Basics of End Mills
Contents

1. Cutting and Cutting Tools
2. Processing by End Mills
3. Cutting Action and Phenomena during Cutting
Contents

1. Cutting and Cutting Tools
2. Processing by End Mills
3. Cutting Action and Phenomena during Cutting
Making products having desired surface shape by...
• putting and moving a cutting tool on a work piece,
• and separating unnecessary parts as chips by breaking with internal stress.

Rapid progress and diversification of cutting technology

Systematic understanding to phenomena is important
to use cutting process effectively!
Tools for Cutting

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

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

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

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

**Features of each tool**
With few cutting edges...Inexpensive production and re-grinding
With many cutting edges...High cutting efficiency

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

**Rake face**
Tool surface in contact with cutting chip

**Cutting chip**
Removed unnecessary part

**Cut surface**
Surface before cut

**Cutting tool**
Instrument for cutting
Also called simply “Tool”

**Finished surface**
Cut surface

**Relief face**
Opposite side of rake face

**Cutting edge**
Intersection of rake face and relief face on tool point
• Tool materials need more than 3 or 4 times the hardness of work material in Vickers Hardness.

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

Coating
(Cover the hardness of tool material)

If coated tools need $\geq x4$ harder than work material...

• 40HRC Hardened steels
  $\gg\gg$ Tool materials need $\geq 1600$Hv
  CrN (Little difficult) TiN (Available)

• 50HRC Hardened steels
  $\gg\gg$ Tool materials need $\geq 2000$Hv
  TiN (Actually difficult) AlCrN (Available)

• 65HRC Hardened steels
  $\gg\gg$ Tool materials need $\geq 3300$Hv
  TiSiN based coating is available
Coating  —Purpose of Coating—

To improve tool life and cutting ability...

Apply coating technology
Tool obtains new characteristics by covering tool surface with coating.

Coating is expected to have...
- Hardness: to make cutting edge stand on work piece
- Heat resistance: not to change in quality under high temperature during cutting
- Toughness: to stop chipping of cutting edge
- Lubricity: to control friction during cutting

Coating methods

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

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

Types of coating

Ceramic-base coating

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

Diamond coating

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

DLC (Diamond-Like Carbon) coating

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

Multi-layer coating

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

Understanding of characteristics & uses of coatings

>>> Improvement of tool life and cutting ability
Summary

What is “Cutting”?
Machining method which puts a hard cutting tool on a part near a edge of a work piece and separates cutting chips by causing plastic deformation.

Advantages of cutting
• Application for various work materials
• Relatively high machining accuracy

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

1. Cutting and Cutting Tools
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Types of End Mill Processing

- Slotting
- Side milling
- Tapering
- Profiling
- Contouring
- Pocket milling
- Ribbing
- Spot facing
Basically down cutting is recommended.

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

**Down cutting**
- Remaining: Allowance for rework

**Up cutting**
- Too much cut: Recovery is impossible
- Direction of deflection
Up Cutting

Slip phenomenon: a cutting edge does not cut but rub a work piece because of too small cutting depth.

Impact to contact material…… Small

>>√ Small chipping toward black surface of material
High milling temperature because of slip phenomenon

>> X Large relief face wearing

Direction of rotation

Feeding direction
Down Cutting

- **Rake face**: Features a small rake face wearing.
- **Cutting edge**: Undergoes large impact at a time of biting.
- **Milling area**: Low milling temperature because of no slip.
- **Impact**: Large chipping toward materials with black rust.

**Direction of rotation**: Feeding direction.

**Thickness of cutting chip**:
A tool rotates clockwise is called “Right cutting edge”.
A tool rotates counter-clockwise is called “Left cutting edge”.
Ordinary end mills are “Right cutting edge” and “Left cutting edge” are very rare.
Right/Left Twisted Blades

Direction of chip evacuation differs in direction of Helix.

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

Ordinary end mills are “right edges & right Helix” and “right edges & left Helix” are very rare.
Terms Used for Parameters 1

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

**Example of side milling**

**Example of slope milling**
Terms Used for Parameters 2

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

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

<table>
<thead>
<tr>
<th>Related values</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter ( \phi D ) [mm]</td>
<td>Twice of the distance from the rotational center (radius)</td>
</tr>
<tr>
<td>( \pi )</td>
<td>The circular constant = 3.14 (Unit: Nil)</td>
</tr>
<tr>
<td>Spindle Speed ( n ) [min(^{-1})]</td>
<td>Revolution per minute [Number of revolutions / min.] ( [min^{-1}]= [rpm: revolutions per minute] )</td>
</tr>
</tbody>
</table>

Circumferential length = Diameter \( x \pi = \pi D \) [mm]

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

\[
V_c = \frac{\pi \times D \text{ [mm]} \times n \text{ [min}^{-1}]}{1 \text{ [min]}} \text{ [mm/min]}
\]

Unit conversion: 1mm = 1/1000 m

\( D \text{ [mm]} = D/1000 \text{ [m]} \) therefore...

\[
V_c = \frac{\pi \times D \text{ [mm]} \times n \text{ [min}^{-1}]}{1000 \times 1 \text{ [min]}} \text{ [m/min]}
\]
Terms Used for Parameters 3

2. Feed per tooth  \( f_z \)  [Unit: mm/t]

Related Values

<table>
<thead>
<tr>
<th>Feed Rate  ( V_f ) [mm/min]</th>
<th>Moving distance (of machine axis) in direction of feed per minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle Speed  ( n ) [min(^{-1})]</td>
<td>Revolutions per minute [Number of revolutions / min.]</td>
</tr>
<tr>
<td>Number of flutes  ( z ) [t]</td>
<td>Number of flutes</td>
</tr>
</tbody>
</table>

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

\[
f = \frac{V_f \ [\text{mm/min}]}{n \ [\text{rev/min}]} = \frac{V_f}{n} \times \frac{\text{mm}}{\text{min}} \times \frac{\text{min}}{\text{rev}} = \frac{V_f}{n} \ [\text{mm/rev}]
\]

In case of 2 flutes:

\[
f = f/2 \ [\text{mm/t}]
\]

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

\[
f_z = \frac{f \ [\text{mm/rev}]}{z} = \frac{V_f}{n \times z} \ [\text{mm/t}]
\]

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Contents

1. Cutting and Cutting Tools

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3. Cutting Action and Phenomena during Cutting
A state of cutting a part close to an edge of a work piece.

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

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Flow shape</th>
<th>Share shape</th>
<th>Tear shape</th>
<th>Crack shape</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Schematic diagram</strong></td>
<td><img src="image1" alt="Flow shape" /></td>
<td><img src="image2" alt="Share shape" /></td>
<td><img src="image3" alt="Tear shape" /></td>
<td><img src="image4" alt="Crack shape" /></td>
</tr>
<tr>
<td><strong>Tool</strong></td>
<td><img src="image1" alt="Flow shape" /></td>
<td><img src="image2" alt="Share shape" /></td>
<td><img src="image3" alt="Tear shape" /></td>
<td><img src="image4" alt="Crack shape" /></td>
</tr>
<tr>
<td><strong>Workpiece</strong></td>
<td><img src="image1" alt="Flow shape" /></td>
<td><img src="image2" alt="Share shape" /></td>
<td><img src="image3" alt="Tear shape" /></td>
<td><img src="image4" alt="Crack shape" /></td>
</tr>
</tbody>
</table>

**Flow shape**
- Cutting chips continuously flow on a rake face.
- Load on cutting edge is constant and a smooth surface is obtained.
- **Most desirable shape.**

Note: Too long cutting chips disturb cutting instead. → need Breaking cutting chips in certain length (by tool geometry, coolant, etc.).

**Share shape**
- Deformation of cutting chips → repeat Sharing
- Finished surface is not good as Flow shape.

**Tear shape**
- Cutting chips pile up on a tool and finally large tear is caused.
- A finished surface has scars and remarkably bad.

**Crack shape**
- Crack occurs during deformation of cutting chips and they become crack shape.
- Crack makes finished surface remarkably worse.

**Reason**

<table>
<thead>
<tr>
<th>Reason</th>
<th>Flow shape</th>
<th>Share shape</th>
<th>Tear shape</th>
<th>Crack shape</th>
</tr>
</thead>
</table>
| **-**  | • Fragile of work piece  
• Low thermal conductivity | • High ductility | **-** | • Fragile of work piece |

**Measure**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Flow shape</th>
<th>Share shape</th>
<th>Tear shape</th>
<th>Crack shape</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>-</strong></td>
<td>• Increase cutting speed</td>
<td>• Decrease cutting depth and increase cutting speed</td>
<td><strong>-</strong></td>
<td>• Increase cutting speed and decrease feed per tooth</td>
</tr>
</tbody>
</table>

**Shape of cutting chips is information source of cutting situation.**
Cutting chips change color by cutting temperature. > By change of chip color, cutting temperature can be estimated.

Cutting heat is a very important element for tool life!
Difference of Tool Shape & Cutting Chips

2-flute type

Comp. A

Comp. E

CFB/CFLB

Ideal shape

Narrow

Wide

Narrow

Wide

X Compressive deformation

X Curled
Setting of Milling Condition

How to increase milling efficiency while reducing tool damage...

Which should be adjusted?

Study case

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

<table>
<thead>
<tr>
<th>Condition</th>
<th>Cutting chips</th>
<th>n min⁻¹</th>
<th>Velocity m/min</th>
<th>Vf mm/min</th>
<th>Feed per tooth mm/t</th>
<th>aₚ mm</th>
<th>aₑ mm</th>
<th>Efficiency mm³/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>4000</td>
<td>125.6</td>
<td>1350</td>
<td>0.0563</td>
<td>10</td>
<td>0.15</td>
<td>2025</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>3000</td>
<td>94.2</td>
<td>1000</td>
<td>0.0556</td>
<td>10</td>
<td>0.15</td>
<td>1500</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>2000</td>
<td>62.8</td>
<td>675</td>
<td>0.0563</td>
<td>10</td>
<td>0.15</td>
<td>1013</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>2000</td>
<td>62.8</td>
<td>675</td>
<td>0.0563</td>
<td>20</td>
<td>0.2</td>
<td>2700</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>2000</td>
<td>62.8</td>
<td>1000</td>
<td>0.0833</td>
<td>20</td>
<td>0.2</td>
<td>4000</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>2000</td>
<td>62.8</td>
<td>1000</td>
<td>0.0833</td>
<td>20</td>
<td>0.4</td>
<td>8000</td>
</tr>
</tbody>
</table>
## Optimization of HMS Milling Condition for SKH51

### Tools after milling on each condition

<table>
<thead>
<tr>
<th>Condition</th>
<th>Radial relief face</th>
<th>Rake face</th>
<th>Cutting chips</th>
<th>Efficiency [mm³/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
<td>2025</td>
</tr>
<tr>
<td>2</td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
<td>1500</td>
</tr>
<tr>
<td>3</td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
<td><img src="image9" alt="Image" /></td>
<td>1013</td>
</tr>
<tr>
<td>4</td>
<td><img src="image10" alt="Image" /></td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
<td>2700</td>
</tr>
<tr>
<td>5</td>
<td><img src="image13" alt="Image" /></td>
<td><img src="image14" alt="Image" /></td>
<td><img src="image15" alt="Image" /></td>
<td>4000</td>
</tr>
<tr>
<td>6</td>
<td><img src="image16" alt="Image" /></td>
<td><img src="image17" alt="Image" /></td>
<td><img src="image18" alt="Image" /></td>
<td>8000</td>
</tr>
</tbody>
</table>

Condition 1 - 3: Tools after 9000mm³ milling  
Condition 4 - 6: Tools after 50000mm³ milling (20min milling with No.5)
Various phenomena during cutting become obstacles to processing.

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

Formation cycle of build-up edge

A part of cutting chips adheres to a tooth part and covers a cutting edge (formation of build-up edge).

(A flow of work materials and cutting chips)

Tool

Build-up edge

Tool

Growth

Adhered substances grow gradually while exhibiting cutting function instead of the original cutting edge.

>> Surface roughness becomes worse.

Build-up edge drops off at a certain size.

>> Tool life decreases.

Measures

• Increase cutting speed and raise temperature
• Provide high lubricity cutting fluid
Phenomena during Cutting — Chattering —

• Various phenomena during cutting become obstacles to process.

Chattering

Phenomenon

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

Influence

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

Measures

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

Cutting resistance

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

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

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

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

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

- \(P\): Cutting power requirement (kW)
- \(F\): Cutting force (kgf)
- \(v\): Velocity (m/min)
- \(\eta\): Mechanical efficiency
“Cutting force” is especially important among three force components (because it is a factor determining power requirement and heat generation).

Generally cutting force is sometimes referred to “cutting resistance”.

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

Factors which may change cutting force (general tendency)

<table>
<thead>
<tr>
<th>Cutting resistance (cutting force)</th>
<th>Small</th>
<th>Large</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work material</td>
<td>Soft</td>
<td>Hard</td>
<td>—</td>
</tr>
<tr>
<td>Tooth part geometry (Rake angle)</td>
<td>Large rake angle</td>
<td>Small rake angle</td>
<td>Cutting force decreases when rake angle is up to about 30°.</td>
</tr>
<tr>
<td>Milling area (Cutting depth x Feed Rate)</td>
<td>Small</td>
<td>Large</td>
<td>Sometimes cutting force decreases by reducing cutting depth and increasing Feed Rate.</td>
</tr>
<tr>
<td>Velocity</td>
<td>Fast</td>
<td>Slow</td>
<td>Cutting force does not change so much in velocity over certain high speed.</td>
</tr>
</tbody>
</table>
Cutting fluid is supplied to a cutting area to obtain fine surface and extend tool life on cutting processing.

3 functions of cutting fluid

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

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

**Cooling**
- Extension of tool life by cooling tool
- Prevention of size deviation by temperature rise of a work piece
Cutting Fluid —Characteristics—

Requirements to cutting fluid

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

No cutting fluid can satisfy all of these requirements.

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

Types and characteristics of cutting fluid

Cutting fluid

- Water-soluble: Fine cooling

- Non water-soluble: Fine lubricity

Elements determining a capacity of non water-soluble cutting fluid

- Viscosity: Low  →  High cleaning & cooling function
  High  →  High lubrication function

- Additive: Contained  →  Cutting ability improves
  (but there is a possibility of corrosion of a work piece or fluid supplying equipment and outbreak of toxic gas during high-temperature milling)

- Fatty oil: Contained
  →  Prevention of occurrence of build-up edge
  Improvement of lubrication function
Cutting Fluid — MQL Processing —

MQL (Minimum Quantity Lubrication)...Milling method using only very small quantity of cutting fluid.

Problems of using cutting fluid

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

Wish to decrease the use amount of cutting fluid

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

Function of cutting fluid on MQL Processing

- Cooling function by evaporation
- Entering a rake face of a tool and forming lubricant film
  - Reduce frictional resistance
- Minimum quantity of cutting fluid is supplied to a cutting point by vacuum suction
  - Continuation of lubrication function

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

(Cooling might be insufficient on processing with large heating value.)
Tool Wear  —Forms of Wear—

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

**Mechanical wear**

![Mechanical wear diagram]

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

**Welding wear**

![Welding wear diagram]

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

**Diffusional wear**

![Diffusional wear diagram]

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

**Chemical wear**

![Chemical wear diagram]

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

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

- **Rake face wear** (Crater)
  - Concavity that occurs near a cutting edge by rake face wear.
  - Likely to occur on high-speed milling of steels by cemented carbide tools.

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

> > End of tool life
Tool Life — Standard & Judgment —

Breakage and wear of an edge part

- Increase of cutting resistance
- Bad finished surface quality

Re-pointing of the edge part or changing cutting tool is needed

**End of tool life**

**Standard for judgment**

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

**Standard for judgment of cemented carbide tool life**

<table>
<thead>
<tr>
<th>Width of relief face wear $w$ (mm)</th>
<th>Max. depth of crater $t$ (mm)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.03</td>
<td>• Accurate light milling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Finishing of non-ferrous alloys, etc.</td>
</tr>
<tr>
<td>0.4</td>
<td>0.05</td>
<td>Milling of alloy steels, etc.</td>
</tr>
<tr>
<td>0.7</td>
<td>0.08</td>
<td>General milling of cast iron, steels, etc.</td>
</tr>
<tr>
<td>1 - 1.25</td>
<td>0.08</td>
<td>Roughing of gray cast iron, etc.</td>
</tr>
</tbody>
</table>
Tool Life —Factors Determining Tool Life—

Tool life equation (F. W. Taylor)

\[ V_c \cdot T^m = C \quad \leftrightarrow \quad T = \left( \frac{C}{V_c} \right)^{\frac{1}{m}} \]

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

From the equation above...

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

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

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

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
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<tbody>
<tr>
<td>Cutting action</td>
<td>Repeating “moving of a cutting edge”, “plastic deformation” and “chip evacuation” continuously.</td>
</tr>
<tr>
<td>Cutting chips</td>
<td>Cutting condition, tool material &amp; heat generation are reflected to chip form. Information source to know a state of cutting.</td>
</tr>
</tbody>
</table>
| Phenomena during cutting     | - Build-up edge  
- Chattering  
Influence on tool life and a finished surface  
Measures to prevent occurrence are needed. |
| Cutting resistance           | Changes according to sharpness of a tool, cutting conditions, etc.  
(Relationship to a condition of cutting, power and cutting heat)                                                                     |
| Cutting fluid                | Need to understand functions of cutting fluid and select suitable one in accordance with the type of cutting.                                    |
| Tool life                    | Use of a tool  
- Deterioration of tool condition by wear, etc.  
- Deterioration of finished surface quality  
- Pay attention to determining tool life and making a fine finished surface  
- Prolong tool life and improve cutting performance by coating technology |