TECHNICAL GUIDE
MILLING

Vol 1

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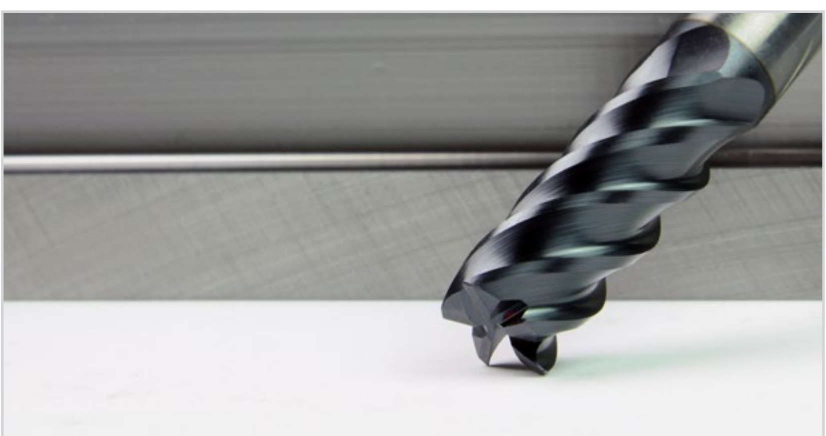
Technical Data *Milling*

CONTENTS



Machining refers to "moving a tool against a work piece and causing it to fracture with large locally generated stress, separating unnecessary parts as chips and creating a new surface according to a desired shape. However, cutting has already been performed since the Stone Age 100,000 years ago. Like the discovery of fire, the action of shaving with a knife made of stones or shells had a great influence on the evolution of humankind.

After the discovery of iron and the industrial revolution, the current cutting process developed. In particular, the birth of end mills has greatly expanded the possibilities of cutting and has contributed greatly to the growth of manufacturing.

In recent years, the technology surrounding end milling has been rapidly improving, including the development of processing machines with high-speed rotating spindles, control software, the holding of workpieces and tool holding, and other supplementary technology.

Here, we will introduce end mills, cutting technology with end mills, processing examples, and re-grinding of end mills.

In addition, in writing, I tried not only to statements based on the results of basic experiments at our company, but also to refer to the literature in the field to create the most accurate picture.

We may revise and clarify this information in the future, so we kindly ask for your kind understanding.

Also, please note that the terms used are those that are commonly used at the manufacturing site and do not necessarily match the ANSI, or ISO terms.

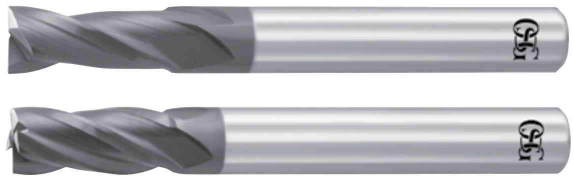
Hideaki Imaizumi

1. Basics of end mills

1.1 What is an end mill?

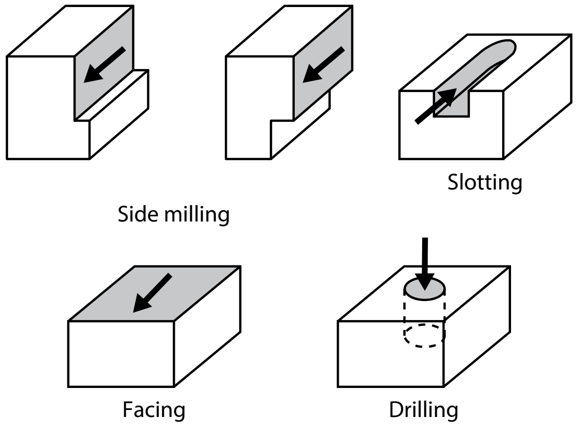
A milling machine is a machine that facilitates the cutting of material through the usage of end mills.
The end mill has the shape shown in Fig. 1.1.1, and there are cutting edges on its outer circumference and end face. This allows the tool to cut in a variety of ways.

Figure 1.1.1 End mill



The end mill can be said to be a multifunctional tool that can perform side milling, slotting, drilling or plunging, and facing with one tool. (Fig.1.1.2)

Figure 1.1.2 Cutting with an end mill



1.2 End Mill Nomenclature

The names of each part of the end mill are shown in Fig. 1.2.1 and Fig. 1.2.2.

Figure 1.2.1 Name of each part (excerpt from JIS B 0172-1993)

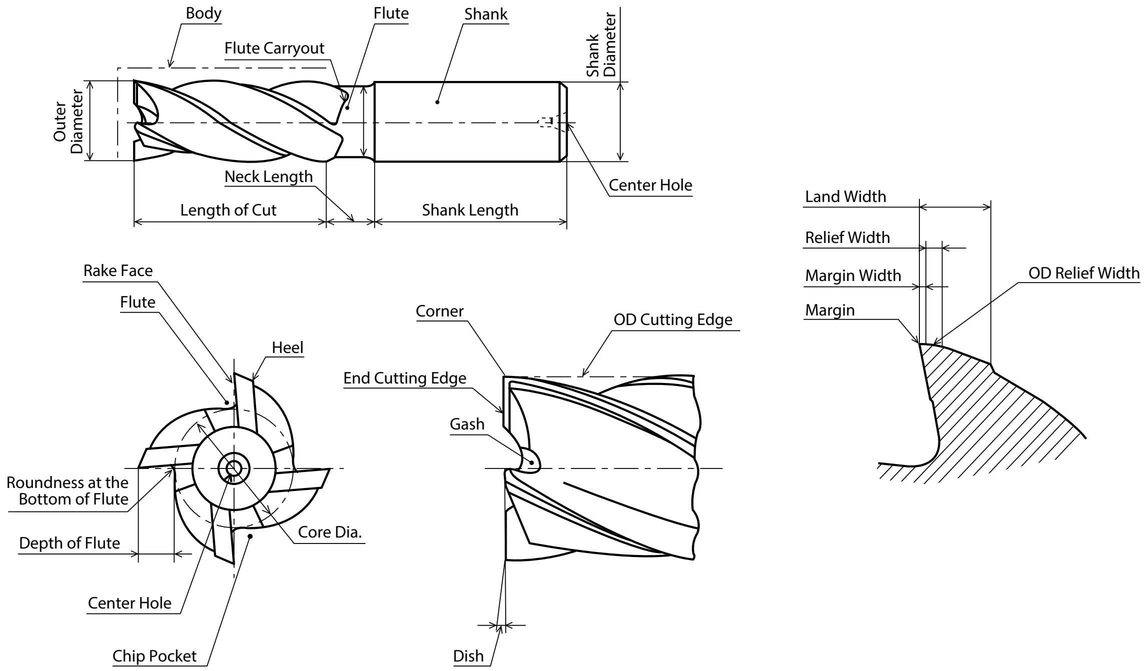
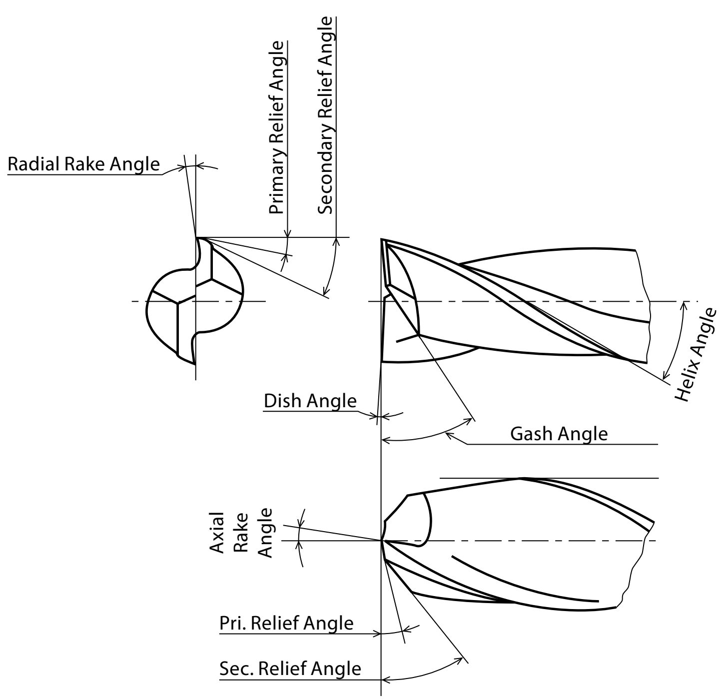


Figure 1.2.2 Corner of end mill (extracted from JIS B 0172-1993)



1.3 Types of end mills

(1) Various end mills

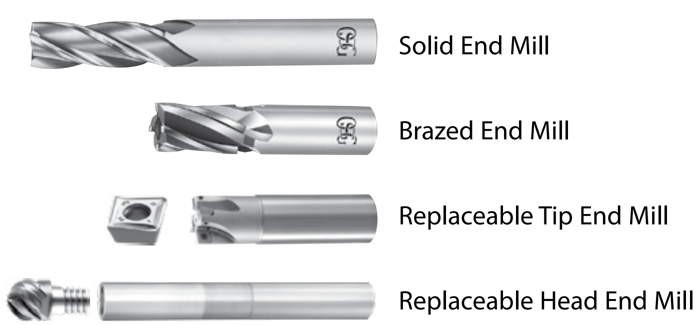
End mills are available in various shapes and specifications according to the application. Figure 1.3.1 shows some typical example.

Figure 1.3.1 Various types of end mills

(2) Classification by structure

End mills are classified into solid end mills in which the cutting edge and shank are integrated, brazed end mills in which the edge material is brazed to the main body, replaceable tip end mills, and replaceable head end mills (Fig. 1.3.2) where the portion of the tool that preforms the cutting is a separate component from the end mill body.
Alternatively, the indexable end mill and the replaceable head end mill are collectively called an indexable end mill.
The parts of an indexable endmill include the throwaway tips called inserts, and a solid body typically made from high speed steel or carbide.

Figure 1.3.2 Classification by structure

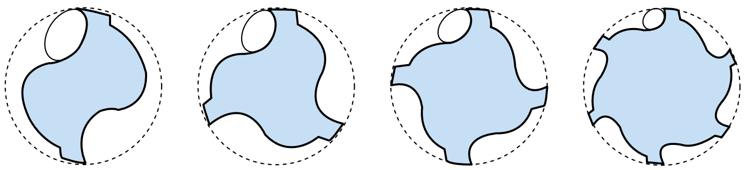


(3) Number of flutes

The number of cutting edges in an end mill can vary from single fluted mills with 1 cutting edge to multi-fluted end mills with as many as 8 more cutting edges. The greater the number of flutes in an end mill, the less room in the flutes to contain these chips.

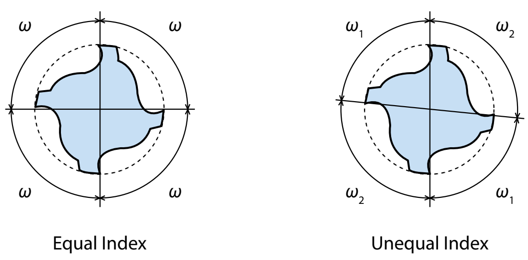
The chip pocket of a tool dictates the chip evacuation properties and enables larger cutting depths and stepovers. However, this comes at a cost of the overall rigidity of the tool. The tool cross-sectional area becomes smaller and the tool rigidity decreases.

Figure 1.3.3 Number of flutes of end mill



Normally, multiple cutting edges are arranged at equal intervals, but some are intentionally unequally divided (Fig. 1.3.4). It is difficult to measure the outer diameter of end mills with odd-numbered blades and end mills with unequal spacing between the cutting edges. In the case of these end mills, measurement is done using digital images or optical devices.

Figure 1.3.4 Equal Index and Unequal Index



(4) End Cut Shapes

The basic shape of the bottom of an end mill, or endcut, is shown in Figure 1.3.4.
Other types of endcuts also include square and radius types with a center hole. Having a center hole has the advantage that accurate re-grinding can be performed, but plunging cannot be performed. Figure 1.3.5 shows an example with and without a center hole.

Figure 1.3.4 End cut shape

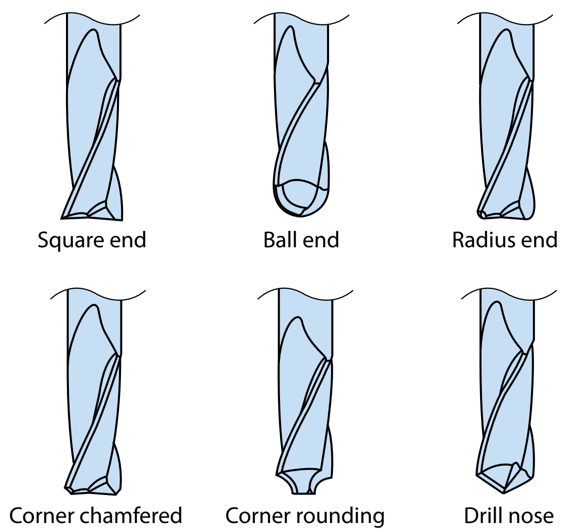
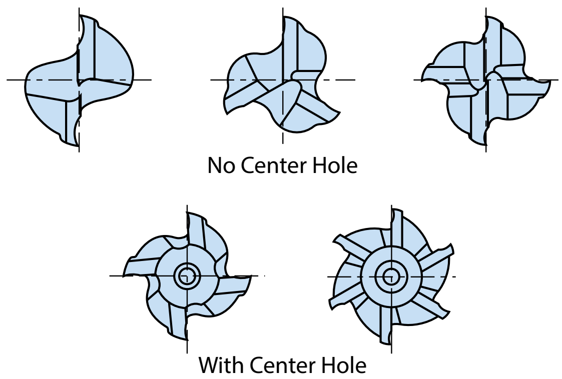


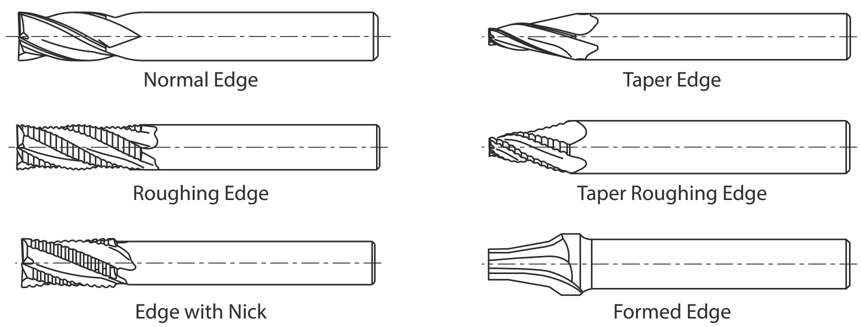
Figure 1.3.5 Presence or absence of center hole



(5) Peripheral cutting edge shape

A typical peripheral edge shape is shown in Figure 1.3.6.

Figure 1.3.6 Peripheral edge shape



6) Peripheral cutting edge and helix direction

When viewed from the shank, an end mill with the cutting edge on the right side is called the right-hand cutting edge, and the one on the left side is called the left-hand cutting edge. The right cutting edge will be used for clockwise rotation and the left cutting edge for counterclockwise rotation (Fig. 1.3.7).
In addition, there are right and left helix directions (Fig. 1.3.8).

Figure 1.3.7 Right and left cutting edge

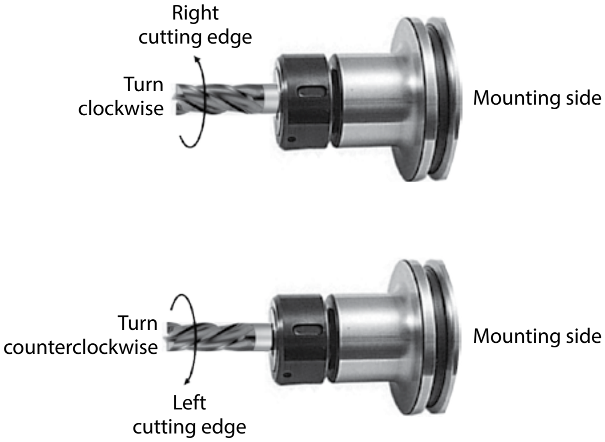
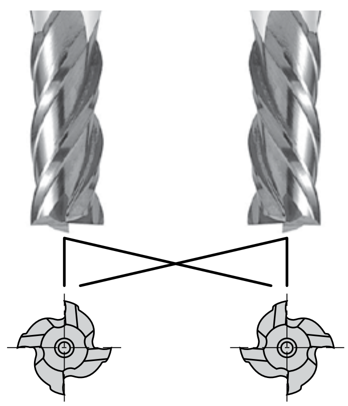


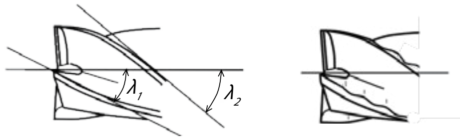
Figure 1.3.8 Helix direction and cutting edge direction



The helix angle of commercially available end mills ranges from 0 degrees (no helix) to about 60 degrees, but a 30 degree helix angle is commonly used. In JIS, those with 40 degrees or more are defined as high-helix end mills.
Normally, each cutting edge has the same helix angle, but there are also end mills in which the helix angle varies depending on the cutting edge, or along the length of the cutting edge.
Examples are shown in Figure 1.3.9 and Figure 1.3.10.

Figure 1.3.9 Example of helix angle

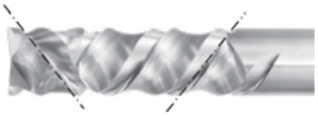
Figure 1.3.10 Special helix end mill



Unequal helix

Example of realizing unequal index and unequal helix by making the rake face wavy

Staggered edge
(Alternate right helix and left helix)



Has both right and left helix

(7) Neck shape

Some end mills do not have a prominent neck that connects the blade and shank, but those with a long tool protrusion length and a short cutting edge will have a clear neck.

The neck shape of these end mills can be a long neck or a tapered neck (also called a pencil neck) (Table 1.1).

Long neck, small diameter end mills are often used for intricate machining of deep parts.

A tapered neck increases tool rigidity (strength against bending and bending) for machining deep parts and complex shapes of free-form surfaces, while avoiding interference with the workpiece.

Table 1.1 Neck Shape

Long Neck	 
Taper Neck (Pencil Neck)	 

(8) Types of shank

Generally, the end mill is attached to the machine by holding the shank (handle) with an interfacing device called a holder (Fig. 1.3.11).

Table 1.2 shows typical shank shapes. A straight shank is most commonly used, but if the end mill comes out of the holder due to load or vibration during cutting, a straight shank with a flat or combination is used. In these shanks, a screw is used to hold onto the tool by clamping the flat. Additionally, there is a threaded type shank that prevents slip out with a screw-like mechanism.

If the cutting load is large and violent vibration occurs, use a 7/24 taper national taper shank, bottle grip taper shank, or double-faced 1/10 taper shank that is directly attached to the machine without using a holder.

Figure 1.3.11. Attaching the end mill to the machine

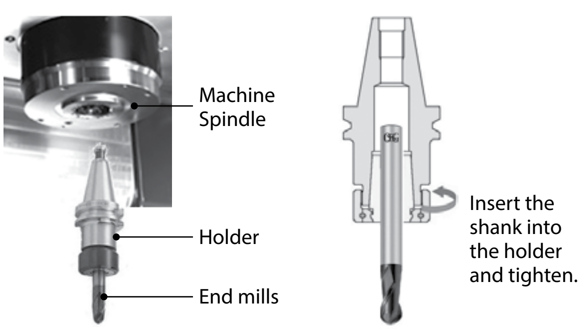
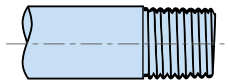
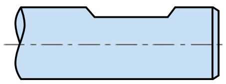
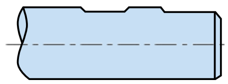
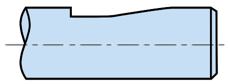
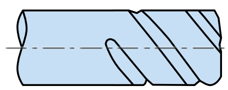
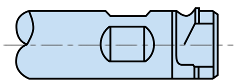
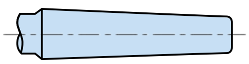
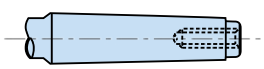
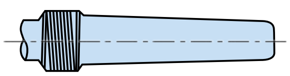
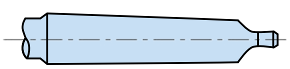
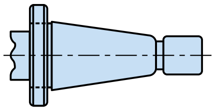
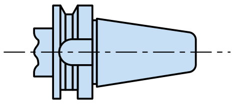
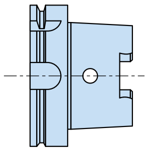


Figure 1.3.12. Example of direct mounting end mill

Figure 1.3.13

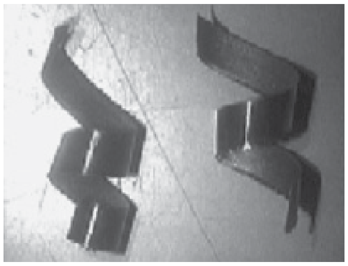
Shape	Name	Shape Drawing	Feature
Straight Shank	Plane Straight Shank		Easy to attach/detach and accurate
	Threaded straight shank		High slip out prevention effect
	Straight shank with flat	  	Adopted to prevent slipping off with a large diameter end mill and to prevent rotation
	Straight shank for shrink fitting with slip-out prevention mechanism		Excellent runout accuracy and high holding power
	Combination straight shank		It can hold very tightly. Used as a pull-out prevention in machining that requires a large load.
Taper Shank	Morse taper shank Brown sharp taper shank		Rarely used in small diameter end mills.
		 	High holding power and less falling even with heavy cutting. High holding power.
			Easy to attach/detach and accurate
	7/24 taper shank (National taper shank)		Attach directly to the machine. Effective for heavy cutting of large diameter end mills.
	7/24 taper shank (Bottle grip taper shank)		Attach directly to the machine. Effective for heavy cutting of large diameter end mills. It can be used with ATC (automatic tool changer).
	1/10 taper shank (2-sided restrained taper shank		Attach directly to the machine. It can be used for high-speed rotation of large-diameter end mills.

(9) Types of indexable milling inserts

There are many types of inserts (throwaway tips). Figure 1.3.13 shows the names of each part of the insert. ISO classifies the products according to their shapes and specifications.

Figure 1.3.15 Chip shape with and without chipbreaker

With chip breaker



Without chip breaker

Many indexable inserts will also include a chip breaker. This is specialized geometry on the insert that aids in creation of smaller and more manageable chips during the machining process.

1.4 Symbols for each part of the end mill

The notation for each part, previously differed depending on the tool maker or country, was standardized by ISO 13399. Excerpts are introduced in Figure 1.4.1 and Figure 1.4.2 and Table 1.4.

Figure 1.4.1 Symbols for each part of the end mill (ISO13399 compliant)

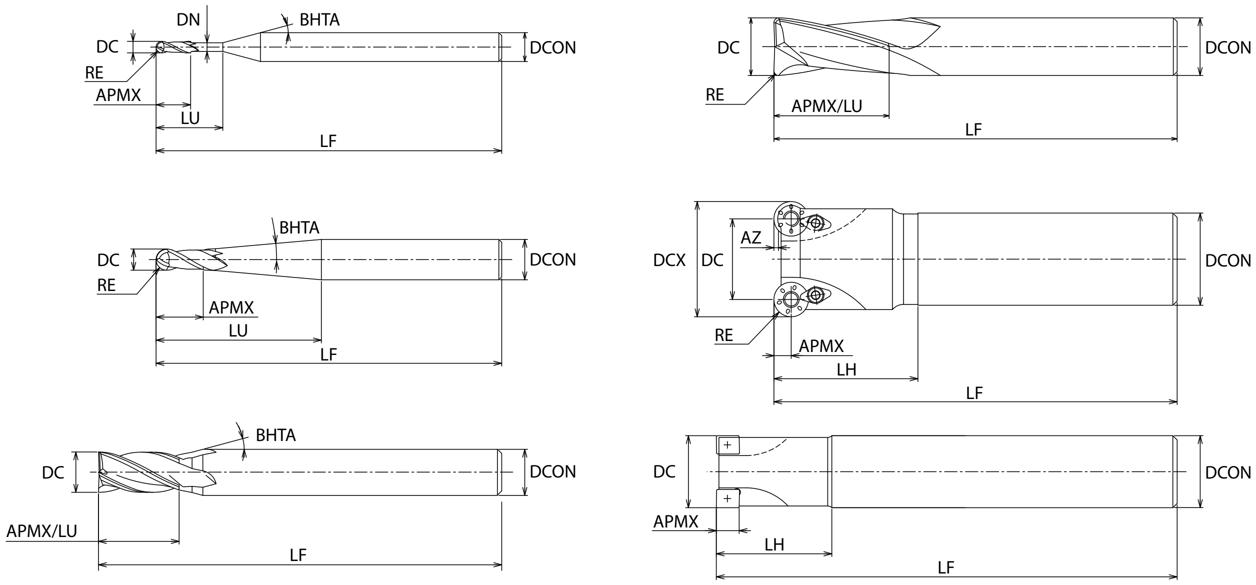


Figure 1.4.2 Symbols for each part of insert (ISO13399 compliant)

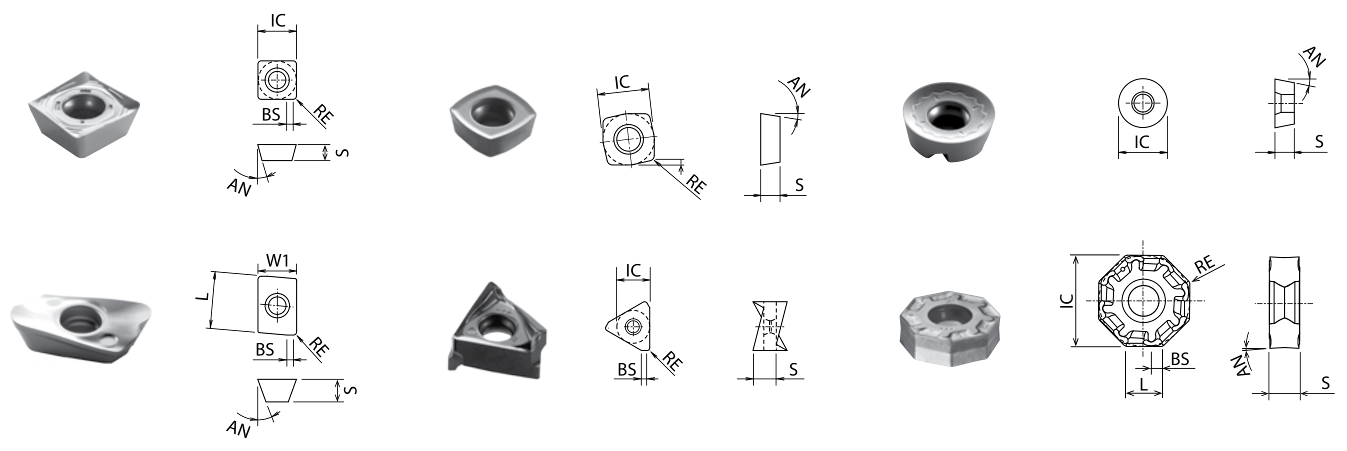


Figure 1.4.2 Symbols for each part of insert (ISO13399 compliant)

End mill symbol	
Symbol	Specification part
APMX	Maximum depth of cut
AZ	Effective inner cutting edge height
BHTA	Body taper half angle
DC	Cutting diameter
DCON	Connection diameter
DCX	Maximum cutting diameter
DN	Neck diameter
LF	Functional length
LH	Neck length
LU	Usable length
RE	Ball end mill radius, corner radius

Insert symbol	
Symbol	Specification part
AN	Main cutting edge relief angle
AS	Wiper edge relief angle
BS	Wiper edge width
IC	Inscribed circle
L	Cutting edge length
RE	Corner radius
S	Insert thickness
W1	Insert width

2. End Mill Blade Material and Surface Treatment

2.1 End mill cutting edge material

Desirable properties for end mill substrates include wear resistance, heat resistance, fracture resistance (toughness), plastic deformation resistance, chemical stability, and thermal conductivity. However, some of these properties are contradictory, and unfortunately there is no ideal material that can satisfy all of them.
Fig. 2.1.1 shows a conceptual diagram showing the characteristics of each end mill blade material.

Figure 2.1.1 Characteristics of various end mill materials

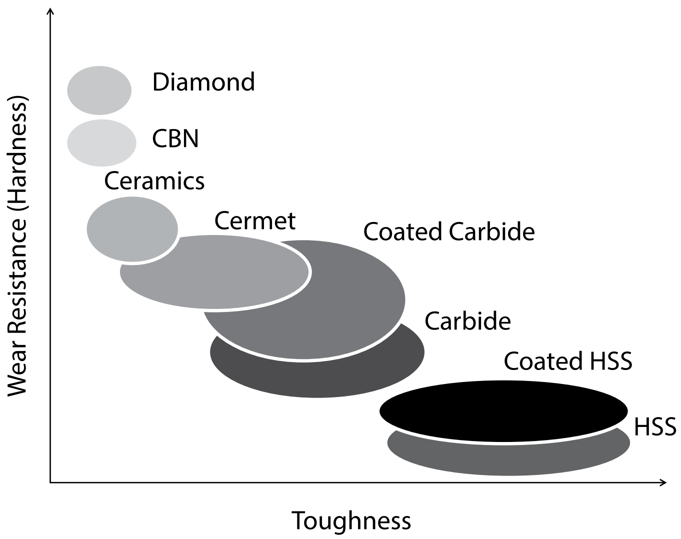


Figure 2.1. Characteristic values of various materials

Material	HSS	Carbide	Cermet	Ceramics	Ceramics	cBN	Diamond (sintered)	Diamond (single crystal)
Hardness (Hv)	800 – 1,100	1,500– 1,900	1,500 – 1,900	1,300 – 1,900	1,500 – 2,000	4,000 – 6,000	6,000 – 12,000	9,000 – 12,000
Young's modulus (GPa)	200 – 220	450 – 650	300 – 500	280 – 310	350 – 390	650 – 750	770 – 920	1,050 – 1,220
Transverse strength (MPa)	2,500 – 5,000	1,500 – 4,000	1,350 – 2,000	1,300 – 1,400	500 – 600	1,000 – 1,500	1,000 – 1,500	(150 – 300)
Specific gravity	7 – 9	13 – 5	6 – 7	3 –6	3 – 6	3 – 5	3 – 5	3.52

(1) High speed tool steel (HSS)

High speed tool steel is an alloy steel containing tungsten (W), molybdenum (Mo), chromium (Cr), vanadium (V) and cobalt (Co) (Table 2.2).

By incorporating powder metallurgy into the manufacturing process, there is also powder HSS that achieves high alloying as well as making the carbide finer and more uniform.

High speed tool steel (HSS) is generally hardened at around 1,200°C and tempered at around 550°C to obtain a hardness of about 64 to 69 HRC.

Highly alloyed powder HSS is available with hardness 70HRC.

Compared to other materials, end mill materials are cheaper, have better workability, and have the advantage that relatively complex tools can be manufactured relatively easily, but It cannot be used in areas where the cutting temperature exceeds the tempering temperature of 550ºC.

Material	Chemical Composition (%)					
	C	W	Mo	Cr	V	Co
SKH55	0.8	6.0	5.0	4.0	2.0	5.0
SKH56	0.8	6.0	5.0	4.0	2.0	8.0
SKH57	1.2	10.0	3.5	4.0	3.4	10.0
SKH59	1.1	1.5	9.5	3.8	1.2	8.0
SKH10	1.5	12.3	-	4.0	5.0	5.0

(2) cemented carbide

Cemented carbide is a mixture of tungsten (W) and carbon (C) particles (tungsten carbide) (WC) that is hardened by using cobalt (Co) as a binder. It is a very hard and wear resistant

Properties such as hardness and toughness of cemented carbide change depending on the particle size of tungsten carbide and the content of cobalt found in the carbide. In addition, for the purpose of improving crater wear resistance, etc., there are some with a slight amount of titanium carbide (TiC) or tantalum carbide (TaC) added.

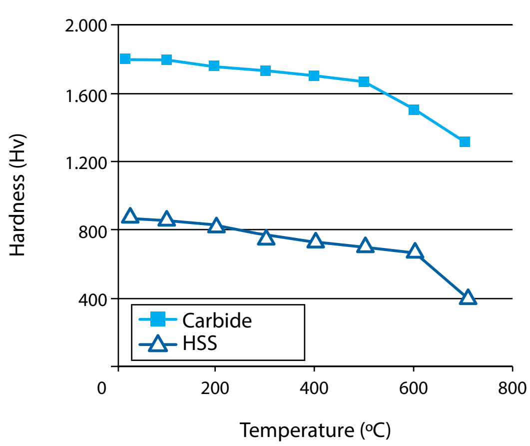
The fine grained tungsten carbide is sometimes referred to as ultrafine grained cemented carbide.

Further, among them, particles with a grain size of 0.5 µm or less are sometimes called "ultra" super-fine particle cemented carbide.

Cemented carbide has about three times the bending resistance compared to high speed tool steel. Therefore, it is difficult for the tool to bend during cutting, and it commonly used for ultra-small diameter solid end mills.

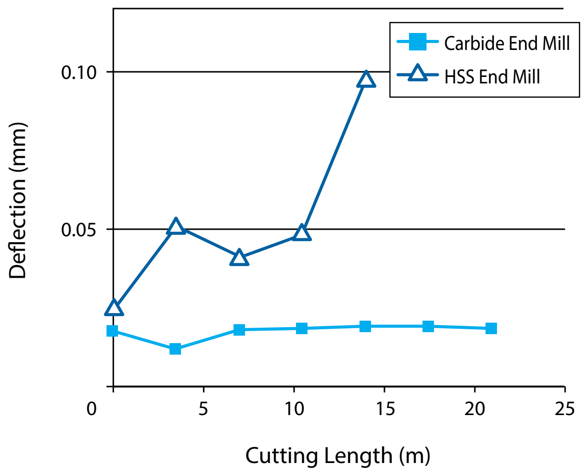
The hardness of high-speed tool steel decreases sharply when the temperature rises to around 600°C, but cemented carbide maintains high hardness even at high temperatures (Fig. 2.1.2).

Figure 2.1.2 High temperature hardness of HSS and Carbide



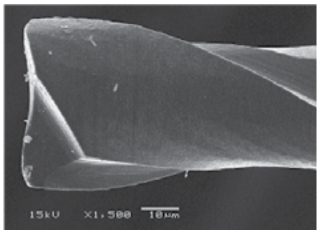
Also regarding the deflection, cemented carbide has a strength that is 2.5 to 3 times that of high-speed tool steel (see Young's modulus in Table 2.1). Therefore, the tool does not easily bend during cutting and prevents the machined surface from tilting or waviness.
Fig. 2.1.3 shows the test results comparing the machining accuracy when performing side cutting with a carbide end mill and an HSS end mill.
By utilizing these characteristics of cemented carbide, fine cutting with ultra-small diameter end mills has also become an alternative to special processing such as beam and etching (Fig. 2.1.4).
In addition, JIS defines the usage of cemented carbide and cermet (classification of cutting super hard tool material) according to ISO material groups. Table 2.3 shows an excerpt of this standard.

Figure 2.1.3 Machining accuracy with carbide end mill and hss end mill

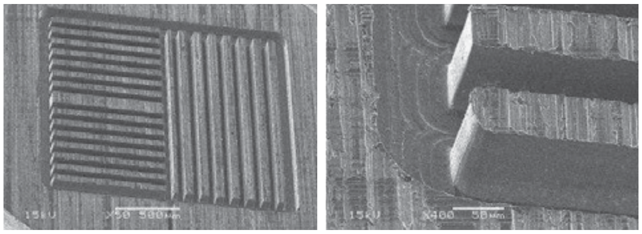


Material : P21 (40HRC)
End Mill : φ.3937 (4 Flute)
Vc : 98.5 SFM (955 rpm)
IPT : 0.002 (7.52 IPM)
Cut Direction : Conventional
DOC : Aa=0.59, Ar=0.0394
Tool Stick Out : 1.378
Coolant : Oil
Machine : Vertical M/c

Figure 2.1.4 Example of precision micromachining with cemented carbide end mill



End mill outer diameter: φ0.05 mm



Width of processing rib: 0.06mm

Table 2.3 Classification of ultra-hard tool materials for cutting (classification according to JIS B 4053)

Major classification of work materials		Specification on classification symbol	Vc	Feed	Hardness	Toughness
P	Iron-based metal with continuous chips	P01	High ↑	↓ High	High ↑	↓ High
		P10				
		P20				
		P30				
		P40				
		P50				
M	Continous type, discontinous type ferrous metal or non-ferrous metal that produces chips	M10	High ↑	↓ High	High ↑	↓ High
		M20				
		M30				
		M40				
K	Ferrous metal or non-metal with discontinous chips	K01	High ↑	↓ High	High ↑	↓ High
		K10				
		K20				
		K30				
		K40				

(3) Cermet

Cermet is a combination of titanium carbide (TiC) and titanium nitride (TiN) with nickel (Ni), cobalt (Co) or molybdenum (Mo).

In other words, it is a composite material of ceramics and metal.

Cermet has a low likelihood to weld with iron-based materials, and when used as a cutting tool blade material, it creates a good glossy finished surface.

It is very effective for improving the quality of the machined surface in the face cutting finish machining of carbon steel and stainless steel.

(4) Ceramics

Ceramics is a word that refers to material comprising of a metallic and non-metal compound. Ceramics include roof tiles, tablewear, pottery, and glass. The origin of ceramics is said to be the Greek word "keramos," which means "hardened clay."

Ceramics are generally lighter than metals, but heavier than plastics. They are more heat resistant, and harder compared to metals , but they also have the disadvantages of being brittle and weak against impact.

Cutting tools based on alumina (Al2O3) and silicon nitride (Si3N4) have been used as indexable tool inserts for turning castings and face milling.

Recently, the toughness of ceramics has been improved by methods such as mixing (dispersing) fiber reinforcement (SiC whiskers), and its applications are expanding.

Table 2.4 Characteristics of main ceramic materials (oxides, nitrides, carbides)

Type	General name	Main component	Vickers hardness Hv	Specific gravity g/cm3	Young's modulus GPa	Melting point ºC	Heat transfer W/(m.k)	Coefficient of thermal expansion x 10^{-6}/ºC
Oxide	Alumina	Al_2O_3	1,500 – 2,000	3.9	350 – 390	2,050	23 – 36	7 – 8
	Zirconia	ZrO_2	1,180 – 1,300	6	200 – 210	2,700	3 – 4	9 – 10
Nitride	Aluminum nitride	AlN	980 – 1,000	3.3	290 – 320	2,200	150 – 160	2.4 – 4
	Silicon nitride	Si_3N_4	1,300 – 1,900	3.2	280 – 310	1,900 (Sublimation)	20 – 28	3 – 3.5
	Sialon	Si_3N_4-Al_2O_3	1,600 – 2,000	3.22	300 – 330		15 – 16	3 – 4
	Titanium nitride	TiN	2,000 – 2,100	5.4	590	2,930	69	9.4
Carbide	Boron carbide	B_4C	3,300 – 3,400	2.51	450 – 460	2,450	20 – 35	5
	Silicon carbide	SiC	2,250 – 2,800	3.15	390 – 430	2,700 (Sublimation)	150 – 170	4 – 4.5
	Titanium carbide	TiC	2,980 – 3,800	4.9	470	3,180	41	7.6

For example, although it is a limited area where the cutting temperature rises, such solid end mills made of fiber reinforced ceramics have come to be used for high speed cutting of heat resistant alloy (Inconel) (Fig. 2.1.5). Note that the main components of ceramics, carbides and nitrides, are widely used as coating film materials.

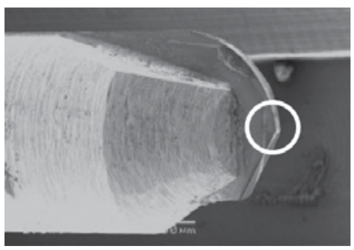
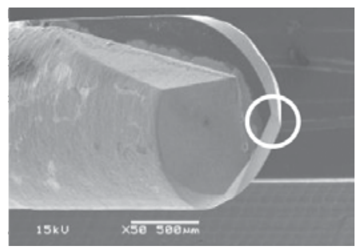
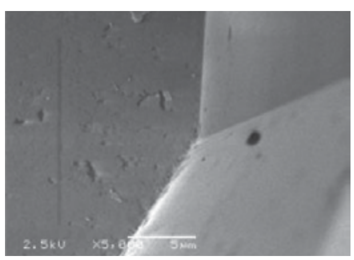
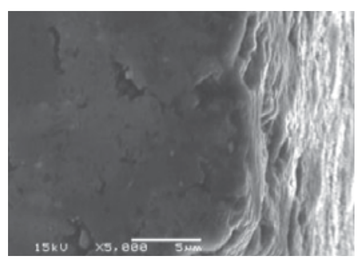
Figure 2.1.5 Example of ceramics end mill

Radius type with short blade length

(5) Diamond

Diamond is the hardest material on earth, has excellent thermal conductivity, is chemically stable, and is also highly transparent. Diamonds with such excellent properties are used for various purposes other than decorations. (By the way, the diamond has special signifigance in April
It is also the birthstone of: "eternal bond, purity".)
There are two types of cutting tools that are used: single-crystal diamonds and diamond sintered compacts (PCD: Polycrystalline diamond) obtained by sintering powdered diamonds.
Diamond single crystals are extremely effective for -precision machining of non-ferrous materials because they can produce extremely sharp cutting edges.
The single crystal of diamond is extremely effective for ultra-precision machining of non-ferrous materials because it can obtain a very sharp cutting edge at the nano level (Fig. 2.1.6).

Figure 2.1.6 Cutting edge condition of single crystal and polycrystalline diamond end mills

Single crystal diamond ball end mill R0.75	Poyrystalline (PCD) diamond ball end mill R0.75
	
	

The diamond sintered body is made by sintering synthetic diamond powder using a binder such as cobalt (Co), usually using cemented carbide as a base metal, and then baking it under high pressure and high temperature (about 50,000 atm, 1,000 thousand degrees).
Diamond sintered bodies are also indispensable tools in the field of non-ferrous metals and non-metal processing.
In recent years, nano crystallization and binderless conversion have been tried. The mechanical properties of single-crystal diamond depend on the orientation, while polycrystalline sintered compacts have the advantage of eliminating the orientation dependence.

(6) cBN (cubic boron nitride)
Cubic boron nitride (cBN), which has the second highest hardness and thermal conductivity after diamond, has less reactivity with iron-based materials and has better thermal and chemical stability than diamond. This makes it possible to process ferrous metals, which diamond has a difficult time handling. (Table 2.5)

Table 2.5 Diamond and cBN

Material		Diamond	cBN
Thermal stability	in the air	Oxidized from 600°C	Stable up to 1,300°C
	Vacuum or inert atmosphere	Stable up to 1,400°C	Stable up to 1,500°C
Reactivity with metals		Graphitization starts at 700°C when coexisting with Fe/Ni/Co	Does not react with Fe/Ni/Co up to 1,350°C

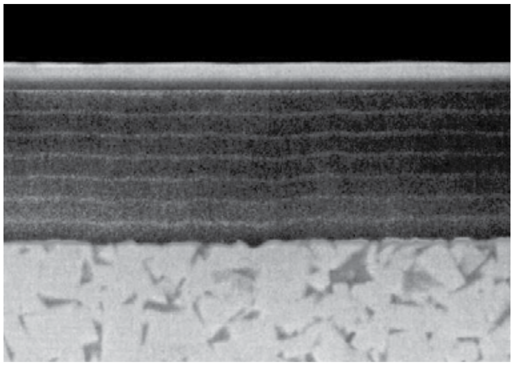
cBN does not exist in nature, and is artificially synthesized using a process similar to diamond under conditions of high temperature and high pressure. At that time, the mechanical and thermal properties of cBN depend on the type and amount of binder used.
In the early days of cBN cutting tools, its use was widespread, mainly for the processing of cast iron, but recently, by refining the grain size of cBN, improving the binder, and revising the tool shape, general carbon steel and hardened steel can be processed. It has also shown a great results in the milling of carbide.

2.2 Surface treatment of end mill

(1) Coating of ceramics film
The methodology of applying a coating to the end mill is collectively called surface treatment. Coating is the latter method of covering the cutting edge with a thin film.
In 1969, inserts (throwaway inserts) were first coated with TiC coating by the CVD method for cutting tools, and when they were commercialized in Germany, the development of coated tools was accelerated in each country.
In the 1980s, TiN coating by the PVD method was applied to solid end mills, and the performance of end mills was dramatically improved.
After that, TiCN film by PVD method and multilayer film such as TiN/TiCN/TiN were also put to practical use.
In the 1990s, as the mainstream base metal for end mills changed from HSS to cemented carbide, TiAlN-based films were developed. Compared to TiN, TiAlN has better thermal conductivity and higher oxidation start temperature, so it has excellent heat resistance and has enabled high-speed cutting of steel and direct engraving cutting after quenching.
On the other hand, a coating film with a very small friction coefficient such as CrN and excellent lubricity was born, and the quality of the machined surface was improved by cutting copper and copper alloys, and the tool life was dramatically improved.
At present, new coatings containing Al/Cr-based, Cr-Si-based, SiC, Zr, etc. have also been put into practical use to further enhance heat resistance and oxidation resistance.
Regarding the film structure, the number of layers has grown from a single layer or from 2 to 3 layers, and composite multi-layered films and nano-laminated films with many layers with different characteristics are being developed one after another (Fig. 2.2.1).

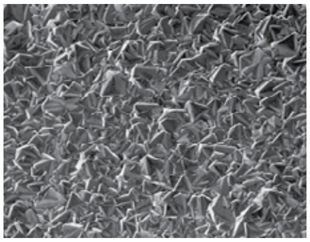
These coating materials are similar to the fine ceramics mentioned above, including TiC and TiN, and some of them have an oxidation start temperature of over 1,300°C.
It is expected that the development and improvement of coatings that will further improve high temperature hardness and lubricity at high temperatures will continue in the future.

Figure 2.2.1 Multilayer coating film

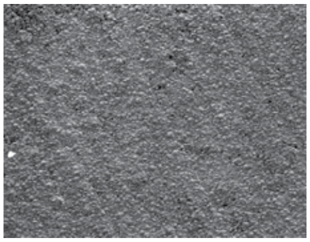


(2) Diamond and DLC coating
Diamond coating is processed by using the CVD method. Since the coating consists of almost 100% pure diamond, it exhibits excellent hardness and high resistance to welding to non-ferrous metals.
Since the diamond coating is an aggregate of diamond crystals grown from small nuclei generated on the surface of the base material, the surface is uneven, and it is conventionally unsuitable for processing requiring finish surface roughness of non-ferrous alloy.
However, in recent years, the technology (1 μm or less) for microcrystallizing the diamond crystals of the film has been established, and it has become possible to form a diamond coating film with a smooth surface. This has made it possible to finish non-ferrous metals without problems, and its applications have expanded (Fig. 2.2.2).

Figure 2.2.2 Microcrystallized diamond coating film



Conventional



Microcrystalline film

Similarly, it is composed of carbon atoms, but the one with an amorphous structure rather than a diamond crystal is called DLC (Diamond Like Carbon). This DLC is also coated as a film (both CVD and PVD methods are possible).Of course, it is not as hard as diamond, but because it has an amorphous structure, it has no directionality, and has the characteristics of excellent smoothness and lubricity.

Table 2.6 Diamond and DLC

	Diamond	DLC
Hardness(Hv)	9,000 – 12,000	1,000 – 8,000
Young's modulus (GPa)	1,050 – 1,220	100 – 760
Crystal form		
Surface morphology	Crystal face	flat

Table 2.7 End mill blade material, surface treatment and main applications

Blade material and surface treatment	Main Purpose	Applicable hardness of work material
High speed tool steel	General cutting of carbon steel, alloy steel, non-ferrous, non-ferrous alloy, etc. Tool life can be extended by using powdered HSS.	HSS: Up to about 35HRC Powder HSS: Up to about 40HRC
Coated High speed tool steel	Longer life and higher cutting speed in general cutting. The effect of coating is great in preventing welding when cutting stainless steel. For TiN alloys and heat-resistant alloys, coating powder HSS is effective.	Coating HSS: Up to about 40HRC Coating powder HSS: up to about 45HRC
Carbide	General cutting of cast iron, non-ferrous, non-ferrous alloy. It can be applied to carbon steel and alloy steel, but its frequency of use is low with the spread of coated carbide.	Up to about 45HRC It is possible up to about 55 HRC for high hardness cemented carbide
Coated Carbide	Supports a wide range of materials and processing forms such as general cutting, hardened steel cutting, and high-speed cutting. The characteristics differ depending on the coating material.	Up to about 60HRC Some of the specifications for high hardness materials can support up to 70HRC, but the life is short.
Cermet	Finish cutting of carbon steel and stainless steel. It is easy to obtain a glossy surface.	Up to about 45HRC
Ceramics	High-speed finishing of castings with face milling using inserts. High-speed cutting of Inconel for solid tools. Limited use.	–
cBN	High-speed finish cutting of cast iron, carbon steel, alloy steel, and hardened steel.	Up to about 70HRC
Diamond	Cutting of Al, Al alloy, Cu, Cu alloy, cemented carbide before sintering and ceramics. Not suitable for ferrous materials.	–
DLC coated carbide	Cutting of Al, Al alloy (low Si), Cu, Cu alloy, etc. Not suitable for ferrous materials.	–
Diamond coated carbide	Cutting of Al, Al alloy, Cu, Cu alloy, cemented carbide before sintering, ceramics, plastic, etc. Greatly improves wear resistance in high silicon aluminum alloy castings. Not suitable for ferrous materials.	–

*The application range and applicable work material hardness range vary depending on the tool shape and specifications, so use the above table as a general guide.

3. Cutting with an end mill

3.1 Cutting mechanism

(1) What is cutting?

"Cutting" is a process in which a tool with a cutting is pressed against the workpiece, and unnecessary parts are separated as chips. It is a method of subtractive manufacturing that creates a shaped part.

(2) Shear deformation

In metal cutting, chips are deformed in the chip formation process, and the metal is removed as short thick chips. (Fig. 3.1.2). This chip deformation in metal cutting is "shear deformation". The state of shear deformation is shown by a simple model (two-dimensional model) as shown in Figure 3.1.3.

3.2 End mill cutting

Figure 3.1.2 Cutting chips

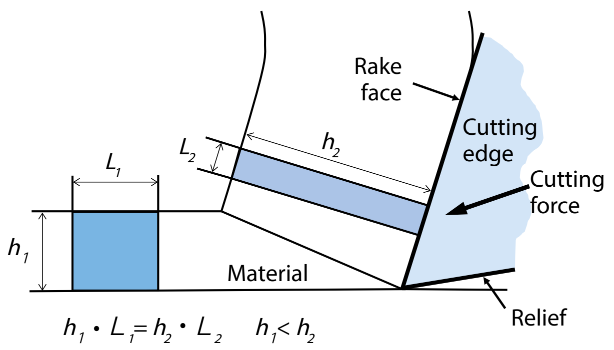
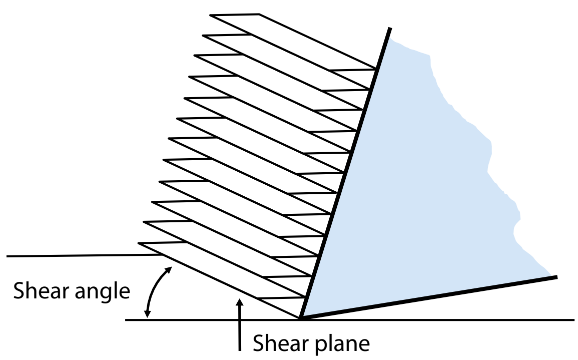


Figure 3.1.3 Shear deformation



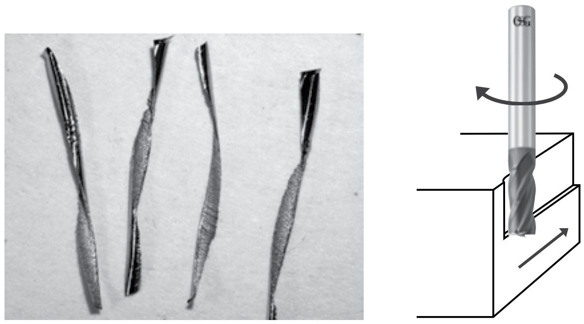
(3) Shear angle and sharpness

A part of the workpiece (cutting surface) that receives pressure from the cutting edge of the tool undergoes shear deformation along the shear plane tangent to the cutting edge. By repeating this, chips are generated and flow outward (Fig. 3.1.4).

The force exerted by the tool that causes shear deformation on the workpiece at this time is called "cutting force". And as a reaction, the force that the tool receives from the work piece is called "cutting resistance". Ideally, cutting resistance should be kept as low as possible while still maintaining good productivity.

Reducing the cutting resistance starts by reducing the force required to deform the chips during the cutting process. Contributions from the material properties, the sharpness of the cutting edge, and the lubrication between the cutting edge and workpiece will affect the cutting resistance. Typically in the machining process, these factors are evaluated based on the sound, surface quality, and tool life of the cutting operation. A steady and consistent sound coupled with an unscratched surface, and long tool life indicates good cutting parameters.

Figure 3.1.4 Example of chips from end mill side cutting



3.2 End mill cutting

(1) Features of end mill cutting

End mill machining (Fig. 3.2.1) with the exception of plunging, has cycles of intermittent cutting and idling as shown in Fig. 3.2.2.

Cutting by rotating the tool, allows time for the tool to cool down during idle periods where the edge of the tool is not in contact with the workpiece. The tool rotation also promotes the evacuation of chips from the cutting area through centrifugal force. Cutting is typically done with a twisted or helical edge. This twist allows the cutting to be performed gradually, reducing the force on the tool and workpart in the direction the tool is being fed. At the same time more force is generated axially which can present issues is the workholding or tool holding is insufficient.

Figure 3.2.2 Idling in end mill processing

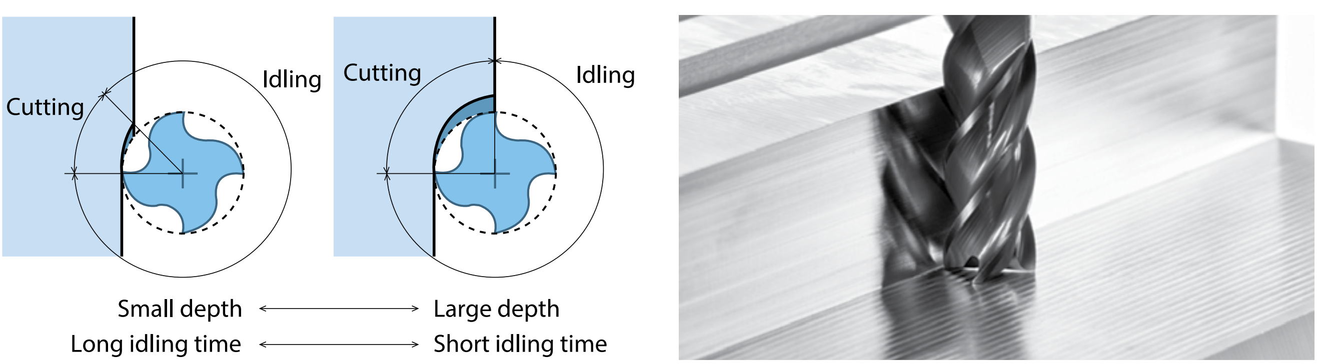


Figure 3.2.3 Change in direction of cutting force

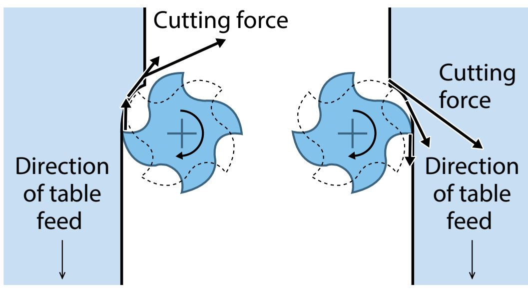


Figure 3.2.4 Moving contact point

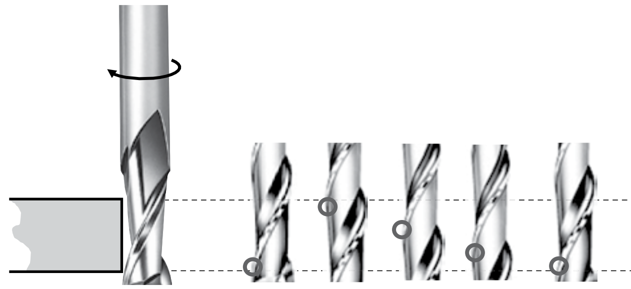


Table 3.2 Characteristics of end mill cutting

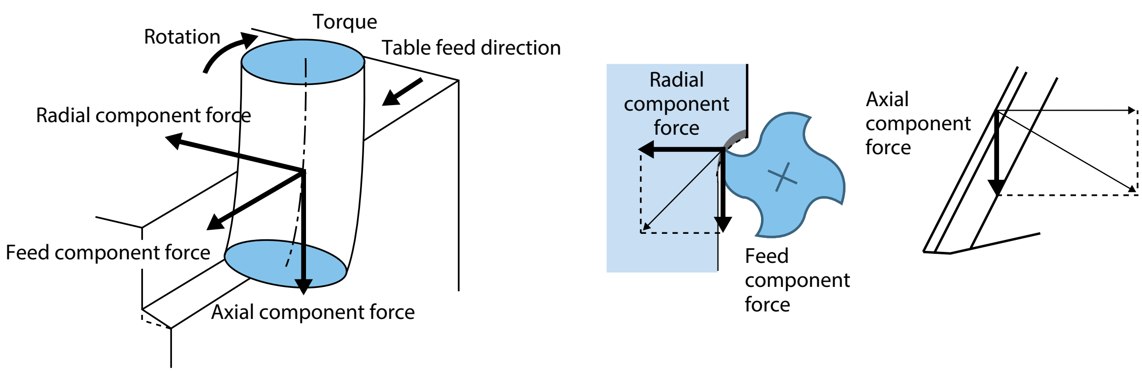
Characteristics of cutting form	Cutting characteristics
Cutting by tool rotation	Cut thickness changes. The direction of the cutting force (cutting resistance) changes. When an idling area occurs, cooling is promoted. Centrifugal force enhances chip evacuation. Changes due to rotation can lead to periodic vibrations.
Cutting with a large aspect ratio (The protruding length is large relative to the outer diameter of the tool)	Tool deflection is likely to occur during processing. Whirling tends to occur during cutting.
Cutting with a helical edge	The cutting force component in the feed direction is reduced. Axial component of cutting resistance becomes large. The effect of inclined cutting is obtained. The chips are forcibly ejected by the action of the screw. The cutting point always moves in the axial direction.
Cutting with multiple cutting edges	At the same time, the length of the cutting edges to be cut changes (the number of cutting edges involved in cutting changes), and the cutting resistance changes. The cutting resistance changes with the resultant force of multiple blades.
Generally cutting by moving in the direction perpendicular to the axis	A large cutting force is generated in the bending direction with respect to the shaft.

(2) Cutting resistance

As mentioned above, a large force is required in the process of cutting. When this force is applied to the end mill to perform cutting, the opposite force acts as a reaction on the end mill.

The cutting resistance in end milling can be measured as the feed force component acting in the feed direction, the radial force component acting in the direction perpendicular to this, and the axial force component as shown in Figure 3.2.5.

Figure 3.2.5 Cutting force component in end mill cutting



The cutting resistance contains fluctuations, but its maximum value governs the required power. The resultant force of the component in the feed direction and the component in the radial direction tries to bend the end mill and holder. If the resultant force exceeds the rigidity of the end mill or holder, bending deformation, or tool deflection, will occur, which will greatly affect the machining accuracy.

Also, when the end mill bends, it tries to return to its original shape, so if this amount of deflection is large and the time between deflection and return is short, it will cause vibration.

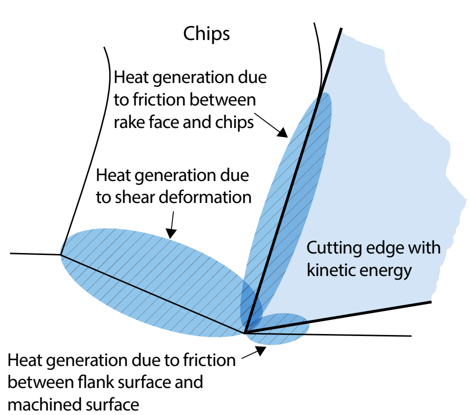
Furthermore, if this resultant force exceeds the elastic limit of the end mill, the end mill will break.

(3) Heat generated by cutting

In end mill cutting, the cutting edge, which has been given kinetic energy by rotation, does the work, but most of this kinetic energy is converted to thermal energy. This is called cutting heat because it is caused by cutting.

The shear deformation caused by cutting as shown in Figure 3.2.6 generates a lot of cutting heat. Furthermore, the friction generated between the cutting edge, the machined surface and the chips also adds as cutting heat.

Figure 3.2.6 Heat generation due to cutting



However, most of the cutting heat flows into the chips. This means that the heat input to the work piece and end mill is extremely low.
In end mill processing, cutting is performed in the situation shown in Figure 3.2.2.
When the cutting edge is cutting, it generates heat, but it immediately turns idle. If the milling method is used to increase the idling time, such as a side milling operation with a low radial stepover, the heat flow to the cutting edge will be reduced since the tool is allowed more time to idle.
Conversely, if the idle time is short and the cutting edge is in contact with the workpiece for a long time, the heat flow into the end mill will increase.

(4) Chatter during cutting
When cutting with an end mill, unnecessary vibration may occur during processing (Fig. 3.2.7). The vibration of the tool, workpiece, and machine is called "chatter vibration".
Chatter vibration is roughly classified into forced vibration and self-excited vibration.
Forced vibration is a phenomenon in which there a source of vibration, that becomes magnified by the characteristics of the machine. Vibration sources include runout of the spindle of the machine, vibration generated by the motor, and periodic fluctuations of cutting resistance due to intermittent cutting.
The runout of the spindle and the vibration of the drive system can be removed by repairs, but if the problem is caused by cutting the solution is more nuanced. If the vibration caused by the fluctuation of cutting forces resonates with the mechanical system or the workpiece, it becomes magnified. This state is known colloquially as chattering.
Subsequently, the resonance in end milling produces an uneven surface for the next flute in the end mill to process.
As a result, the vibration due to chattering, or resonance becomes self-sustaining as each cutting edge continuously processes uneven surfaces. This regenerative chatter vibration is the most troublesome form of chattering in end milling.
In machining, rotational speeds that produce chattering should be avoided by reducing the rotational speed of the tool.

Figure 3.2.7 Machined surface when chatter vibration occurs

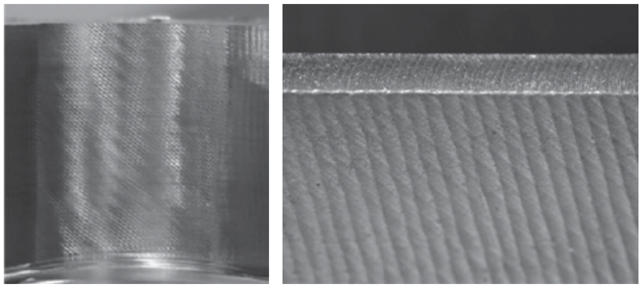
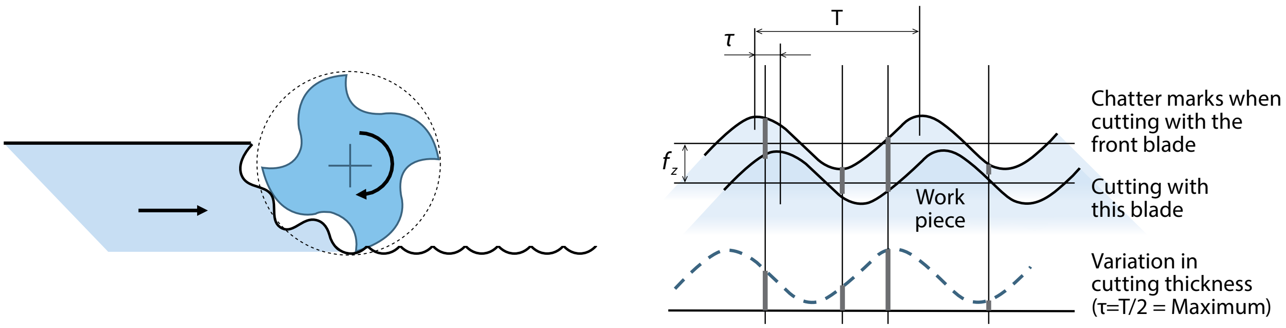


Figure 3.2.8 Play chatter vibration model



(5) Tool wear

Continuous machining with an end mill will gradually erode the cutting edge of the tool. Some typical modes of wear are shown in Figure 3.2.9.Different forms of erosion are typically referred to by either the affected location on the tool or by the shape of the wear. For example, wear that progresses on the rake face of an end mill is called rake face wear, and wear that erodes large depressions into the tool is called crater wear(Fig. 3.2.10).

Wear can also be classified by the mechanism that causes the degradation of the tool. Examples include: mechanical wear, welding, diffusion wear, thermal cracking and plastic deformation.

Constituent cutting edge is a phenomenon that occurs when welding occurs at the cutting edge and shear stays inside the chips that flow above it and does not reach the welding portion. Regardless of the rake angle of the cutting edge, it is said that it is formed at an angle of 30 to 40° as shown in Figure 3.2.12. Since this repeats growth and loss, it deteriorates the roughness of the machined surface and induces chipping of the cutting edge when dropping.

Figure 3.2.9 Wear mode of end mill

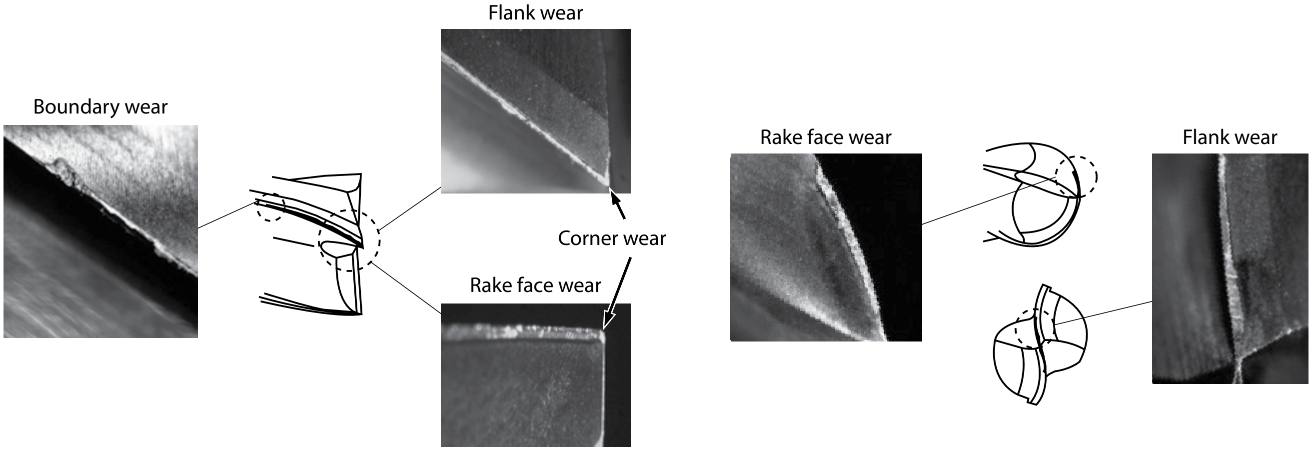


Figure 3.2.10 Crater wear

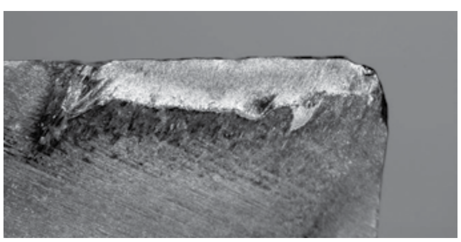


Figure 3.2.11 Chipping

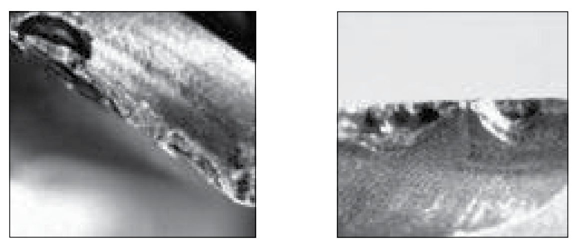
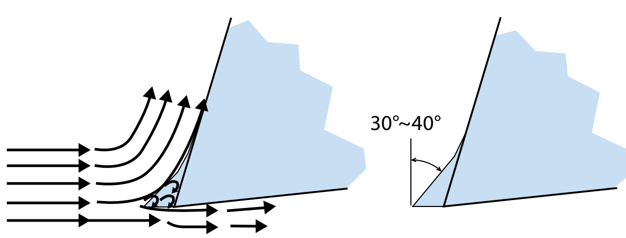


Figure 3.2.12 Component cutting edge

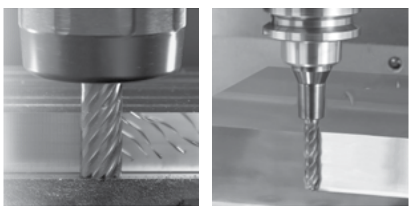


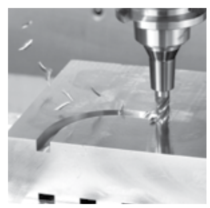
3.3 End Mill processing Methods

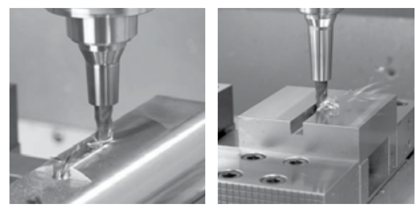
The basic processing forms of the end mill are side milling, groove milling, and hole processing.
A general-purpose milling machine without CNC control can only perform two-dimensional machining, but a CNC-controlled milling machine or machining center can combine the movements of the X-axis, Y-axis, and Z-axis.
Processing such as helical cutting of holes, trochoidal milling of wide grooves, or curved surface milling Becomes possible with CNC machining. Usage of ball nosed end mills and radius end mills to preform free-form surface 3D machining, or profiling is also possible. Figure 3.3.1 shows an example of this kind of processing
When machining a 3D surface, you can improve machining efficiency and machining accuracy by combining multiple machining methods such as contour machining, scan line machining, and helical machining.
With a 5-axis machine, changing the tool posture (or turning the workpiece) avoids interference with the workpiece and holder, and it becomes possible to use the end mill with a smaller overhang length. It is also possible to avoid machining at a ball end mill center where the cutting speed of 0 (Fig. 3.3.2).
Mill turn processing is a method of cutting a rotating workpiece with a rotating end mill. Figure 3.3.3 shows an example.

Figure 3.3.1 Main processing form of end mill


Curved (side) milling


Side milling (shouldering)


Curved (slotting) milling


Slotting


3D free-form surface processing


Pocketing

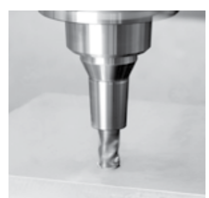

Hole making

Figure 3.3.2 Example of 5-axis machining

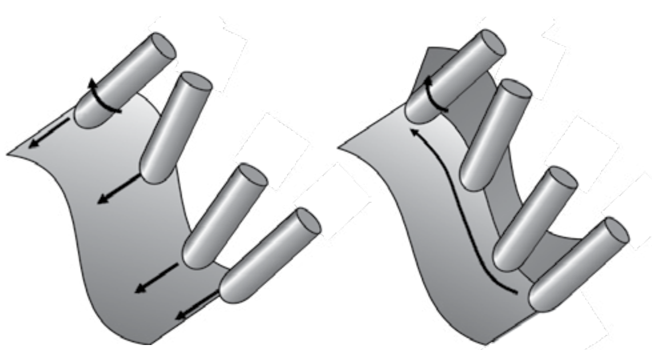
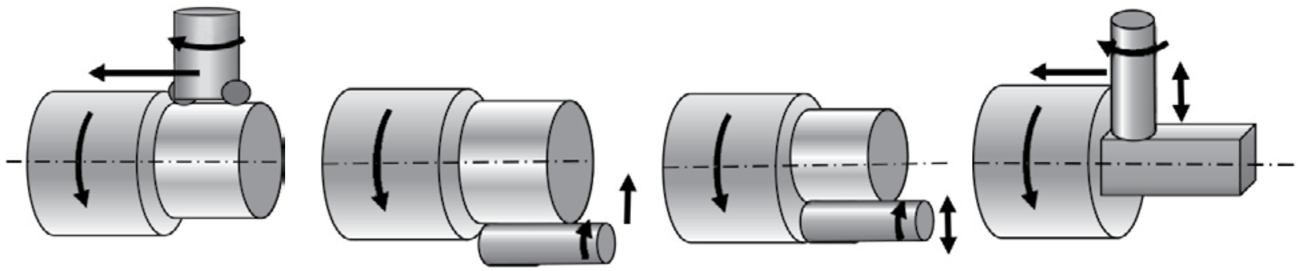


Figure 3.3.3 Example of mill turn processing



4. Cutting conditions

4.1 Cutting speed

(1) What is cutting speed?

The cutting speed in end milling is the relative speed of the end mill compared to the workpiece.
During a milling operation, the feed rate is much smaller than the speed obtained by rotation, so the cutting speed, vc, in end milling is generally determined as follows.

$$Vc=\frac{\pi \cdot DC \cdot n}{1000} \cdots\cdots\cdots\cdots\cdots\cdots (4.1)$$

Vc: Cutting Speed (m/min)

π: Pi

Dc: End mill outer diameter (mm)

n: Rotation speed (min^{-1})

A specific amount of force is required to generate high enough stress inside the work piece, causing shearing and separation. That force is directly related to the cutting speed vc. Since force is expressed by the product of mass and acceleration, the cutting speed is the driving factor for cutting. Therefore, cutting cannot be realized unless the cutting speed exceeds a certain level.
In other words, the higher the cutting speed, the greater the cutting force generated
The plastic deformation in metal cutting generates a large amount of heat.

(2) Cutting speed and processing accuracy

When cutting carbon steel and alloy steels, increasing the cutting speed tends to increase the shear angle and reduce the size of the chips. (Fig. 4.1.1)
In other words, since the amount of shear deformation is small, the cutting resistance will be reduced. This means that even with the same rake angle as the cutting speed increases, the apparent sharpness of the tool improves.

Figure 4.1.1 Cutting speed and shear angle

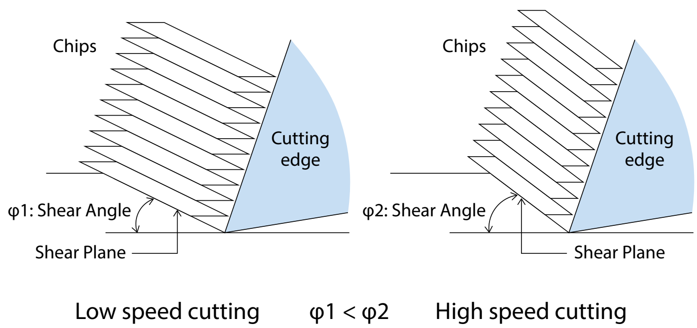
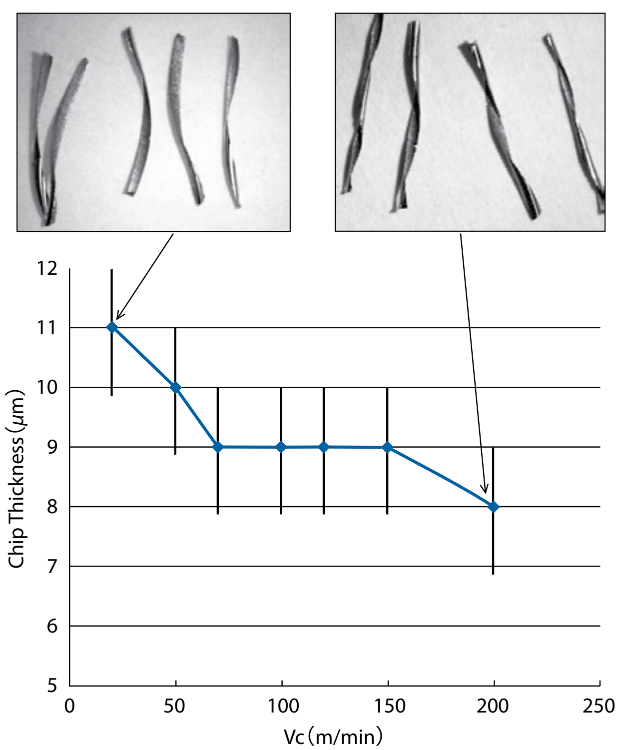
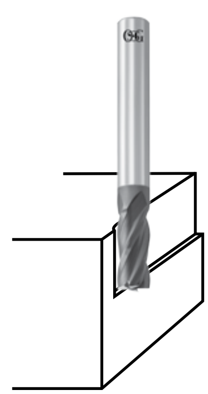


Figure 4.1.2 shows the results of an actual investigation of the relationship between cutting speed and chip thickness using a coated carbide end mill.
The generation of thin chips will reduce cutting resistance and improve the quality of the machined surface.

Figure 4.1.2 Cutting speed and chip thickness

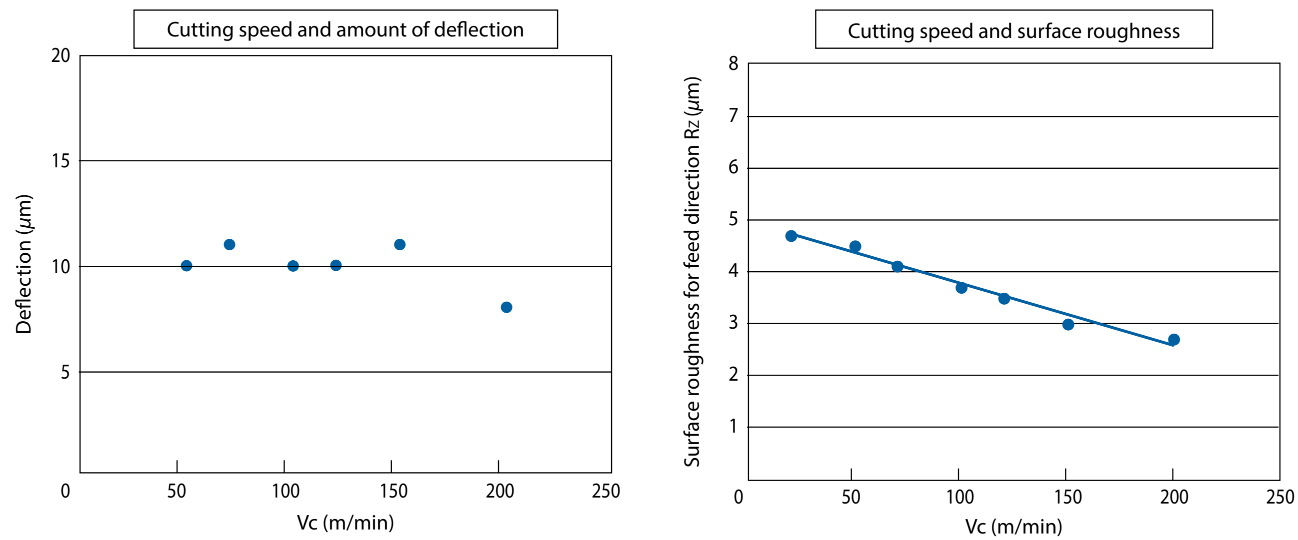


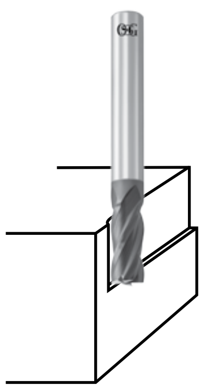


End mill: .3937 Coated Carbide End mill 4 flute
Material: 1050
DOC: Aa=.3937; Ar=.0197
Vc: See chart
IPT: 0.00276
Coolant: Dry

Fig. 4.1.3 shows the results of measuring the machined surface accuracy and machined surface roughness when adjusting the cutting speed in the side milling of carbon steel using a coated carbide end mill.
The result of this experiment shows, the amount of tilt of the machined surface is not affected much by the cutting speed, but the machined surface roughness improves as the cutting speed increases.

Figure 4.1.3 Cutting speed and surface accuracy



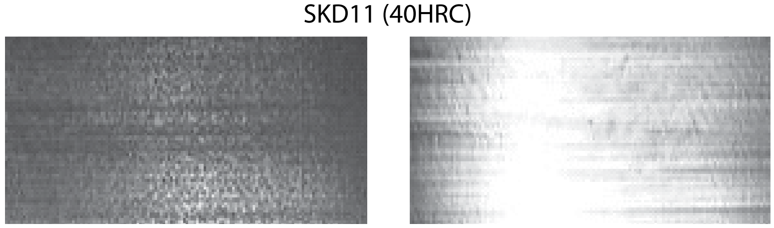


End mill: .3937 Coated Carbide End mill 4 flute
Material: 1050
DOC: Aa=.3937; Ar=.0197
Vc: See chart
IPT: 0.00276
Coolant: Dry

Furthermore, Fig. 4.1.4 shows photographs of two machined surfaces at cutting speeds of 20 m/min and 150 m/min, respectively. You can see that a higher cutting speed significantly increases the glossiness of the surface.

Figure 4.1.4 Cutting speed and surface quality

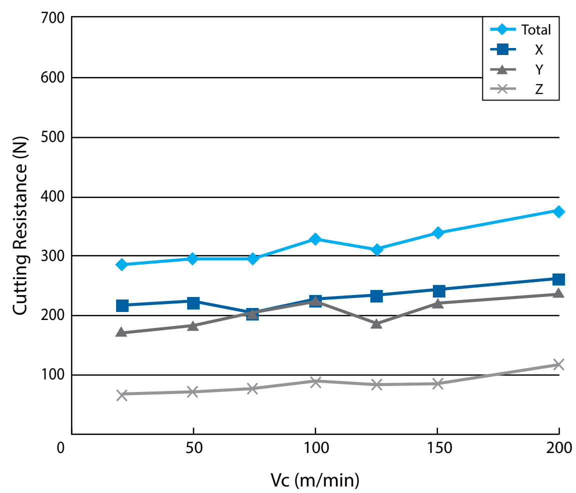
SKD11 (40HRC)

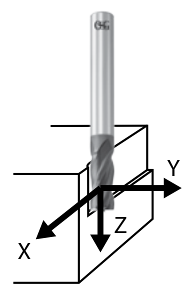


vc=20m/min　　vc=150m/min

Figure 4.1.5 shows the results of an investigation between cutting speed and cutting resistance. Although the cutting resistance tends to increase slightly as the cutting speed increases, the amount of change in cutting resistance is clearly smaller than the amount of change in cutting speed.
An increase in cutting speed promotes an increase in shear angle and consequently suppresses an increase in cutting resistance.
Figure 4.1.6 shows the measurement results of cutting resistance at each cutting speed with a ball end mill. The results show that the cutting resistance decreases as the cutting speed increases.
In ball end mills, increasing the cutting speed increases the shear angle and decreases the amount of shear deformation reducing the chip thickness. The improvement of the machinability near the center of the ball is also a major factor and reduces the cutting resistance.

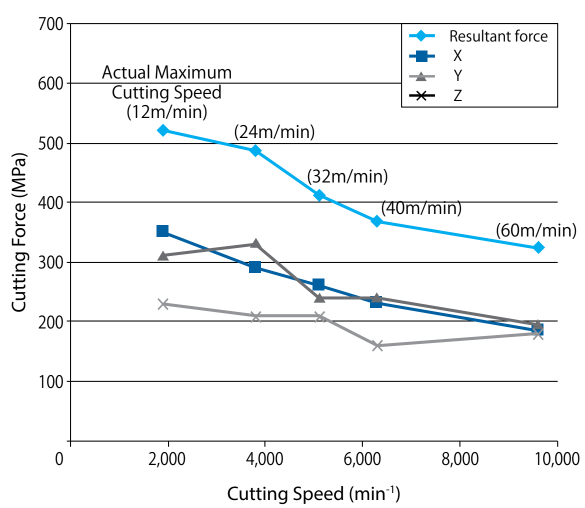
Figure 4.1.5 Cutting speed and cutting resistance

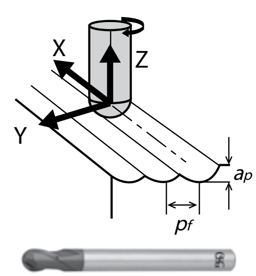




End mill :	.3937 Coated Carbide End mill 4 flutes
Material :	1050
DOC :	Aa=.3937; Ar=.0197
Vc :	See chart
IPT :	0.00276
Coolant :	Dry

Figure 4.1.6 Cutting resistance in ball end mill





End mill:	Coated carbide ball nose end mill R5
Material:	1050
Cutting Speed:	1,900 – 9,600 min-1
Feed Rate:	0.1mm/t
Depth of cut:	ap=0.2mm; pf=0.1mm
Cutting Direction:	Climb
Coolant:	Dry
Machine:	Vertical MC (BT40)

(3) Cutting speed and tool life

As the cutting speed increases, the amount of heat generated by friction and shear deformation increases and the wear of the tool progresses faster.
Conventionally, the following tool life equation (F.W. Taylor) relates the tool life and speed of round cutting tools.

$$Vc \cdot T^{m} = C \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (4.3)$$

Vc: Cutting Speed (m/min)
T: Cutting Time of Tool Life
m: A constant
C: A constant

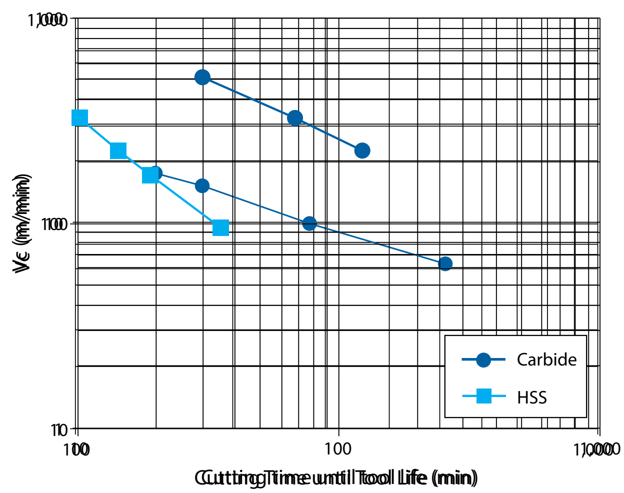
For each material, tools were run at various speeds and conditions to estimate how each factor affect the tool life. Then the results were compiled and the effects of all the parameters, with the exception of cutting speed, were condensed into the material constant m.
In this tool life equation, a larger cutting speed, the shorter the tool life time.

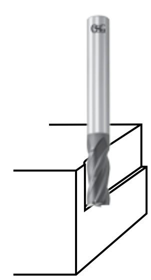
Figure 4.1.7 shows the test results of cutting carbon steel S50C with a coated powder HSS end mill, and this life equation fits well.

This figure shows the cutting speed on the vertical axis and the tool life time on the horizontal axis, each of which is shown on a logarithmic scale, and is called a "V-T diagram" or "V-T graph". When the above-mentioned life equation holds, in this graph, the data will be arranged in a straight line that descends to the right.

Figure 4.1.8 shows an example of wet slotting in each of the HSS end mill and the carbide end mill. In this case as well, the points are aligned in a straight line on the VT line.

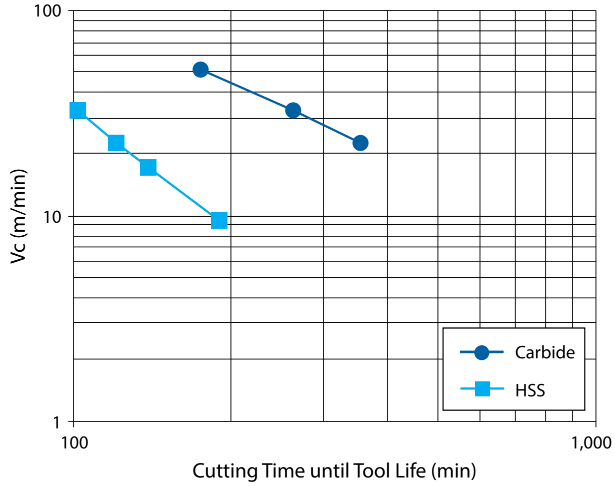
Figure 4.1.7 Example of cutting speed and tool life





End mill :	Coated powder HSS end mill φ16 4 flutes
Material :	1049
Cutting speed :	63 ~ 176 m/min
Feed rate :	0.09mm/t
Depth of cut :	Ap= 10mm; ae=1mm
Cutting direction :	Climb milling
Coolant :	Air blow
Machine :	Vertical MC(BT50)
Tool life criteria :	Flank wear 0.4 mm

Figure 4.1.8 Cutting speed and tool life in carbide / HSS end mills

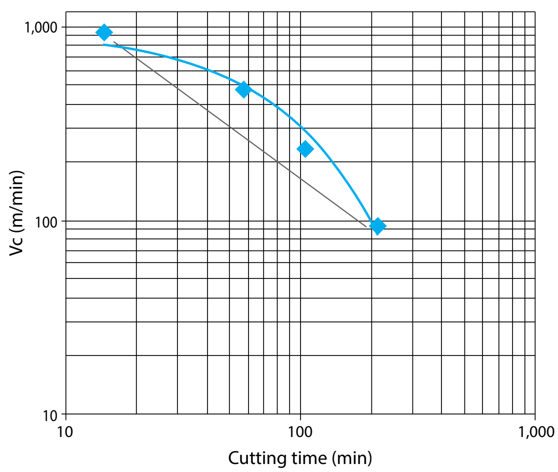


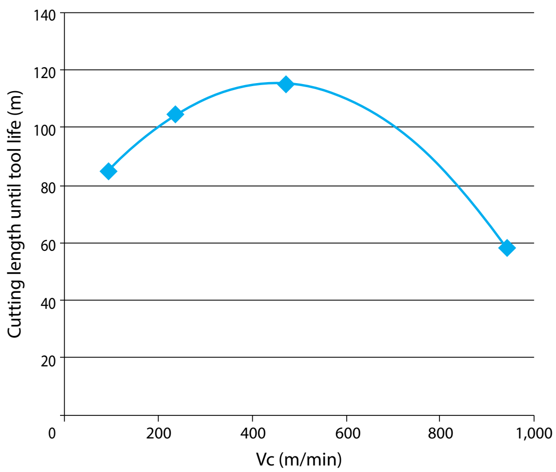
End mill : Carbide 6mm 2 flute HSS 6mm 2 flutes
Material : 1045
DOC : Aa= 6mm
Feed : 0.03mm/t
Coolant : Oil
Machine : Vertical M/C
Criteria : OD wear width 0.4mm

Figure 4.1.9 shows an example. At the same time, a graph with the cutting speed on the horizontal axis and the cutting endurance length on the vertical axis is also shown.

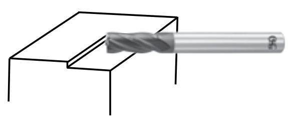
According to this result, for example, the machining efficiency is quadrupled and the cutting durability of the tool is improved by about 30% when the cutting speed is about 400 m / min rather than when the cutting speed is about 100 m / min.

Figure 4.1.9 Advantages of high-speed cutting





End mill : Coated carbide end mill φ15 4 flutes
Material : 1049
Cutting speed : 94 ~ 942 m/min
Feed rate : 0.05mm/t
Depth of cut : Ap= 15mm; ae=0.15mm
Cutting direction : Climb milling
Coolant : Air blow
Machine : Vertical MC(BT40)
Tool life criteria : Flank wear 0.1 mm



As the cutting speed increases, the shear angle increases (the chips become thinner), and the surface area of the generated chips increases, making it easier for cutting heat to transfer into the chips. Furthermore, the improvement of machinability (sharpness) due to the change in shear angle also adds to the above-mentioned effects and slows down the progress of tool wear. Figure 4.1.10 shows the changes in cutting speed and wear morphology during turning, but it is probable that similar changes in wear morphology also occur in end mill machining for intermittent cutting.

Figure 4.1.10 Cutting temperature and tool wear mode

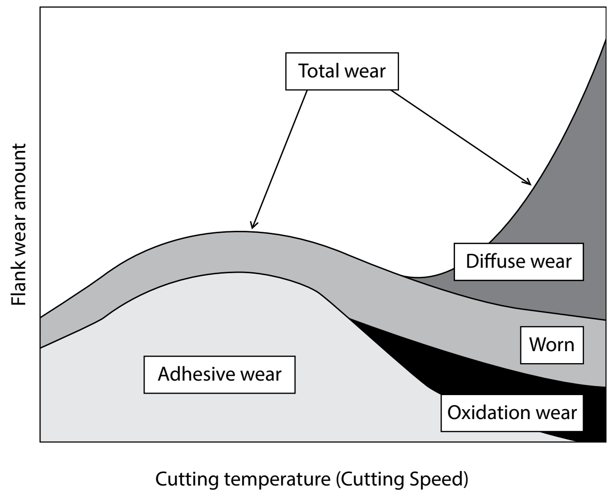
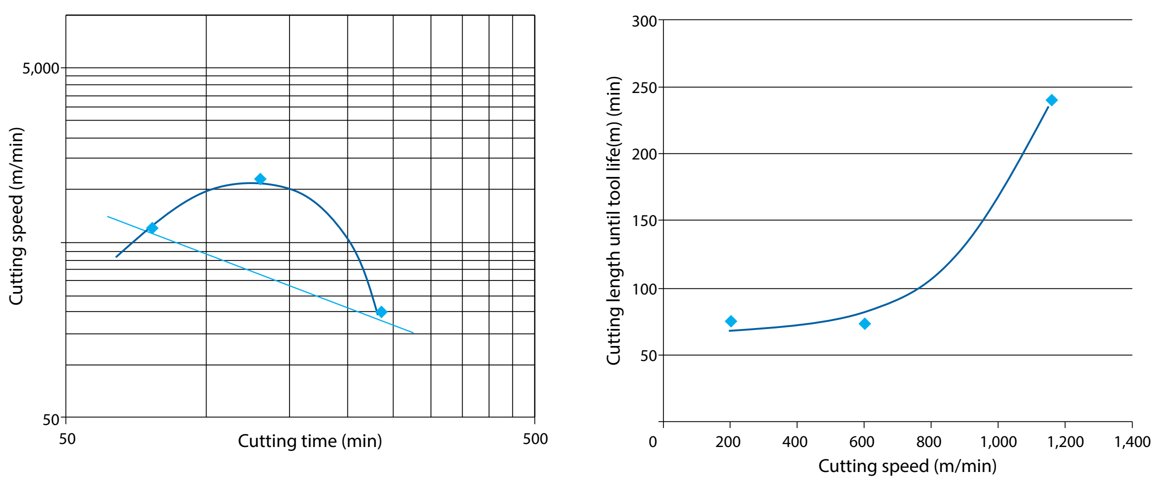
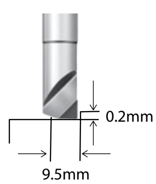


Figure 4.1.11 shows an example of a cBN end mill.
The superiority at a cutting speed of 1,160 m / min is clearly visible.

Figure 4.1.11 Cutting speed and tool life with cBN end mill



End mill :	cBN end mill φ10 1 flutes
Material :	A48 Class No.35
Cutting speed :	200 ~ 1,160 m/min
Feed rate :	0.05mm/t
Depth of cut :	Ap=2mm; ae=9.5mm
Cutting direction :	Climb milling
Coolant :	Air blow
Machine :	Vertical MC(BT30)
Tool life criteria :	Flank wear 0.2 mm



The concept behind high-speed milling is to perform high-precision machining with high efficiency in the high-speed region where the progress of tool wear is moderate. Research on high-speed milling has been actively conducted in Japan since the late 1980s. After that, high-speed machining centers, high-speed CNCs, CAMs, tooling, tools, etc. appeared, and high-speed milling has rapidly become widespread as an extremely effective method for achieving high-efficiency and high-precision machining.

(4) Cutting speed, runout and vibration

End milling is intermittent cutting, and the cutting resistance fluctuates periodically. The discontinuous shearing in the chip generation process described above and the periodic change in the cutting edge length in contact with the workpiece described later also cause fluctuations in cutting resistance. An increase in rotational speed shortens the fluctuation period, while an increase in aspect ratio (L / D), and an increase in cutting resistance lead to an increase in amplitude.

When the rotation speed is increased, there may be a region where vibration suddenly occurs, because resonance occurs when periodic fluctuations are near an integral fraction of the natural frequency of the mechanical system or workpiece. It can be avoided by avoiding the rotation speed in the region where vibration due to resonance is large. If chatter occurs regardless of resonance, reduce the cutting resistance.

On the other hand, in addition to the deflection of the tool due to cutting resistance, there is also vibration due to the cumulative runout of the spindle, holder, and end mill (Fig. 4.1.12). The runout here is the difference between the maximum and minimum values of each blade that can be measured with a dial gauge as shown in Fig. 4.1.13 when the end mill is attached to the machine spindle.

The runout of the end mill not only deteriorates the machining accuracy but also shortens the tool life (Fig. 4.1.14) (Fig. 4.1.15).

The value of this runout tends to be amplified as the rotation speed increases.

Figure 4.1.12 Causes of runout when installing the end mill

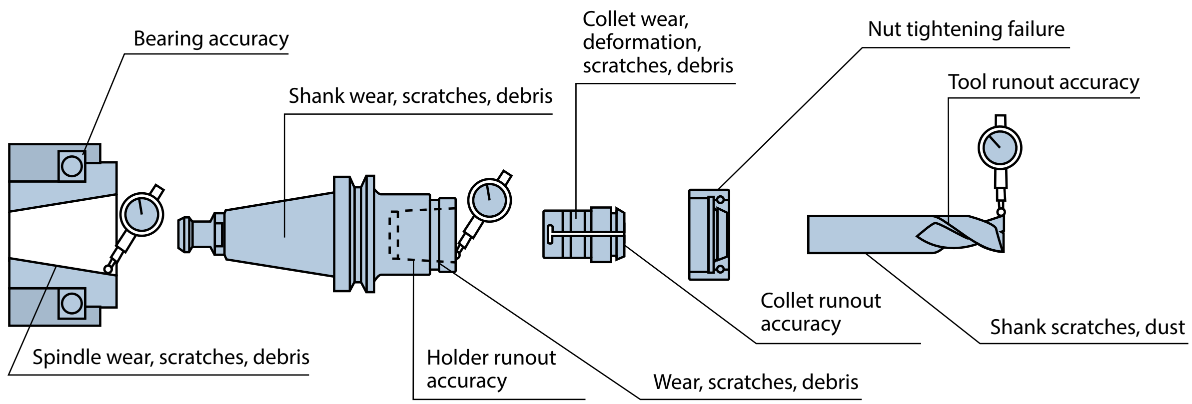


Figure 4.1.13 Measurement of runout of the outer peripheral edge

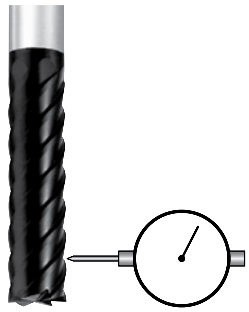
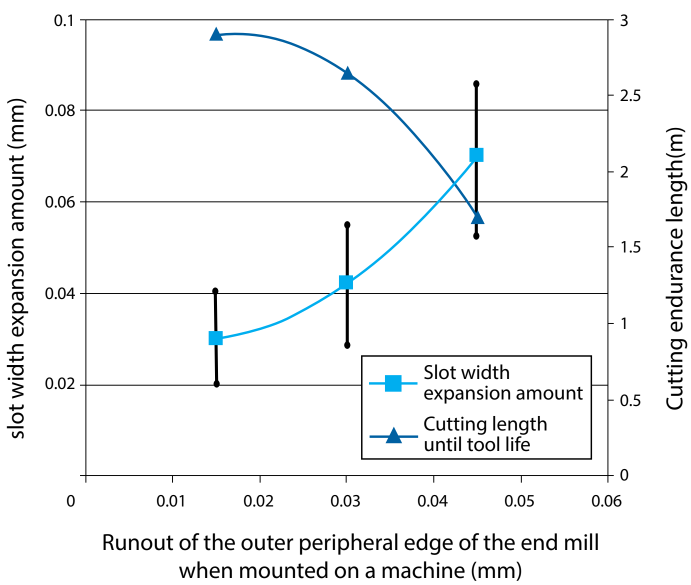
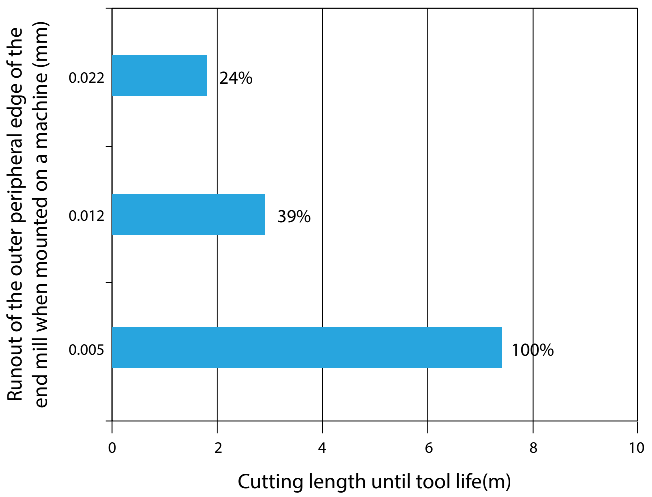


Figure 4.1.14 Runout, machining accuracy and tool life



End mill :	HSS end mill φ16 2 flutes
Material :	1045 (94~96 HRC)
Cutting speed :	34 m/min (680min^{-1})
Feed rate :	0.04mm/t (56mm/min)
Depth of cut :	Ap= 10mm Slotting
Coolant :	Oil
Machine :	Vertical milling machine
Tool life criteria :	Flank wear 0.2 mm

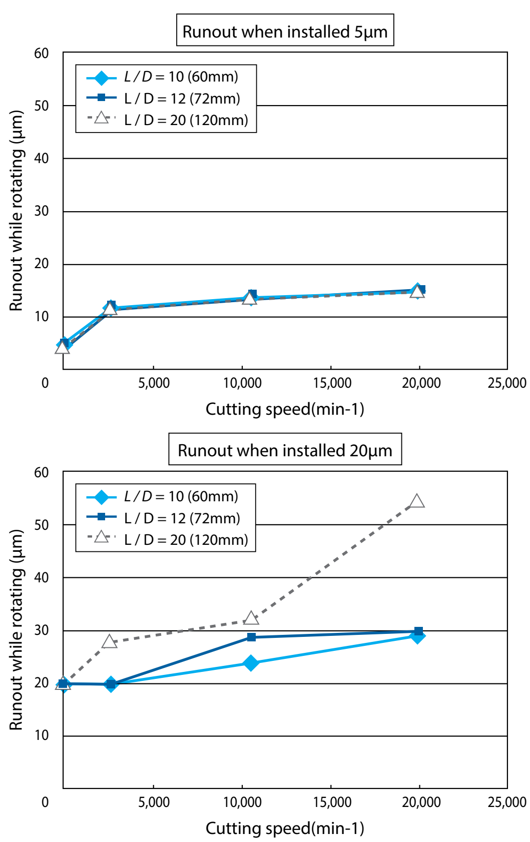
Figure 4.1.15 Carbide end mill runout and tool life



End mill : Coated carbide end mill φ4 2 flutes
Material : H13 (40HRC)
Cutting speed : 36m/min (2,866min^{-1})
Feed rate : 0.08mm/t (46mm/min)
Depth of cut : Ap = 2mm Slotting
Coolant : Oil
Machine : Vertical milling machine
Tool life criteria : Flank wear 0.1 mm

Figure 4.1.16 shows the results of investigating the effect of rotation speed on runout. The runout value during rotation was recorded with an optical measuring instrument.
As the rotation speed increases, the runout value increases, and as the aspect ratio (L / D) increases, the runout magnitude becomes even more pronounced. This increase in periodic runout, combined with the resonance mentioned above, causes chatter vibration.

Figure 4.1.16 Increase in runout due to high-speed rotation



Machine: Horizontal MC (BT40)

Material		Vc (m/min)							
		HSS	Coated HSS	Fine grain carbide	Carbide	Coated Carbide			cBN
		General	General	General	General	General	Roughing by Indexable	High Speed Milling	High Speed Milling
Cast iron	FC250	20~25	25~30	30~35	40~80	40~150	100~300	~320	~2,000
	FCD400	20~25	20~30	25~35	40~70	40~150	70~150	~300	~2,000
Cast iron	SS400	25~40	25~40	35~40	60~80	60~150	80~250	~300	
Carbon Steel	S45C S50C	20~30	25~35	30~35	60~80	60~150	80~220	~300	
Alloy Steel	SCM440 SNCM415	20~30	25~35	30~35	60~80	60~150	80~220	~300	
Pre-hardned Steel	NAK55 HPM1 HPM2	15~20	18~25	25~30	50~70	50~150	60~120	~300	
	NAK80 HPM50	12~18	15~20	20~25	40~60	40~150	50~120	~300	~1,000
Alloy Tool Steel	SKD11	8~12	12~18	20~25	40~70	40~150	100~180	~300	
	SKD61	12~18	12~25	20~30	50~70	50~150	100~200	~300	
Stainless Steel	SUS304	15~20	20~30			30~70	60~250	~200	
Hardness Steel	38~45HRC		12~18	20~25	40~60	40~130	50~80	~300	~1,000
	45~55HRC					25~100		~250	~1,000
	55~60HRC					20~80		~160	~1,000
Non-ferrous Alloy	Copper	25~60	30~70	35~80	60~90	60~300		~500	
	Aluminium	50~100	50~120	50~150	60~300	60~300	200~1,100	~2,000	
Titanium Alloy	Ti-6Al-4V	10~15	10~18	15~20	18~35	18~60	40~80	~100	
Nickel Alloy	Inconel Nimonic	4~6	5~8		12~18	12~30	20~40	~80	

The above table show a rough guideline and does not compensate for the machining speed that can be machined,

4.2 Feed rate

(1) What is the feed rate?

Feed in end mill processing refers to the relative movement between the end mill and the work piece. And the speed of this movement is called "feed rate".

Generally, the feed rate is indicated by the amount of movement Vf (mm / min) per minute of the machine table and spindle.

At this time, the feed amount per rotation of the end mill and the feed amount per tooth are as follows.

$$fr = \frac{Vf}{n} \quad \cdots\cdots (4.4)$$

$$fz = \frac{Vf}{z \cdot n} \quad \cdots\cdots (4.5)$$

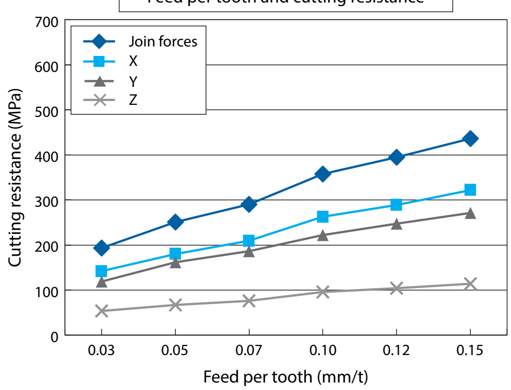
fr: Feed amount per rotation(mm/rev)
fz: Feed amount per tooth(mm/t)
Vf: Feed rate(mm/min)
z: Number of flute
n: Rotation speed per minutes (min^{-1})

This feed rate per tooth affects the thickness of the chips generated.
By expressing the feed rate in terms of the feed amount per tooth, it becomes easier to make relative judgments such as whether the feed amount is excessive or too small.

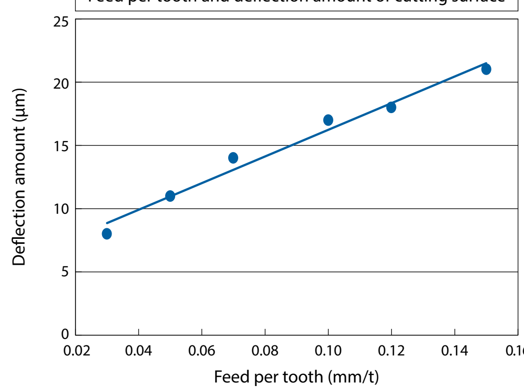
(2) Feed amount and processing accuracy
An increase in the feed amount per tooth will increase the shear deformation amount, which will lead to an increase in cutting resistance as shown in Fig. 4.2.1. An increase in cutting resistance will increase the amount of deflection and runout of the end mill, and will worsen the machining accuracy.
Therefore, in finish machining that requires strict machining accuracy, the required machining accuracy is a constraint on the feed amount per tooth.

Table 4.2.1 feed per tooth and deflection amount of cutting surface

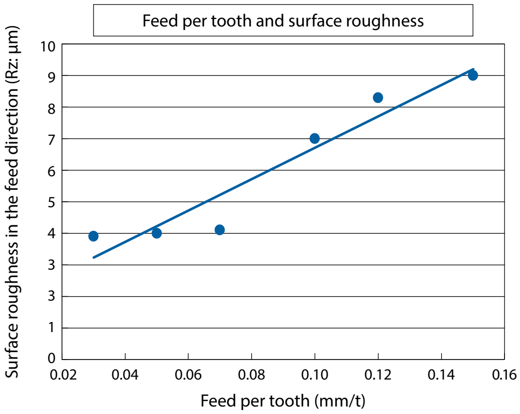
Feed per tooth and cutting resistance

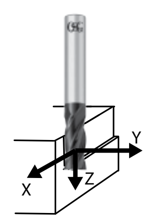


Feed per tooth and deflection amount of cutting surface



Feed per tooth and surface roughness



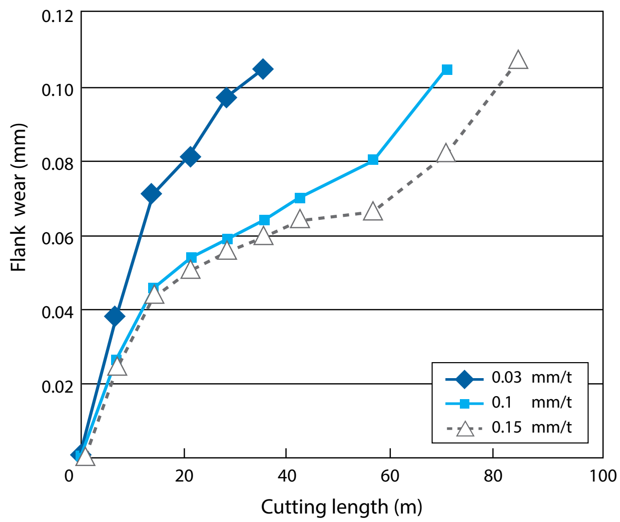


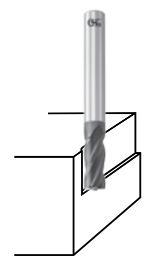
End mill :	Coated carbide end mill φ10 4 flutes
Material :	1049
Depth of cut :	Ap=10mm, ae=0.5mm
Cutting speed :	70 m/min
Cutting direction :	Climb milling
Coolant :	Dry
Machine :	Vertical MC(BT40)

(3) Feed amount and tool life

Figure 4.2.2 shows the experimental results comparing the feed rate per tooth and the progression of tool wear.
It can be seen that the amount of tool wear for the same cutting length is reduced by increasing the feed amount per tooth.
In other words, increasing the feed rate per tooth will extend the tool life.
This is due to how many times the machined surface and the cutting edge contact while cutting the same distance.
However, care must be taken as an excessive feed amount per tooth will increase cutting resistance and induce chipping of the cutting edge.
Cutting ductile materials also leads to the generation of tough burrs, and brittle materials also leads to the generation of chipping.

Figure 4.2.2 Transition of feed amount per tooth and tool wear



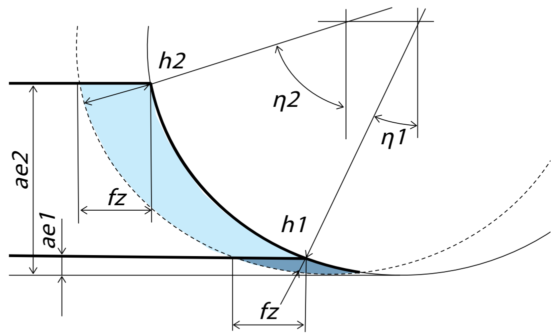


End mill :	Coated carbide end mill φ10 4 flutes
Material :	1049
Depth of cut :	Ap=10mm, ae=0.5mm
Cutting speed :	70 m/min
Cutting direction :	Climb milling
Coolant :	Dry
Machine :	Vertical MC(BT40)

(4) How to determine the feed amount

The feed amount per tooth will be determined within the range where the rigidity of the end mill (including material characteristics), the rigidity of the machine and the work piece, and the holding rigidity of the end mill and the work piece can withstand the cutting resistance.
If the size is increased beyond this, vibration will occur, the cutting edge will chip immediately after cutting, and the end mill will break.
Similar to the feed amount, the depth of cut is a condition that has a large effect on cutting resistance.
As the depth of cut increases, the amount of work per unit time increases, so the cutting resistance increases. In particular, the radial depth of cut has a significant effect on determining the feed rate.
Figure 4.2.3 shows the relationship between the cutting depth and the cutting thickness in the radial direction when the feed amount per tooth is the same.
It can be seen that even if the feed amount per tooth is the same, the cutting thickness increases as the cutting depth in the radial direction increases.

Figure 4.2.3 Cutting depth and cutting thickness with the same feed



f_z : Feed amount per tooth
h_1 : Cut thickness
h_2 : Cut thickness
a_{e1} : Radial depth of cut
a_{e2} : Radial depth of cut
η_1 : Cutting angle
η_2 : Cutting angle

Even with the same feed amount per blade, the cutting thickness increases as the cutting depth increases.

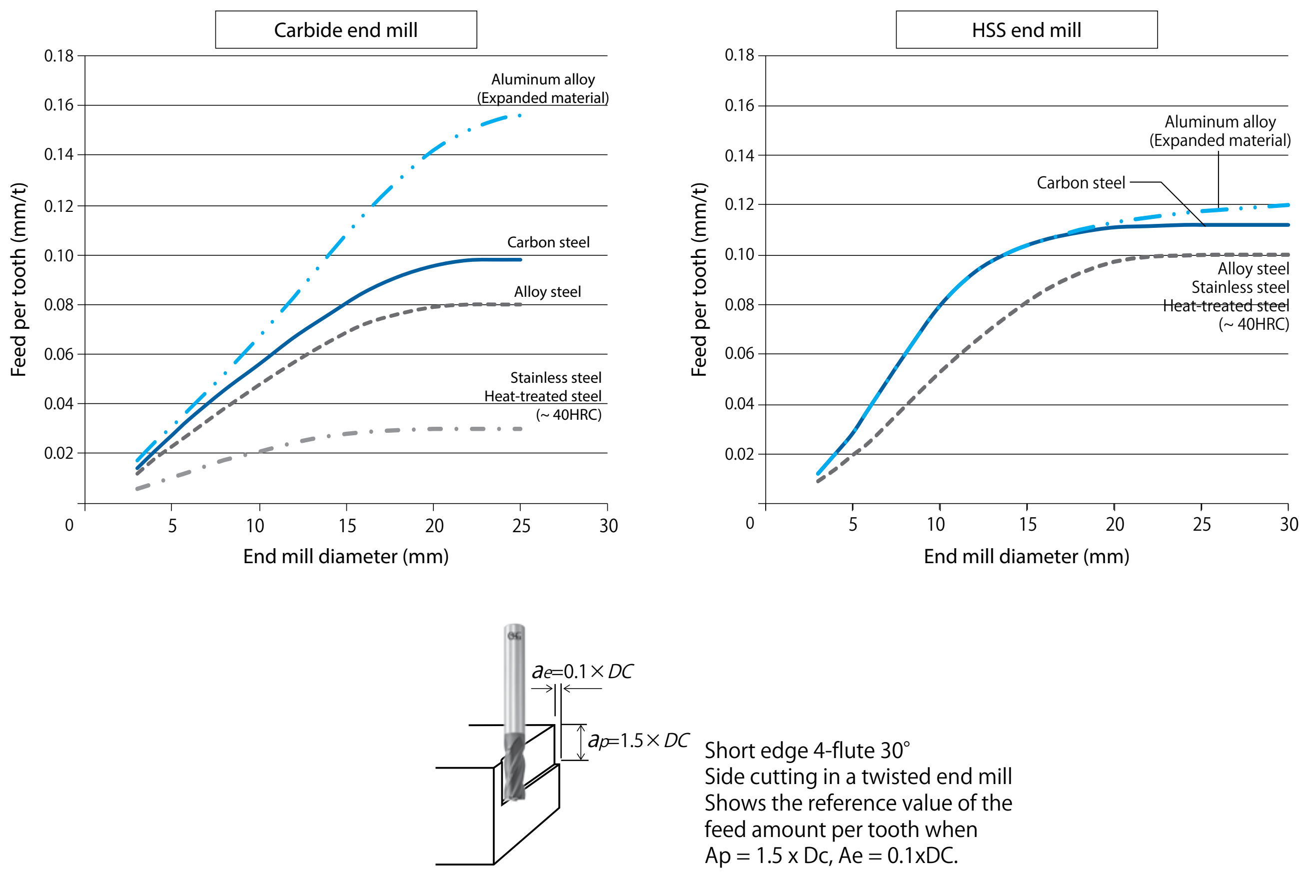
At this time, the relationship between the cutting depth and the maximum cutting thickness can be approximately expressed by the following equation.

$$ha \fallingdotseq fz \cdot \sin \eta$$
$$= \frac{2fz}{DC}\sqrt{ae \cdot DC - ae^2}$$
$$= 2fz\sqrt{\frac{ae}{DC}\left(1 - \frac{ae}{DC}\right)} \cdots\cdots\cdots (4.6)$$

ha: Maximum cutting thickness (mm)
η: Rotation angle of the cutting edge
fz: Feed amount per tooth (mm / t)
ae: Radial depth of cut (mm)
DC: End mill outer diameter

Generally, the feed amount per tooth of the end mill is shown as the reference value shown in Fig. 4.2.4.
Using this value as a guide, correction will be made according to the depth of cut (cutting amount) and the rigidity of the end mill. For example, for medium blade length, it is 80% of this value, and for long blade length, it is about 50-60%. Finally, the feed amount per tooth is determined by making adjustments according to the required machining accuracy and machined surface roughness. Additionally many tool manufacturers will also include their own recommendations on the ideal speeds and feeds dependent on each material and milling application.

Figure 4.2.4 Reference feed amount per tooth



Short edge 4-flute 30°
Side cutting in a twisted end mill
Shows the reference value of the feed amount per tooth when Ap = 1.5 x Dc, Ae = 0.1xDC.

4.3 Cutting depth

(1) What is the depth of cut?

Machining efficiency is determined by the volume removed per unit time (chip discharge). In end milling, the product of the depth of cut and the feed rate is the volume removed per unit time.

The depth of cut of the end mill is usually represented by the depth of cut (ap) in the axial direction and the depth of cut (ae) in the radial direction (Fig. 4.3.1).

Therefore, the volume removed per minute (chip discharge) can be calculated by the following formula (Fig. 4.3.2).

$$Q = \frac{ap \cdot ae \cdot Vf}{1000} \quad \cdots\cdots \quad (4.7)$$

Q: Removal volume per minute (chip discharge) (cm3 / min)

ap: Axial depth of cut (mm)

ae: Radial depth of cut (mm)

Vf: Feed rate (mm / min)

(2) Effect of cutting depth

As the depth of cut in the radial direction increases, the cooling time due to idling becomes shorter as shown in Fig. 4.3.3, and the chips generated by the increase in the cut thickness become thicker (Fig. 4.2.6).

Thick chips have a smaller surface area per unit volume, so the heat inflow to chips decreases and the inflow of heat to the cutting edge of the end mill increases.

Slotting is a form of milling which maximizes the radial depth of cut. In slotting, the outer peripheral cutting edge within the radius is always cutting, and the bottom edge corner is always in contact with the machined surface even when not cutting.

As a result, the cooling effect due to idling is reduced, and cutting heat is more likely to flow into the tool. Therefore, the cutting speed cannot be increased by much.

Furthermore, in slotting, in addition to the problem of cutting heat, cutting is performed while being contained between 2 walls, so problems such as chip evacuation and chip recutting are likely to occur.

Figure 4.3.1 Depth of cut

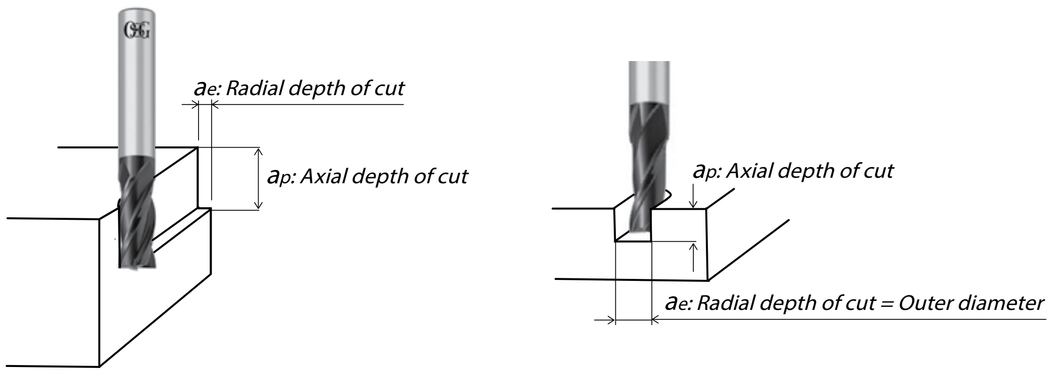


Figure 4.3.2 Chip emissions

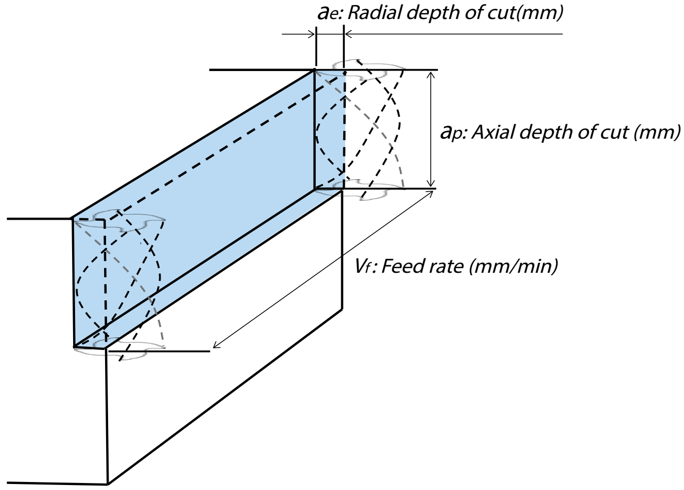
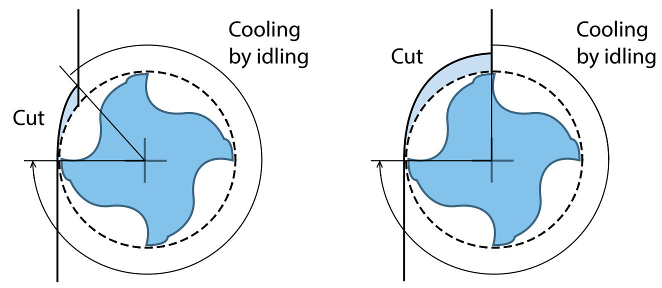


Fig. 4.3.3 Depth of cut and idling time



Increasing the cutting depth also increases cutting resistance and reduces the expulsion of cutting heat, which leads to the generation of a work-affected layer and an increase in tensile residual stress on the work surface.
When increasing the cutting depth in the axial direction (in side cutting), the idling time does not decrease and the cutting thickness does not increase as shown in Fig. 4.3.3.
In this respect, it is more advantageous than increasing the depth of cut in the radial direction, but there are multiple cutting edges that perform cutting at the same time, and the cutting edge length involved in cutting also increases as shown in Fig. 4.3.4. Cutting resistance also increases by this amount.
Furthermore, changes in the cutting position can cause fluctuations in the bending moment, which promotes the occurrence of waviness on the machined surface.

(3) Cutting depth and processing accuracy
If the depth of cut in the radial direction is increased, the cutting resistance will increase significantly as shown in Fig. 4.3.5. Along with this increase, the amount of tilt of the machined surface also increases, and the roughness of the machined surface also deteriorates.
Even if the depth of cut in the axial direction increases, if the cutting edge length for cutting increases at the same time, the cutting resistance will increase and the machining accuracy will deteriorate.

Figure 4.3.4 Axial depth of cut and simultaneous contact cutting edge length

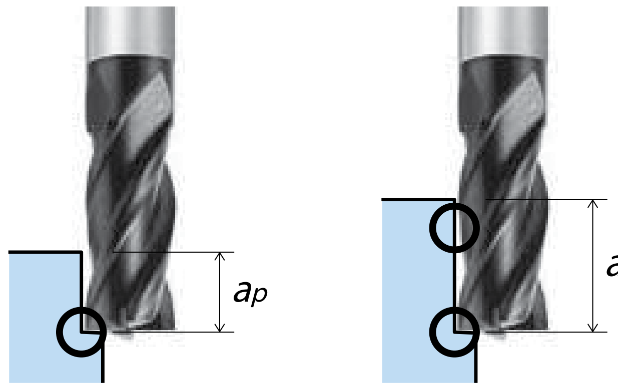
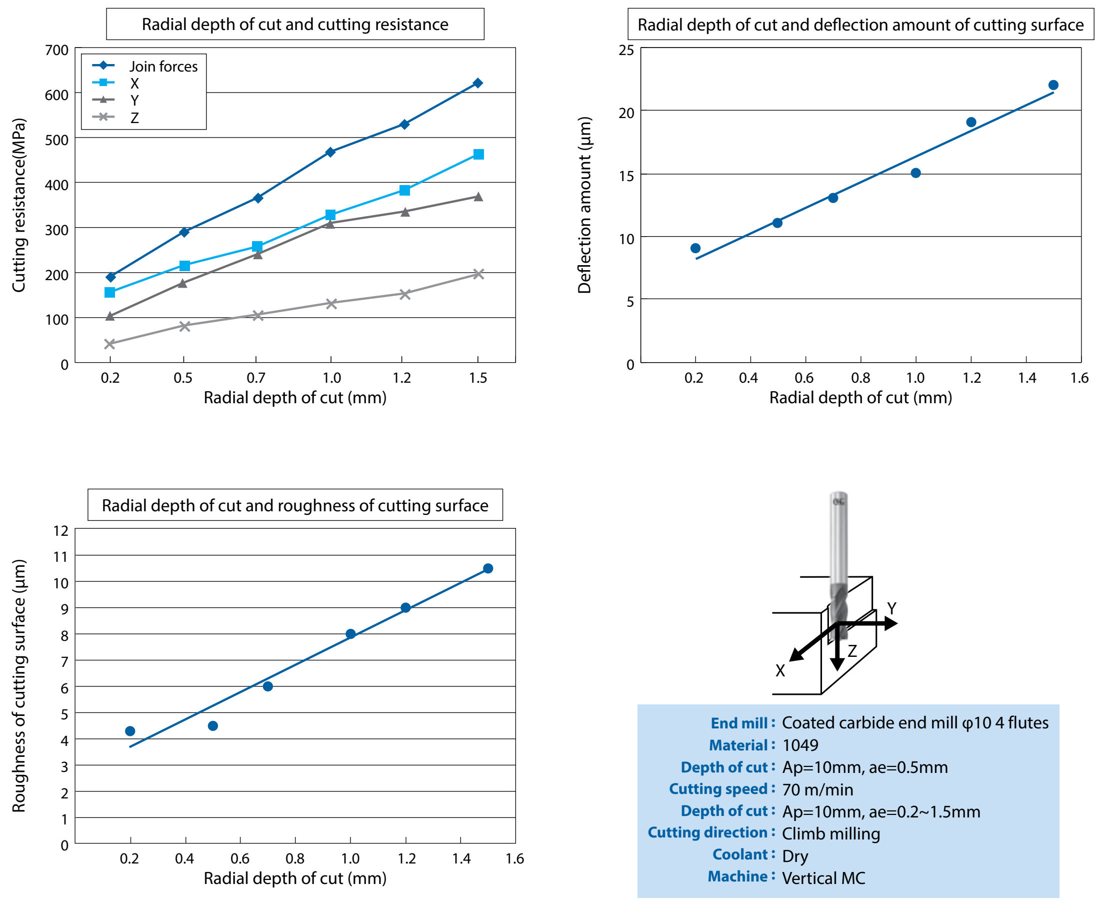


Figure 4.3.5 Radial depth of cut, cutting resistance, machining accuracy



4.4 Precautions when Determining Conditions

It is important to understand that the three main conditions of cutting are not determined individually, but are interconnected.
Table 4.2 summarizes the basic interrelationships of each cutting condition.

Table 4.2 Interrelationship of cutting conditions

Items for cutting conditions UP	Thermal phenomenon when each cutting condition is increased		Cutting resistance and vibration when each cutting condition is increased		Basic response when each cutting condition is updated			
	Generation of cutting heat	Tool temperature rise	Cutting resistance	Vibration	Cutting speed	Feed rate	Axial depth of cut	Radial depth of cut
Increase of cutting speed	Great increase	Almost nothing	Slight increase	Increased area of occurrence		△	⬇	⬇⬇
Increase of feed rate	Increase	Slight increase	Increase	Increased area of occurrence	△		⬇⬇	⬇⬇
Increase of axial depth of cut	Increase	Increase	Increase	Increased area of occurrence	⬇	⬇⬇		⬇
Increase of radial depth of cut	Increase	Great increase	Great increase	Great Increased area of occurrence	⬇⬇	⬇⬇	⬇	

△ : The applicable area becomes narrower.
⬇ : Need to be reduced.
⬇⬇ : Need to be greatly reduced.

4.5 Pick feed

The amount of shift in the direction perpendicular to the feed direction of the end mill (Fig. 4.5.1) when machining a free curved surface of a mold is called "pick feed".
And the height of the peaks created by the pick feed and the radius of the ball end mill is called "cusp height". The geometric surface roughness perpendicular to the feed direction is determined by this cusp height (Fig. 4.5.2).

Figure 4.5.1 Pick feed and cusp height

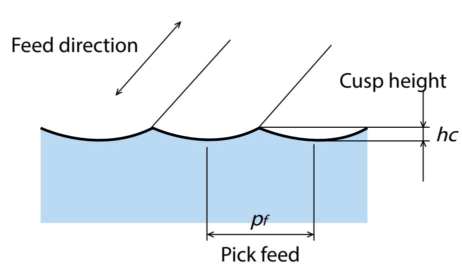
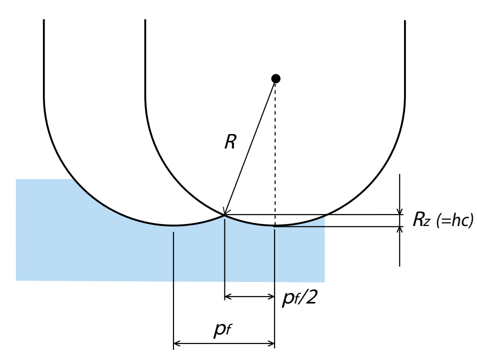


Figure 4.5.2 Theoretical surface roughness in ball end milling



$$hc = R - \sqrt{R^2 - \left(\frac{Pf}{2}\right)^2} \cdots\cdots\cdots\cdots (4.8)$$

hc: Cusp height
R: Radius of ball
Pf: Pick feed

The expansion of this formula is as follows.

$$(R - hc)^2 = R^2 - \frac{Pf^2}{4}$$
$$R^2 - 2R \cdot hc + hc^2 = R^2 - \frac{Pf^2}{4}$$
$$hc\,(2R - hc) = \frac{Pf^2}{4} \cdots\cdots\cdots\cdots (4.9)$$

At this time, hc << 2R, so make it as follows.

$$2R - hc \fallingdotseq 2R \cdots\cdots\cdots\cdots (4.10)$$

Then, the theoretical roughness (Rz), which is closer to the equation (4.9), can be expressed as follows.

$$Rz = hc = \frac{Pf^2}{8R} \cdots\cdots\cdots\cdots (4.11)$$

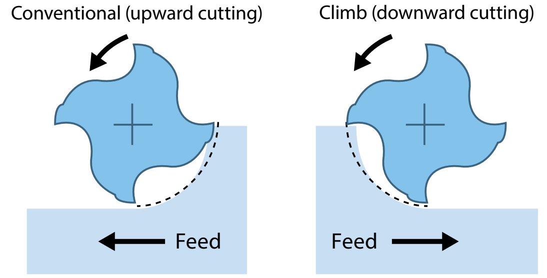
The surface roughness in the feed direction is determined by the feed amount per blade, but in reality, the runout of each of the spindle, holder, and tool is not 0, so these runouts are used in conjunction with the pick feed to determine the tool trajectory.
Therefore, even if the pick feed is made small enough with respect to the feed amount per rotation to meet a desired surface roughness, the roughness may not be improved in the feed direction. Likewise, if the pick feed is increased, it will set a baseline roughness and no matter how small the feed amount per rotation is, the finished surface roughness will not improve. In short, both the pick feed and feed per tooth need to be adjusted in conjunction to obtain the best possible surface finish.

4.6 Cutting direction (up cut and down cut)

(1) Cutting direction and tool life

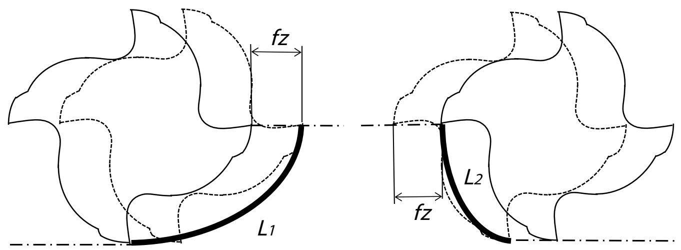
Figure 4.6.1 shows the conventional (upward cutting) and climb (downward cutting).

Figure 4.6.1 Conventional (upward cutting) and Climb (downward cutting)



Upcut and downcut are determined by the feed direction with respect to the rotation of the end mill.
In upcut, the cutting edge (cutting thickness) in the work piece starts from zero and gradually increases.
Therefore, the impact at the start of cutting is reduced, but the cutting edge is more likely to cause an upward slip phenomenon, and mechanical rubbing wear progresses faster.
In the down cut, on the contrary, the cutting progresses in the direction that the cut gradually becomes smaller. Since an appropriate cutting thickness can be secured at the start of cutting, the slipping phenomenon is less likely to occur, and the chip thickness becomes zero at the end of cutting, which improves chip separation.
The locus of the cutting edge in end mill cutting is a trochoid curve, and Fig. 4.6.2 shows the conceptual diagram.

Figure 4.6.2 Concept of cutting edge trajectory

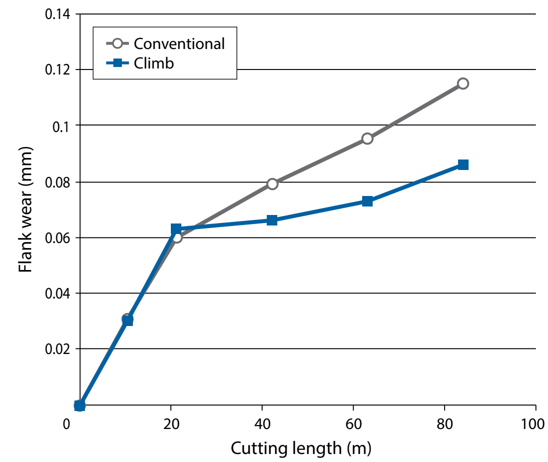


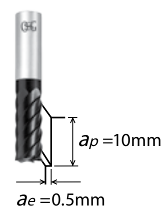
fz : Feed amount per tooth
L_1 : Cutting arc of cutting edge (conventional)
L_2 : Cutting arc of cutting edge (climb)

In the upcut, it becomes an arc L1 in which the feed amount is added to the rotation. On the other hand, in the down cut, the arc L2 is obtained by subtracting the feed amount.
Comparing the arc lengths L1 and L2, you can see that L2 is smaller.
The feed amount of one blade is very small, so this difference is small, but since the end mill rotates thousands to tens of thousands of revolutions per minute, if the cutting distance becomes long, this difference of accumulation will be larger.

Due to the above effects, the downcut has a slower progress of blade edge wear than the upcut, and the tool life is longer under otherwise identical circumstances.
Figure 4.6.3 shows the results of actual comparative measurement of tool wear progress with upcut and downcut.
It can be seen that the progress of wear is slower with the downcut.

Figure 4.6.3 Cutting direction and tool life





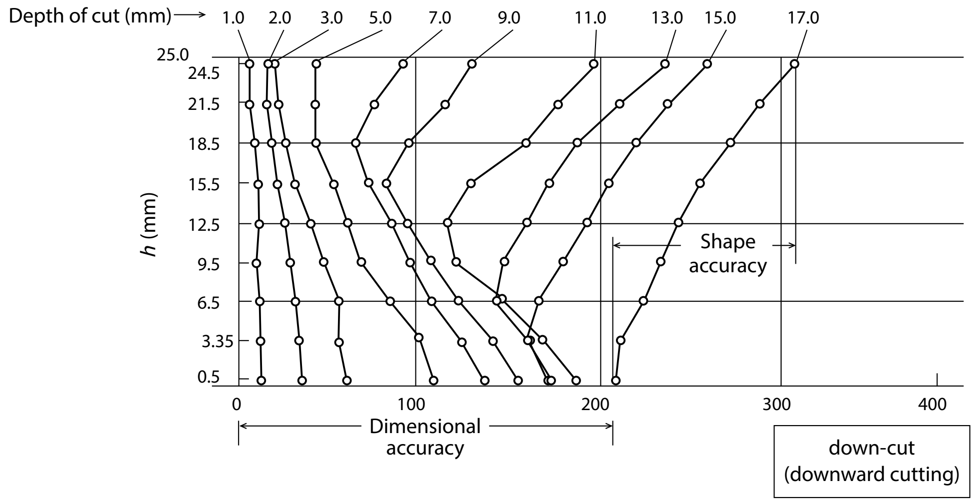
End mill :	Coated carbide end mill φ10 6 flutes
Material :	1049
Cutting speed :	3,200 min^{-1}(100m/min)
Feed rate :	1,300mm/min(0.068mm/t)
Depth of cut :	Ap=10mm, ae=0.5mm
Coolant :	Water soluble
Machine :	Vertical MC(BT40)

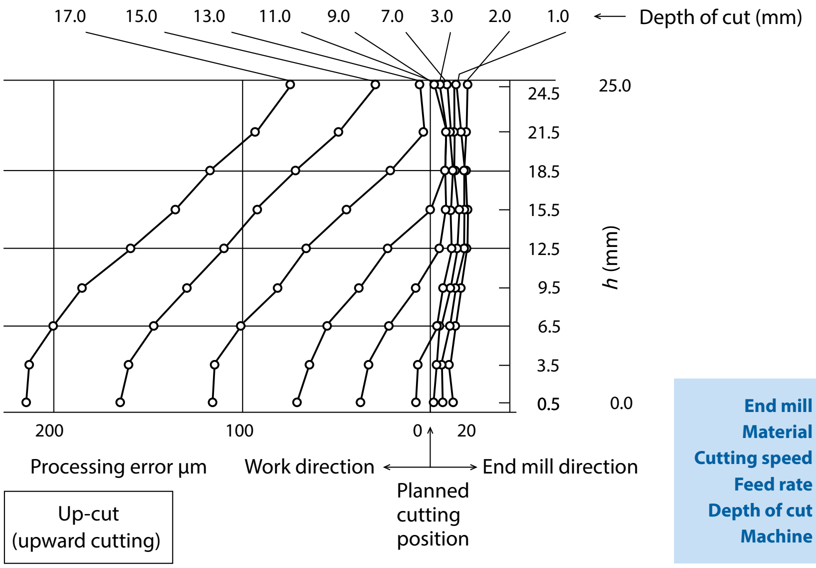
However, as an exception, if there is hardened layer on the surface of the part, it may be possible to prevent chipping of the cutting edge and extend the tool life with upcuting. Alternatively, if the mechanical rigidity or the holding rigidity of the work piece is insufficient, up-cutting may prevent chipping of the cutting edge.

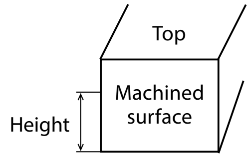
(2) Cutting direction and machining accuracy

Figure 4.6.4 shows the measurement results of the accuracy of the machined surface when the depth of cut in the radial direction is changed for each of the upcut and downcut.
Using down cut, the part is undercut at all depths of cut. On the other hand, with upcut, undercut occurs in the area where the depth of cut is small, but if the depth of cut exceeds 11-12mm, it becomes overcut.

Figure 4.6.4 Cutting direction and shape accuracy (Precision Machinery Vol. 41, No. 3, March 1975, Contouring accuracy by end mill, Yoshiya Fujii, from Hiroiku Iwabe)







End mill :	φ32mm (SKH3)
Material :	A48 Class No. 35
Cutting speed :	32.6m/min
Feed rate :	0.08mm/t
Depth of cut :	Aa=25mm (Plane width 25mm), ar = 1~17mm
Machine :	Vertical milling machine (#2)

Table 4.3 shows a comparison of the general characteristics of conventional milling and climb milling.

Table 4.3 Comparison of upcut and downcut

Item	Conventional(upward cut)	Climb(downward cut)
Theoretical roughness of the machined surface	$Rz = \dfrac{fz^2}{8\left(\dfrac{DC}{2} + \dfrac{fz \cdot z}{\pi}\right)}$	$Rz = \dfrac{fz^2}{8\left(\dfrac{DC}{2} - \dfrac{fz \cdot z}{\pi}\right)}$
	fz: Feed amount per blade Dc: End mill blade outer diameter z: number of flute	
Cutting resistance	• Feed direction (feed component force): Larger than downcut. • Right angle direction (main component force): Smaller than down cut.	• Feed direction (feed component force): Larger than up cut. • Right angle direction (main component force): Smaller than up cut.
Tool life	• Since the cutting thickness starts from zero, the surface slides until the cutting edge bites into the work piece, so the flank wear progresses faster.	• Since cutting is started without causing the slip phenomenon, the progress of flank wear is slower than in upcut. • Since cutting starts from the surface of the work piece, the wear of the cutting edge increases when processing a hard surfaced work such as cast iron.
Feed rate and backlash	• The power consumption of table feed is large. • Backlash is removed naturally.	• Low power consumption for table feed. • Need to remove backlash.
Impact and vibration	• Cut thickness gradually increases from zero and suddenly becomes zero at the end, so impact force acts at this time.	• Because cutting starts from the maximum cutting thickness and gradually decreases, impact acts when the cutting edge bites into the work piece. • Because vibration is more likely to occur than upcut, mechanical rigidity is required.
Shape accuracy of machined surface	According to Figure 4.6.4	
Impact on processed surface	• Work-hardenable materials create a hardened layer • When the cutting edge comes off, the chip thickness becomes thicker, so burrs and edge chips are likely to occur at the edges of the machined surface.	• Less work-hardenable material

(3) Processing in which conventional milling and climb milling are mixed
Up to this point, we have explained the difference between conventional milling and climb milling, but in slotting as shown in Fig. 4.6.5, those milling methods are performed at the same time.

Cutting starts from the conventional milling, and from the center of the machined slot, it changes to the climb milling. Even if the cutting method is not slotting, both conventional milling and climb milling can occur when the radial cut exceeds the end mill radius (Fig. 4.6.6) or when the cutting area extends to both sides of the tool center (Fig. 4.6.7).

Figure 4.6.5 Cutting direction for Slotting (conventional and climb)

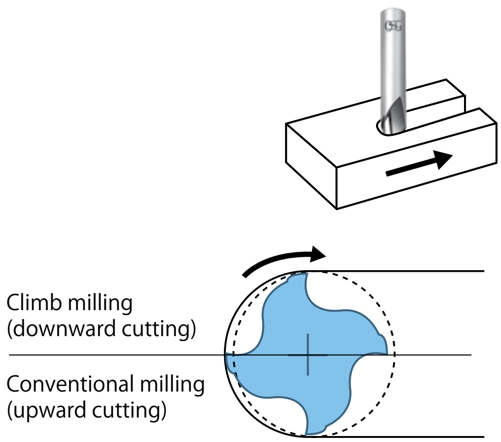


Figure 4.6.6 Mixing conventional and climb (radial depth> tool radius)

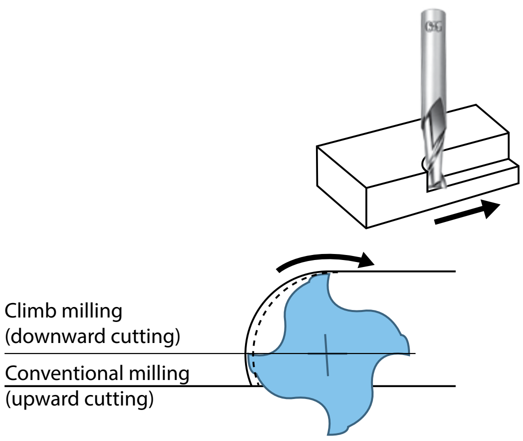
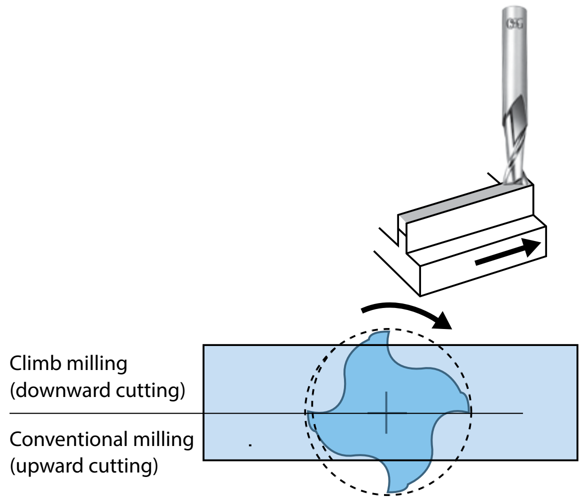
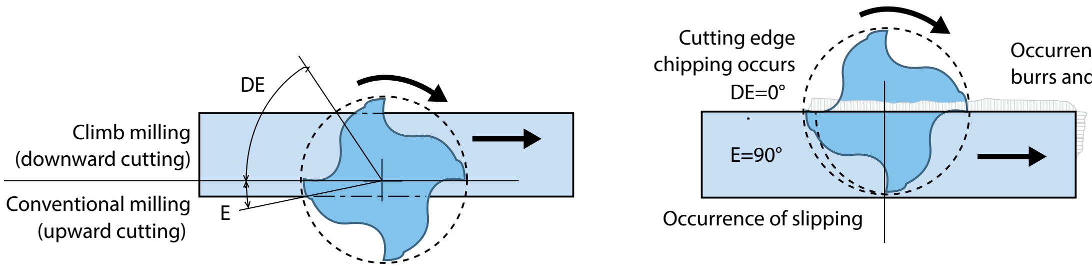


Figure 4.6.7 Cutting that straddles the conventional side and the climb side



In frontal cutting as shown in Fig. 4.6.8, the angle formed by the line connecting the center of the end mill and the contact point of the cutting edge and the feed direction is called the engagement angle.
On the other hand, the angle formed by the line connecting the center of the end mill and the exit point of the cutting edge in the feed direction is called the disengagement angle.
It will be a conventional-cut in the engagement angle area and a climb-cut in the disengage angle area.
Therefore, when the engagement angle is large, the slipping phenomenon at the time of biting is likely to occur.
If the disengagement angle is small, the main cutting will be performed by conventional-cut, the chip thickness at the cutting edge outlet will be thicker, and the chipping and burrs of the work piece will be more likely to occur.
When the disengage angle is 0 °, cutting ends when the chip thickness reaches a maximum, so chipping of the cutting edge is likely to occur.

Figure 4.6.8 Engagement angle and disengagement angle



E: Engage angle (bite angle)
DE: Disengage angle (exit angle)

	Small	Large
Engage angle E	—	• Upslip phenomenon occurs • Large rubbing wear
Disengage angle DE	• Chipping of cutting edge occurs (0º) • Ductile material causes burrs, and brittle materials cause burrs (negative).	—

4.7 Cutting fluid

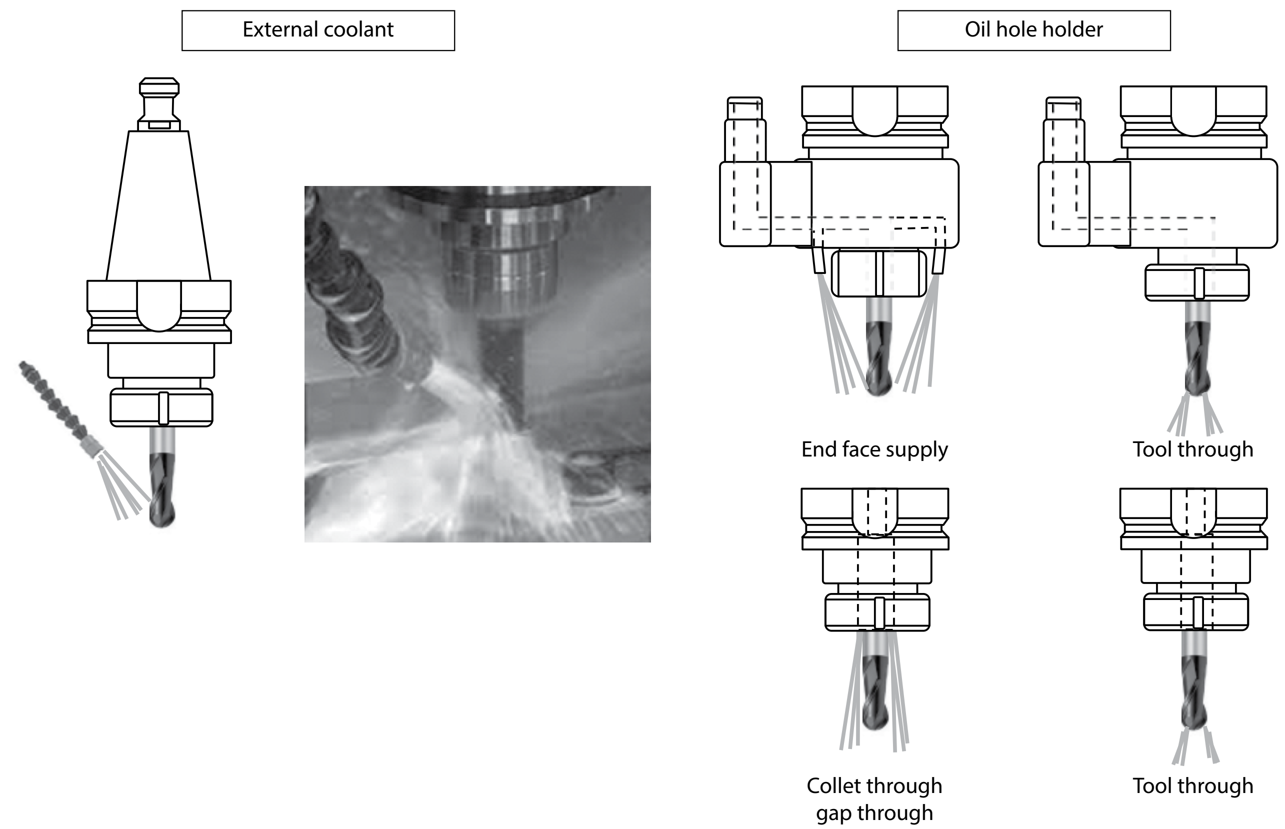
The main effects of cutting fluids are lubrication, cooling, and forced chip discharge.
The added lubrication from using a cutting fluid, or coolant, reduces the friction generated between the chip and the rake face of the cutting edge, and the newly machined surface and the flank surface of the cutting edge. As a result of the reduced friction, the tool life can be prolonged.

Furthermore, during the cutting process new chips, with almost no oxidation or other stains, are created and in a chemically active state. The rake face of the end mill, which is rubbed against chips, is also clean. Therefore, the chips and the rake face are always in a state where they are prone to adhesion.
The addition of cutting fluid also prevents adhesion by interposing between these chips and the rake face.

In addition, the cutting fluid also cools down the work area. The cooling effect reduces the thermal expansion of the work piece, prevents deterioration of dimensional accuracy, and lowers the temperature of the cutting edge of the end mill to prevent softening of the cutting edge and extend the tool life.
However, when using a cutting fluid with a large cooling effect, the cutting edge of the end mill will repeatedly generate heat and rapidly cool.
This may cause large thermal strain and cause thermal cracks within the tool. Lowering the cutting edge temperature may generate a built up cutting edge, which may shorten the tool life or worsen the machined surface roughness.
To solve these problems, there are methods such as MQL, minimum quantity lubrication, which has a large lubrication effect but a small cooling effect, and chip evacuation by air blow, which does not create aggressive heating-cooling cycles.

Primary concerns when using cutting fluid to evacuate chips include, the volume and pressure of the cutting fluid, but the direction in which the cutting fluid is applied and the method of supply are just as important.
Efficient chip removal is an integral part of the machining process. Chips which remain near the work area can scratch the machined surface, or even break the end mill.

Figure 4.7.1 Typical supply method of cutting fluid



5. Each part element and cutting characteristics of the end mill

5.1 Basic characteristics of helix flute

(1) Helix direction and characteristics

In the case of a right hand cut, right hand helix or left hand cut, left hand helix end mill, chips will flow from the end cut side to the shank side (Fig. 5.1.1). The cutting resistance (axial component force) acts to pull out the end mill in the direction of the work piece according to the screw principle.

Conversely, if the left hand cut mill is twisted to the right or the right hand cut mill is twisted to the left, chips will flow toward the end cut side. The cutting resistance acts in a direction that pushes the end mill toward the shank.

As can be seen from the cutting situation in Fig. 5.1.2, when using an end cut, the rake angle in the axial direction (axial direction) is negative (negative angle) in end mills with a right-handed left-helix or a left-handed right-helix. As a result, the chip thickness is larger, and it is generated discontinuously through bending, so smooth, consistent cutting is not possible.

Figure 5.1.1 Chip discharge direction based on the screw principle

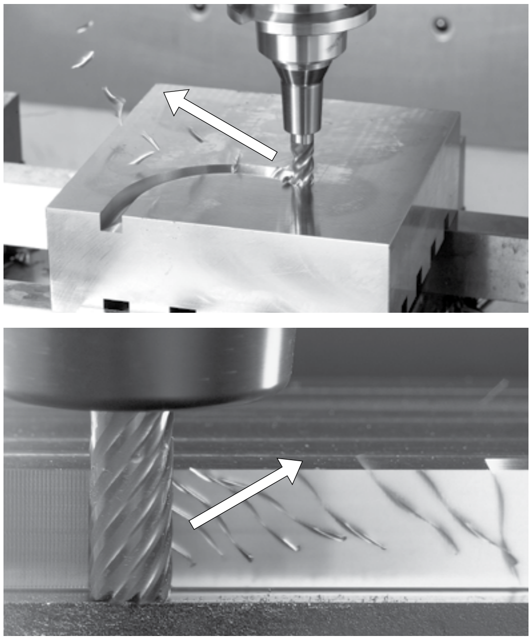
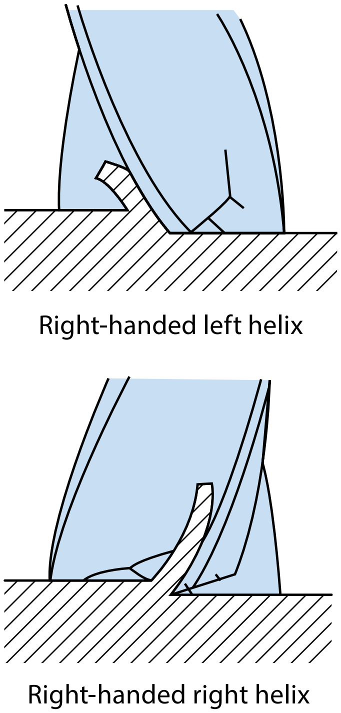


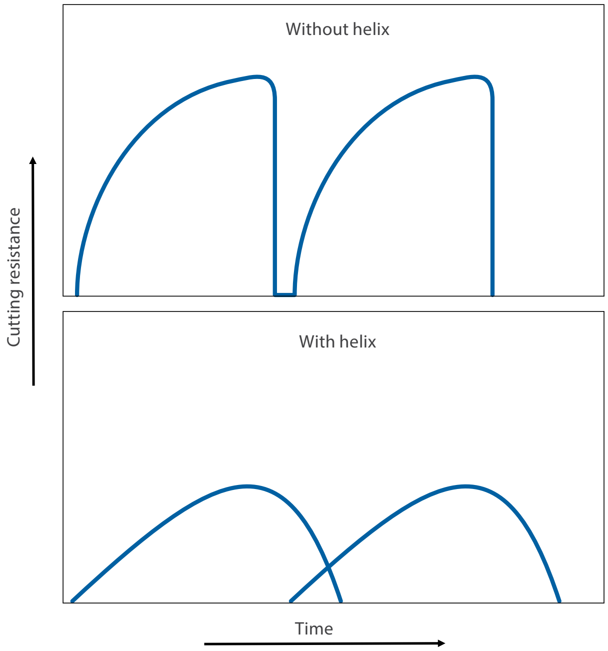
Figure 5.1.2 Helix direction and cutting



(2) Cutting resistance with a helix flute

Figure 5.1.3 shows the fluctuation of cutting resistance when cutting with a straight-edged end mill with untwisted flute and an end mill with twisted flute. With a straight helix end mill, the cutting becomes extremely intermittent cutting, and the amplitude of cutting resistance becomes large. In the case of a twisted flute, this fluctuation is small and smooth.

Figure 5.1.3 Fluctuation of cutting resistance



As shown in Fig. 5.1.4, the cutting resistance of a helix flute end mill is divided into the axial direction of the end mill and the component force in the feed direction. As a result, the cutting resistance in the feed direction is smaller than that of the straight flute, and the feed speed can be increased accordingly.

(3) Inclined cutting action by helix flute

A cutting method in which the cutting edge is tilted rather than perpendicular to the feed direction, such as end mill cutting with a helix flute, is called "inclined cutting". In inclined cutting, the effective rake angle (outer peripheral rake angle) has a large effect on the cutting edge angle (vertical rake angle) as shown in Fig. 5.1.5.

$$\tan \gamma = \frac{\tan \gamma_0}{\cos \lambda} \quad \cdots\cdots\cdots\cdots (5.1)$$

γ : Radial rake angle

γ0 : Vertical rake angle

λ : Helix angle

In addition, the same amount of cutting is performed with a long cutting edge, so the load can be distributed. Inclined cutting is always performed when using a tool with a helix.

(4) Problems with helix flute

As the torsional angle increases, the axial component force increases, making it easier for the end mill to come off the holder, and when cutting thin-walled work pieces, the force that lifts the work piece upward, causing chatter vibration (Fig. 5.1.6).
Additionally, the larger the helix angle, the sharper the corners and the lower the strength.
Therefore, the larger the helix angle, the more likely it is that the corners will be damaged (Fig. 5.1.7).
In addition, sharp corners tend to bite into the work piece during cutting, which may cause the work surface to swell depending on the work content.

Figure 5.1.4 Component force of cutting resistance

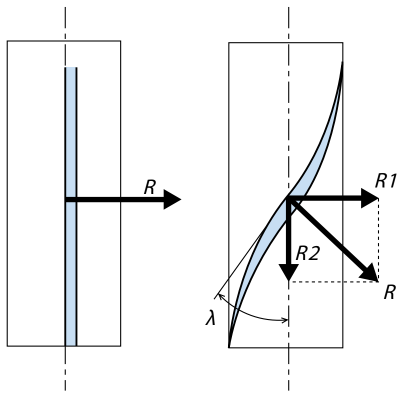


Figure 5.1.5 Effect of inclined cutting

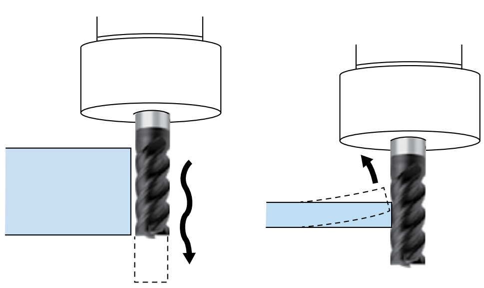


Figure 5.1.6 Problems with strong helix flute

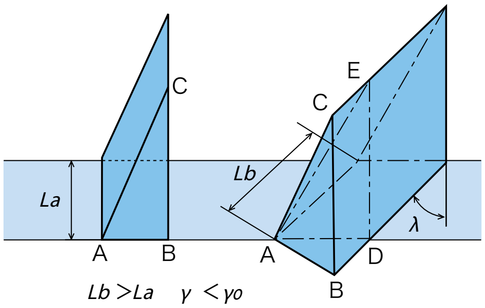
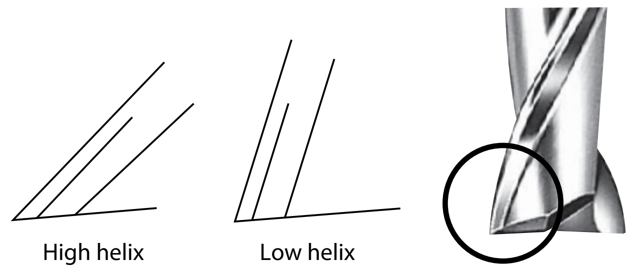


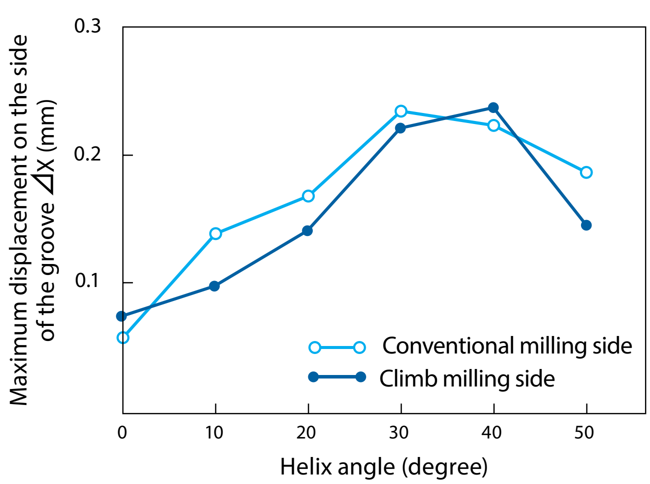
Figure 5.1.7 Helix angle and corner shape

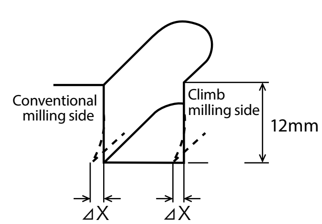


5.2 Helix angle and processing accuracy

Figure 5.2.1 shows the test results comparing the amount of displacement (the amount of sagging) when slotting is performed with end mills with different helix angles.
When slotting with a helix flute end mill, the sharp corners of the right hand cut, right hand helix end mill on the conventional milling side work freely on the work piece and bend the end mill at the start of cutting.
With the passage of time, the cutting position shifts from the corner to the shank. As the cutting position moves to the shank, the bending moment decreases and the amount of deflection also decreases.
This corner biting phenomenon on the conventional milling side is most noticeable when the relationship when milling with a large helix in deeper depths as shown in Fig. 5.2.2.

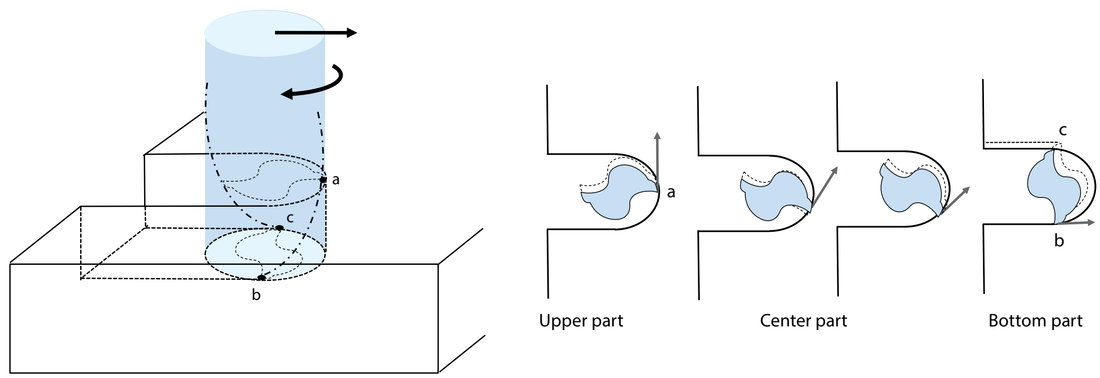
Figure 5.2.1 Helix angle and amount of tilt during slotting
(From the processing technology data file of the Institute of Technology, Machinery Promotion Association)





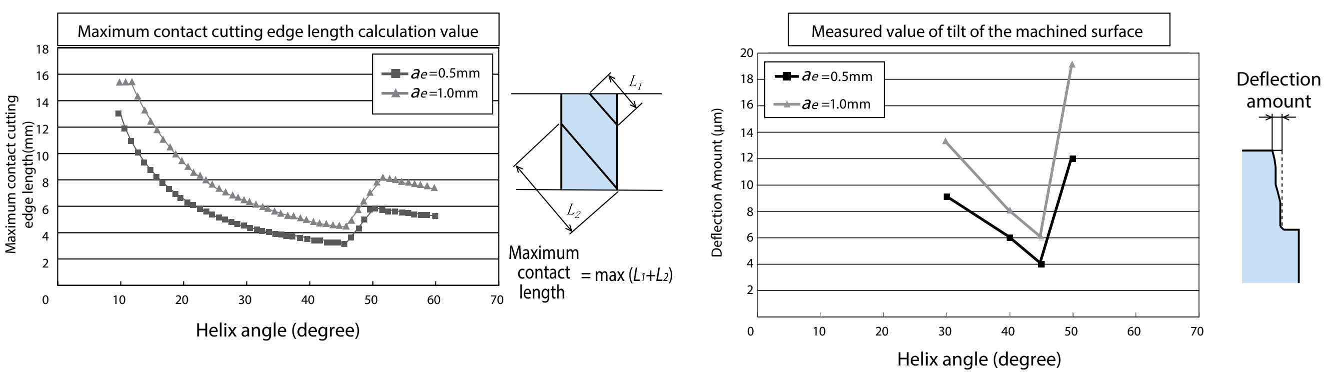
End mill : HSS φ12 2 flute
Material : SNC28 (HB269)
Cutting speed : 29 m/min
Feed rate : 50 mm/min
Depth of cut : Aa=12mm
Coolant : Oil

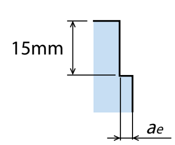
Figure 5.2.2 Tilt of slot



Here, the maximum contact cutting edge length indicates the maximum value (L1 + L2) of the cutting edge length at which the helix flute of the end mill contacts the work piece at the same time.
The length of the cutting edge in contact with the work piece changes over time as shown in Figure 5.2.4.
The maximum contact cutting edge length also changes depending on the change in the helix angle. Figure 5.2.3 shows the comparison between the calculated value of the maximum contact cutting edge length (maximum value of L1 + L2) and the value of the amount of tilt of the machined surface in the actual test. You can see that there is a strong correlation.

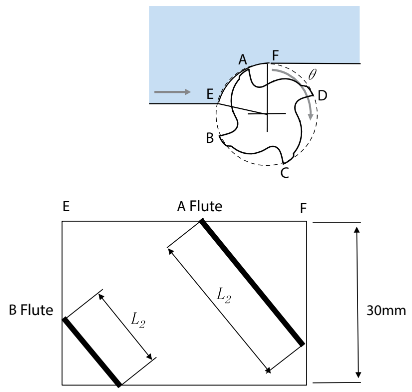
Figure 5.2.3 Helix angle and machining accuracy



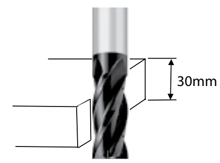


End mill :	Coated carbide φ10 2 flute
Material :	1049
Cutting speed :	80 m/min
Feed rate :	0.1mm/t
Depth of cut :	Aa=15mm, ar=0.5, 1mm
Cutting direction :	Climb milling
Coolant :	Air blow
Machine :	Vertical MC

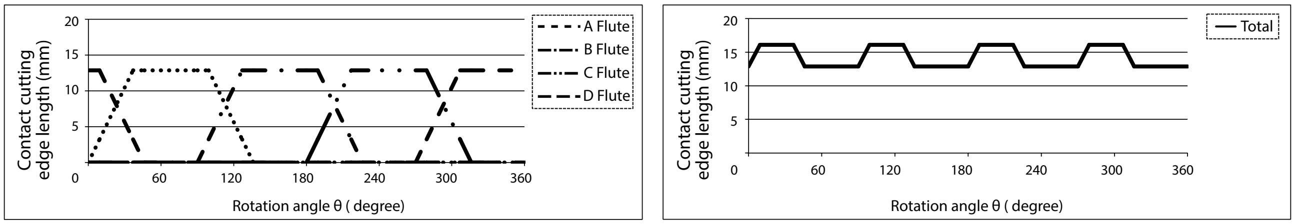
Figure 5.2.4 Simultaneous contact cutting edge length



Development view of the cutting part



End mill diameter : 20 mm
Helix angle : 30 degree (Right-helix)
Radial depth of cut : 2mm
Plain width : 30 mm



Changes in the length of the contact cutting edge cause fluctuations in cutting resistance, which causes swelling and tipping of the machined surface.
The larger the maximum value of this cutting edge length, the larger the cutting resistance. Also, if this amount of change is large, the fluctuation range of cutting resistance will be large.
The mechanism of cutting with the helix flute of an end mill is quite difficult, and it is difficult to explain all of this in a concise and clear manner, but here we have only briefly explained general phenomena. Table 5.1 shows a guideline for selecting the helix angle.

Table 5.1 Guideline for helix angle selection (based on standard helix)

Helix angle	Cutting resistance			Efficiency			Machined surface accuracy		
	Cutting torque	Bending resistance	Axial component force	Feed amount	Depth of cut	Chip evacuation	Roughness	Swell	Deflection of machine surface
15 (low)	△	△	◎	△	△	△	△	◎	◎ (slot)
30 (standard)	○	○	○	○	○	○	○	○	○
45 (high)	○	○	△	◎	○	◎	○	Depends on the depth of cut	
50 (high)	○	○	×	◎	◎	◎	○		

◎ Best ○ Good △ Not good × Bad

5.3 Effect of special helix flute

(1) End mill with both left and right helix flutes

Figure 5.3.1 shows an example of an end mill with both right-handed and left-handed helix flutes. This is an attempt to obtain the required machining quality by making good use of the characteristics of both the helix flutes described above. It is effective in preventing burrs from forming on both surfaces and preventing peeling of the surface layer when different materials are laminated on the surface layer.

Figure 5.3.2 shows end mills used for trimming carbon fiber resin and this laminate, which are special end mills used to prevent surface fiber peeling and fluffing (usually called routers). The right-helix main cutting edge is engraved with the left-helix secondary cutting edge.

Figure 5.3.2 Special torsion end mill with secondary cutting edge

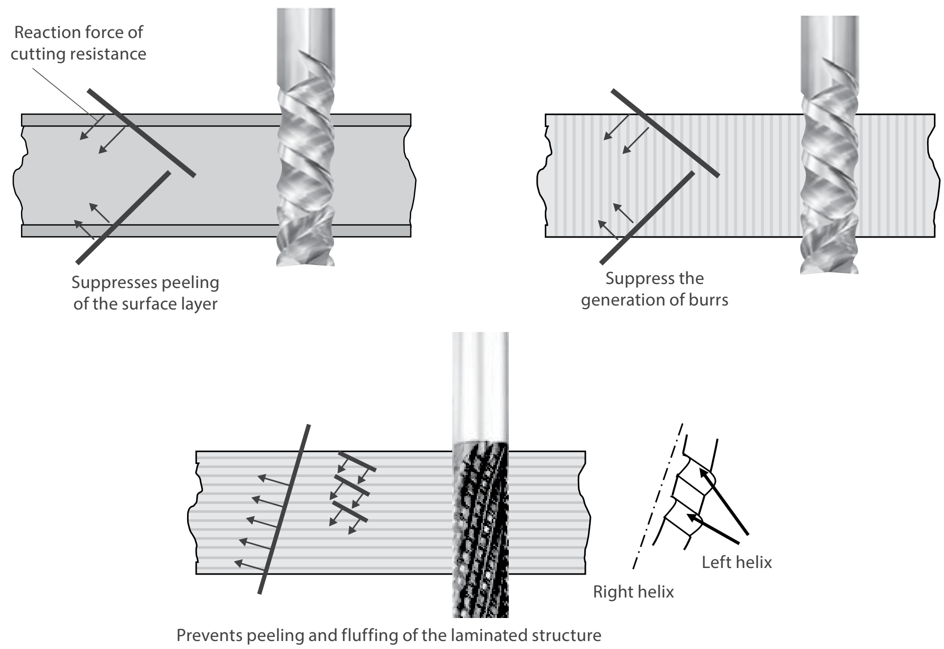


Figure 5.3.3 is an example of an unequal helix flute end mill (unequal lead end mill) with different helix angles of adjacent grooves.

The unequal helix flute end mill has the effect of suppressing self-excited vibration during cutting. At this time, when cutting is performed with an end mill as shown in Fig. 5.3.3, the same single flute is used as shown in Fig. 5.3.4. Even so, the phase of vibration reproduction will shift depending on the cutting position.

Figure 5.3.3 Unequal helix end mill

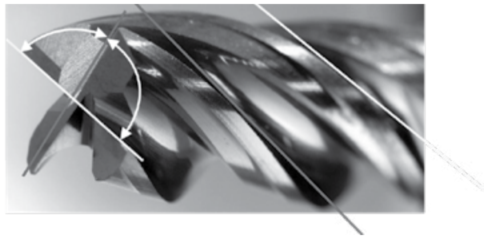
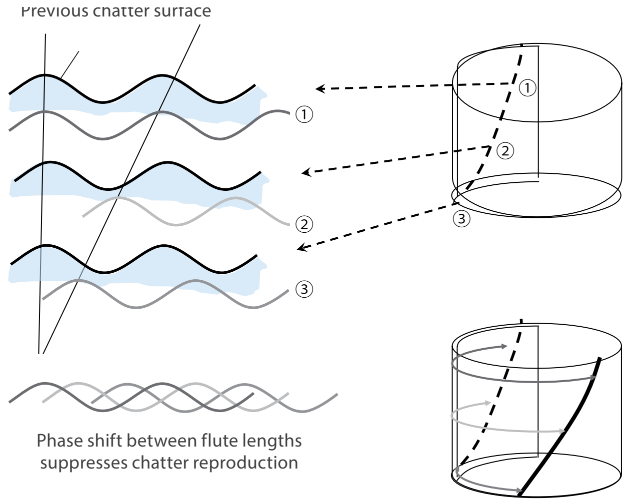
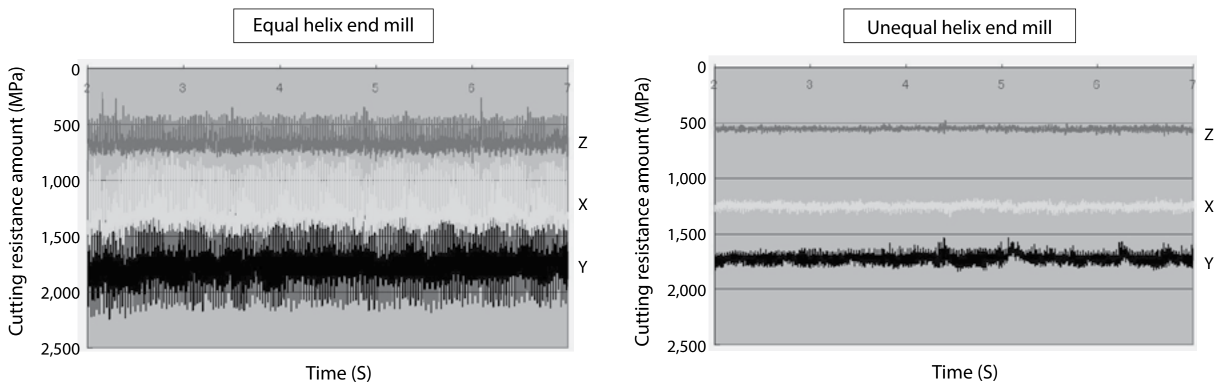


Figure 5.3.4 Effect of Unequal helix

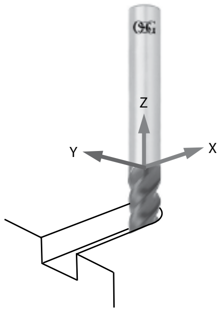


With an equal helix end mill, the same chatter vibration is reproduced over the entire cutting edge being cut. On the other hand, in the unequal-helix flute end mill, the next blade cuts while changing the phase difference of vibration with respect to the chattering surface of the previous cutting edge.
The unequal index flute also breaks the phase cycle of the regeneration chatter, but in this way there is no phase shift between the same cutting edges.
Figure 5.3.5 shows an actual vibration isolation example with an unequal-helix flute end mill. Since there is a difference in the helix angle and the vertical rake angle changes due to this, the cutting resistance value itself cannot be simply compared. However, it is clear that the amplitude of cutting resistance is small with the unequal helix flute and self-excited vibration is suppressed.

Figure 5.3.5 Example of unequal helix end mill processing



End mill : Coated carbide φ10 4 flute (equal helix, unequal helix)
Material : 304 stainless steel
Cutting speed : 70 m/min (2,228 rpm)
Feed rate : 0.05mm/t (446mm/min)
Depth of cut : Aa=10mm (slotting)
Coolant : Water soluble
Machine : Vertical MC (BT40)



In this way, the unequal helix flute has an anti-vibration effect that suppresses self-excited vibration, but it also has the disadvantage that the chip shape changes due to the difference in helix and the feed amount per tooth (Fig. 5.3.6). Therefore, it is difficult to use if the machining accuracy such as the squareness of the machined surface is very strict. Also, as the flute length becomes longer, the difference in helix must be reduced. This can be addressed in the manner shown in Figure 5.3.7, but there are also special cutting edge end mills that solve these problems (Figure 5.3.8).

In this end mill, the anti-vibration effect can be obtained by incorporating an unequal index and unequal helix, and the same width can be cut with a longer cutting edge than the normal cutting edge end mill, so the load is dispersed. In addition, the occurrence of burrs on ductile materials can be suppressed by changing the direction of cutting force (direction of cutting resistance) (Fig. 5.3.9).

Figure 5.3.6 Unequal helix flute and feed rate per tooth

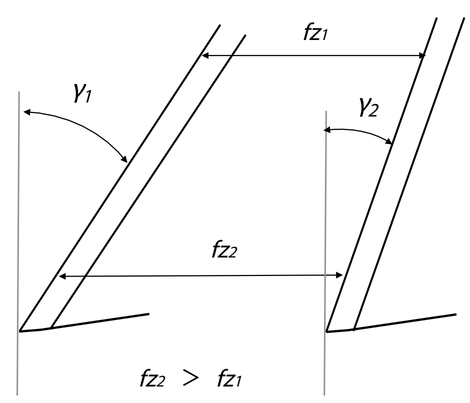


Figure 5.3.7 Flute length limit of unequal helix flute and example solution

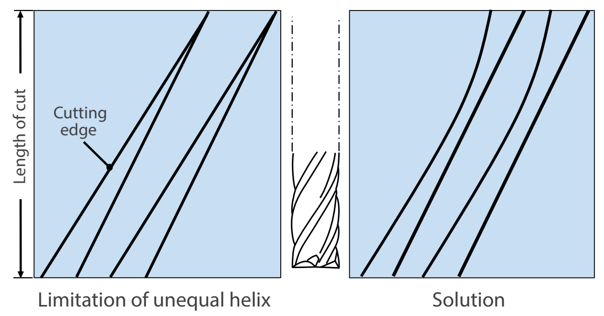


Figure 5.3.8 End mill with a wavy twisting flute that conforms to a sine wave

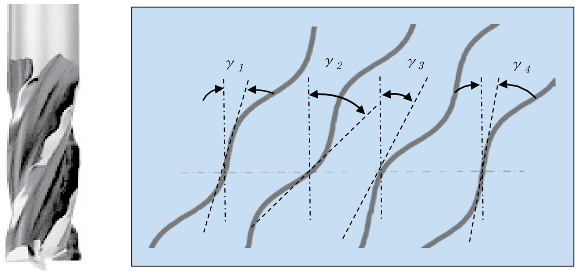
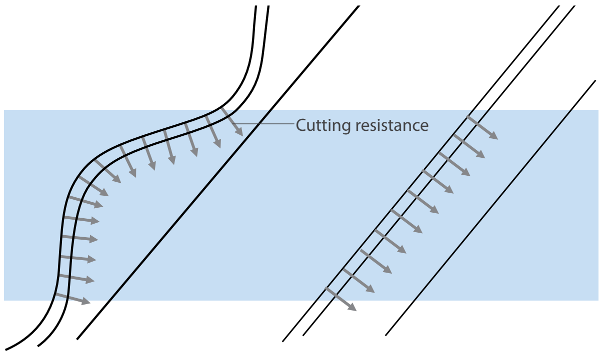


Figure 5.3.9 Characteristics of wavy twisted flute



5.4 Number of flutes and cutting characteristics

We have already explained the relationship between the number of flutes and the tip pocket, but we must not forget the following as the cutting characteristics due to the difference in the number of flutes:
As the number of flutes increases, the number of cutting edges that come into contact with the machined surface at the same time increases as shown in Fig. 5.4.1. At this time, the maximum value of the cutting edge length that is in contact with the work piece at the same time fluctuates as described above.
Figure 5.4.2 shows the maximum contact cutting edge length when the number of flutes and the helix angle change. Increasing the maximum contact cutting edge length leads to an increase in cutting resistance.

Figure 5.4.1 Increase in cutting edge contact points due to increase in the number of flutes

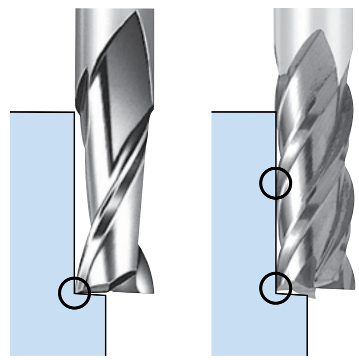


Fig. 5.4.2 Number of flutes, helix angle and maximum contact cutting edge length

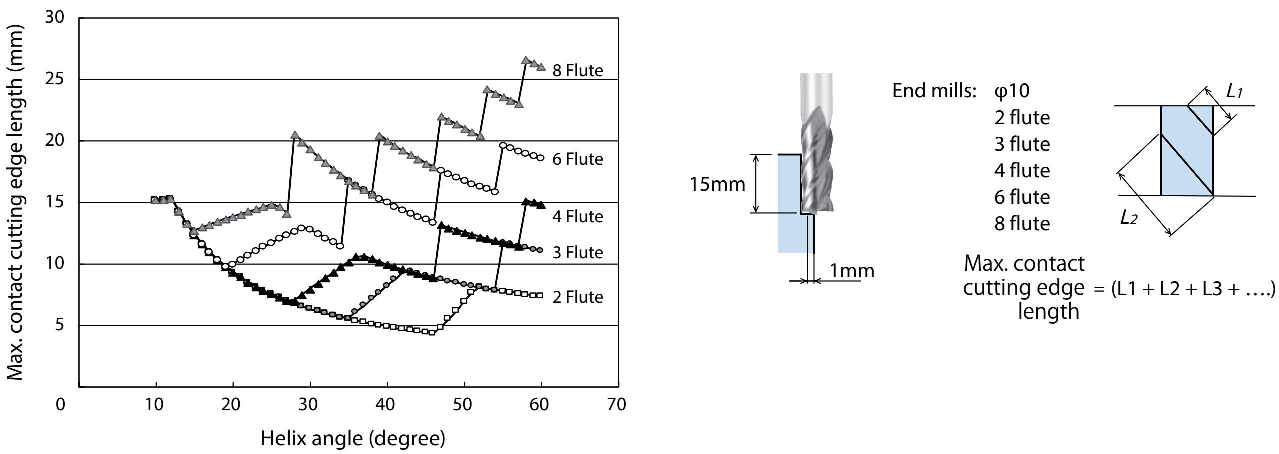


Figure 5.4.3 shows the effect of the difference in the number of flutes in slotting. When the end mill causes the largest deflection due to cutting resistance, if the cutting edge is cutting the part that finally remains as the machined surface like a 4-flute end mill, the machined surface will collapse. (Table 5.2).

Figure 5.4.3 4-Flute Problem in Slotting

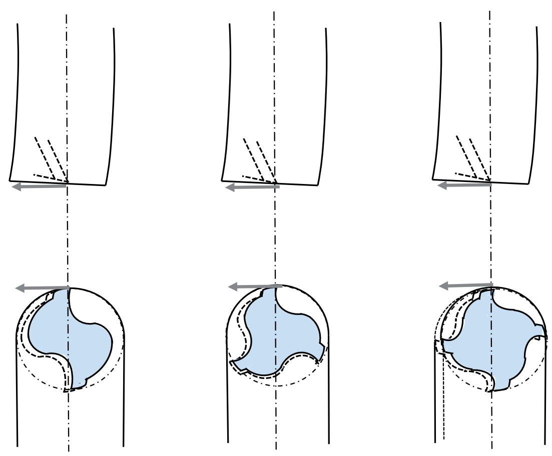


Table 5.2 Guideline for selecting the number of end mill flues

Selection conditions		# of flute 2 flute	3 flute	4 flute	6 flute
Strength of end mill	Torsional rigidity	△	○	○	◎
	Flexural rigidity	△	○	○	◎
	Breaking strength	△	○	○	◎
Machined surface accuracy	Roughness	○	○	◎	◎
	Swell	○	○	◎	◎
	Deflection of Machined surface	○	○	◎	◎
Tool life	Abrasion life (Constant feed amount per blade)	○	○	◎	◎
	Broken life (Constant processing efficiency)	○	○	◎	◎
Chip evacuation	Chip clogging (Accommodation capacity)	◎	◎	△	△
	Chip evacuation	◎	◎	△	△
Ease	Ease of grinding	◎	△	○	△
	Grinding accuracy (Variation for each cutting edge)	◎	△	○	△

Selection conditions		# of flute 2 flute	3 flute	4 flute	6 flute
Slotting	Chip evacuation	◎	◎	△	-
	Slot width expansion	◎	◎	△	-
	Deflection of machined surface	◎	◎	△	-
Side milling	Machined surface accuracy	△	△	○	◎
	Chatter vibration	◎	◎	○	○
Drilling	Chip evacuation	◎	◎	△	-
	Hole expansion	○	◎	△	-
	Chatter vibration	○	◎	△	-
Work Material	Non-ferrous material	◎	◎	○	△
	Cast iron	○	○	◎	◎
	Alloy steel	○	○	◎	◎
	High hardened steel	○	○	◎	◎

◎ Best ○ Good △ Not good

5.5 Outer flute shape and cutting characteristics

Among the end mills, there is a roughing end mill with a wavy outer flute as shown in Fig. 5.5.1. As the name implies, this is an end mill dedicated to rough cutting.
With a roughing flute (wavy outer peripheral flute), cutting is performed at the top of the serrated edges, so chips are cut into smaller pieces and become finer, improving the storage capacity in the chip pocket. It also improves the bite to the work material and reduces the rubbing phenomenon of the cutting edge (Fig. 5.5.2).
Furthermore, as can be seen in Fig. 5.5.3, the length of the simultaneous cutting edge becomes shorter, and the correlation between the wavy outer peripheral flute and the rake angle causes an unequal twisting action as shown in Fig. 5.5.4, resulting in suppression of self-excited vibration.
In addition, since the wavy outer peripheral flute increases the surface area of the cutting edge, the efficiency of dissipating cutting heat increases, and the valleys help the penetration of the cutting fluid, promoting the cooling and lubricating actions during cutting.

Figure 5.5.1 Roughing end mill

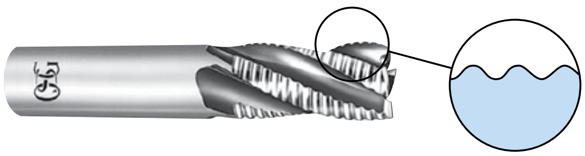


Figure 5.5.2 Chips of roughing end mill

Figure 5.5.3 Cutting mechanism of roughing end mill

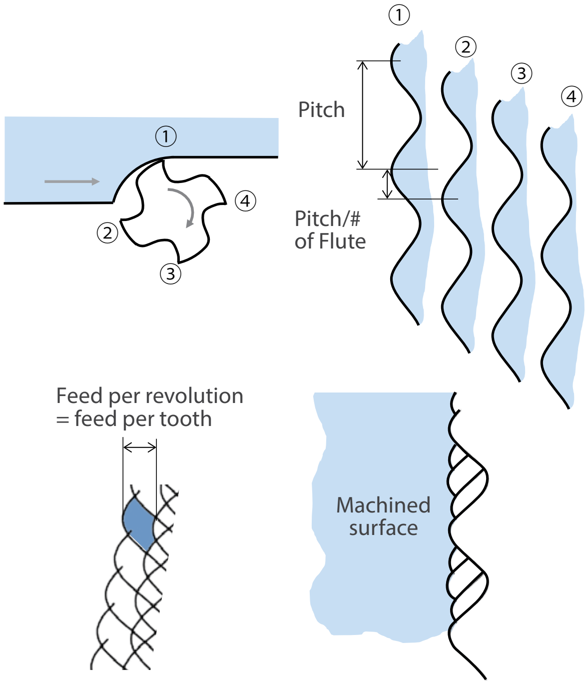
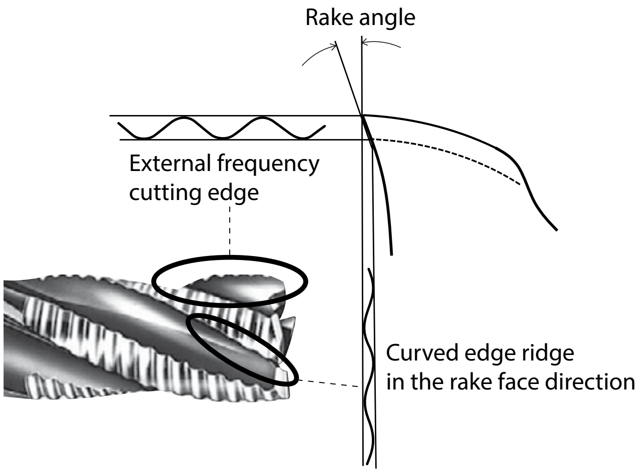


Figure 5.5.4 Unequal twisting action of wavy cutting edge



Due to the synergistic effect described above, the roughing end mill can reduce the cutting resistance and enable heavy cutting with a large cutting depth.

Figure 5.5.5 shows the results of comparative measurement of cutting power between a normal end mill and a roughing end mill. It can be seen that the cutting power of the roughing end mill is usually 15 to 30% lower than that of the end mill.

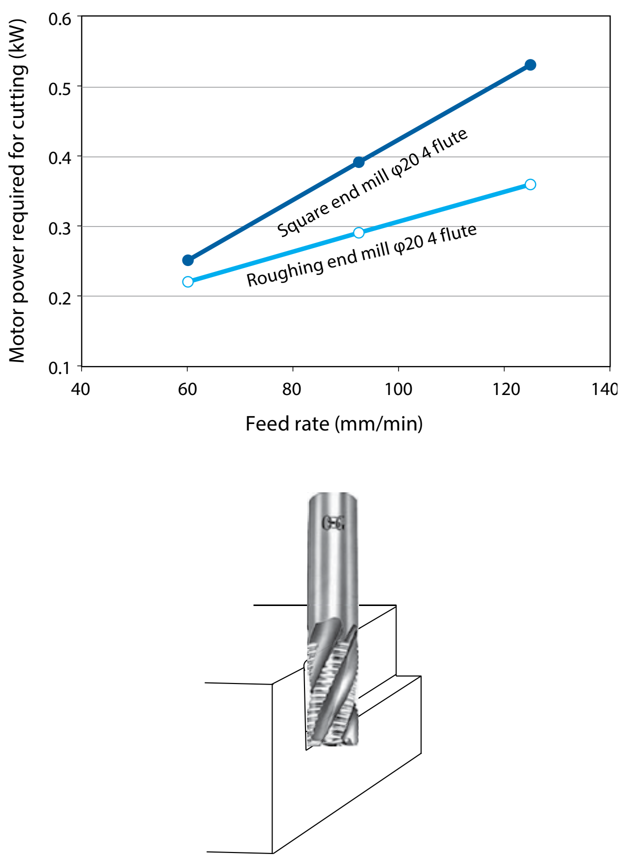
Figure 5.5.6 shows an end mill with a thin groove called a nick on the outer peripheral flute. This nick also has the same features as the wavy outer peripheral flute, and has the effect of dividing chips into small pieces, preventing chatter vibration, and reducing cutting resistance.

As you can see from the shape of the wavy outer peripheral flute, the roughness of the machined surface is about 100 µm Rz. On the other hand, if it is an end mill with a nick, it can be set to about 20 to 50 µm Rz as shown in Fig. 5.5.7.

Figure 5.5.8 shows a roughing end mill with a replaceable cutting edge.

The tip arrangement is set (stepped) to produce the same effect as the nicked perimeter flute, or the effect of unequal twisting.

Figure 5.5.5 Reduction of cutting power by roughing end mill



End mill : HSS end millφ20 4 flute (normal, roughing)
Material : 1049
Cutting speed : 25 m/min (403 rpm)
Depth of cut : Aa=30mm, ae=5mm
Coolant : Oil
Machine : Vertical MC (BT50)

Figure 5.5.6 End mill with nick

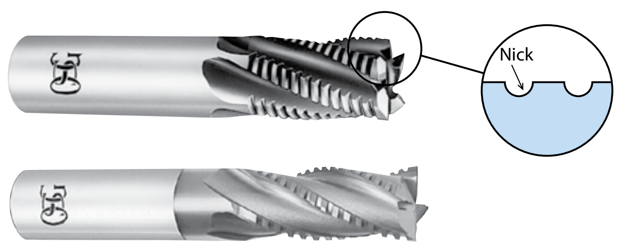


Figure 5.5.7 Cutting mechanism of roughing end mill

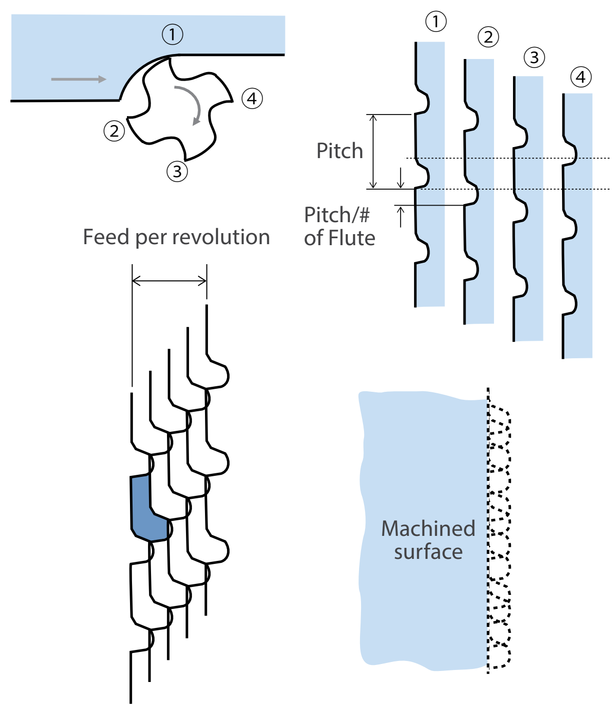
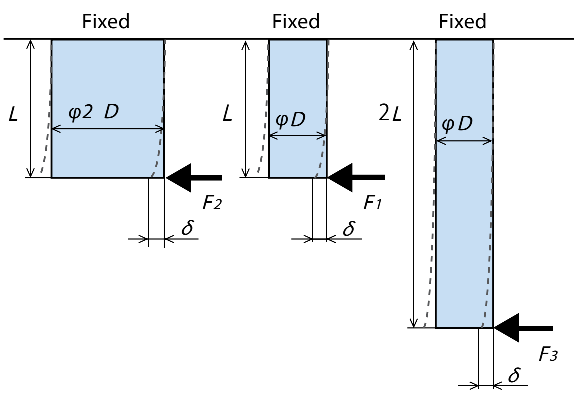


Figure 5.5.8 Replaceable cutting edge roughing end mill

5.6 Impact of aspect ratio (L / D)

In a round bar with a fixed upper end as shown in Fig. 5.6.1, the following relationship generally holds.

Figure 5.6.1 Flexural strength of round bar



$$\delta = \frac{F \cdot L^3}{3 \cdot E \cdot I} \cdots\cdots\cdots\cdots (5.3)$$

δ : Deflection amount
F : Force applied in the bending direction (F_1, F_2, F_3)
L : Round bar length
E : Young's modulus
I : Moment of inertia of area

That is, it is replaced by the following formula.

$$F = \frac{3 \cdot E \cdot I \cdot \delta}{L^3} \cdots\cdots\cdots (5.4)$$

The moment of inertia of area is calculated by the following formula.

$$I = \frac{\pi \cdot D^4}{64} \cdots\cdots\cdots (5.5)$$

D : Round bar diameter

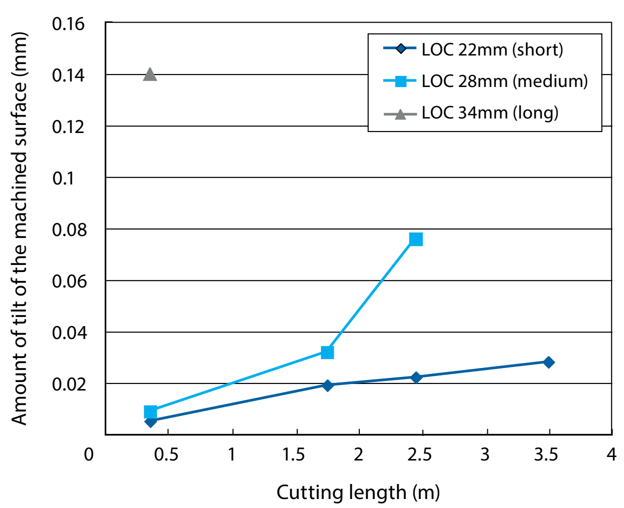
From equations (5.4) and (5.5), it can be seen that F is proportional to D to the 4th power and inversely proportional to L to the 3rd power. Therefore, the following equation holds.

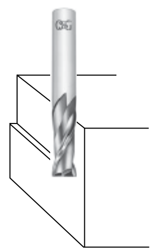
$$F_2 = \frac{1}{2^3} F_1 = \frac{F_1}{8} \cdots\cdots\cdots (5.6)$$

$$F_3 = 2^4 F_1 \quad = 16 F_1 \cdots\cdots\cdots (5.7)$$

In other words, a round bar with twice the length (2L) causes, δ, deflection with only 1/8 of the force of a round bar with a length of L. Therefore, if the flute length (protruding length) of the end mill is doubled, the rigidity will be reduced to 1/8. Also, if the diameter D of the round bar is doubled to 2D, the deflection of δ will not occur unless a force as large as 16 times is applied.
In other words, if the outer diameter of the end mill is doubled, the rigidity will be 16 times higher.
The ratio between the flute length (protruding length) and the outer diameter is referred to as "aspect ratio" or "L / D (Elbaidi)".
Here, the explanation is based on the simple model (beam strength), but in actual machining, it is necessary to consider the amount of protrusion including the holder from the end face of the spindle.
Figure 5.6.2 shows the results of measuring the flute length and machining accuracy (the amount of sagging on the machined surface). The longer the flute length, the greater the amount of deflection of the end mill and the worse the machining accuracy.

Figure 5.6.2 Flute length and machining accuracy

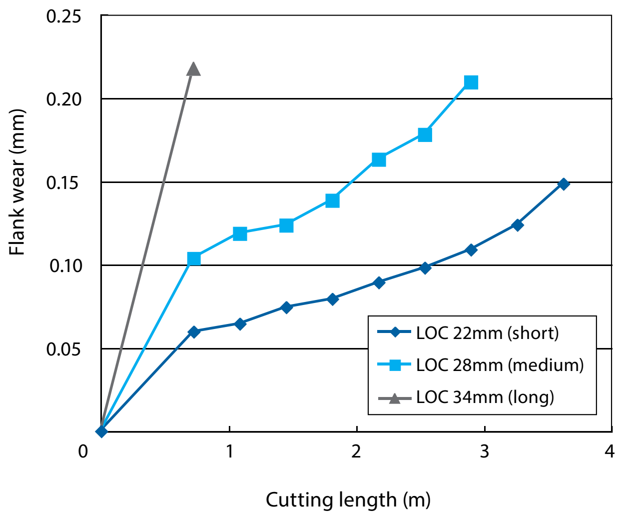


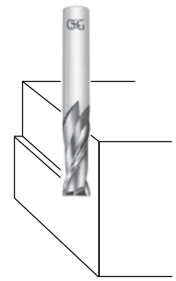


End mill : Carbide end mill φ10 2 flute (LOC 22mm, 28mm, 34mm)
Material : H13 (40HRC)
Cutting speed : 30 m/min
Feed rate : 0.02mm/t
Depth of cut : Aa=10mm, ae=0.5mm
Cutting direction : Conventional milling
Coolant : Oil
Machine : Vertical MC

Not only that, the longer the flute length, as shown in Figure 5.6.3, the faster the cutting edge wears.
When the flute length is doubled, the rigidity is reduced to 1/8, but as can be seen from the test results in Fig. 5.6.4, the tool life is reduced to 1/10 or less.

Figure 5.6.3 Transition of flute length and flank wear

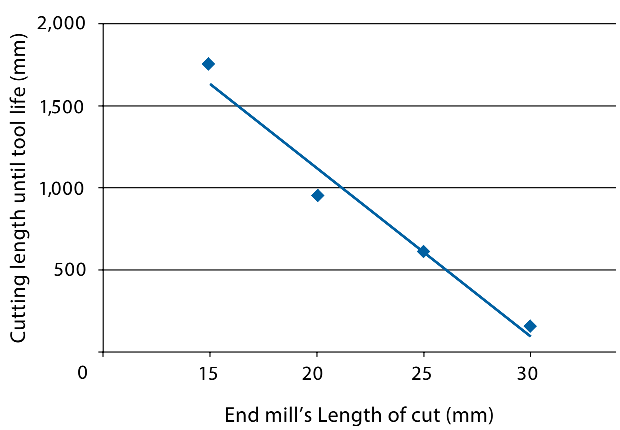




End mill : Carbide end millφ10 2 flute (LOC 22mm, 28mm, 34mm)
Material : H13 (40HRC)
Cutting speed : 30 m/min
Feed rate : 0.02mm/t
Depth of cut : Aa=10mm, ae=0.5mm
Cutting direction : Conventional milling
Coolant : Oil
Machine : Vertical MC

Figure 5.6.5 shows the cutting adaptation area for each tool protrusion length in a solid ball end mill made of cemented carbide.
The greater the overhang length, the greater the bending moment generated during cutting. This promotes the occurrence of chatter vibration, which narrows the cutting adaptation area.
In this test, it can be seen that the cutting adaptation area becomes very narrow when L / D = 8.

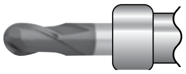
Figure 5.6.4 Flute length and tool life



End mill : HSS end mill φ10 2 flute (LOC 15mm, 20mm, 25mm, 30mm)
Material : H13 (32~36HRC)
Cutting method : Slotting
Cutting speed : 10 m/min (340min-1)
Feed rate : 0.037mm/t (25mm/min)
Depth of cut : Aa=5mm
Coolant : Oil
Machine : Vertical milling machine

Figure 5.6.5 Overhang length and cutting area

Cutting area at L / D = 4 (protruding length 40 mm)



RPM (min^{-1})	DOC (mm)	Cutting status (cutting sound) ○ : Small △: Medium ×: Large, chattering							
3,350	3 (0.3D)	○	○	○	○	○	○	○	○
	2 (0.2D)	○	○	○	○	○	○	○	○
	1 (0.1D)	○	○	○	○	○	○	○	○
7,000	3 (0.3D)	○	○	○	△	△	△	△	△
	2 (0.2D)	○	○	○	○	○	○	○	○
	1 (0.1D)	○	○	○	○	○	○	○	○
Feed /tooth (mm)		0.025	0.05	0.075	0.1	0.125	0.15	0.175	0.2

Cutting area at L / D = 6 (protruding length 60 mm)

RPM (min^{-1})	DOC (mm)	Cutting status (cutting sound) ○ : Small △: Medium ×: Large, chattering							
3,350	3 (0.3D)	○	○	○	○	○	○	○	○
	2 (0.2D)	○	○	○	○	○	○	○	○
	1 (0.1D)	○	○	○	○	○	○	○	○
7,000	3 (0.3D)	×	×	○	△	△	△	△	△
	2 (0.2D)	×	×	○	○	○	○	○	○
	1 (0.1D)	×	○	○	○	○	○	○	○
Feed /tooth (mm)		0.025	0.05	0.075	0.1	0.125	0.15	0.175	0.2

Cutting area at L / D = 8 (protruding length 80 mm)

RPM (min^{-1})	DOC (mm)	Cutting status (cutting sound) ○ : Small △: Medium ×: Large, chattering							
3,350	3 (0.3D)	×	×	×	×	×	×	×	×
	2 (0.2D)	×	○	○	○	○	○	○	○
	1 (0.1D)	○	○	○	○	○	○	○	○
7,000	3 (0.3D)	×	×	×	×	×	×	×	×
	2 (0.2D)	×	×	△	Broken				
	1 (0.1D)	×	×	△	○	○	△	△	△
Feed /tooth (mm)		0.025	0.05	0.075	0.1	0.125	0.15	0.175	0.2

End mill : Coated carbide ball nose end mill φ10 (R5) 2 flute (L/D =4,6,8)
Material : NAK55 (40HRC)
Coolant : Air blow
Machine : Vertical MC (BT40)

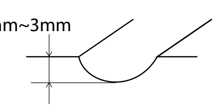
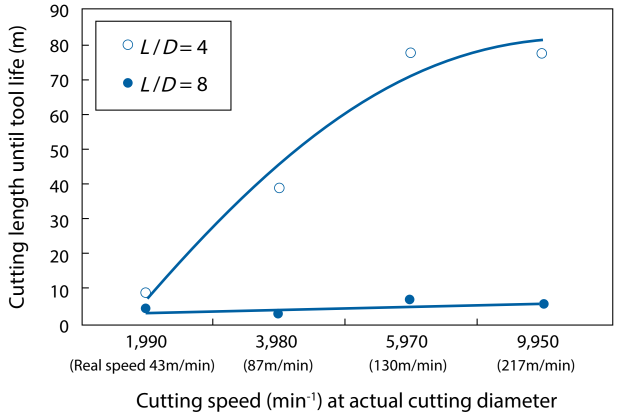


Figure 5.6.6 Projection length and tool life at each cutting speed



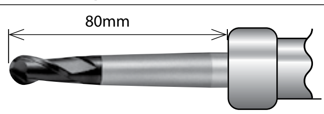
End mill : Coated carbide ball nose end mill φ8 (R4) 2 flute (L/D=4, 8)
Material : H13 (50HRC)
Cutting speed : 1,990 ~ 9,950 min-1
Feed rate : 0.075mm/t
Depth of cut : Aa=2mm, Pf=0.8mm
Cutting direction : Climb milling
Coolant : Air blow
Machine : Vertical MC (BT40)

We have already explained that there are areas where the progress of cutting edge wear slows down as the cutting speed increases. Figure 5.6.6 shows the relationship between the cutting speed and the tool life when the aspect ratio (L / D) increases (L / D = 8).
As can be seen from this result, it is difficult to utilize the high-speed milling method in an environment where the aspect ratio (L / D) is large and the bending moment increases.
In order to reduce the bending moment while the outer diameter and protrusion length of the end mill are restricted, the radial component force of the cutting resistance and the feed component force should be reduced, or the tool rigidity should be increased (the Young's modulus should be increased). (Or increase the tool cross-sectional area within the constrained tool diameter).

If a large protrusion length is required, but the flute length may be short, and even if the neck is tapered, there is no interference with the work piece or jig, use a taper neck end mill. As a result, the decrease in tool rigidity can be minimized. Such measures are very effective in expanding the cutting application area and extending the tool life. Figure 5.6.7 shows the effectiveness of the tapered neck shape in a carbide solid ball end mill. It can be seen that the cutting adaptation area has expanded compared to Figure 5.6.5.

Figure 5.6.7 Effect of taper neck

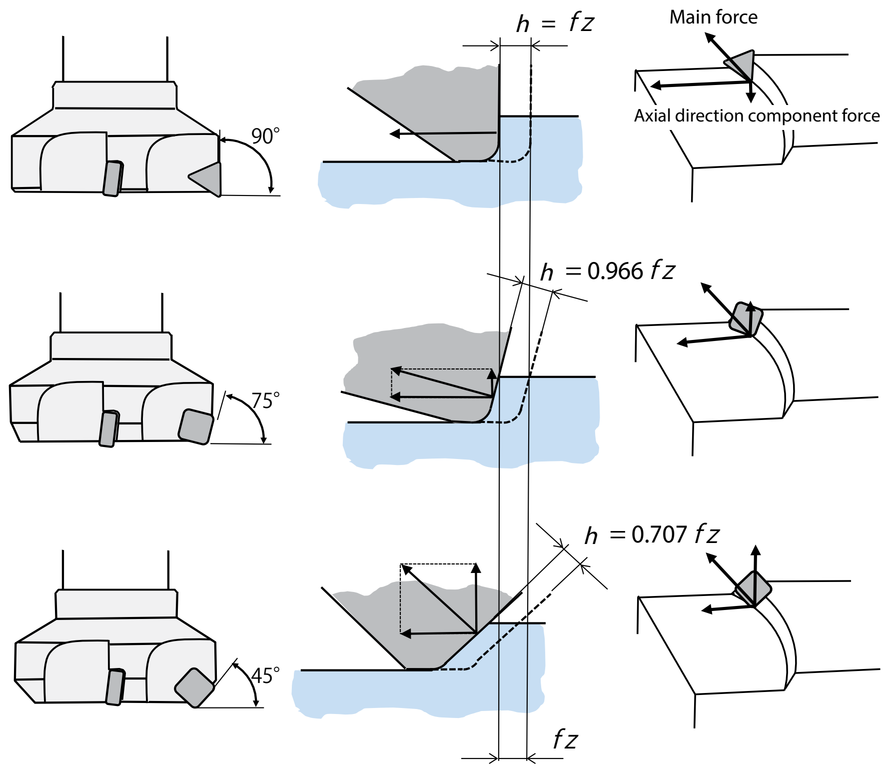
Cutting area with a protruding length of 80 mm on a taper neck end mill



RPM (min-1)	DOC (mm)	Cutting status (cutting sound) ○: Small △: Medium ×: Large, chattering							
3,350	3 (0.3D)	○	○	○	○	○	○	○	○
	2 (0.2D)	○	○	○	○	○	○	○	○
	1 (0.1D)	○	○	○	○	○	○	○	○
7,000	3 (0.3D)	×	×	×	×	×	×	×	×
	2 (0.2D)	×	○	○	△	△	△	△	△
	1 (0.1D)	×	○	○	○	△	△	△	△
Feed /tooth (mm)		0.025	0.05	0.075	0.1	0.125	0.15	0.175	0.2

End mill : Coated carbide taper neck ball nose end mill φ10 (R5) 2 flute, shank φ12
Material : P21 (40HRC)
Coolant : Air blow
Machine : Vertical MC (BT40)

Figure 5.7.1 Cutting angle, cutting thickness and cutting resistance



5.7 End cut shape and cutting characteristics

Figure 5.7.1 shows the relationship between the cutting angle and the cutting thickness in frontal cutting. The angle formed by the machined surface and the cutting edge are called the cutting angle.
When the cutting angle is reduced, the cutting thickness is reduced and the cutting resistance per unit cutting edge length is reduced. This tends to extend the tool life.
If the depth of cut is reduced, the feeding force component of the cutting resistance will be smaller, but the axial component force will be larger. In other words, a force acts on the workpiece in the direction of pressing as a cutting force (Table 5.3).

Table 5.3 Cutting angle and cutting characteristics

Cutting angle	90°	75°	45°
Chip shape	Thick and narrow	Thinner than 90°	Thin and wide
Cutting resistance	Back component force is in the negative direction	Feed component force is smaller than 90º, back component force is smaller than 45 º	Back component force gets big
Cutting status	No force works in the direction of pressing the work piece. Strain is unlikely to occur in thin-walled structures. Chips are likely to occur when cutting cast iron.	The force acts in the direction of pressing the work piece, but it is small. Less likely to cause distortion in thin-walled structures.	A force acts in the direction of pressing the work piece. Strain is likely to occur in thin-walled structures. It is unlikely that chipping will occur when cutting cast iron.

The same can be said when comparing the square type and the radius type. When cutting with the same cutting depth and the same feed amount as shown in Fig. 5.7.2, it can be seen that the cutting thickness is thinner for the radius type (Fig. 5.7.3).
Furthermore, if a rake angle in the axial direction is set for the R part of this radius type, or if it has a helix flute specification, not only the chip thickness is reduced by the action of the helix flute, but also the cutting resistance is dispersed, and the feed amount per tooth is increased (Fig. 5.7.4).

However, since these cutting edges have a long simultaneous contact cutting edge length with the machined surface, if this exceeds the reduction effect of the cutting resistance dispersion described above, chattering will be rather induced.

Figure 5.7.2 Cut thickness of square type and radius type

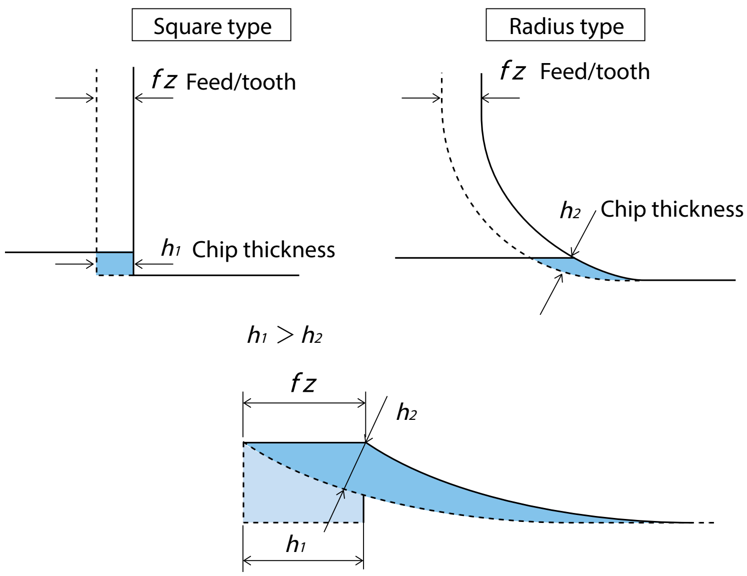


Figure 5.7.3 Example of radius end mill

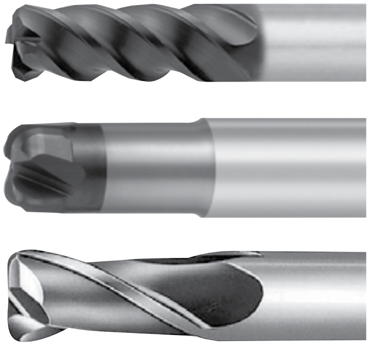


Figure 5.7.4 Twist angle of corner R

6 End mill regrinding

6.1 When and how to regrind

(1) Timing of regrinding

The progress of cutting edge wear generally follows the process shown in Figure 6.1.1. When initial wear occurs, steady wear that shows stable progress continues, and eventually it progresses to the area of accelerated wear where the progress speed accelerates.

Therefore, the time for regrinding should be performed before accelerated wear occurs. Table 6.1 shows the approximate regrinding time in terms of the amount of wear on the flank surface.

Figure 6.1.1 General wear progress

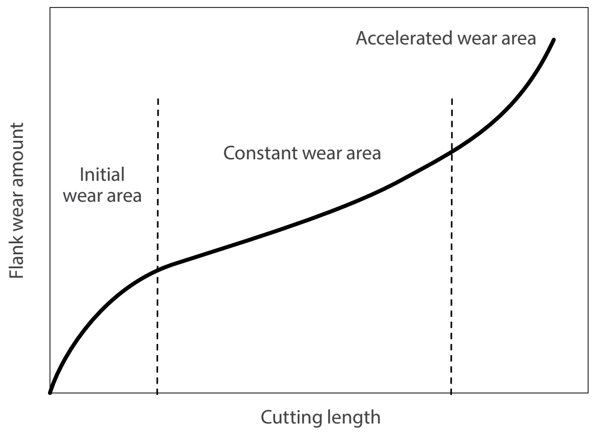


Table 6.1 Estimated regrinding time based on the amount of wear on the flank surface

Type of processing	End mill diameter	Flank wear amount
Roughing	10~12	0.1 ~0.2
	12~30	0.25~0.45
	30~	0.3 ~0.5
Finishing	10~12	0.1 ~0.15
	12~30	0.15~0.25
	30~	0.2 ~0.3

(2) Re-grinding part

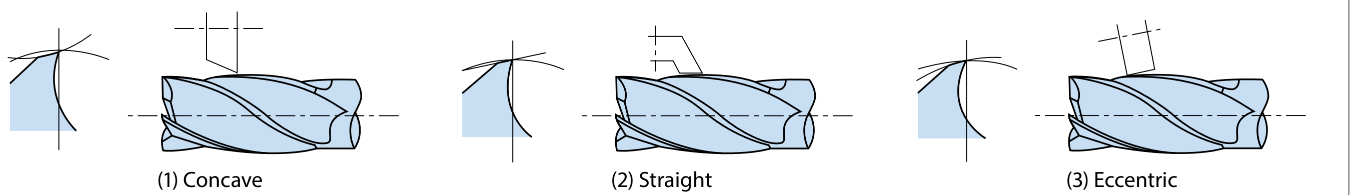
In general, regrinding of end mills is mainly performed on the outer peripheral flank surface, but for end mills for keyway machining where changes in outer diameter dimensions are not allowed, the flute length is shortened and the end cut is reground. Similarly for the ball end mill, the flute length is shortened and the ball part is reattached. Roughing end mills with wavy outer cutting edge regrind the rake face of the flute.

(3) Re-grinding the outer peripheral flank

Grinding of the outer peripheral flank surface is performed by a forced lead method (a method in which the blade is attached along the helix of the flute) using a CNC tool grinder. It is possible to grind by following the helix of the flute using a blade holder with a manual all-purpose grinder, but it requires skill. There are three types of grinding methods as shown in Figure 6.1.2.

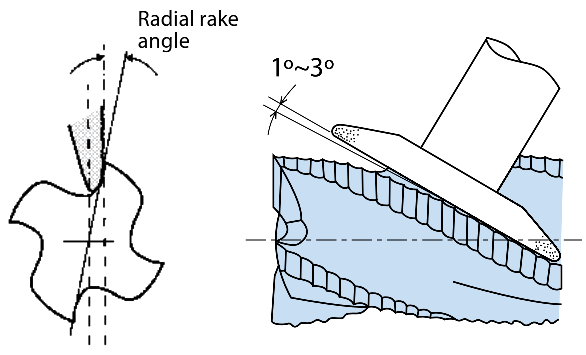
The concave method is a method in which the outer circumference of the grindstone is ground and the clearance angle is obtained by the deviation between the center of the end mill and the center of the grindstone. The flank has a concave shape and the strength of the cutting edge is weakened.
In the flat method, a cup grindstone is used to set the clearance angle by shifting the position of the cutting edge from the center of the end mill.
On the other hand, in the eccentric method, the flank has a convex R shape, and a large flare amount can be secured while maintaining the strength of the cutting edge. Many new end mills are ground this way.

(4) Regrinding the rake face



(4) Regrinding the rake face
Roughing end mills and form tools are reground from the rake face. A CNC grinding machine should be used to create a grinding wheel path that follow the lead of the tool's flute. When grinding a HSS end mill with a center hole, the tool can be held between centers and a grinding wheel can follow the path of the flute. However, this method requires a high amount of skill and poses a high risk of burning as well as chipping. Figure 6.1.3 shows how to grind a rake face by using a grinding wheel tilted 2 degrees from the lead angle. This allows for smaller engagement of the grinding wheel, resulting in less resistance and better surface finish. The rake angle is determined by the positioning of the grinding wheel.
Rake angle

Figure 6.1.3 Grinding wheel positioning when regrinding rake



(5) Regrinding the end cut

Since end cut regrinding is performed with a linear grinding path, general purpose grinding machinery can effectively be used for regrinding end cuts. A concavity angle of 1-3 degrees should be created when grinding the primary relief. Furthermore, corner protection can be added when adding the end gashing by extending the gash to the peripheral cutting edge by 0.05-0.2mm. Regrinding ball end or corner radius end mills requires a special attachment to existing machinery, or CNC grinding machinery when high tolerances are required.

6.2 Grinding wheels and grinding parameters

Grinding parameters for both HSS and carbide end mills are shown in table 6.5 below. Diamond grinding wheels have low resistance and tend to oxidize at around 600deg celcius. It is best to use caution by taking smaller grinding depths and using appropriate coolant.

End Mill	Regrind Area	Wheel		Speed (m/min)	Feed (mm/min)	Depth of cut (mm)	
		Grain Type	Grain Size			Rough	Finish
HSS	Radial Relief Rake End Cut	WA	#60-80	1000-2000	50-200	0.010-0.1	0.005-0.010
	Radial Relief Rake End Cut	cBN	#140-400	1400-1800			
Carbide	Radial Relief Rake End Cut	Diamond	#150-400	1000-1500			

7 Troubleshooting and Solutions

Table 7.1 offers some general troubleshooting tips for milling. These should only be used as a general guide as there are cases when several factors can account for one problem.

Problem	Reason	Solution
Cutting Edges Chipping	Feed rate is too slow	Lower feed rate
	Feed is too high upon entry	Decrease feed upon entry
	Depth of cut is too large	Decrease depth of cut
	Surface speed is too high	Decrease RPM
	Surface speed is too low	Increase RPM
	Low setup rigidity	Decrease rpm and feed. Decrease depth of cut. Reduce number of flutes. Use conventional milling
	Low power machinery	Decrease rpm and feed. Decrease depth of cut. Reduce number of flutes. Use smaller diameter tooling
	Weak workholding	Decrease rpm and feed. Decrease depth of cut. Reduce number of flutes. Use smaller diameter tooling. Use conventional milling.
	Climb milling	Switch to conventional milling to decrease impact at cutting edge
	Conventional Milling	Switch to climb milling to improve chip evacuation.
	Re cut chips	Switch to climb milling. Use coolant or air blow to aid in chip evacauation
	Use of coolant	Use MQL or air blow to reduce thermal shock.
	Loose inserts	Re-attach inserts. Use a torque wrench to determine appropriate tightening torque.
	Large runout	Re-attach tool to holder. Use a precise holder. Check spindle runout.
	High rake angle	Change tool. Use a tool with no chip breaker. Adjust rake angle.
	Weak tool corner	Use a tool with corner gash extension. Use a radius or chamfered tool.
	Incorrect tool material	Choose appropriate tool for application.
	Large tool overhang	Reduce rpm and feed. Reduce depth of cut. Use a rigid holder.
Wear	Surface speed is too high	Reduce rpm.
	surface speed is too low	Increase RPM. Use non water soluble coolant.
	Feed rate is too slow	Increase feed rate.
	Conventional Milling	Use climb milling
	Use of water soluble coolant	Use oil based coolant or MQL, or use air blow.
	Recut chips	Use climb milling. Use air or coolant to aid in chip evacuation. Increase feed rate.
Failure	Depth of cut is too large	Reduce depth of cut. Use roughing end mill. Reduce rpm and feed.
	Feed rate is too fast.	Increase surface speed. Decrease feed rate.
	Large tool overhang	Use a rigid holder. Reduce rpm and feed rate. Reduce depth of cut.
	Worn collet	Replace collet
	Worn tool	Regrind tool. Replace tool.
Poor Surface Finish	Surface speed is too low	Increase rpm
	Feed rate is too fast	increase rpm. Decrease feed rate
	Depth of cut is too large	Decrease dpeth of cut.
	Recut chips	Use coolant or air blow to aid in chip evacuation.
	Climb milling	Use convenional milling.
	Lack of lubrication	Use MQL or oil based coolant. Use a coated tool.
	Large runout	Re-attach tool to holder. Use a precise holder. Check spindle runout.
	Worn tool	Regrind tool. Replace tool.

Problem	Reason	Solution
Deflection	Feed rate is too fast	Decrease feed rate. Use a tool with higher flute count.
	Depth of cut is too large	Reduce Depth of cut.
	Low holder rigidity	Use rigid holder
	Low tool rigidity	Use solid carbide tooling. Use large diameter tooling. Reduce flute length. Reduce tool overhang.
	Large tool overhang	Use larger diameter tool. Use a precise holder
	Lack of sharpness	Use a tool with larger rake angle. Use an insert with a chipbreaker.
	Influence of previous operation	Reduce amount of deflection from previous operation. Use a semi finish operation.
	Milling direction	Use conventional milling for finishing and climb milling for roughing.
	Lack of lubrication	Use coolant.
	Worn tool	Regrind tool. Replace tool.
Part out of Tolerance	Low tool rigidity	Use solid carbide tooling. Use large diameter tooling. Reduce flute length. Reduce tool overhang.
	Loose inserts	Re-attach inserts. Use a torque wrench to determine appropriate tightening torque.
	Large runout	Re-attach tool to holder. Use a precise holder. Check spindle runout.
	Large tool overhang	Retighten the holder to remove runout. Retighten the insert to remove runout. Change the holder. Use a shrink fit holder. Check the runout of the machine spindle.
	Long tool stick out length	Use a larger diameter tool. Use a shrink fit holder.
Chatter and Vibrations	Surface speed is too high	Decrease RPM.
	Resonance	Adjust rpm until a non resonant frequency is found.
	Feed rate is too low	Reduce feed rate.
	Depth of cut is too large	Decrease depth of cut.
	Low setup rigidity	Decrease depth of cut. Use a tool with lower flute count.
	Low tool rigidity	Use solid carbide tooling. Use large diameter tooling. Reduce flute length. Reduce tool overhang.
	Too many flutes	Use a tool with lower flute count.
	Tool overhang is large	Use larger diameter tool. Use a precise holder
	Large cutting forces	Decrease depth of cut. Use a roughing style end mill. Use a tool with lower flute count. Use an insert with a chipbreaker.
	Rake angle is too large	Adjust rake angle. Use different tool.
	Relief angle is too large	Adjust relief angle. Use different tool.
Burrs	Surface speed is too low	Increase RPM.
	Feed rate is too high	Reduce feed rate.
	Depth of cut is too large	Reduce depth of cut. Use roughing and finishing operatoins.
	Worn tool	Regrind tool. Replace tool.
	Rake angle is too small	Use larger rake angle tool. Change chip breaker style.
	Milling direction	Use climb milling. Use small engagement angle and large disengagement angle.
BUE	Surface speed is too low	Increase RPM
	Dry machining	Use coolant.
	Material properties	Use a coated tool. Use different tool substrate.
	Rake angle is too small	Use tool with lrager rake angle. Change chip breaker style.
"coba kake"	Feed rate is too high	Reduce feed rate.
	Conventional Milling	Since a chipping occurs when the tool is pulled out, devise a tool path. Lower the feed rate on exit
	Climb milling	Since a chip is generated when the tool enters, devise a tool path. Lower the feed rate at the entrance.
Chips tangling (drilling)	Surface speed is too low	Increase RPM, to increase centrifugal force.
	Feed rate is too slow	Increase feed rate to create a thicker chip that breaks easier.
	Feed rate is too fast	For softer materials, reducing the feed rate will break chips easier.
	Non-step drilling	Use peck drilling method.
	Existing predrill hole	Perform drilling operation after drilling with end mill. Use peck drilling.
	Incorrect chip breaker	Use correct insert for application.

8. Glossary of Terms

End Mill Terminology

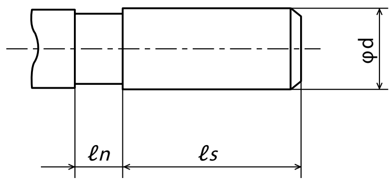
Axial Rake	Rake angle in the axial diretion
Outer Diameter	The diameter of the cutting edge portion of the tool
Radial cutting edge	Cutting edges on the periphery of the tool.
Gash	A flute on the bottom of the tool that creates the end cut.
Cutting Edge	A sharp edge created on a tool with a rake angle and relief angle.
Neck	Portion of the tool that connects the shank and flute portion. Some tools do not have a neck.
Neck Diameter	Diameter of the neck portion of the tool.
Shank	The handle portion of the end mill
Shakn diameter	Diameter of the shank portion of the tool.
Primary Cutting Edge	The portion of the end mill responsible for majority of the cutting it is performing
Core Diameter	The diameter of the core of the flutes of the tool.
Rake Face	The portion of the tool that chips pass through after being cut.
Square Edge	End mills without a corner radius
Straight Shank	Cylindrical shank tool.
Straight Edge	Cylindrical flute tool.
Throwaway Inserts	Disposable cutting edge inserts that are attached to an indexable tool via screw.
Non Center cutting	An end mill with a center hole in the end cut.
Center Cutting	An end mill with a center cut that extends to the center of the tool.
Overall Length	The length of the tool from end cut to shank end.
End Cut	The axial cutting edges of the tool.
End Concavity	The concavity from the end of the peripheral edge to the center of the end cut of the tool.
Insert	Cutting edge portions that are secured via brazing or screws.
Chip pocket	Amount of space for chip evacution during milling.
Compression Flute	A tool with an alternating helix direction
Straight Flute	A tool with no helix angle.
Taper shank	A shank that is tapered in geometry
Tapered Cutter	A tool with a cutting edge that is tapered in geometry
Equal End cut	End cut with the same cutting edge length
Relief Face	The portion of the tool grinded off to relieve the face of the tool with contactign the workpeice during machining.
Chip breaker (nick)	A small slot in the radial cutting edge of a tool to break chips into smaller segments
Chip breaker tool(nicked)	A tool with multiple nicks.
Helical Flute	A tool with a helix flute.
Number of Flutes	The number of cutting edges on and end mill
Length of Cut	The length of the cutting edge portion of the tool.
Left hand helix	A helix that twists in the counter clockwise direction
Left hand cut	A cutting edges that cutts in left handed direction when viewed from the shank end of the tool.
Supplementary cutting edge	A portion of the tool that does not perform the majority of cutting.
Unequal End Cut	When the end cutting edges of a tool vary in length.
Flat	A small flat portion that is grinded onto the shank of the tool for tool holding.
Ball end	An end mill with a ball shaped end cut profile.
Margin	Where no relief is grinded, a margin is left.

Right hand helix	A helix that twists in the clockwise direction
Right hand cut	A cutting edge that cuts in the right handed direction when viewed from the shank end of the tool.
Flute bottom	The lowest point of the flute portion of the tool.
Flute depth	The depth of the lowest point of the flute portion of the tool.
Chamfer tool	An end mill with a chamfering cutting edge.
Radius tool	An end mill with a corner radius.
Radial Rake	The rake angle of the peripheral cutting edges
Roughing Edge	A wave form cutting edge
Lead	The amount of axial direction a helix travels when rotating once around a cylindrical object
Conventional Milling	When the diretion of rotation and diretion of feed are opposite during milling. Cutting in the upward direction.
Feed per revolution	The amount of linear movement of a tool per one rotation of its tool around its access. Fr=Vf/n
Wet Milling	Machining that occurs while using coolant.
MQL	Minimum Quantity Lubricant. Machining using a minimal amount of coolant sprayed onto the tool in a mist form.
Engagement Angle	An angle between the center of the tool and where the cutting edge engages the workpeice when machining linearly.
Stress	The amount of stress experienced by an object when subjected to an outside force.
Table Fede	The rate at which a tool moves relative to the machine.
Spindle speed	The amount of rotations that an object performs in a given amount of time.
Depth of cut	The amount of material removed from a workpiece when cut with an end mill.
Tool life	The point at which a tool has been worn enough to be deemed no longer usable. In a lab, this can be determine by flank wear, where as in a real world setting, the resulting performance of the tool can be used to determine tool life.
Tool life equatoin	FW Taylors equation: VC*T=C wjere VC = speed, T = tool life , m,C = fixed value. This is not a theoretical equation, but an actual one. A tool should be tested multiple times with different parameters until the equatoin is satisfied and a wear pattern can be determined
Rigidity	The amount of resistance an object will have to deformation when subjected to an outside force. Resistnace to bending/ twisting. Different from hardness.
High speed milling	Using minimal depth of cut and high speed cutting parameters during milling.
Axial Depth of Cut	The depth that the tool is cutting to in the axial direction.
Cutting speed	The speed at which a cutting edge passes through material. Expressed as Vc.
Cutting force	The amount of resistance that a tool's cutting edge will feel during machining. Can be broken down into spindle forces, feed forces and thrust forces.
Semi dry machining	Machining using a minimal amount of coolant sprayed onto the tool in mist form. Often reffered to as MQL.
Shear	A strain in the structure of an object produced by pressure, when its layers are laterally shifted in relation to eachother.
Shear Angle	The amount of force at which an object is sheared.
Plastic Deformatoin	A permanent deformation or change in the shape of an object without fracture under the action of an outside fore.
Climb milling	When the direction of rotation and the direction of feed are the same during milling.
Tooling	Tooling refers to the tool holder that connects machine to tool.
Dry Machining	Machining without the use of coolant.
Tolerance	The allowable amount of variation of a specifed dimenion.
Radial depth of cut	the depth that the tool is cuting into the radial directoin.
Relative cutting forces	The amount of cutting forces in relation to 1mm^2
Pick Feed	When 3d machining typically in mold parts, pick feed refers to the amount of movement the tool moves perpendicular to the tool path with each pass.
Feed per tooth	The amount of linear movement of a tool each time a cutting edge contacts the workpiece. Fz= Vf / (zn)
Chatter	A phenomemon where resonance occurs during machinining to cause a tool to vibrate eratically. Can be highly detri-mental to tool life and part quality.
Interpolation	Help
Young's Modulus	A measure of elasticity, equal to the ratio of the stress acting on a substance to the strain produced.

9. Reference Material

Geometry of a straight shank tool

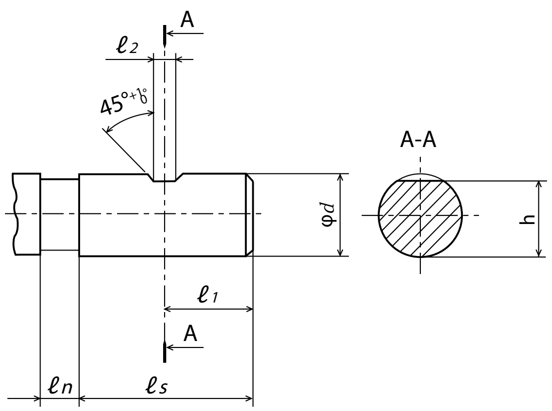
Plain straight shank standard dimensions (JIS B 4005-1998)



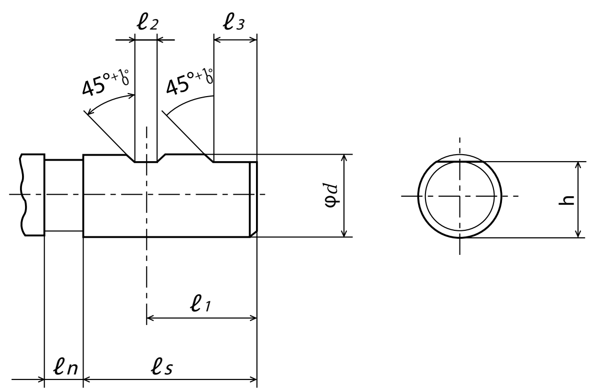
<table>
<tr><th colspan="2">Shank Diameter</th><th colspan="7">Shank length
ℓs</th><th>Reference</th></tr>
<tr><th rowspan="2">Standard dimenison</th><th rowspan="2">H8 tolerance</th><th colspan="6">Standard Dimension</th><th rowspan="2">Tolerance</th><th rowspan="2">Neck length
ℓn</th></tr>
<tr><th>R</th><th>M</th><th>L</th><th>E</th><th>F</th><th>G</th></tr>
<tr><td>3</td><td>0
−0.014</td><td rowspan="3">28</td><td rowspan="2"></td><td>36</td><td>45</td><td>56</td><td>70</td><td rowspan="16">+2
0</td><td rowspan="2">4</td></tr>
<tr><td>4</td><td rowspan="2">0
−0.018</td><td>40</td><td>50</td><td>60</td><td>80</td></tr>
<tr><td>5</td><td>36</td><td>45</td><td>56</td><td>70</td><td>90</td><td>6</td></tr>
<tr><td>6</td><td></td><td rowspan="2">36</td><td>40</td><td>50</td><td>60</td><td>80</td><td>100</td><td rowspan="2">8</td></tr>
<tr><td>8</td><td rowspan="2">0
−0.022</td><td>45</td><td>56</td><td>70</td><td>90</td><td>110</td></tr>
<tr><td>10</td><td>40</td><td>50</td><td>60</td><td>80</td><td>100</td><td>125</td><td>10</td></tr>
<tr><td>12</td><td rowspan="2">0
−0.027</td><td rowspan="2">45</td><td rowspan="2">56</td><td rowspan="2">70</td><td rowspan="2">90</td><td rowspan="2">110</td><td rowspan="2">140</td><td rowspan="4">12</td></tr>
<tr><td>14</td></tr>
<tr><td>16</td><td></td><td rowspan="2">48</td><td rowspan="2">60</td><td rowspan="2">80</td><td rowspan="2">100</td><td rowspan="2">125</td><td rowspan="2">160</td></tr>
<tr><td>18</td><td></td></tr>
<tr><td>20</td><td rowspan="2">0
−0.033</td><td>50</td><td>70</td><td>90</td><td>110</td><td>140</td><td>180</td><td>16</td></tr>
<tr><td>25</td><td>56</td><td>80</td><td>100</td><td>125</td><td>160</td><td>200</td><td>20</td></tr>
<tr><td>32</td><td rowspan="2">0
−0.039</td><td>60</td><td>90</td><td>110</td><td>140</td><td>180</td><td>225</td><td></td></tr>
<tr><td>40(42)</td><td>70</td><td>100</td><td>125</td><td>160</td><td>200</td><td>250</td><td>22</td></tr>
<tr><td>50</td><td></td><td>80</td><td>110</td><td>140</td><td>180</td><td>225</td><td>280</td><td></td></tr>
<tr><td>63</td><td>0
−0.046</td><td>90</td><td>125</td><td>160</td><td>200</td><td>250</td><td>315</td><td></td></tr>
</table>

Straight shank with flat standard dimensions (JIS B 4005-1998)

With flat
(shank dia 6mm-20mm)



Double flat
(shank diameter 25-63mm)



Unit: (mm)

Shank Diameter		Shank length		ℓ1		Flat width ℓ2		Flat width ℓ3		h		Reference
Standard Dimension	tolerance	Standard Dimension	tolerance	Standard Dimension	tolerance	Standard Dimension	tolerance	Standard Dimension	tolerance	Standard Dimension	tolerance	Neck length
6	0 −0.008	36	+2 0	18	0 −1	4.2	+0.2 0	—	—	4.8	0 −0.4	8
8	0 −0.009					5.5				6.6		
10		40		20		7				8.4		10
12	0 −0.011	45		22.5		8				10.4		12
16		48		24		10				14.2		
20	0 −0.013	50		25		11				18.2		16
25		56		32		12		17	+1 0	23		20
32	0 −0.016	60		36		14		19		30		
40		70		40						38		22
50		80		45		18		23		47.8		
63	0 −0.019	90		50						60.8		

Material standards Table

General structural steel

Carbon steel

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
SS330	A	S235JR		
	B			
	C			
SS400	D	S275JR		
	50			
	55			
	58			
	65			
SS490	70	S355JR		
	C			
	D			
SM570	C			
	D			
SM490A	D			
SM490B	E			
SM490C	A			
SM490Y	B			
SM520	50W			
SV330	A			
SV400	B			

Alloy steel

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
S15C	1015	C15E	15	C15E4
		C15R		C15M2
S15CK		C15E		C15E4
		C15R	20	C15M2
S25C	1025	C25		C25
		C25E		C25E4
		C25R		C25M2
S45C	1045	C45	45	C45
		C45E		C45E4
		C45R		C45M2
S50C	1049		50	C50
		C50E		C50E4
		C50R		C50M2
SB410	Grade415	P265GH		PT410GH
SB450	Grade450	P295GH		PT450GH
SB450 M	GradeA			
SB480	Grade485	P295GH		PT480GH
SB480 M	GradeB			

Alloy steel

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
SCM415			15CrMo	
SCM418			20CrMo	18CrMo4
				18CrMoS4
SCM418H		18CrMo4		18CrMoS4
		18CrMoS4		18CrMoS4
SCM420		18CrMo4		
		18CrMoS4		
SCM421		22CrMoS3-5		
SCM430	4130		30CrMo	
SCM432				
SCM435	4137		35CrMo	34CrMo4
				34CrMoS4
SCM435H	4135H			34CrMo4
				34CrMoS4
SCM440	4140	42CrMo4	42CrMo	42CrMo4
		42CrMoS4		42CrMoS4
SCM440H	4140H			42CrMo4
				42CrMoS4
SCM445	4145			
SCM445H	4145H			
SCM822				
SCM822H				
SCr415			15Cr	
SCr415H			15CrH	
SCr420	5120		20Cr	20Cr4
				20CrS4
SCr420H	5120H		20CrH	20Cr4H
				20CrS4
SCr430	5130		30Cr	
SCr430H	5130H			34Cr4
				34CrS4
SCr435	5132		35Cr	34Cr4
				34CrS4
				37Cr4
				37CrS4
SCr435H	5135H			34Cr4
				37Cr4
SCr440	5140	41Cr4	40Cr	41Cr4
		41CrS4		41CrS4
SCr440H	5140H		40CrH	41Cr4
				41CrS4
SCr445				
SMn420	1522		20Mn2	22Mn6
SMn420H	1522H			22Mn6H
SMn433			30Mn2	
SMn433H				
SMn438	1541		40Mn2	36Mn6
SMn438H	1541H			36Mn6H
SMn443	1541		45Mn2	42Mn6
SMn443H	1541H			42Mn6H
SNC236				

Carbon tool steel

Japan JIS	USA ASTM/AISI	Europe EN	China GB	ISO
SNC415				
SNC415H				
SNC631				
SNC631H				
SNC815				
SNC815H				15NiCr13
SNC836			12CrNi2H	
SNCM220	8617	20NiCrMo2-2		20NiCrMo2
	8620	20NiCrMoS2-2		20NiCrMoS2
SNCM220H	8620H		20CrNiMoH	20NiCrMo2
				20NiCrMoS2
SNCM240	8640			41CrNiMo2
				41CrNiMoS2
SNCM415				
SNCM420	4320			
SNCM420H	4320H		20CrNi2MoH	
SNCM431				
SNCM439	4340			
SNCM447				
SNCM616				
SNCM625				
SNCM630				
SNCM815				

Carbon tool steel

Japan JIS	USA ASTM/AISI	Europe EN	China GB	ISO
SK140			T13	
SK120	W1-11 1/2		T12	C120U
SK105	W1-10		T11	C105U
SK95	W1-9		T10	
SK90				C90U
SK85	W1-8		T8Mn	
SK80				C80U
SK75			T8	
SK65			T7	
SKS2				
SKS11	F2			
SKS21			W	
SKS31				105WCr1
SKS41				
SKS43	W2-91/2			105V
SKS44	W2-81/2			
SKS51	L6			
SUJ2	52100			B1

Die steel

Japan JIS	USA ASTM/AISI	Europe EN	China GB	ISO
SKD11	D2		Cr12MoV	
SKD61	H13		4Cr5MoSiV1	X40CrMoV5-1

High speed steel

Japan JIS	USA ASTM/AISI	Europe EN	China GB	ISO
SKH2	T1			HS18-01
SKH50				HS1-8-1
SKH51	M2			HS6-5-2
SKH52	M3-1			HS6-6-2
SKH53	M3-2			HS6-5-3
SKH54	M4			HS6-5-4
SKH55				HS6-5-2-5
SKH56	M36			
SKH57				HS10-4-3-10
SKH58	M7			HS2-9-2
SKH59	M42			HS2-9-1-8

Tool steel

Japan JIS	USA ASTM/AISI	Europe EN	China GB	ISO
SKT3				
SKT4				55NiCrMoV7
SKT6				45NiCrMo16

Pipe steel

Japan JIS	USA ASTM/AISI	Europe EN	China GB	ISO
STAM290GB		E155		
SGP	TypeF(A)	S195T		
STKM11A	1008	E155		
STPT370	A	P235GH		
STB340	A	P235GH		
STPG370	A	P235TR2		
STS370				
STPT410	B	P265GH		
STB410	C	P265GH		
	A-1			
STPG410	B	P265TR2		
STK400	A	E320		TS9
STKM12B				
STKR400		S275JR		
STAM390G				
STS410				
STKM14A		CFSC4		
STKM13C	1020	CFSC4		
STKM18C		E355		
STKM19A		E355		
STKM19C		E355		
STK490		E355		TS18
STKR490		S275JR		
STS480				
STKM12A				R33
STKM12B				
STKM13A	1020	E235		
STKM13C	1020	CFSC4		R37
STKM14B	1026			

Pipe steel

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
	1025			
STKM14C	1026			
	1025			
STKM17A	1050			
STKM18B		E355		R50
STKM18C		E355		
STKM19A		E355		
STKM19C		E355		

Heat resistant steel

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
SUH1		1.4718		X45CrSi93
SUH3				
SUH4				
SUH11				X50CrSi182
SUH21				
SUH31				
SUH35		1.4871		
SUH36				
SUH37				
SUH38				
SUH309	S30900			
SUH310	S31000			
SUH330				
SUH409		X6CrTi12		X6CrTi12
SUH409L	S40910			X2CrTi12
SUH446	S44600			X15CrN26
SUH600				
SUH616	S42200			
SUH660				
SUH661				

Free cutting steel

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
SUM21	1212			9S20
SUM22	1213	9SMn28	Y15	11SMn28
SUM22L		9SMnPb28	Y12Pb	11SMnPb28
SUM23	1215			
SUM23L				
SUM24L	12L14			11SMnPb28
SUM25				12SMn35
SUM31	1117			
SUM31L				
SUM32			Y20	
SUM41	1137		Y30	
SUM42	1141			
SUM43	1144			44SMn28

Spring steel

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
SUP6				60Si8
SUP7	9260			60Si8
SUP9	5155			55Cr3
SUP9A	5160			60Cr3
SUP10	6150			51CrV4
SUP11A	51B60			60Cr3
SUP12				55SiCr6-3
SUP13	4161			60CrMo3-3

Stainless steel

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
SUS304	S30400	1.4301		L-No6X5CrNi18-9
SUS405	S40500	1.4002		L-No66X6CrAl13
SUS420F	S42020	1.4029		
SUS430	S43000	1.4016		L-No67X6Cr17
SUS430LX	S43035	1.4510		L-No70X3CrTi17
SUS440A	S44002	1.4109		
SUS630	S17400	1.4542		L-No101-X5CrNiCuNb16-4
SUS631	S17700	1.4568		L-No102X7CrNiAl17-7
SUS410	S41000	1.4006		L-No82X12Cr13

Cast iron

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
SCH15	HT	GX50NiCrCoW35-25-15-5		GX40NiCrSi35-17
	HT50			

Cast iron

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
FC250	Class No.250B	EN-GJL-250		ISO185/JL/250
FC300	Class No.300B	EN-GJL-300		ISO185/JL/300

Ductile Cast iron

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
FCD400-18	60-40-18	EN GJS-400-18		400-18S
FCD400-15	60-40-18	EN GJS-400-15		400-15S
FCD600-3	80-55-06	EN GJS-600-3		600-3

Aluminum Alloys

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
A1080P		EN AW-1080A	1A80	
A1070P		EN AW-1070A		
A1050P			1A50	
A1100P	1100	EN AW-1100		Al99.0Cu
A1200P	1200	EN AW-1200		Al99.0
A2014P	2014	EN AW-2014		AlCu4SiMg
A2017P	2017			
A2017AP	2014	EN AW-2017		AlCu4MgSi(A)
A2024P	2024	EN AW-2024		AlCu4Mg1
A2024PC	Alclad 2024			
A2024BE	2024	EN AW-2024		AlCu4Mg1
A2024BD	2024	EN AW-2024		AlCu4Mg1
A2024W	2024	EN AW-2024		AlCu4Mg1
A2024TD	2024	EN AW-2024		AlCu4Mg1
A2024S	2024	EN AW-2024		AlCu4Mg1
A3003P	3003	EN AW-3003		AlMn1Cu
A5052P	5052	EN AW-5052	5A02	AlMg2.5
A5052BE	5052	EN AW-5052		
A5052BD	5052	EN AW-5052		AlMg2.5
A5052W	5052	EN AW-5052		AlMg2.5
A5052TD	5052	EN AW-5052		AlMg2.5
A5052TWA	5052			Al-Mg4.5Mn0.7
A5052S	5052	EN AW-5052		
A5052FH				
A5083BD		EN AW-5083		Al-Mg4.5Mn0.7
A5083W		EN AW-5083		Al-Mg4.5Mn0.7
A5083TE	5083	EN AW-5083		Al-Mg4.5Mn0.7
A5083TD	5083	EN AW-5083		Al-Mg4.5Mn0.7
A5083TWA	5083			
A5083S	5083	EN AW-5083		Al-Mg4.5Mn0.7
A6061P	6061	EN AW-6061		Al-Mg1SiCu
A6063TE	6063	EN AW-6063		Al-Mg0.7Si
A7075P	7075	EN AW-7075	7A09	AlZn5.5MgCu
A7075BE	7075	EN AW-7075		AlZn5.5MgCu
A7075BD	7075	EN AW-7075		AlZn5.5MgCu
A7075TE	7075	EN AW-7075		AlZn5.5MgCu
A7075TD	7075	EN AW-7075		AlZn5.5MgCu
A7075S	7075	EN AW-7075		AlZn5.5MgCu
A7075FH	7075	EN AW-7075		
A7075FD	7075	EN AW-7075		

Cast aluminum

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
AC1B	204.0	EN AC-21000		AlCu4MgTi
AC2A		EN AC-45200		AlSi5Cu3Mn
AC2B	319.0	EN AC-45200		AlSi5Cu3Mn
AC3A		EN AC-44100	ZAlSi2	AlSi12(b)
AC4A		EN AC-43100		AlSi10Mg
AC4B		EN AC-46200		AlSi8Cu3
AC4C	356.0	EN AC-42000	ZALSi7Mn	AlSi7Mg
AC4CH	A356.0	EN AC-42100		AlSi7Mg0.3
AC4D	355.0	EN AC-45300		AlSi5Cu1Mg

Cast aluminum

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
AC5A	242.0			
AC7A	514.0	EN AC-51300		AlMg5
AC8A		EN AC-48000	ZALSi2Cu2Mg1	AlSi12CuMgNi
AC8B				
AC8C	332.0			
AC9A				
AC9B				
ADC1	A413.0	EN AC-44300		AlSi12(Fe)
ADC3	A360.0	EN AC-43400		AlSi10Mg(Fe)
ADC5	518.0			
ADC6	515.0			
ADC10	A380.0	EN AC-46200		AlSi8Cu3
ADC10Z	A380.0	EN AC-46500		AlSi9Cu3(Fe)(Zn)
ADC12	383.0			AlSi11Cu3(Fe)
ADC12Z	383.0	EN AC-46100		AlSi11Cu2(Fe)
ADC14	B390.0			AlSi17Cu4Mg

Magnesium alloy

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
MD1B	AZ91B			
MD1D	AZ91D	EN-MB21120		MgAl9Zn1(A)
MD2B	AM60B	EN-MB21230		MgAl6Mn
MD3B	AS41B	EN-MB21320		MgAl4Si
MD4	AM50A	EN-MB21220		MgAl5Mn
MD5		EN-MC21210		MgAl2Mn
MD6	AS21A	EN-MB21310		MgAl2Si

Copper

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
C1020P	C10200(B152:97)	CW008A		
C1020PS	C10200(B152:97)	CW008A		
C1020R	C10200(B152:97)	CW008A		
C1020RS	C10200(B152:97)	CW008A		

Brass

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
C2600P	C26000(B36:01)	CW505		
C2600R	C26000(B36:01)	CW505		
C2600RS	C26000(B36:01)	CW505		

Bronze

Japan	USA	Europe	China	ISO
JIS	ASTM/AISI	EN	GB	
C6140P	C61400(B169:01)			

Hardness comparison Chart

HRC Rockwell C hardness	HV Vickers hardness	Brinell hardness HB 10mm ball, 29.4 kN load			Rockwelll hardness			Superficial Rockwell hardness diamond cone			Shore hardness HS	Tensile Strength	HRC Rockwell C hardness
		Standard ball	Tungsten ball	Tungsten carbide ball	A scale 588.4N load diamond cone	B scale 980.7N dia 1/16in ball	D scale 980.37N load diamond cone	15N scale 147.1N load	30N scale 294.2N load	45N scale 441.3N load			
68	940	-	-	-	85.6	-	76.9	93.2	84.4	75.4	97	-	68
67	900	-	-	-	85.0	-	76.1	92.9	83.6	74.2	95	-	67
66	865	-	-	-	84.5	-	75.4	92.5	82.8	73.3	92	-	66
65	832	-	-	739	83.9	-	74.5	92.2	81.9	72.0	91	-	65
64	800	-	-	722	83.4	-	73.8	91.8	81.1	71.0	88	-	64
63	772	-	-	705	82.8	-	73.0	91.4	80.1	69.9	87	-	63
62	746	-	-	688	82.3	-	72.2	91.1	79.3	68.8	85	-	62
61	720	-	-	670	81.8	-	71.5	90.7	78.4	67.7	83	-	61
60	697	-	613	654	81.2	-	70.7	90.2	77.5	66.6	81	-	60
59	674	-	599	634	80.7	-	69.9	89.8	76.6	65.5	80	-	59
58	653	-	587	615	80.1	-	69.2	89.3	75.7	64.3	78	-	58
57	633	-	575	595	79.6	-	68.5	88.9	74.8	63.2	76	-	57
56	613	-	561	577	79.0	-	67.7	88.3	73.9	62.0	75	-	56
55	595	-	546	560	78.5	-	66.9	87.9	73.0	60.9	74	2079	55
54	577	-	534	543	78.0	-	66.1	87.4	72.0	59.8	72	2010	54
53	560	-	519	525	77.4	-	65.4	86.9	71.2	58.6	71	1952	53
52	544	500	508	512	76.8	-	64.6	86.4	70.2	57.4	69	1883	52
51	528	487	494	496	76.3	-	63.8	85.9	69.4	56.1	68	1824	51
50	513	475	481	481	75.9	-	63.1	85.5	68.5	55.0	67	1755	50
49	498	464	469	469	75.2	-	62.1	85.0	67.6	53.8	66	1687	49
48	484	451	455	455	74.7	-	61.4	84.5	66.7	52.5	64	1638	48
47	471	442	443	443	74.1	-	60.8	83.9	65.8	51.4	63	1579	47
46	458	432	432	432	73.6	-	60.0	83.5	64.8	50.3	62	1530	46
45	446	421	421	421	73.1	-	59.2	83.0	64.0	49.0	60	1481	45
44	434	409	409	409	72.5	-	58.5	82.5	63.1	47.8	58	1432	44
43	423	400	400	400	72.0	-	57.7	82.0	62.2	46.7	57	1383	43
42	412	390	390	390	71.5	-	56.9	81.5	61.3	45.5	56	1334	42
41	402	381	381	381	70.9	-	56.2	80.9	60.4	44.3	55	1294	41
40	392	371	371	371	70.4	-	55.4	80.4	59.5	43.1	54	1245	40
39	382	362	362	362	69.9	-	54.6	79.9	58.6	41.9	52	1216	39
38	372	353	353	353	69.4	-	53.8	79.4	57.7	40.8	51	1177	38
37	363	344	344	344	68.9	-	53.1	78.8	56.8	39.6	50	1157	37
36	354	336	336	336	68.4	(109.0)	52.3	78.3	55.9	38.4	49	1118	36
35	345	327	327	327	67.9	(108.5)	51.5	77.7	55.0	37.2	48	1079	35
34	336	319	319	319	67.4	(108.0)	50.8	77.2	54.2	36.1	47	1059	34
33	327	311	311	311	66.8	(107.5)	50.0	76.6	53.3	34.9	46	1030	33
32	318	301	301	301	66.3	(107.0)	49.2	76.1	52.1	33.7	44	1000	32
31	310	294	294	294	65.8	(106.0)	48.4	75.6	51.3	32.5	43	981	31
30	302	286	286	286	65.3	(105.5)	47.7	75.0	50.4	31.3	42	951	30
29	294	279	279	279	64.7	(104.5)	47.0	74.5	49.5	30.1	41	932	29
28	286	271	271	271	64.3	(104.0)	46.1	73.9	48.6	28.9	41	912	28
27	279	264	264	264	63.8	(103.0)	45.2	73.3	47.7	27.8	40	883	27
26	272	258	258	258	63.3	(102.5)	44.6	72.8	46.8	26.7	38	863	26
25	266	253	253	253	62.8	(101.5)	43.8	72.2	45.9	25.5	38	843	25
24	260	247	247	247	62.4	(101.0)	43.1	71.6	45.0	24.3	37	824	24
23	254	243	243	243	62.0	100.0	42.1	71.0	44.0	23.1	36	804	23
22	248	237	237	237	61.5	99.0	41.6	70.5	43.2	22.0	35	785	22
21	243	231	231	231	61.0	98.5	40.9	69.9	42.3	20.7	35	775	21
20	238	226	226	226	60.5	97.8	40.1	69.4	41.5	19.6	34	755	20
(18)	230	219	219	219	-	96.7	-	-	-	-	33	736	(18)
(16)	222	212	212	212	-	95.5	-	-	-	-	32	706	(16)
(14)	213	203	203	203	-	93.9	-	-	-	-	31	677	(14)
(12)	204	194	194	194	-	92.3	-	-	-	-	29	647	(12)
(10)	196	187	187	187	-	90.7	-	-	-	-	28	618	(10)
(8)	188	179	179	179	-	89.5	-	-	-	-	27	598	(8)
(6)	180	171	171	171	-	87.1	-	-	-	-	26	579	(6)
(4)	173	165	165	165	-	85.5	-	-	-	-	25	549	(4)
(2)	166	158	158	158	-	83.5	-	-	-	-	24	530	(2)
(0)	160	152	152	152	-	81.7	-	-	-	-	24	520	(0)

*Values denoted in brackets () are not typically inside the range of values for this hardness test.

shaping your dreams

Safe use of cutting tools

- Use safety cover, safety glasses and safety shoes during operation.
- Do not touch cutting edges with bare hands.
- Do not touch cutting chips with bare hands. Chips will be hot after cutting.
- Stop cutting when the tool becomes dull.
- Stop cutting operation immediately if you hear any abnormal cutting sounds.
- Do not modify tools.
- Please use appropriate tools for the operation. Check dimensions to ensure proper selection.

FOR MORE INFORMATION CONTACT US

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