Milling 101

CONTENTS

Introduction of Milling

- Material-removal operation:
  - Cutting and shaping materials by means of a rotating cutting tool.
- Cutting tool is the main interface between your machine and your work material.
  - Much like how custom tires on a high-end sports car ensure a peak driving experience.
- Maximum material-removal efficiency:
  - Selected cutting tool, employed machining parameters.

Introduction of Milling

- Select all proper variables necessary for a successful milling operation, historically is:
  - Tribal knowledge / "our ways of doing things"
  - An art form
  - Not easily transferred to others

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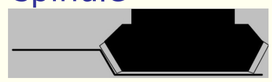
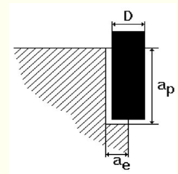
Categories of Milling

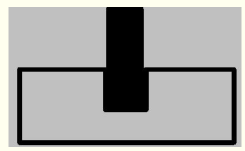
- Face milling
  - Creating a flat surface on the workpiece
  - Cutting plane ⊥ axis of spindle



- Periphery milling (Side milling)
  - Cutting plane // axis of spindle



- Slot milling
  - Disc mills and End mills



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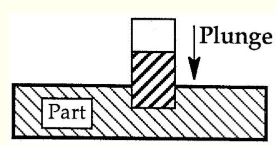
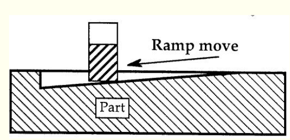
Categories of Milling

- Z-axis plunge milling
  - Higher material-removal rate with long reach capability
  - Cutter forces are directed into the cutter axially

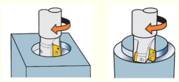


- Ramping
  - Creates angled surface
  - Used as lead in/out
    - Pocketing

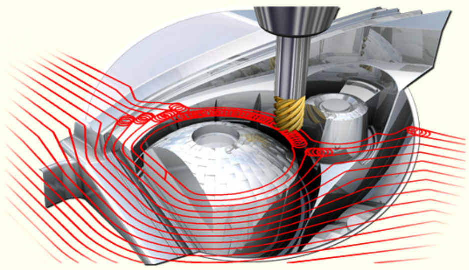


Categories of Milling

- Helical and Circular interpolation
  - Creating cylindrical surface
  - Creating entry points for later applications

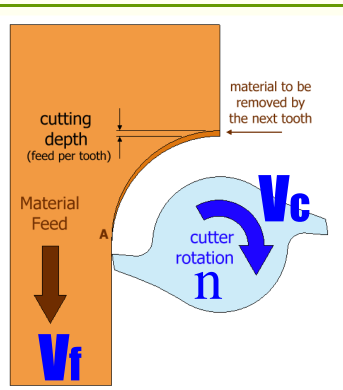


- Trochoidal

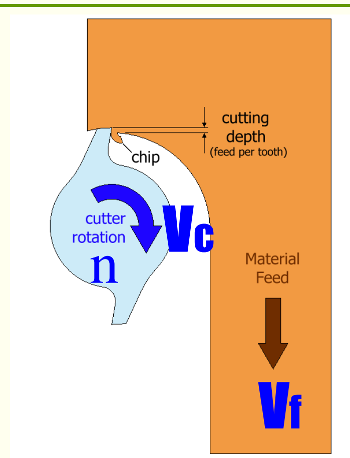


Helical Interpolation

Cutting Parameters



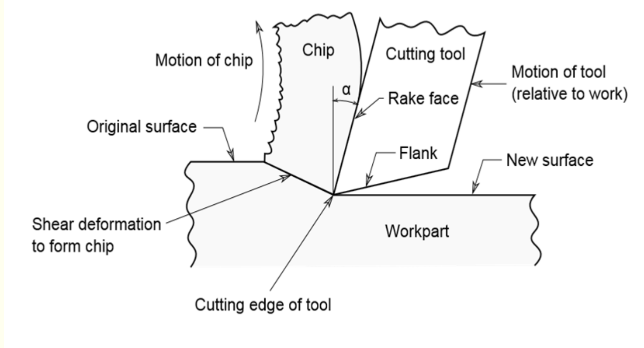
Conventional Milling

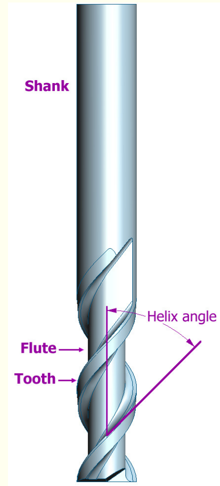


Climb Milling

Cutting Parameters

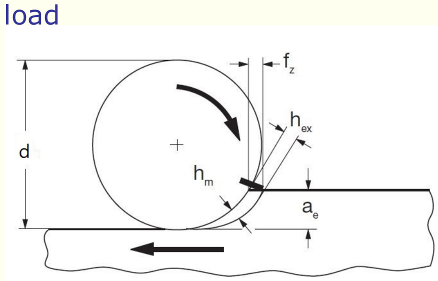
- Cutting stability ↑, if helix and normal rake angles ↑





Cutting Parameters

- Feed per tooth, f_z:
  - Linear distance traveled by the cutter during engagement of a single cutting tooth
  - Sometimes quoted as chip load

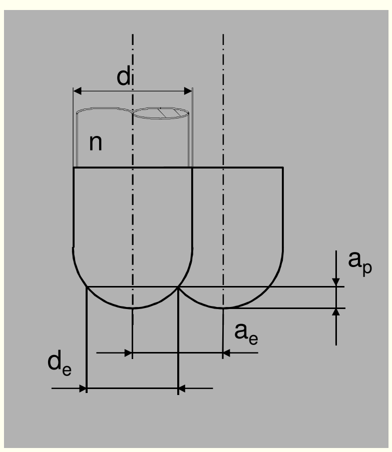


- Chip thickness:
  - Average chip thickness h_m
  - Maximum chip thickness h_{ex}
  - Amount taken by each insert as it advances through the arc of the cut.
  - Define a milling cutter's performance

Cutting Parameters

- a_p: Axial depth of cut or Stepdown (mm)
- a_e: Radial depth of cut or Stepover (mm)
- n: Spindle rotational speed (rpm)
- V_c: Cutting speed (m/min)
- f_z: Feed per tooth per revolution (mm)
- z : Number of tooth or flute or cutting edge
- V_f: Feed rate or table feed (mm/min)
- Q: Material removal rate (mm^3/min)

Cutting Parameters



$$Q = a_p \times a_e \times V_f \quad [mm^3/min]$$

$$V_f = f_z \times n \times z \quad [mm/min]$$

$$d_e = 2 \times \sqrt{a_p (d - a_p)} \quad [mm]$$

$$V_c = \frac{\pi \times n \times d_e}{1000} \quad [m/min]$$

Cutting Parameters

- General cutting data:

Work Materials	Cutting Speed V_c (m/min) HSS	Carbide	Feed per tooth f_z (mm) for Tool Diameter Range (mm) < 3	3 - 6	6 - 12	12 - 25	> 25
Pure Aluminum	200	268	0.050	0.050	0.127	0.152	0.177
Aluminum Alloy	75	200	0.040	0.040	0.120	0.145	0.150
Stainless Steel 304	23	67	0.010	0.020	0.045	0.070	0.100
Copper	140	300	0.020	0.045	0.045	0.010	0.120
Steel 4140	20	82	0.012	0.012	0.025	0.050	0.076

Type of processing	ap [% or mm]	ae [% or mm]
Roughing	25% - 50%	50% - 80%
Semi-finishing	3% - 4%	20% - 40%
Finishing	0.1 - 0.2 mm	0.1 - 0.2 mm

Cutting Parameters

- Manufacturer's supplied cutting data:

Cutter: Kwan Fung, End Mill, Solid carbide, with coating, z = 4, Helix angle = 30 deg
Material: Aluminium or Copper

Type of processing	Vc [m/min]	ap [% or mm]	ae [% or mm]	f_z [mm]
Side Cutting	300	< 100%	< 50%	0.010 - 0.071
Slot Cutting	300	< 100%	100%	0.009 - 0.058

d [mm]	3	4	5	6	8	10	12	16	20
	f_z [mm]								
Side Cutting	0.010	0.014	0.019	0.027	0.035	0.045	0.053	0.071	0.070
Slot Cutting	0.009	0.012	0.015	0.019	0.029	0.036	0.043	0.047	0.058

Cutter: Kwan Fung, End Mill, Solid carbide, with coating, z = 2, Helix angle = 30 deg
Material: Aluminium or Copper

Type of processing	Vc [m/min]	ap [% or mm]	ae [% or mm]	f_z [mm]
Side Cutting	300	< 100%	< 50%	0.020 - 0.142
Slot Cutting	300	< 100%	100%	0.018 - 0.116

d [mm]	3	4	5	6	8	10	12	16	20
	f_z [mm]								
Side Cutting	0.020	0.028	0.038	0.054	0.070	0.090	0.106	0.142	0.140
Slot Cutting	0.018	0.024	0.030	0.038	0.058	0.072	0.086	0.094	0.116

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Cutting Parameters

- Manufacturer's supplied cutting data:

Cutter: Fraisa AX series, End Mill, Solid carbide, with or without coating, z = 2, Helix angle = 40 deg (for z = 3, f_z ~= 75% of that f_z of z=2)

Material: Unalloyed aluminium

Type of processing	Vc [m/min]	ap [% or mm]	ae [% or mm]	f_z [mm]
Side Cutting	350	150%	40%	0.04 - 0.215
Slot Cutting	300	50%	100%	0.025 - 0.165

	f_z [mm]								
d [mm]	3	4	5	6	8	10	12	16	20
Side Cutting	0.040	0.050	0.050	0.075	0.100	0.125	0.125	0.185	0.215
Slot Cutting	0.025	0.035	0.040	0.050	0.065	0.085	0.100	0.135	0.165

Cutter: Fraisa AX series, End Mill, Solid carbide, with or without coating, z = 2, Helix angle = 40 deg (for z = 3, f_z ~= 75% of that f_z of z=2)

Material: Wrought aluminium alloys Si < 6%

Type of processing	Vc [m/min]	ap [% or mm]	ae [% or mm]	f_z [mm]
Side Cutting	900	150%	40%	0.035 - 0.225
Slot Cutting	900	50%	100%	0.025 - 0.150

	f_z [mm]								
d [mm]	3	4	5	6	8	10	12	16	20
Side Cutting	0.035	0.045	0.055	0.070	0.090	0.115	0.135	0.180	0.225
Slot Cutting	0.025	0.030	0.040	0.045	0.060	0.075	0.090	0.120	0.150

Cutter: Fraisa AX series, End Mill, Solid carbide, with or without coating, z = 2, Helix angle = 40 deg (for z = 3, f_z ~= 75% of that f_z of z=2)

Material: Unalloyed copper

Type of processing	Vc [m/min]	ap [% or mm]	ae [% or mm]	f_z [mm]
Side Cutting	600	150%	40%	0.030 - 0.200
Slot Cutting	600	50%	100%	0.020 - 0.135

	f_z [mm]								
d [mm]	3	4	5	6	8	10	12	16	20
Side Cutting	0.030	0.040	0.050	0.060	0.080	0.100	0.120	0.160	0.200
Slot Cutting	0.020	0.025	0.035	0.040	0.055	0.065	0.080	0.105	0.135

Cutter: Fraisa AX series, End Mill, Solid carbide, with or without coating, z = 2, Helix angle = 40 deg (for z = 3, f_z ~= 75% of that f_z of z=2)

Material: Thermoplastics

Type of processing	Vc [m/min]	ap [% or mm]	ae [% or mm]	f_z [mm]
Side Cutting	1200	150%	40%	0.040 - 0.250
Slot Cutting	1200	50%	100%	0.025 - 0.165

	f_z [mm]								
d [mm]	3	4	5	6	8	10	12	16	20
Side Cutting	0.040	0.050	0.650	0.750	0.100	0.125	0.150	0.200	0.250
Slot Cutting	0.025	0.035	0.040	0.050	0.065	0.085	0.100	0.135	0.165

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Cutting Parameters

- Manufacturer's supplied cutting data:

Cutter: Fraisa AX series, Ball Nose, Solid carbide, with or without coating, z = 2, Helix angle = 40 deg

Material: Wrought aluminium alloys Si < 6%

Type of processing	Vc [m/min]	ap [% or mm]	ae [% or mm]	f_z [mm]
Plane	900	10%	20%	0.060 - 0.200

	f_z [mm]								
d [mm]	3	4	5	6	8	10	12	16	20
Plane	0.060	0.080	0.100	0.090	0.120	0.150	0.120	0.160	0.200

Cutter: Fraisa AX series, Ball Nose, Solid carbide, with or without coating, z = 2, Helix angle = 40 deg

Material: Unalloyed copper

Type of processing	Vc [m/min]	ap [% or mm]	ae [% or mm]	f_z [mm]
Plane	600	10%	20%	0.060 - 0.200

	f_z [mm]								
d [mm]	3	4	5	6	8	10	12	16	20
Plane	0.060	0.080	0.100	0.090	0.120	0.150	0.120	0.160	0.200

Cutter: Fraisa AX series, Ball Nose, Solid carbide, with or without coating, z = 2, Helix angle = 40 deg

Material: Thermoplastics

Type of processing	Vc [m/min]	ap [% or mm]	ae [% or mm]	f_z [mm]
Plane	1200	10%	20%	0.060 - 0.200

	f_z [mm]								
d [mm]	3	4	5	6	8	10	12	16	20
Plane	0.060	0.080	0.100	0.090	0.120	0.150	0.120	0.160	0.200

Cutting Parameters

- Manufacturer's supplied cutting data:

Cutter: Fraisa SX series, End Mill, Solid carbide, with coating, z = 4, Helix angle = 55 deg
Material: Stainless Steel [Cr-Ni]

Type of processing	Vc [m/min]	ap [% or mm]	ae [% or mm]	f_z [mm]
Side Cutting	80	100%	50%	0.015 - 0.105
Slot Cutting	80	50%	100%	0.015 - 0.105

	f_z [mm]								
d [mm]	3	4	5	6	8	10	12	16	20
Side Cutting	0.015	0.020	0.025	0.030	0.040	0.055	0.065	0.085	0.105
Slot Cutting	0.015	0.020	0.025	0.030	0.040	0.055	0.065	0.085	0.105

Cutter: Fraisa SX series, End Mill, Solid carbide, with coating, z = 4, Helix angle = 55 deg
Material: Stainless Steel [Cr-Ni-Mo]

Type of processing	Vc [m/min]	ap [% or mm]	ae [% or mm]	f_z [mm]
Side Cutting	40	100%	50%	0.015 - 0.105
Slot Cutting	40	50%	100%	0.015 - 0.105

	f_z [mm]								
d [mm]	3	4	5	6	8	10	12	16	20
Side Cutting	0.015	0.020	0.025	0.030	0.040	0.055	0.065	0.085	0.105
Slot Cutting	0.015	0.020	0.025	0.030	0.040	0.055	0.065	0.085	0.105

Cutter: Fraisa SX series, End Mill, Solid carbide, with coating, z = 4, Helix angle = 55 deg
Material: Heat resistant steel [17-4 PH]

Type of processing	Vc [m/min]	ap [% or mm]	ae [% or mm]	f_z [mm]
Side Cutting	25	100%	50%	0.015 - 0.085
Slot Cutting	25	50%	100%	0.015 - 0.075

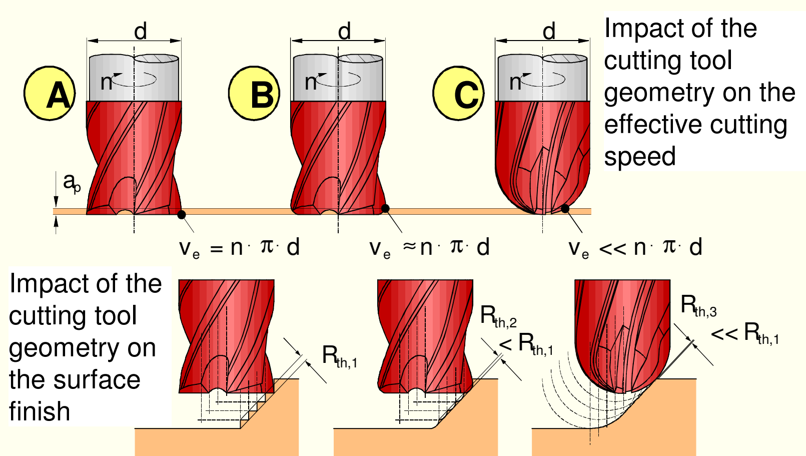
	f_z [mm]								
d [mm]	3	4	5	6	8	10	12	16	20
Side Cutting	0.015	0.020	0.025	0.030	0.035	0.045	0.050	0.060	0.085
Slot Cutting	0.015	0.020	0.025	0.030	0.035	0.045	0.050	0.060	0.075

Cutter: Fraisa SX series, End Mill, Solid carbide, with coating, z = 4, Helix angle = 55 deg
Material: Nickel base alloys prec.-hard. [Inconel 718]

Type of processing	Vc [m/min]	ap [% or mm]	ae [% or mm]	f_z [mm]
Side Cutting	15	100%	50%	0.015 - 0.085
Slot Cutting	15	50%	100%	0.015 - 0.075

	f_z [mm]								
d [mm]	3	4	5	6	8	10	12	16	20
Side Cutting	0.015	0.020	0.025	0.030	0.035	0.045	0.050	0.060	0.085
Slot Cutting	0.015	0.020	0.025	0.030	0.035	0.045	0.050	0.060	0.075

Cutting Parameters



Horse Power at Cutter (HPC)

- HPC = MRR / K:
  - MRR: Material Removal Rate (inch^3 / min) = Q / 16387
    - Q = Material Removal Rate in mm^3/min
  - K: K factor depends on hardness of materials

- MRR = a_p x a_e x V_f
  - a_p = depth of cut (inch)
  - a_e = width of cut (inch)
  - V_f = feed rate (inch per minute, ipm)

- Horse power at motor (HPm) = HPC / E
  - E = 0.75 to 0.9

Horse Power at Cutter (HPC)

- K factor:
  - A power constant represents the no. of in^3 of materials per minute that can be removed by one horsepower.
  - Materials, Hardness (HB), K factor:
    - Stainless Steel / Wrought Iron / Cast Iron, 135-275, 1.54-0.76
    - Stainless Steel / Wrought Iron / Cast Iron, 286-421, 0.74-0.50
    - Titanium, 250-375, 1.33-0.87
    - Iron-based, 180-320, 0.91-0.53
    - Aluminum alloys, 30-150, 6.25-3.33
    - Copper, 150, 3.33
    - Copper alloys, 100-150, 3.33
    - Copper alloys, 151-243, 2.00
- Machines in EMF:
  - Cincinnati Milacron: 5000 rpm, 14.5 kW
  - Chevalier QP2040-L: 8000 rpm, 11 kW
  - Hartford MVP-8: 16000 rpm, 7.5 kW
  - Mikron VCP600: 24000 rpm, 13.5 kW

Cutting Parameters

- Case study 1 – Roughing:
  - Aluminum 6061; Pocketing, Roughing - Raster
  - HSS End Mill dia = 8 mm; 3 flutes
  - From "General Cutting Data":
    - V_C = 75
    - f_z = 0.060 (reduced from 0.12, as the tool overhang is too long)

General Cutting Data:

Work Materials	Cutting Speed V_c (m/min) HSS	Carbide	Feed per tooth f_z (mm) for Tool Diameter Range (mm) < 3	3 - 6	6 - 12	12 - 25	> 25
Aluminum Alloy	75	200	0.040	0.040	0.120	0.145	0.150

    - a_p = 2 mm (i.e. 25% of tool diameter)
    - a_e = 4 mm (i.e. 50% of tool diameter)

Type of processing	ap [% or mm]	ae [% or mm]
Roughing	25% - 50%	50% - 80%

Cutting Parameters

- Case study 1 – Roughing :
  - Estimated cutting parameters are:
    - V_f = 538
    - HPC = 0.0409

Tool Type =	End Mill	*Effective diameter of cutter*	
d (mm) =	8	d_{eff} (mm) =	8.0000
V_c (m/min) =	75		
z =	3		
f_z (mm) =	0.060		
ap (mm) =	2.00	br (mm) =	6.9282
ae (mm) =	4.00	R_{th} (mm) =	2.0000
		If force spindle speed =:	
n (rpm) =	2,985	n_{eff} (rpm) =	2985
V_f (mm/min) =	538	$V_{c,eff}$ (m/min) =	75
		$V_{f,eff}$ (mm/min) =	537
Q (mm^3/min) =	4,304	Q_{eff} (mm^3/min) =	4,298
Cutting Materials =	Aluminum alloys; HB = 30-150	f_z (mm) =	0.060
K factor =	4.79		
HPC (hp) =	0.0548	HPC_{eff} (hp) =	0.0548
HPC (kW) =	0.0409	HPC_{eff} (kW) =	0.0409

Cutting Parameters

- Case study 2 - Finishing:
  - Aluminum 6061; Pocket, Constant Z Finishing
  - HSS End Mill dia = 6 mm; 4 flutes
  - From "General Cutting Data":
    - V_C = 75 and f_z = 0.040

General Cutting Data:

	Cutting Speed V_c (m/min)		Feed per tooth f_z (mm) for Tool Diameter Range (mm)				
Work Materials	HSS	Carbide	< 3	3 - 6	6 - 12	12 - 25	> 25
Aluminum Alloy	75	200	0.040	0.040	0.120	0.145	0.150

- a_p = 3 mm (i.e. 50% of tool diameter for side cutting of end mill)
- a_e = 0.15 mm (the finishing thickness)

Type of processing	ap [% or mm]	ae [% or mm]
Roughing	25% - 50%	50% - 80%
Semi-finishing	3% - 4%	20% - 40%
Finishing	0.1 - 0.2 mm	0.1 - 0.2 mm

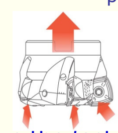
Cutting Parameters

- Case study 2 - Finishing:
  - With the highest possible spindle speed n = 3000rpm:
    - V_f = 480
    - HPC = 0.021

Tool Type =	End Mill	*Effective diameter of cutter*	
d (mm) =	6	d_{eff} (mm) =	6.0000
V_c (m/min) =	75		
z =	4		
f_z (mm) =	0.040		
ap (mm) =	3.00	br (mm) =	6.0000
ae (mm) =	0.15	R_{th} (mm) =	3.0000
		If force spindle speed =:	
n (rpm) =	3,979	n_{eff} (rpm) =	3000
V_f (mm/min) =	637	$V_{c,eff}$ (m/min) =	57
		$V_{f,eff}$ (mm/min) =	480
Q (mm^3/min) =	287	Q_{eff} (mm^3/min) =	216
Cutting Materials =	Aluminum alloys; HB = 30-150	f_z (mm) =	0.040
K factor =	4.79		
HPC (hp) =	0.0037	HPC_{eff} (hp) =	0.0028
HPC (kW) =	0.0027	HPC_{eff} (kW) =	0.0021

Note on Low Speed Machining

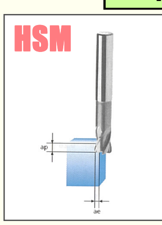
- Realizing high material removal rate Q is the goal.
- High speed machining – leverage spindle speed
  - Speed is only the means.
- Low speed machining – cutting tool technology
  - Roughing with high feed mills
    - Cutting edge geometry that takes advantage of axial chip thinning to achieve a higher feed rate V_f
    - High horse power cuts
    - To make as much use as possible of the machine's horsepower
    - Experimenting with different choice of tools in HPC, Q and f_z
  - Solid carbide end mills capable of heavy depth of cut a_p and feed per tooth f_z
    - For Al, $f_z > 0.25$ mm is possible
  - Finishing by high-flute-count (i.e. z) end mills
    - Higher z can achieve better V_f at lower n
    - Internal corners of part have to be machined first before the fast finishing passes are run.



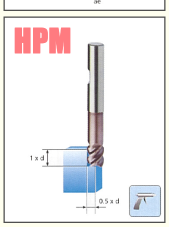
HSM versus HPM

fraisa

Material: Hardened Tool Steel 52 - 56 HRc

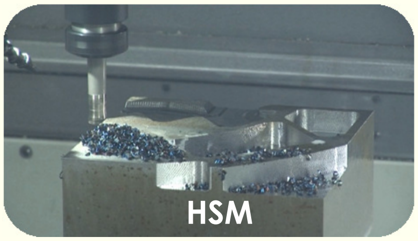


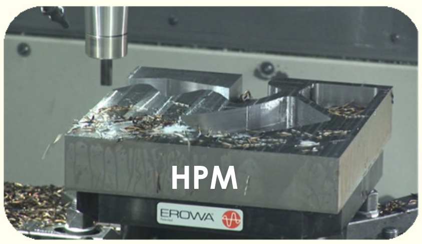
Ø	z	v_c	f_z	a_p	a_e	n	v_f	Q
[mm]	[-]	[m/min]	[mm]	[mm]	[mm]	[min⁻¹]	[mm/min]	[mm³/min]
6	4	120	0.10	0.60	0.80	6370	2550	1'224
8	4	120	0.10	0.80	0.90	4770	1910	1'375
10	4	120	0.10	1.00	1.00	3820	1530	1'530
12	4	120	0.12	1.20	1.10	3180	1525	2'013
16	4	120	0.14	1.50	1.20	2390	1340	2'412

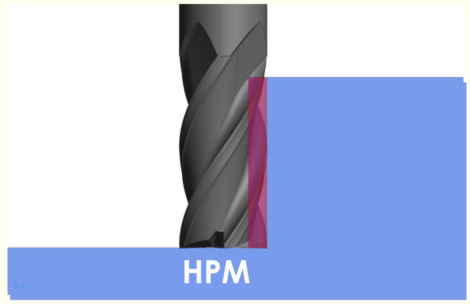


Ø	z	v_c	f_z	a_p	a_e	n	v_f	Q
[mm]	[-]	[m/min]	[mm]	[mm]	[mm]	[min⁻¹]	[mm/min]	[mm³/min]
6	4	45	0.020	6.00	3.00	2120	170	3'100
8	4	45	0.027	8.00	4.00	1590	170	5'400
10	4	45	0.033	10.00	5.00	1270	170	8'500
12	4	45	0.040	12.00	6.00	1190	190	13'700
16	4	45	0.053	16.00	8.00	900	190	24'300

HSM versus HPM







- HPM with improved strategy:
  - Tool overload cannot be tolerated at HPM.
  - Constant tool loading and engagement angle

Design & Manufacturing Services Facility

HSM versus HPM

HPM cutting – slow motion illustration

Chip – color, size, and shape

Cutting Tools

- Two performance criteria
  - Thermal hardness (temperature stability)
  - Toughness or rupture strength
- Quality base material
  - Temperature resistance
  - Hardness
  - Wear resistance (stable cutting edges)
  - Toughness
- Appropriate coating
  - Resistance against oxidation, abrasion, adhesion
  - Thin layer (sharp cutting edges for finishing)
  - Thermal insulation
  - Reduced friction

Cutting Tools

$$\delta = \frac{Fl^3}{3EI}$$

F = Force at end of cylinder

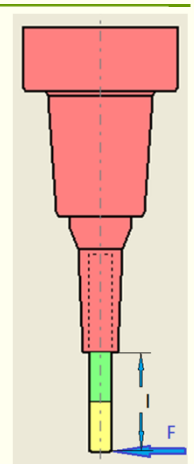
l = Length of overhang

E = Young's Modulus of base material

$$\mathrm{I} = \frac{\pi d^4}{64}\ ;\mathrm{d} = \text{Diameter of cutting tool}$$

$$\delta \propto \frac{l^3}{d^4}$$

$$\frac{1}{2} d \Rightarrow 16\,\delta \quad or \quad 2l \Rightarrow 8\,\delta$$



Cutting Tools

- Cutting tool materials:
  - Sorted from best toughness characteristics (top) to best thermal hardness (bottom).
    - HSS (uncoated and coated - not suitable for HSM)
    - Sintered hard carbide (uncoated and coated)
    - Ceramics
    - CBN
- Never use tools that have been used to machine metal to cut plastic.
  - HSS cutters work best for plastics.
  - Carbide cutters work better for aluminum and other metals.

Cutting Tools

1. Hardness < 42 HRC: TiN and TiCN coated Carbide
2. Hardness > 42 HRC: TiAlN coated Carbide
3. Hardness > 60: PCBN
4. Cast Iron: CBN and ceramic
5. Aluminum: Poly crystalline diamonds (PCD) and Cermet

- Physical vapour deposition (PVD)
  - Solid carbide
  - Results in sharper cutting edge
- Chemical vapour deposition (CVD)
  - Mass production of inserts

Conventional vs HSM Machining

Conventional	HSM
The contact time between tool and work is large	Contact time is short
Less accurate work piece	More accurate work piece
Cutting force is large	Cutting force is low
Low surface finish	High surface finish
Material removal rate is low	Material removal rate is high
Cutting fluid is required	Cutting fluid is not required