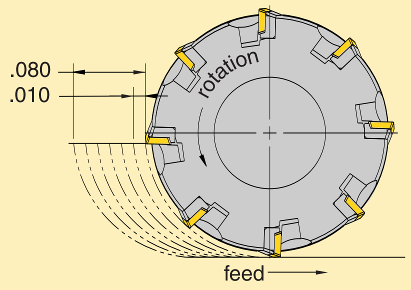
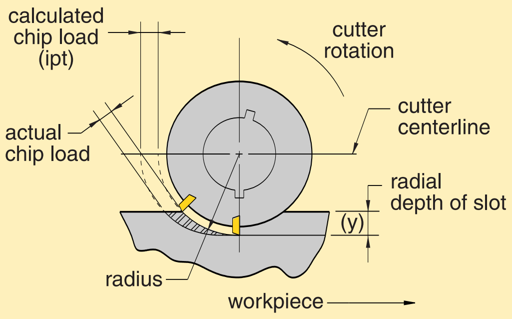
Technical Information

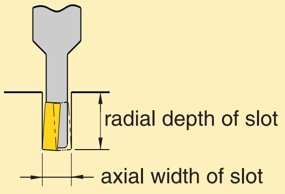
Formulas

to find	given	formula
sfm	D rpm	$\text{sfm} = \frac{\pi \times D \times \text{rpm}}{12}$
rpm	D sfm	$\text{rpm} = \frac{12 \times \text{sfm}}{\pi \times D}$
ipr	ipm rpm	$\text{ipr} = \frac{\text{ipm}}{\text{rpm}}$
ipm	ipt rpm nt	$\text{ipm} = \text{ipt} \times \text{nt} \times \text{rpm}$
ipt	nt ipm rpm	$\text{ipt} = \frac{\text{ipm}}{\text{nt} \times \text{rpm}}$
ipt	nt ipr	$\text{ipt} = \frac{\text{ipr}}{\text{nt}}$

legend		
sfm	=	surface feet per minute
rpm	=	revolutions per minute
D	=	cutter diameter
ipr	=	inch (advance) per revolution
ipm	=	(feed) inches per minute
ipt	=	inch per tooth (chip load)
nt	=	number of effective teeth or inserts in cutter
π	=	3.1416







slot milling

example:

given	calculated		
6" cutter diameter 8 teeth in cutter 600 sfm .010 ipt	rpm =	$\frac{12 \times 600}{3.1416 \times 6}$	= 382
	ipm =	.010 x 8 x 382	= 30.6
	ipr =	$\frac{30.6}{382}$	= .080

Slotting or Periphery Milling

True or actual chip load on the cutting edge of the insert is equal to the programmed chip load only when 50% or more of the cutter's diameter is engaged in the cut (lead angle not considered). Anything less than half the diameter of the cutter means that the actual chip load is reduced by some percentage. The smaller the radial depth of cut, the greater the decrease in actual chip load.

It's very important to maintain a chip load which is great enough to ensure heat dissipation and prevent work hardening. A sufficient chip load will also create stability between the cutter and the workpiece.

The formulas shown below are used to determine the programmed chip load, or feed rate necessary to obtain the desired load on the insert cutting edge as it enters the workpiece. These formulas should be applied whenever an arbor mounted slotting cutter is being used, or when less than half the diameter of a face mill or end mill is engaged in the cut. The lighter the radial depth of cut, the more important it becomes to apply these productivity formulas.

Productivity Formulas

$$\textbf{chip load (ipt)} = \frac{\left(\frac{\sqrt{(\text{dia.} - y) \times (y)}}{\text{radius}}\right) \times \left(\frac{\text{ipm}}{\text{rpm}}\right)}{\text{nt}}$$

or

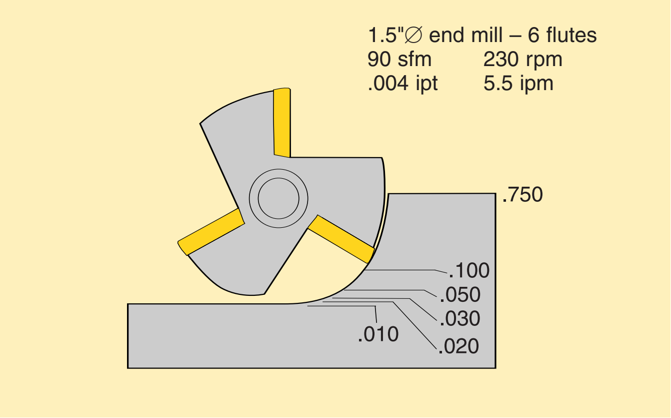
$$\textbf{ipm} = \frac{\text{rpm} \times \text{nt} \times \text{ipt}}{\left(\frac{\sqrt{(\text{dia.} - y) \times (y)}}{\text{radius}}\right)}$$

Technical Information

Feed Rate Compensation

Operations such as **periphery milling with a light radial depth of cut or slotting with an arbor mounted cutter** require a calculation for feed rate compensation to maintain the proper chip load on the insert edge at entry into the cut. The calculated chip load and actual chip load can be dramatically different, depending on the radial depth and the cutter diameter. For instance, the actual chip load on entry for a 3/4" diameter cutter taking a .010 radial depth cut is only 23% of the calculated chip load. It is not uncommon to encounter built-up edge, work-hardening, or chatter problems if the following formula is not applied. Minimal cutter runout is critical to obtaining an equal chip load on each flute of the cutter too. A side benefit to applying this formula is increased productivity as feed rates can increase dramatically.

radial depth of cut	actual chip load (ipt)	feed required (ipm) to maintain .004 ipt	increase
.750	.0040	5.5	0%
.100	.0020	11.5	109%
.050	.0014	15.3	178%
.030	.0011	19.6	256%
.020	.0009	23.9	335%
.010	.0006	33.8	515%



Formulas—Horsepower

metal removal rate

The metal removal rate (mrr) calculation is a good basis for determining metalcutting efficiency.

mrr = doc x woc x ipm = cu. inches/min.

horsepower consumption

Milling cutters can consume significant amounts of horsepower. Very often it is the lack of horsepower that is the limiting factor when deciding on a particular operation. On applications where large diameter cutters or heavy stock removal is necessary, it's advantageous to first calculate the necessary horsepower requirements.

NOTE: Spindle efficiency "E" varies from 75 to 90%.
(E = .75 to .90)

A suitable formula for calculating horsepower (HP_c) at the cutter is:

$$HP_c = \frac{mrr}{K}$$

example:
width of cut . . . . 1.64"
depth of cut 200
feed . . . . 19.5 ipm
4140 220 HB. . . ."K" factor 1.56

mrr = .200 x 1.64 x 19.5 = 6.4 cu. in./min.

$$HP_c = \frac{6.4}{1.56} = 4.1 \text{ HP at the cutter}$$

For horsepower at the motor (HP_m), use formula:

$$HP_m = \frac{HP_c}{E} \qquad HP_m = \frac{4.1}{.8} = 5.1$$

In determining horsepower consumption, "K" factors must be used. The "K" factor is a power constant that represents the number of cubic inches of metal per minute that can be removed by one horsepower.

NOTE: "K" factors vary depending on the hardness of the material.

"K" Factors

work material	hardness HB	"K" factor
steels, and wrought and cast irons (plain carbon alloy steels, and tool steels)	85-200	1.64
	201-253	1.56
	254-286	1.28
	287-327	1.10
	328-371	.88
	372-481	.69
	482-560	.59
	561-615	.54
precipitation hardening stainless steels	150-450	1.27-.42
cast irons (gray, ductile, and malleable)	150-175	2.27
	110-190	2.0
	176-200	1.89
	201-250	1.52
	251-300	1.27
	301-320	1.19
stainless steels, and wrought and cast irons (ferritic, austenitic, and martensitic)	135-275	1.54-.76
	286-421	.74-.50
titanium	250-375	1.33-.87
high-temperature alloys, nickel, cobalt base	200-360	.83-.48
iron base	180-320	.91-.53
nickel alloys	80-360	.91-.53
aluminum alloys	30-150 (500 kg)	6.25-3.33
magnesium alloys	40-90 (500 kg)	10.0-6.67
copper	150	3.33
copper alloys	100-150	3.33
	151-243	2.0

Formulas–Horsepower: New Method for Calculating When Using High-Shear Cutters

Over the past 50 years, metal removal rates (mrr) and power constants have served as the conventional values used to calculate horsepower. Although this is a relatively common method of calculating horsepower, **a more accurate method has been developed when milling with high shear cutters. This new approach utilizes the following information:**

1. calculating tangential force (F_t)
2. ultimate material strength
3. cross-sectional area of the chip
4. number of inserts in the cut
5. machinability factor
6. tool wear factor
7. calculating torque
8. calculating horsepower at cutter
9. calculating horsepower at motor

Tangential Force, Torque, and Horsepower Calculations In Face Milling with High Shear Milling Cutters

1. calculation of tangential force (ft.-lbs.)

Calculation of tangential force is important since it produces torque at the spindle and accounts for the greatest portion of machining power at the cutting tool. Using this tangential force formula is a quick way to determine the approximate forces that fixtures, part wall sections, or spindle bearings will endure. Tangential force is calculated with the following formula:

$$F_t = S \times A \times Z_c \times C_m \times C_w \qquad \text{(lbs.)}$$

where: S = ultimate strength of the work material (psi)
A = cross-sectional area of the chip removed by the milling insert (in.^{2})
Z_c = number of inserts in cut
C_m = machinability factor
C_w = tool wear factor

2. ultimate material strength (psi)

The approximate relationship between the ultimate material strength and hardness of the most commonly used work materials such as steels, irons (for example: gray cast iron), titanium alloys (Ti – 6Al – 4V), and aluminum alloys (2024, 5052) can be expressed by the empirical formula:

$$S = 500 \times HB \qquad \text{(psi)}$$

where HB = Brinell hardness numbers obtained, primarily, at the 3000-kgf load. When testing soft metals such as aluminum alloys, the 500-kgf load is used. Hardness obtained at the 500-kgf load should be converted into the hardness equivalent of the 3000-kgf load by using the load factor of 1.15. For example, 130 HB at the 500-kgf load is equivalent to 150 HB at the 3000-kgf load (130 x 1.15 = 150). If hardness is given in Rockwell "B" or Rockwell "C" numbers, see Appendix 1 (page M462).

3. cross-sectional area of the chip (A)

Cross-sectional area of the chip (Fig. 2) is defined by:

$$A = d\,f \ (\text{in.}^2\text{, or mm}^2)$$

where: d = axial depth of cut (in., or mm)
f = feed per tooth (in., or mm)

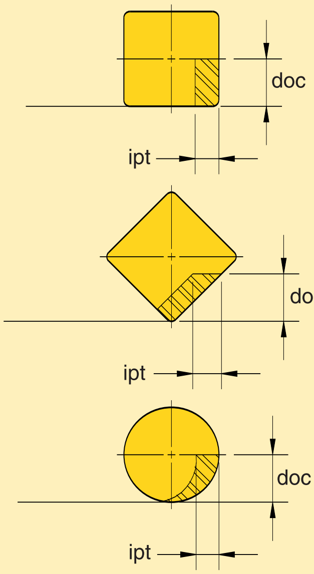


Figure 1: Cross-sectional area of the chip and insert's shape

4. number of inserts in cut (Z_c)

The number of inserts in the cut (simultaneously engaged with work material) depends on the number of inserts in the cutter "Z" and the engagement angle (α). This relationship is shown by the formula:

$$Z_c = \frac{Z \times \alpha^\circ}{360^\circ}$$

The engagement angle depends on the width of cut "W" and cutter diameter "D". This angle is found from the geometry of figure 2 (formulas to calculate engagement angle and the number of inserts in the cut at any width of cut are given in Appendix 2, page M462).

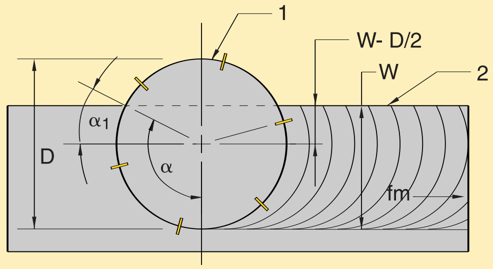


Figure 2: Schematic for calculating the number of inserts in cut

1 = milling cutter
2 = workpiece
α = engagement angle
α_1 = the angle between cutter centerline and cutter radius to the peripheral point of exit or entry
W = width of cut (woc)
D = cutter diameter
fm = workpiece feed motion

Tangential Force, Torque, and Horsepower Calculations In Face Milling with High Shear Milling Cutters

If the width of cut equals cutter diameter (W/D = 1.0), the engagement angle $\alpha = 180°$ and $Z_c = \frac{Z \times 180°}{360°} = 0.5Z$. If the width of cut is equal to half of the cutter's diameter (W/D = 0.5), the engagement angle $\alpha = 90°$ and $Z_c = \frac{Z \times 90°}{360°} = .25Z$. The values of Z_c, depending on the given W/D ratios, are shown in Table 1.

Table 1

W/D	.88	.80	.75	.67	.56	.38	.33	.19	.125
Z_c	.38Z	.35Z	.33Z	.30Z	.27Z	.21Z	.20Z	.14Z	.12Z

5. machinability factor (C_m)

Machinability factor is used to indicate degree of difficulty in machining various workpiece materials. Table 2 shows machinability factor values for some of the most common workpiece materials.

Table 2

workpiece material	C_m W/D≤.67	 .67<W/D<1.0	 W/D=1.0
carbon and alloy steels	1.0	1.15	1.3
stainless steel	2.0	2.15	2.3
gray cast iron	1.0	1.15	1.3
titanium alloys	1.0	1.20	1.4
aluminum alloys	1.0	1.05	1.1

The values of C_m are based on milling tests with a torque dynamometer at different cutting conditions. It has been found that machinability factor depends on type of work material and the ratio of radial width of cut to cutter diameter (W/D).

This ratio determines the uniformity of the chip thickness. When W/D = 1.0, the chip at the point of entry starts off at zero thickness. It increases to a maximum thickness at the centerline of the cutter, and thins off to zero again at the point of exit. This type of cut generates maximum friction at the cutting edge, and machinability factor reaches its maximum value. The optimal cutting conditions are obtained when W/D = 2/3 = .67. The thickness of the chip is practically uniform, the friction is minimal, and machinability factor decreases to its minimum value.

More extensive testing will determine machinability factors for a larger variety of work materials and improve the accuracy for calculating tangential force and power consumption.

6. tool wear factor (C_w)

For milling with sharp cutting tools (short time operation), tool wear factor $C_w = 1.0$. For a longer operation (before the inserts are indexed), the following tool wear factors are considered:

- light face milling $C_w = 1.1$
- general face milling $C_w = 1.2$
- heavy-duty face milling $C_w = 1.3$

7. calculation of torque (in.-lb.)

The torque "T" generated by tangential force is calculated using the following formula:

$$T = F_t \times D/2 \qquad \text{(in.-lb.)}$$

where D = cutter diameter

8. calculating horsepower (HP_c or HP_m)

The machining power at the cutter (sharp edges) is calculated by either of these two formulas:

$$HP_c = \frac{F_t \times sfm}{33{,}000}$$

or

$$HP_c = \frac{T \times rpm}{63{,}000}$$

where sfm = peripheral cutting speed (sfm)
rpm = spindle speed (rpm)
33,000 and 63,000 = conversion factors

9. The required power at the motor is calculated using the following formula (HP_m):

$$HP_m = \frac{HP_c}{E}$$

where E = machine tool efficiency factor (E = .75 to .90)

NOTE: Spindle efficiency varies from 75 to 90%.

Tangential Force, Torque, and Horsepower Calculations In Face Milling with High Shear Milling Cutters (cont'd.)

Example for Calculating Horsepower

given values

milling cutter KSSISR – 492 – SE443 – 45 – 06:

effective diameter	$D = 4.92$ in.
number of inserts	$Z = 6$

workpiece material:

alloy steel	AISI 4140
hardness	220 HB

machining conditions:

spindle speed	rpm	=	349
cutting speed	sfm	=	450
machine feed rate	ipm	=	19.5
inch per tooth (chip load)	ipt	=	.008 in.
axial depth of cut	doc	=	.200 in.
radial width of cut	woc	=	1.64 in.
W/D ratio	W/D	=	.33

Step-By-Step Calculations

1. calculating tangential force

1.1 ultimate strength of the work material

$S = 500 \times HB = 500 \times 220 = 110{,}000$ psi

1.2 cross-sectional area of the chip

$A = doc \times ipt = .200 \times .008 = .0016 \text{ in.}^2$

1.3 number of inserts in cut:

width of cut-to-diameter ratio (w/d)

$W/D = 1.64 / 4.92 = .33$ (See Table 1, page M448.)

Now use Z_c value shown in Table 1 under .33.

$Z_c = .20 \times Z = .20 \times 6 = 1.2$ inserts in cut.

NOTE: Z = number of inserts in cutter.

1.4 tangential force

$F_t = S \times A \times Z_c \times C_m \times C_w$

$F_t = 110{,}000 \times .0016 \times 1.2 \times 1.1 \times 1.1 = 256$ lbs.

NOTE: $C_m = 1.1$ and $C_w = 1.1$

2. calculating torque at the cutter

$$T = (F_t \times D)/2 = \frac{256 \times 4.92}{2} = 630 \text{ in.-lb.}$$

3. calculating horsepower

- At the cutter...reference formulas in paragraph 8 on page M448

$$HP_c = \frac{F_t \times sfm}{33{,}000} = \frac{256 \times 450}{33{,}000} = 3.5 \text{ hp}$$

or

$$HP_c = \frac{T \times rpm}{63{,}000} = \frac{630 \times 349}{63{,}000} = 3.5 \text{ hp}$$

- At the motor...reference formula in paragraph 9 on page M448

where E = machine tool efficiency factor (E = .75 to .90)

$$HP_m = \frac{HP_c}{E} = \frac{3.5}{.8} = 4.4 \text{ hp}$$