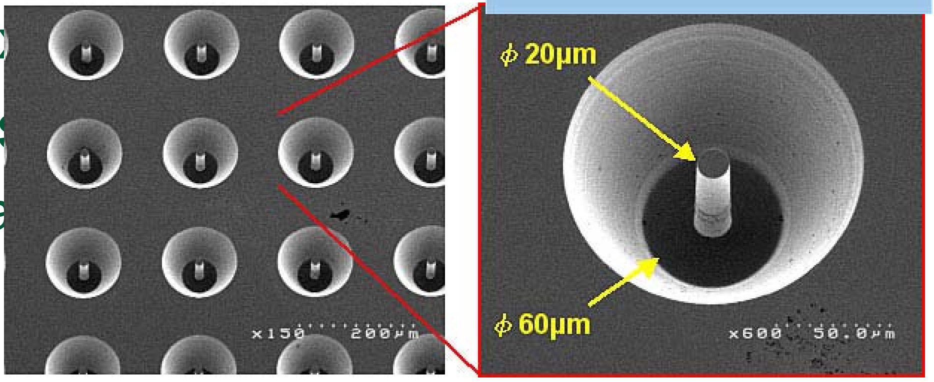
超精密工作機械



工作機械に必要な特性

- 位置決め精度 (Positioning)
  - 分解能（Resolution: ~10nm/step)
  - 剛性（Stiffness: 1000N/μm)
- 位置決め精度(Positioning)
  - 運動精度(Linearity：0.1μm/200mm)
  - 多軸補間（Multi-a
- 位置決め
  - 熱安定
  - Anti-vi


超精密5軸ナノ加工機
FANUC ROBONANO α-0iB

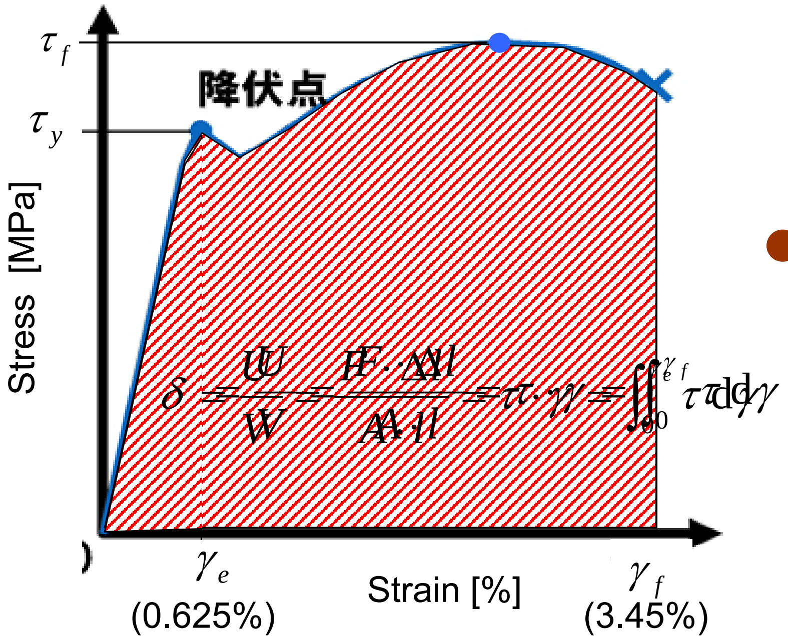


工作物ー材料

材料
- 金属
  - 鉄
  - アルミ
  - 銅
- 非金属
  - プラスチック
  - ガラス
  - セラミックス
  - シリコン

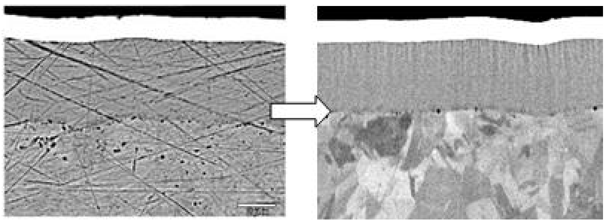
材料
- 延性材料
  - 金属
  - プラスチック
  - ゴム
- 脆性材料
  - セラミックス
  - シリコン
  - ガラス

除去メカニズム：応力ーひずみ曲線



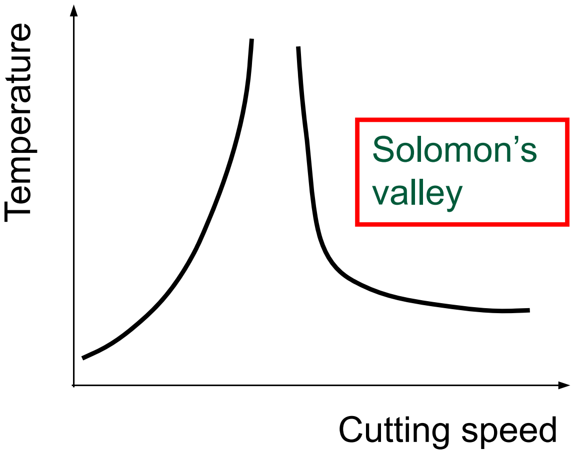
$$\delta = \frac{U}{W} = \frac{F\cdot\Delta l}{A\cdot l} = \tau\cdot\gamma = \int_0^{\gamma_f} \tau\,\mathrm{d}\gamma$$

- Example: Steel (S45C)
  - E=210GPa, G=80GPa
  - τ_y=0.6GPa, τ_f=1.3GPa
  - γ_e=0.625%, γ_f=3.45%
- Specific removal energy (=Specific share stress)
  - Theoretically δ=1.0GPa
  - Practically ω=4.7GPa



High speed machining

- C.Solomon (German) first proposed in1931
  - Temperature goes high together with cutting speed in the low speed region, meets its maximum and then comes down as cutting speed keeps increasing.
  - Undiscovered Solomon’s valley

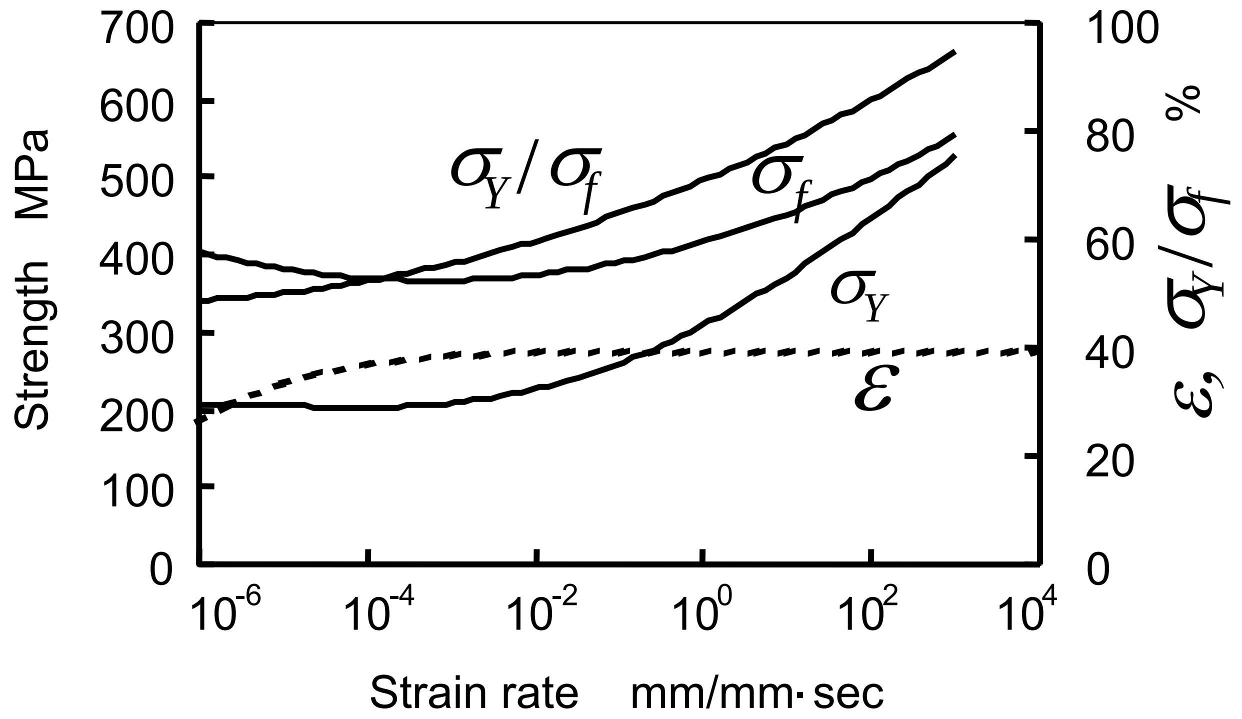


Solomon’s valleyへの探検

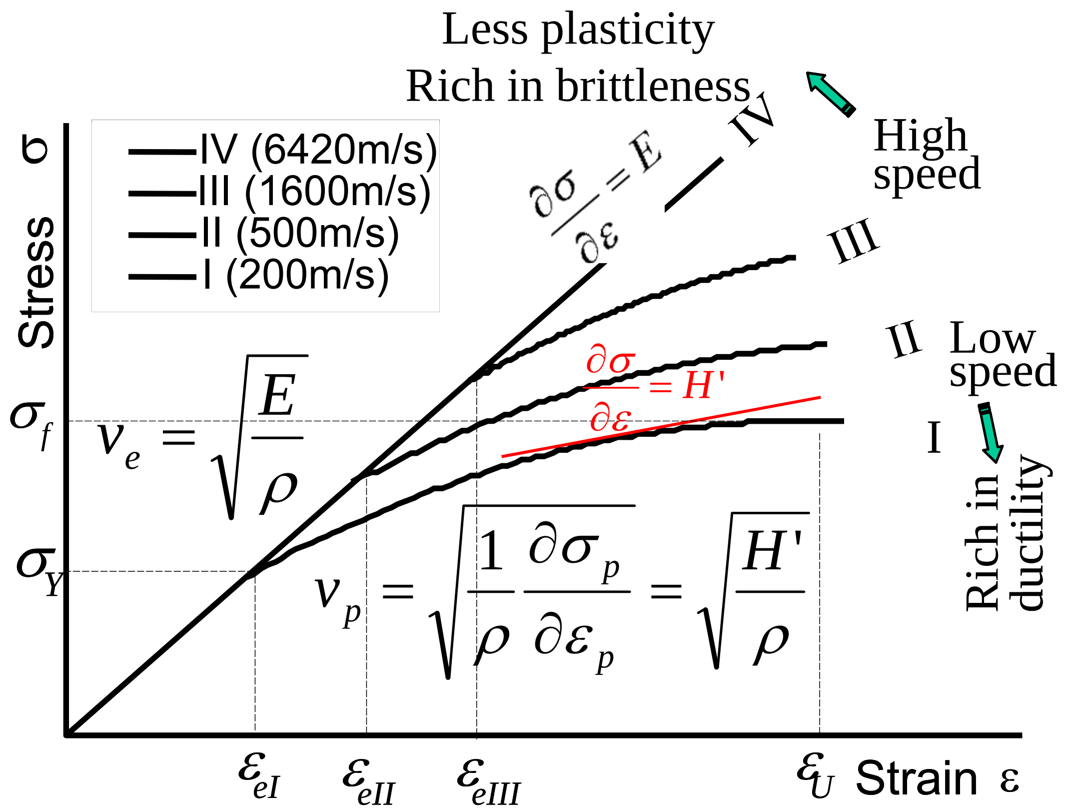
- In 1950s, by Von Karman
  - Experiments based on theory of critical impact speed
- In 1960s, by Lockheed and Tanaka
  - Use of rifle to get higher speed
- In 1980s, By Eda
  - Use of rocket to boost up the cutting speed

見果てぬ夢. . . .

降伏応力vs.材料の強度



延性材料の動的特性



$$v_e=\sqrt{\frac{E}{\rho}}$$

$$v_p=\sqrt{\frac{1}{\rho}\frac{\partial\sigma_p}{\partial\varepsilon_p}}=\sqrt{\frac{H'}{\rho}}$$

塑性伝播速度

$$\frac{\partial^2 u}{\partial t^2} = v^2 \frac{\partial^2 u}{\partial x^2} \qquad v_e = \sqrt{\frac{E}{\rho}} \qquad v_p = \sqrt{\frac{1}{\rho}\frac{\partial \sigma_p}{\partial \varepsilon_p}} = \sqrt{\frac{H'}{\rho}}$$

ρ ： density of material

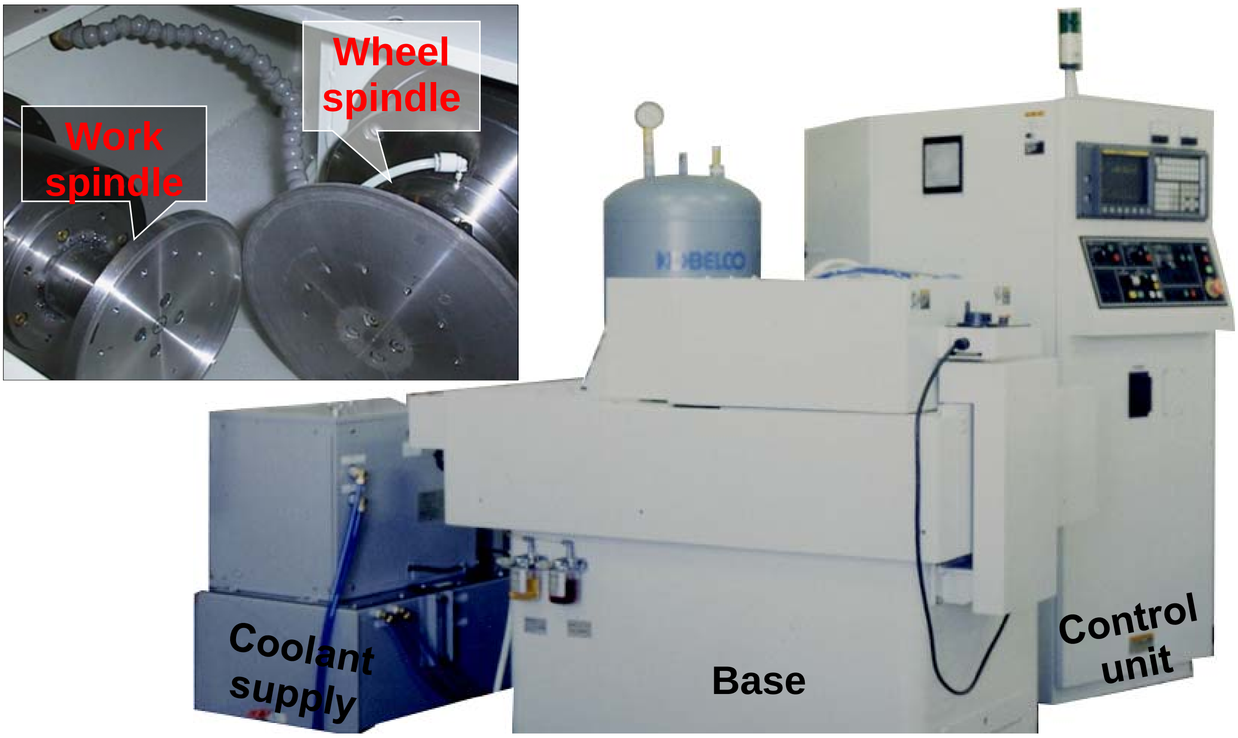
σ ： stress

ε ： plastic strain

- **Rich in plasticity**
- **Relatively low v_p**

Material	v_p m/s
Al alloy (5056)	300
Pure Al (1199)	200

Experimental set-up



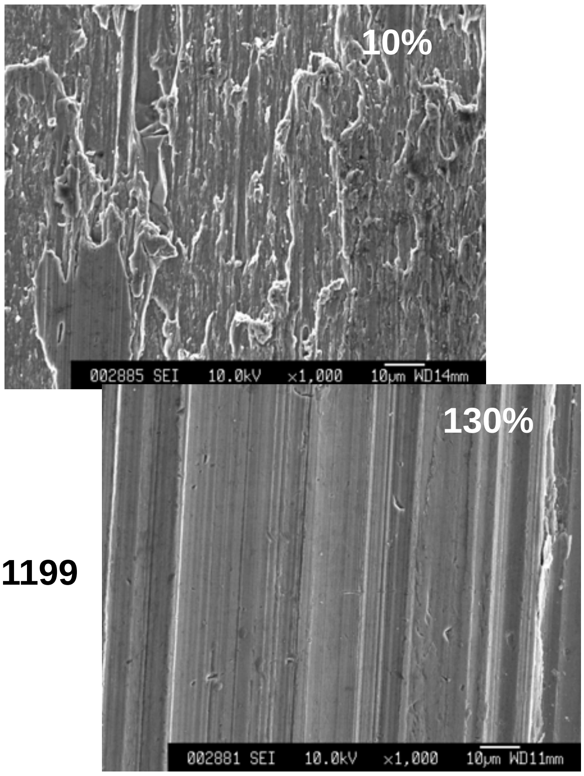
工作機械の仕様

Spindle	Type	Aerostatic bearing
	Diameter	50 mm
	Rotational speed	5,000～50,000 rpm
	Rotational accuracy	(at 50,000 rpm)
	axial	0.2µm
	radial	0.2µm
Table	Stroke (X-axis)	60 mm
	(Z-axis)	150 mm
	Motion error	
	Yawing (X-axis)	0.1µm/60 mm
	Pitching (X-axis)	0.1µm/60 mm
	Yawing (Z-axis)	0.1µm/150 mm
	Pitching (Z-axis)	0.1µm/150 mm
	Feed rate	1～1260 µm/min
	Resolution	10 nm/step

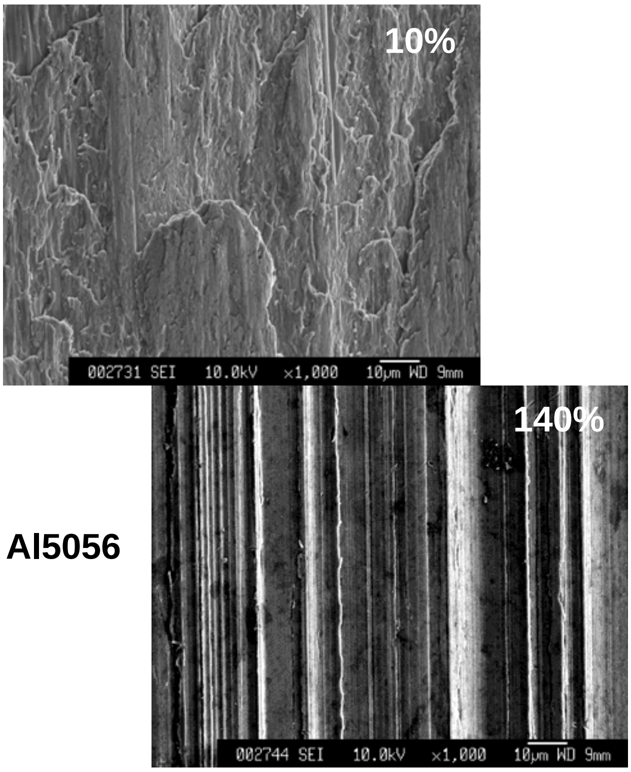
実験条件

Grinding wheel	**SD140N100M60 3.0**
Work piece	**Al alloy A5056 (v_p =300m/s)** **Pure Al (99.99%) A1199 (v_p =200m/s)**
Workpiece diameter	**150 mm**
Wheel diameter	**200 mm**
Depth of cut	**0.5, 1 µm/step (or 21.7 nm/rev)**
Speed ratio V_s / v_w	**1**
Speed ratio $(V_s + v_w)/v_p$	**10, 60, 80, 90, 100, 110, 140%**

Morphology

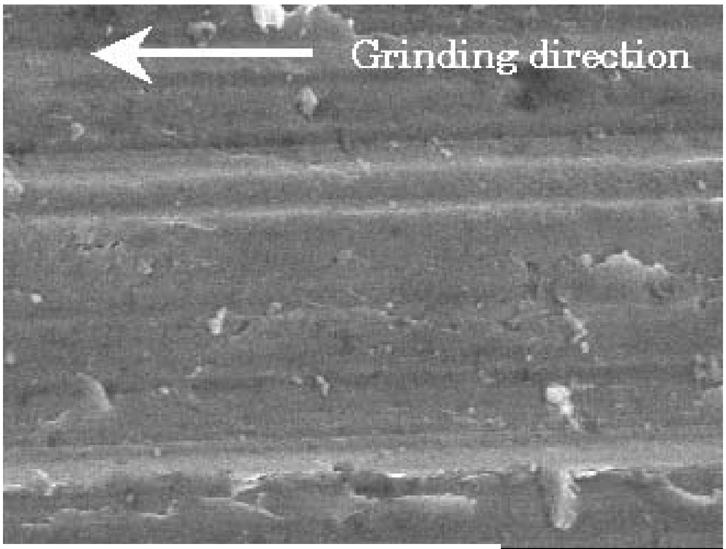


Al1199

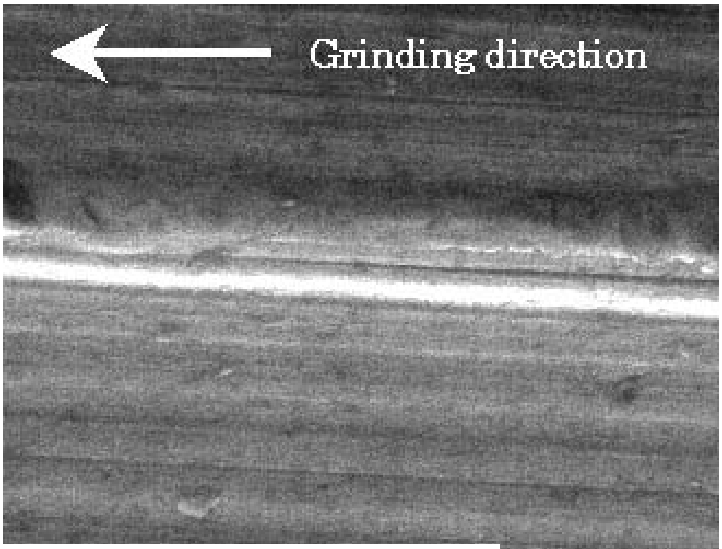


Al5056

Zoom up view (by SEM)

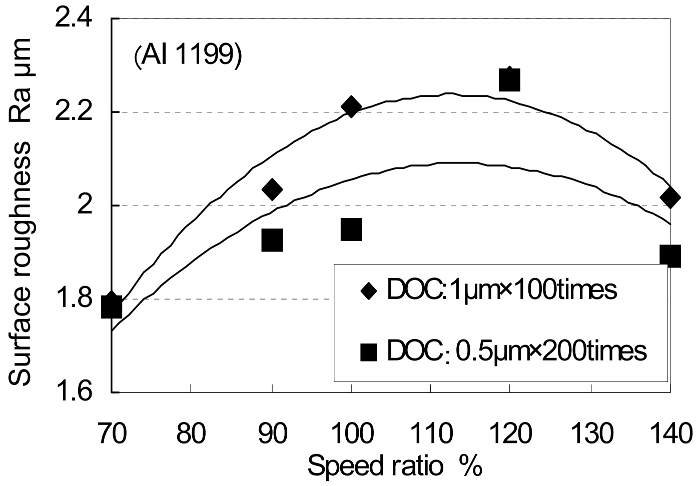


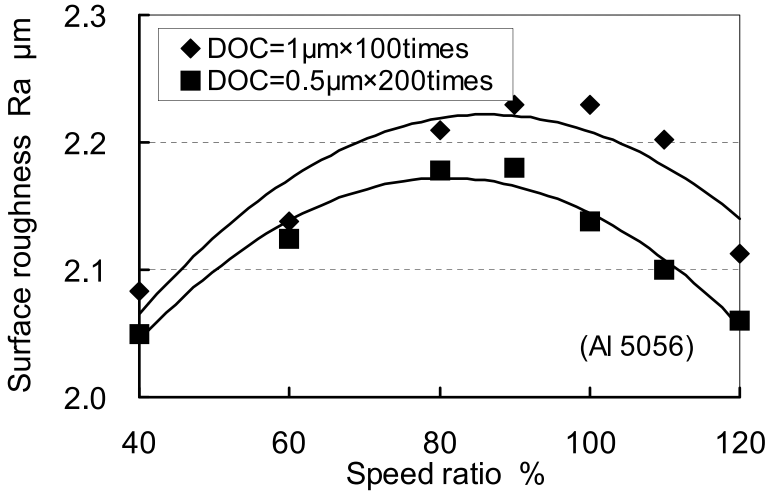
(a) $Vs+v_w=140\text{m/s}$



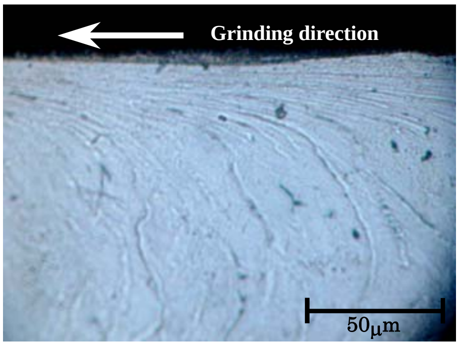
(b) $Vs+v_w=280\text{m/s}$

Roughness variation

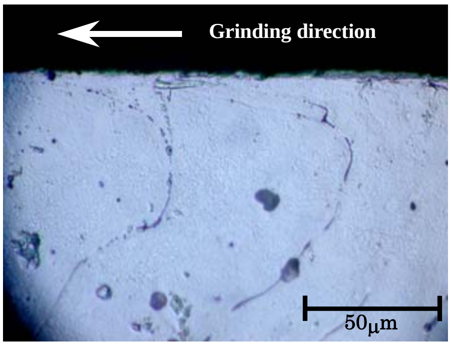




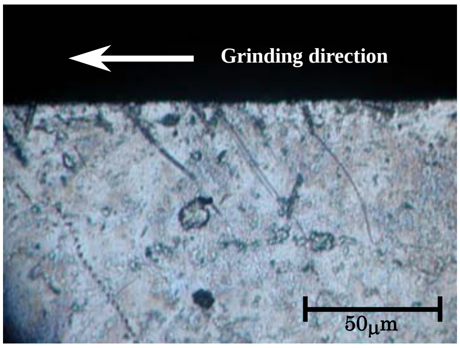
Cross-sectional view



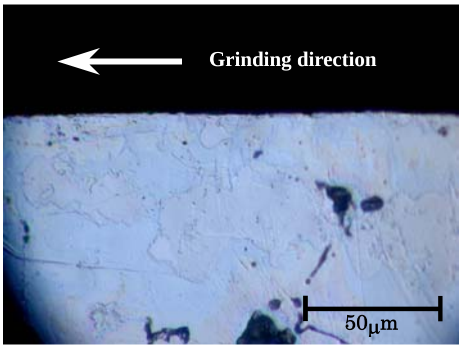
(a) Al 1199 at speed ratio of 10%



(b) Al 5056 at speed ratio of 60%

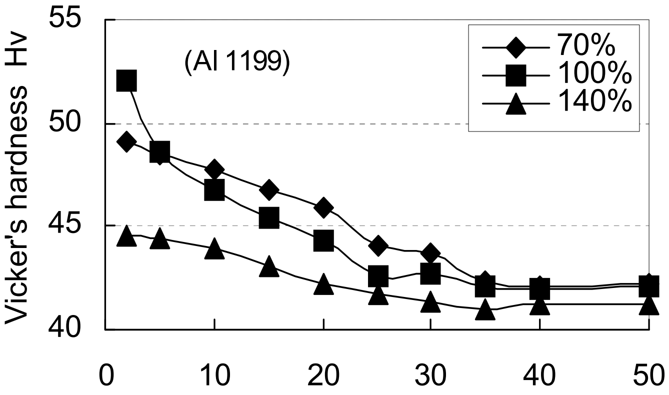


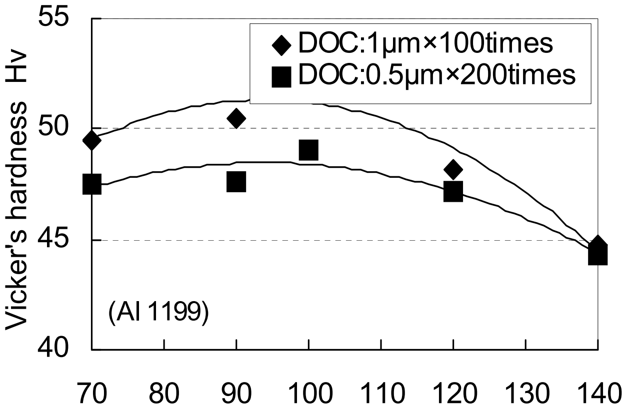
(c) Al 1199 at speed ratio of 140%

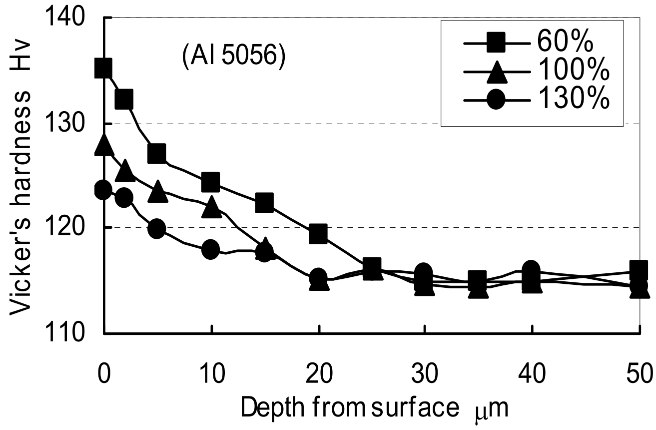


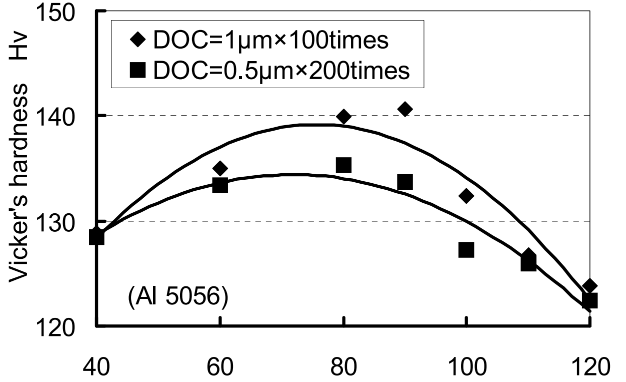
(d) Al 5056 at speed ratio of 130%

Hardness variation

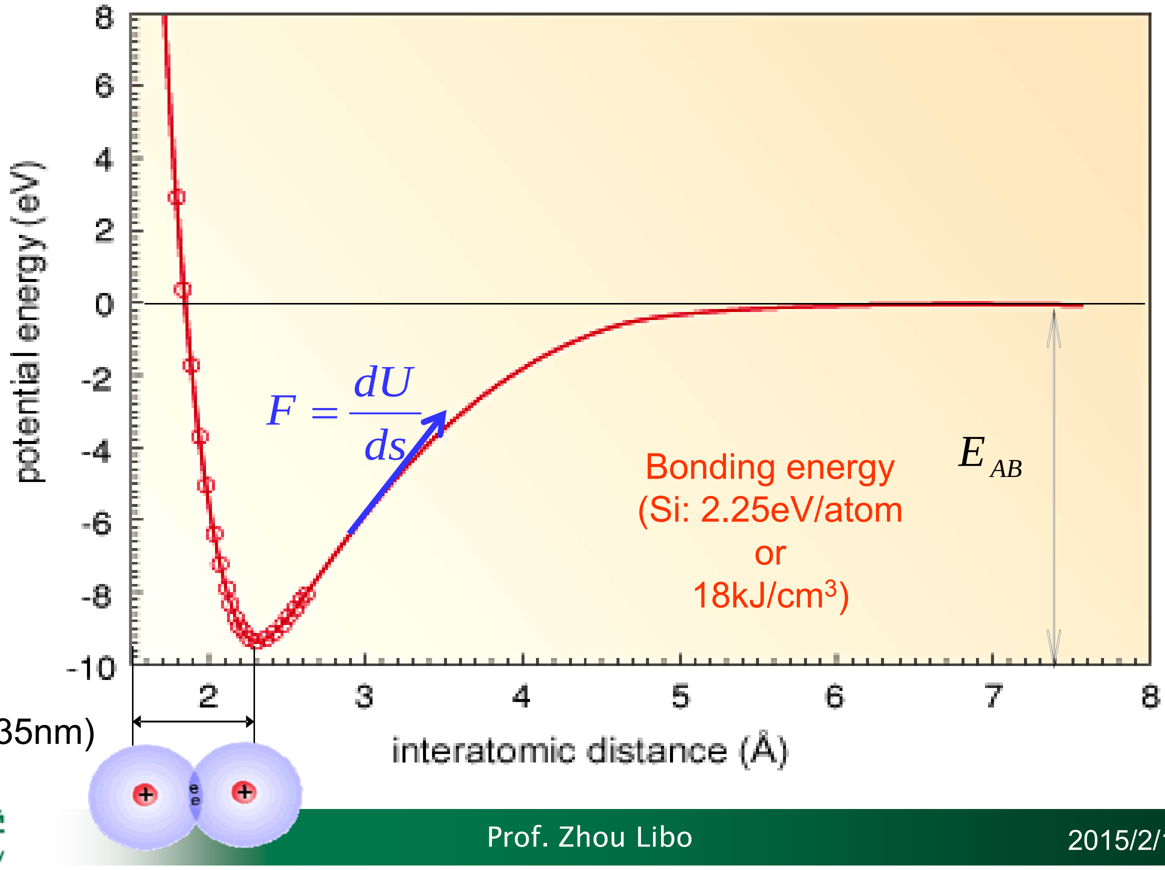








原子間結合エネルギ

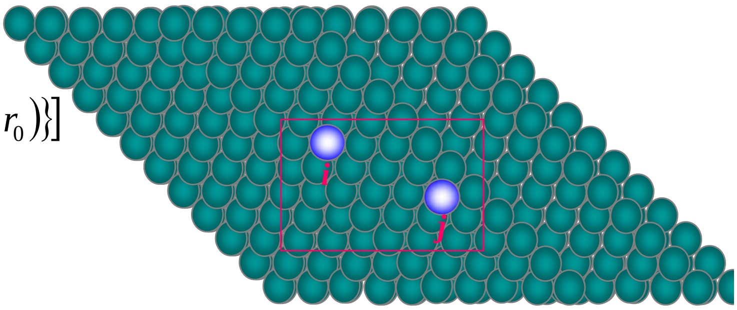


Interatomic spacing（0.235nm)

Interatomic force ➔ Movements

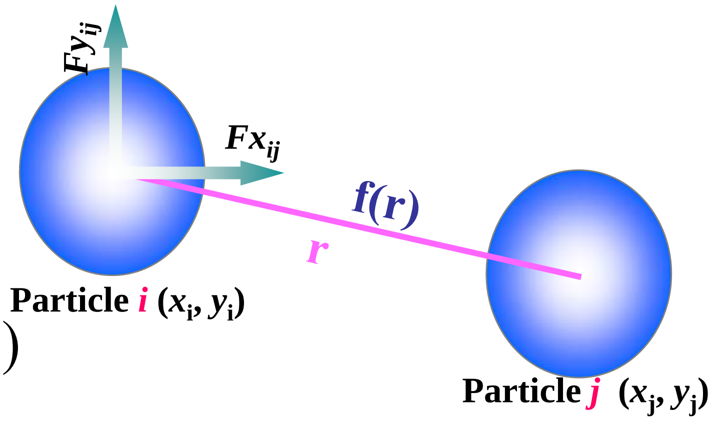
Inter-atomic force given by potential

$$f(r)=\frac{d\phi(r)}{dr}=2\alpha D\left[\exp\{-2\alpha(r-r_0)\}-\exp\{-\alpha(r-r_0)\}\right]$$



Interaction between particle *i* and *j*

$$\begin{cases} Fx_{ij}=\dfrac{x_i-x_j}{r_{ij}}f(r) \\ Fy_{ij}=\dfrac{y_i-y_j}{r_{ij}}f(r) \end{cases}$$



Force acting on the particle *i*

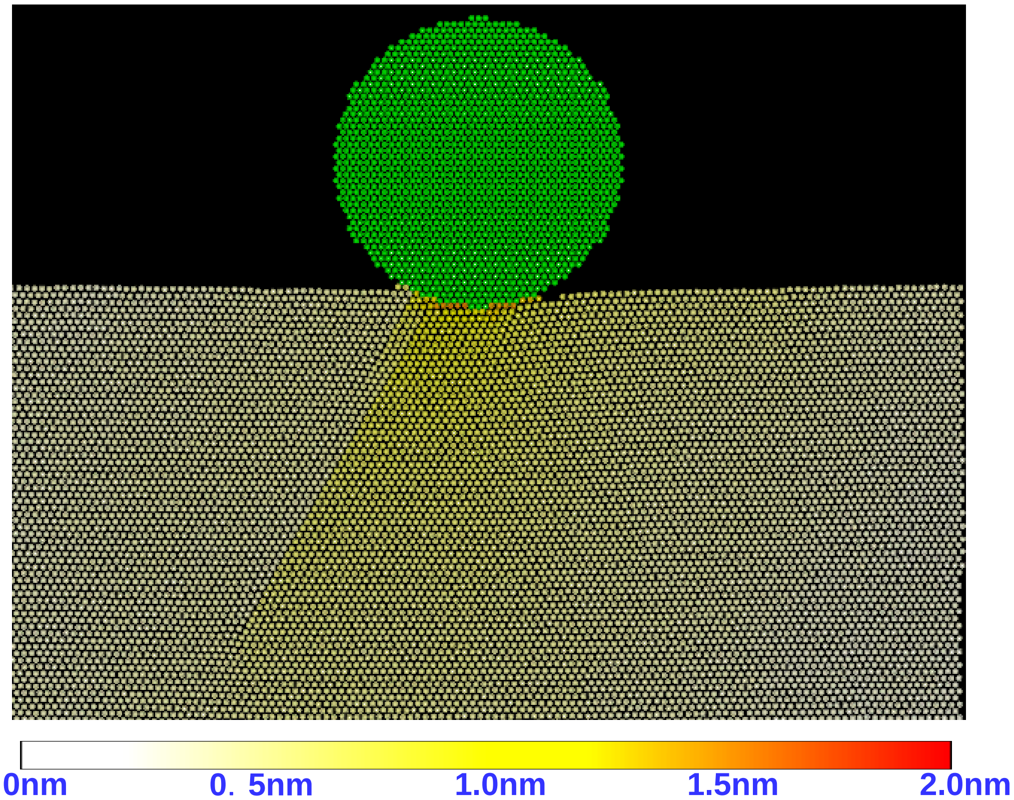
$$\begin{cases} Fx_i=\sum Fx_{ij} \\ Fy_i=\sum Fy_{ij} \end{cases} \qquad m\frac{d^2\boldsymbol{r}_i(t)}{dt^2}=\boldsymbol{F}_i(t)$$

Simulation parameters

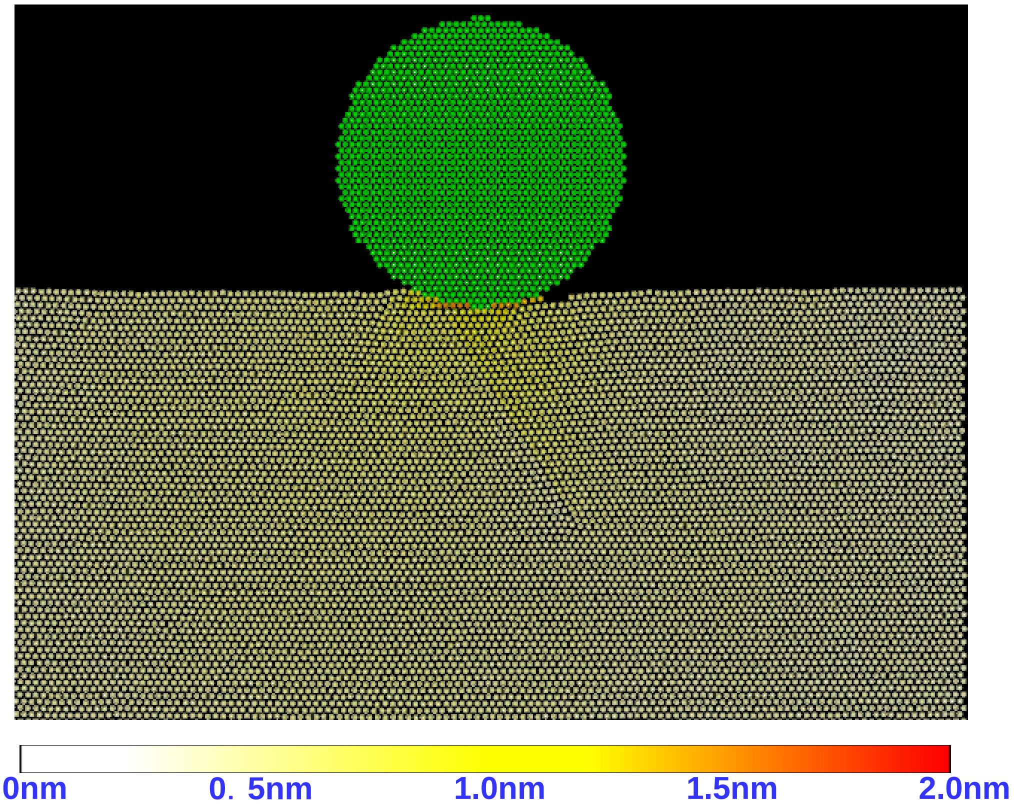
Abrasive grain	**Rigid diamond C (111)**
Workpiece	**Al (111) (fcc metal) (plasticity propagation speed $\underline{v_p = 200\sim300\text{m/s}}$)**
Model	**2-D Plane strain**
Inter-atomic potential	**Morse (Al-Al, Al-C)**
Integral calculation	**Leap frog**
Initial temperature *T*	**300 K**
Diameter of abrasive *D*	**10.4 nm**
Grinding speed *V*	**50 - 2000m/s**
Work speed *v*	**0**
Depth of cut *d*	**2 nm (8 atom layers)**
Grinding distance *l*	**67 nm**

$$v_p=\sqrt{\frac{1}{\rho}\cdot\frac{\partial\sigma_{sp}}{\partial\varepsilon_{sp}}}$$

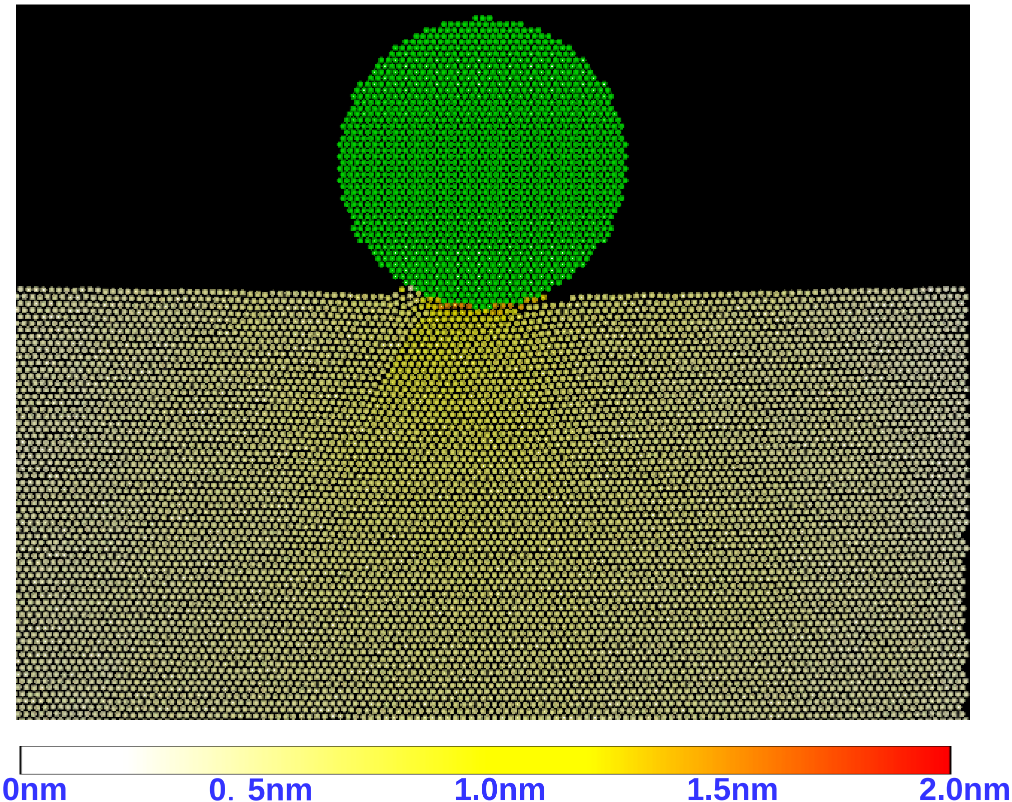
Traveling distance at V＝100m/s



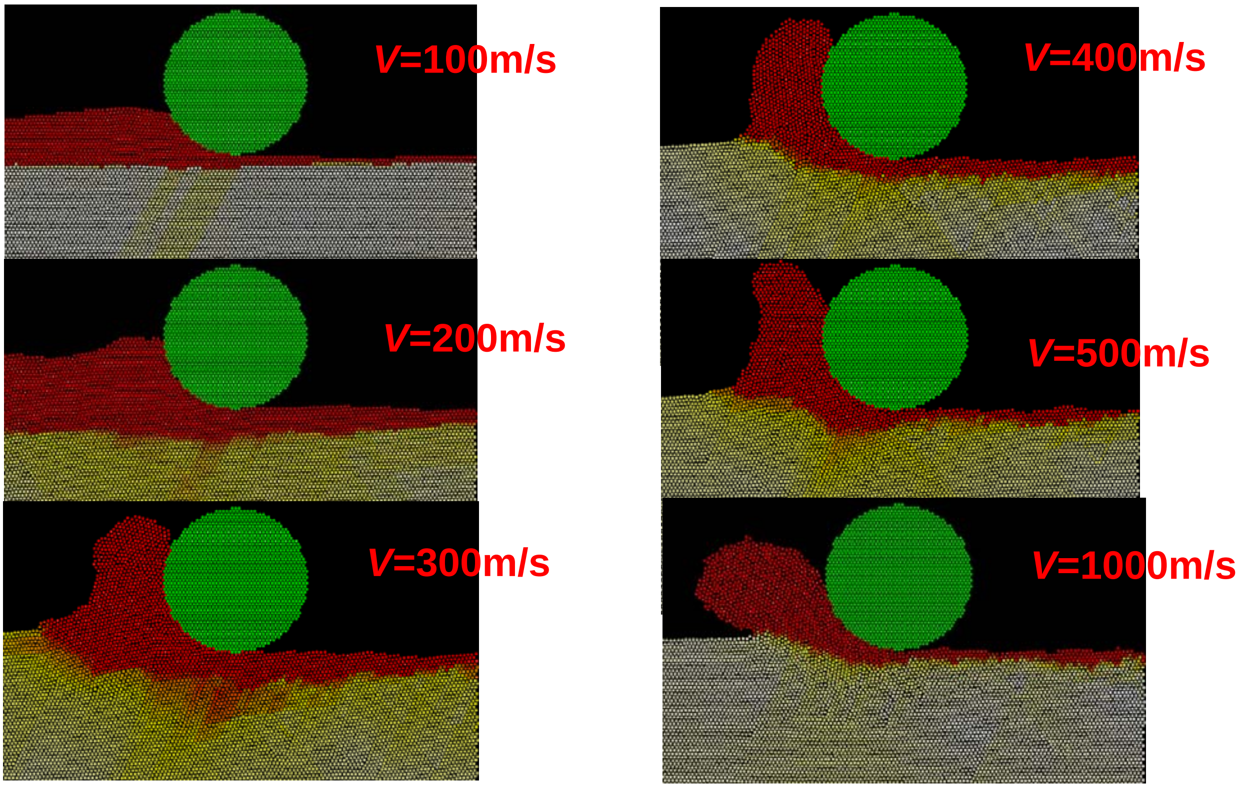
Traveling distance at V＝300m/s



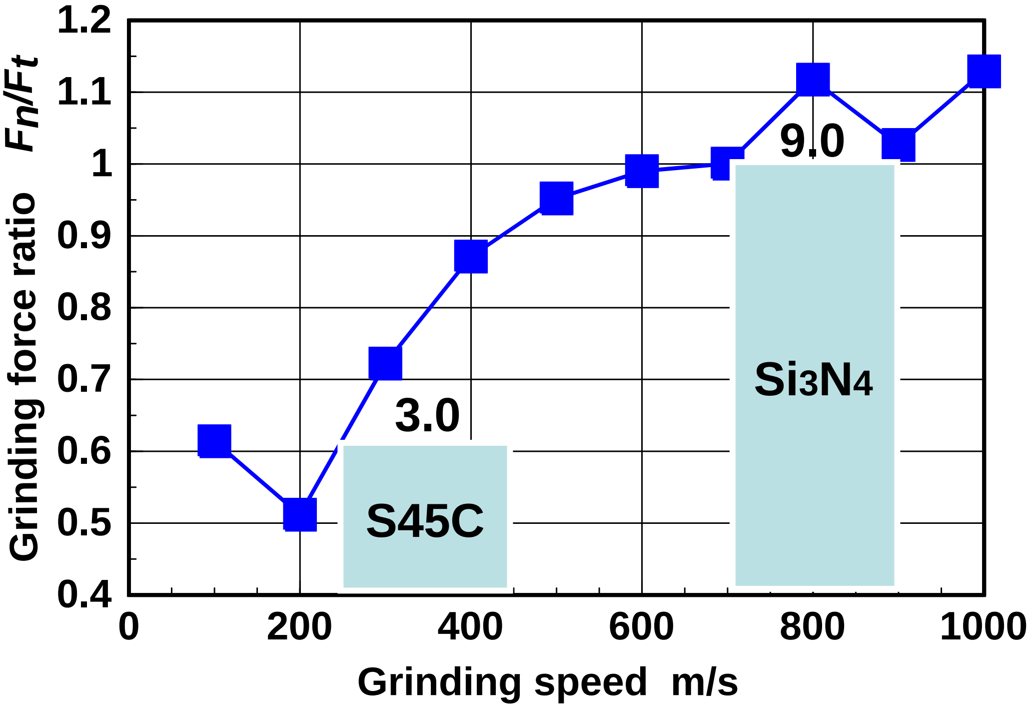
Traveling distance at V＝1000m/s



Traveling Distance of Atom



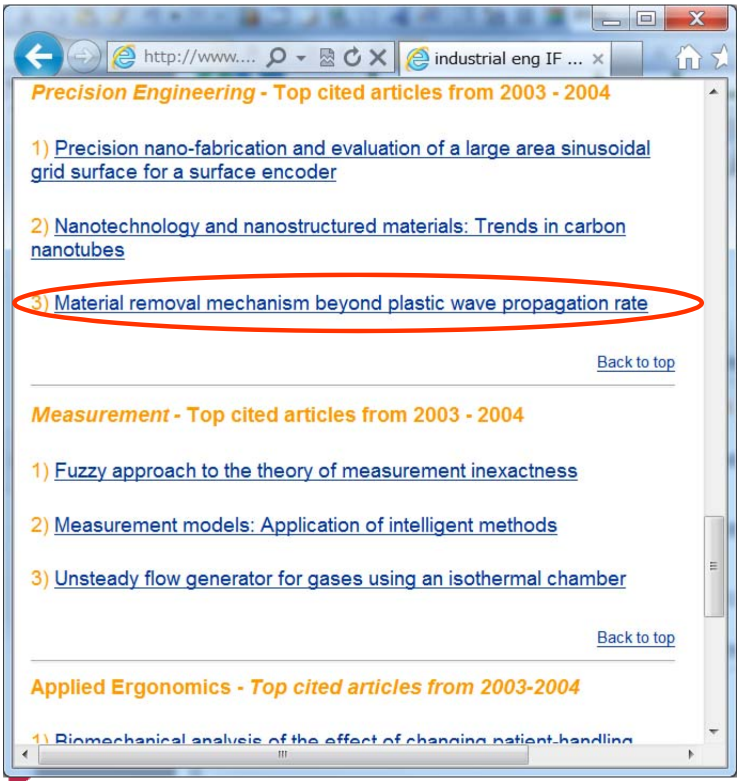
Grinding Force Ratio



得られた成果

- “High speed” は再定義する必要がある：塑性伝播速度と材料に依存.
- 塑性伝播速度を超えて切削すると，延性材料の弾性域が大きくなり，脆性的な挙動を示す．その結果，塑性変形が小さくなり，仕上げ面粗さを含む加工品位の向上ができる.
- 分子動力学シミュレーションにより，上述の現象を理論的に証明した.

Top cited paper of PE in 2003/04



Precision Engineering - Top cited articles from 2003 - 2004

1) Precision nano-fabrication and evaluation of a large area sinusoidal grid surface for a surface encoder

2) Nanotechnology and nanostructured materials: Trends in carbon nanotubes

3) Material removal mechanism beyond plastic wave propagation rate

Back to top

Measurement - Top cited articles from 2003 - 2004

1) Fuzzy approach to the theory of measurement inexactness

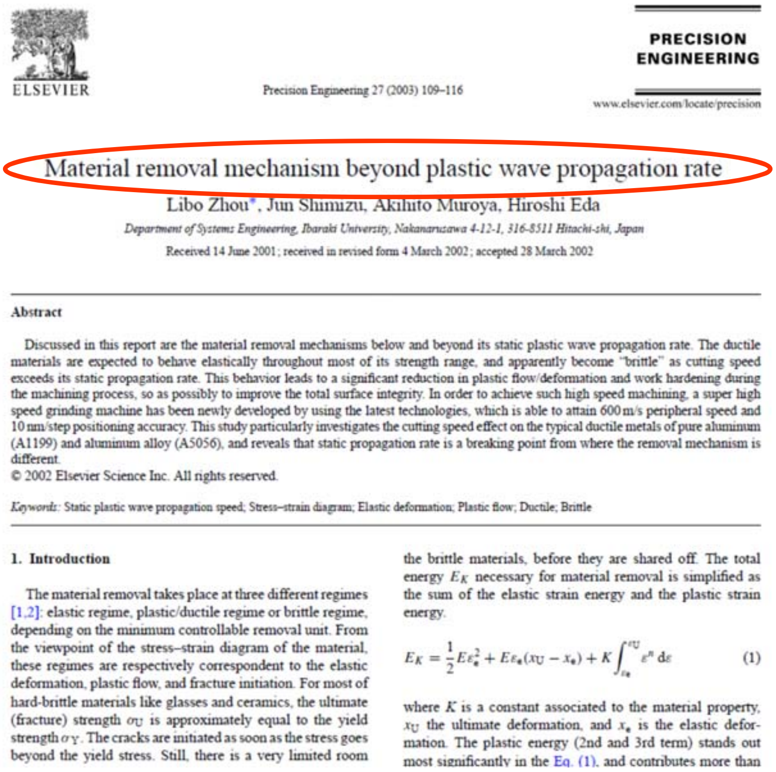
2) Measurement models: Application of intelligent methods

3) Unsteady flow generator for gases using an isothermal chamber

Back to top

Applied Ergonomics - Top cited articles from 2003-2004

1) Biomechanical analysis of the effect of changing patient-handling



ELSEVIER

Precision Engineering 27 (2003) 109–116

PRECISION ENGINEERING

www.elsevier.com/locate/precision

Material removal mechanism beyond plastic wave propagation rate

Libo Zhou*, Jun Shimizu, Akihito Muroya, Hiroshi Eda

Department of Systems Engineering, Ibaraki University, Nakanarusawa 4-12-1, 316-8511 Hitachi-shi, Japan

Received 14 June 2001; received in revised form 4 March 2002; accepted 28 March 2002

Abstract

Discussed in this report are the material removal mechanisms below and beyond its static plastic wave propagation rate. The ductile materials are expected to behave elastically throughout most of its strength range, and apparently become "brittle" as cutting speed exceeds its static propagation rate. This behavior leads to a significant reduction in plastic flow/deformation and work hardening during the machining process, so as possibly to improve the total surface integrity. In order to achieve such high speed machining, a super high speed grinding machine has been newly developed by using the latest technologies, which is able to attain 600 m/s peripheral speed and 10 nm/step positioning accuracy. This study particularly investigates the cutting speed effect on the typical ductile metals of pure aluminum (A1199) and aluminum alloy (A5056), and reveals that static propagation rate is a breaking point from where the removal mechanism is different.

© 2002 Elsevier Science Inc. All rights reserved.

Keywords: Static plastic wave propagation speed; Stress–strain diagram; Elastic deformation; Plastic flow; Ductile; Brittle

1. Introduction

The material removal takes place at three different regimes [1,2]: elastic regime, plastic/ductile regime or brittle regime, depending on the minimum controllable removal unit. From the viewpoint of the stress–strain diagram of the material, these regimes are respectively correspondent to the elastic deformation, plastic flow, and fracture initiation. For most of hard-brittle materials like glasses and ceramics, the ultimate (fracture) strength σ_U is approximately equal to the yield strength σ_Y. The cracks are initiated as soon as the stress goes beyond the yield stress. Still, there is a very limited room the brittle materials, before they are shared off. The total energy E_K necessary for material removal is simplified as the sum of the elastic strain energy and the plastic strain energy.

$$E_K = \frac{1}{2}E\varepsilon_e^2 + E\varepsilon_e(x_U - x_e) + K\int_{\varepsilon_e}^{\varepsilon_U} \varepsilon^n \, d\varepsilon \quad (1)$$

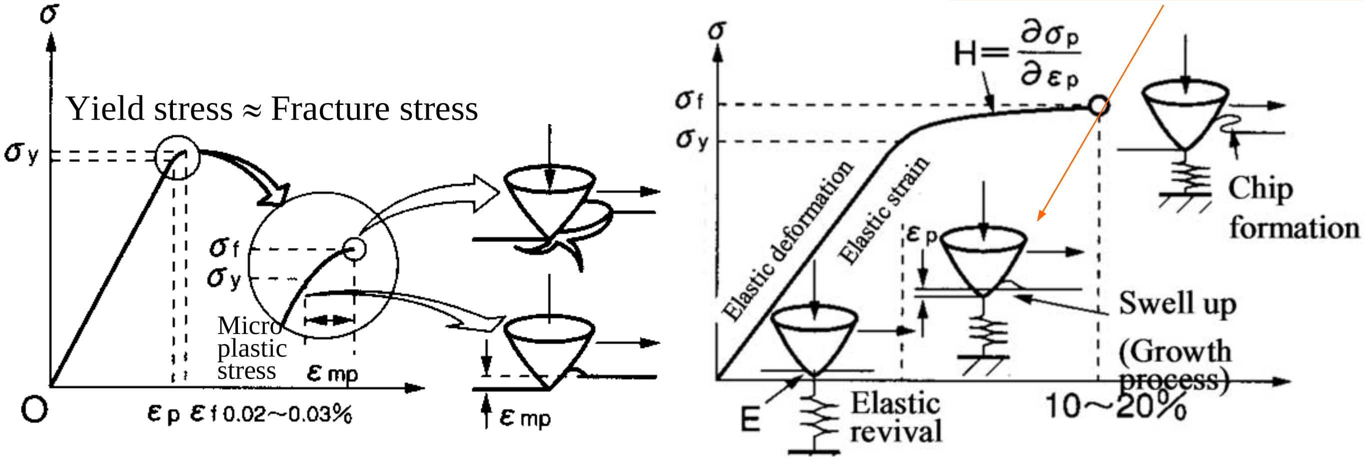
where K is a constant associated to the material property, x_U the ultimate deformation, and x_e is the elastic deformation. The plastic energy (2nd and 3rd term) stands out most significantly in the Eq. (1), and contributes more than

---

脆性材料 vs. 延性材料

応力ーひずみ曲線

注意：塑性変形エネルギ➔熱



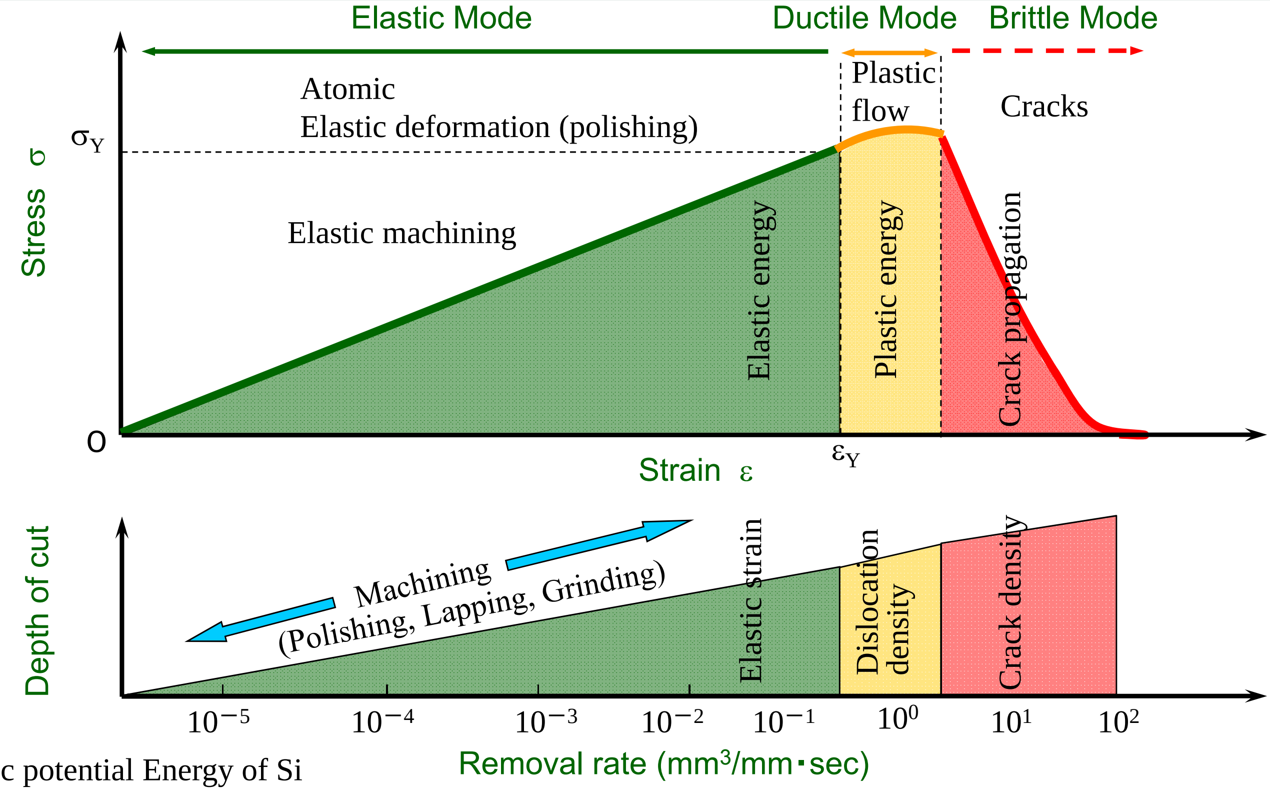
(a) Brittle material

脆性材料

(b) Ductile material

延性材料

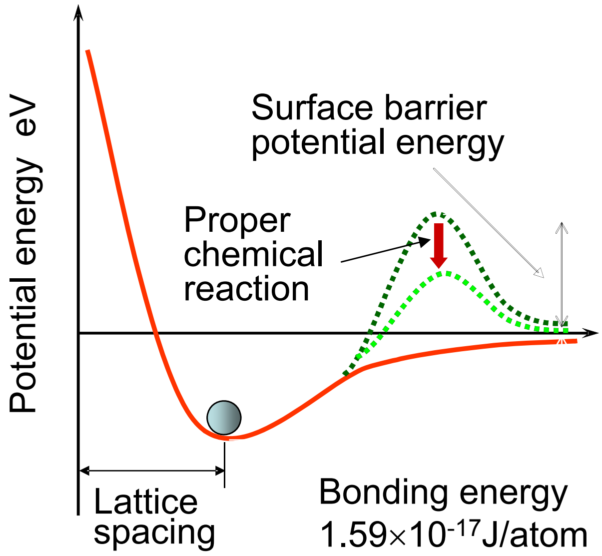
加工のモード



Atomic potential Energy of Si
(15.9x10^{-18} J/atom or 8x10^{5} J/cm^{3})

研究目的と方法

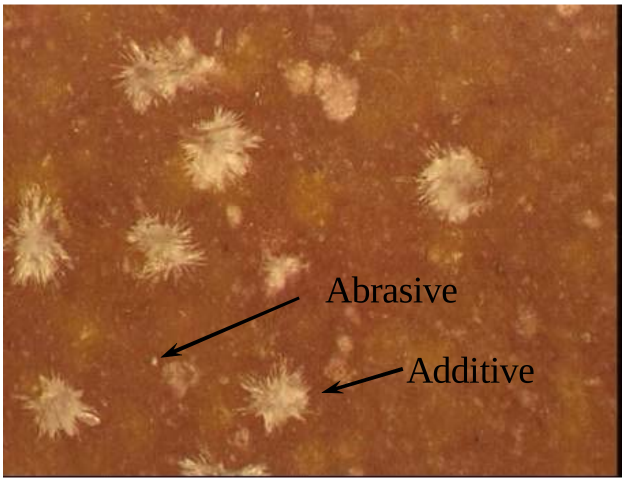
- Objective
  - to generate a perfect (defect free) surface by fixed abrasive process
- Methodology
  - by introducing chemical reaction into grinding process



Expected chemical reaction

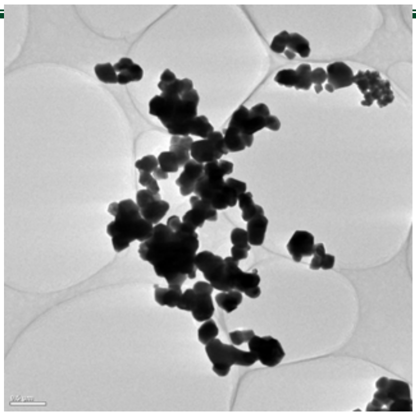
Abrasive (CeO_2,SiO_2) ⇔ Si
Additives (Na_2CO_3) ⇔ Si
Coolant (KOH) ⇔ Si

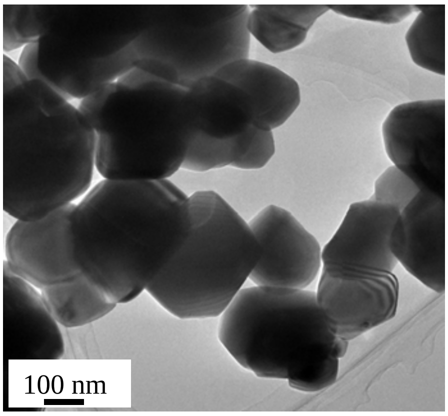
CMG wheel

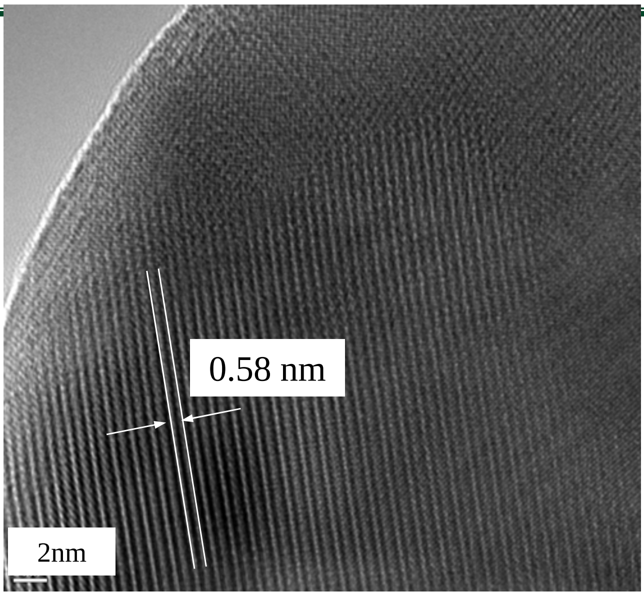


CEROX 1650 Av. Size: 2±1μm, purity: 70%

CeO$_2$ abrasives







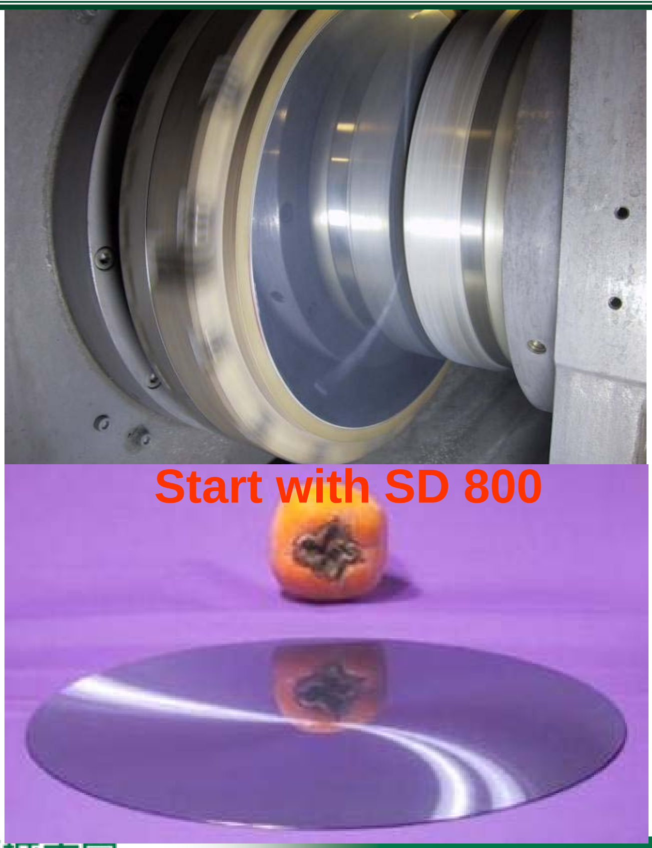
Lattice fringe with spacing 0.58 nm

Average particle size : 1.5μm

Experimental conditions

Machine tool	Horizontal type precision grinder	
Wheel	SD800J75DK100	CMG3000
Workpiece	ϕ300mm Si wafer [100]	
Work revolution	1500 rpm	500 rpm
Wheel revolution	50 rpm	50 rpm
Feed rate	30, 20,10 μm/min	0.1 [kgf/cm^2]
Coolant	10 [ℓ/min]	Dry, (10 [ℓ/min])

Dry CMG process

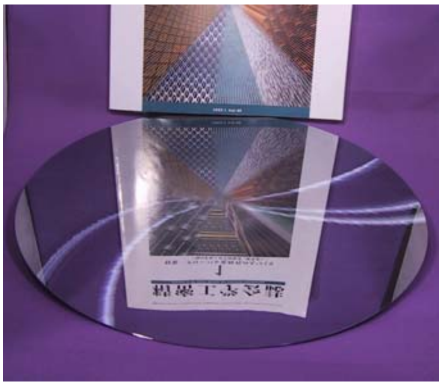


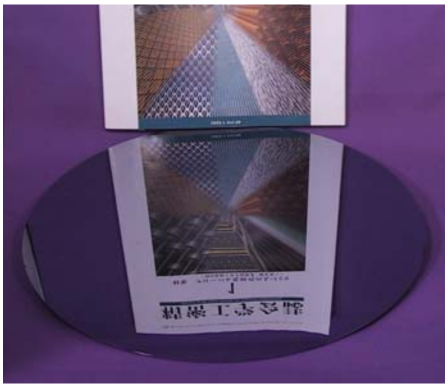
Start with SD 800

Finish by CMG

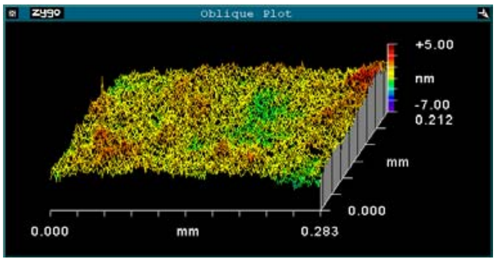
Finished surface roughness

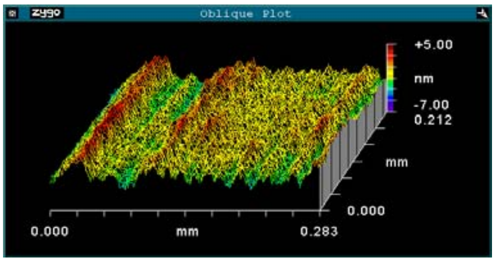
Polished SD3000 CMG

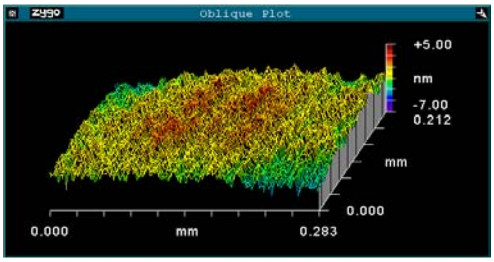




Commercialized year 2000 year 2002





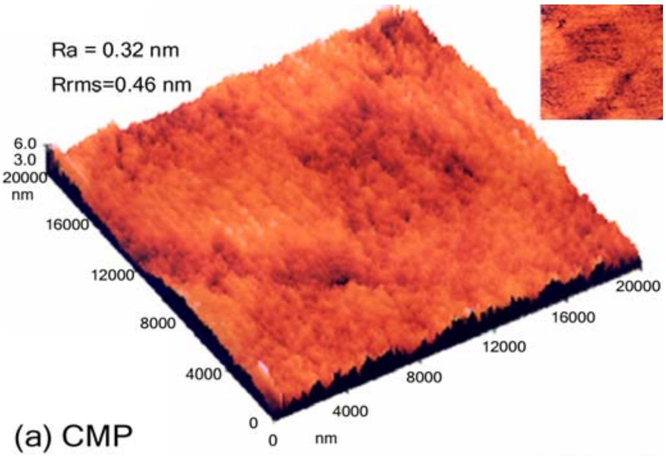


Ra=0.76nm, Ry=5.2nm

Ra=0.81nm, Ry=5.8nm

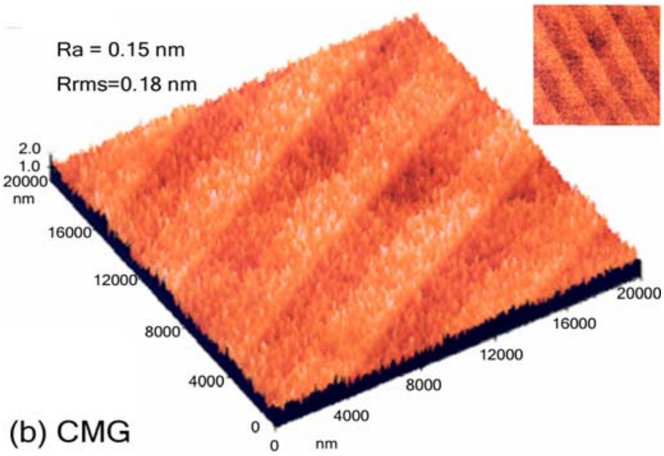
Ra=0.79nm, Ry=5.4nm

AFM observation on (100)


Ra = 0.32 nm

Rrms=0.46 nm

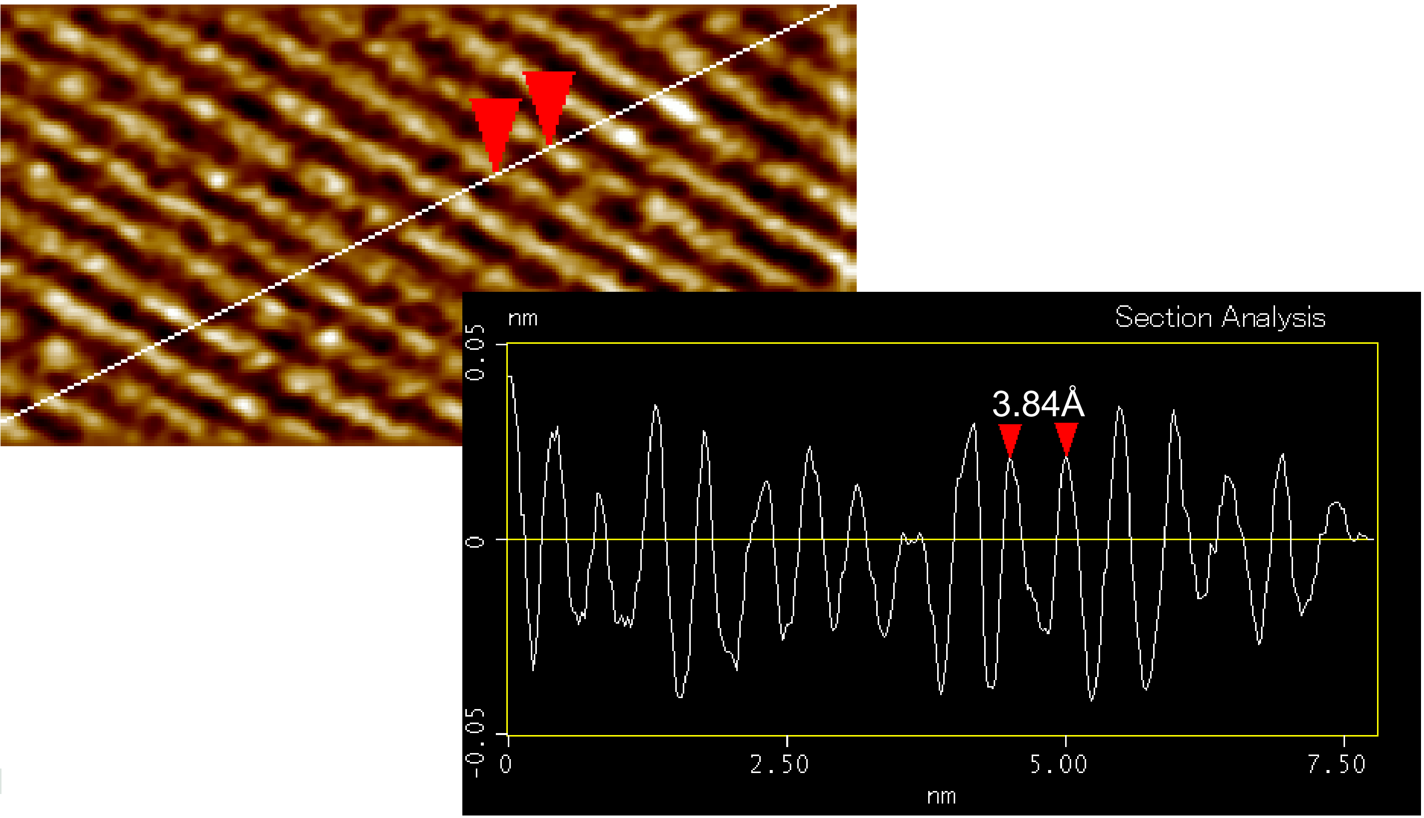
(a) CMP


Ra = 0.15 nm

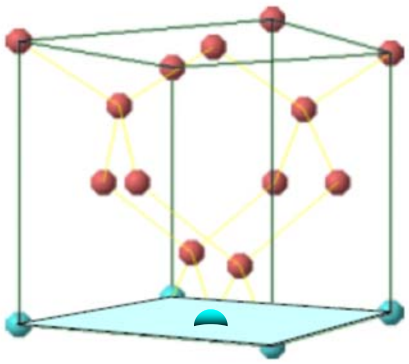
Rrms=0.18 nm

(b) CMG

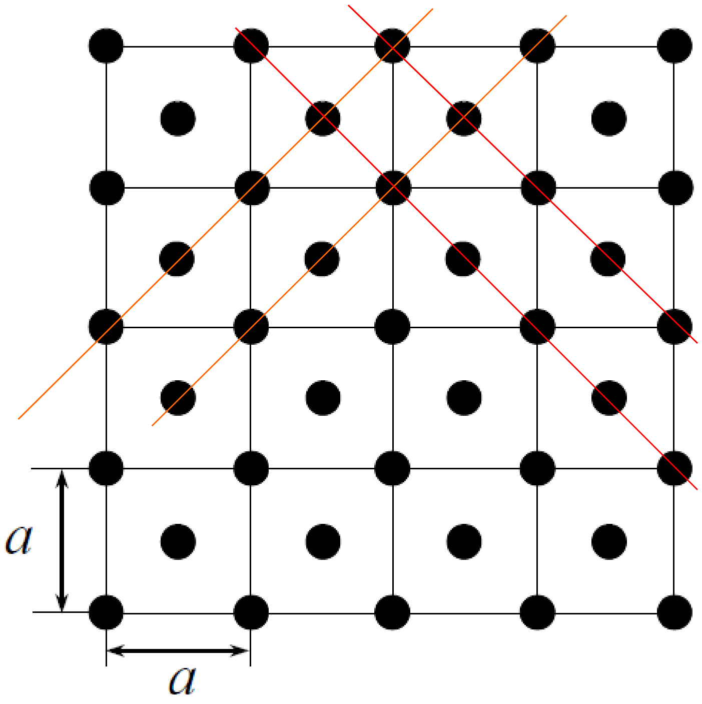
CMG quality



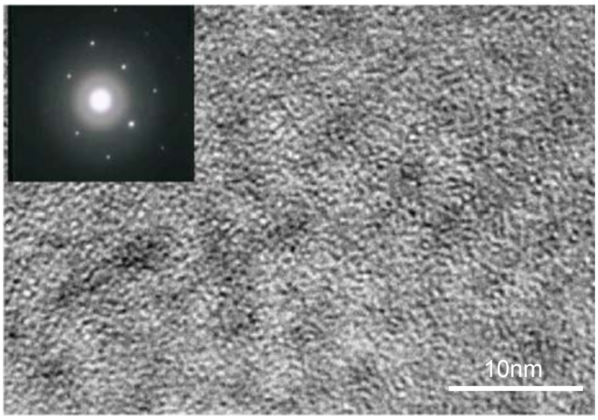
{100} plan @ 0a position



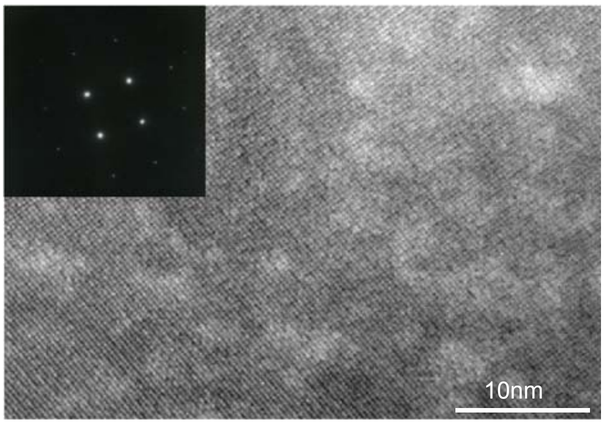
$\sqrt{2}/2a = 3.84$ Å



TEM observation

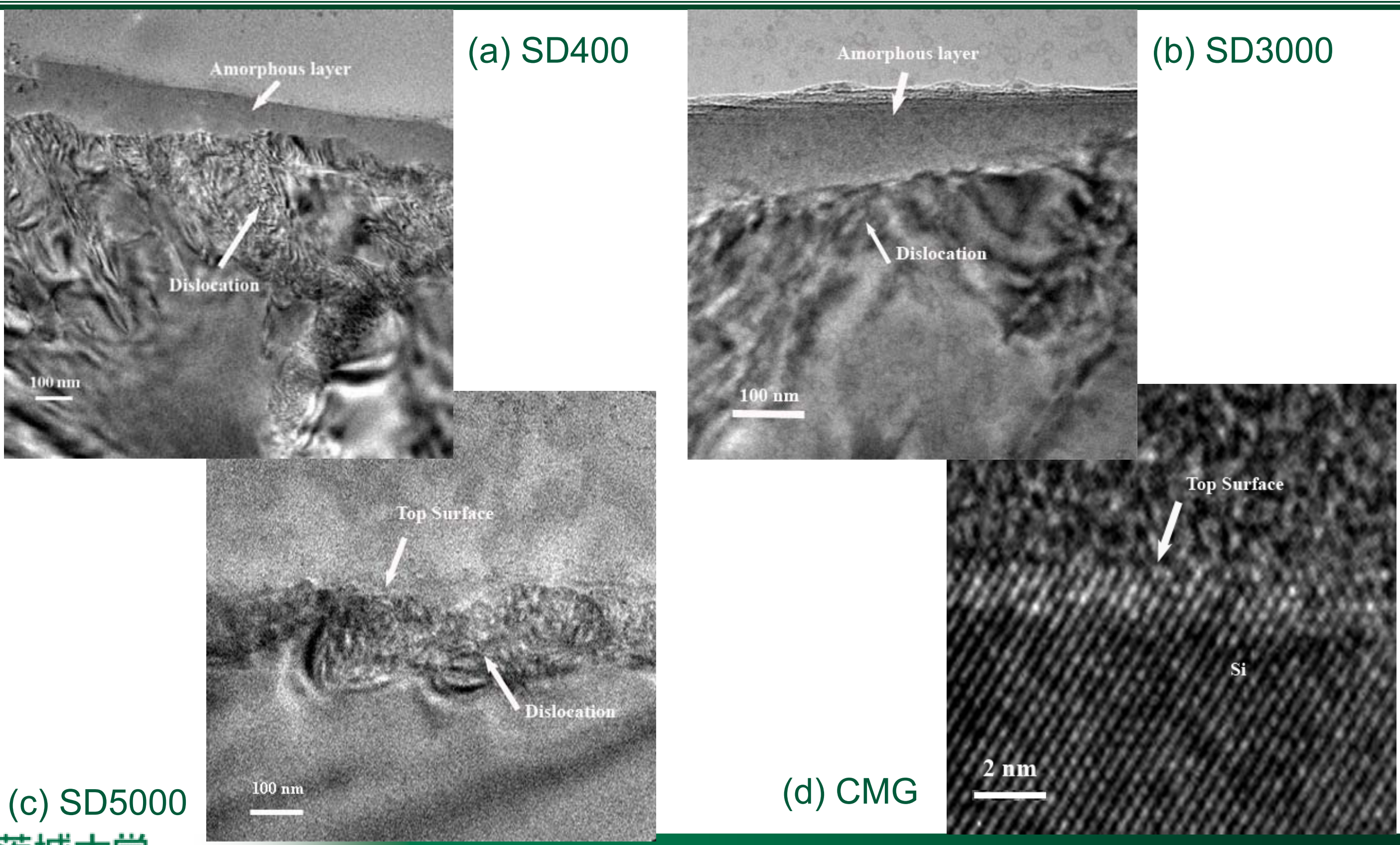


(a) CMP



(b) CMG

TEM observation



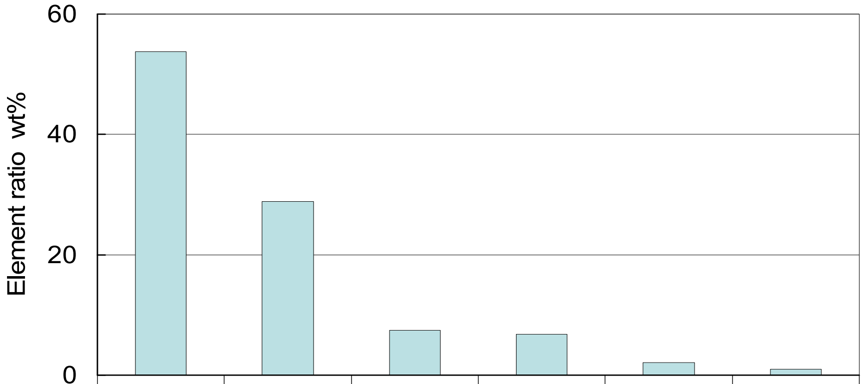
(a) SD400

(b) SD3000

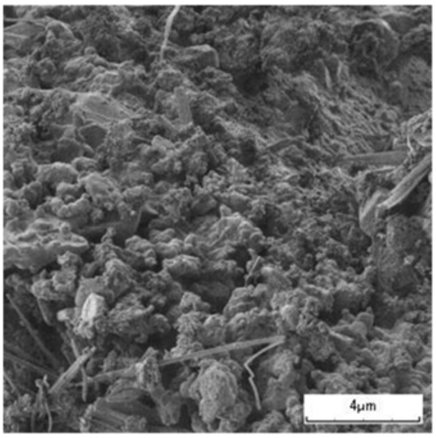
(c) SD5000

(d) CMG

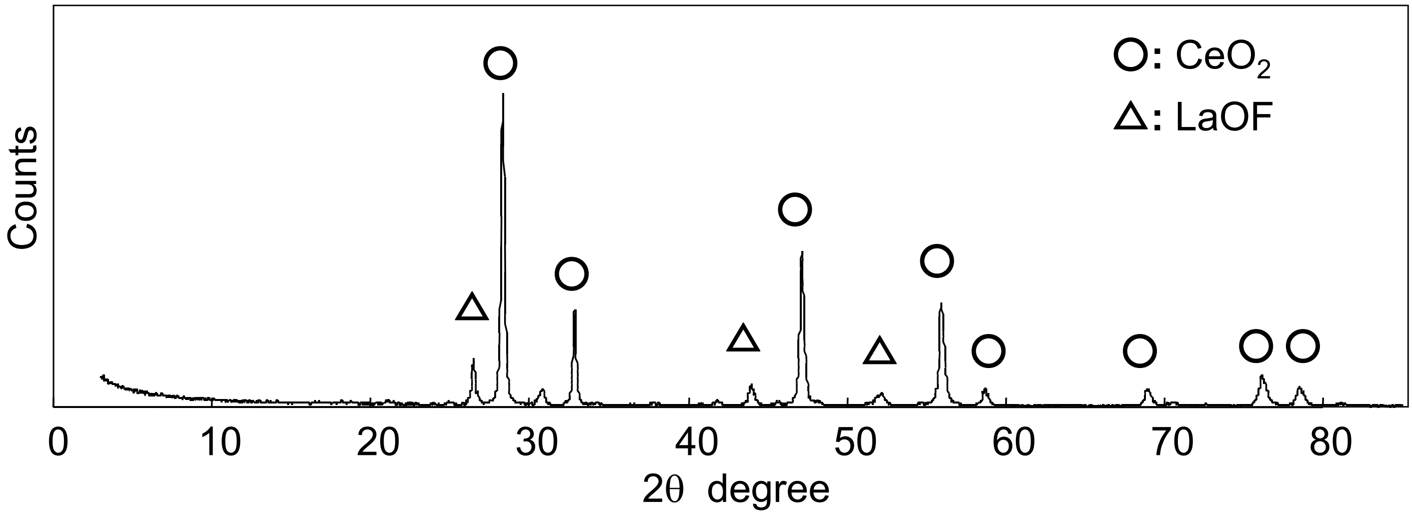
CMG Wheel element analysis



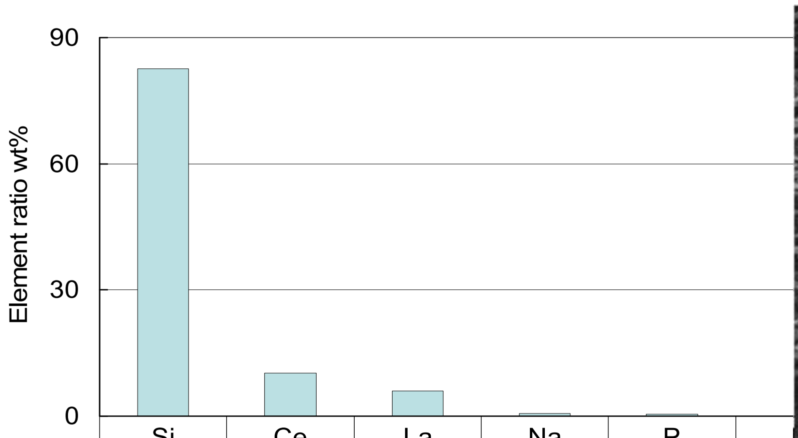
	Ce	La	Na	F	P	Si
wt%	53.8	28.9	7.5	6.8	2.1	1.0



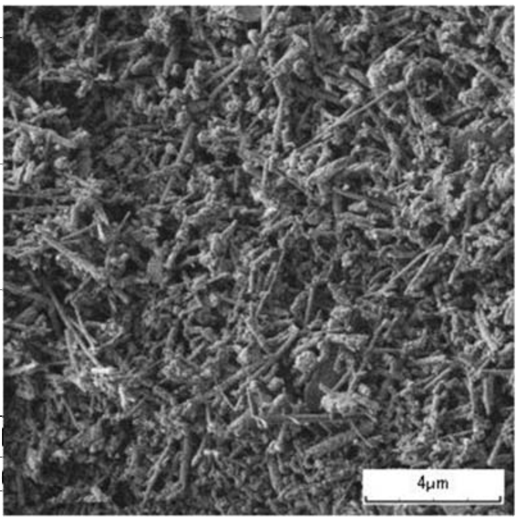
CMG wheel composition analysis



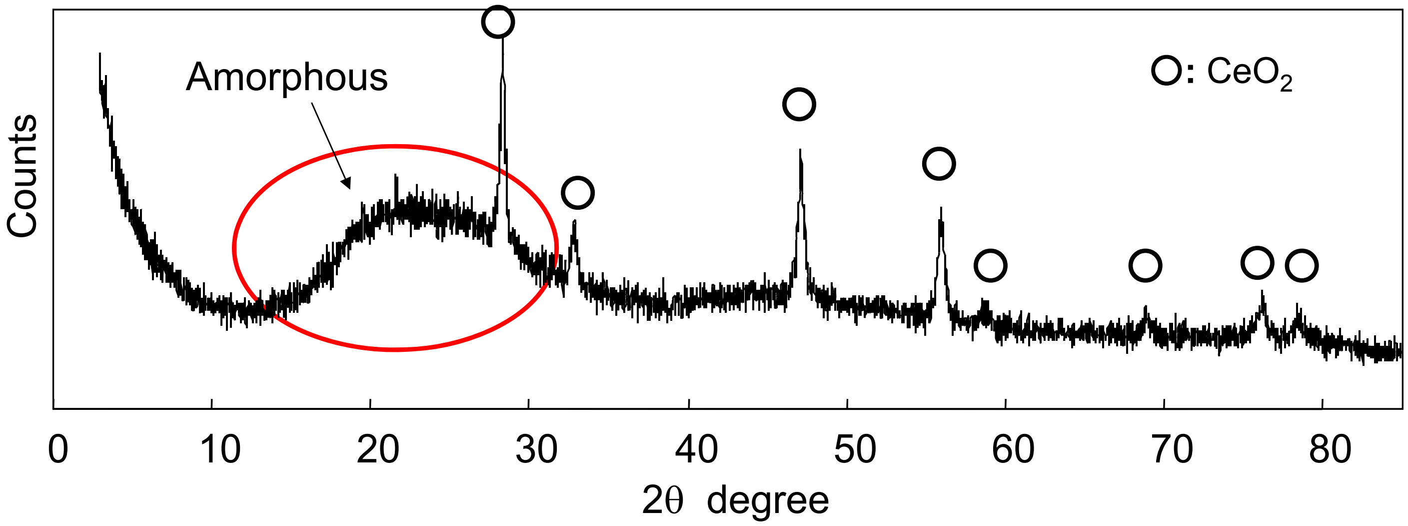
Grinding waste element analysis



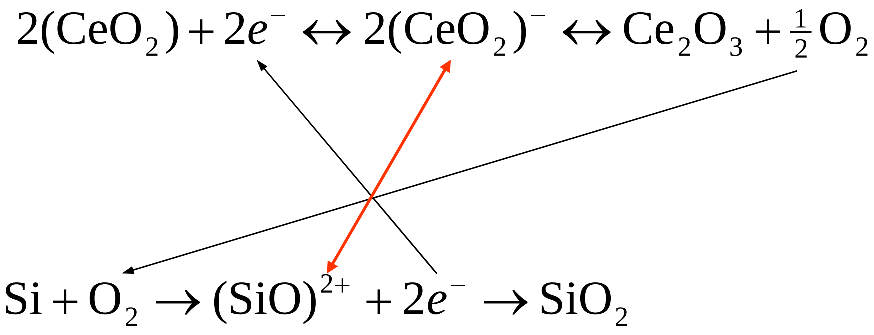
	Si	Ce	La	Na	P
wt%	82.6	10.3	6.0	0.6	0.4



Grinding waste composition analysis



Chemical reaction at CMG



$$2(\mathrm{CeO_2}) + 2e^- \leftrightarrow 2(\mathrm{CeO_2})^- \leftrightarrow \mathrm{Ce_2O_3} + \tfrac{1}{2}\mathrm{O_2}$$

$$\mathrm{Si} + \mathrm{O_2} \rightarrow (\mathrm{SiO})^{2+} + 2e^- \rightarrow \mathrm{SiO_2}$$

⇩

$$(\mathrm{SiO})^{2+} + 2(\mathrm{CeO_2})^- \rightarrow \mathrm{Ce_2O_3} \cdot \mathrm{SiO_2}$$

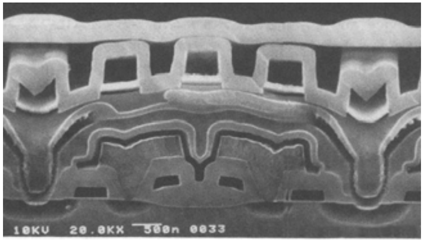
(Amorphous)

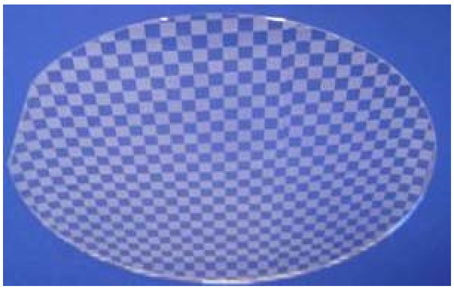
Process simplification

Wafer	Single crystal Silicon (100), t=850➔ 100 μm	
Process	CMP (commercialized)	CMG
1st stage	Lapping (or grinding) (detail unknown)	Grinding by SD800 V = 2000min^{-1}, v = 500min^{-1}, f = 20mm/min
2nd stage	Polishing (detail unknown)	Grinding by CMG3000, V = 500min^{-1}, v = 50min^{-1}, P = 0.01MPa
3rd stage	Polishing (detail unknown)	
4th stage	CMP	

CMG の応用

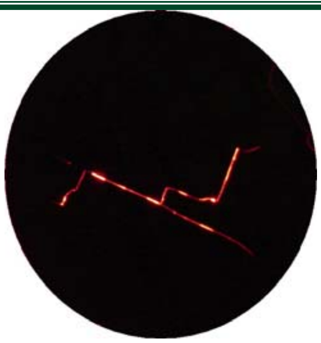
- Back-grinding: extremely thin wafer
  - Power device (IGBT) (Automotive, etc.)
  - Mobile device (Electronics)
- Replacement of free slurry
  - Bare wafer processing（Semiconductor material）
  - Planarization (IC manufacturer)
- Other electronic and photonic substrate
  - Crystallized glass (Electronics and optics)
  - Compound semiconductor (LT, Sapphire)



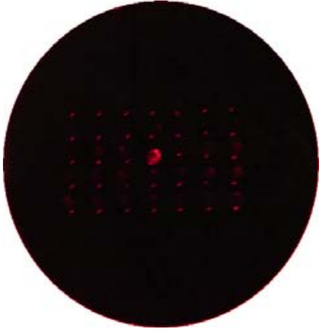


最近の研究成果

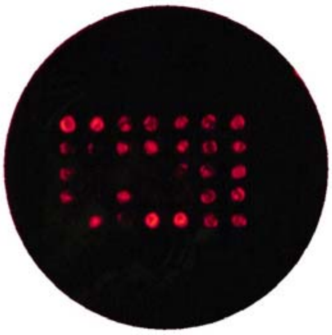
65µm



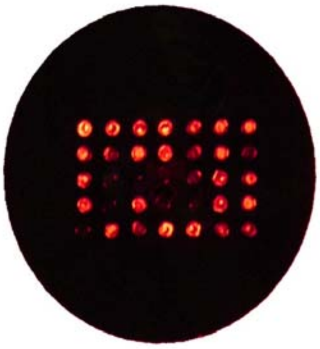
50µm



40µm



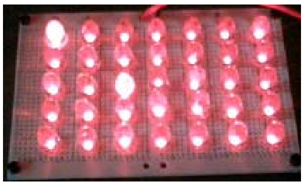
30µm



20µm

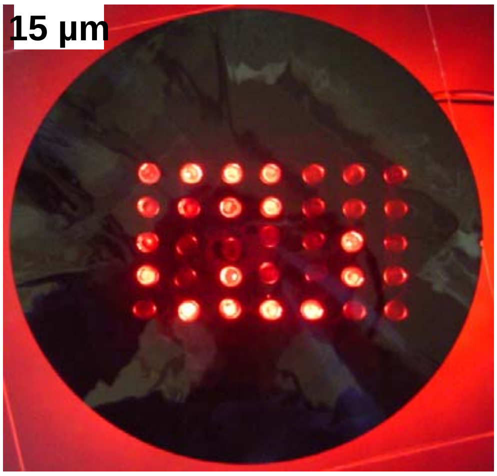
15µm

5µm

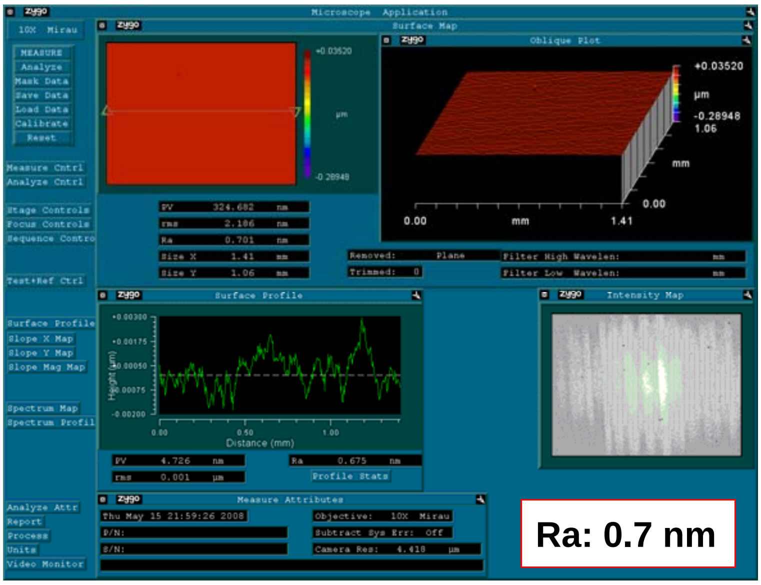


LED panel

Recent results



Extremely-thin ground Si wafer



PV 324.682 nm
rms 2.186 nm
Ra 0.701 nm
Size X 1.41 mm
Size Y 1.06 mm
Removed: Plane
Trimmed: 0
Filter High Wavelen: mm
Filter Low Wavelen: mm

PV 4.726 nm
rms 0.001 µm
Ra 0.675 nm

Thu May 15 21:59:26 2008
P/N:
S/N:
Objective: 10X Mirau
Subtract Sys Err: Off
Camera Res: 4.418 µm

Ra: 0.7 nm

Surface roughness of CMG wafer

Thank you for your attention

Please contact

lbzhou@mx.ibaraki.ac.jp

for question, suggestion or comment.