Primitive tools to cut and scrape go back at least 150,000 yrs

Subtractive Processes: Machining

2.810

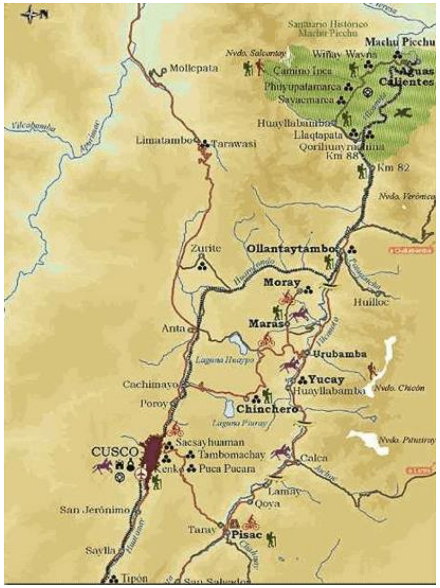
T. Gutowski

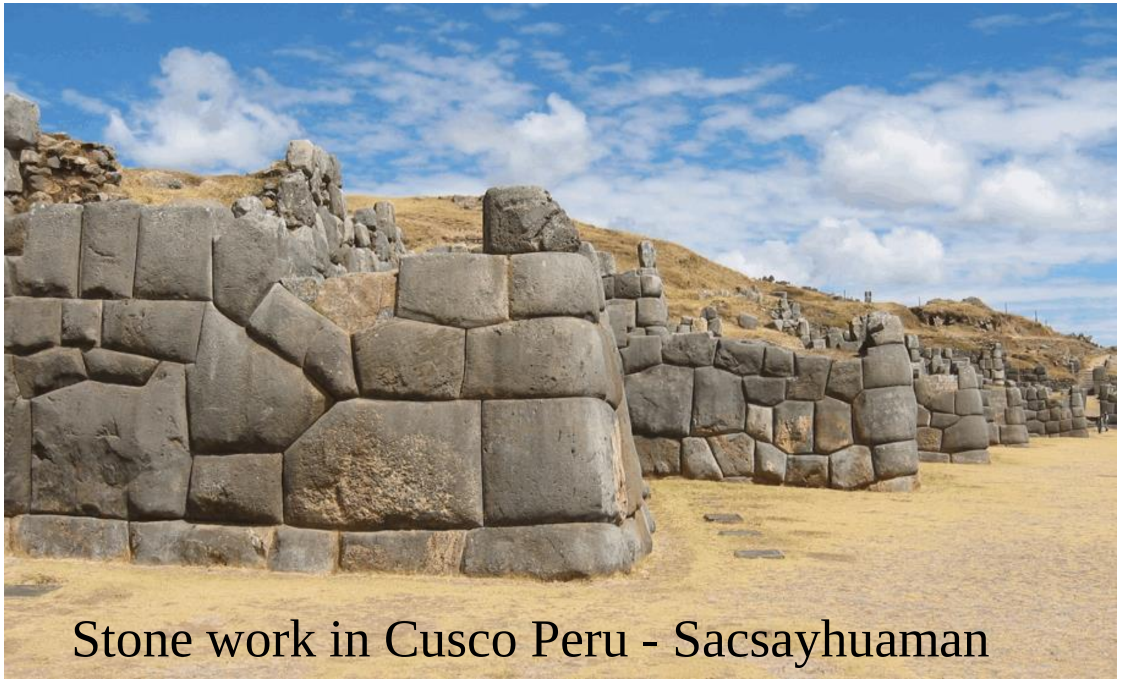
5 axis machining of aluminum

Machining tutorial:

http://electron.mit.edu/~gsteele/mirrors/www.nmis.org/EducationTraining/machineshop/mill/intro.html

Ancient Tools & Structures

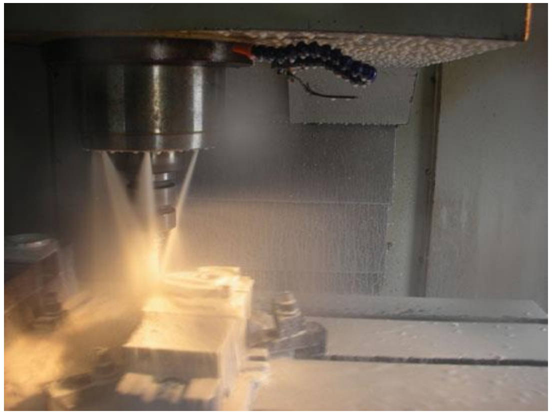




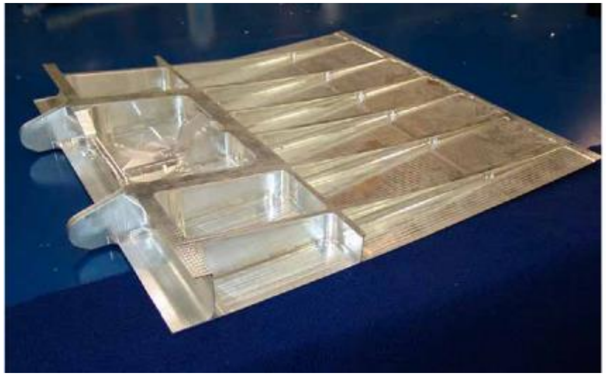
Stone work in Cusco Peru - Sacsayhuaman

Modern Machining Practice

5 axis



High speed



Complex parts

New Configurations

Readings

- Kalpakjian & Schmid Machining chapters are extensive: Ch 21-27
- Design for Machining handout

Outline

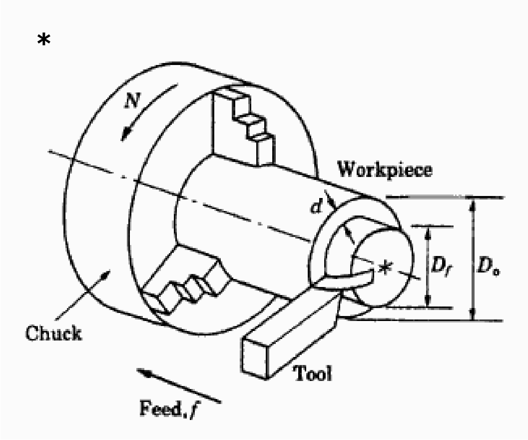
1. Basics
2. Machine Configurations
3. Production Configurations
4. Processing Planning
5. Environment

Basics: Machining Process

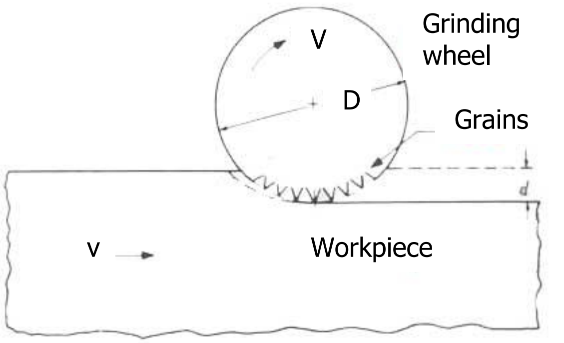
- Single point machining
  - Turning, boring, trepanning, planing
- Multiple point machining
  - Drilling, milling, reaming, sawing, broaching, grinding
- Tool Stationary: turning, boring…
- Tool moves: sawing, milling, drilling, broaching
- Work Piece moves: milling, boring…
- Both move: milling, 5 axis milling

Machining processes

Turning

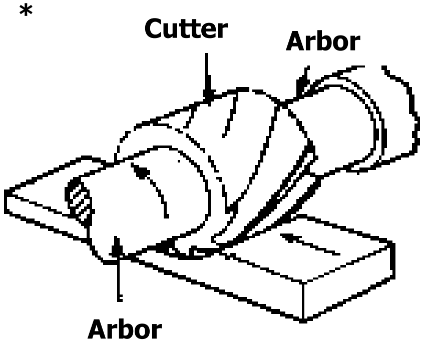


Grinding

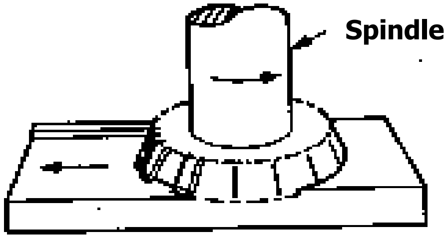


Milling

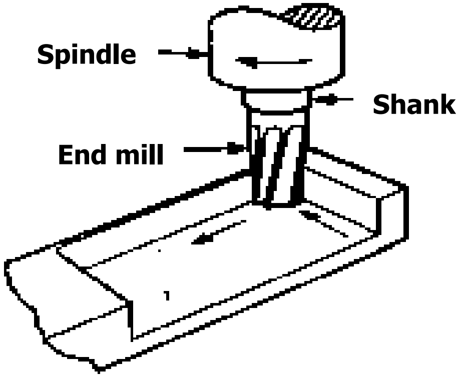
*



Horizontal Slab milling



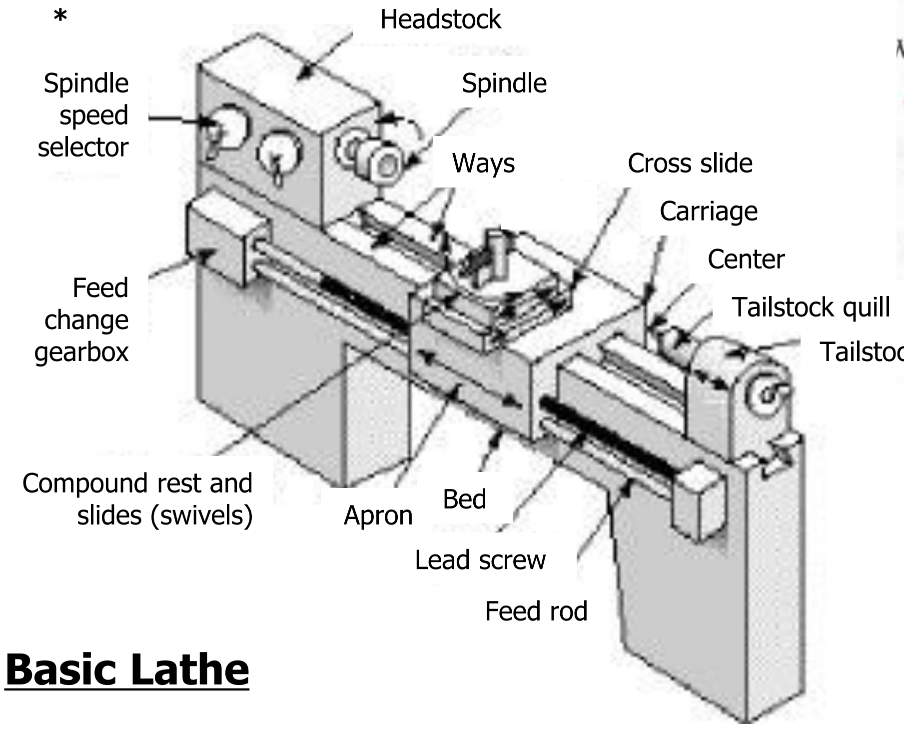
Face milling



End milling

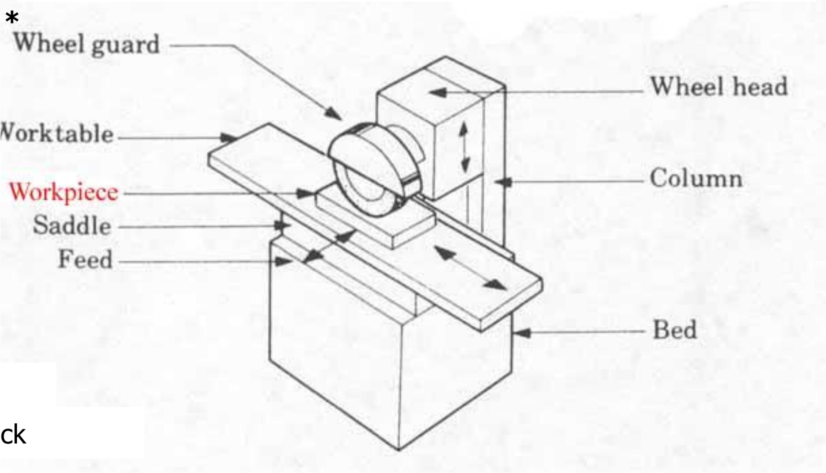
* Source: Kalpakjian, “Manufacturing Engineering and Technology”

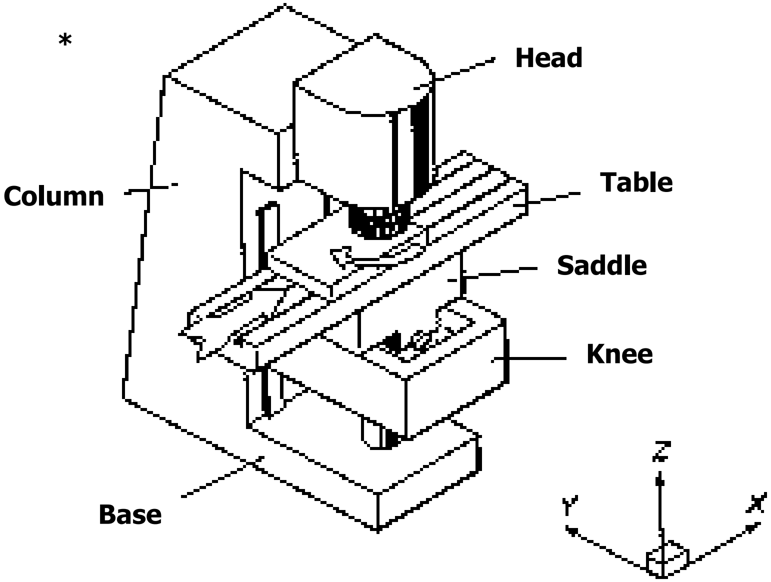
Machine Tools



Basic Lathe

Horizontal-spindle surface grinder

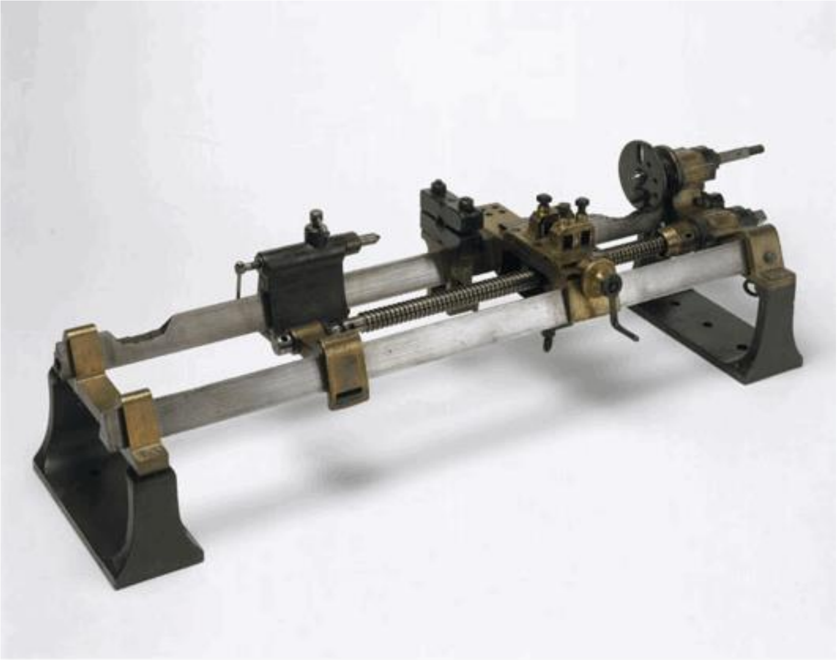




Vertical-Spindle Mill

* Source: Kalpakjian, “Manufacturing Engineering and Technology”

Historical Development of Machine Tools

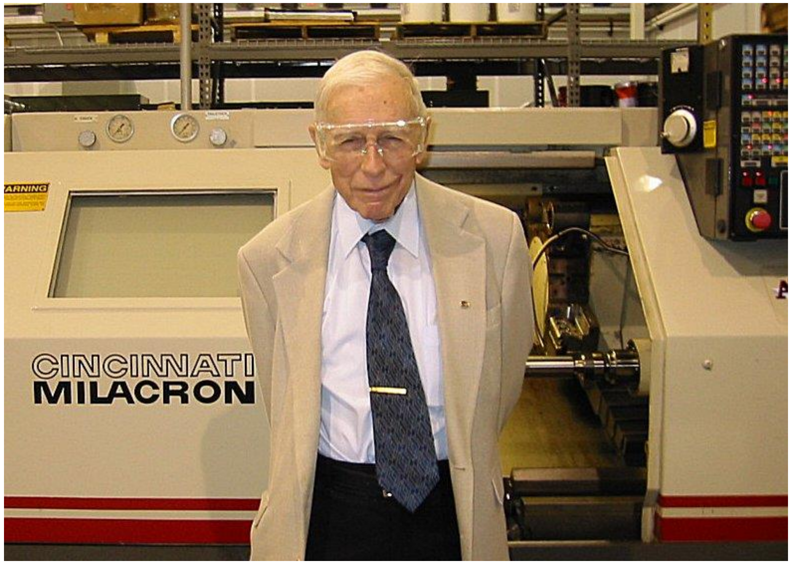


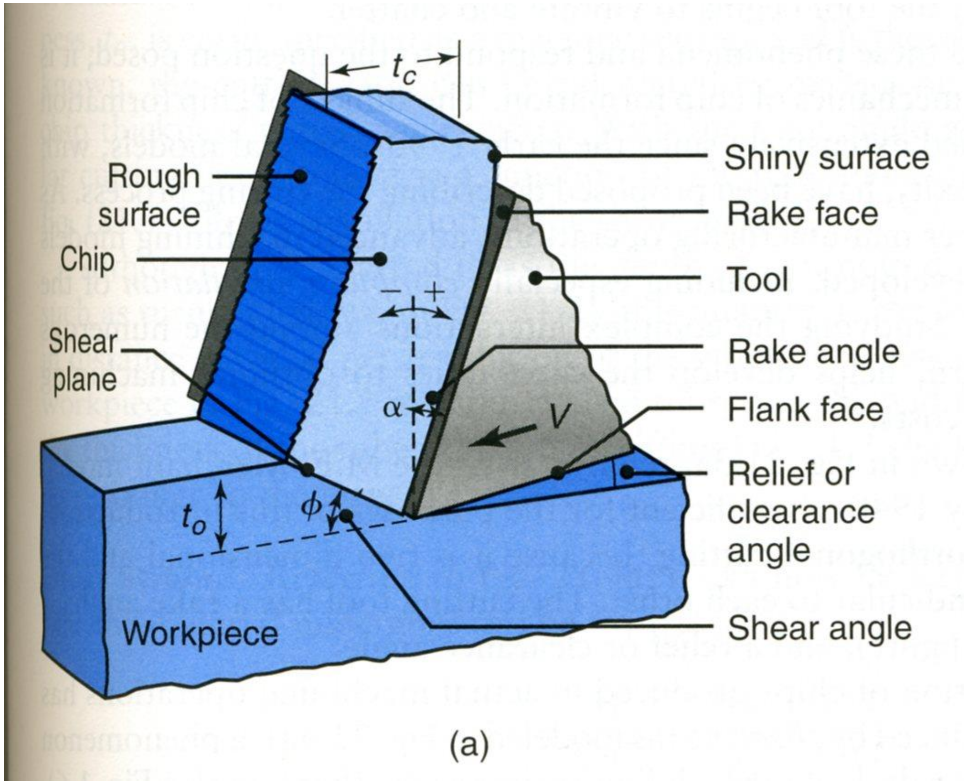
Henry Maudslay, American System, CNC, Transfer Lines…

Basic Mechanics Issues

- Shear strain
- Power, plastic work
- Friction, forces
- Temperature rise
- Heat, Tool materials, Rate limits

Basic Machining Mechanism

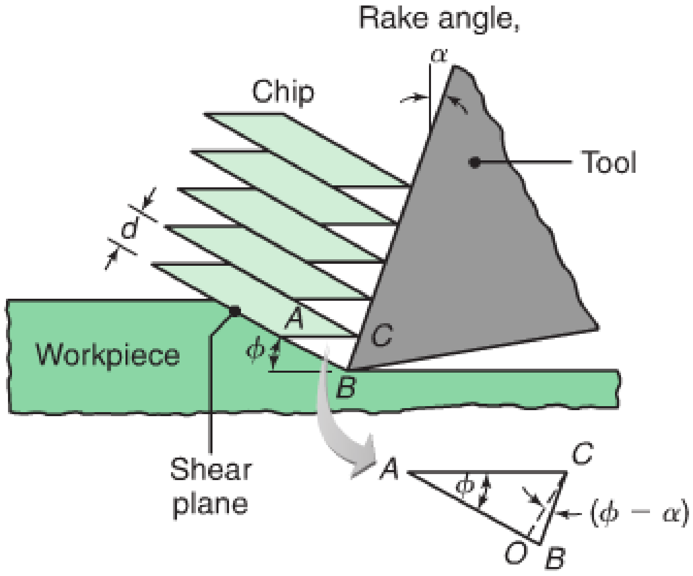




Eugene Merchant’s model for orthogonal cutting

Video on plastic deformation in machining

Basic Machining Mechanism



(a)

$$\gamma = \frac{AB}{OC} = \frac{AO}{OC} + \frac{OB}{OC}$$

Shear takes place in
a narrow zone near
the tool tip at angle ϕ,
the tool has rake angle α,
the resulting shears is γ
From geometry,

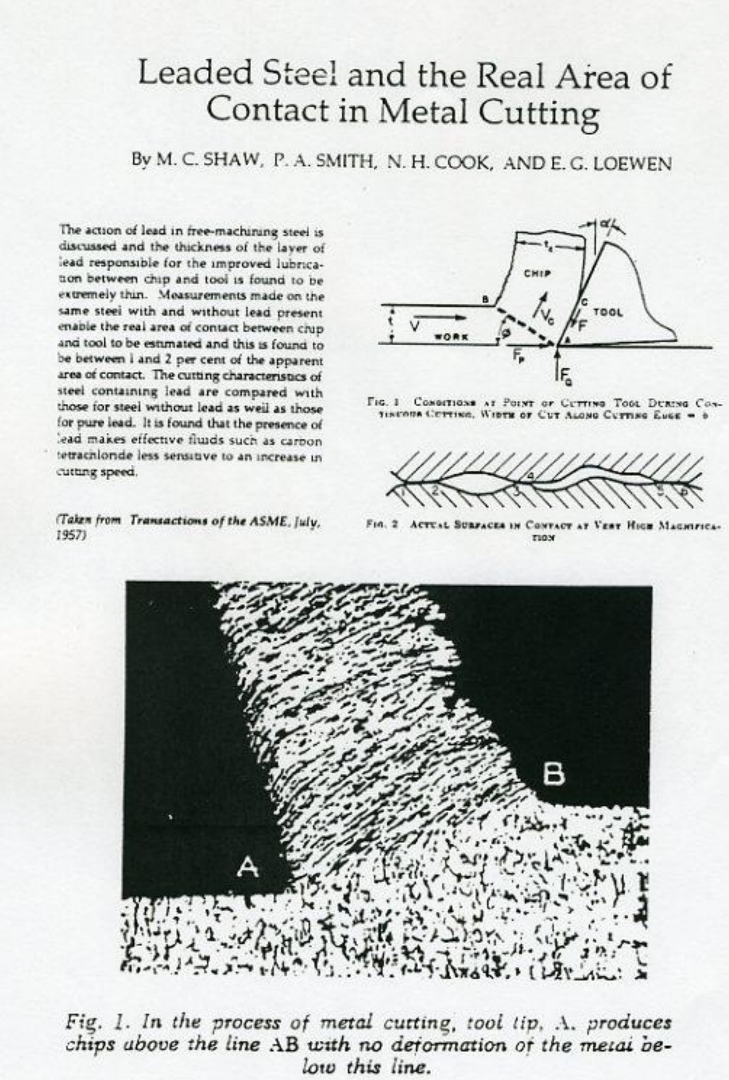
γ= cot(ϕ) + tan (ϕ - α)

γ becomes large for small ϕ,
and small or negative α

Early paper on cutting mechanics

Prof Milt Shaw

Prof Nate Cook



Leaded Steel and the Real Area of Contact in Metal Cutting

By M. C. SHAW, P. A. SMITH, N. H. COOK, AND E. G. LOEWEN

The action of lead in free-machining steel is discussed and the thickness of the layer of lead responsible for the improved lubrication between chip and tool is found to be extremely thin. Measurements made on the same steel with and without lead present enable the real area of contact between chip and tool to be estimated and this is found to be between 1 and 2 per cent of the apparent area of contact. The cutting characteristics of steel containing lead are compared with those for steel without lead as well as those for pure lead. It is found that the presence of lead makes effective fluids such as carbon tetrachloride less sensitive to an increase in cutting speed.

(Taken from ***Transactions of the ASME****, July, 1957)*

FIG. 1 CONDITIONS AT POINT OF CUTTING TOOL DURING CONTINUOUS CUTTING, WIDTH OF CUT ALONG CUTTING EDGE = b

FIG. 2 ACTUAL SURFACES IN CONTACT AT VERY HIGH MAGNIFICATION

Fig. 1. In the process of metal cutting, tool tip, A, produces chips above the line AB with no deformation of the metal below this line.

Basic Machining Mechanism

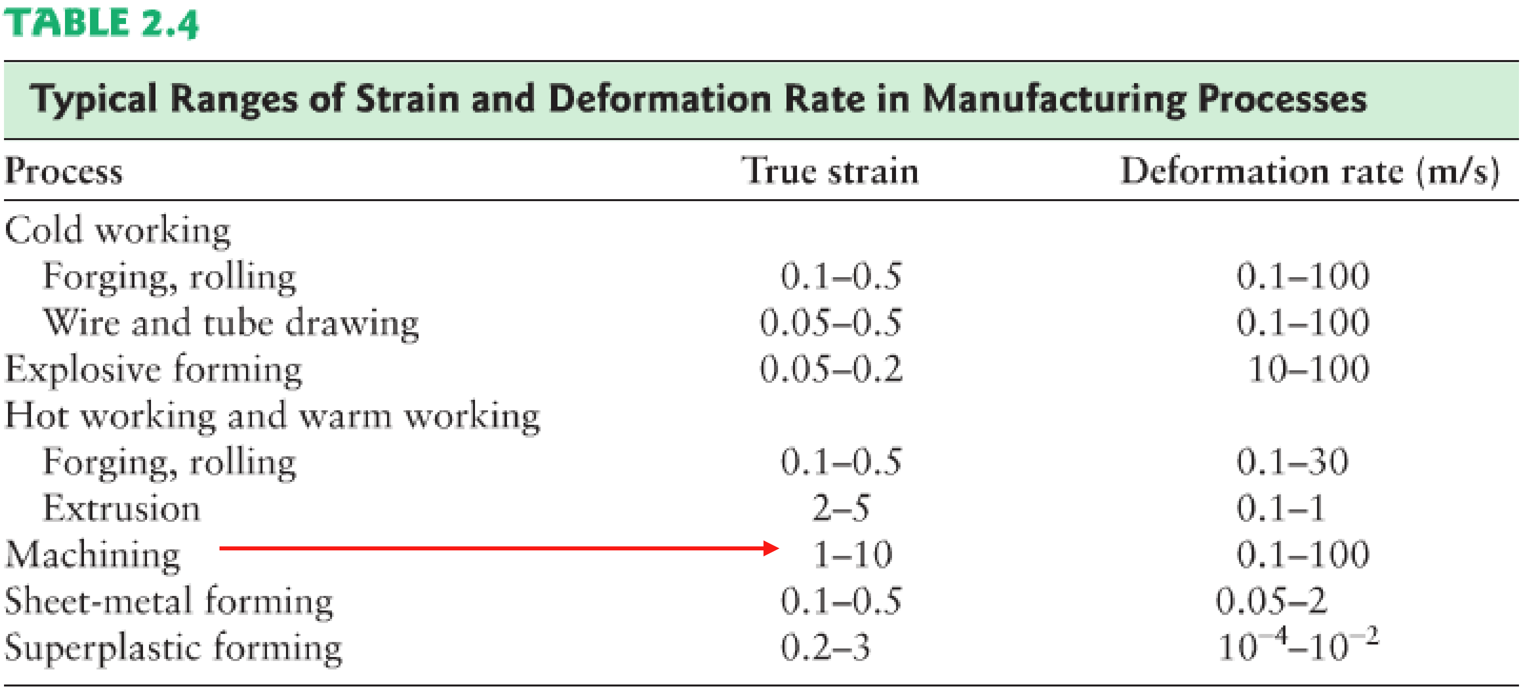
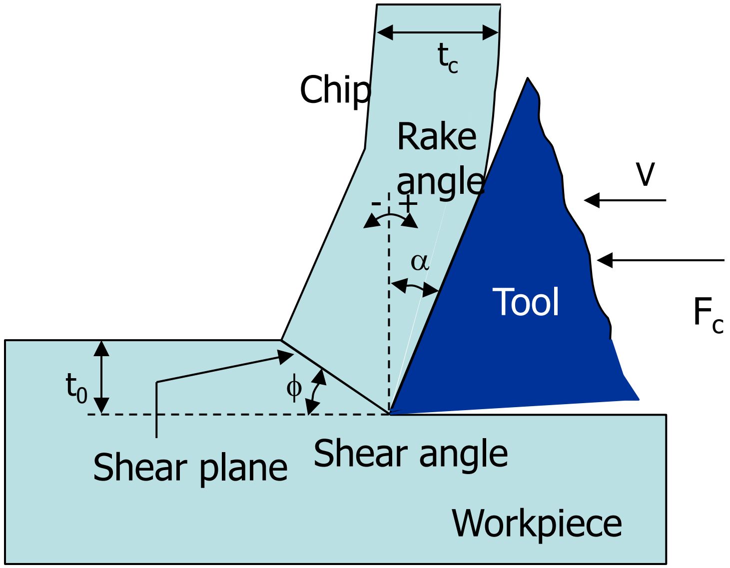


TABLE 2.4

Typical Ranges of Strain and Deformation Rate in Manufacturing Processes

Process	True strain	Deformation rate (m/s)
Cold working		
Forging, rolling	0.1–0.5	0.1–100
Wire and tube drawing	0.05–0.5	0.1–100
Explosive forming	0.05–0.2	10–100
Hot working and warm working		
Forging, rolling	0.1–0.5	0.1–30
Extrusion	2–5	0.1–1
Machining	1–10	0.1–100
Sheet-metal forming	0.1–0.5	0.05–2
Superplastic forming	0.2–3	10^{-4}–10^{-2}

Basic Machining Mechanism



$$F_c \cdot V = \text{Power} = \frac{d(\text{work})}{dt} = \dot{\text{work}}$$

$$\frac{\dot{\text{work}}}{\dot{\text{vol}}} = \text{specific energy} = u_S$$

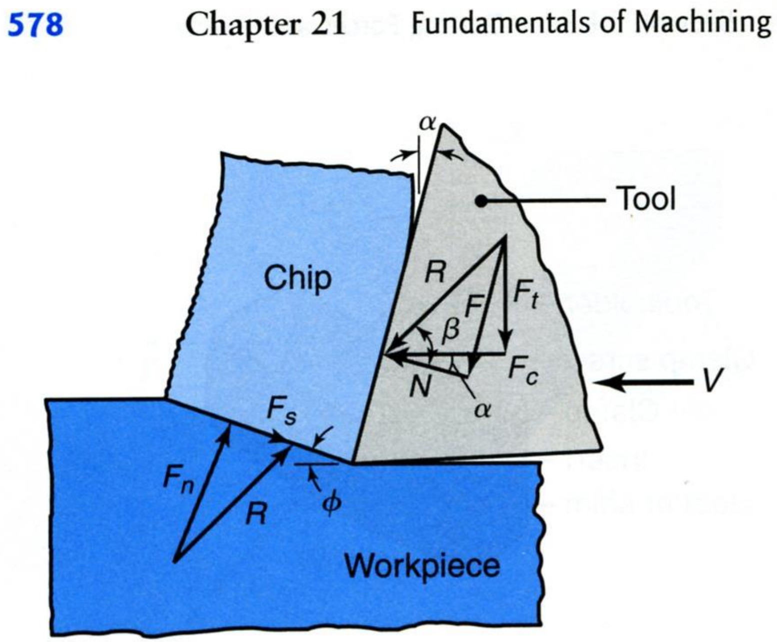
$$u_S = u_{\text{plastic work}} + u_{\text{friction}}$$

$$u_p = \int \bar{\sigma}\, d\bar{\varepsilon} \cong \tau\gamma \qquad (2 \le \gamma \le 4)$$

$$u_p \cong \tau\gamma \cong \frac{Y}{2} \cdot 3$$

Friction?

Cutting forces



(a)

F_c = cutting force
N = normal force
F = friction force
R = resultant force
F_t = thrust force
μ= friction coef
β = friction angle

$$\mu = \frac{F}{N} = \tan\beta$$

The Merchant Equation

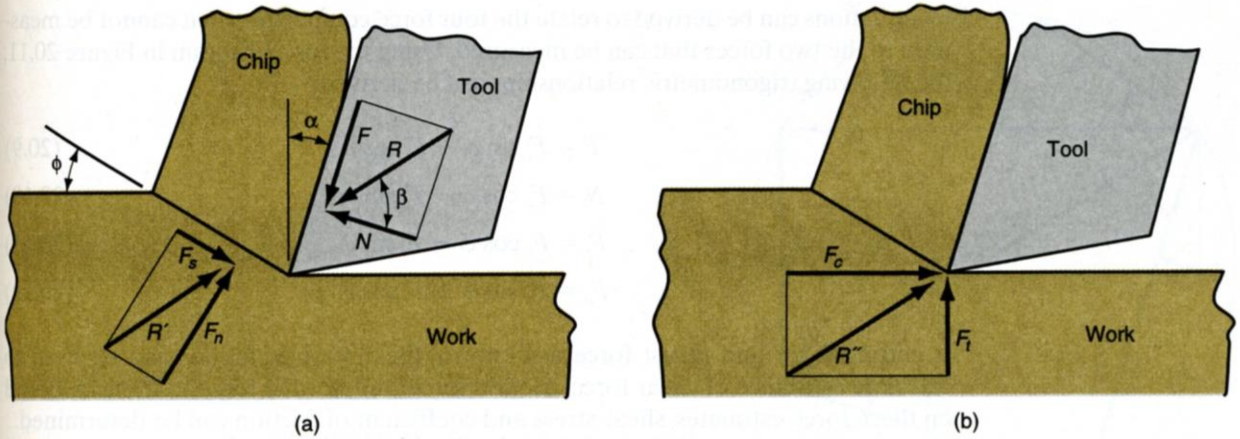


FIGURE 20.10 Forces in metal cutting: (a) forces acting on the chip in orthogonal cutting, and (b) forces acting on the tool that can be measured.

$$\tau_s = \frac{F_s}{A_s} = \frac{F_c \cos\phi - F_t \sin\phi}{t_o w / \sin\phi}$$

$$\boxed{\phi = 45^o + \frac{\alpha}{2} - \frac{\beta}{2}}$$

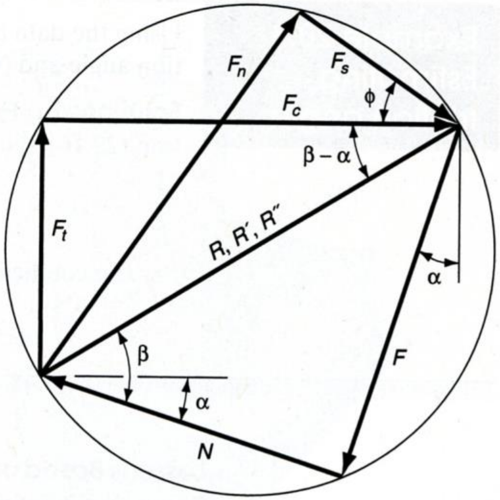


FIGURE 20.11 Force diagram showing geometric relationships between F, N, F_s, F_n, F_c, and F_t.

Ref. Groover

The Thrust Force

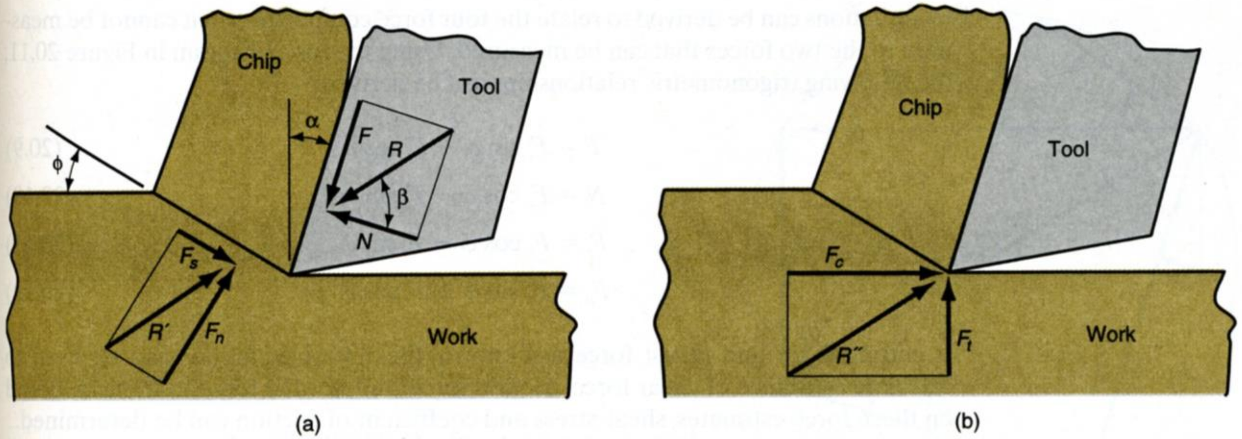


FIGURE 20.10 Forces in metal cutting: (a) forces acting on the chip in orthogonal cutting, and (b) forces acting on the tool that can be measured.

$$F_t = F_c \tan(\beta - \alpha)$$

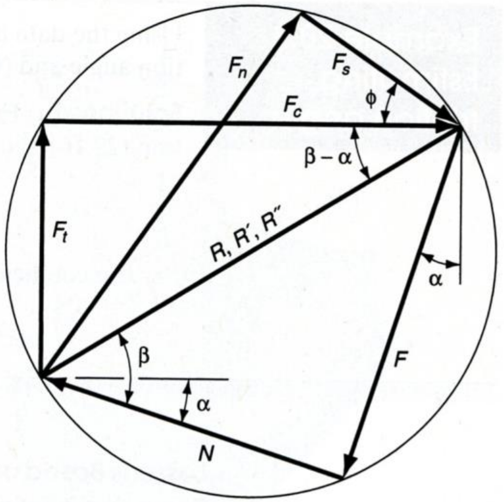
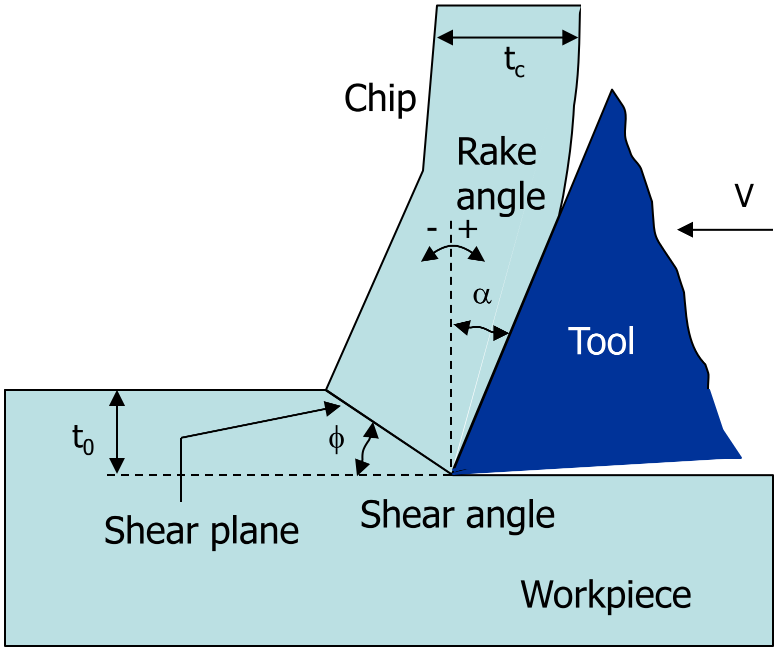


FIGURE 20.11 Force diagram showing geometric relationships between F, N, F_s, F_n, F_c, and F_t.

Ref. Groover

Basic Machining Mechanism



$$u_S = u_{\text{plastic work}} + u_{\text{friction}}$$

$$u_p \cong \frac{Y}{2} \cdot 3$$

if friction work

is on the order of plastic work

then: $u_s \cong 3Y \cong H$

Approximation

$u_s \sim H$ (Hardness)

Specific energy, u_s

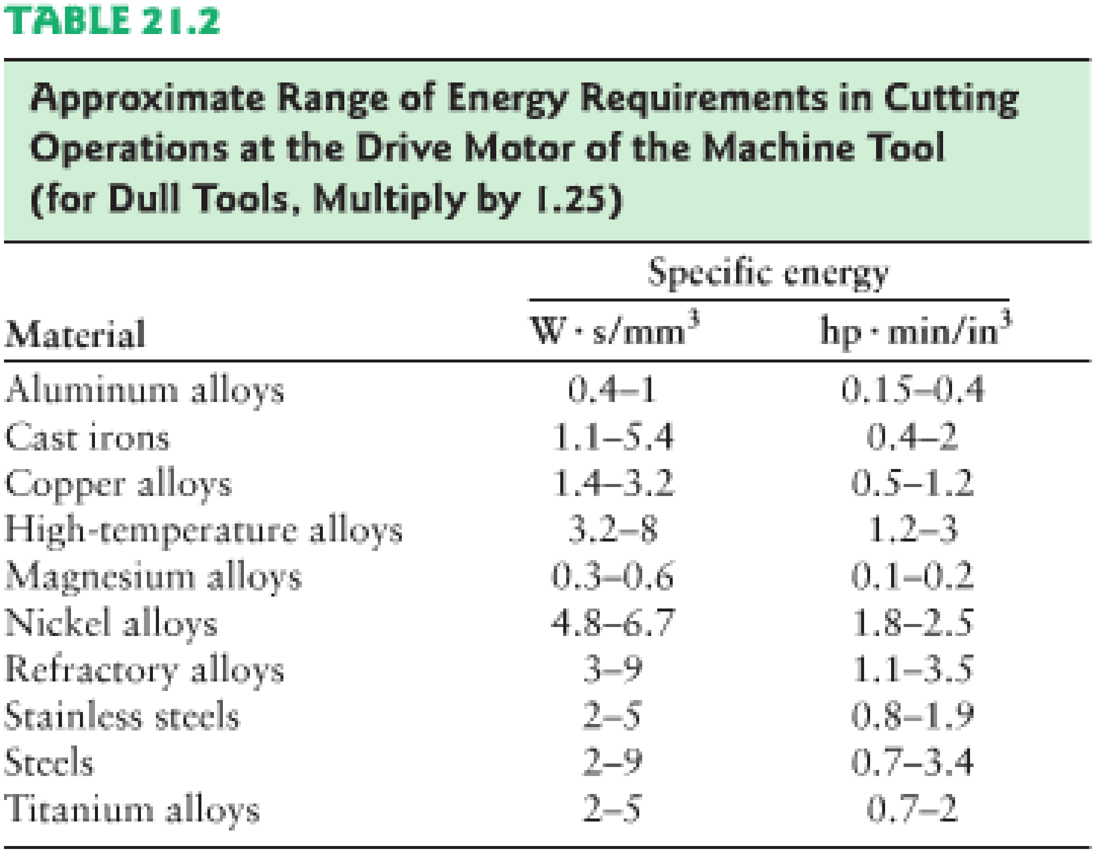


TABLE 21.2

Approximate Range of Energy Requirements in Cutting Operations at the Drive Motor of the Machine Tool (for Dull Tools, Multiply by 1.25)

Material	Specific energy $\mathrm{W \cdot s/mm^3}$	Specific energy $\mathrm{hp \cdot min/in^3}$
Aluminum alloys	0.4–1	0.15–0.4
Cast irons	1.1–5.4	0.4–2
Copper alloys	1.4–3.2	0.5–1.2
High-temperature alloys	3.2–8	1.2–3
Magnesium alloys	0.3–0.6	0.1–0.2
Nickel alloys	4.8–6.7	1.8–2.5
Refractory alloys	3–9	1.1–3.5
Stainless steels	2–5	0.8–1.9
Steels	2–9	0.7–3.4
Titanium alloys	2–5	0.7–2

For comparison see Table 26.2 for grinding

Basic Machining Mechanism

Hence we have the approximation;

$$\boxed{\text{Power} \approx u_s \text{ X MRR}}$$

MRR is the Material Removal Rate or d(Vol)/dt

Since Power is

$$P = F_c * V$$

and MRR can be written as,

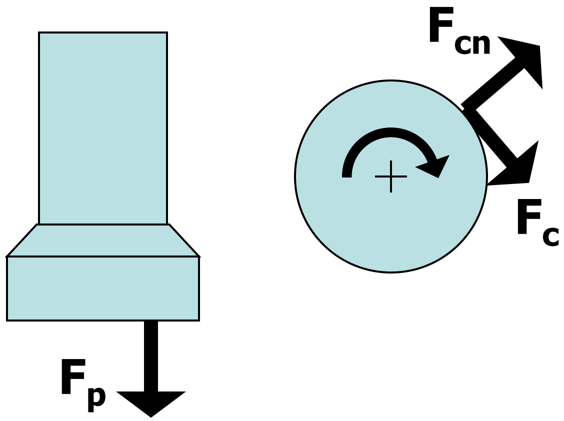
$$d(Vol)/dt = A * V$$

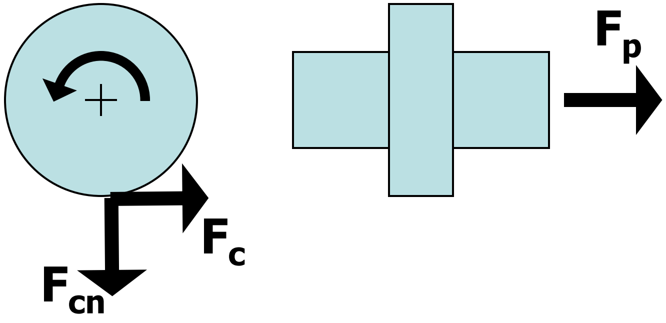
Where A is the cross-sectional area of the undeformed chip, we can get an estimate for the cutting force as,

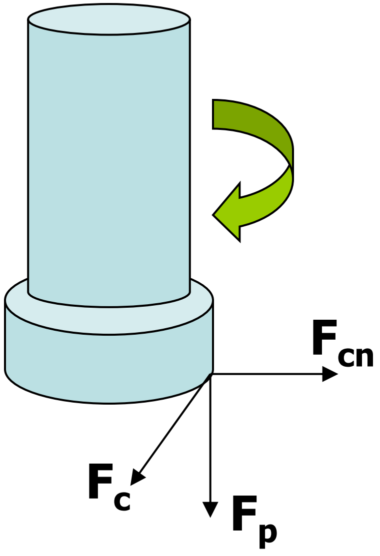
$$\boxed{F_c \approx u_s \times A}$$

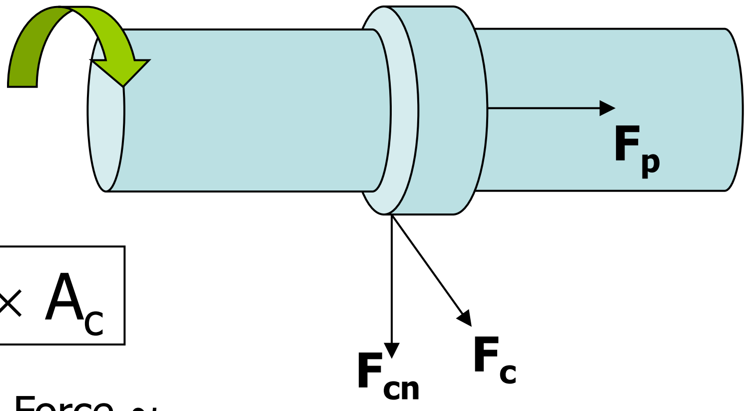
Note that this approximation is the cutting force in the cutting direction.

Cutting Force Directions in Milling





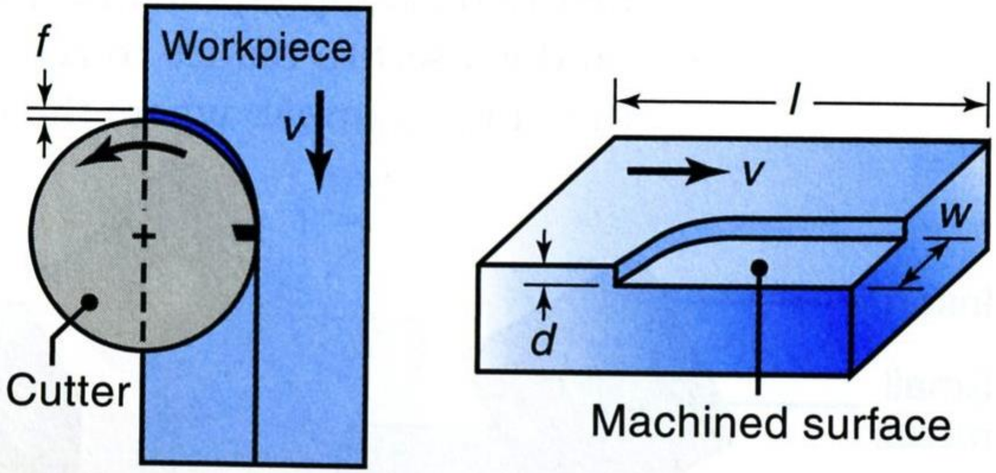




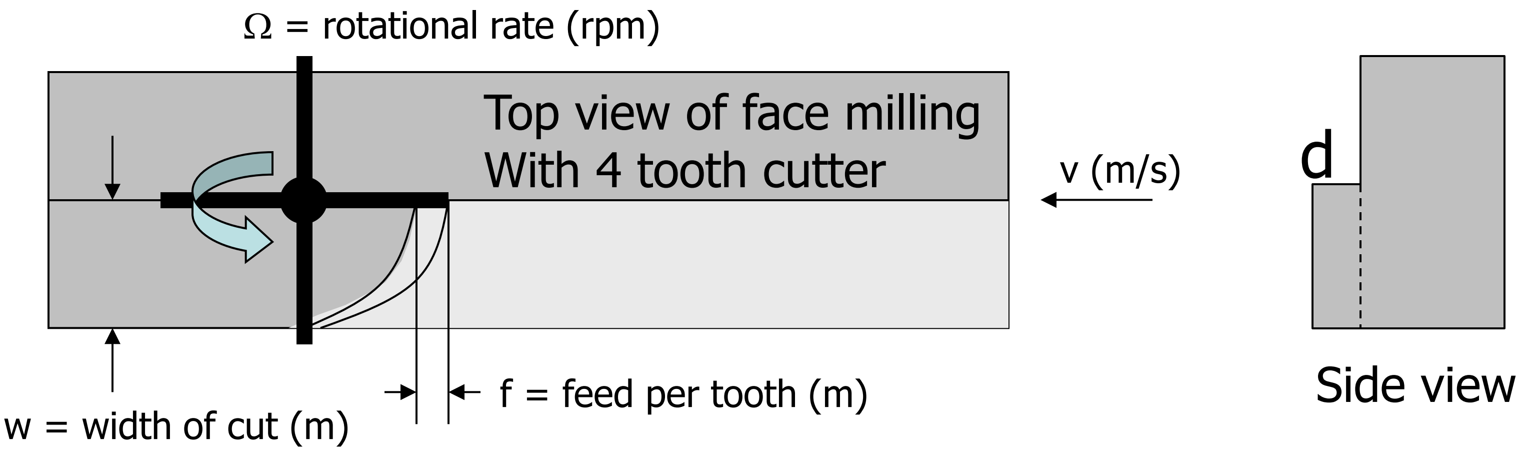
$$\boxed{F_c \sim H \times A_c}$$

(Tangential Cutting Force ~
Chip Cross-section × Hardness)

Face Milling



Feed per Tooth and MRR



Ω = rotational rate (rpm)

Top view of face milling
With 4 tooth cutter

v (m/s)

d

w = width of cut (m)

f = feed per tooth (m)

Side view

Consider the workpiece moving into the cutter at rate **"v".** In travel time **t'** the feed is **v t'**. The time for one rotation is **t'** = $1/\Omega$. The travel for one tooth is **$1/4\Omega$.** Hence the feed per tooth is **f = v/4Ω.** In general, a cutter may have "N" teeth, so the ***feed per tooth*** is

$$f = v / N\Omega$$

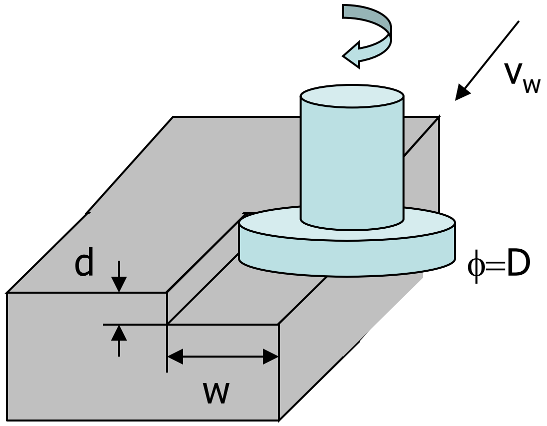
The material removal rate (MRR) is,

$$Force \approx f\,d\,u$$

$$MRR = v\,w\,d$$

where "d" is the depth of the tool into the workpiece.

Ex) Face milling of Al Alloy



N = 4 (number of teeth)
D = 2″ (cutter diameter)

Let w = 1″ (width of cut), d=0.1″ (depth of cut)
f = 0.007″ (feed per tooth),
v_s = 2500 ft/min (surface speed; depends on cutting tool material; here, we must have a coated tool such as TiN or PCD)

The rotational rate for the spindle is

$$\Omega = v_s / \pi D = 4775 \text{ rpm}$$

Now, we can calculate v_w, workpiece velocity,

$$f = v_w / N\,\Omega \Rightarrow v_w = 134 \text{ [in/min]}$$

Material removal rate, MRR = v_w*w*d = 13.4 [in^3/min]
Power requirement, P = u_s*MRR = 5.36 [hp]
Cutting force / tooth, F ~ u_s*d*f = 111 [lbf]

u_s from Table 21.2 (20.2 ed 4); Note 1 [hp min/in^3] = 3.96*10^5 [psi]

TABLE 24.2

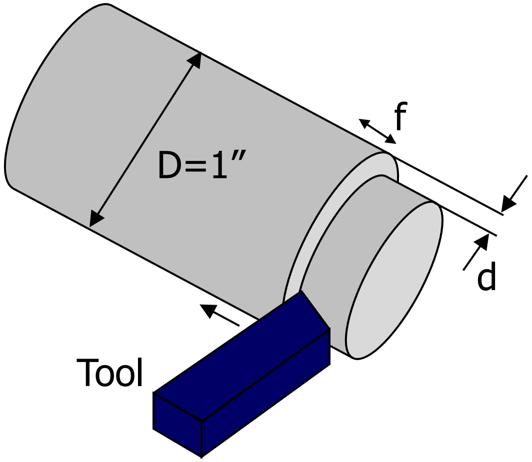
General Recommendations for Milling Operations

Material	Cutting tool	General-purpose starting conditions		Range of conditions	
		Feed mm/tooth (in./tooth)	Speed m/min (ft/min)	Feed mm/tooth (in./tooth)	Speed m/min (ft/min)
Low-carbon and-free machining steels	Uncoated carbide, coated carbide, cermets	0.13–0.20 (0.005–0.008)	120–180 (400–600)	0.085–0.38 (0.003–0.015)	90–425 (300–1400)
Alloy steels					
Soft	Uncoated, coated, cermets	0.10–0.18 (0.004–0.007)	90–170 (300–550)	0.08–0.30 (0.003–0.012)	60–370 (200–1200)
Hard	Cermets, PcBN	0.10–0.15 (0.004–0.006)	180–210 (600–700)	0.08–0.25 (0.003–0.010)	75–460 (250–1500)
Cast iron, gray					
Soft	Uncoated, coated, cermets, SiN	0.10–10.20 (0.004–0.008)	120–760 (400–2500)	0.08–0.38 (0.003–0.015)	90–1370 (300–4500)
Hard	Cermets, SiN, PcBN	0.10–0.20 (0.004–0.008)	120–210 (400–700)	0.08–0.38 (0.003–0.015)	90–460 (300–1500)
Stainless steel, Austenitic	Uncoated, coated, cermets	0.13–0.18 (0.005–0.007)	120–370 (400–1200)	0.08–0.38 (0.003–0.015)	90–500 (300–1800)
High-temperature alloys Nickel based	Uncoated, coated, cermets, SiN, PcBN	0.10–0.18 (0.004–0.007)	30–370 (100–1200)	0.08–0.38 (0.003–0.015)	30–550 (90–1800)
Titanium alloys	Uncoated, coated, cermets	0.13–0.15 (0.005–0.006)	50–60 (175–200)	0.08–0.38 (0.003–0.015)	40–140 (125–450)
Aluminum alloys					
Free machining	Uncoated, coated, PCD	0.13–0.23 (0.005–0.009)	610–900 (2000–3000)	0.08–0.46 (0.003–0.018)	300–3000 (1000–10,000)
High silicon	PCD	0.13 (0.005)	610 (2000)	0.08–0.38 (0.003–0.015)	370–910 (1200–3000)
Copper alloys	Uncoated, coated, PCD	0.13–0.23 (0.005–0.009)	300–760 (1000–2500)	0.08–0.46 (0.003–0.018)	90–1070 (300–3500)
Plastics	Uncoated, coated, PCD	0.13–0.23 (0.005–0.009)	270–460 (900–1500)	0.08–0.46 (0.003–0.018)	90–1370 (300–4500)

Source: Based on data from Kennametal, Inc.

Note: Depths-of-cut, *d*, usually are in the range of 1 to 8 mm (0.04 to 0.3 in.). PcBN: polycrystalline cubic-boron nitride. PCD: polycrystalline diamond. See also Table 23.4 for range of cutting speeds within tool material groups.

Ex) Turning a stainless steel bar



Recommended feed = 0.006″ (Table 23.4 (22.4))
Recommended surface speed = 1000 ft/min

$$\Omega = \frac{1000 \text{ ft/min}}{\pi * 1'' * 1\text{ft}/12''} = 3820 \text{ rpm}$$

Let d = 0.1″

Material removal rate, MRR = 0.1*0.006*(π*1*3820) = 7.2 [in^3/min]

Power requirement, P = u_s*MRR = 1.9*7.2 = 13.7 [hp]

Cutting force / tooth, F ~ u_s*d*f = (1.9*3.96*10^5)*(0.1*0.006)
= 450 [lbf]

u_s from Table 21.2 (20.2 ed 4); Note 1 [hp min/in^3] = 3.96*10^5 [psi]

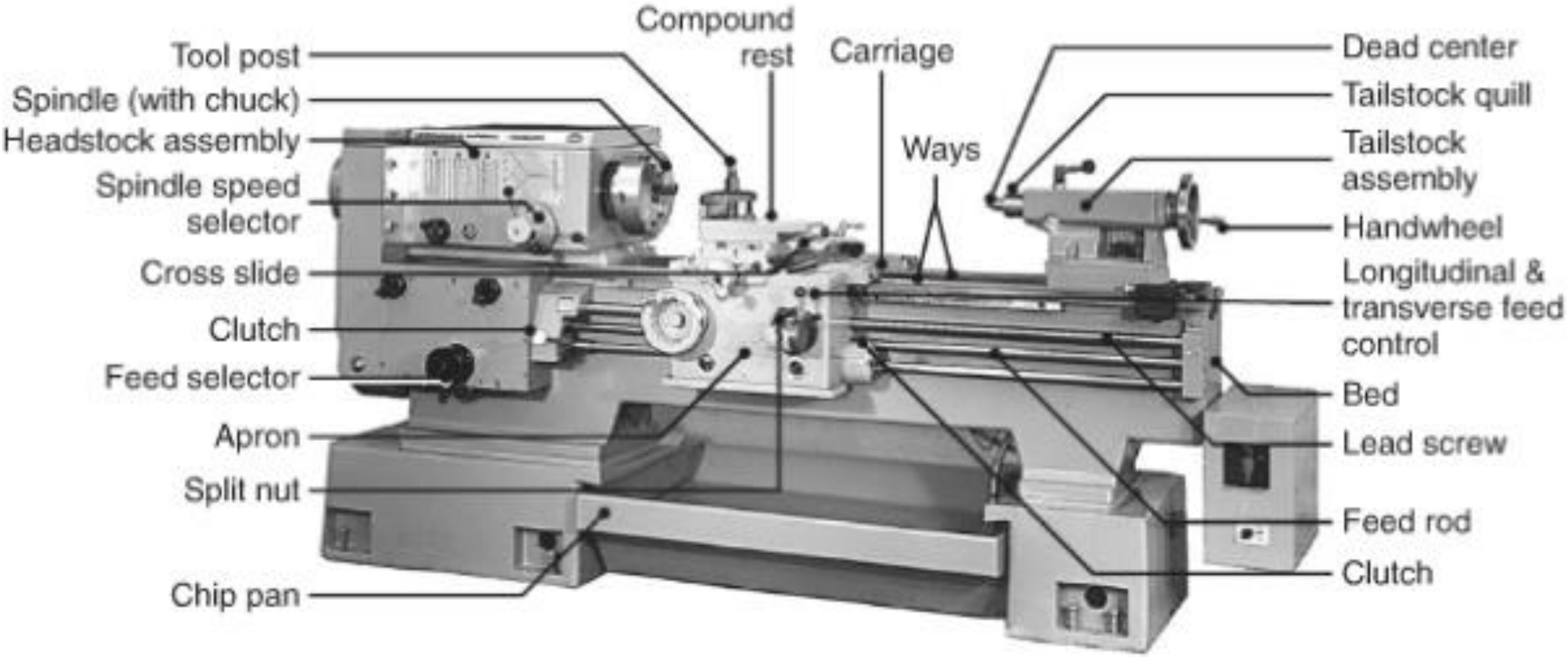
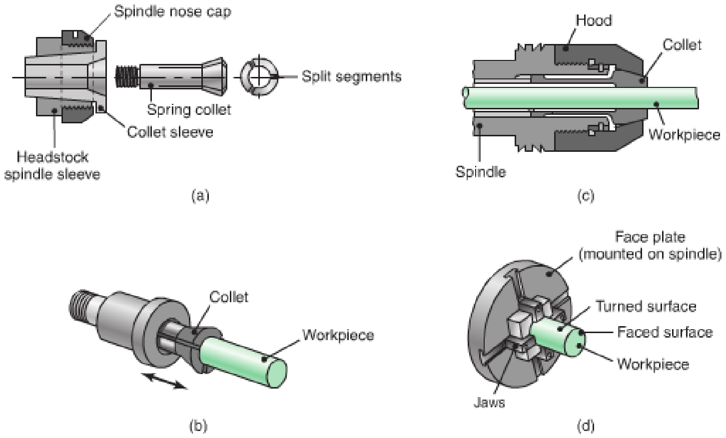


FIGURE 23.2 General view of a typical lathe, showing various components. *Source*: Courtesy of Heidenreich & Harbeck.



Temperature Rise in Cutting

Adiabatic Temperature Rise:

$$\rho\, c\, \Delta T = u_S$$

Note : $u_S \sim H$, Hardness

$\Delta T_{adiabatic} \approx \frac{1}{2} T_{melt}$ (Al & Steel)

Interface Temperature:

$$\Delta T = 0.4\,(H / \rho\, c)(v\, f / \alpha)^{0.33}$$

v = cutting speed

f = feed

α = thermal diffusivity of workpiece

Note $v\, f / \alpha$ = Pe = convection/conduction

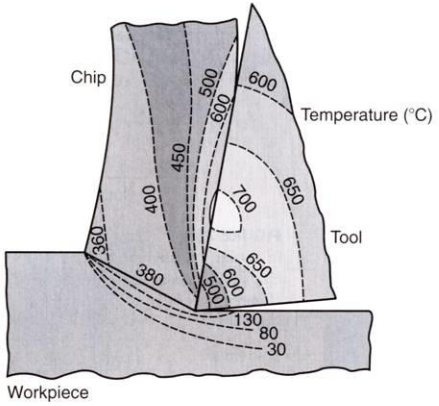


FIGURE 21.12 Typical temperature distribution in the cutting zone. Note the severe temperature gradients within the tool and the chip, and that the workpiece is relatively cool. *Source:* After G. Vieregge.

Typical temperature distribution in the cutting zone

* Reference: N. Cook, "Material Removal Processes"

* Source: Kalpakjian, and Schmidt 5th ed

Effect of temperature on Hardness

Section 22.1 Introduction **601**

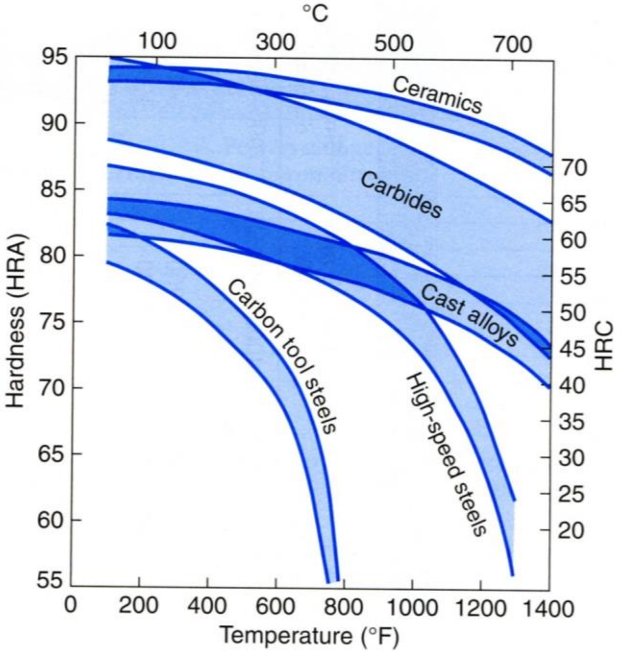


FIGURE 22.1 The hardness of various cutting-tool materials as a function of temperature (hot hardness); the wide range in each group of materials is due to the variety of tool compositions and treatments available for that group.

Section 22.7 Cubic Boron Nitride **613**

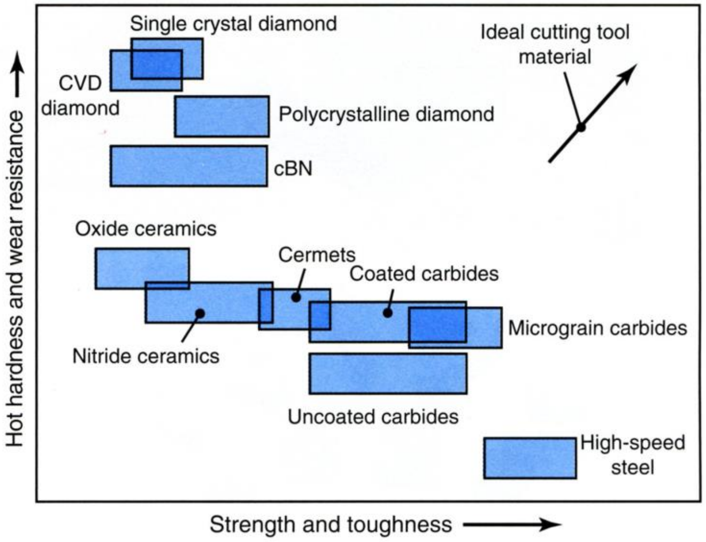


FIGURE 22.9 Ranges of mechanical properties for various groups of tool materials. HIP = hot isostatically pressed. (See also Tables 22.1–22.5.)

Tool Life

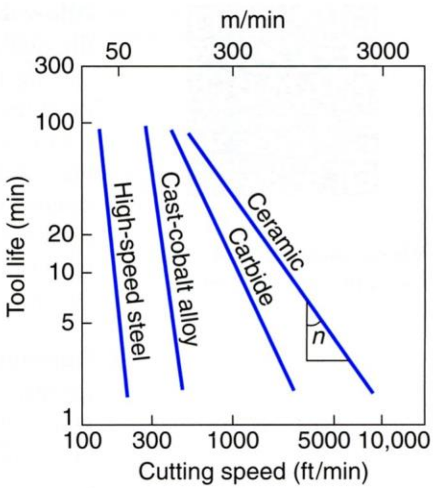


FIGURE 21.17 Tool-life curves for a variety of cutting-tool materials. The negative reciprocal of the slope of these curves is the exponent *n* in the Taylor tool-life equation (21.25), and *C* is the cutting speed at *T* = 1 min, ranging from about 200 to 10,000 ft/min in this figure.

Frederick Winslow Taylor
-1856 to 1915

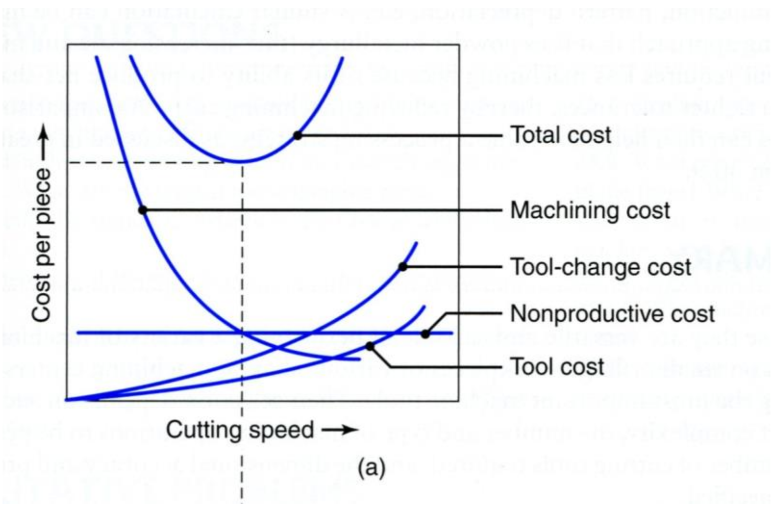
- Tool life
- Scientific management

$$VT^n = C$$

$$T = \left(\frac{C}{V}\right)^{1/n}$$

Note C = V for T = 1 min.
range for n is 0.08 to 0.7
See text Ch 21

Optimum cutting speed range



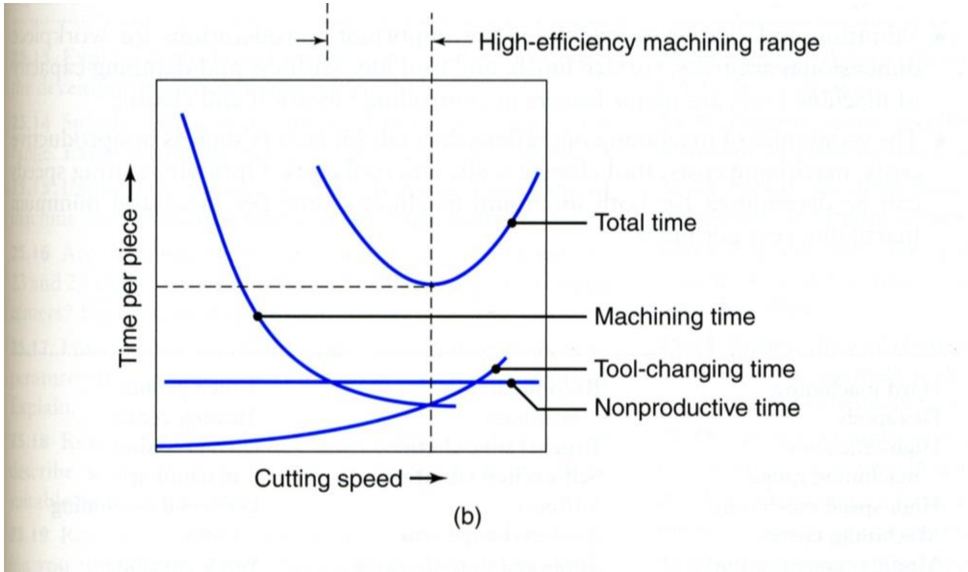


FIGURE 25.17 Graphs showing (a) cost per piece and (b) time per piece in machining; note the optimum speeds for both cost and time. The range between the two is known as the *high-efficiency machining range*.

Effect on Productivity

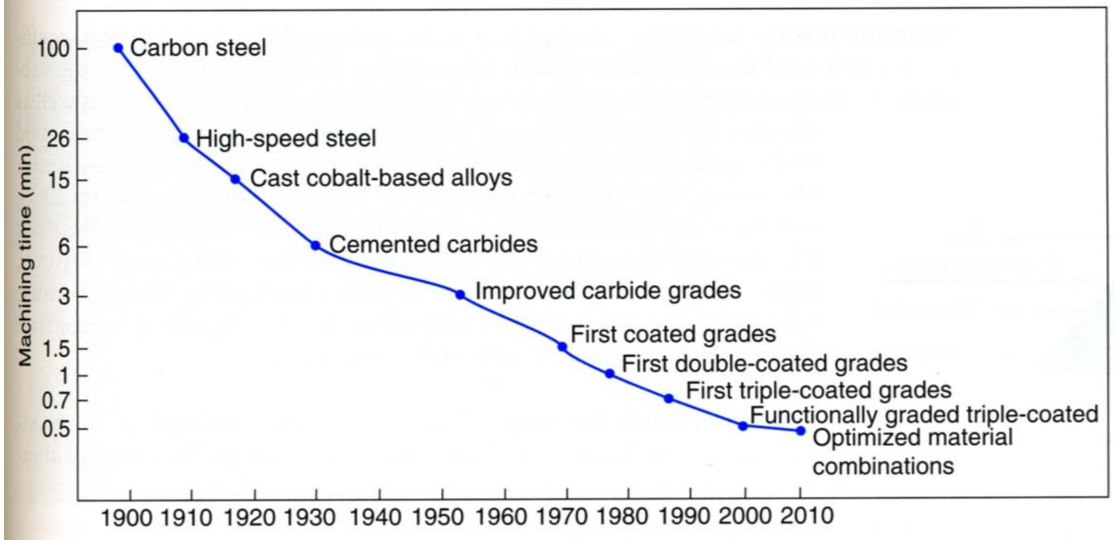


FIGURE 22.6 Relative time required to machine with various cutting-tool materials, indicating the year the tool materials were first introduced; note that machining time has been reduced by two orders of magnitude within a 100 years. *Source:* Courtesy of Sandvik.

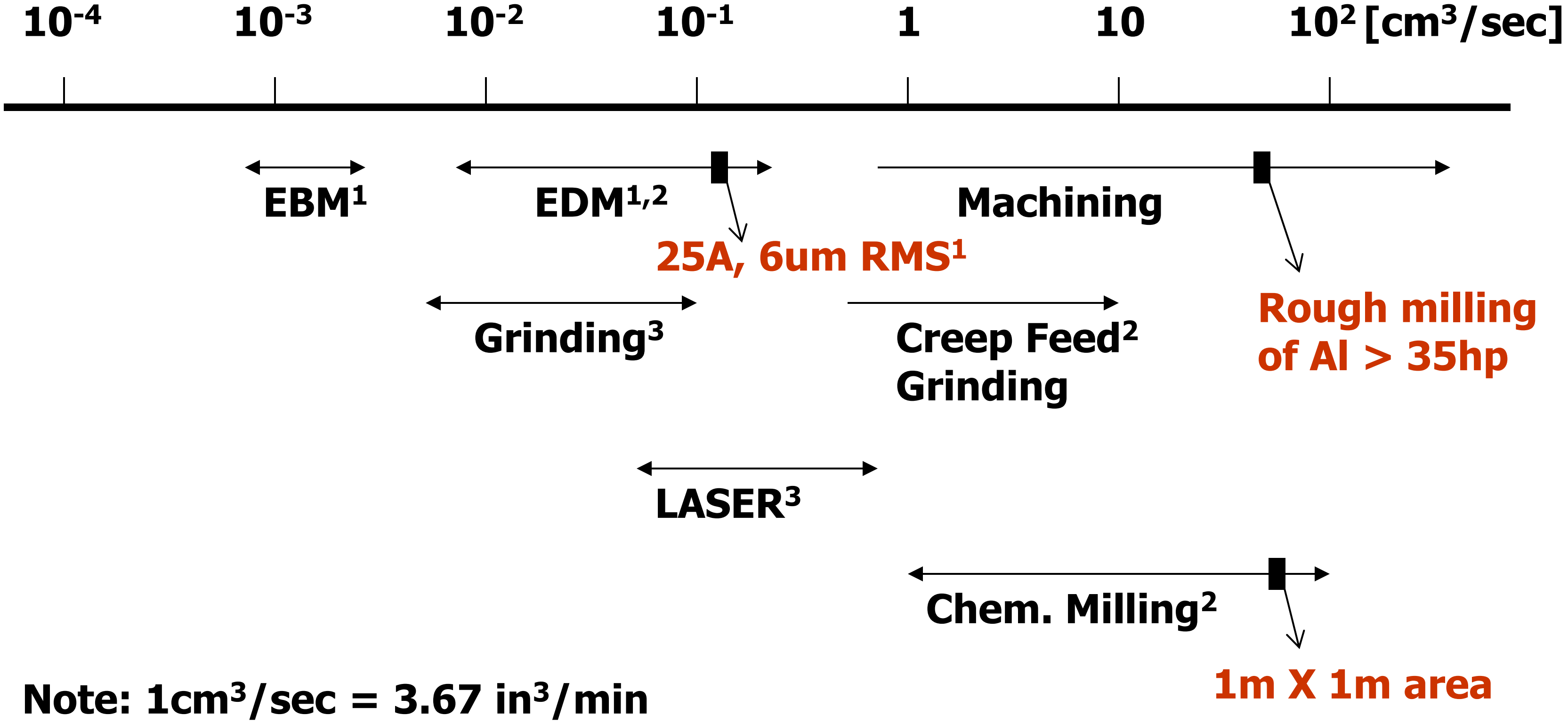
100 to 0.5 in 110 years → ~ 5%/yr

Limits to MRR in Machining

- Spindle Power – for rigid, well supported parts
- Cutting Force – may distort part, break delicate tools
- Vibration and Chatter – lack of sufficient rigidity in the machine, workpiece and cutting tool may result in self-excited vibration
- Heat – heat build-up may produce “welding”, poor surface finish, excessive work hardening; can be reduced with cutting fluid

See Video on Rate Limits In Machining

Typical Material Removal Rate



10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} [cm^3/sec]

EBM[1]

EDM[1,2]

Machining

25A, 6um RMS[1]

Rough milling of Al > 35hp

Grinding[3]

Creep Feed[2] Grinding

LASER[3]

Chem. Milling[2]

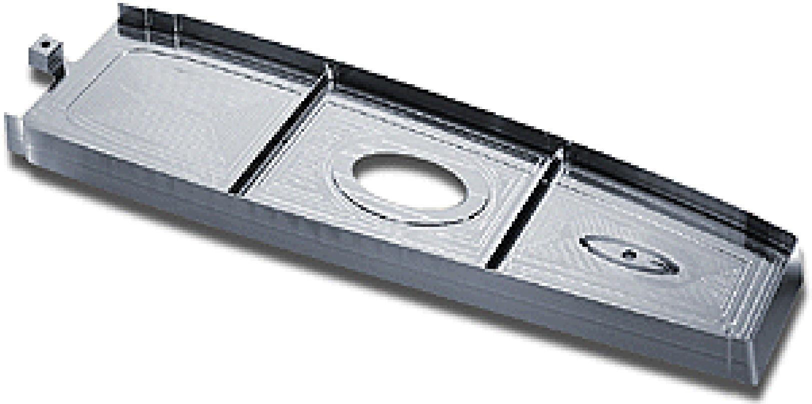
1m X 1m area

Note: 1cm^3/sec = 3.67 in^3/min

* References: 1. Advanced Methods of Machining, J.A.McGeough, Chapman and Hall, 1988
2. Manufacturing Engineering and Technology, S. Kalpakjian, Addison-Wesley, 1992
3. Laser Machining, G. Chryssolouris, Springer-Verlag, 1991

High speed Machining and Assembly

- High Speed Machined aluminum parts are replacing built-up parts made by forming and assembly (riveting) in the aerospace industry. The part below was machined on a 5-axis Makino (A77) at Boeing using a 8-15k rpm spindle speed, and a feed of 240 ipm vs 60 ipm conventional machining. This part replaces a build up of 25 parts. A similar example exists for the F/A-18 bulkhead (Boeing, St. Louis) going from 90 pieces (sheetmetal build-up) to 1 piece. High speed machining is able to cut walls to 0.020” (0.51mm) without distortion. Part can be fixtured using “window frame” type fixture.



$$\boxed{MRR = f\,d * N\,\Omega\,w}$$

High Speed Machining

Example #1 light cuts in hard material

http://www.youtube.com/watch?v=DCxZwSwf64U

Examples #2 high removal rates

http://www.youtube.com/watch?v=fvP5PYQ_3O8&feature=related

Variation Vs Part Size

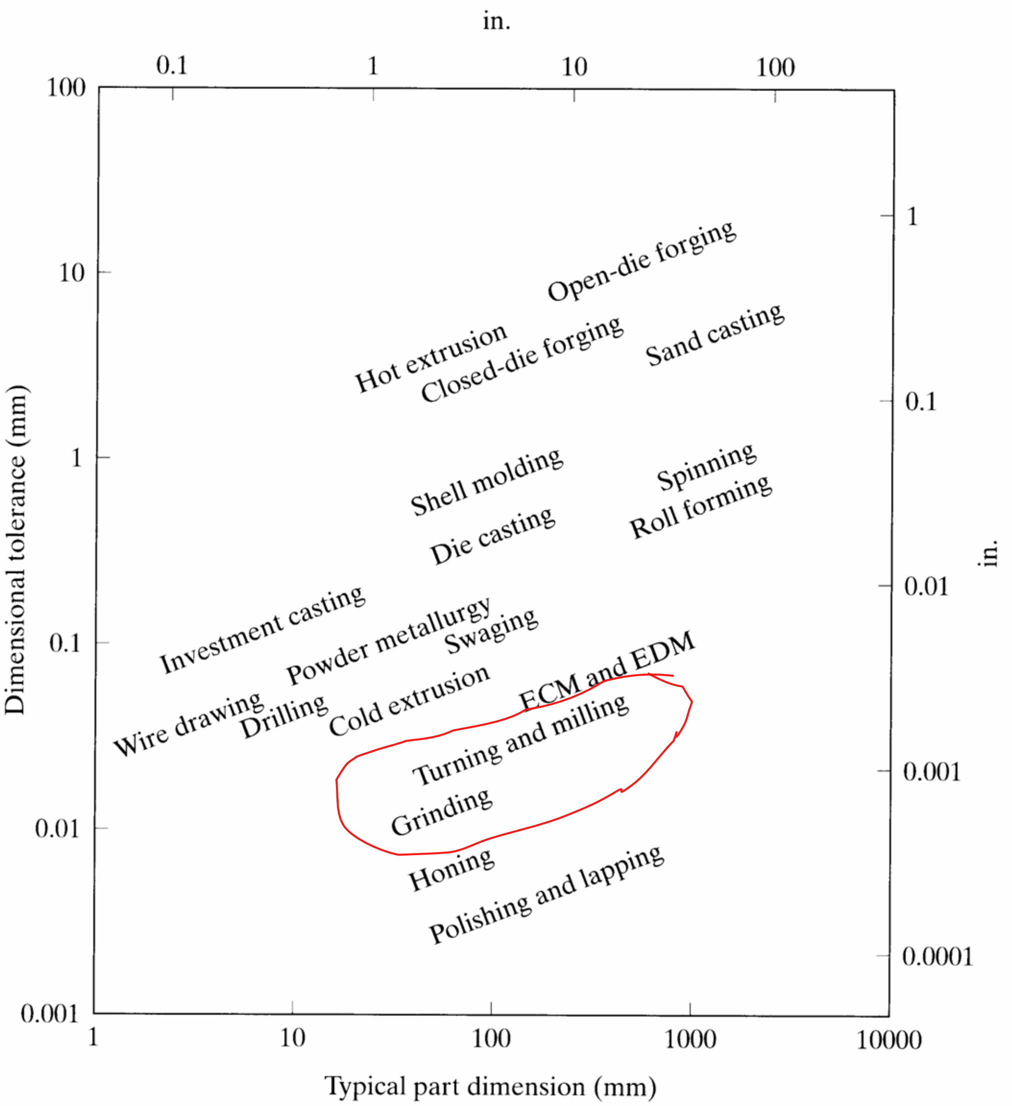
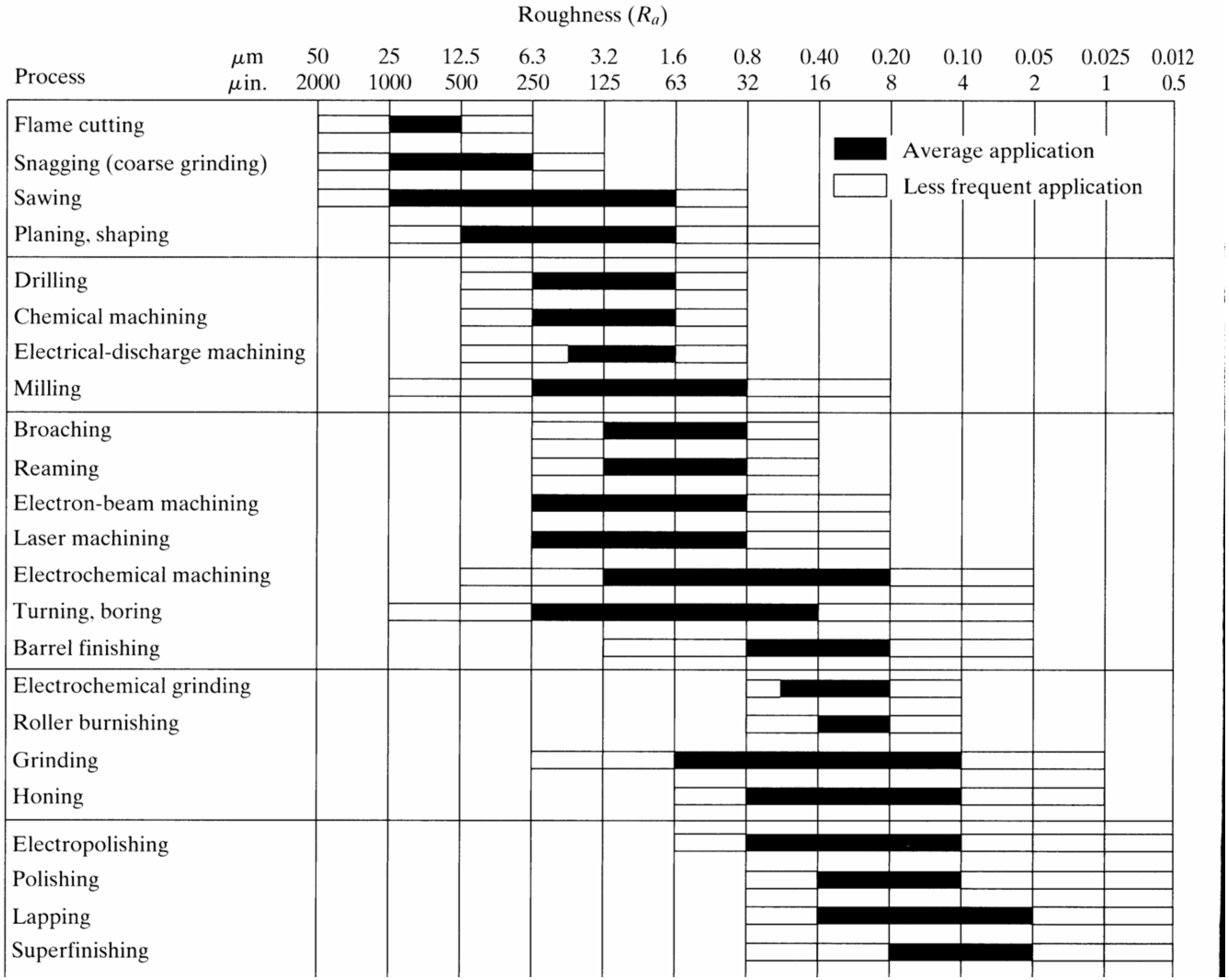


FIGURE 22.14 The range of surface roughnesses obtained in various machining processes. Note the wide range within each group, especially in turning and boring. See also Fig. 26.4.



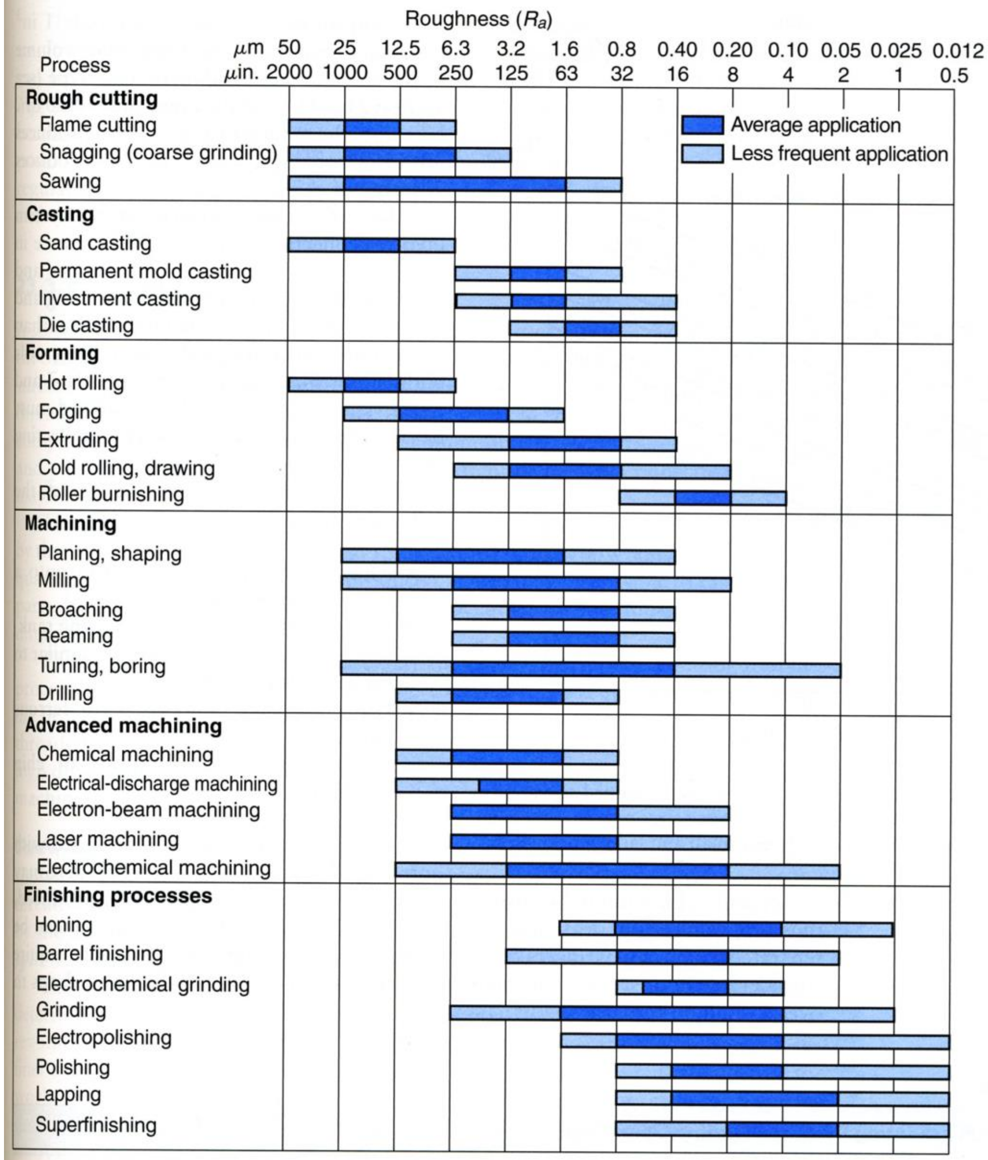


FIGURE 23.14 The range of surface roughnesses obtained in various processes; note the wide range within each group, especially in turning and boring.

Relative cost for tighter tolerances

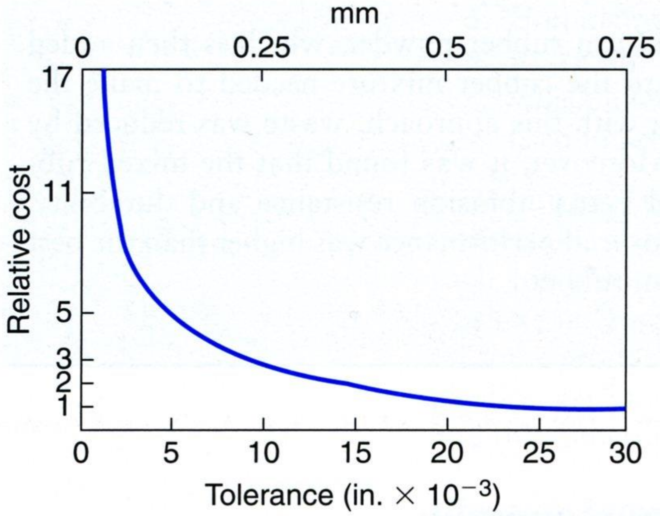


FIGURE 40.2 Dependence of manufacturing cost on dimensional tolerance.

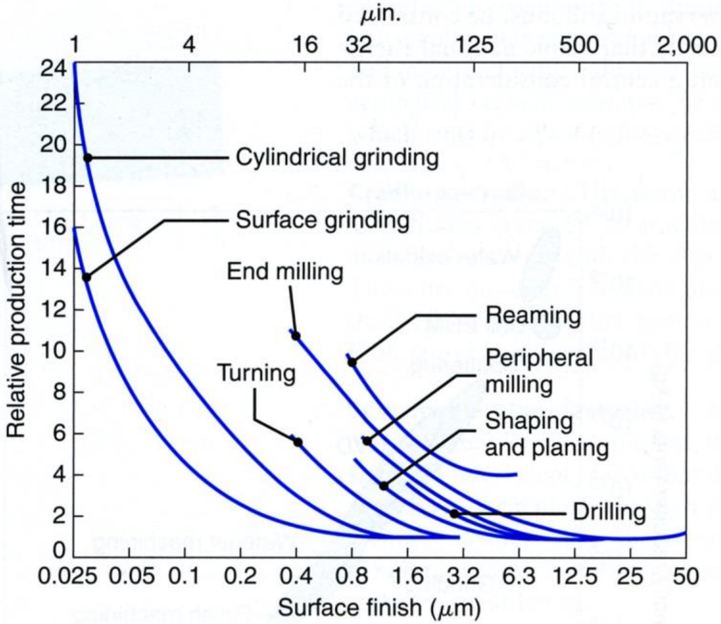


FIGURE 40.3 Relative production time as a function of surface finish produced by various manufacturing processes. (See also Fig. 26.35.)

Machine tool configurations

- Machine tool

  number of axes, spindles, serial and parallel configurations

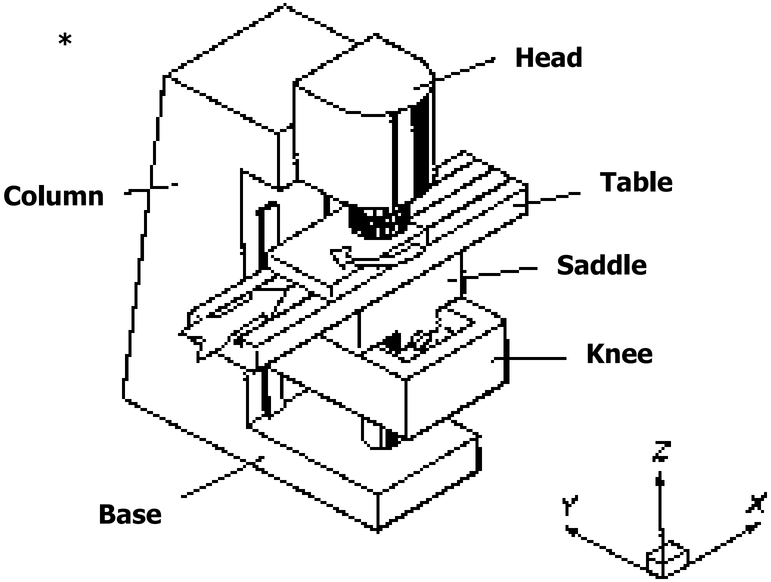
- Cutter geometry

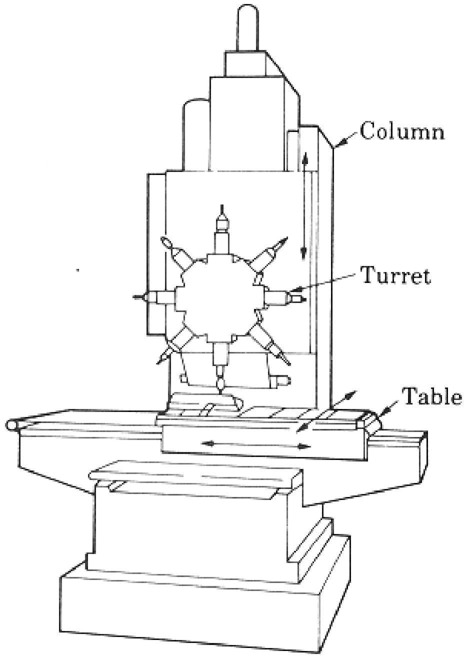
  Form tool, cutter radius, inserts, tool changers

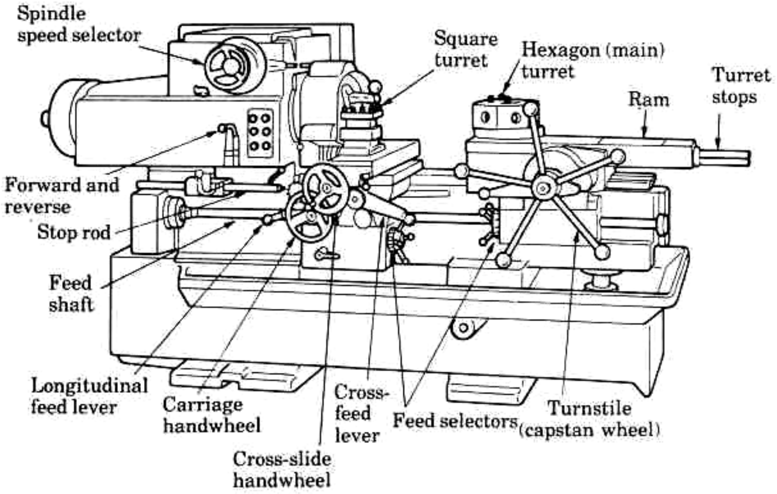
- Software

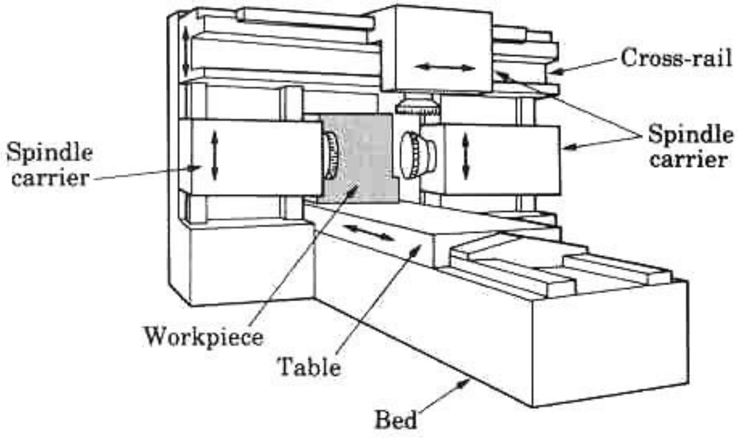
  flexibility, geometrical compensation, “look ahead” dynamics compensation

*









* Source: Kalpakjian, “Manufacturing Engineering and Technology”

A machinist at the Boeing Commercial Airplane Group skin and spar factory in Tacoma inspects the raw material that will be milled to produce a lower-wing skin panel for a 777 aircraft. The material would be lowered onto a specially designed, 270-foot Cincinnati Millicron skin mill, one of the largest in the world. This 950,000-square-foot manufacturing plant at Tacoma began work on 777 program-related assemblies in July 1992.

Machine control: Long bed CNC gantry mills achieve unprecedented accuracy

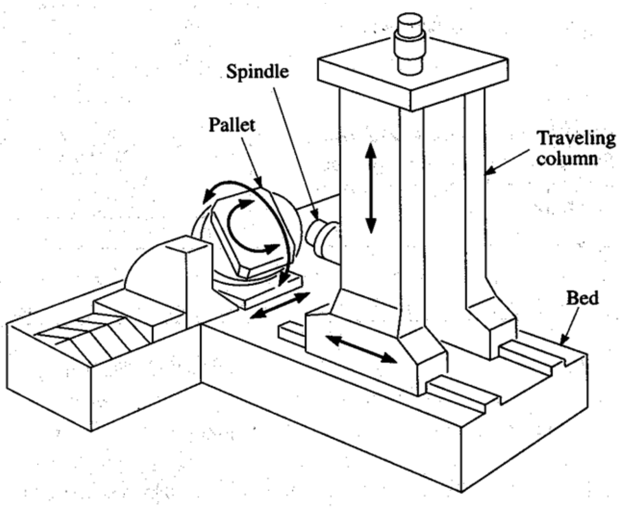
A Siemens Volumetric Compensation System and proprietary temperature compensation system combine with laser calibration to achieve +/- 0.003 in. accuracies.

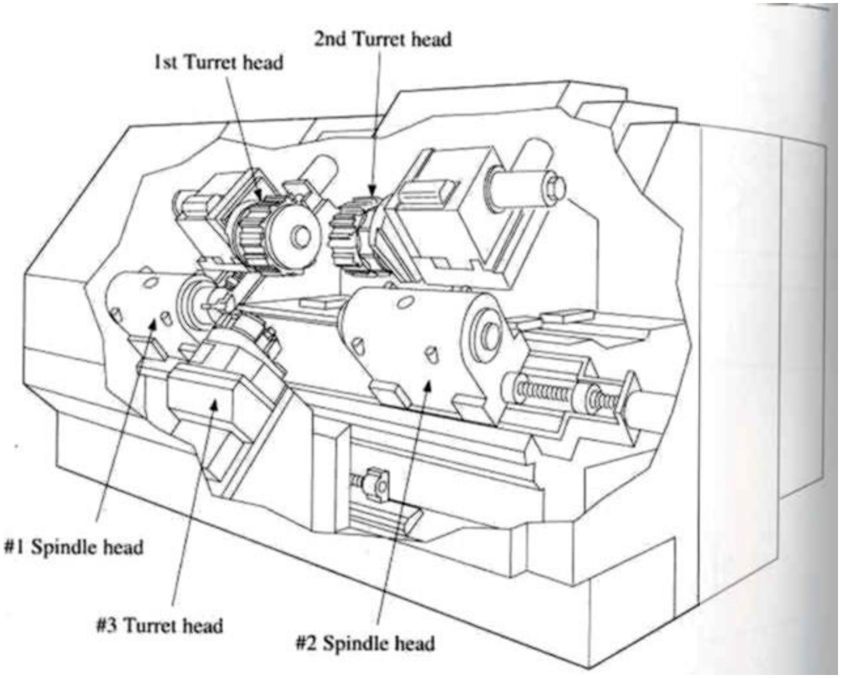
Renee Robbins -- Control Engineering, 8/12/2009

Coast Composites is a vertically integrated supplier of Invar tooling, as

Coast Composites Inc., part of the UK-based Hampson Industries Plc, is a major supplier of Invar tooling, as well as resin transfer molds and mandrels used in the composite lay-up and manufacture of today's advanced flight-critical aerospace structures. Coast also builds tooling for the construction of end products like satellite reflectors used in the telecom and military markets. On the large, long bed CNC gantry mills used at its main facility in Irvine,

Invar tooling and mandrels produced at Coast Composites are used for the production of various commercial and military aircraft.





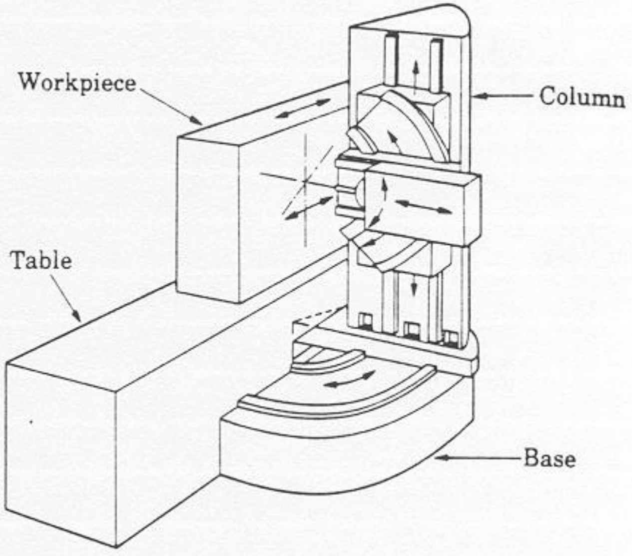
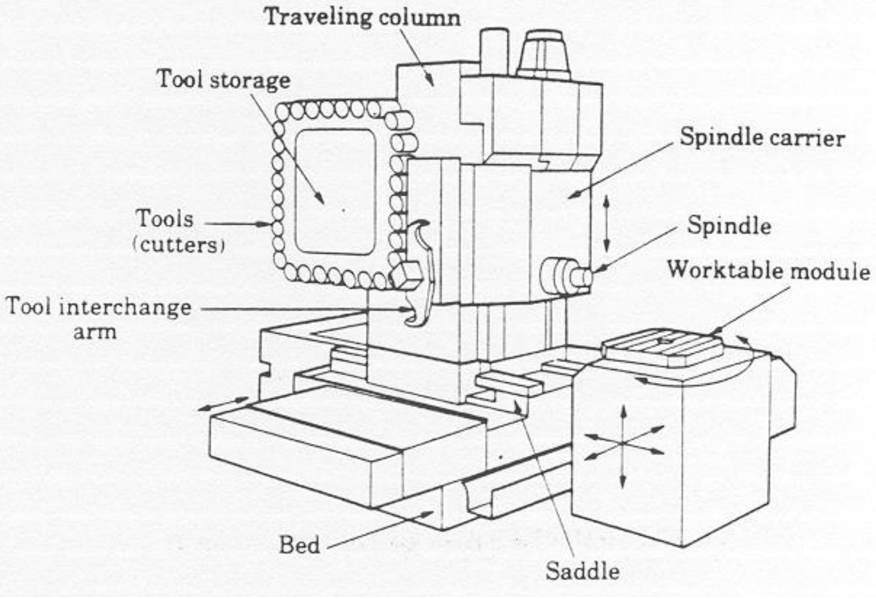
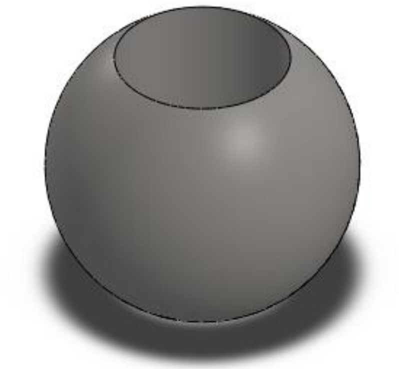


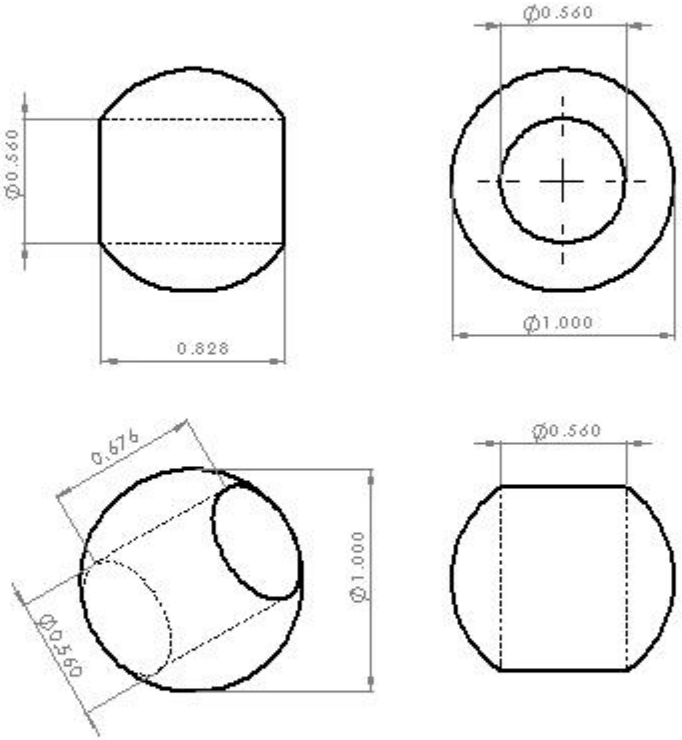
FIGURE 23.21

Schematic illustration of a five-axis profile milling machine. Note that there are three principal linear and two angular movements of machine components.

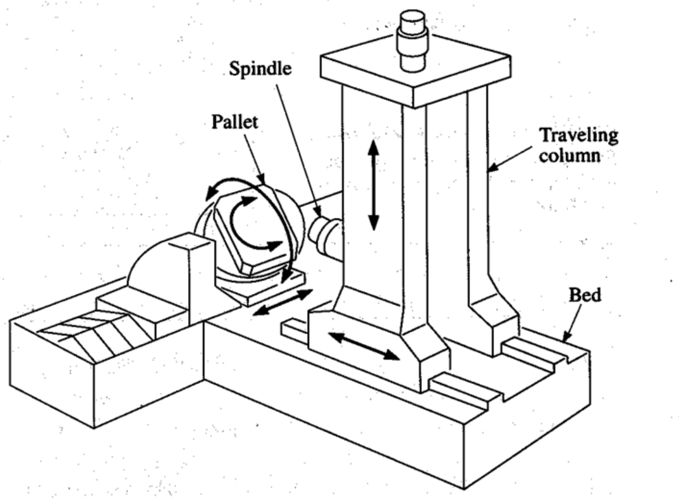


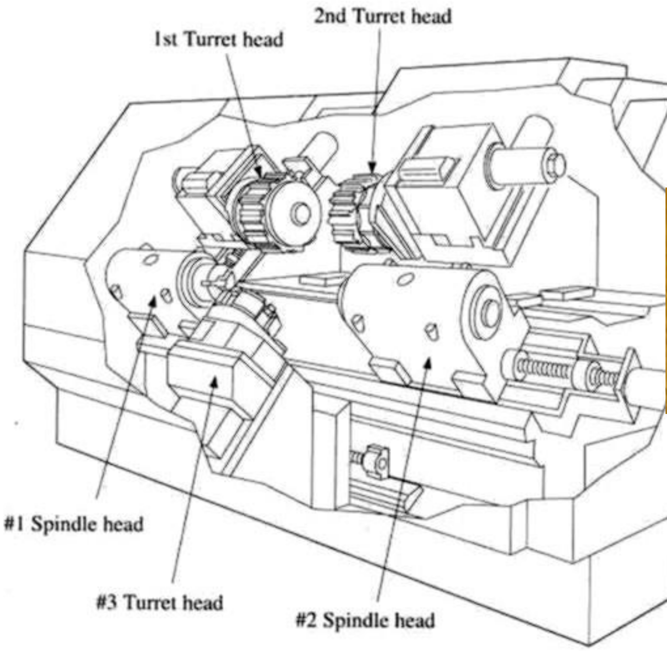
* Source: Kalpakjian, "Manufacturing Engineering and Technology"





How would you make this ball for a ball valve?





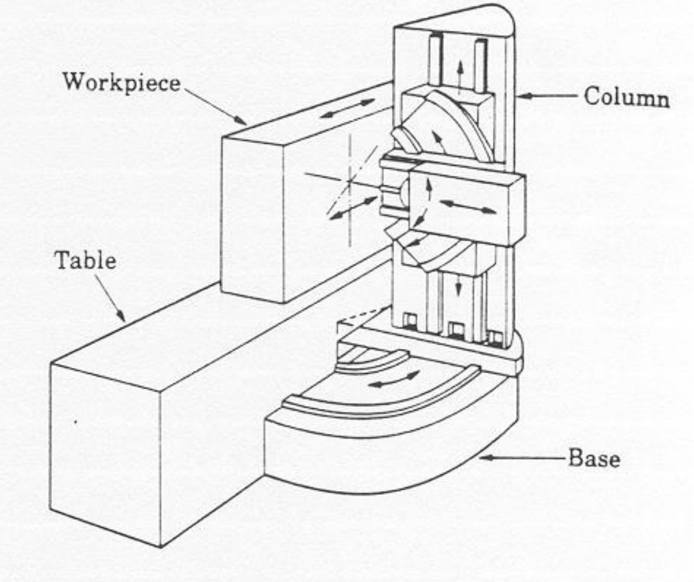
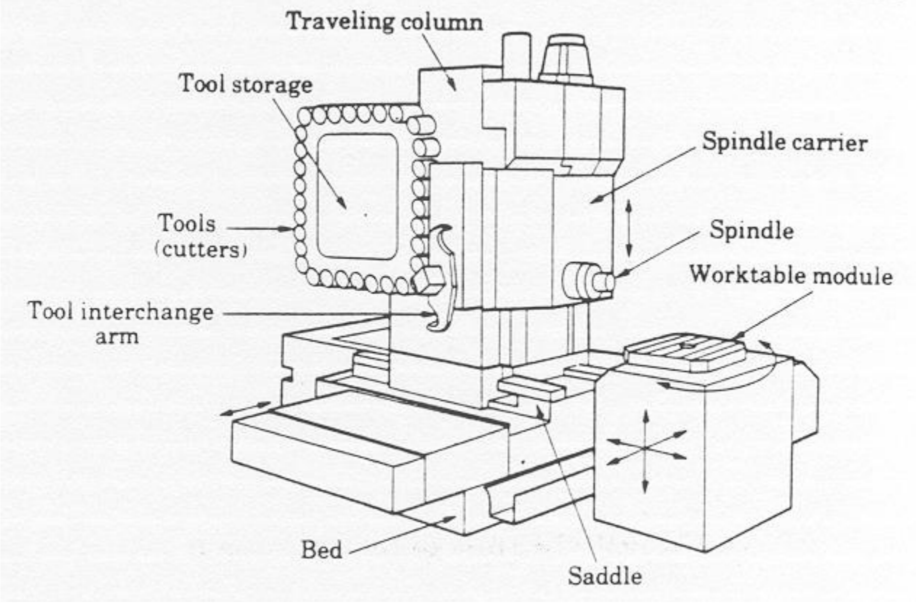


FIGURE 23.21

Schematic illustration of a five-axis profile milling machine. Note that there are three principal linear and two angular movements of machine components.



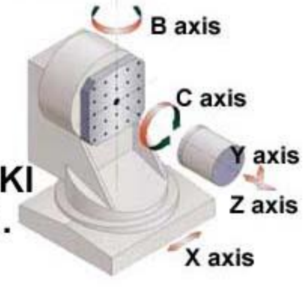
* Source: Kalpakjian, “Manufacturing Engineering and Technology”

Go to

http://www.youtube.com/watch?v=yU_RHiHudag&feature=related

http://www.youtube.com/watch?v=0u2xC60-oMI&NR=1

For 5 axis machining demos

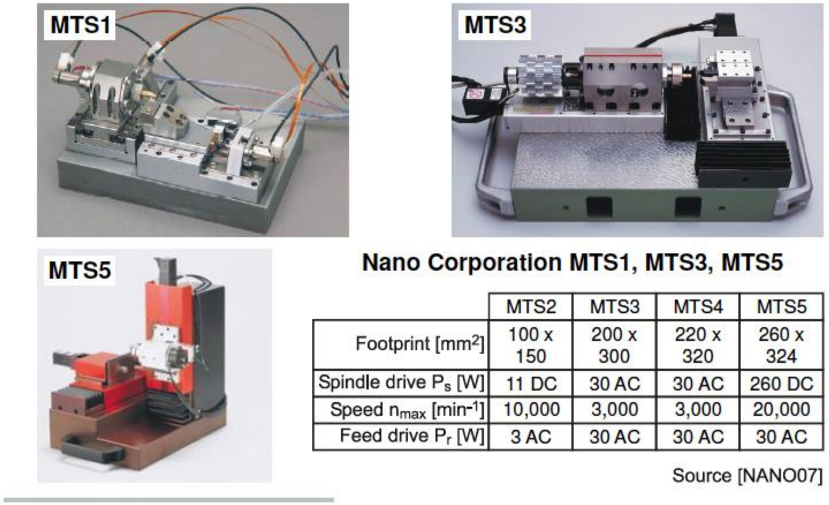


**MITSUI-SEIKI
5 Axis Appl.
Know-how**

Hawk TC-200

New developments:

Micro machines



Nano Corporation MTS1, MTS3, MTS5

	MTS2	MTS3	MTS4	MTS5
Footprint [mm^2]	100 x 150	200 x 300	220 x 320	260 x 324
Spindle drive P_s [W]	11 DC	30 AC	30 AC	260 DC
Speed n_{max} [min^{-1}]	10,000	3,000	3,000	20,000
Feed drive P_r [W]	3 AC	30 AC	30 AC	30 AC

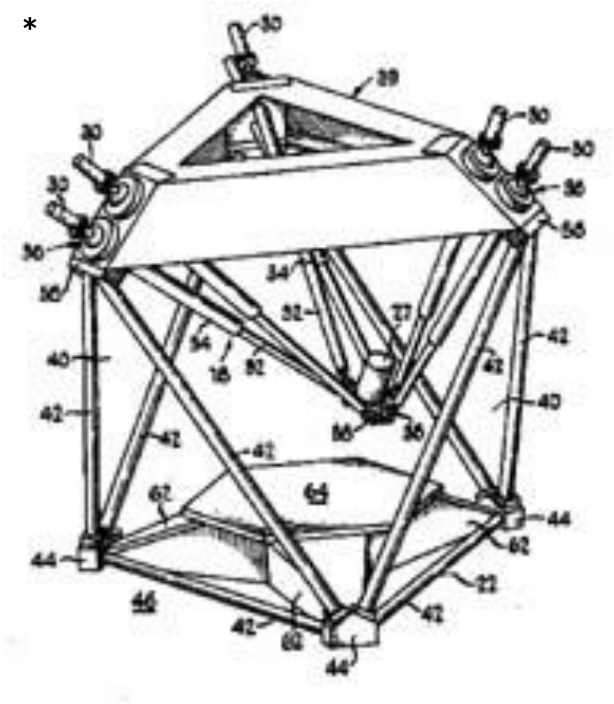
Source [NANO07]

Figure 3.14: Nano Corporation micro machines

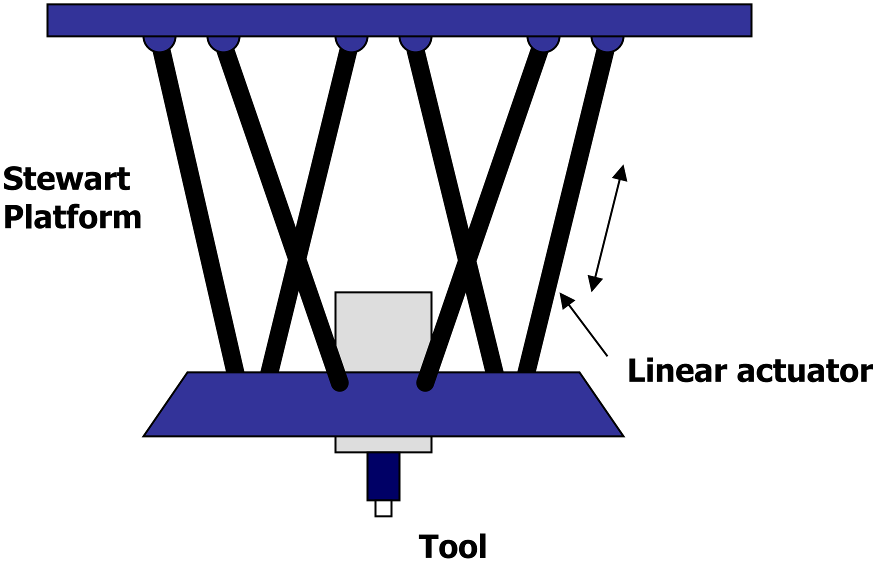
Diamond turning
And grinding of optical parts

Hexapod Milling Machines

*



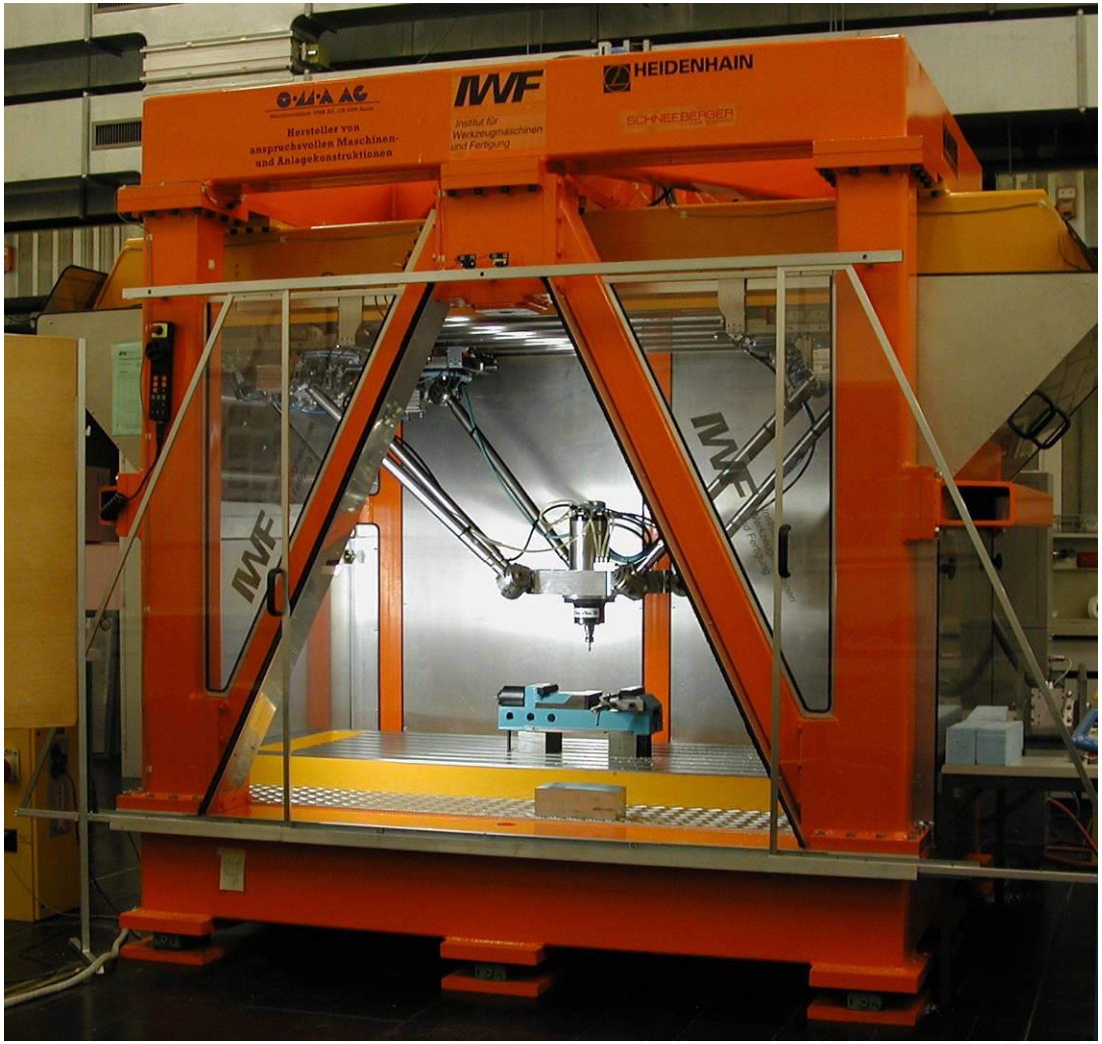
Hexapod machining center
(Ingersoll, USA)



Schematics

* Source: http://macea.snu.ac.kr/eclipse/background/background.html

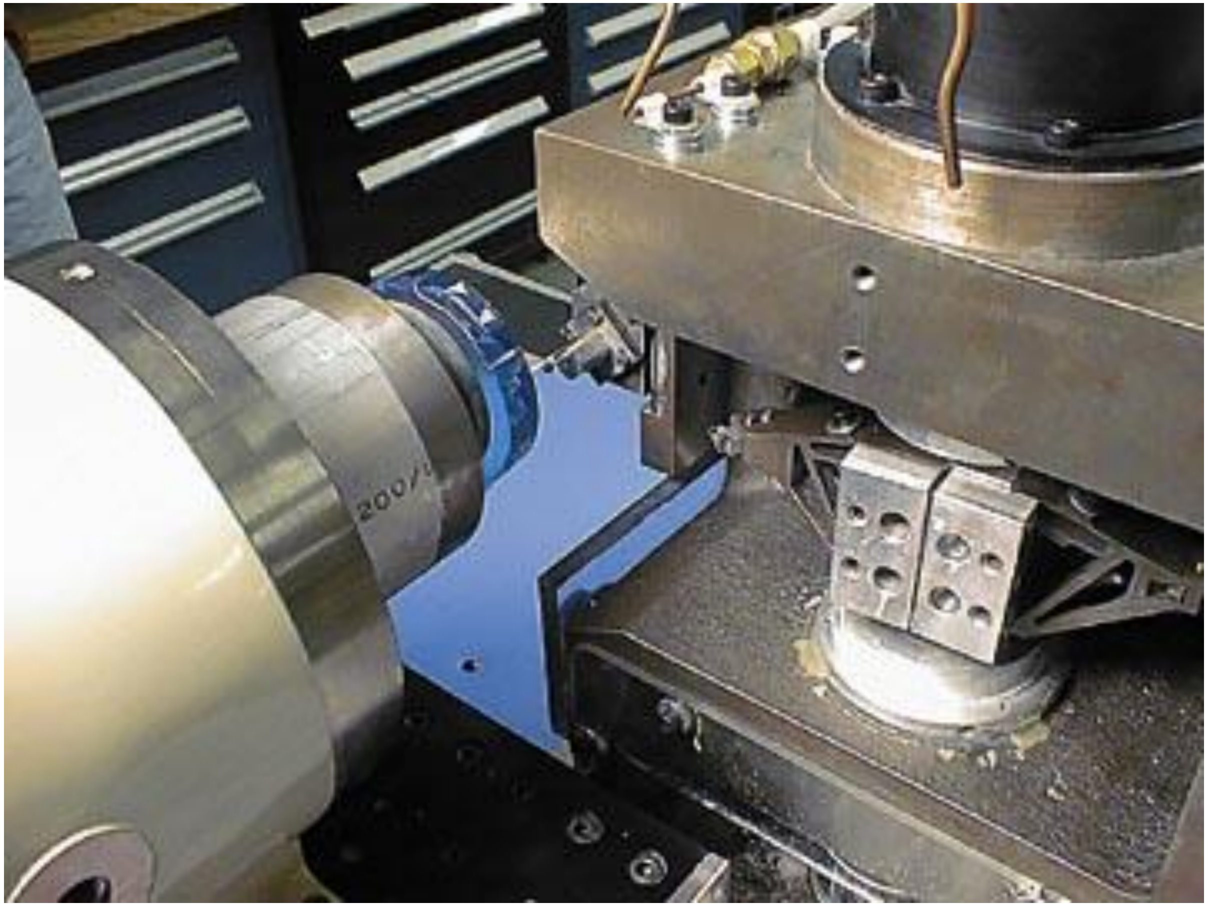
Institut für Werkzeugmaschinen und Fertigung
Hexaglide from Zurich (ETH)

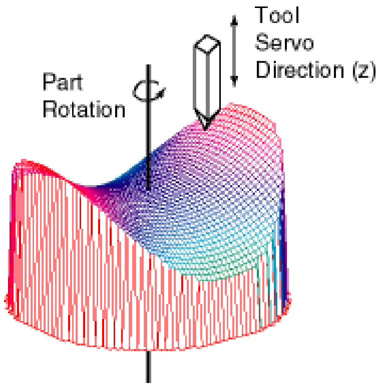


www.iwf.mavt.ethz.ch/

Fast Tool Server

http://web.mit.edu/pmc/www/index.html





NC machine tool developed at MIT mid 1950's

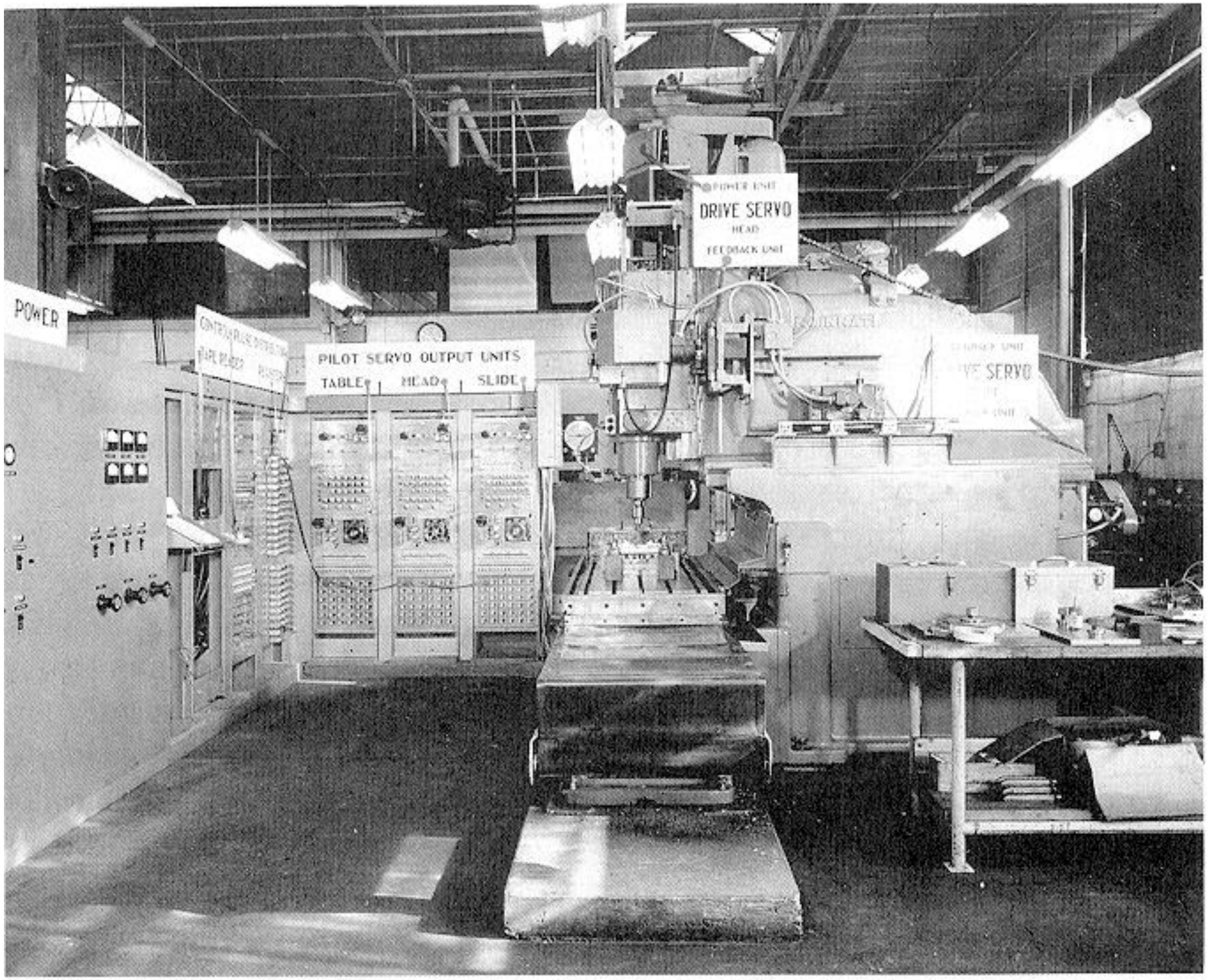


FIG. 2.2. The MIT numerically controlled milling machine.

* Source: Reintjes, "Numerical Control 1991"

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NUMERICAL CONTROL

Making a New Technology

J. Francis Reintjes