Basics of End Mills

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What is “Cutting”?

What is “Cutting”?

Making products having desired surface shape by...
•putting and moving a cutting tool on a work piece,
•and separating unnecessary parts as chips by breaking with internal stress.

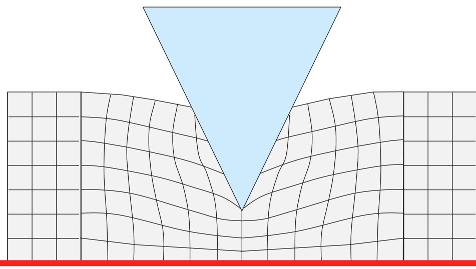

Image drawing

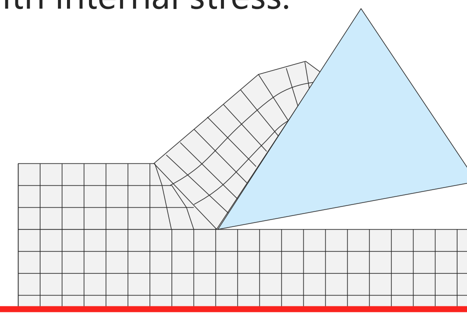

Image drawing

a) Cutting work piece by chisel
・Plastic deformation on both sides of the cutting part
・Need big force to pushing in

b) Scraping an edge of work piece by cutting tool
・ Plastic deformation occurs only to cutting chips
・Work piece itself does not deform

Material of work piece

Metals, woods, plastics, etc.

Features

Higher accuracy than chip-less processing

Rapid progress and diversification of cutting technology

Systematic understanding to phenomena is important to use cutting process effectively!

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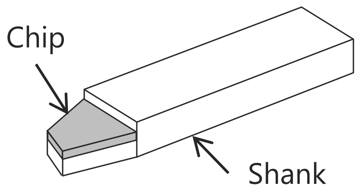
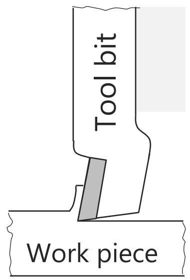
Tools for Cutting

Tool bit

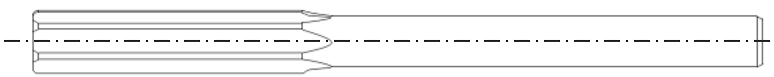




(Cutting image by tool bit)

A cutting tool for lathe, planer, shaper, boring machine, etc.

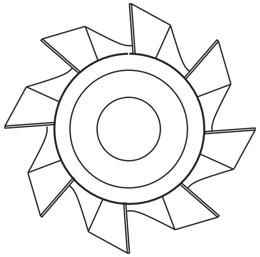
Reamer



A cutting tool for making inside wall of a drilled hole smooth and accurate.

Milling cutter

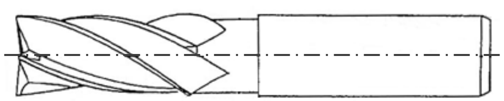
A rotary cutting tool having many cutting edges on the periphery or an end face of a cylinder and a cone.



Drill

A tool for drilling.
Cutting edges are only on a top.

End mill



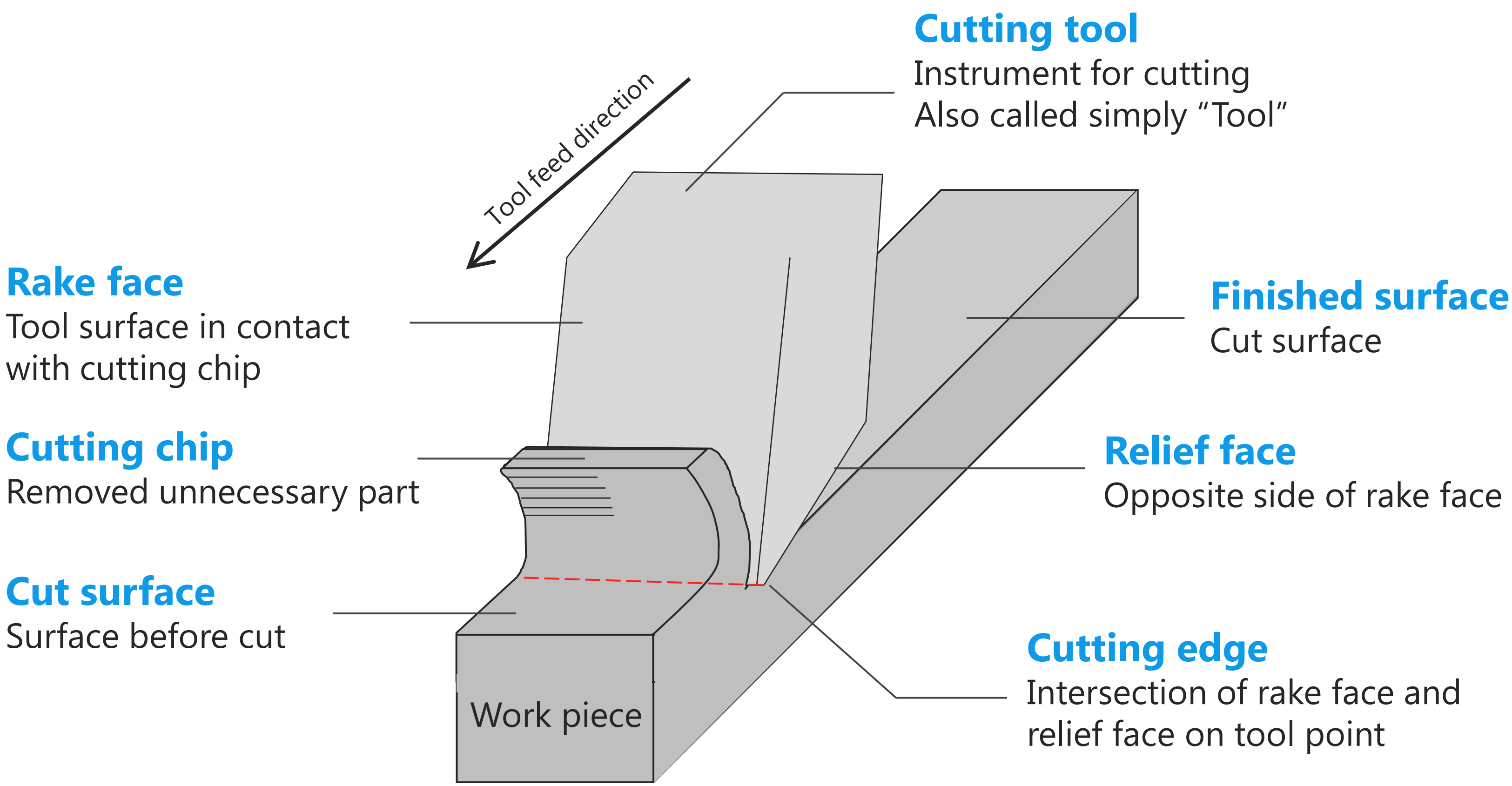
A multi-functional tool which has cutting edges on the periphery and an end face.
Side milling, curved surface milling and drilling are possible only by one tool.

Features of each tool

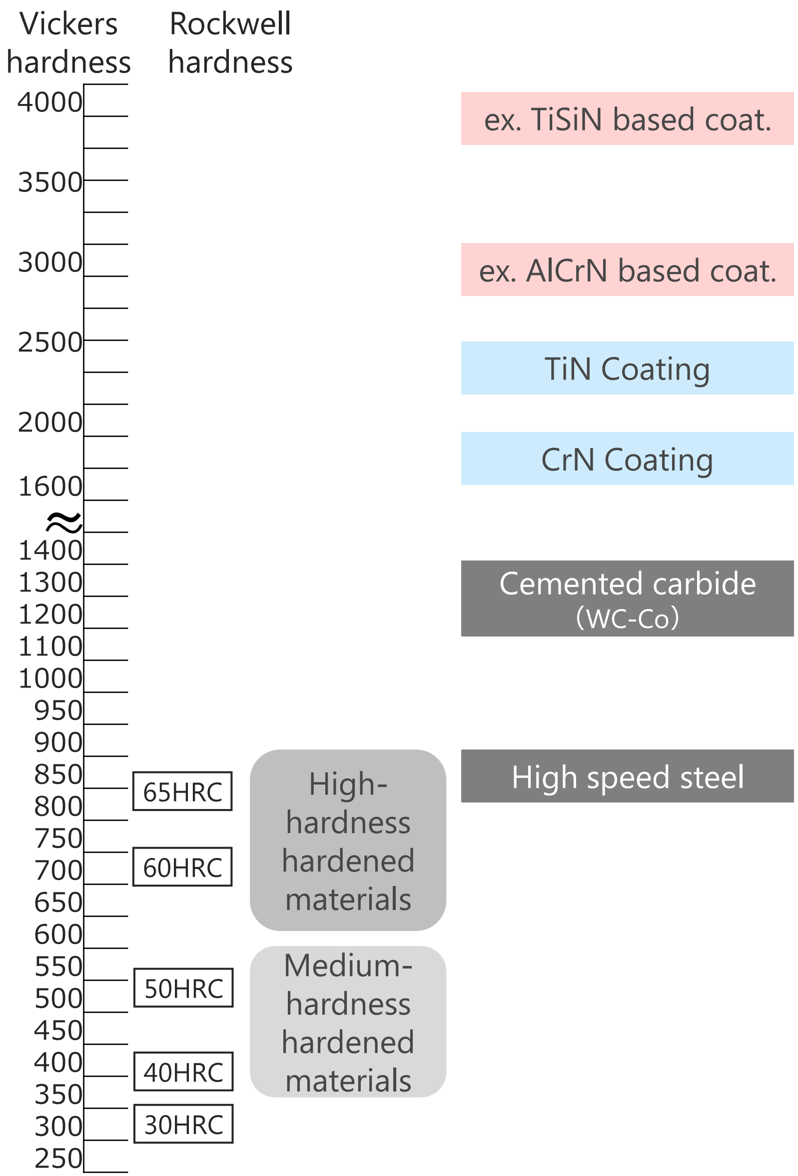
With few cutting edges…Inexpensive production and re-grinding
With many cutting edges…High cutting efficiency

Understanding of features of each tool and also cutting actions are important for economical & efficient processing!

Cutting Related Parts and Names



Work Material vs. Tool Material —Comparison of Hardness—



•Tool materials need more than 3 or 4 times the hardness of work material in Vickers Hardness.

•Cemented carbide tool can process work materials up to 30HRC. Processing 40HRC is a little difficult.
High-speed steel tool is not possible to process hardened steels.

Coating
(Cover the hardness of tool material)

If coated tools need ≥ x4 harder than work material...

•40HRC Hardened steels
>>> Tool materials need ≥ 1600Hv
CrN (Little difficult) TiN (Available)

•50HRC Hardened steels
>>> Tool materials need ≥ 2000Hv
TiN (Actually difficult) AlCrN (Available)

•65HRC Hardened steels
>>> Tool materials need ≥ 3300Hv
TiSiN based coating is available

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Coating —Purpose of Coating—

To improve tool life and cutting ability…

Apply coating technology

Tool obtains new characteristics by covering tool surface with coating.

Coating is expected to have…

- **Hardness** to make cutting edge stand on work piece
- **Heat resistance** not to change in quality under high temperature during cutting
- **Toughness** to stop chipping of cutting edge
- **Lubricity** to control friction during cutting

Coating methods

PVD method (**P**hysical **V**apor **D**eposition)

Coating method by reacting evaporated metal and reaction gas.
Process temperature is relatively low (≤500°C).

CVD method (**C**hemical **V**apor **D**eposition)

Coating method by thermochemical reaction.
Able to deposit on complicated shape, but cannot apply to some materials because of high treatment temperature (900-1000°C).

Coating —Actual Use of Coating—

Types of coating

Ceramic-base coating

Highly hard and heat resistant. Characteristic can be changed by adding other elements.

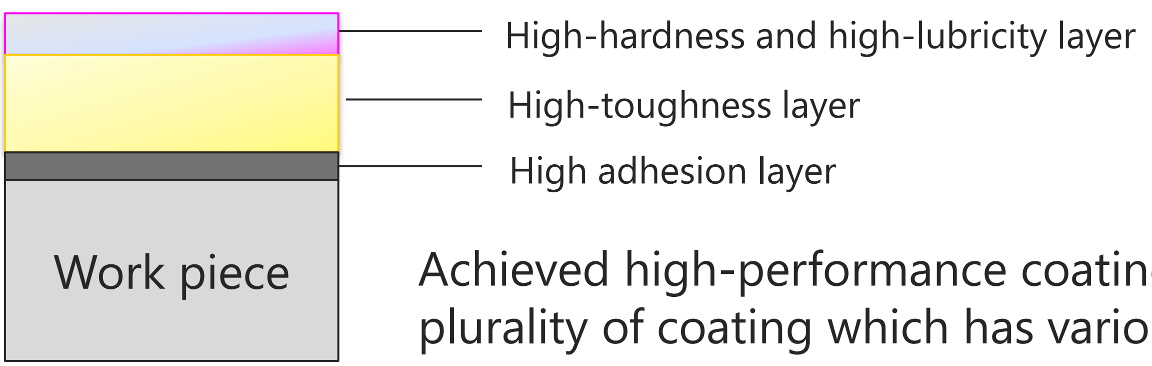
Diamond coating

Excellent hardness and anti-welding ability toward non-ferrous metals.
(Coatings constructed by carbon atoms is not suitable for ferrous materials.)

DLC (Diamond-Like Carbon) coating

Carbon based coating which is excellent in smoothness and lubricity, but not as hard as diamond.

Multi-layer coating



Achieved high-performance coating by piling up a plurality of coating which has various characteristics.

Understanding of characteristics & uses of coatings
>>>Improvement of tool life and cutting ability

Summary

What is "Cutting"?

Machining method which puts a hard cutting tool on a part near a edge of a work piece and separates cutting chips by causing plastic deformation.

Advantages of cutting

•Application for various work materials
•Relatively high machining accuracy

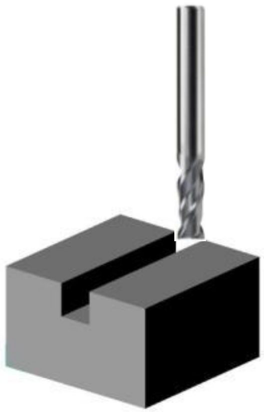
Cutting and tools

•Understanding features of each tools and appropriate use are important for economical & efficient processing.
•Tools need to be more than 3 times harder than a work material.

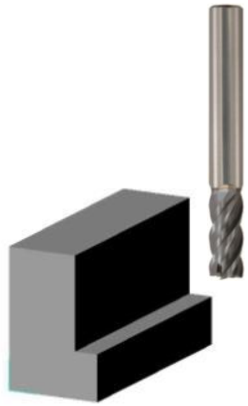
Contents

Types of End Mill Processing

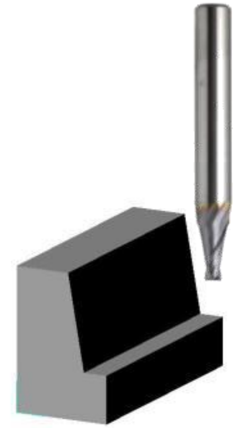
Slotting



Side milling

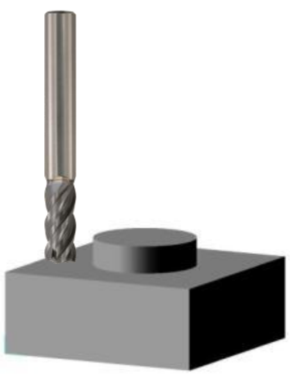


Tapering

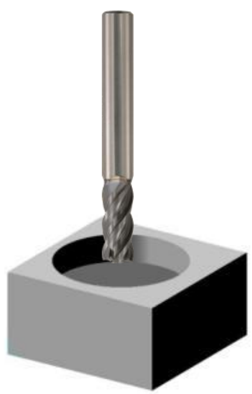


Profiling

Contouring

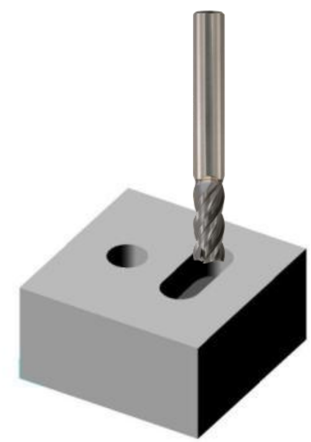


Pocket milling



Ribbing

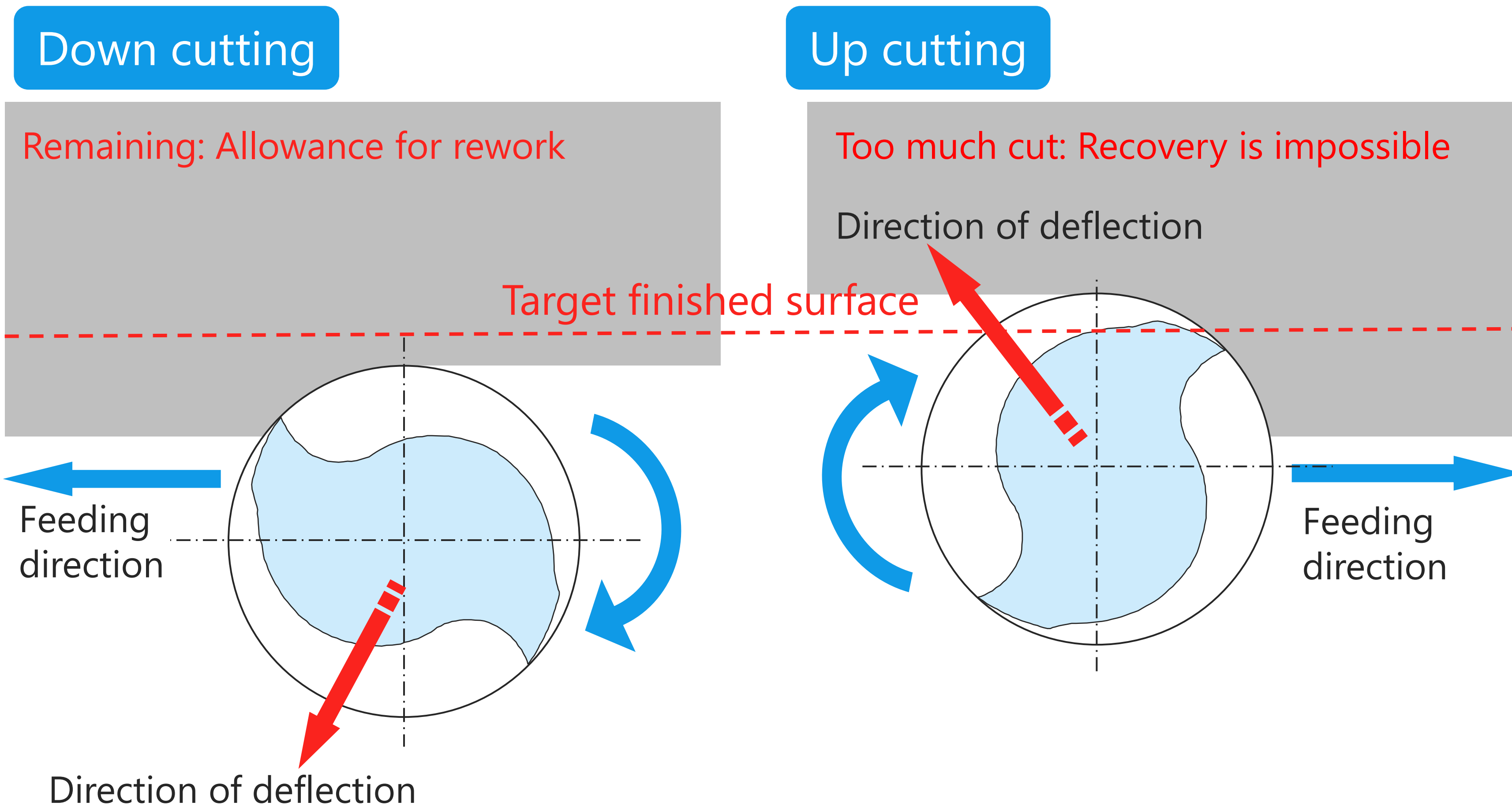
Spot facing



Processing Method —Down Cutting vs. Up Cutting—

Basically down cutting is recommended.

Generally down cutting is recommended for the whole range of metal processing considering direction of deflection and finished surface quality.
For resin materials, up cutting sometimes makes better finished surface.



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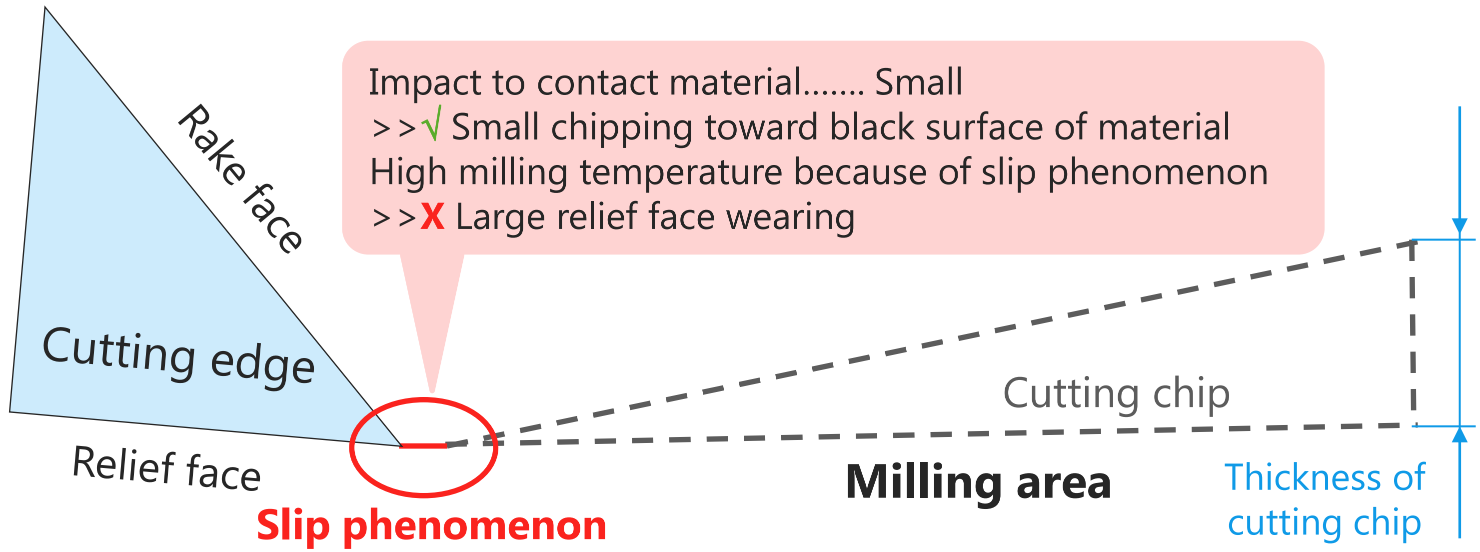
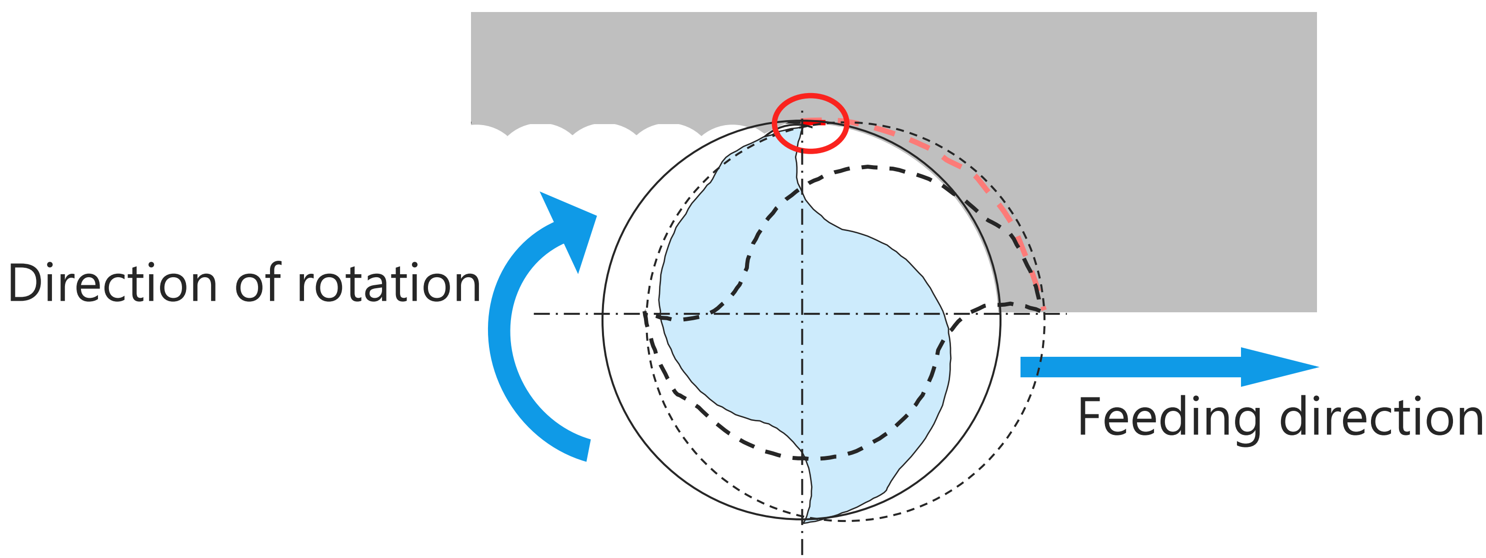
Up Cutting



Slip phenomenon: a cutting edge <u>does not cut but rub a work piece</u> because of too small cutting depth



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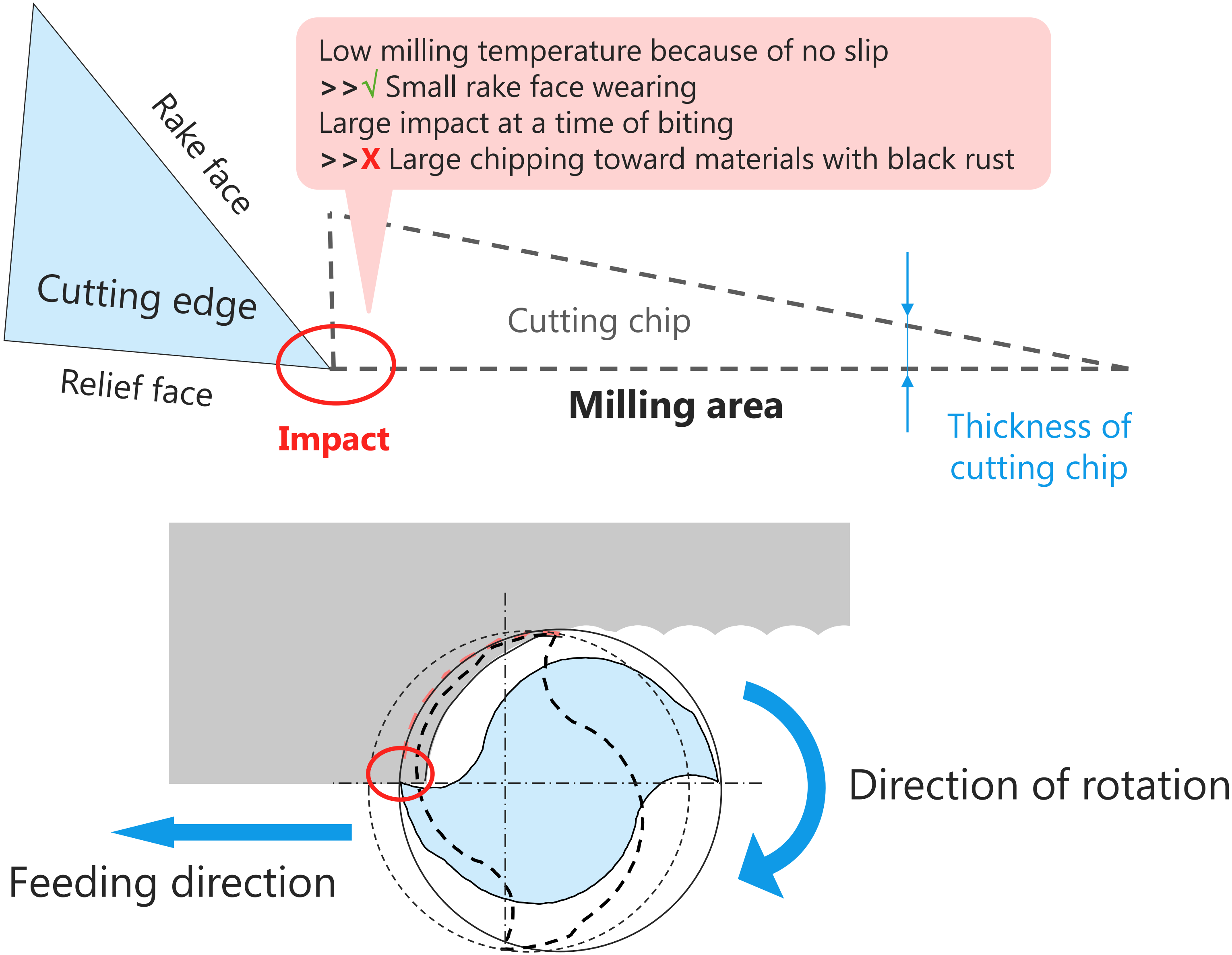
Down Cutting



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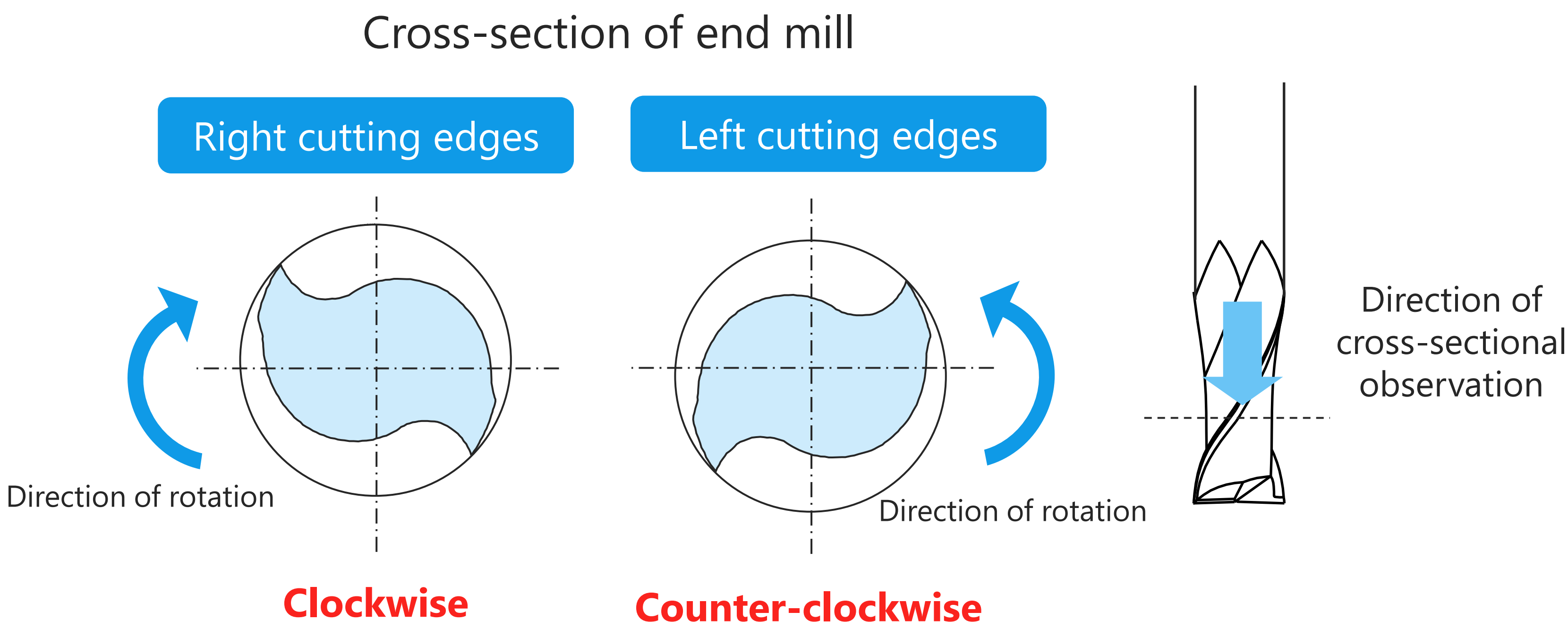
Right/Left Cutting Edge

Direction of rotation differs in direction of cutting edge



A tool rotates clockwise is called “Right cutting edge”.

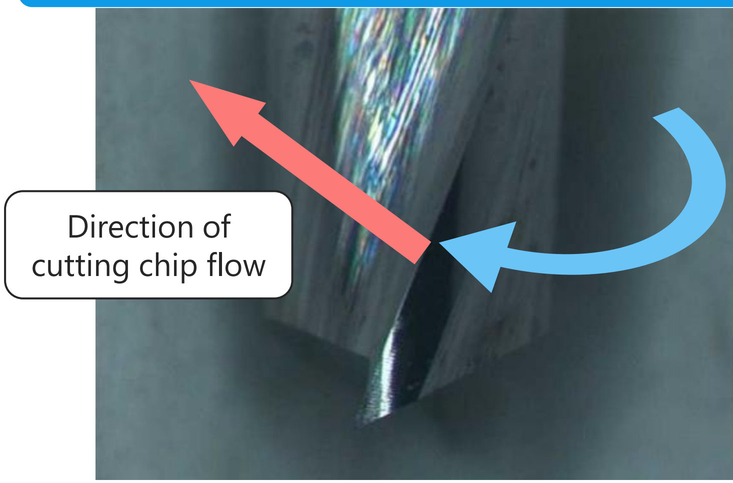
A tool rotates counter-clockwise is called “Left cutting edge”.

Ordinary end mills are “Right cutting edge” and “Left cutting edge” are very rare.

Right/Left Twisted Blades

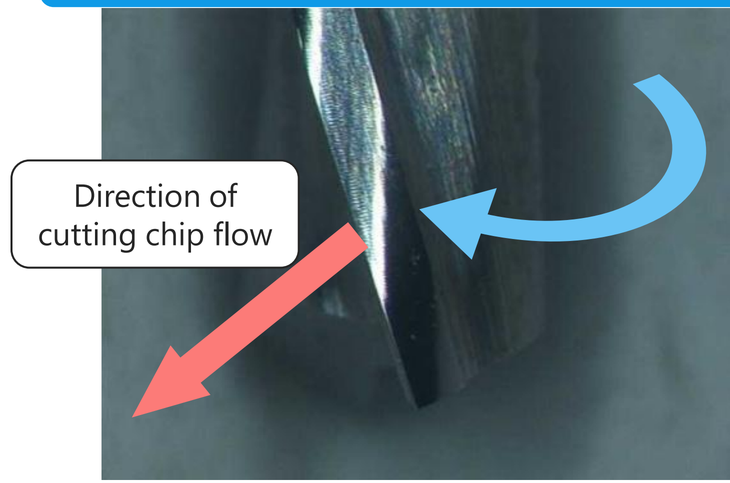
Direction of chip evacuation differs in direction of Helix.

Right cutting edges & right Helix



Raised upward

Right cutting edges & left Helix



Lowered downward

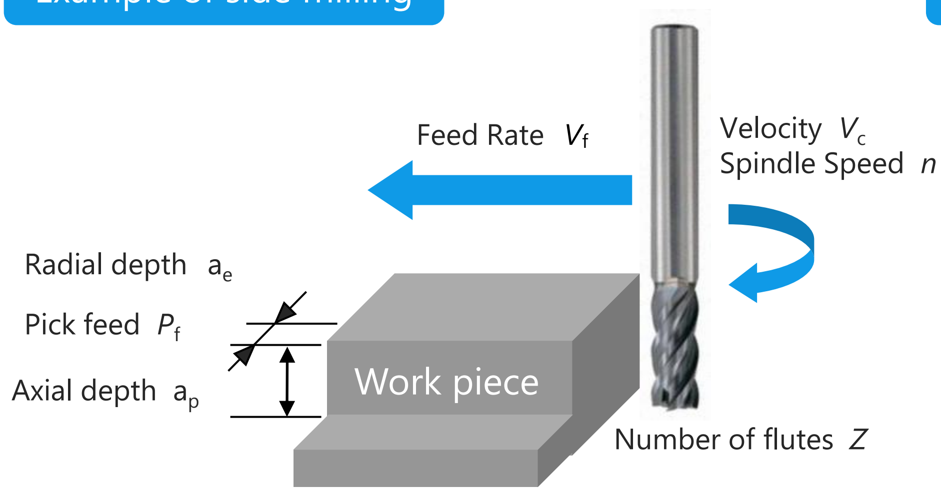
Right edges & right Helix: cutting chips are evacuated upward
Right edges & left Helix: cutting chips are evacuated downward

Ordinary end mills are “right edges & right Helix” and “right edges & left Helix” are very rare.

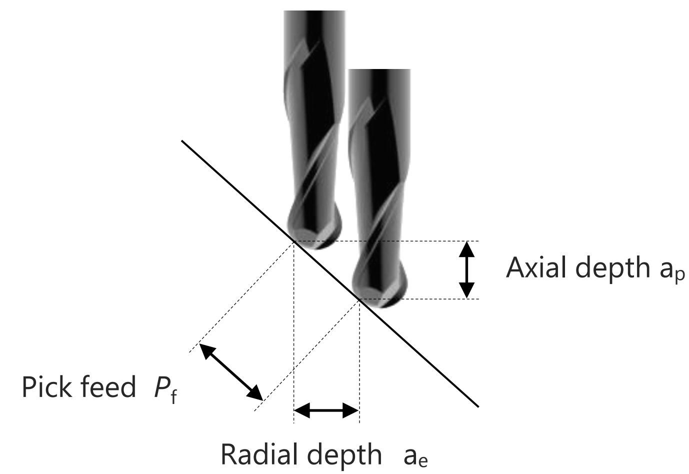
Terms Used for Parameters 1

Parameter	Conventional expression	Recommended expression	Unit	Meaning
Velocity	V	V_c	m/min	Moving distance of an optional point on the circumference per unit (1min)
Spindle Speed	N	n	min^{-1}	Revolutions per min
Feed Rate	F	V_f	mm/min	Moving distance in direction of feed per unit (1min)
Feed per tooth	Sz	f_z	mm/t	Lateral moving distance from one tooth comes to another does
Feed	f	f	mm/rev	Lateral feed rate (moving distance) per one rotation
Number of flutes	Z	Z	-	Number of tool flutes
Axial depth	Ad	a_p	mm	Axial cutting amount
Radial depth	Rd	a_e	mm	Radial cutting amount
Pick feed	Pf	P_f	mm	Moving distance of tool

Example of side milling



Example of slope milling



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Terms Used for Parameters 2

1. Velocity (peripheral speed) *Vc* [Unit: m/min]

… Moving distance of an optional point on the circumference per unit (1 minute)

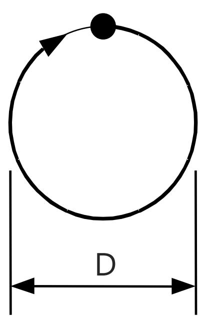
Related values

Diameter ϕD [mm]	Twice of the distance from the rotational center (radius)
π	The circular constant = 3.14 (Unit: Nil)
Spindle Speed n [min^{-1}]	Revolution per minute [Number of revolutions / min.] [min^{-1}]=[rpm: **r**evolutions **p**er **m**inute]

Circumferential length = Diameter x π = πD [mm]

Velocity (peripheral speed) *Vc*: Moving distance per minute = Circumferential length x Spindle rotation speed

$$Vc = \frac{\pi \times D\,[mm] \times n\,[min^{-1}]}{1\,[min]}\ [mm/min]$$



Unit conversion: 1mm=1/1000 m

D [mm]=D/1000 [m] therefore…

$$Vc = \frac{\pi \times D\,[mm] \times n\,[min^{-1}]}{1000 \times 1\,[min]}\ [m/min]$$

Terms Used for Parameters 3

2. Feed per tooth fz [Unit: mm/t]

Related Values

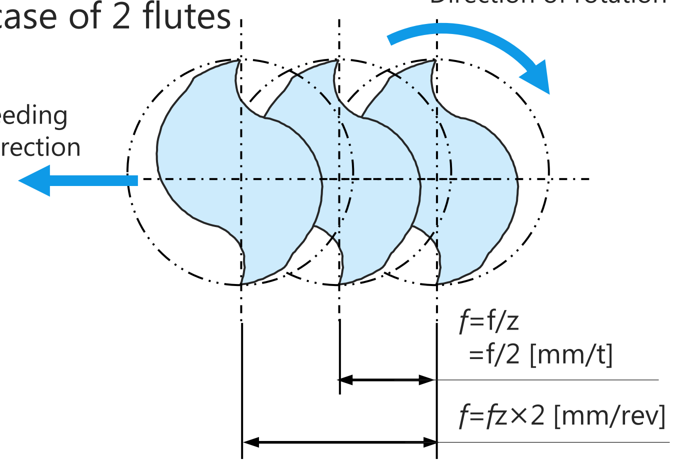
Feed Rate Vf [mm/min]	Moving distance (of machine axis) in direction of feed per minute
Spindle Speed n [min^{-1}]	Revolutions per minute [Number of revolutions / min.] [min^{-1}]=[rpm: **r**evolutions **p**er **m**inute]
Number of flutes z [t]	Number of flutes

The amount of feed per rotation f [mm/rev] is as below. (rev=revolution: rotation)

$$f = \frac{Vf\ [\text{mm/min}]}{n\ [\text{rev/min}]} = \frac{Vf}{n}\ \left[\frac{\text{mm}}{\text{min}}\right] \times \left[\frac{\text{min}}{\text{rev}}\right]$$

$$= \frac{Vf}{n}\ [\text{mm/rev}]$$

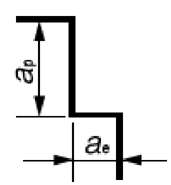
In case of 2 flutes



The amount of feed per tooth fz [mm/t] is...
calculated by dividing the amount of feed per rotation by number of tooth (flutes) which contributes for milling.

$$fz = \frac{f\ [\text{mm/rev}]}{z} = \frac{Vf}{n \times z}\ [\text{mm/t}]$$

The other items used for parameters
Radial depth : a_e
Axial depth : a_p



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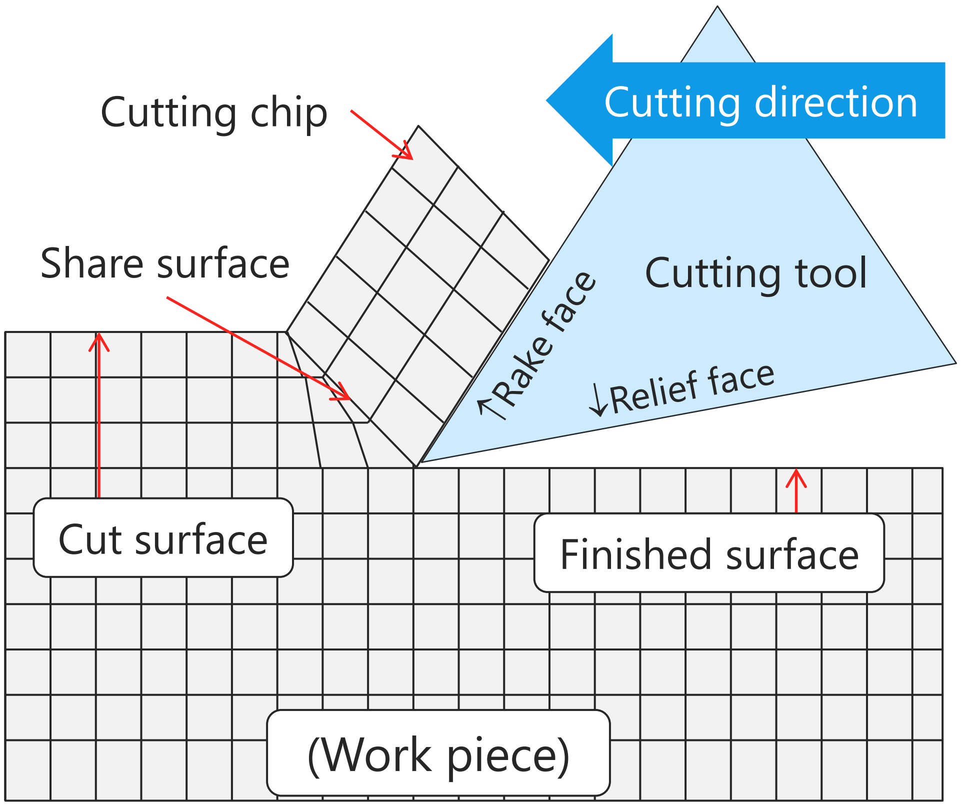
Cutting Action

Model diagram of cutting action



A state of cutting a part close to an edge of a work piece.

Procedure of cutting

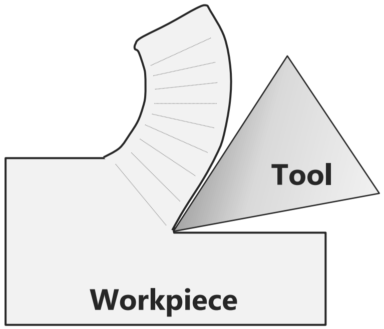
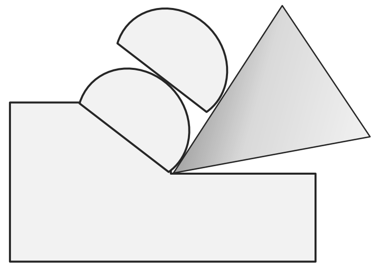
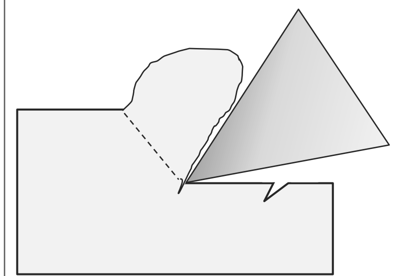
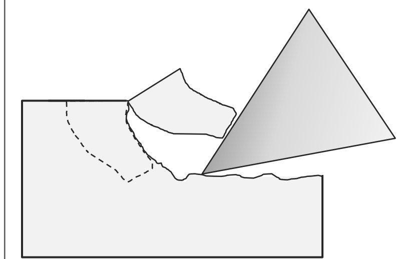
Cutting edge moves forward

Rake face compresses a part to be chipped off and share occurs

Cutting chips are evacuated following rake face of cutting edge

•Plastic deformation occurs only on cutting chips and there is almost no deformation on a work piece.
•Shape of cutting chips changes by cutting conditions.

Shape of Cutting Chips

	Flow shape	Share shape	Tear shape	Crack shape
Schematic diagram				
Characteristic	•Cutting chips continuously flow on a rake face. •Load on cutting edge is constant and a smooth surface is obtained. •Most desirable shape. Note: Too long cutting chips disturb cutting instead. →need Breaking cutting chips in certain length (by tool geometry, coolant, etc.).	•Deformation of cutting chips → repeat Sharing •Finished surface is not good as Flow shape.	•Cutting chips pile up on a tool and finally large tear is caused. •A finished surface has scars and remarkably bad.	•Crack occurs during deformation of cutting chips and they become crack shape. •Crack makes finished surface remarkably worse.
Reason	-	•Fragile of work piece •Low thermal conductivity	•High ductility	•Fragile of work piece
Measure	-	•Increase cutting speed	•Decrease cutting depth and increase cutting speed	•Increase cutting speed and decrease feed per tooth

Shape of cutting chips is information source of cutting situation.

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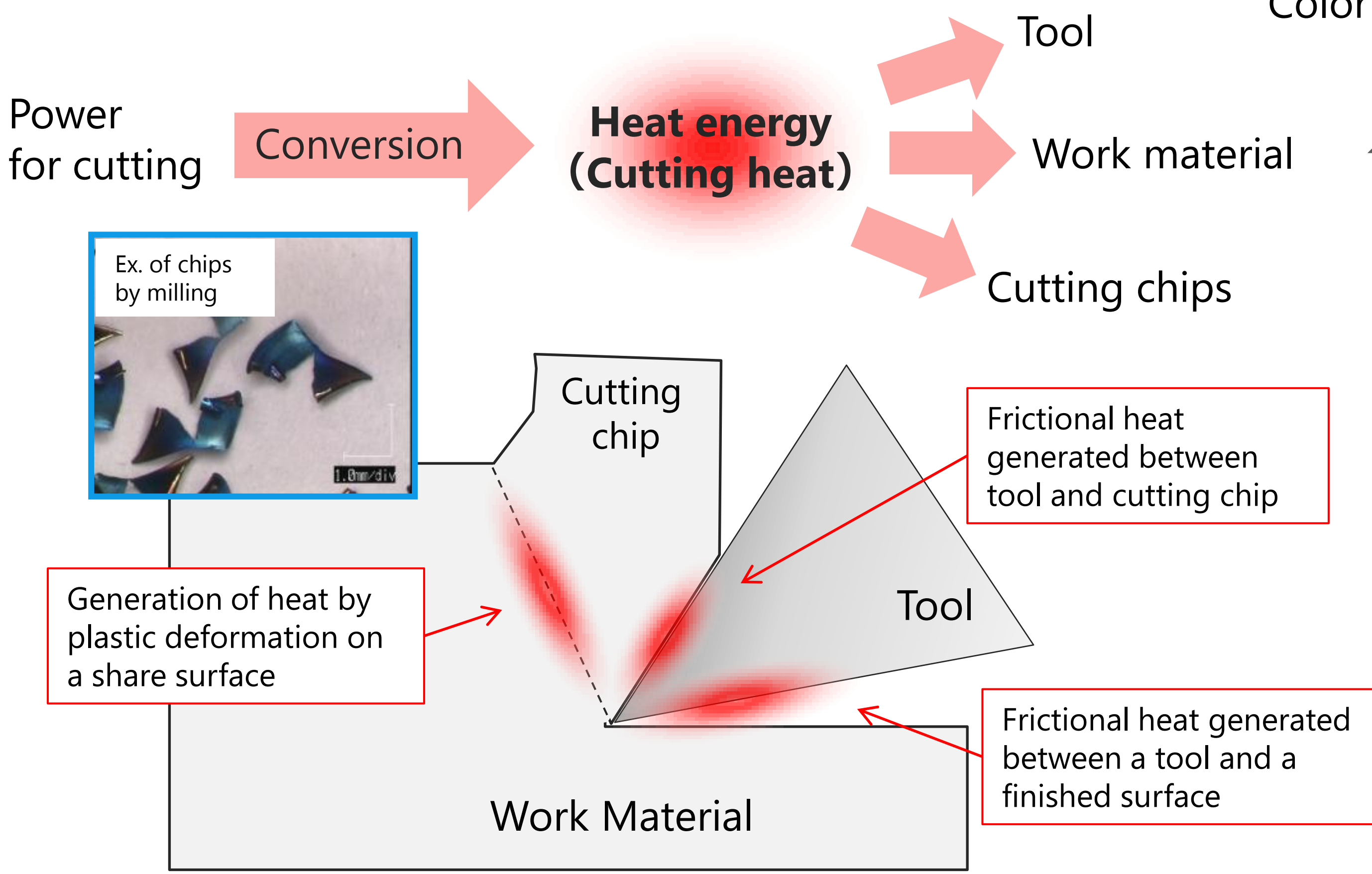
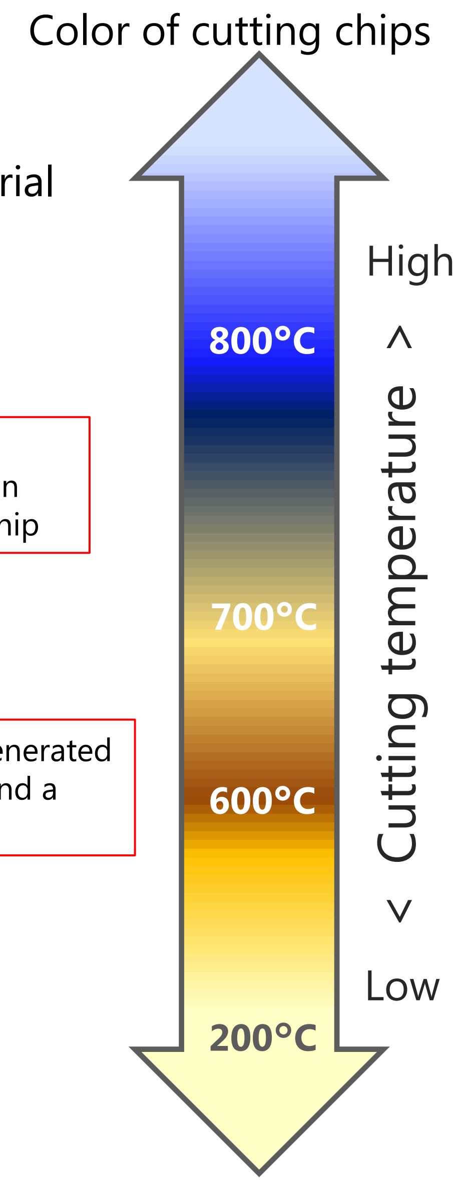
Shape of Cutting Chips —Heat Generation & Cutting Temperature—





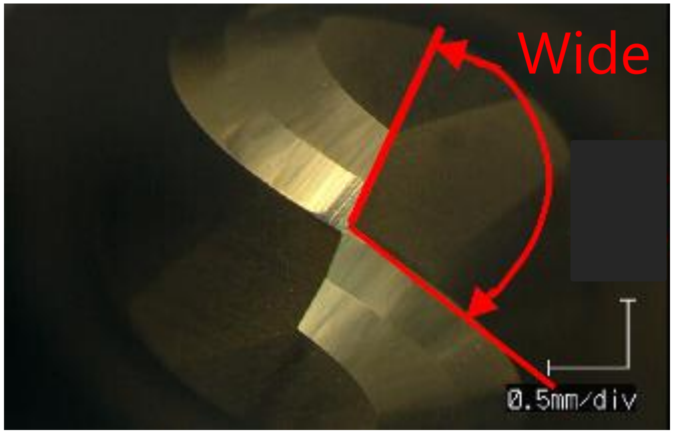
•Cutting chips change color by cutting temperature.

> By change of chip color, cutting temperature can be estimated.

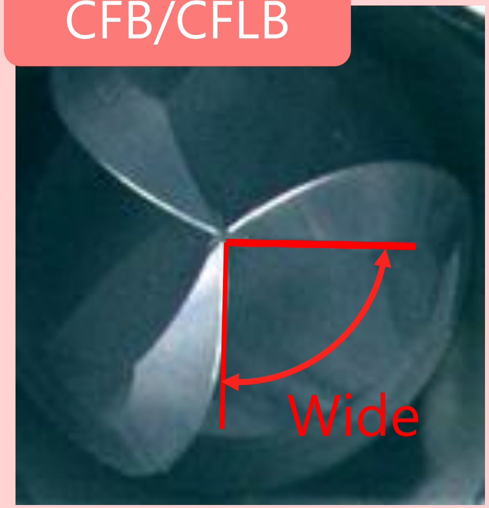
Cutting heat is a very important element for tool life!

Difference of Tool Shape & Cutting Chips

2-flute type

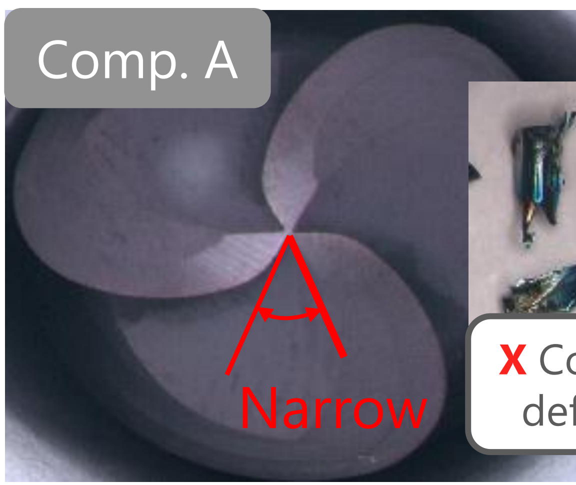


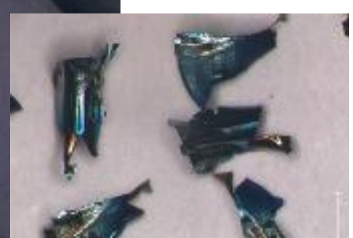
CFB/CFLB



√ Ideal shape

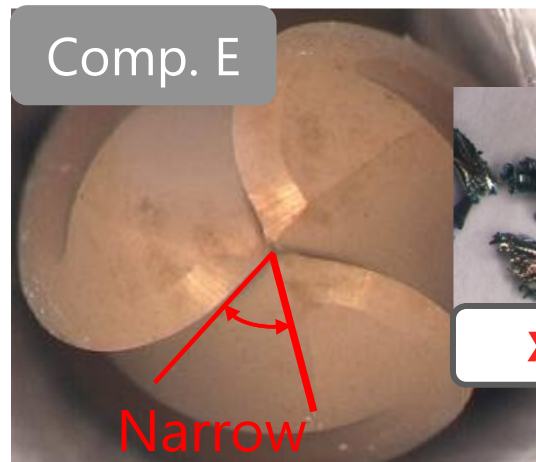
Comp. A





X Compressive deformation

Comp. E



X Curled

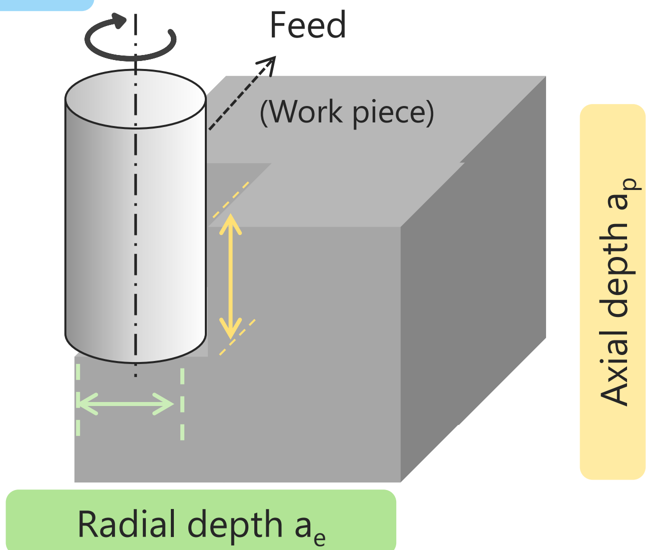
Setting of Milling Condition

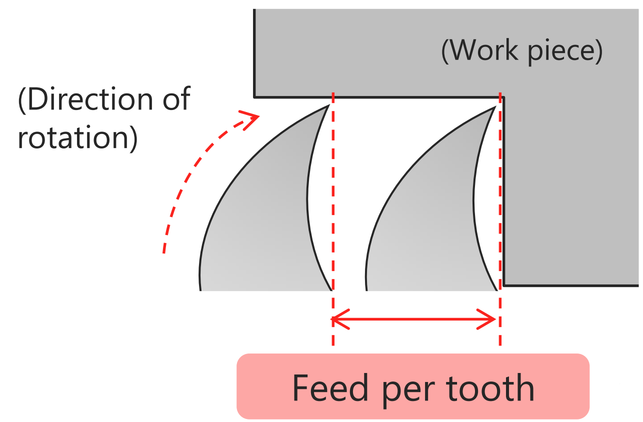
How to increase milling efficiency while reducing tool damage…

Velocity (Spindle Speed)	Axial depth a_p
Feed per tooth	Radial depth a_e

Which should be adjusted?

Velocity (Spindle Speed)





<u>Study case</u>

Tool: HMS 6100-2200 (ϕ10 x Length of cut: 22)
Work material: SKH51 (63HRC)
Coolant: Air blow   Details: Side milling

Optimization of HMS Milling Condition for SKH51

Condition	Cutting chips	n min^{-1}	Velocity m/min	Vf mm/min	Feed per tooth mm/t	a_p mm	a_e mm	Efficiency mm^3/min
1		4000	125.6	1350	0.0563	10	0.15	2025
2		3000	94.2	1000	0.0556	10	0.15	1500
3		2000	62.8	675	0.0563	10	0.15	1013
4		2000	62.8	675	0.0563	20	0.2	2700
5		2000	62.8	1000	0.0833	20	0.2	4000
6		2000	62.8	1000	0.0833	20	0.4	8000

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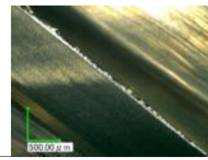
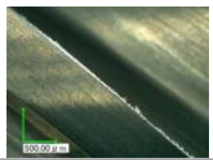
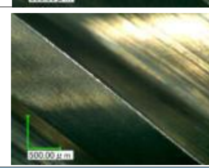
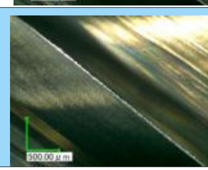
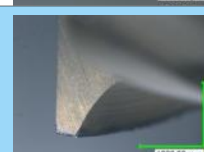
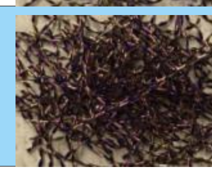
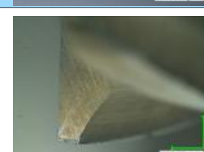
Optimization of HMS Milling Condition for SKH51

Tools after milling on each condition

Condition 1 - 3 : Tools after 9000mm^3 milling
Condition 4 - 6 : Tools after 50000mm^3 milling (20min milling with No.5)

Condition	Radial relief face	Rake face	Cutting chips	Efficiency [mm^3/min]
1				2025
2				1500
3				1013
4				2700
5				4000
6				8000

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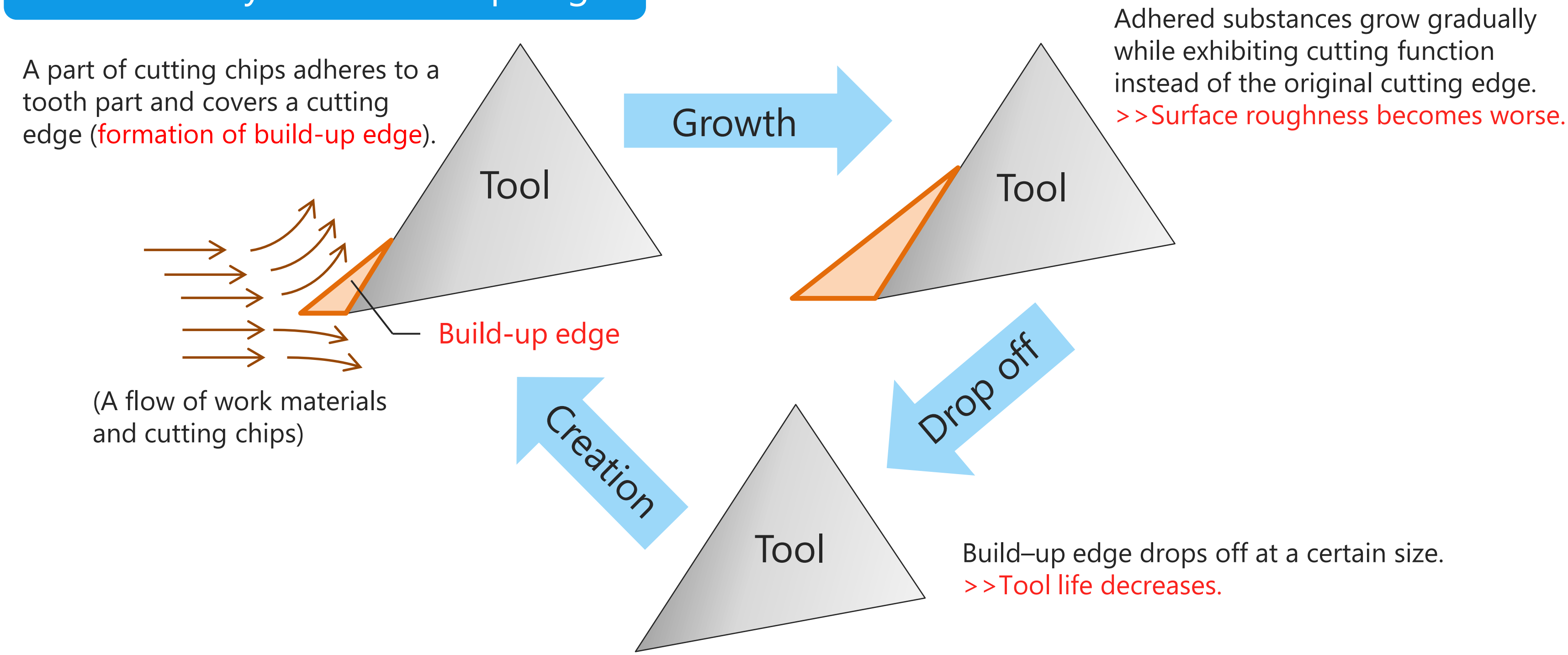
Phenomena during Cutting —Build-up Edge—

●Various phenomena during cutting become obstacles to processing.

Build-up edge…A phenomenon that a part of cutting chips covers a cutting edge and exhibits cutting function instead of the cutting edge.

Formation cycle of build-up edge



Measures

- Increase cutting speed and raise temperature
- Provide high lubricity cutting fluid

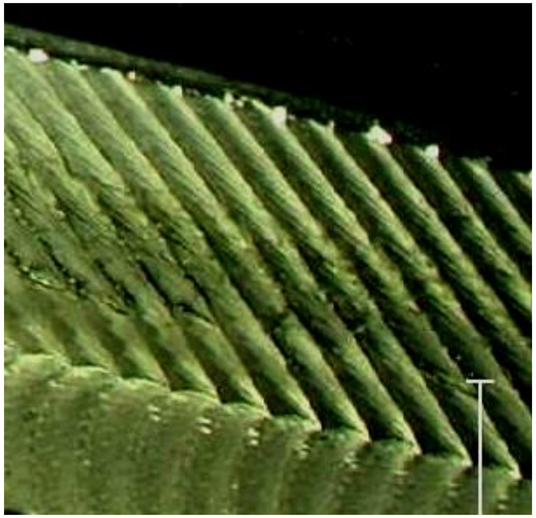
Phenomena during Cutting —Chattering—

●Various phenomena during cutting become obstacles to process.

Chattering

Phenomenon

•On cutting processing, resonance occurs among a work piece, a tool and a machine and stripes appear on a finished surface.



Stripes appeared on a work piece by chattering

Influence

•Surface roughness becomes worse and tool life decreases.
•Sometimes difficult to continue because of chattering.

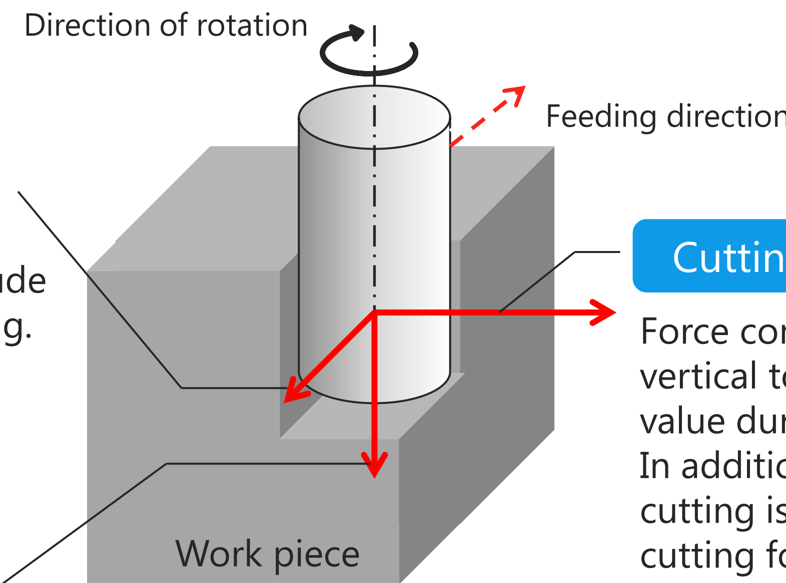
Measures

•Adjust clumping of a work piece and a tool (overhang) and a movement component of a machine.
•Adjust quantity of cutting motion such as cutting speed, Feed Rate, axial/radial depth, etc..

Cutting Resistance —Each Component—

Cutting resistance

...Reaction force caused when a cutting tool is pushed into a work piece.
It is considered as three force components.



Feed force

Horizontal force component in a feed direction.
It determines a magnitude of feed power for cutting.

Cutting force

Force component acts in a direction vertical to feed force. It affects heating value during cutting.
In addition, power requirement during cutting is calculated by a magnitude of cutting force.
(ex. In case of round cutting by a lathe)

$$P = \frac{F \times v}{60 \times 102 \times \eta}$$

P: Cutting power requirement (kW)
F: Cutting force (kgf)
v: Velocity (m/min)
η: Mechanical efficiency

Thrust force

Axial force component.
It becomes force to deform a work piece and a tool, and decreases accuracy when it is large.

Cutting Resistance —Magnitude and Changing Factor—

•"Cutting force" is especially important among three force components (because it is a factor determining power requirement and heat generation).

Generally cutting force is sometimes referred to "cutting resistance".

•Cutting resistance (cutting force) changes according to cutting conditions.

Factors which may change cutting force (general tendency)

Cutting resistance (cutting force)	Small	Large	Note
Work material	Soft	Hard	—
Tooth part geometry (Rake angle)	Large rake angle	Small rake angle	Cutting force decreases when rake angle is up to about 30°.
Milling area (Cutting depth x Feed Rate)	Small	Large	Sometimes cutting force decreases by reducing cutting depth and increasing Feed Rate.
Velocity	Fast	Slow	Cutting force does not change so much in velocity over certain high speed.

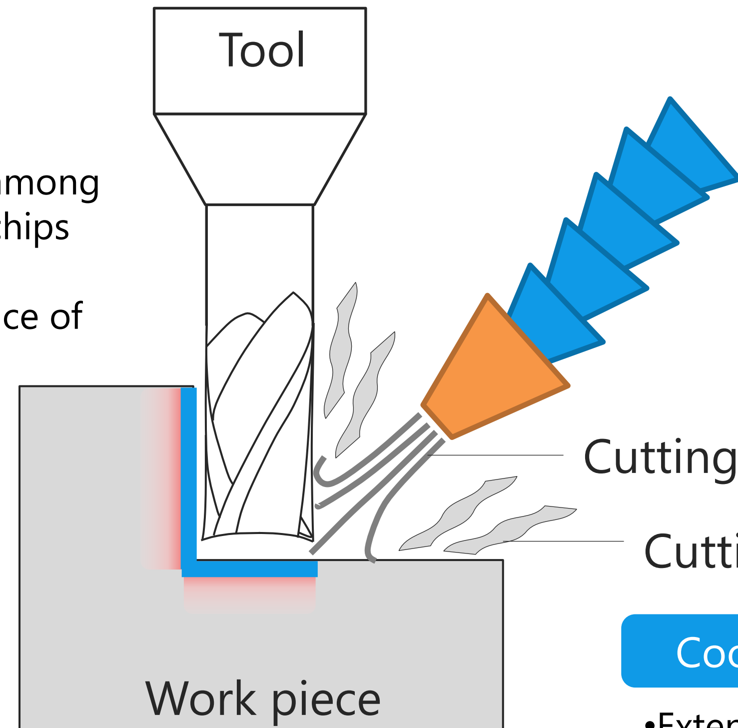
Cutting Fluid —Functions—

Cutting fluid is supplied to a cutting area to obtain fine surface and extend tool life on cutting processing.

3 functions of cutting fluid

Lubrication

•Prevention of friction among cutting edges, cutting chips and a finished surface
•Prevention of occurrence of build-up edge



Cleaning

Prevention of chipping and scars on a finished surface by washing away cutting chips

Cooling

•Extension of tool life by cooling tool
•Prevention of size deviation by temperature rise of a work piece

Cutting Fluid —Characteristics—

Requirements to cutting fluid

- Be harmless to humans
- Do not erode a work piece, a machine and paints
- Has a low risk of ignition and smoking
- Be small in putrefaction, degeneration, etc.

No cutting fluid can satisfy all of there requirements.

↓

Appropriate cutting fluid differs depending on which is important among "tool life", "finished surface" and "efficiency".

Types and characteristics of cutting fluid

Cutting fluid

- Water-soluble: Fine cooling
- Non water-soluble: Fine lubricity

Elements determining a capacity of non water-soluble cutting fluid

- Viscosity: Low → High cleaning & cooling function
  High → High lubrication function
- Additive: Contained → Cutting ability improves
  (but there is a possibility of corrosion of a work piece or fluid supplying equipment and outbreak of toxic gas during high-temperature milling)
- Fatty oil: Contained
  → Prevention of occurrence of build-up edge
  Improvement of lubrication function

Cutting Fluid —MQL Processing—

MQL (**M**inimum **Q**uantity **L**ubrication)...Milling method using only very small quantity of cutting fluid.

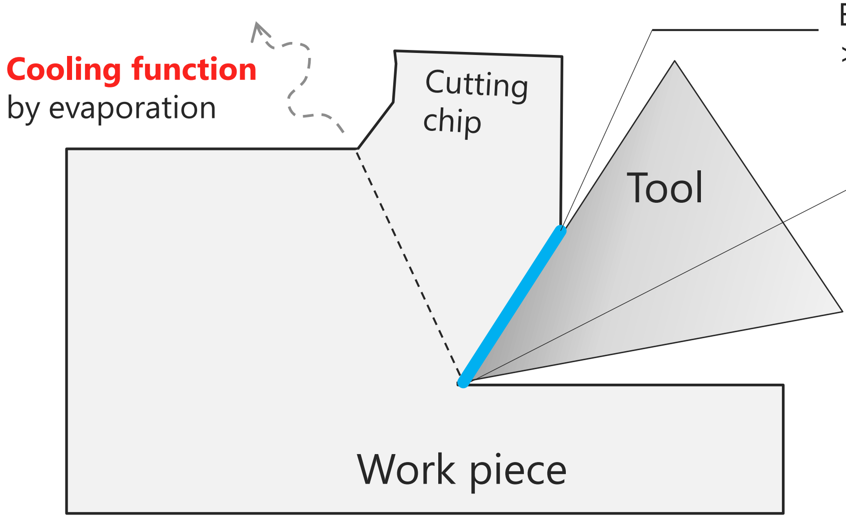
Problems of using cutting fluid

Cost: Expense for cutting fluid and an electric bill to work a pump
Environmental load: Treatment of used waste liquid, mass consumption of electrical energy

Wish to decrease the use amount of cutting fluid

MQL Processing, which atomizes small quantity (2-10ml/hour) of cutting fluid by high pressure air, attracts attention. (There is a case that reduces energy cost by 25% and cutting fluid cost by 95% by adoption of MQL.)

Function of cutting fluid on MQL Processing



Entering a rake face of a tool and forming lubricant film
>>**Reduce frictional resistance**

Minimum quantity of cutting fluid is supplied to a cutting point by vacuum suction
>>**Continuation of lubrication function**

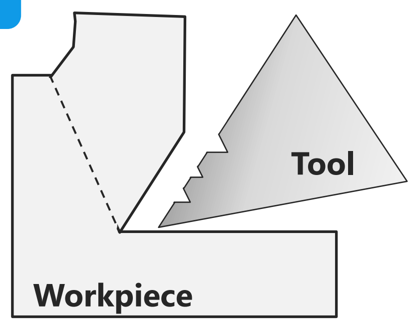
MQL is a effective method using lubrication function of cutting fluid at the most!

(Cooling might be insufficient on processing with large heating value.)

Tool Wear —Forms of Wear—

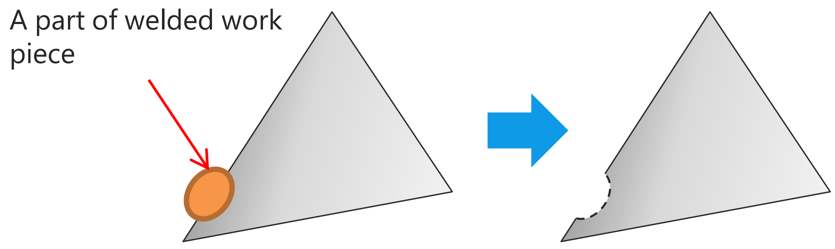
•A cutting edge wears when continuous milling is performed.
•Tool wear shows various forms according to its factor. Notable examples are as follows.

Mechanical wear



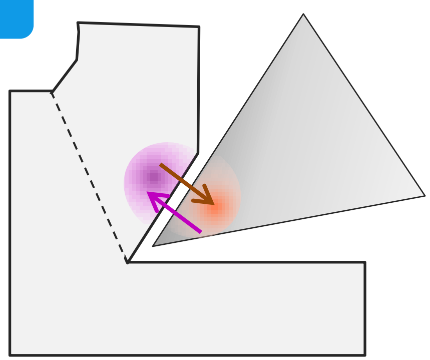
Hard particles in a work piece scratch and shave off a cutting edge.

Welding wear



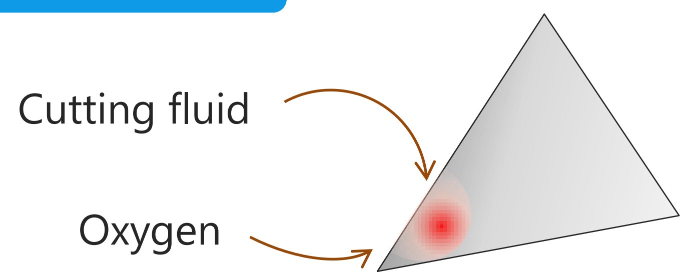
A part of work piece is welded on a rake face, and takes a part of the tool away when the welded piece peels off.

Diffusional wear



Mutual diffusion occurs between a work piece and a tool, and a soft compound is formed.

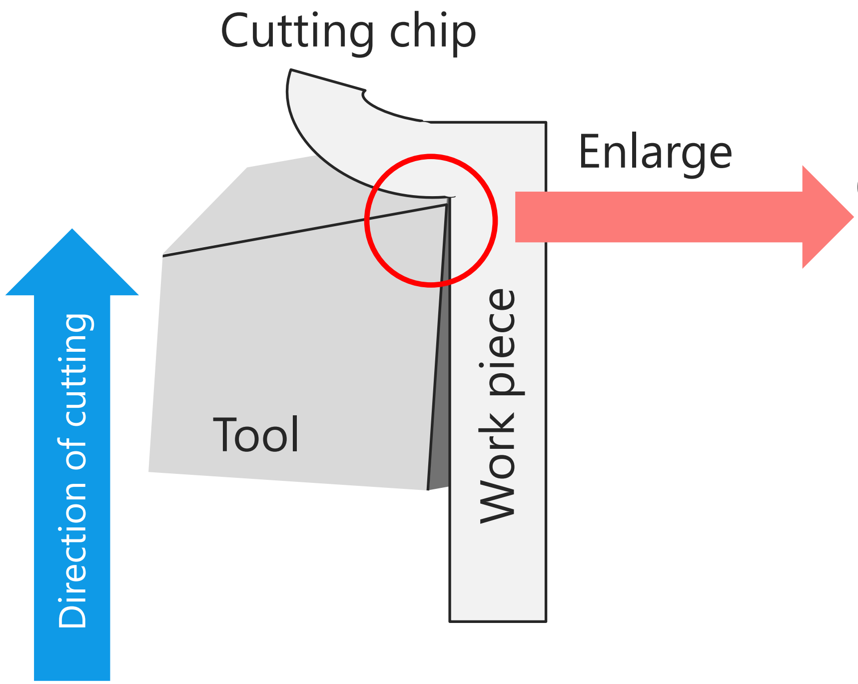
Chemical wear

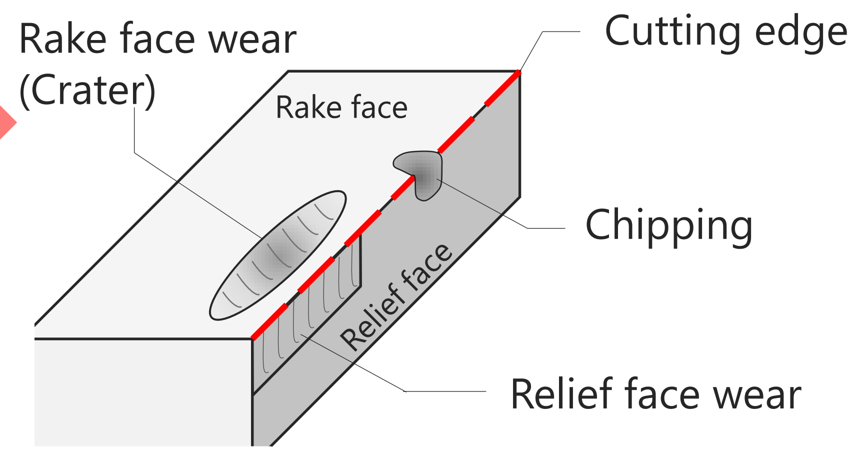


Compound is made by reaction between a tool and other materials (cutting fluid, oxygen in the air, etc.) and removed.

Tool Wear —Part of Wear—

Wear of an edge part is called as below depending on where it occurs.





Crater is
-concavity that occurs near a cutting edge by rake face wear.
-likely to occur on high-speed milling of steels by cemented carbide tools.

When wear occurs and progresses, re-pointing of an edge part or changing cutting tool is needed.

＞＞End of tool life

Tool Life —Standard & Judgment—

Breakage and wear of an edge part → •Increase of cutting resistance •Bad finished surface quality → Re-pointing of the edge part or changing cutting tool is needed

II

End of tool life

Standard for judgment

- •Shiny stripes occur on a finished surface
- •Change of finished size or roughness of a finished surface reaches a certain value
- •Thrust force or feed force of cutting resistance increases quickly
- •Cutting force of cutting resistance increases by a certain value compared to a beginning of milling
- •Wear of an edge part reaches a certain value

Standard for judgment of cemented carbide tool life

Width of relief face wear *w* (mm)	Max. depth of crater *t* (mm)	Application
0.2	0.03	•Accurate light milling •Finishing of non-ferrous alloys, etc.
0.4	0.05	Milling of alloy steels, etc.
0.7	0.08	General milling of cast iron, steels, etc.
1 - 1.25	0.08	Roughing of gray cast iron, etc.

Tool Life —Factors Determining Tool Life—

Tool life equation (F. W. Taylor)

$$V_c \cdot T^m = C \Leftrightarrow T = \left(\frac{C}{V_c} \right)^{\frac{1}{m}}$$

V_c: Velocity (m/min) T: Tool life
m: Constant C: Constant

From the equation above…

Increase of velocity (V_c) → Decrease of tool life (T)
(because of increase of **cutting heat** by increase of speed on a tool end)

↓

•Selection of heat-resistant tool material
•Ingenuities to reduce cutting heat (adjustment of milling condition and appropriate use of cutting fluid) are important!

(Recently, there are almost no tools that are directly applicable to the equation above because of advances in coated cemented carbide tools for improving heat resistance.
In addition, intermittent cutting such as processing by end mills shows tendency different from the equation above.)

Summary

Cutting action

Repeating "moving of a cutting edge", "plastic deformation" and "chip evacuation" continuously.

Cutting chips

Cutting condition, tool material & heat generation are reflected to chip form.

→ Information source to know a state of cutting

Phenomena during cutting

•Build-up edge
•Chattering

Influence on tool life and a finished surface

↓

Measures to prevent occurrence are needed.

Cutting resistance

Changes according to sharpness of a tool, cutting conditions, etc..
(Relationship to a condition of cutting, power and cutting heat)

Cutting fluid

Need to understand functions of cutting fluid and select suitable one in accordance with the type of cutting.

Tool life

Use of a tool → Deterioration of tool condition by wear, etc. → Deterioration of finished surface quality

•Pay attention to determining tool life and making a fine finished surface
•Prolong tool life and improve cutting performance by coating technology