航空機用材料の切削シミュレーション

第4回CMIシンポジウム
航空機製造技術の飛躍的発展を目指して
― 最新の話題と航空機事業への新規参入について―
平成28年10月14日（金）

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本日のお品書き

1. 切削現象とシミュレーションの流れ
2. 切削シミュレーション
3. チタン合金の切削シミュレーション
   - 3.1 圧延チタン合金の異方性
   - 3.2 エンドミルの切削シミュレーション
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4. 炭素繊維強化プラスチックの切削シミュレーション
   - 4.1 CFRPの二次元切削
   - 4.2 CFRPのエンドミル切削シミュレーション
   - 4.3 CFRPのドリル切削シミュレーション
   - 4.4 CFRP/チタン合金重積材の切削シミュレーション

1. 切削現象とシミュレーションの流れ

切削シミュレーションの展開

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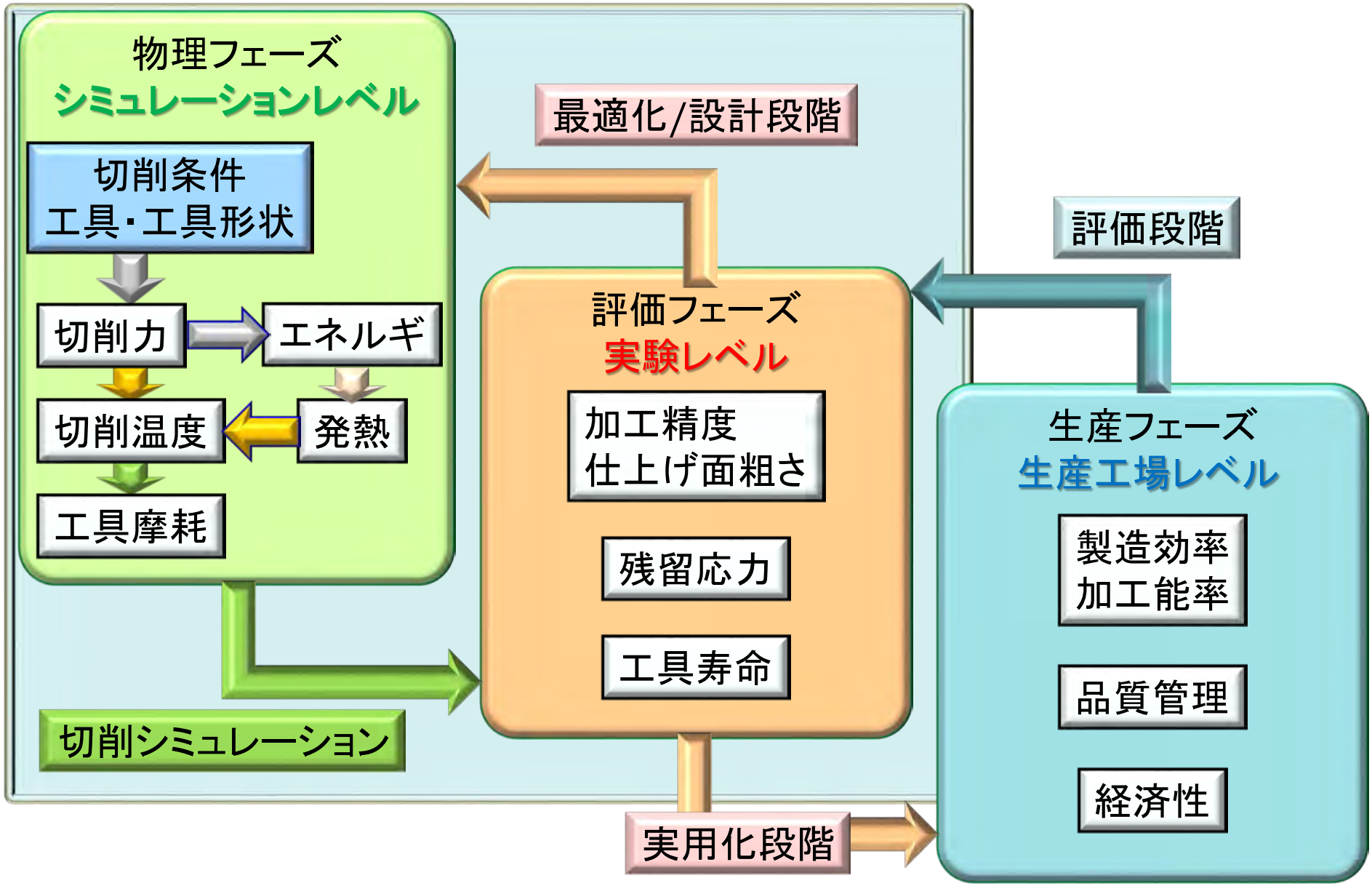
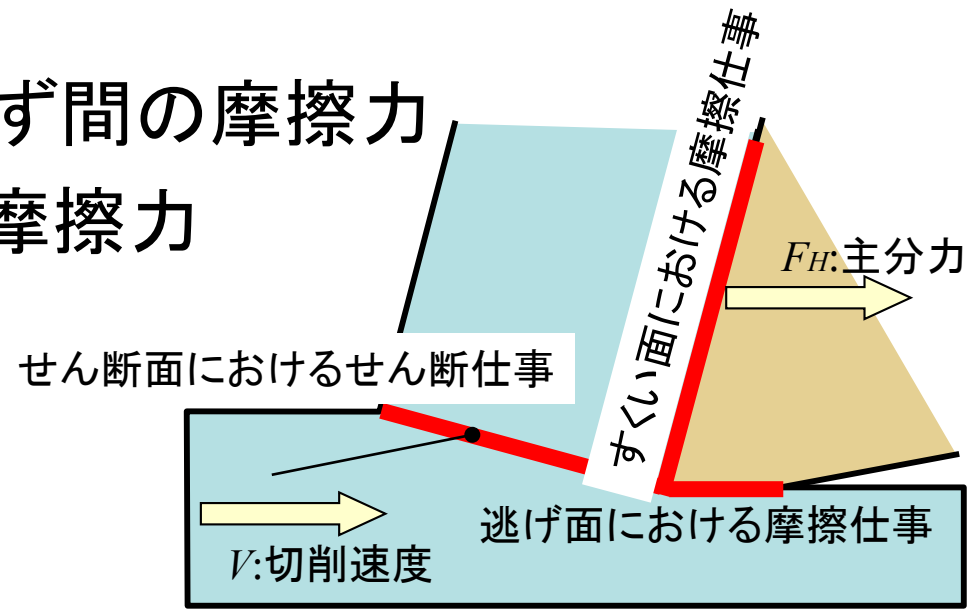
Manufacturing System and Processing Lab.
MSP Lab.

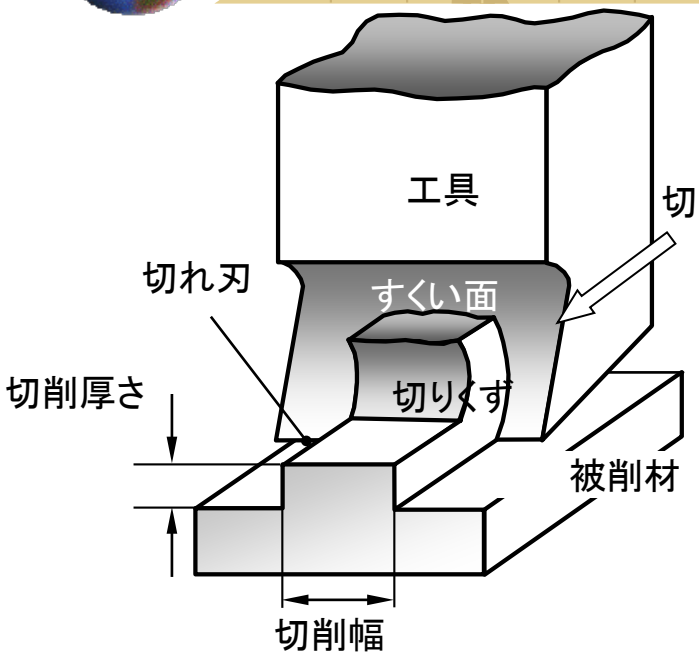


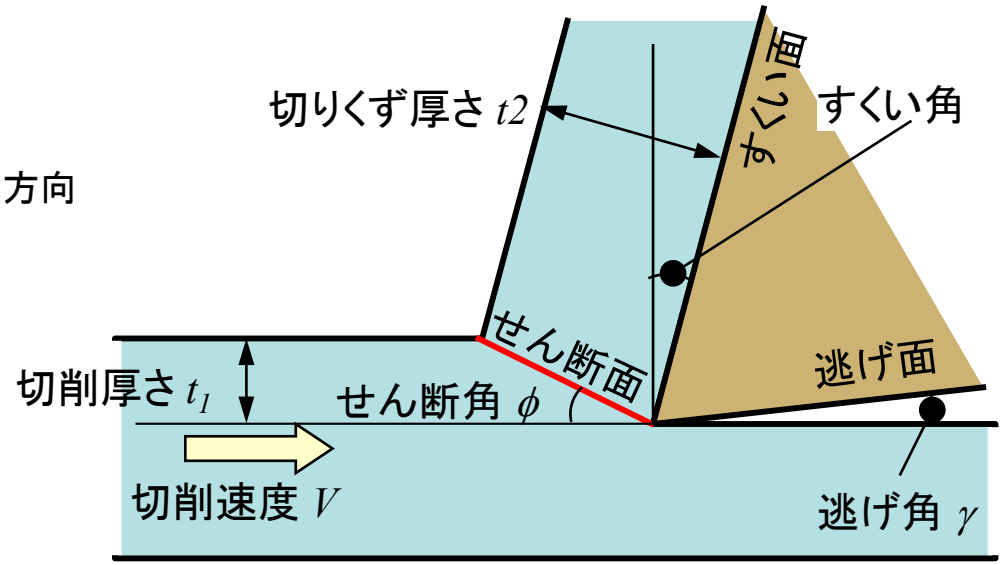
切削する力とは???

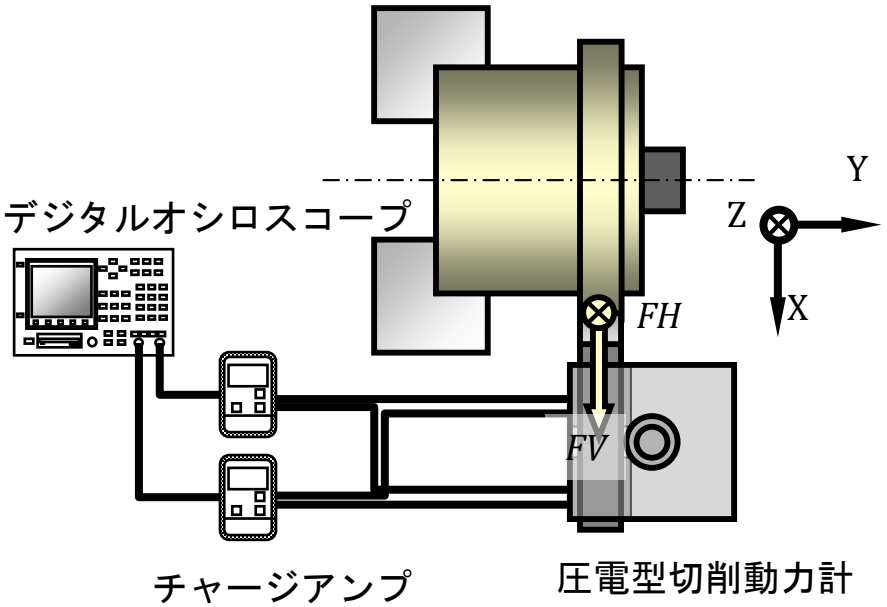
- 切れ刃の押込み力
- 切りくず生成力
  - 材料の変形
    - せん断変形
  - 摩擦
    - すくい面と切りくず間の摩擦力
- 逃げ面と仕上げ面の摩擦力



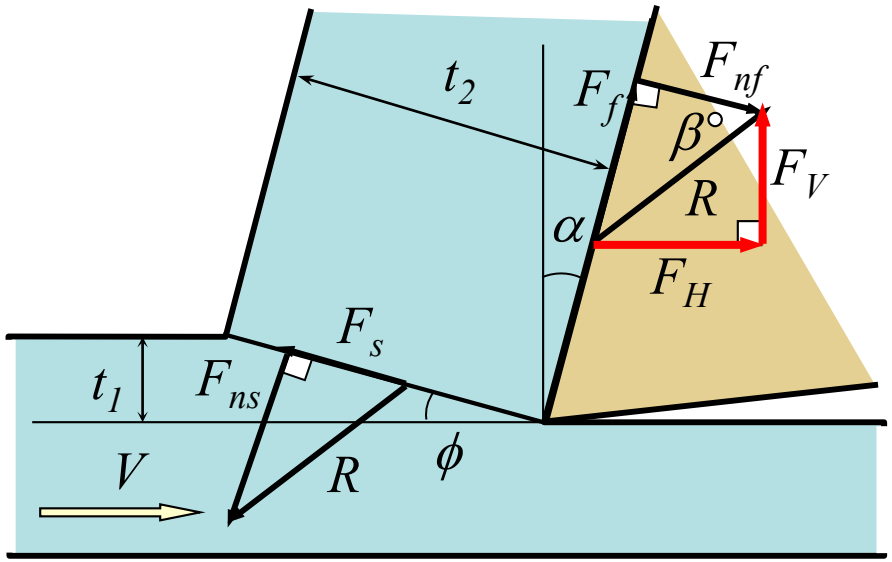
二次元切削


工具
切削方向
切れ刃
すくい面
切削厚さ
切りくず
被削材
切削幅


切りくず厚さ t2
すくい面
すくい角
せん断面
逃げ面
切削厚さ t1
せん断角 φ
切削速度 V
逃げ角 γ


デジタルオシロスコープ
Y
Z
X
FH
FV
チャージアンプ
圧電型切削動力計

二次元切削モデル



R : 切削合力(切削抵抗)
α : すくい角
ϕ : せん断角
β : 摩擦角

切削抵抗

$$R = \frac{\tau_s b t_1}{\sin\phi\cos(\phi+\beta-\alpha)}$$
$$F_H = \frac{\tau_s b t_1 \cos(\beta-\alpha)}{\sin\phi\cos(\phi+\beta-\alpha)}$$
$$F_V = \frac{\tau_s b t_1 \sin(\beta-\alpha)}{\sin\phi\cos(\phi+\beta-\alpha)}$$

せん断角 ϕ

$$\tan\phi = \frac{(t_1/t_2)\cos\alpha}{1-(t_1/t_2)\sin\alpha}$$

すくい面の摩擦係数μ・摩擦角β

$$\mu = \tan\beta = \frac{F_f}{F_{nf}} = \frac{F_V + F_H\tan\alpha}{F_H - F_V\tan\alpha}$$

せん断面せん断応力 τ_s

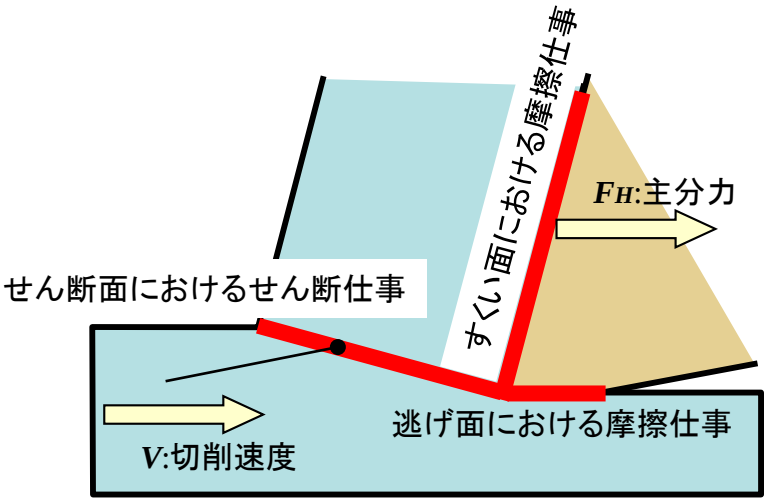
$$\tau_s = \frac{(F_H\cos\phi - F_V\sin\phi)\sin\phi}{b t_1}$$

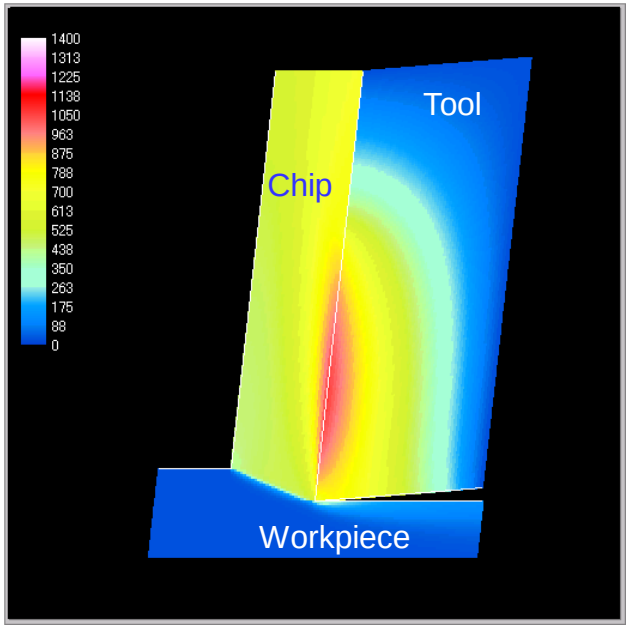
切削エネルギ

- 切削動力 (切削エネルギ)

$$U = F_H \times V$$

- 消費エネルギ
  - せん断面におけるせん断仕事
  - すくい面における摩擦仕事
  - 逃げ面における摩擦仕事
    (工具摩耗がある場合)
  - せん断面を通過する材料運動l量変化に伴う運動エネルギ
  - 新創成面の表面エネルギ
  - 表層および切りくずの残留ひずみエネルギ





摩耗特性式

- 摩耗支配因子
  - 接触面の応力分布
  - 接触面の温度分布
- 摩耗の形態
  - すくい面摩耗：凝着拡散摩耗
  - 逃げ面摩耗：機械的な引っ掻き摩耗
- 摩耗特性式

応力依存係数　　温度依存係数

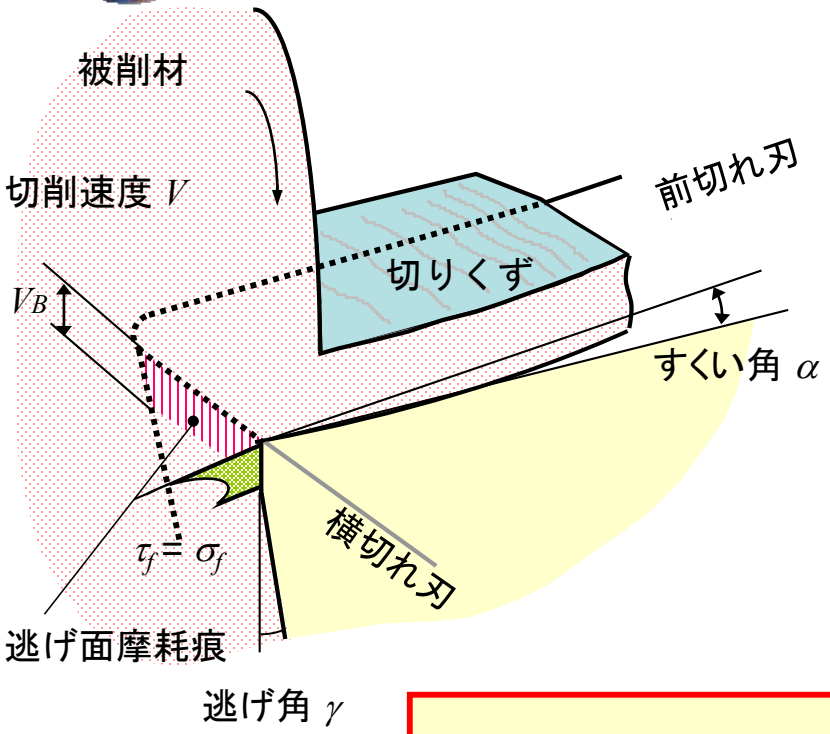
$$\frac{dW}{dL} = C\sigma_f \exp\left(-\frac{\lambda}{\theta_f}\right)$$

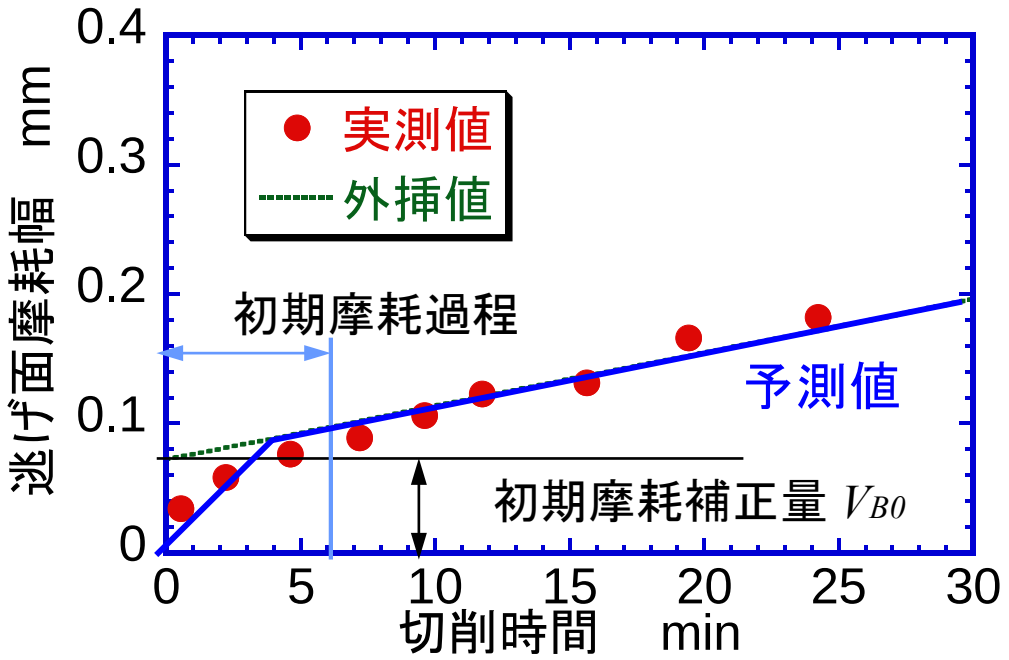
単位面積単位擦過距離あたりの摩耗体積

摩耗面の応力

摩耗面の温度

逃げ面摩耗予測





$$V_B(T) = V_{B0} + \int_0^T \left(\frac{dV_B}{dT} \right) dT$$

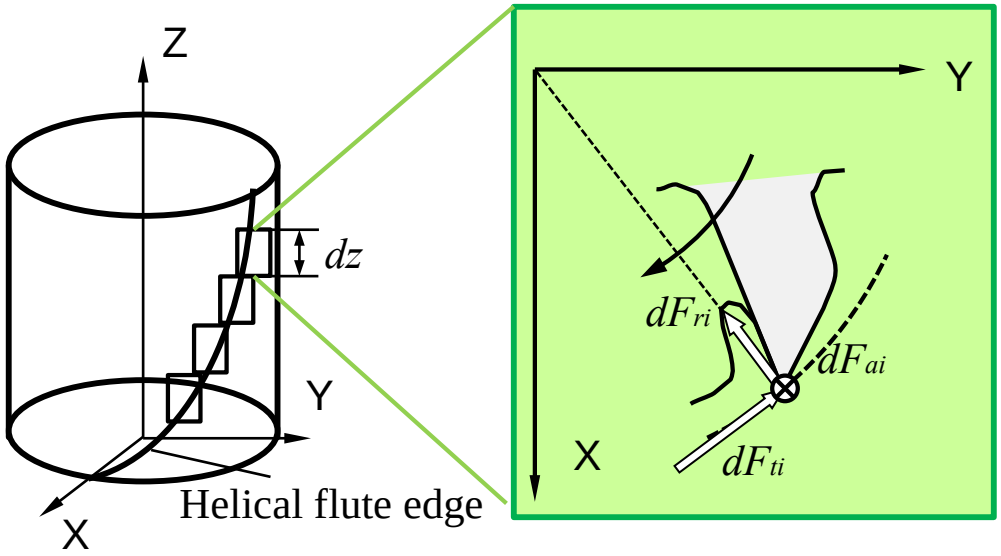
$$\frac{dV_B}{dt} = C\sigma_f \exp\left(-\frac{\lambda}{\theta_f} \right) \cdot \left(\frac{1}{\tan\gamma} - \tan\alpha \right) V$$

σ_f: 逃げ面摩耗痕上の応力
θ_f: 逃げ面摩耗痕上の温度

2. 切削シミュレーション

切削シミュレーション手法

切削係数法



$$dF = k_p dS + k_c dA$$

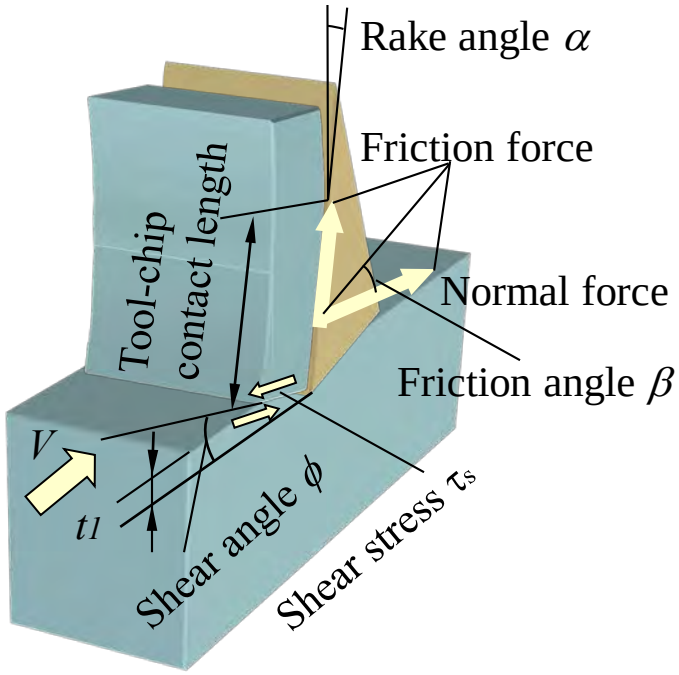
- 切れ刃長さSと比押込み力k_p，切削面積Aと比切削抵抗k_cに基づき切削力を解析
- 切削厚さや切れ刃長さの幾何学的計算のみであるため，計算時間が短い．(エンドミル，振動解析に拡張)
- 出力は切削三分力
- 比切削抵抗のデータベース管理が実用化の鍵

切削シミュレーション手法

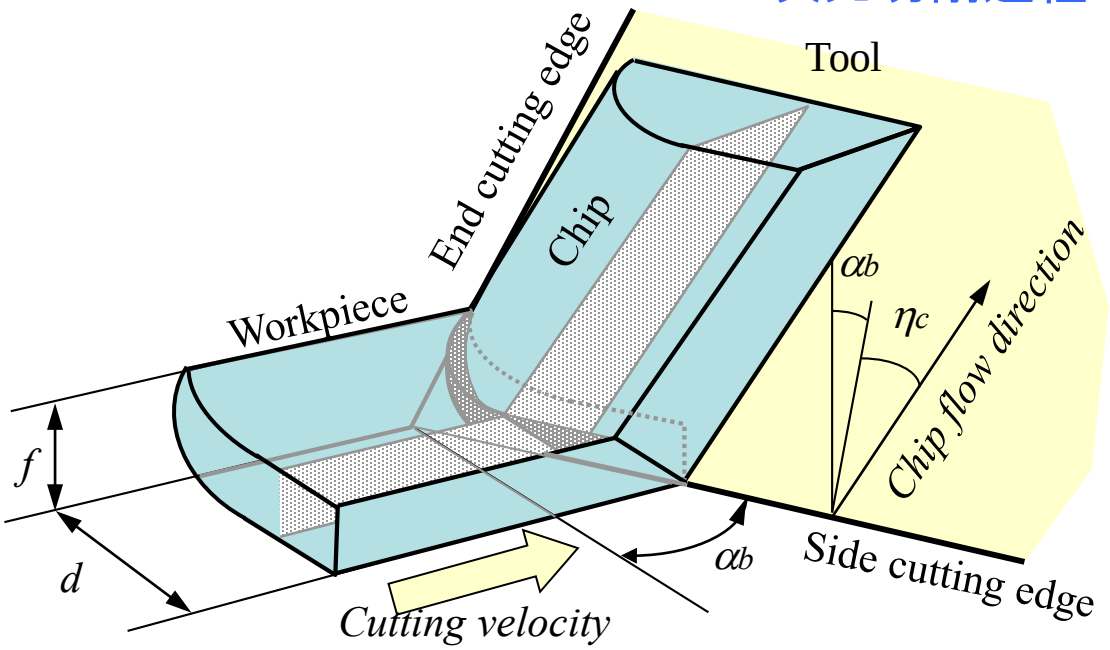
エネルギ解析法

- 切削速度と切りくず流出速度を含む面での二次元切削を積み重ねて切削力を解析
- 切りくず流出方向の探索に時間を要する
- 出力は切削三分力，切りくず流出方向，せん断仕事とすくい面上の摩擦仕事(温度解析，摩耗予測に拡張)

二次元切削試験



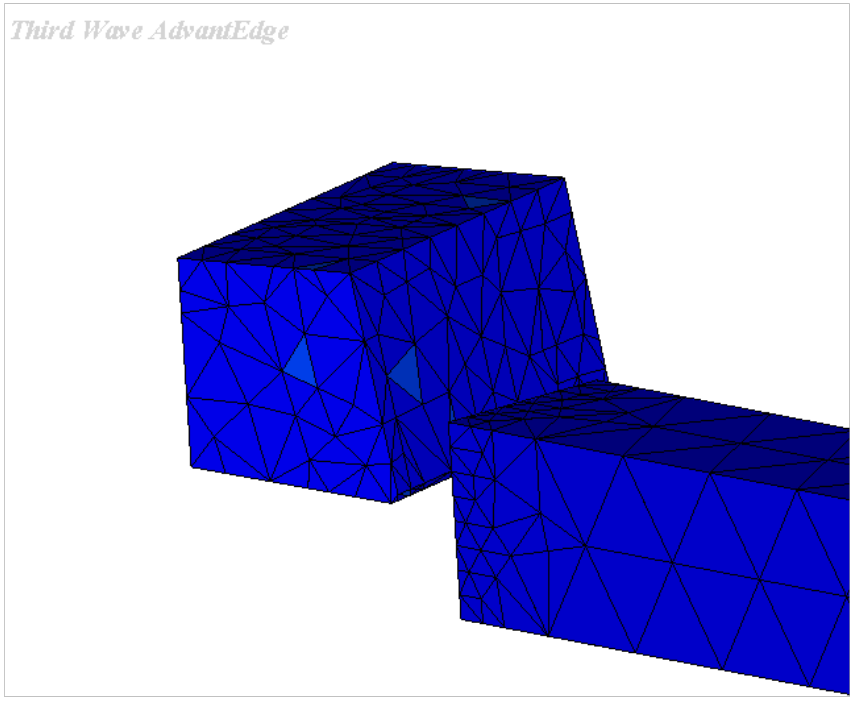
三次元切削過程

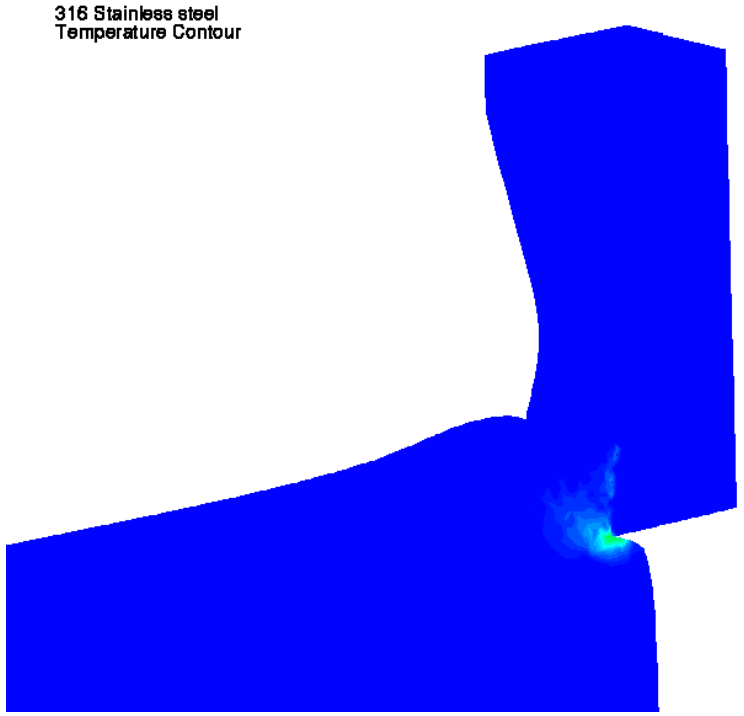


切削シミュレーション手法

有限要素法

- 材料の流動応力特性に基づく塑性力学的解析
- マトリックス解析のため解析時間が長くなる(実用的な三次元切削過程を解析するには，時間的な問題が大きい)
- 出力は材料および工具内の応力，ひずみ，切削三分力，切りくず形態，温度
- 解析時間の短縮化が実用化の鍵(計算機性能の向上に期待)





シミュレーションの課題と利用

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シミュレーションの課題

1. 解析精度
   - 精度はできるだけ高く
2. 解析時間
   - 解析時間はできるだけ短く
3. 汎用性
   - 多くの事例に対応
   - 多くの現象を解析
4. データベースの管理・充実
   - データベースの社内管理
   - データベースの拡張性

シミュレーションの効果

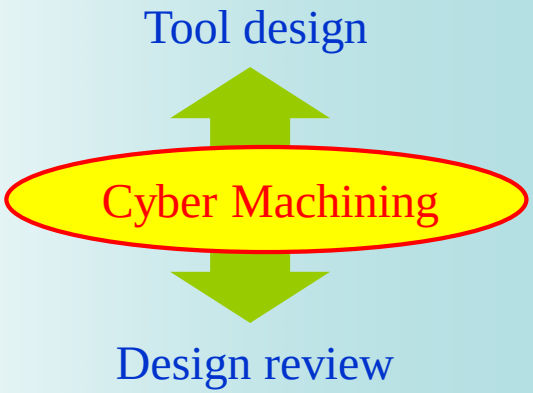
1. 開発・実用化期間の短縮
   - 試行錯誤の削減
2. 開発費の削減
   - 材料・工具・人件費の削減

シミュレーションの利用

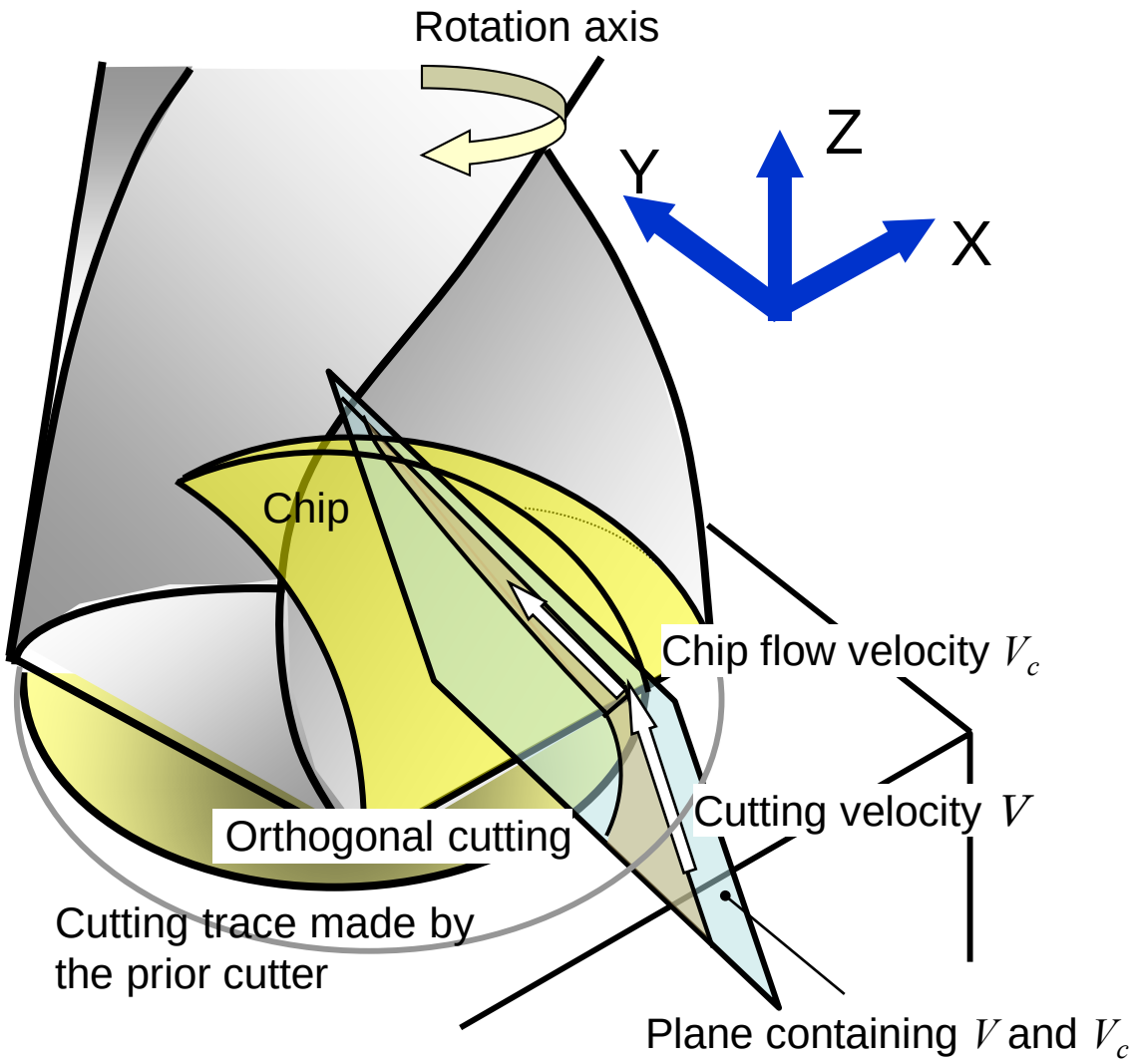
1. 現象解明・理解
   - わかるシミュレーション
   - 説明するシミュレーション
   - 説得するシミュレーション
2. プロセスの改善
   - 切削条件の見直しと最適化
   - 工具の見直しと設計

切削シミュレーション

- マシニングセンタにおける切削作業
  - エンドミル加工
  - ドリル加工
  - リーマ加工
  - タッピング加工
- データベース：二次元切削データ
  - 工具と被削材との組み合わせによって管理
- 入力情報
  - 被削材
  - 工具材質
  - 工具形状―切れ刃形状を任意に定義
  - 切削条件
- 出力情報
  - 切削力
  - 切りくず流出方向
  - 切削モデルと切削エネルギ
  - 切削温度・工具摩耗・動的切削過程における工具軸変位



エンドミル・ドリル切削モデル



- 切りくずモデル

  二次元切削モデルの重ね合わせ

  二次元切削データ

$$\left.\begin{aligned}\phi &= \exp(A_{00}V + A_{01}t_1 + A_{02}\alpha + A_{03})\\ \tau_s &= \exp(A_{10}V + A_{11}t_1 + A_{12}\alpha + A_{13})\\ \beta &= \exp(A_{20}V + A_{21}t_1 + A_{22}\alpha + A_{23})\\ l_c &= \exp(A_{30}V + A_{31}t_1 + A_{32}\alpha + A_{33})\end{aligned}\right\}$$

- 切りくず流出方向

切削エネルギ最小

切削エネルギ
＝せん断エネルギ+摩擦エネルギ

3. チタン合金の切削シミュレーション

エンドミルの切削力

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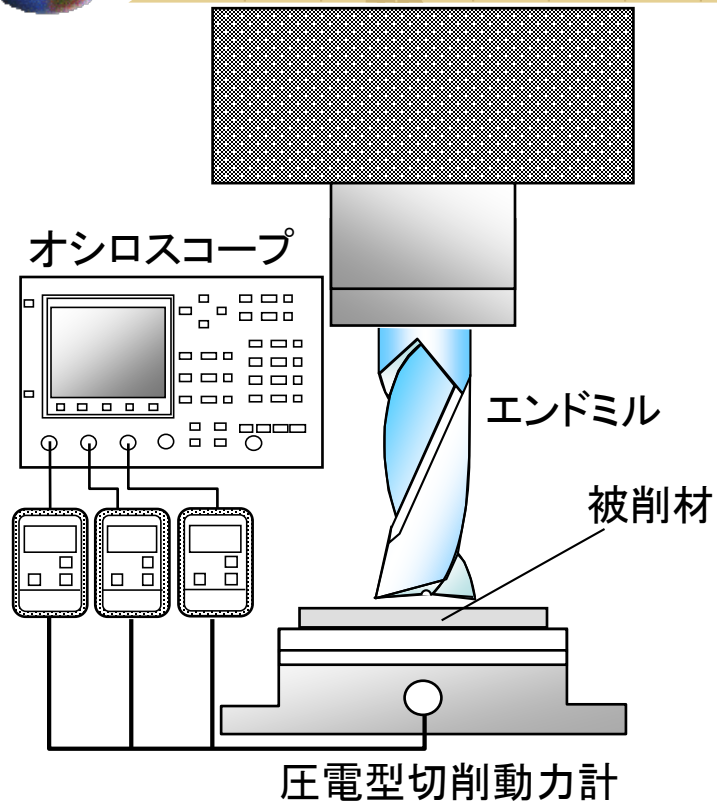
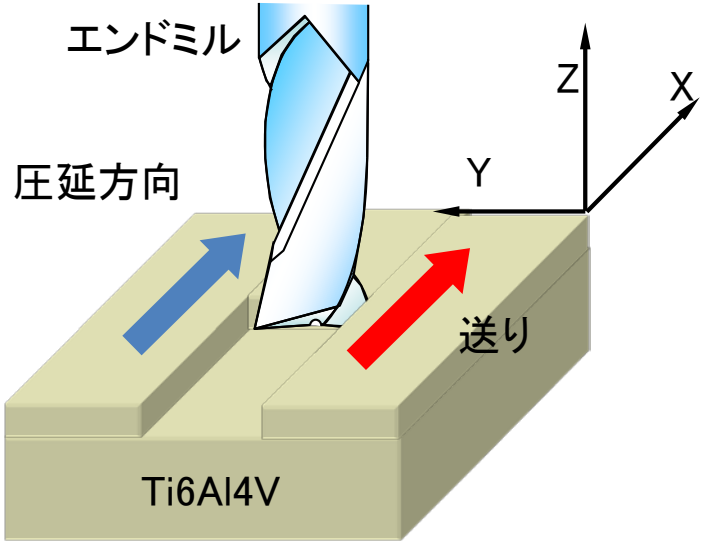
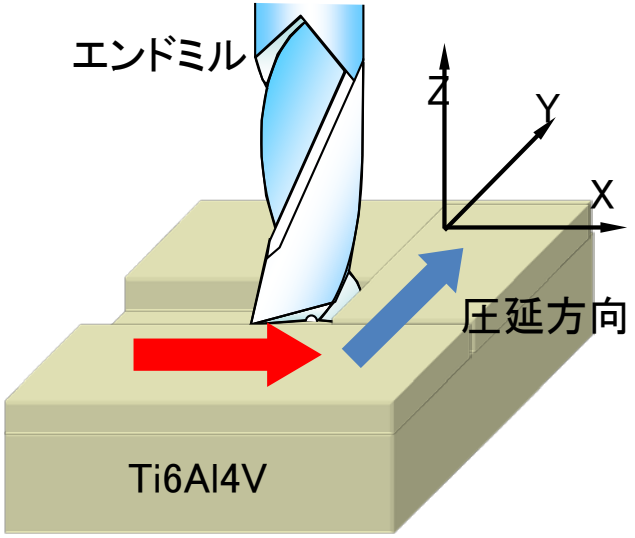
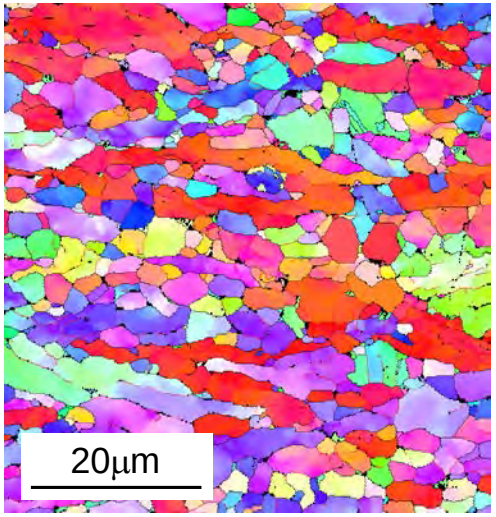


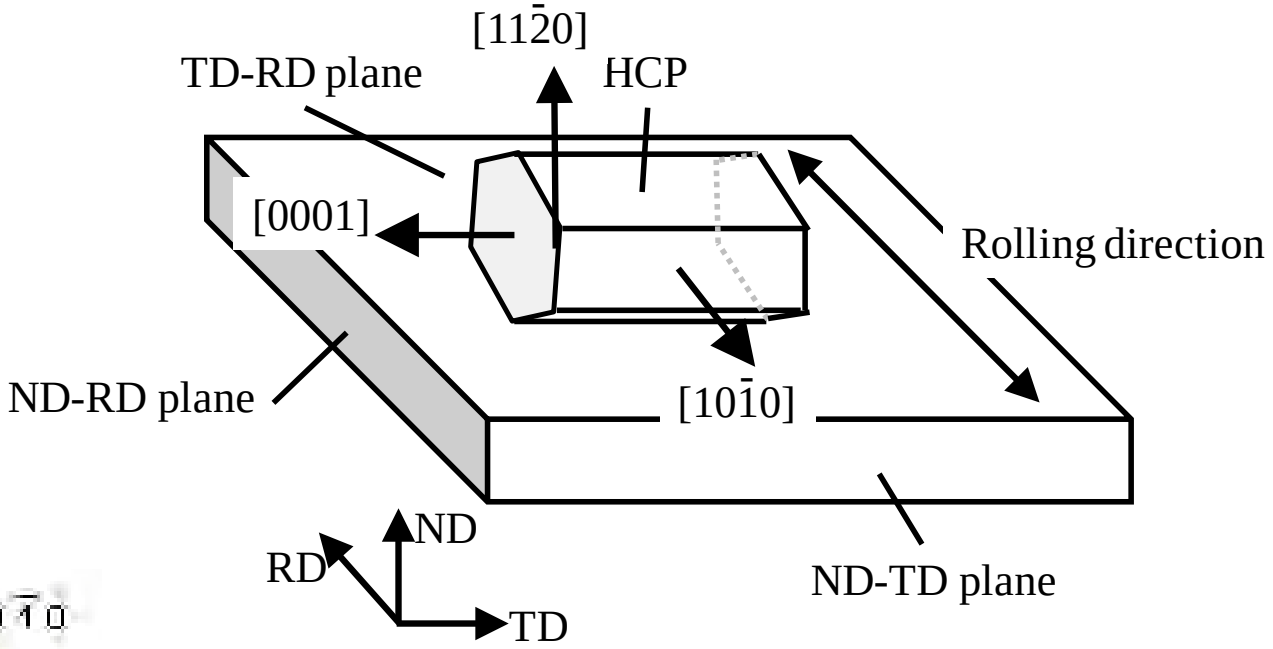


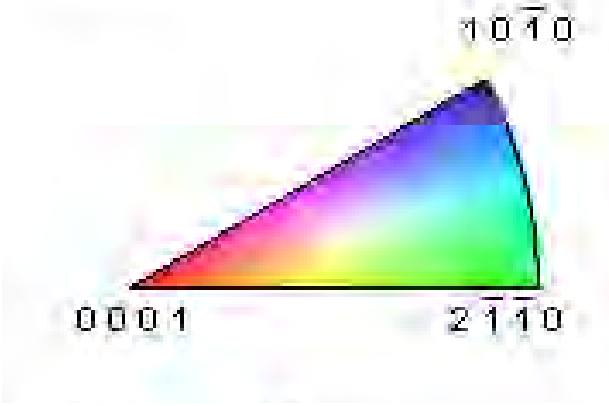


エンドミル	Ti6Al4V
材質	超硬
直径	10 mm
半径方向すくい角	5 deg
ねじれ角	30 deg

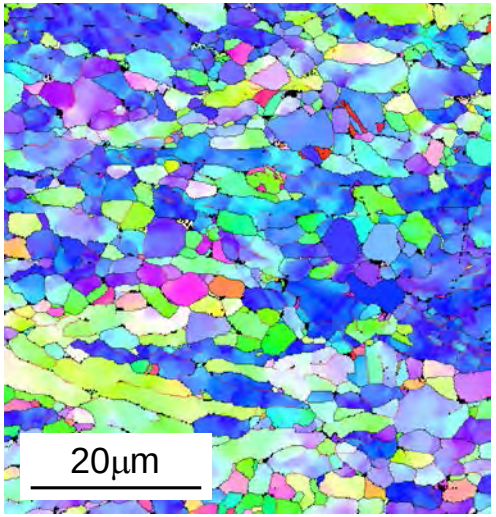
圧延チタンの結晶方位



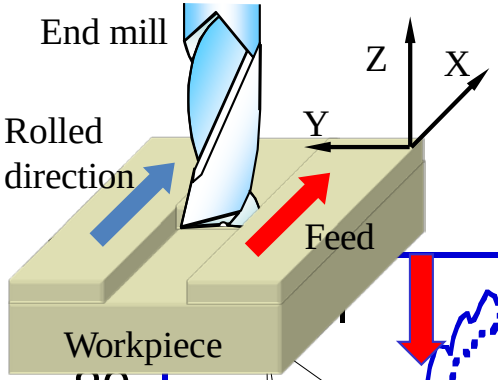




Element	C	Al	O	Fe	V	H	N	Ti
Wt %	0.03	6.13	0.12	0.04	4.1	0.005	0.01	Remainder



チタン合金の切削力

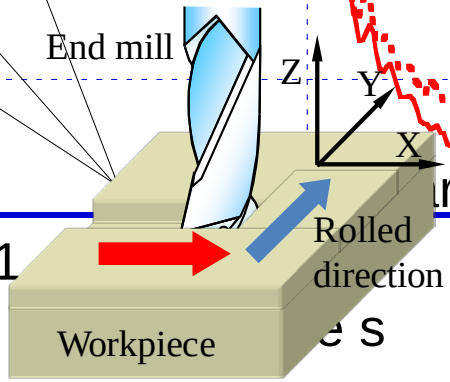


X (parallel)
X (perpendicular)
Y (parallel)
Y (perpendicular)
Z (parallel)
Z (perpendicular)

Force N

80
40
0
-40
-80
-120

0
0.01

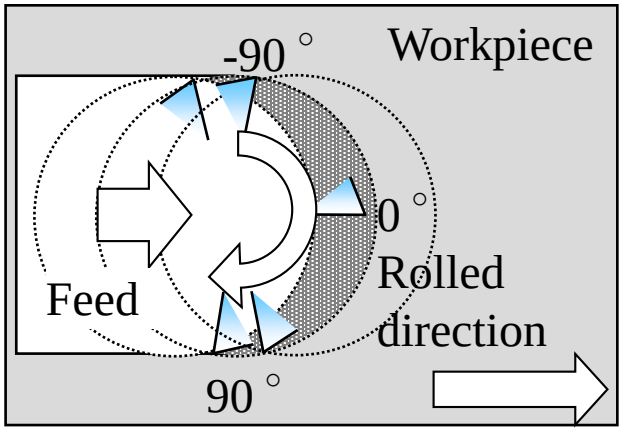


Cutting speed: 50 m/min
Feed rate: 0.05 mm/tooth
Axial depth of cut: 1mm

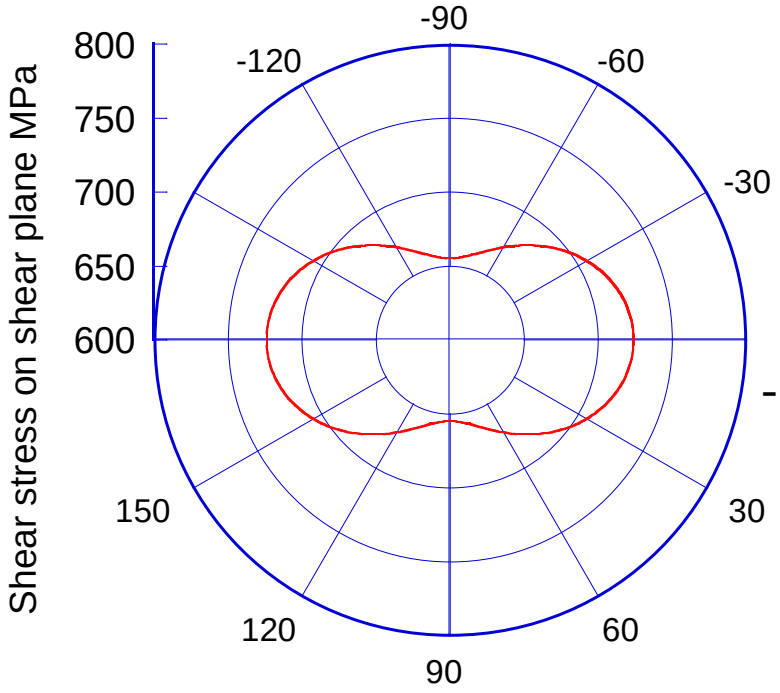
チタン合金の異方性

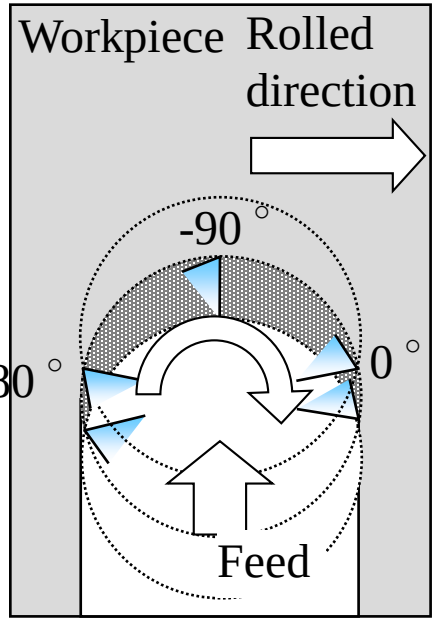
$$\phi = \exp(0.3323V + 225.2t_1 + 1.864\alpha - 1.196)$$
$$\tau_s = \exp\{-0.1622V - 4919.5t_1 + 0.289\alpha + 20.36(1 + 0.005\cos 2(\varphi - \theta))\}$$
$$\beta = \exp(-5797.6t_1 + 0.165\alpha - 0.297)$$

Cutting speed V = 50 m/min
Uncut chip thickness t_1 = 0.05 mm
Rake angle α = 20 deg



Parallel





Parallel

チタン合金の切削力シミュレーション

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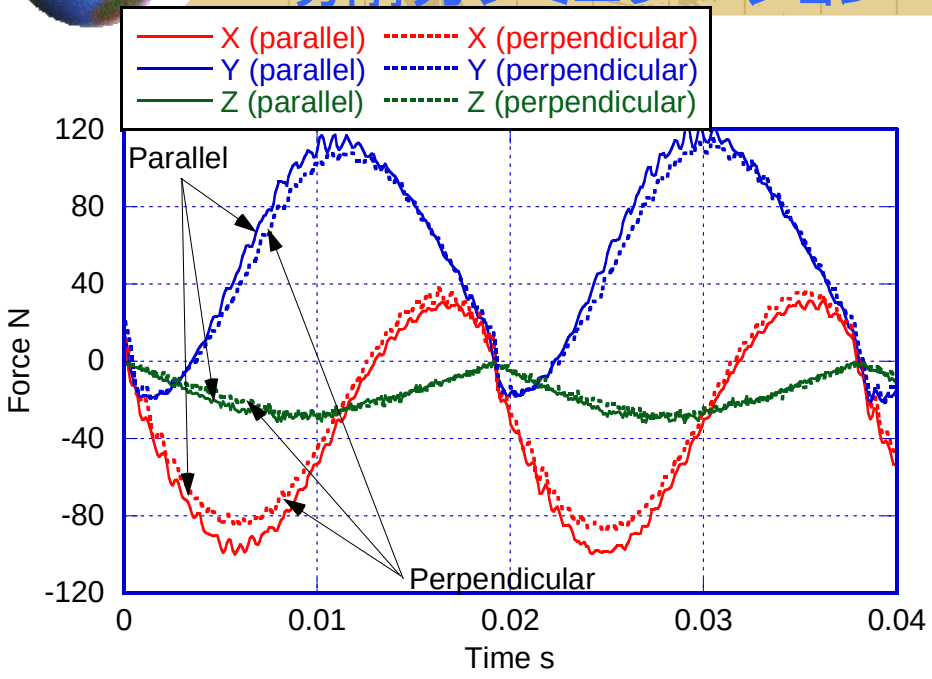
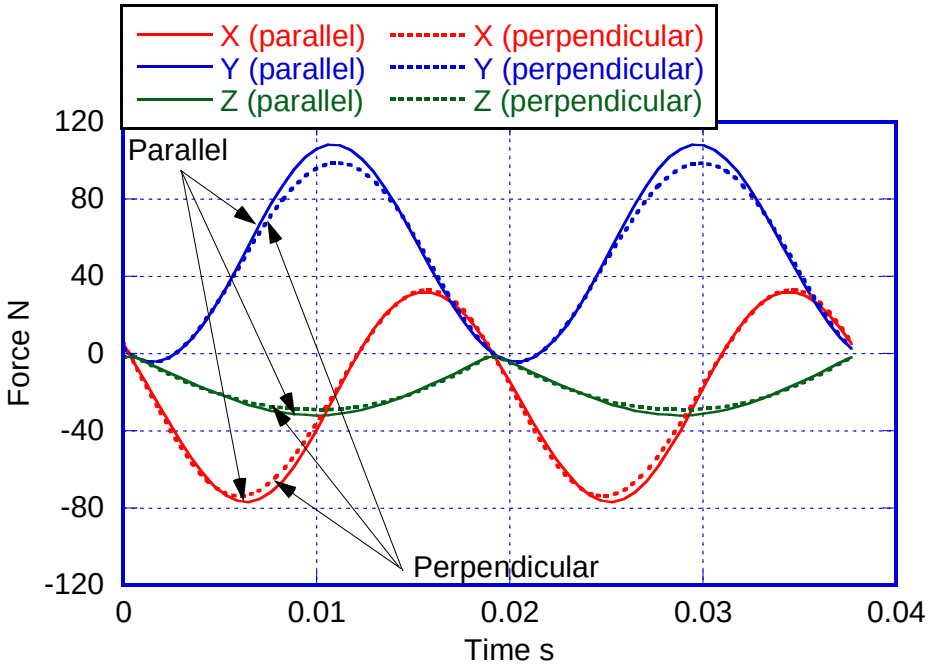
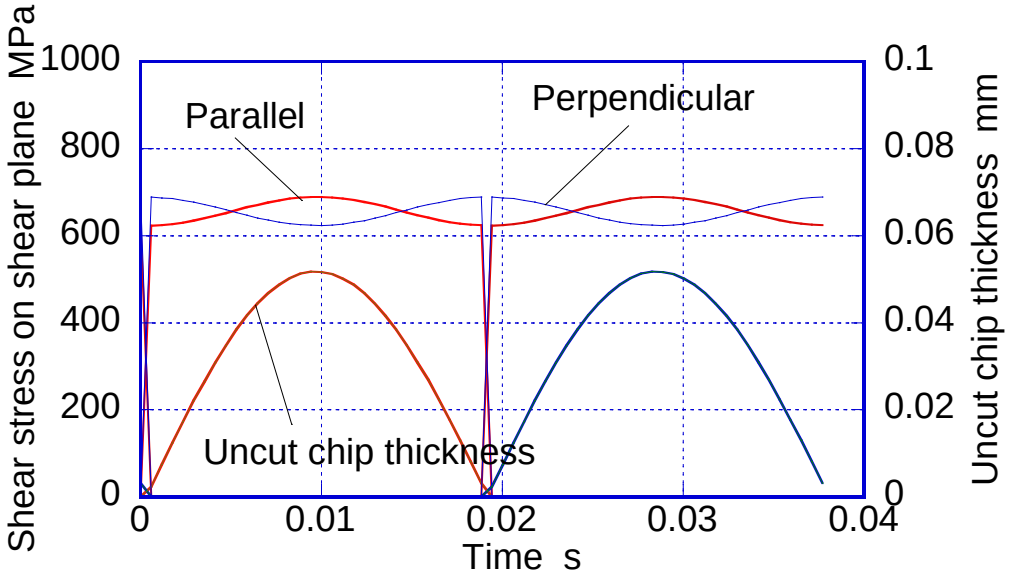


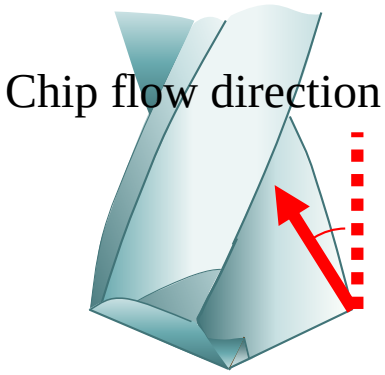


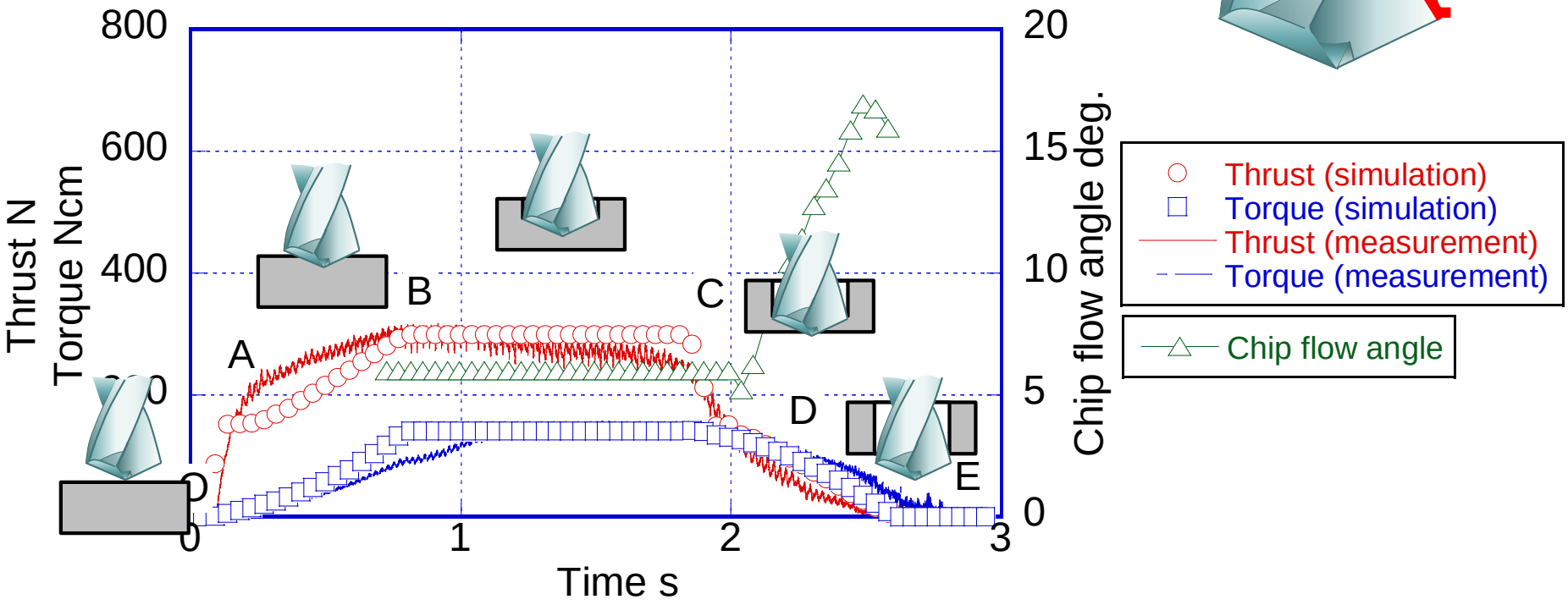
Cutting conditions		Tool	
Cutting speed	50 m/min 1592 rpm	Diameter	10 mm
Feed rate	0.05 mm/tooth	Radial rake angle	13 deg
Axial depth of cut	1.0 mm	Axial rake angle	30 deg



切削力シミュレーション

Drill geometry			
Diameter	6 mm	Numbers of edges	2
Helix angle	30 deg.	Material	Carbide
Wedge angle	120 deg.	Thinning	X type





The spindle speed, 1327 rpm; feed rate, 0.1mm/rev.

リップ端部の二次元モデルとFEM解析

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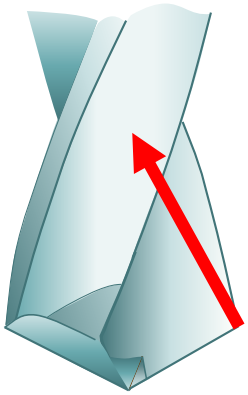
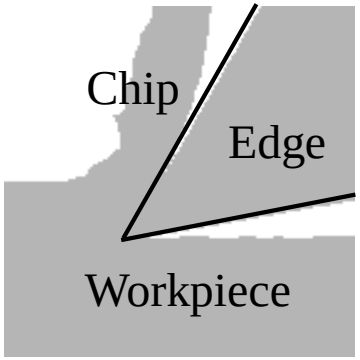
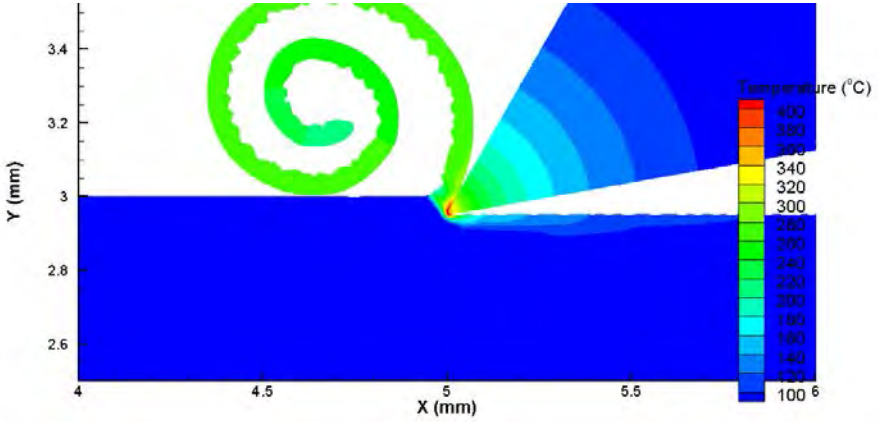
MSP Lab.

THIRD WAVE AdvantEdge™

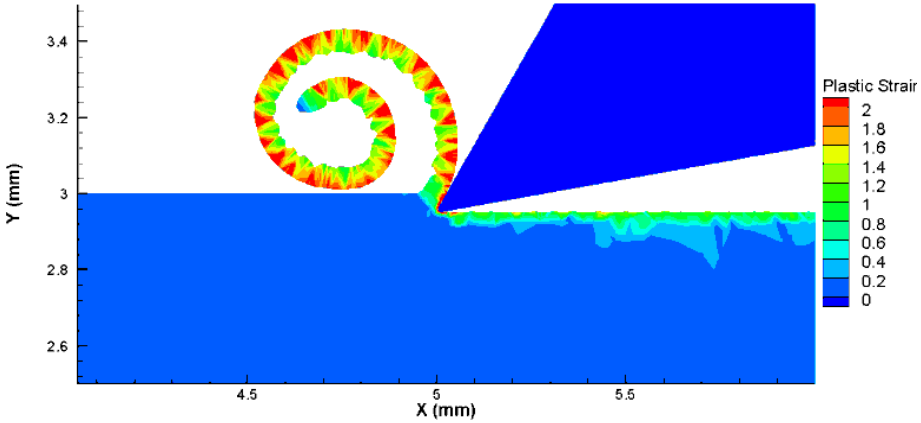




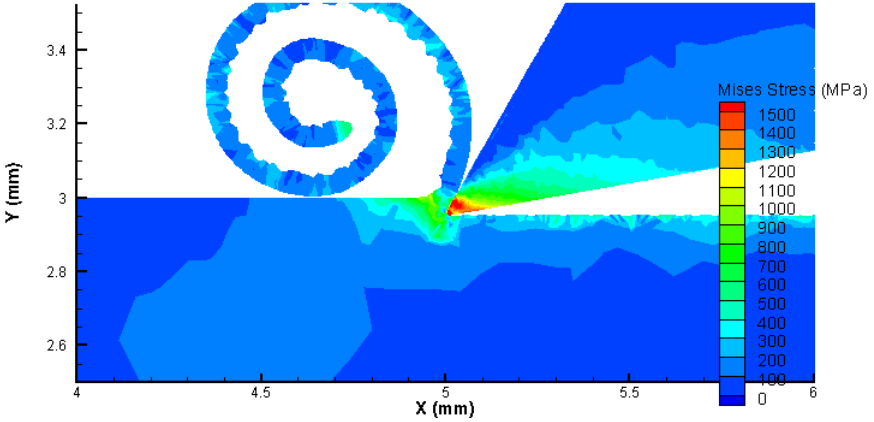
Temperature



Plastic strain

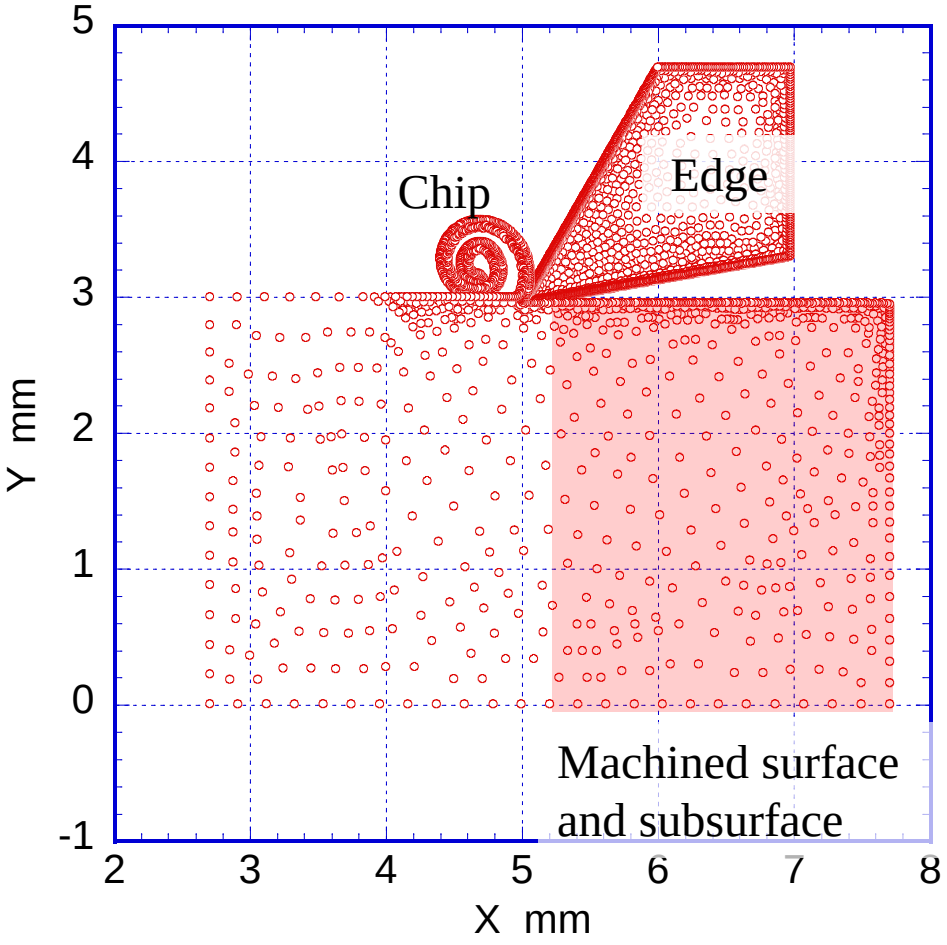


Mises stress

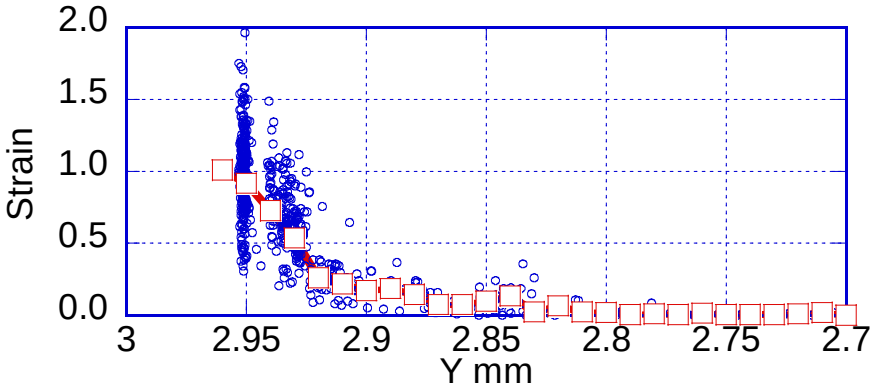


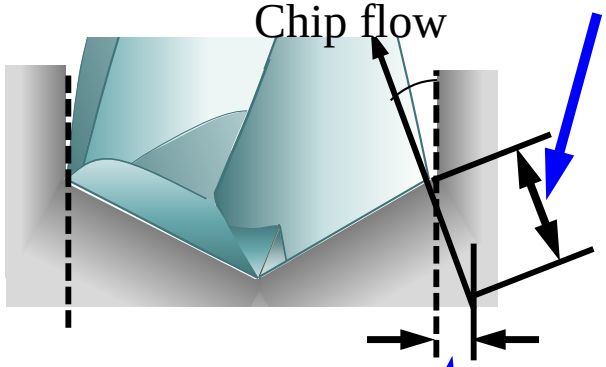
Cutting speed, 50 m/min; Feed rate, 0.1 mm/rev.(0.05 mm/tooth)

仕上げ表層部のひずみ



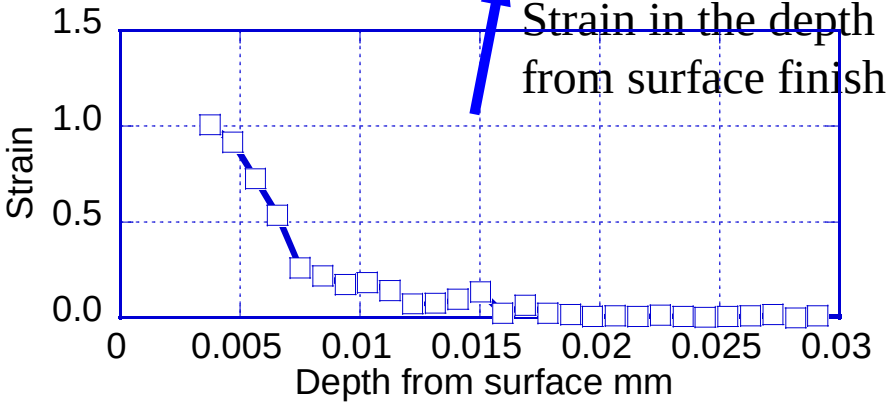
Feed rate, 0.1 mm/rev.(0.05 mm/tooth)



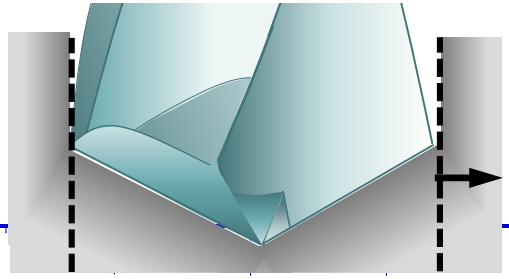


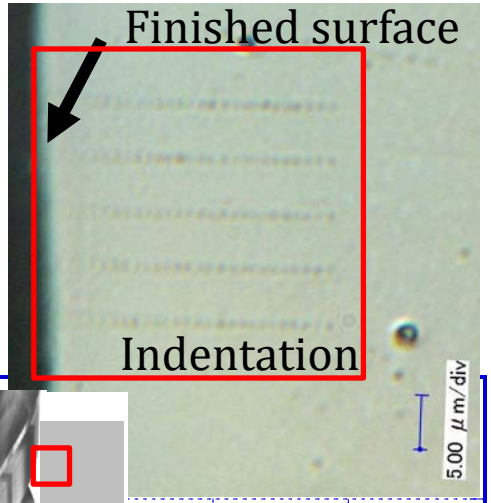
Strain in chip flow direction

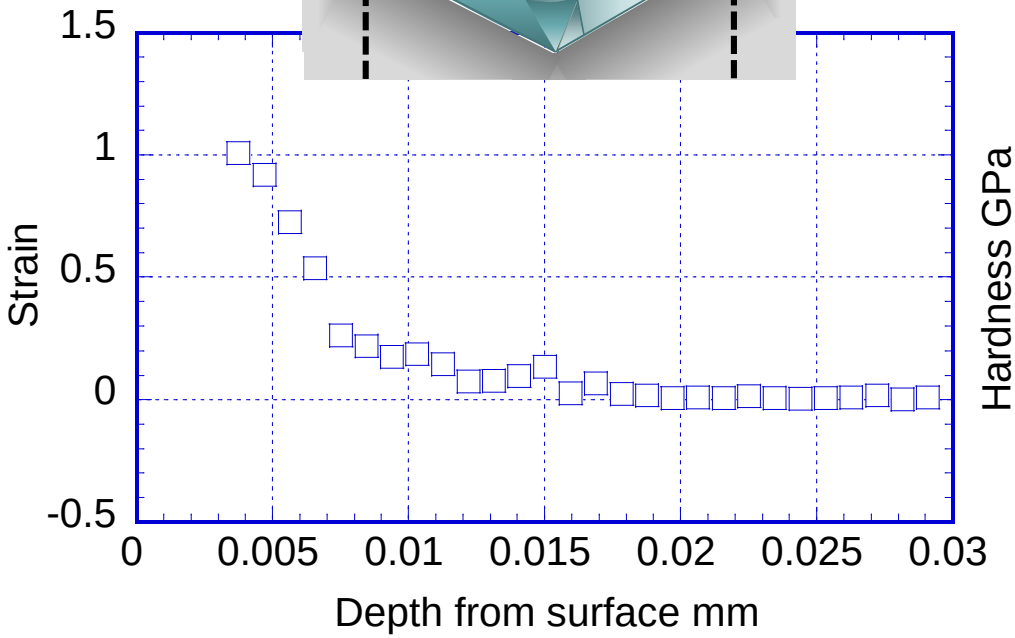
Strain in the depth from surface finish

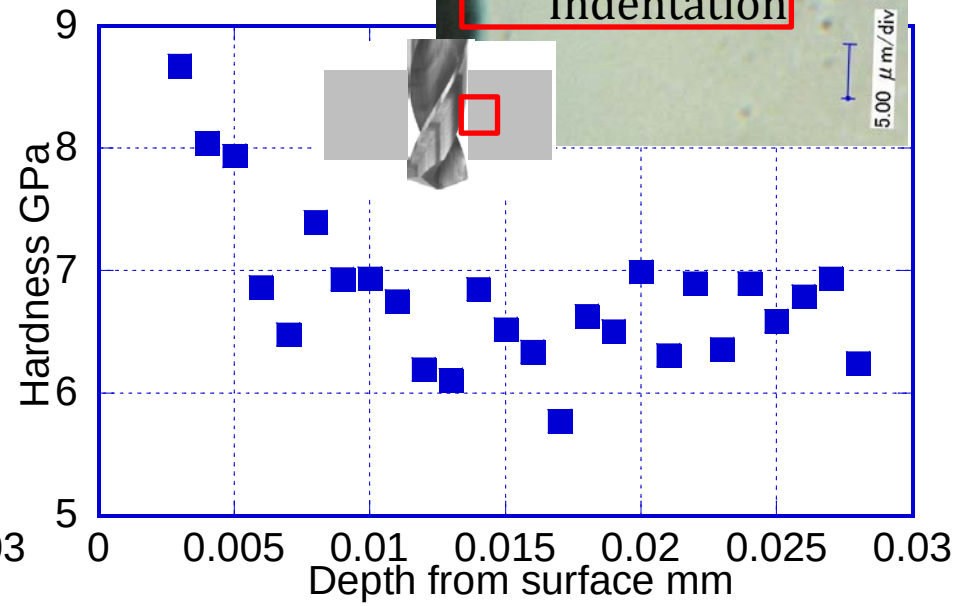


ひずみ分布と表層硬度分布



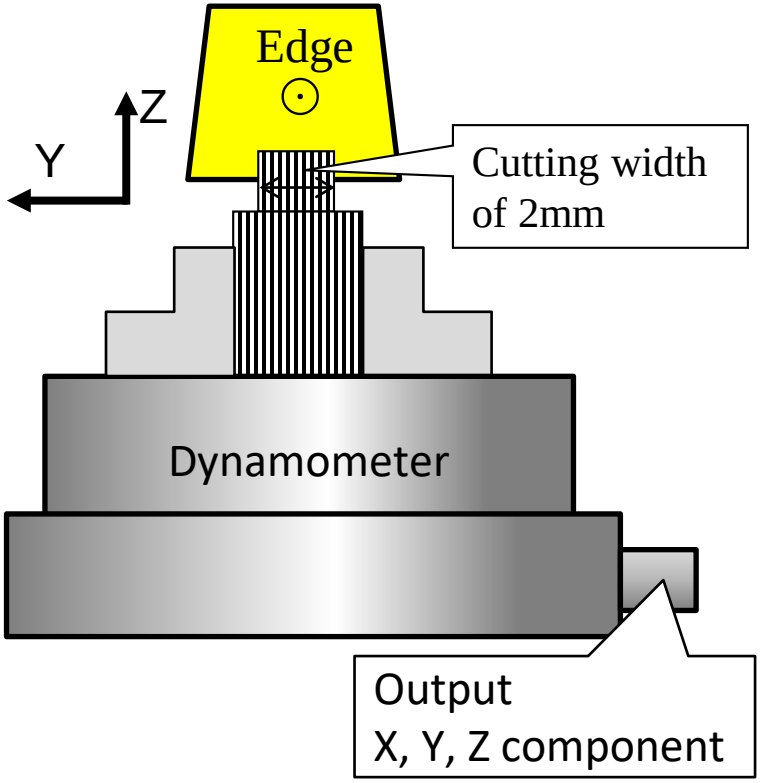


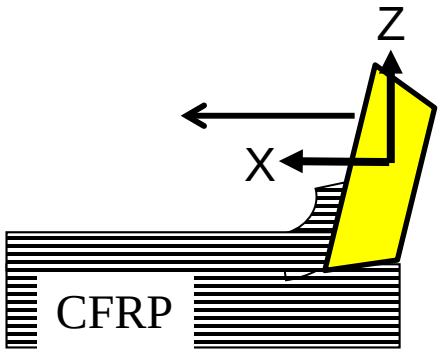




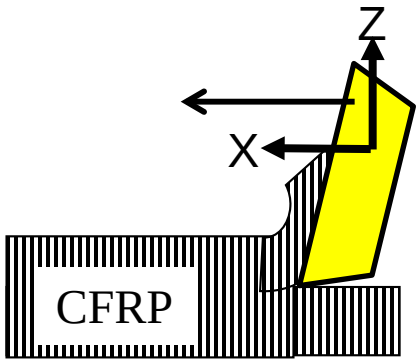
4.炭素繊維強化プラスチックの切削シミュレーション

二次元切削試験

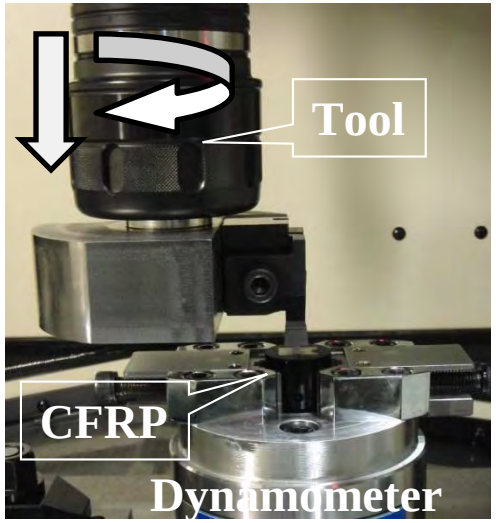


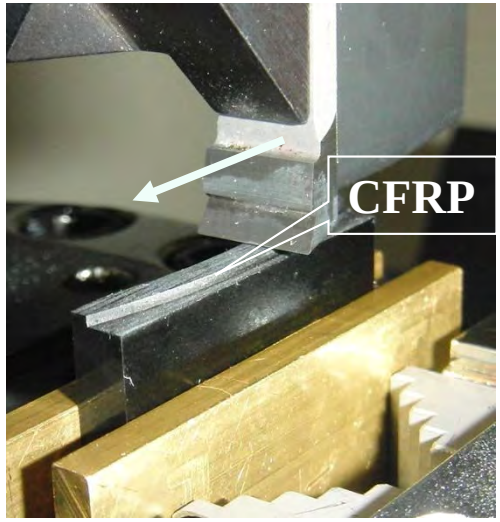


Parallel to the fibers

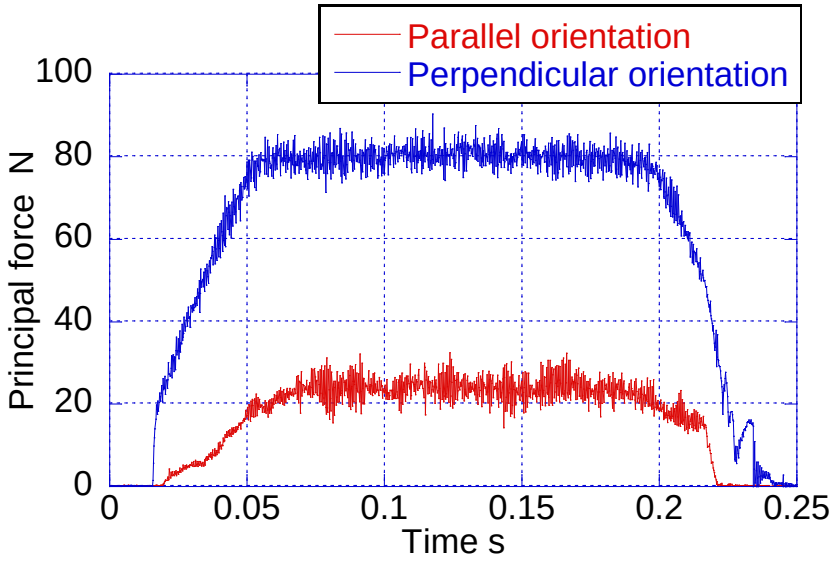


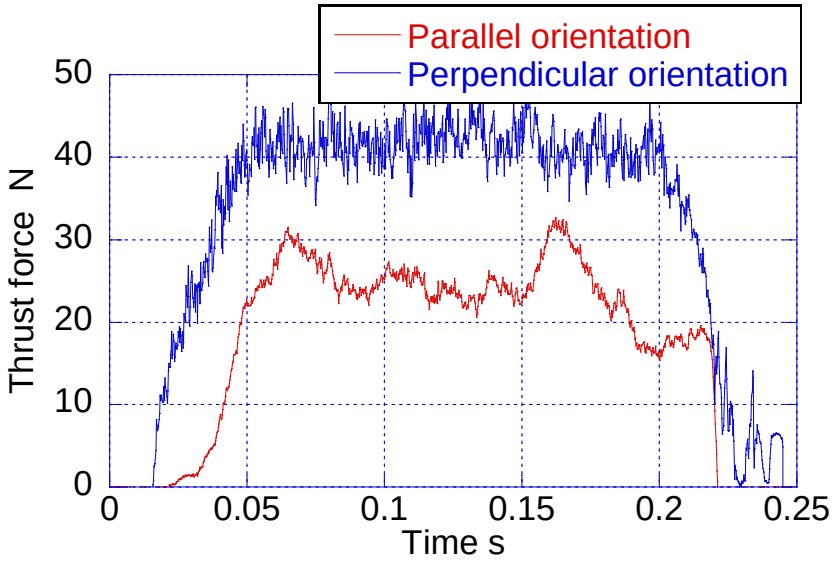
Perpendicular to fibers

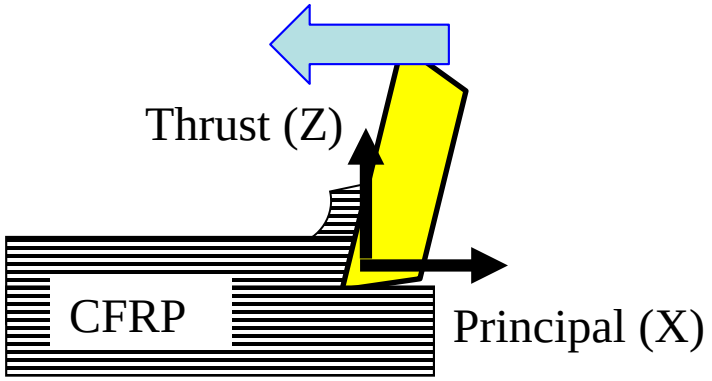




CFRPの切削力

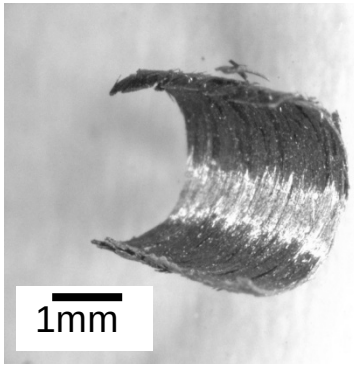
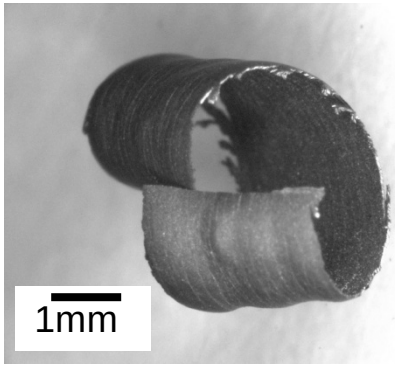
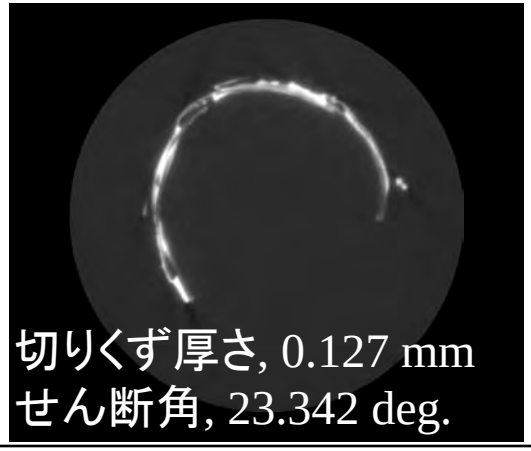
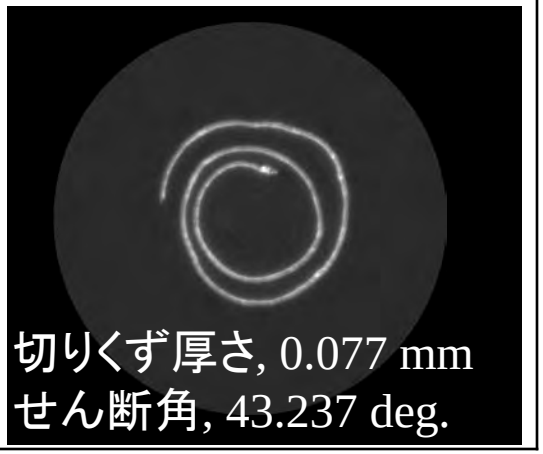






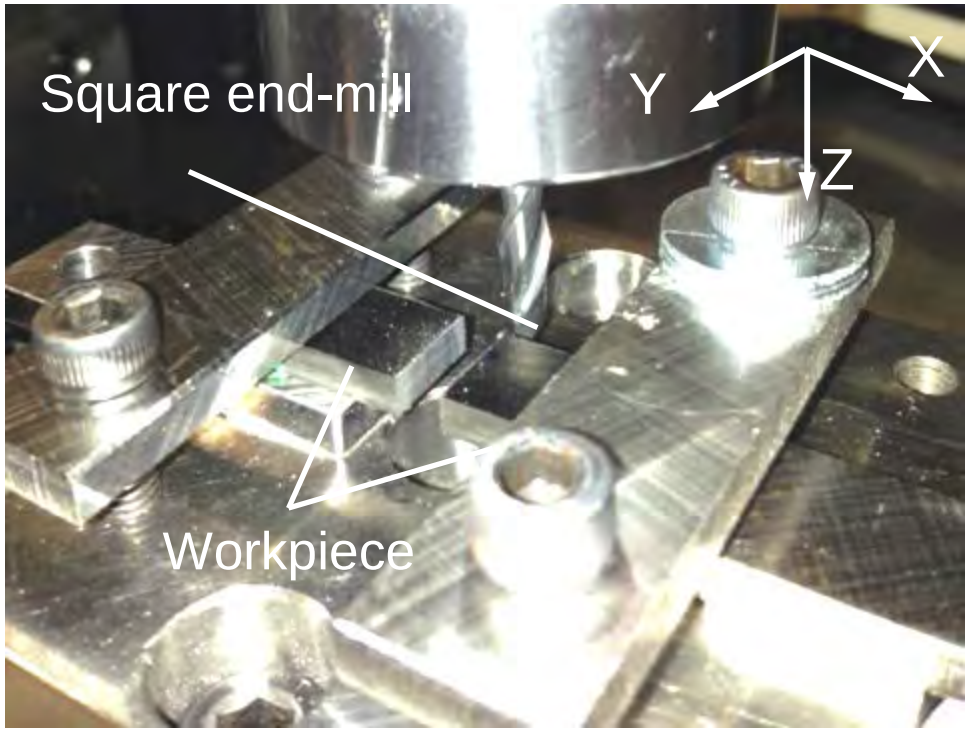
Workpiece	CFRP
Tool	Carbide (JIS K10) Rake angle 30 degrees
Cutting conditions	
Cutting speed	10 m/min
Uncut chip thickness	0.05 mm
Lubrication	Dry

CFRPの切りくず

切削方向	繊維方向	繊維方向に直角
光学顕微鏡写真		
CT 画像		

CFRPのエンドミル切削

Tool	Square end mill ϕ5mm, 2edges TiAlN coated
CFRP	T800 grade Unidirection Thickness, 4mm Width 11.5mm
Cutting conditions	
Cutting speed	50 m/min
Feed rate	0.05 mm/tooth
Feed to Fiber angle	0, 90 degrees



繊維の配向に対する送り方向の影響

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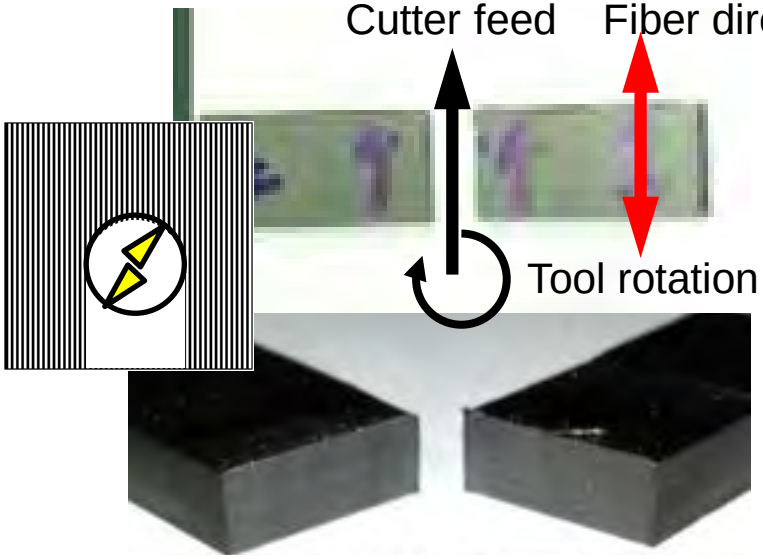
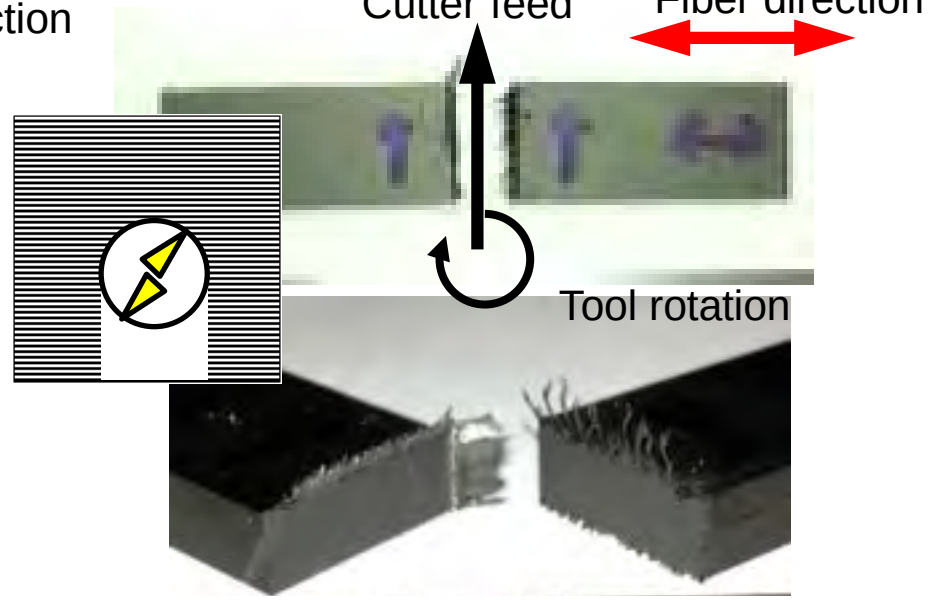
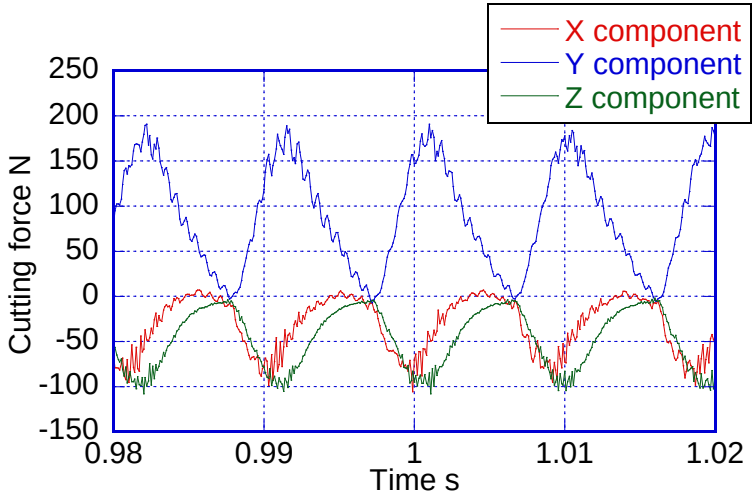
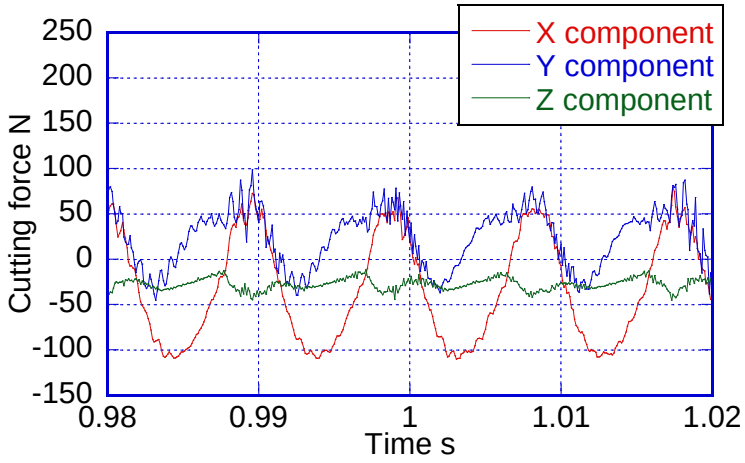
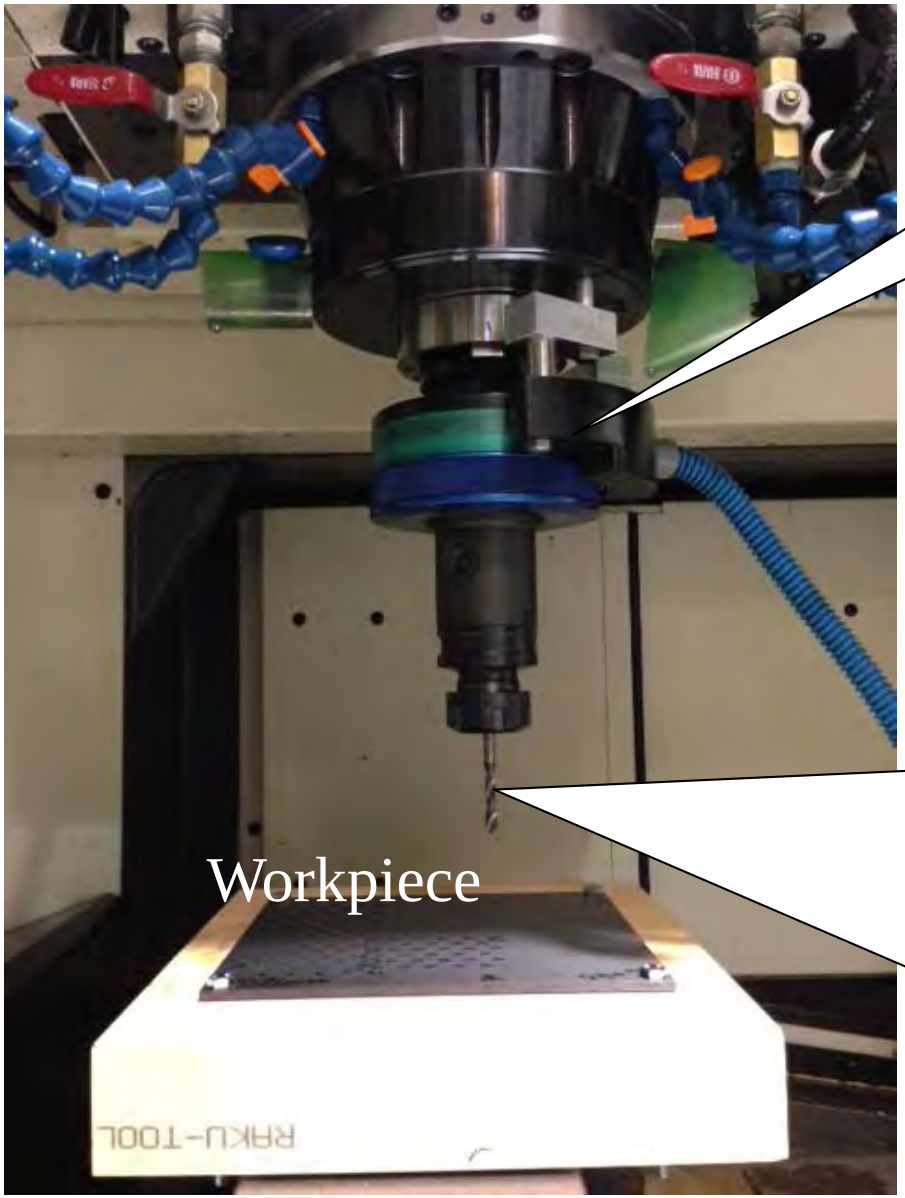




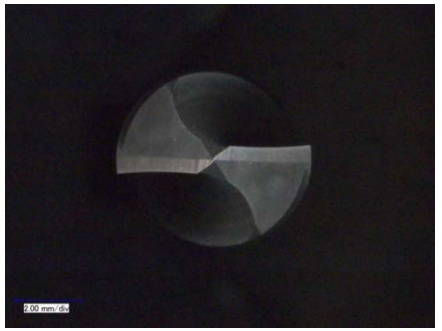




ドリル切削

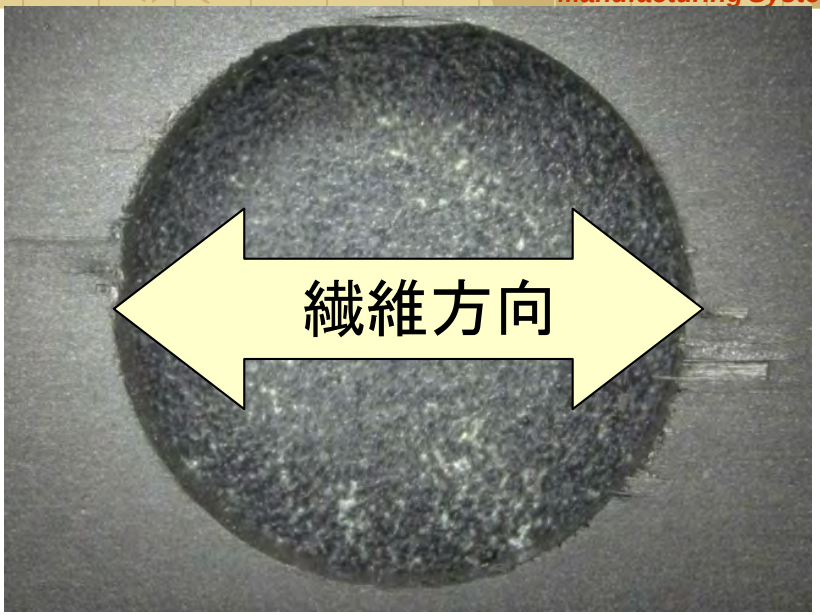


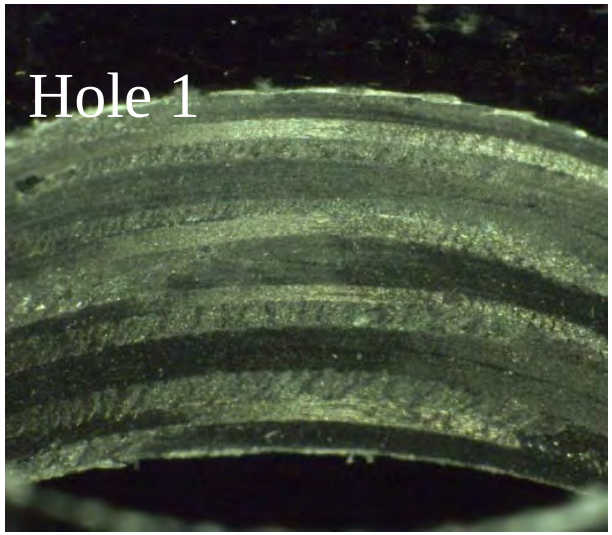
Piezoelectric dynamometer
9123B(Kistler)

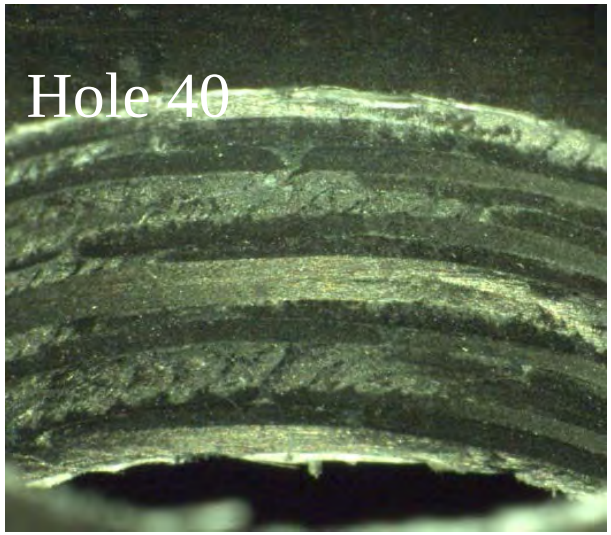


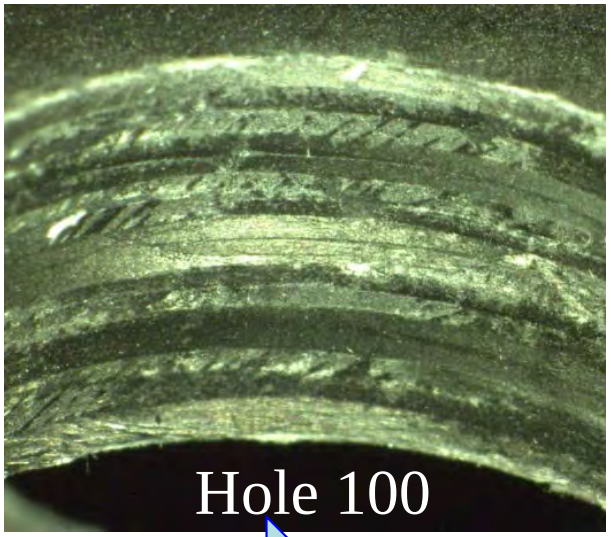
Helix angle	30deg
Wedge angle	120deg
Number of edge	2
Diameter	6mm
Material	Carbide
Thinning	X type
Coating	TiAlN

層間剥離



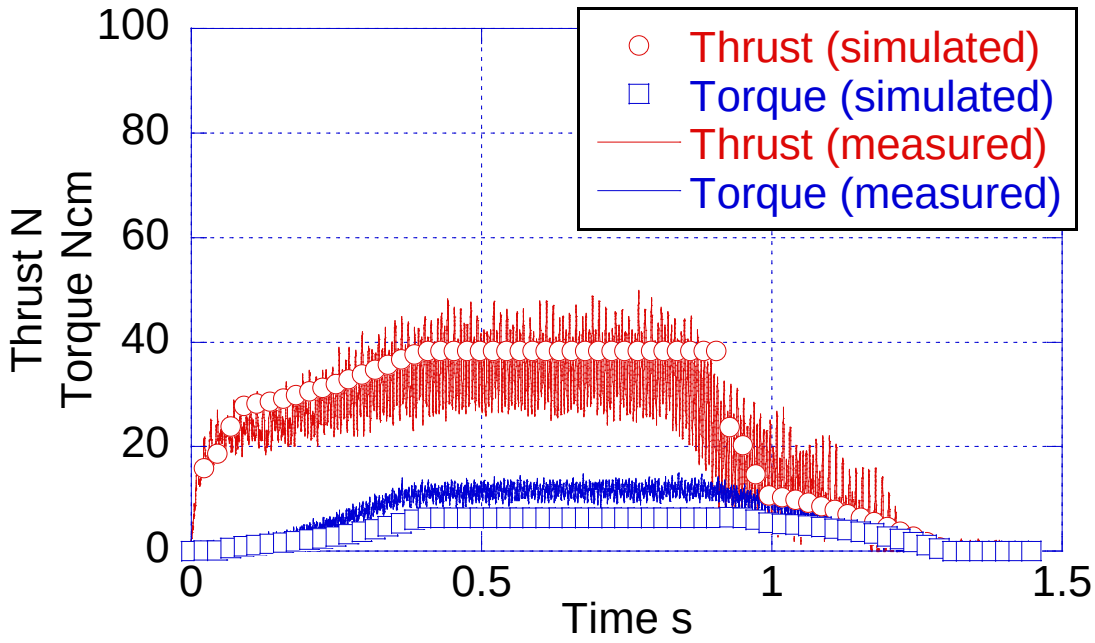






工具摩耗

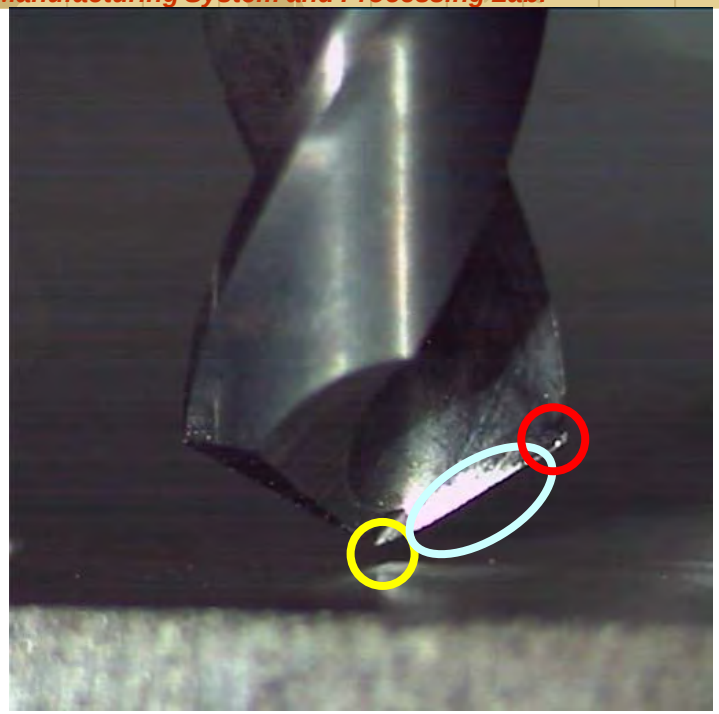
切削力シミュレーション



Workpiece	CFRP (commercial material) Laminated with fiber orientation at 0 and 90 degrees alternatively
Plate thickness	4 mm
Spindle speed	2653 rpm (50 m/min at 6 mm diameter)
Feed rate	0.1 mm/rev (0.05 mm/edge)
Lubrication	dry

ドリル形状の役割

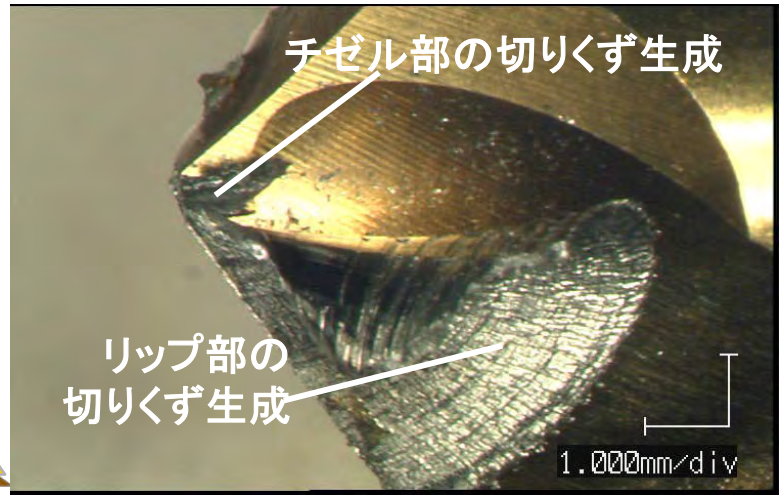
- チゼル
  - 穴の直進性の制御
- リップ
  - 材料除去，切りくず制御
- リップ端部
  - 穴の仕上げ



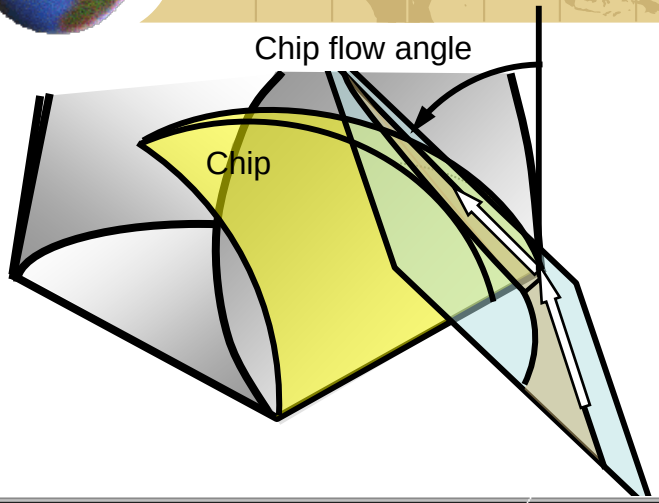
リップ端部の切削温度と工具摩耗

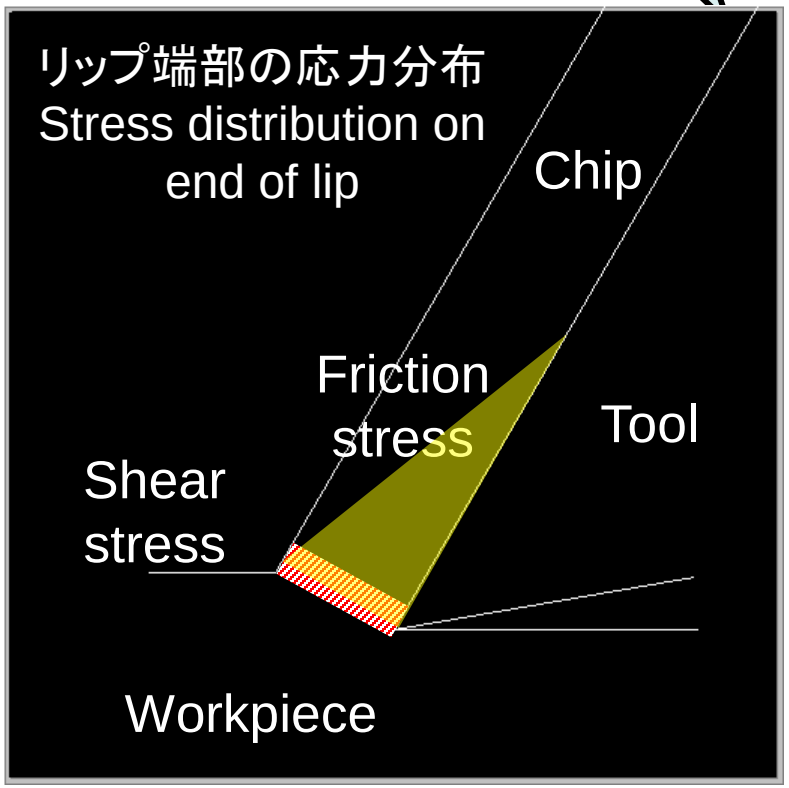
↓

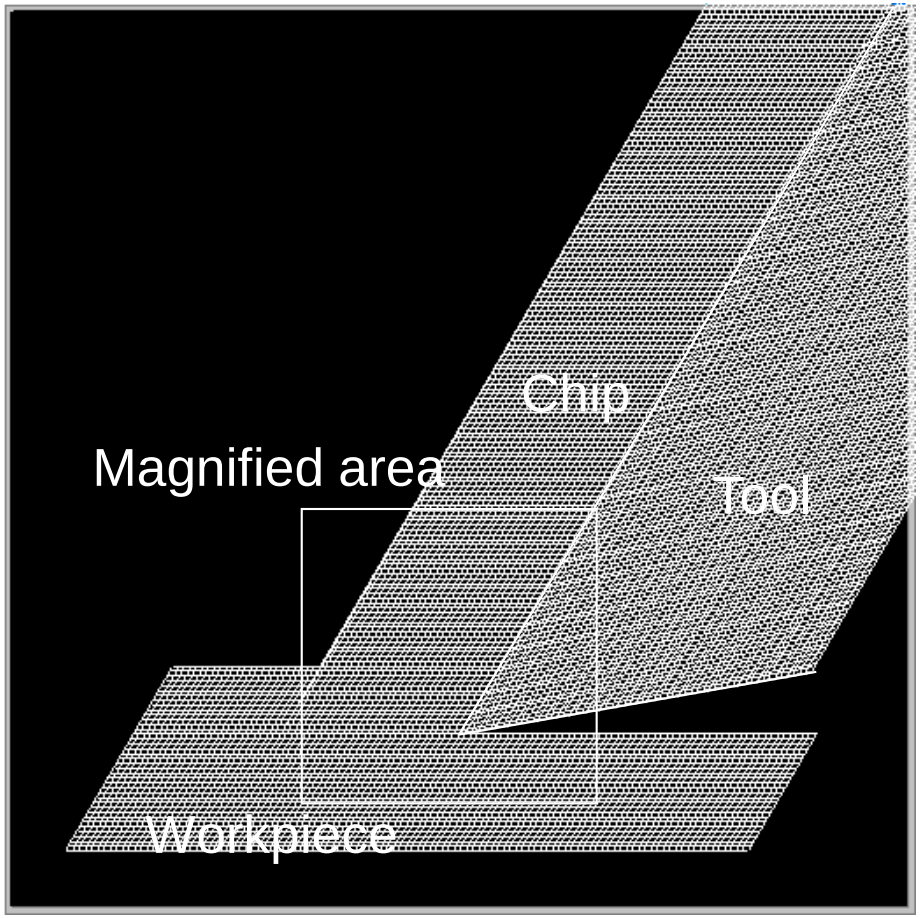
穴の加工品位



応力分布と温度解析







$$\rho c \frac{\partial \theta}{\partial t} = div(k grad\theta) - div(\rho c \mathbf{v}\theta) + S$$

t, time; θ, temperature; K, thermal conductivity; ρ, density; c, specific heat; $\mathbf{v}$, velocity; S, heat generation.

CFRPと炭素鋼の温度分布

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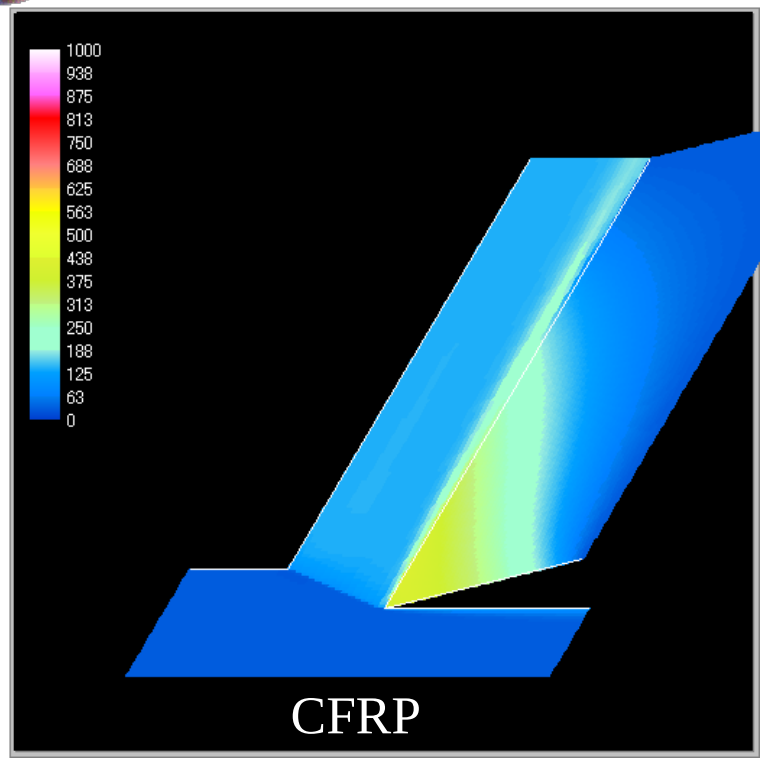
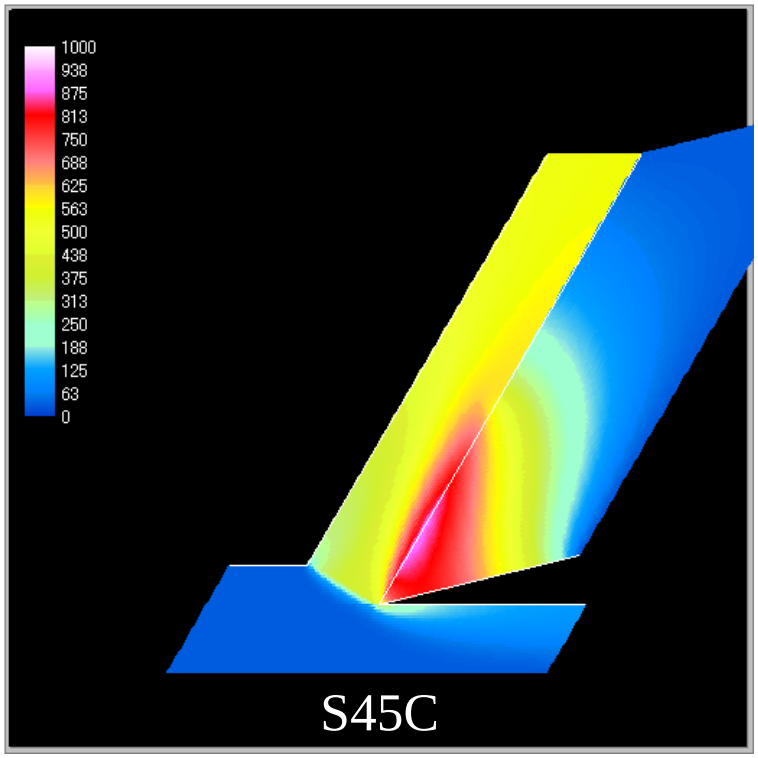
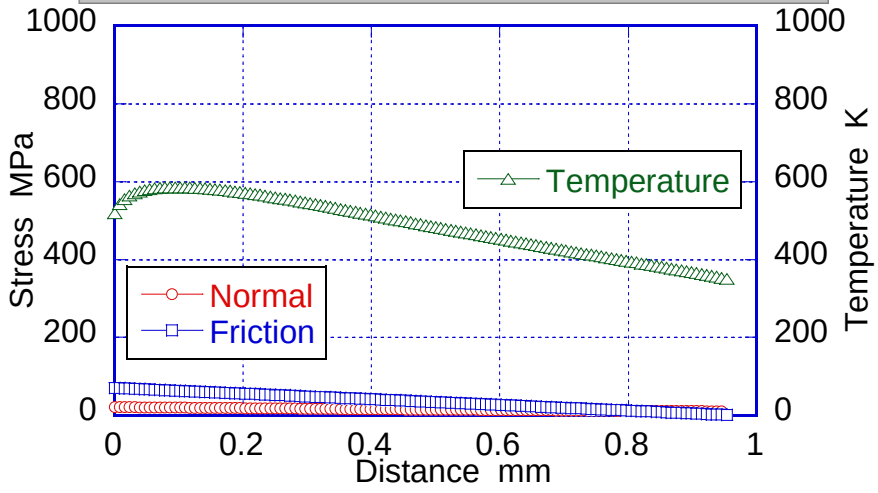
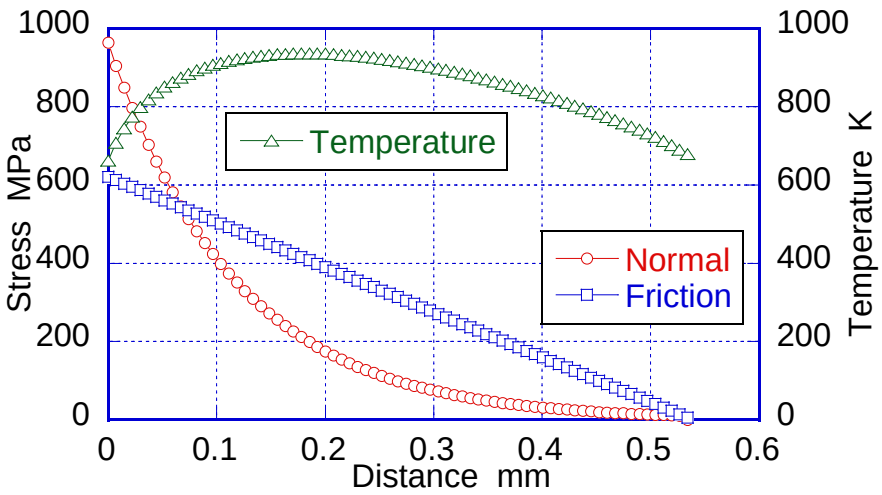
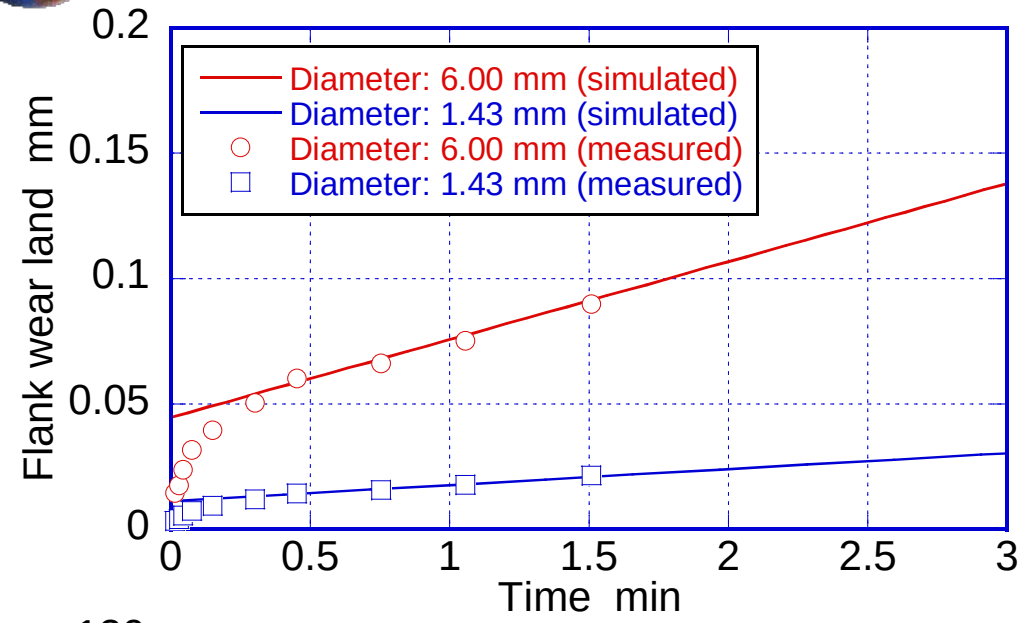


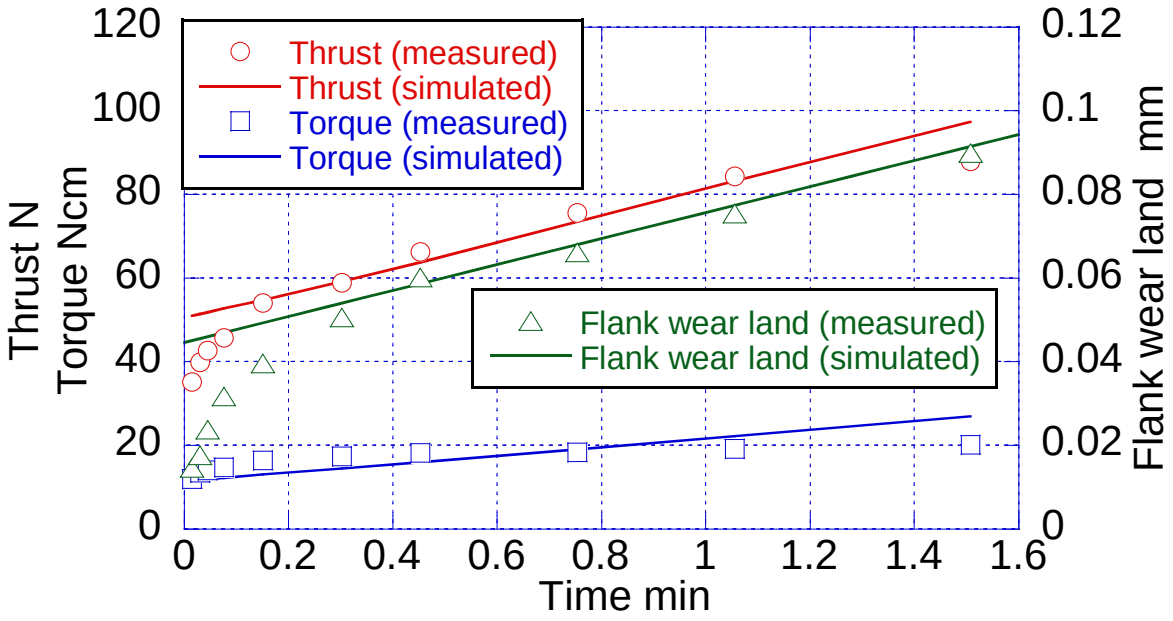


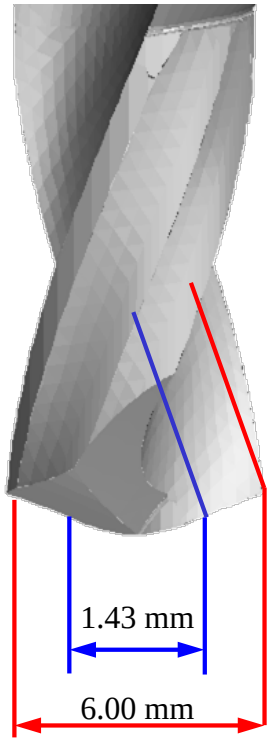




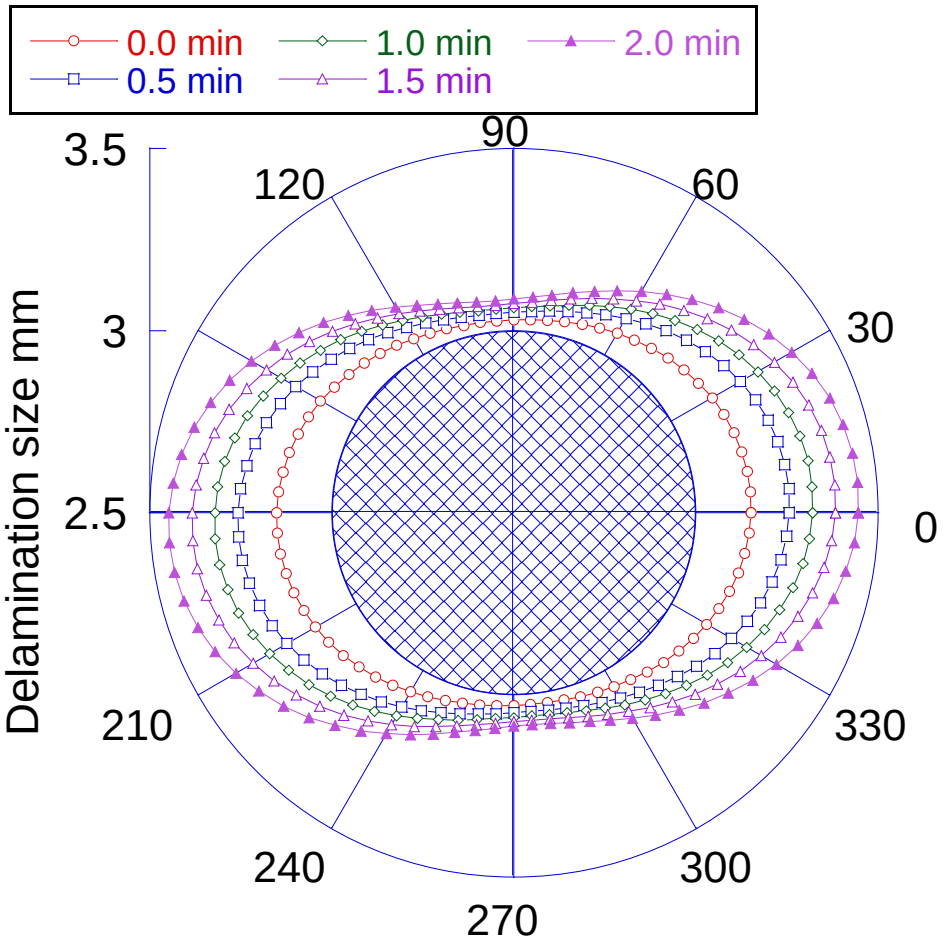
工具摩耗進行に伴う切削力変化

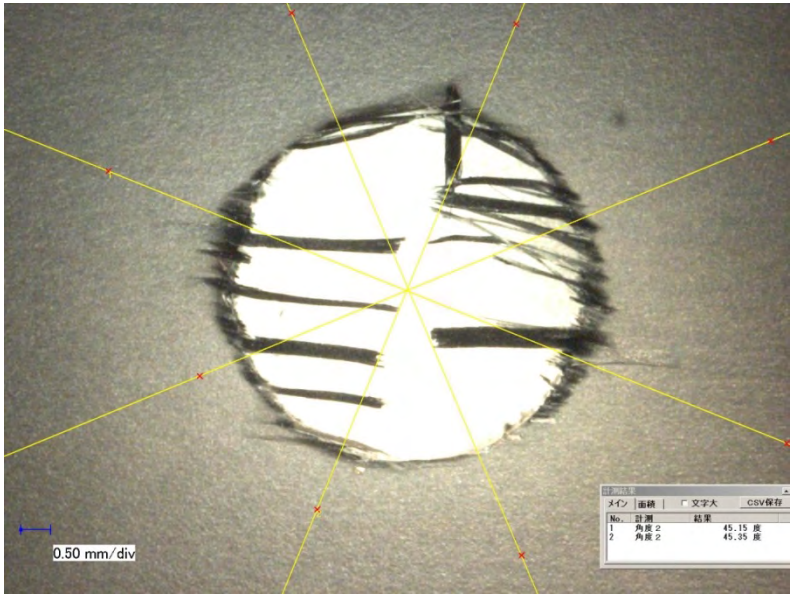






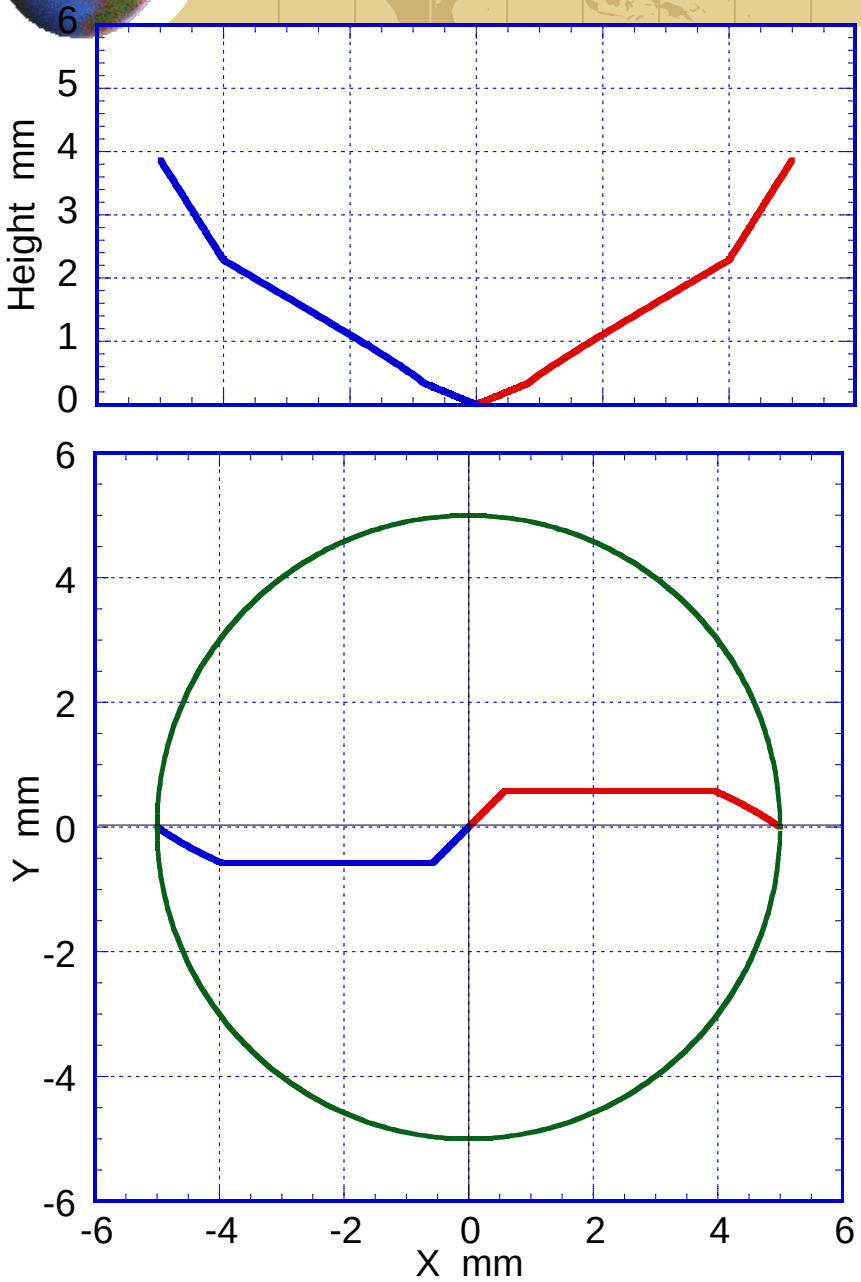
剥離の時系列シミレーション

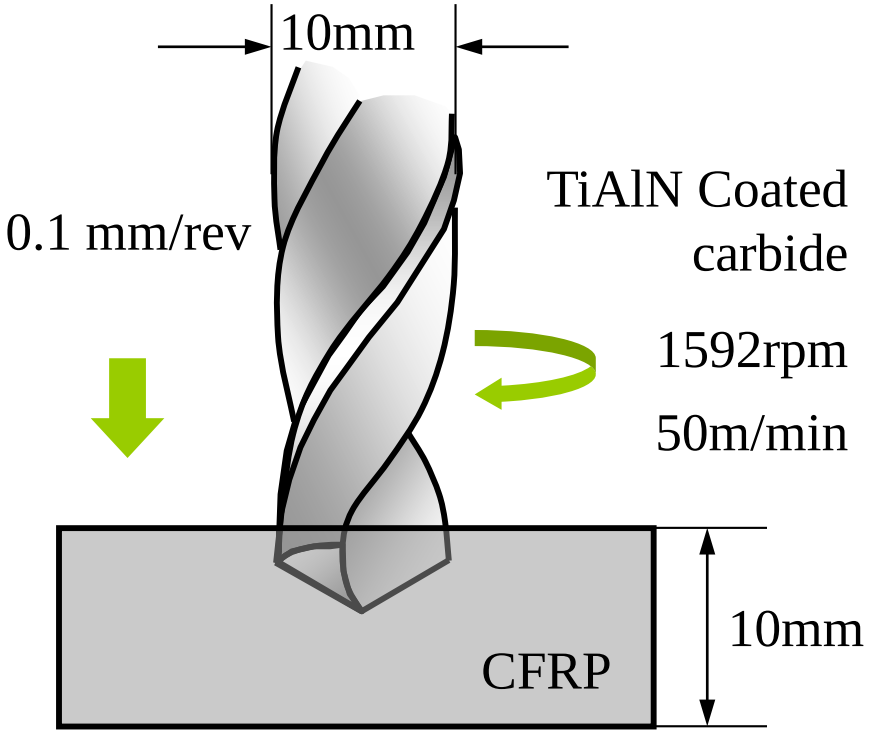




Fiber orientation

ダブルアングルドリル

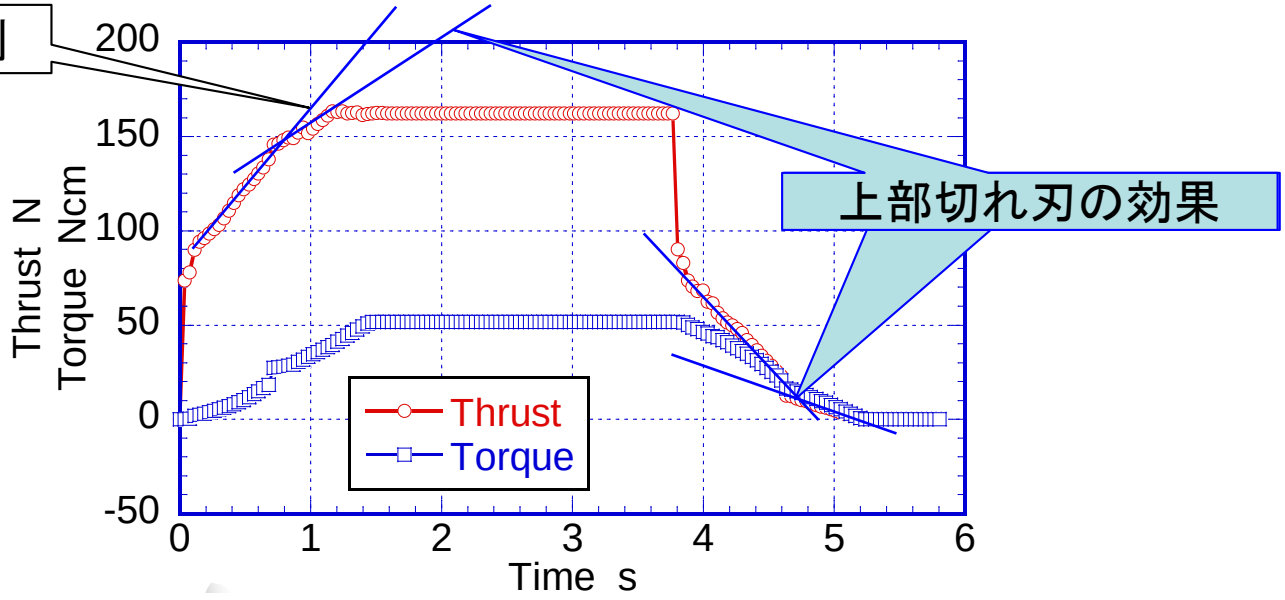


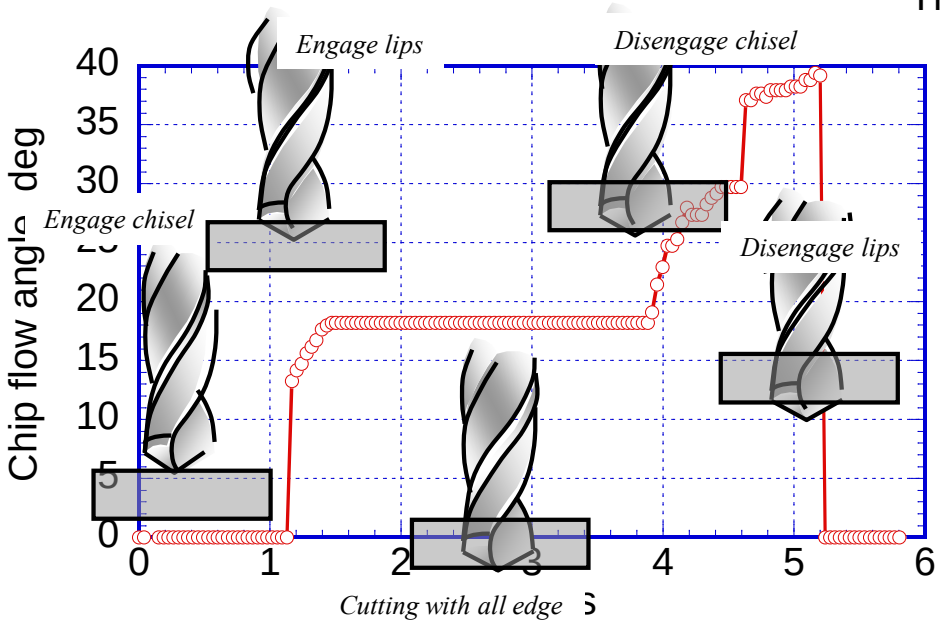


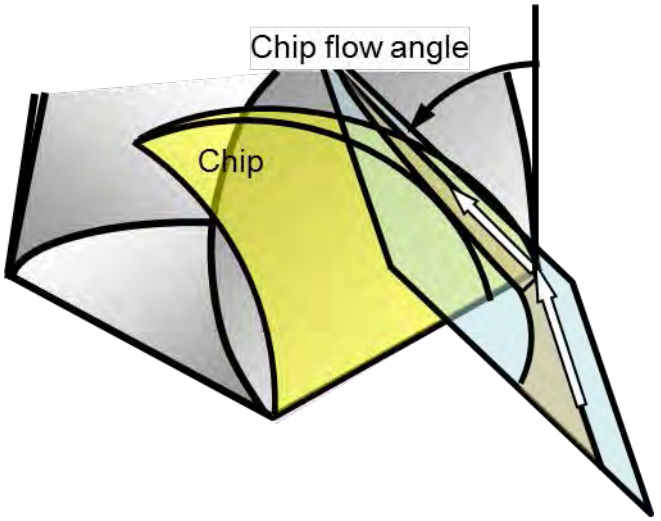
Diameter	10mm
Primary wedge angle	120 deg
Secondary wedge angle	65 deg
Helix angle	30 deg
Thinning	X type

切削力の変化

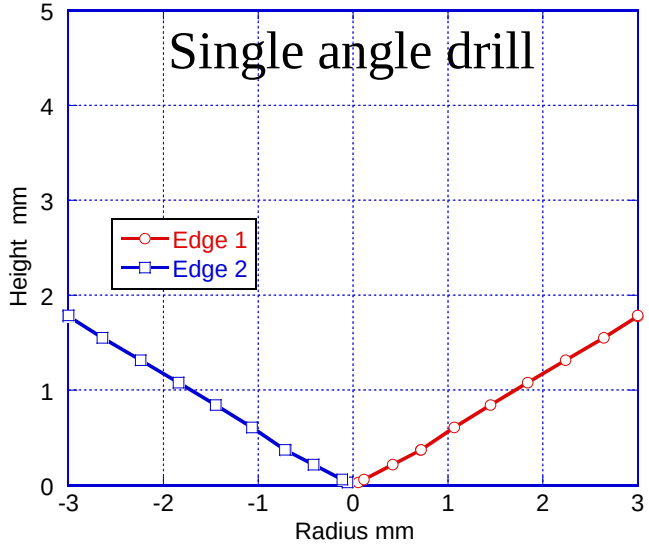
下部切れ刃の切削

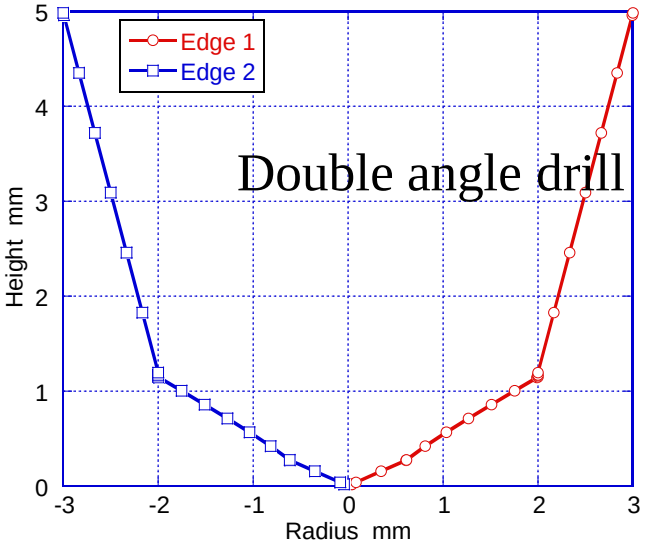


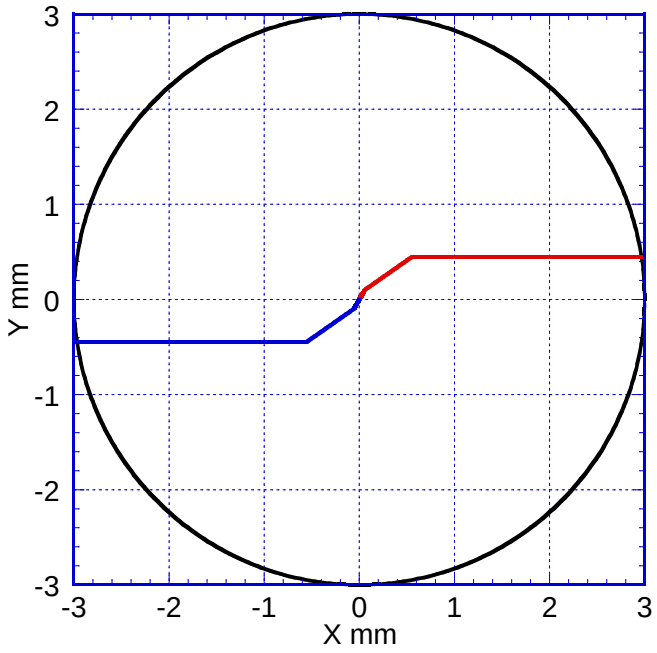


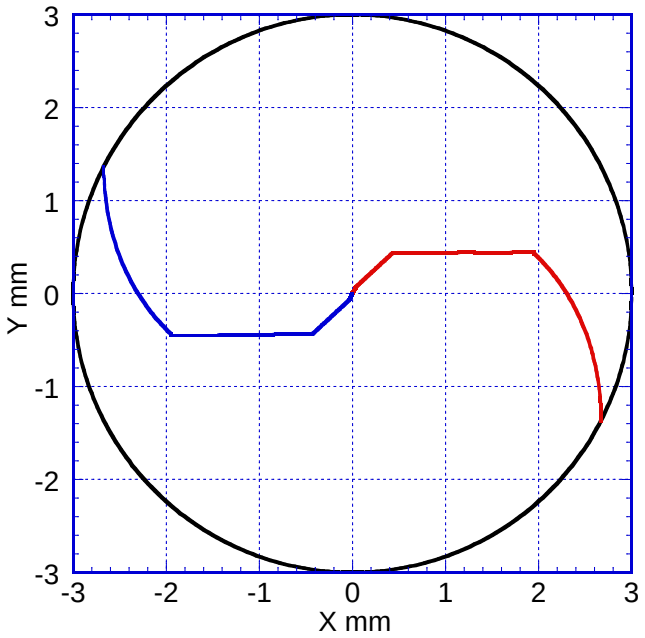


シングル・ダブルアングルドリル









ダブルアングルドリルの剥離抑制効果

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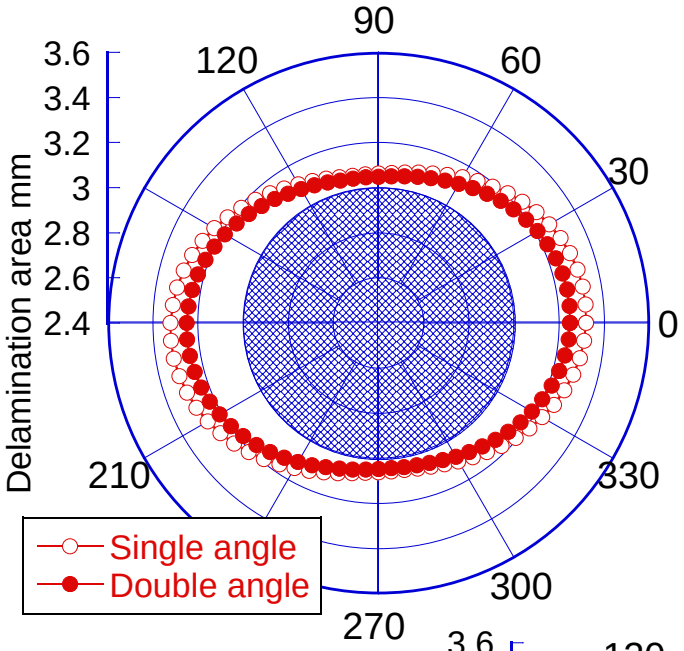
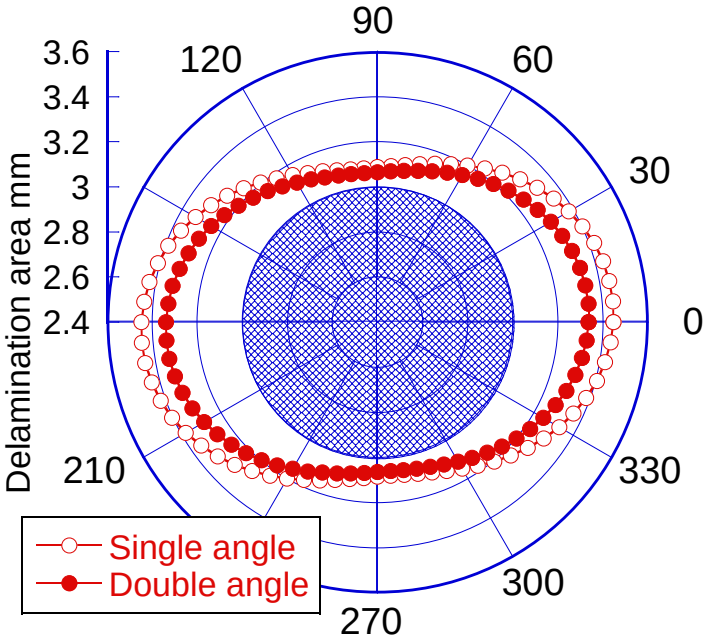
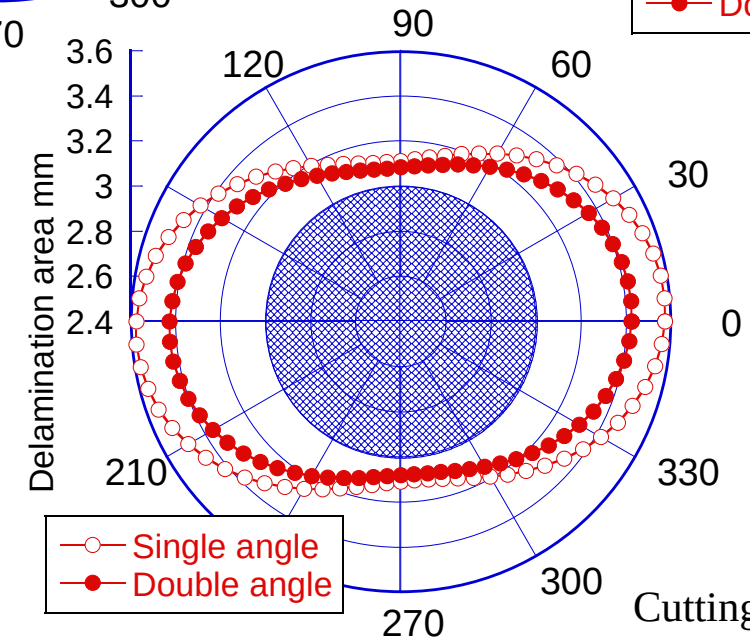
MSP Lab.



Cutting time: 1 min



Cutting time: 2 min



Cutting time: 3 min

CFRP/Ti 合金の重積材

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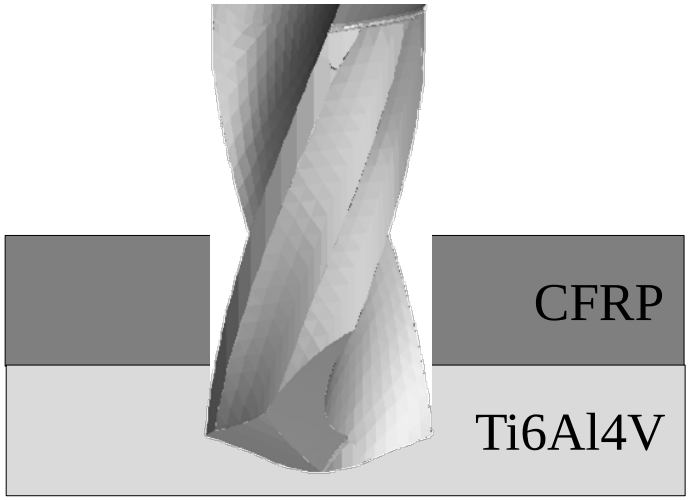
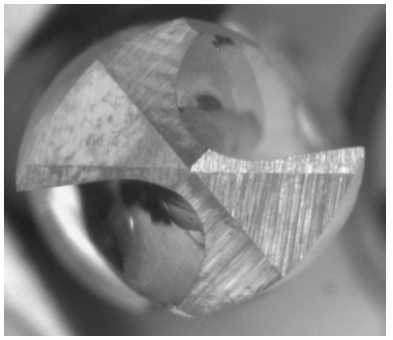
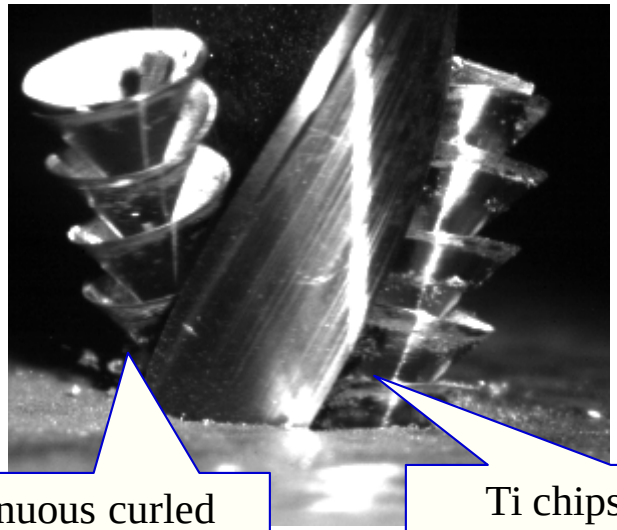




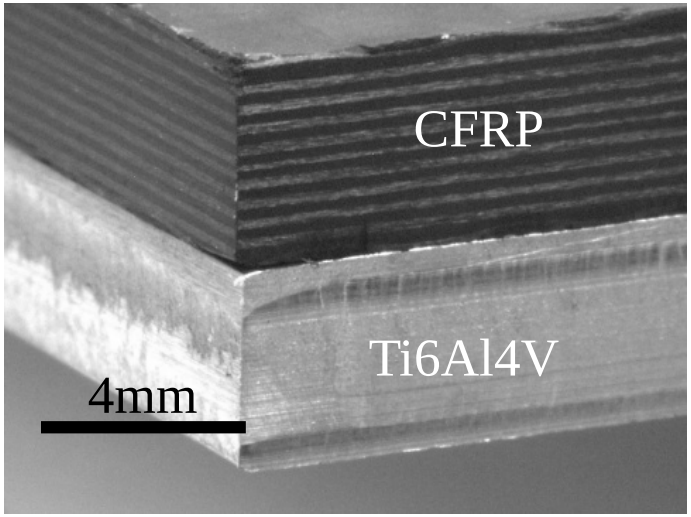
Helix angle	20deg
Wedge angle	120deg
Number of edge	2
Diameter	6mm
Material	Carbide
Thinning	X type
Coating	TiAlN



Continuous curled chip of Ti

Ti chips scratch the finished surface of CFRP

重積材の切削力



CFRP with the carbide tool

ϕ=exp(0.1149V+30470t_1+0.0485α-2.708)

τ_s=exp(-0.6737V-4679t_1-2.182α+18.87)

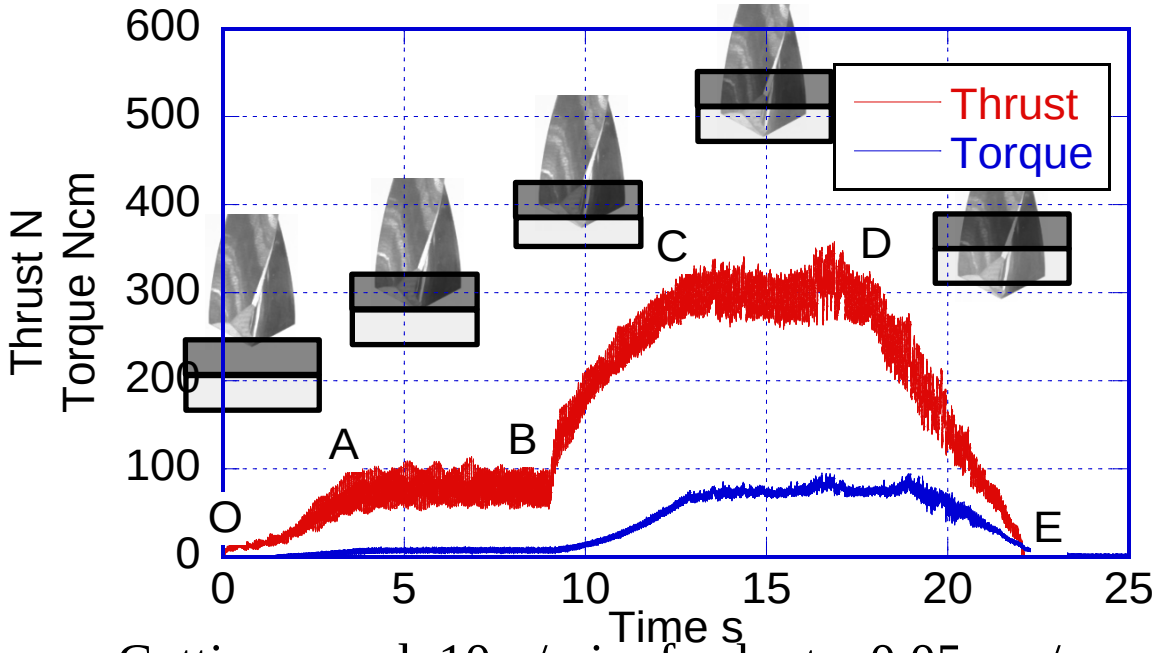
β=exp(-0.1643V-1132t_1+1.742α-0.452)

Ti6Al4V with the carbide tool

ϕ=exp(0.3194V+579.7t_1+0.6553α-1.399)

τ_s=exp(-0.3204V-145.3t_1-1.016α+20.64)

β=exp(-0.0582V-2159t_1+0.1824α-0.234)



ϕ, shear angle;
τs, shear stress on shear plane
β, friction angle
V, cutting velocity
t_1, cutting thickness
α, rake angle.

Cutting speed, 10m/min; feed rate, 0.05mm/rev

重積材の切削シミュレーション

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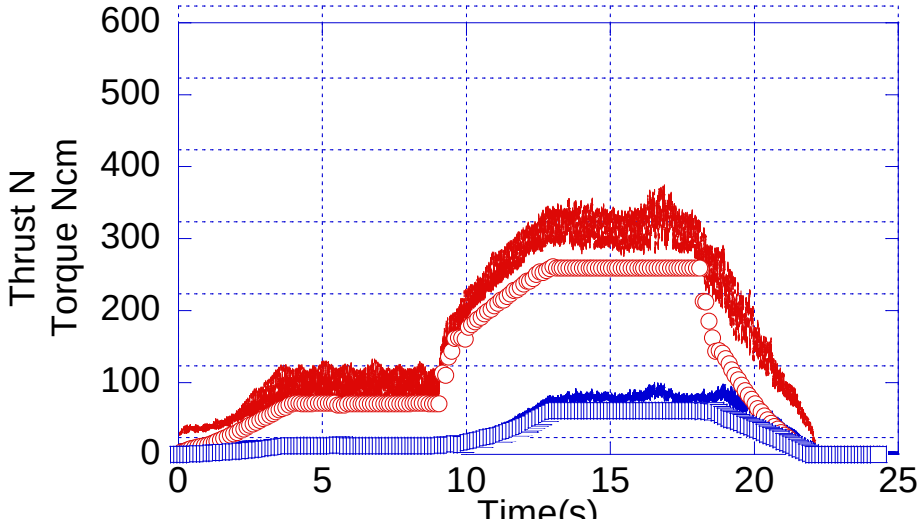
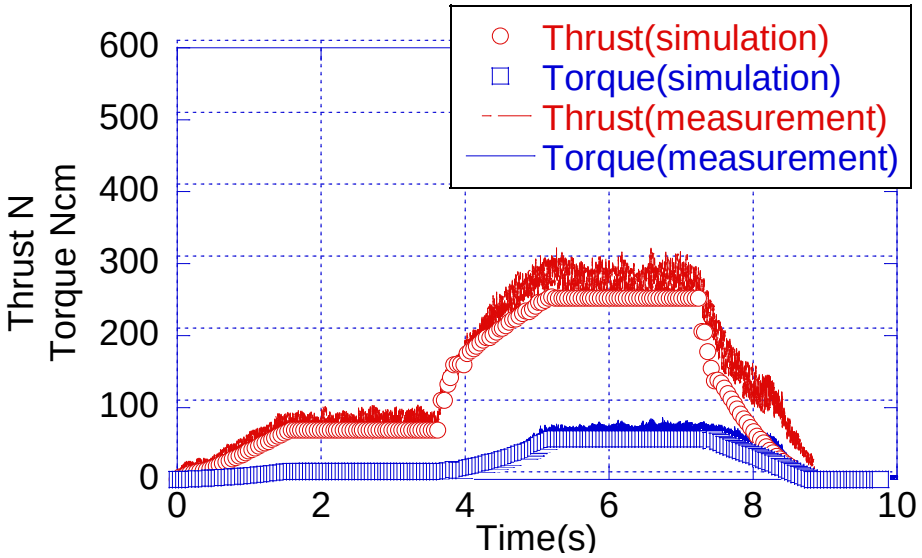
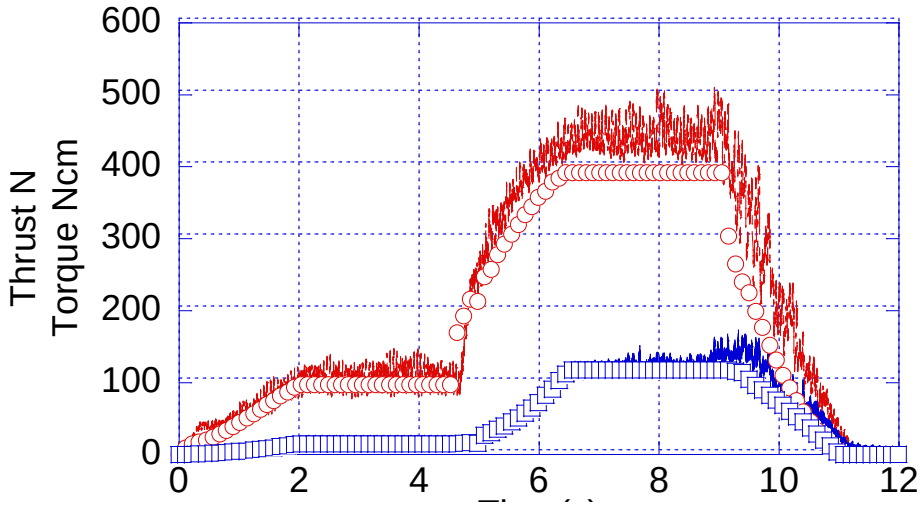


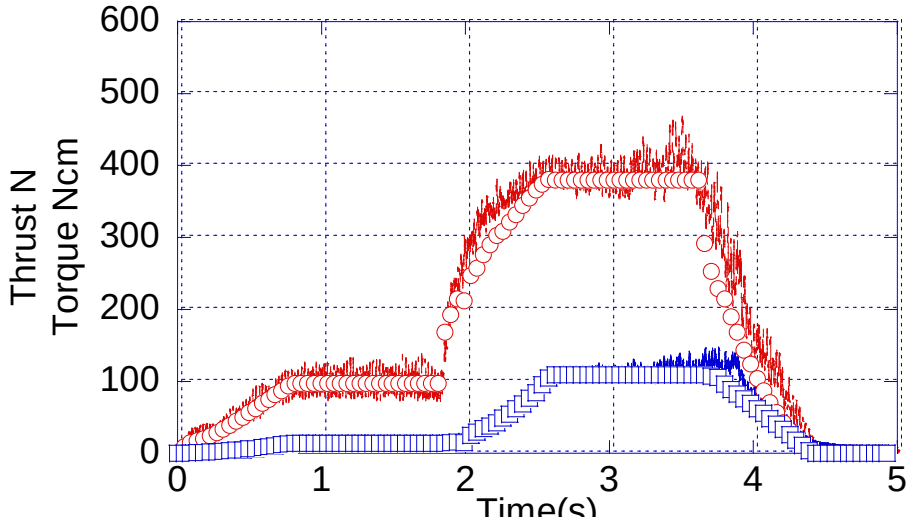
Speed, 10m/min; feed rate, 0.05mm/rev



Speed, 25m/min; feed rate, 0.05mm/rev

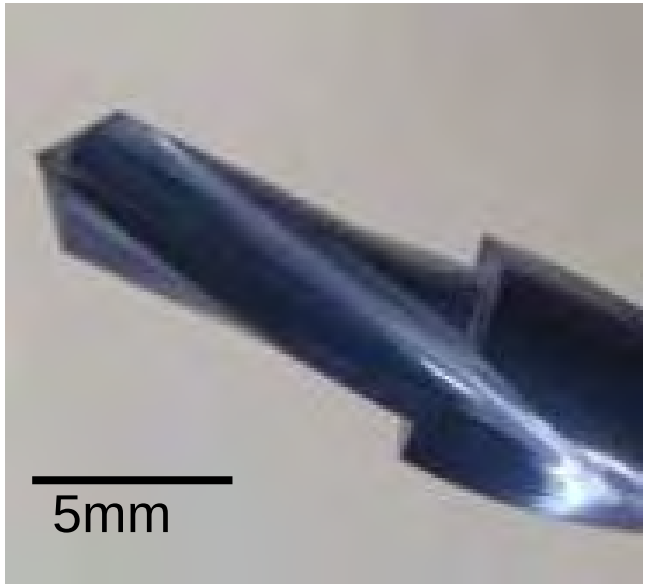


Speed, 10m/min; feed rate, 0.1mm/rev



Speed, 25m/min; feed rate, 0.1mm/rev

CFRP/Ti合金重積材用ドリル



Geometry of step drill	
Helix angle	20deg
Wedge angle at point	118deg
Wedge angle at step	180deg
Number of edge	2
Diameter for pre-machining	4mm
Diameter for finish	6mm
Axial length of point - step	10mm
Material	Carbide
Thinning	X type
Coating	TiAlN

- 仕上げ用切れ刃の先端角180°
- 下穴用ドリル直径4mm
- 下穴用ドリルの長さ（10mm）＞被削材板厚（8mm）

Cutting forces of step drills

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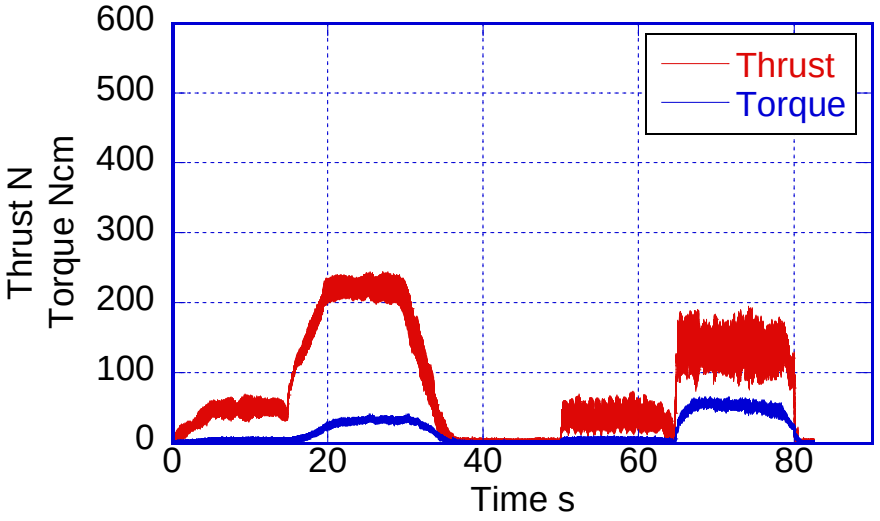
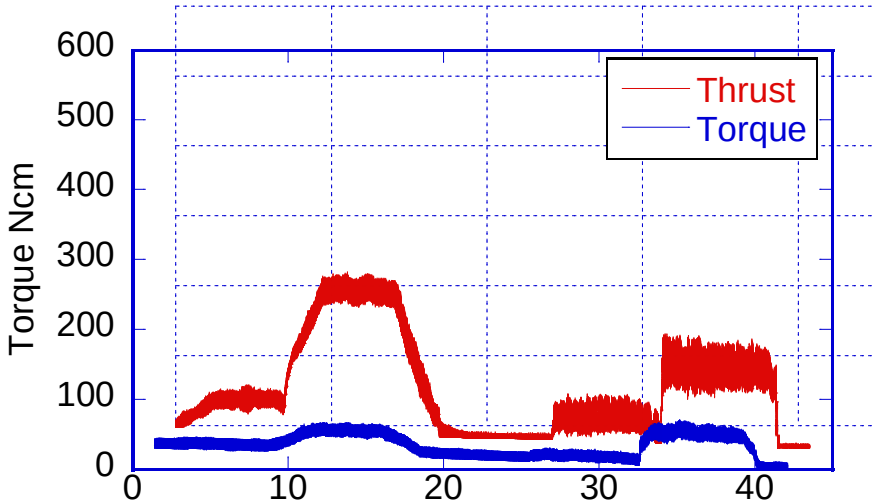
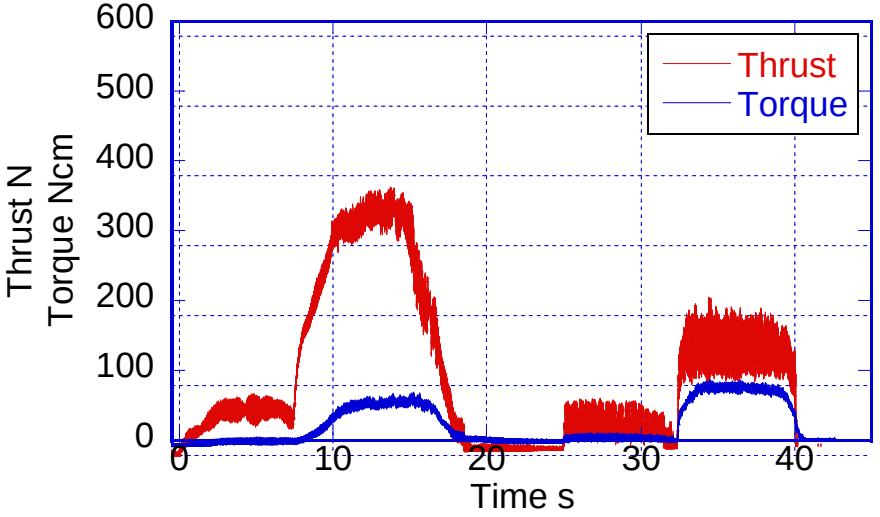


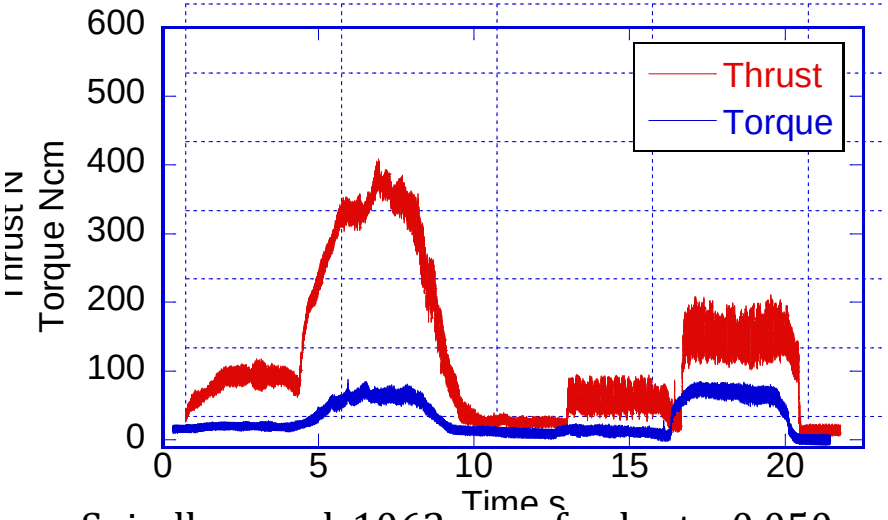
Spindle speed, 531 rpm; feed rate, 0.025 mm/rev



Spindle speed, 1062 rpm; feed rate, 0.025 mm/rev

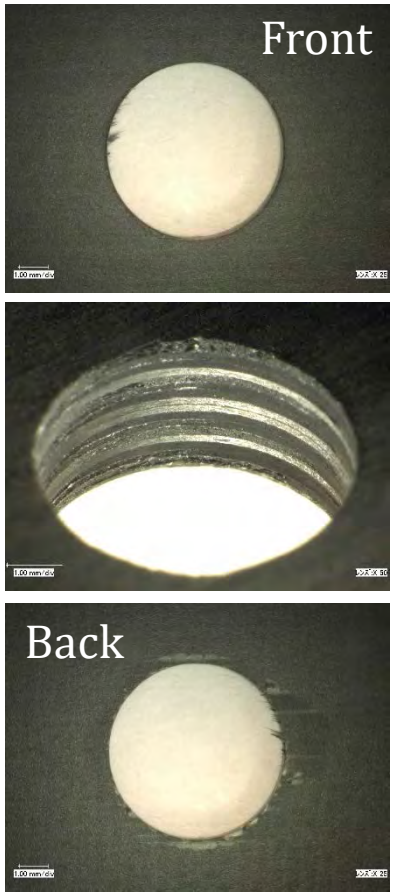


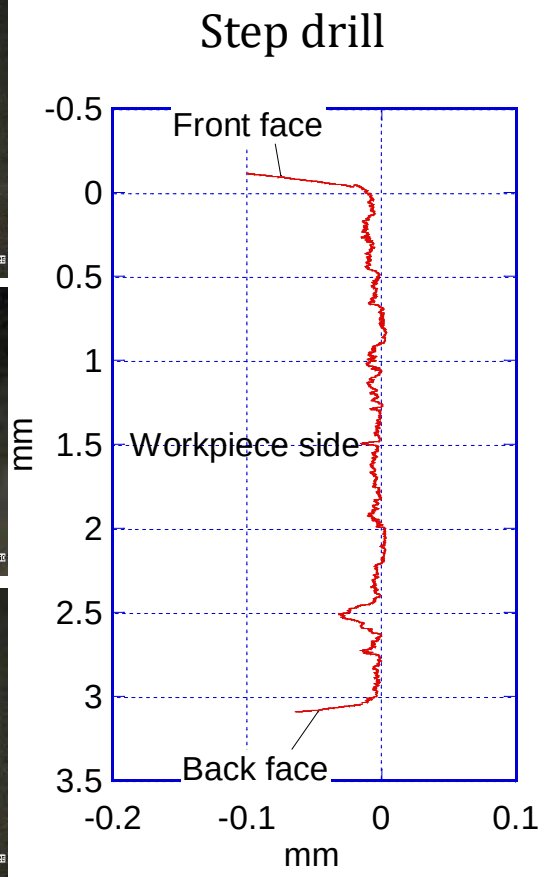
Spindle speed, 531 rpm; feed rate, 0.050 mm/rev

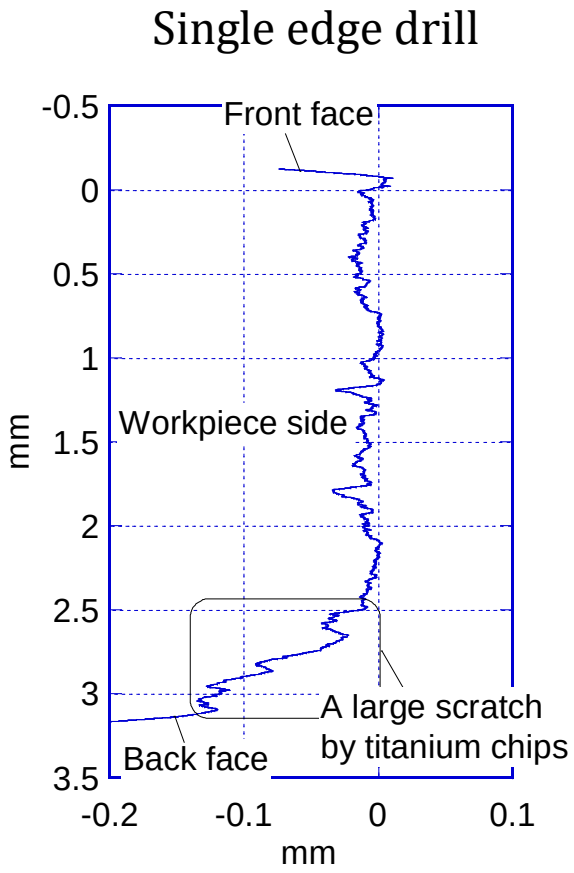


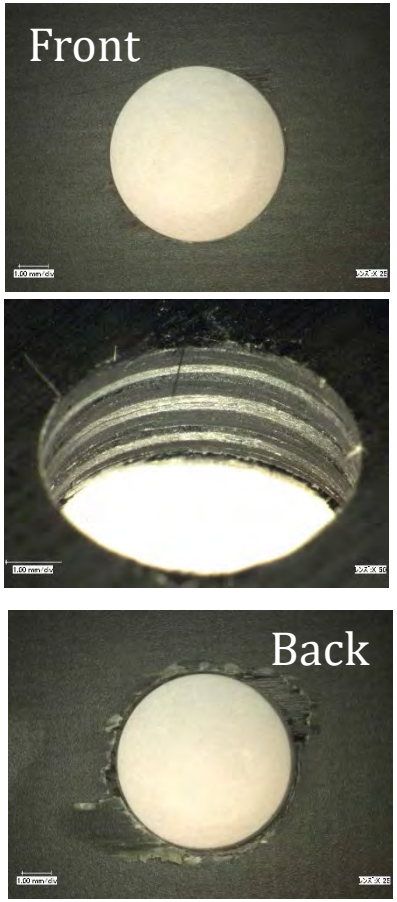
Spindle speed, 1062 rpm; feed rate, 0.050 mm/rev

Surface finishes

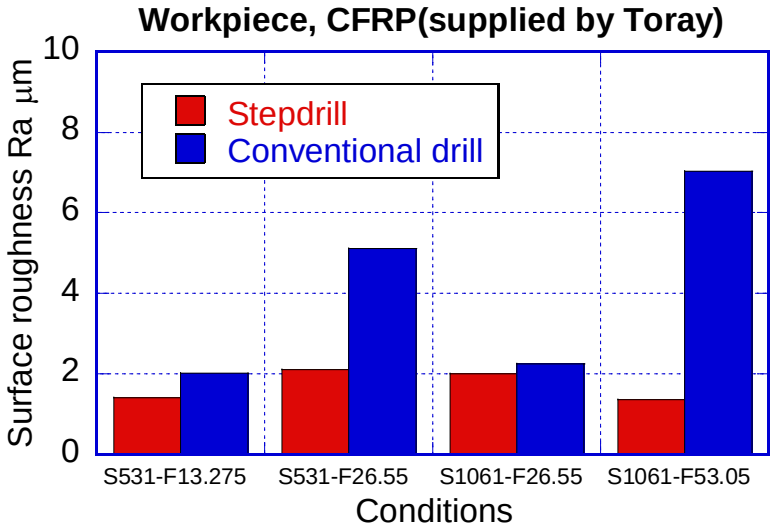


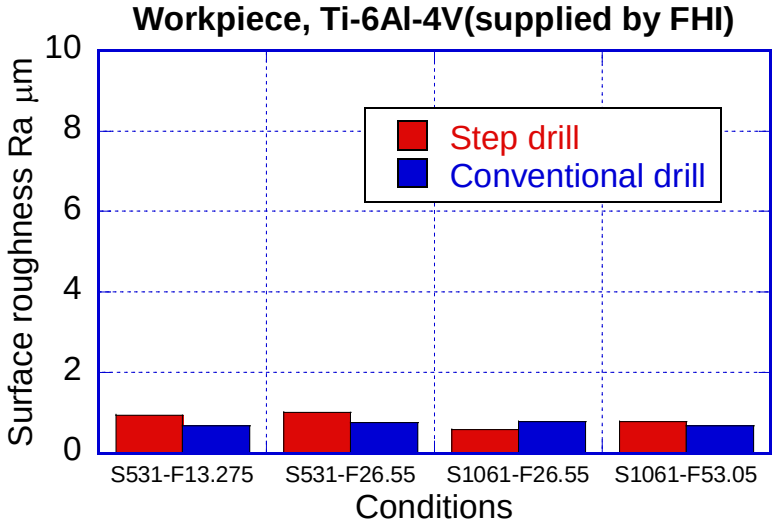


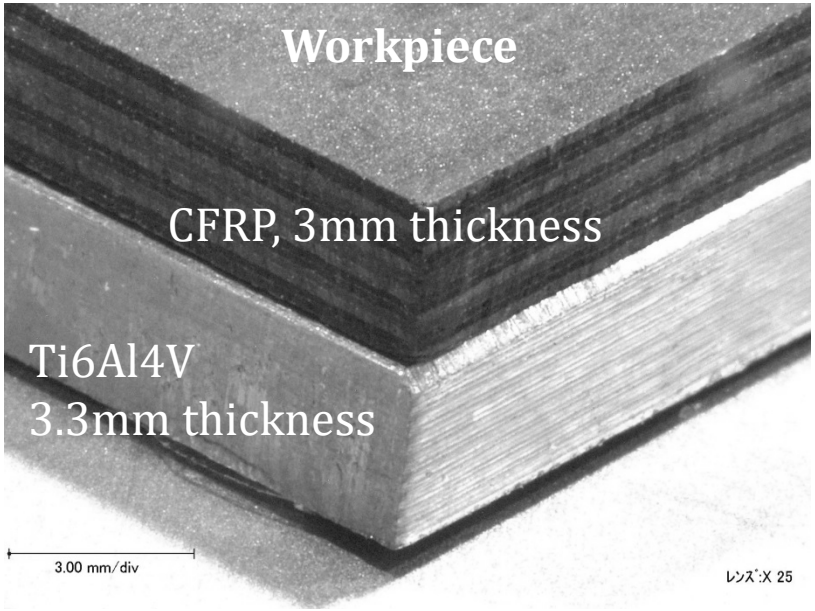




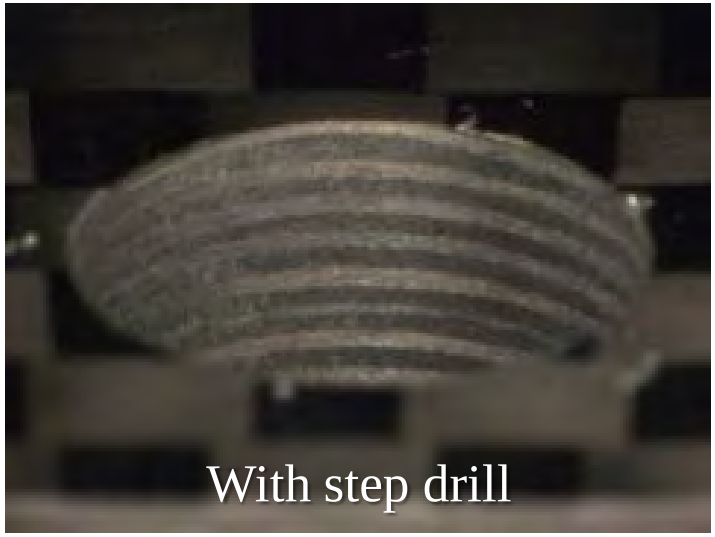
Cutting speed, 531rpm(10m/min at 6mm diameter)
feed rate, 26.55mm/min(0.05mm/rev)

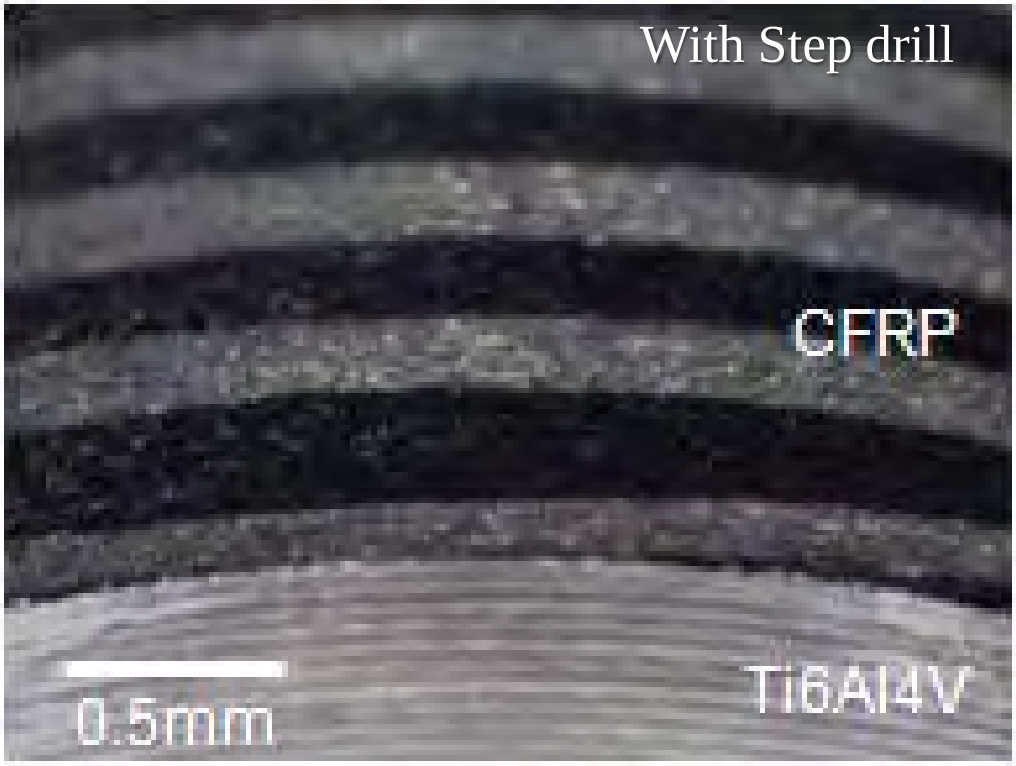

Workpiece, CFRP(supplied by Toray)
Surface roughness Ra μm
10
8
6
4
2
0
Stepdrill
Conventional drill
S531-F13.275
S531-F26.55
S1061-F26.55
S1061-F53.05
Conditions


Workpiece, Ti-6Al-4V(supplied by FHI)
Surface roughness Ra μm
10
8
6
4
2
0
Step drill
Conventional drill
S531-F13.275
S531-F26.55
S1061-F26.55
S1061-F53.05
Conditions


Workpiece
CFRP, 3mm thickness
Ti6Al4V
3.3mm thickness
3.00 mm/div
ﾚﾝｽﾞ:X 25

ステップドリルで仕上げ面改善





Thank you
御清聴ありがとうございます.