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

Subtractive Processes: Machining

2.810

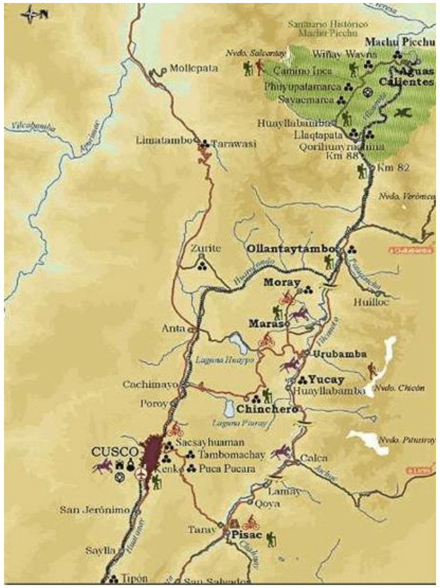
T. Gutowski

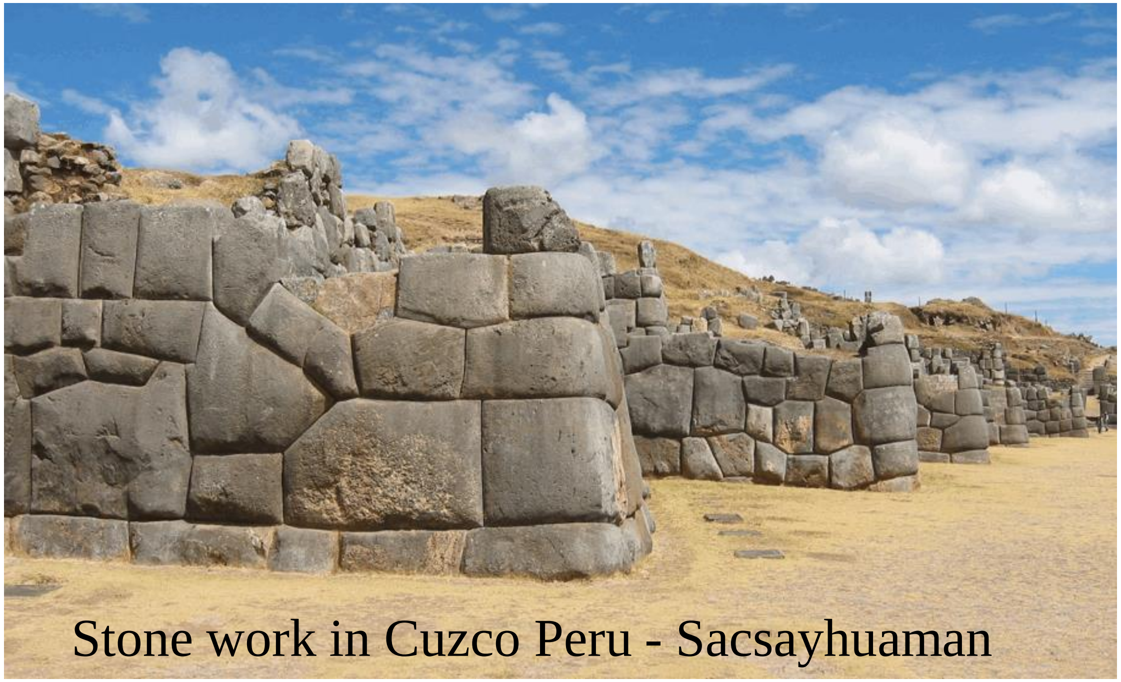
5 axis machining of aluminum

Machining tutorial:

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

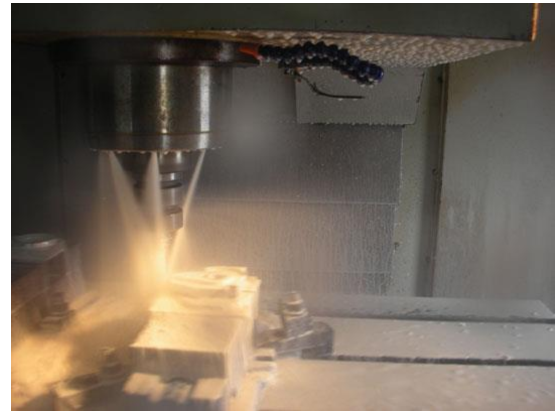
Ancient Tools & Structures



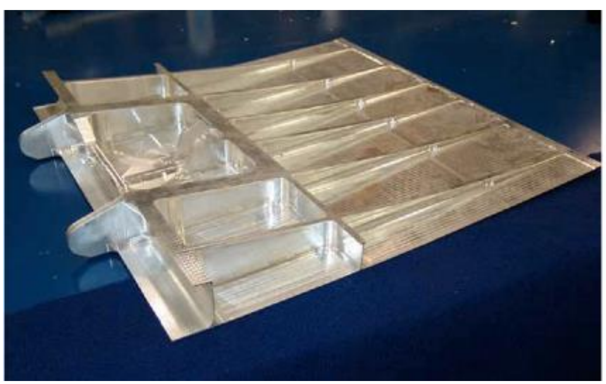

Stone work in Cuzco Peru - Sacsayhuaman

Modern Machining Practice

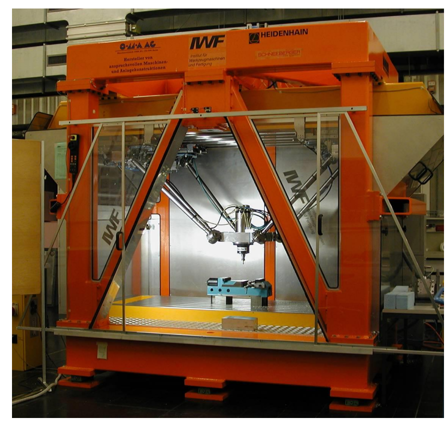
5 axis



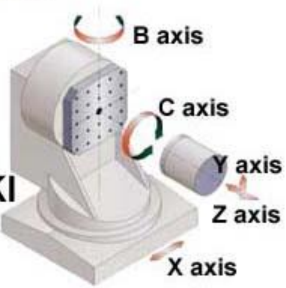
High speed



Complex parts



New Configurations



MITSUI-SEIKI
5 Axis Appl.
Know-how

Why machining is still important

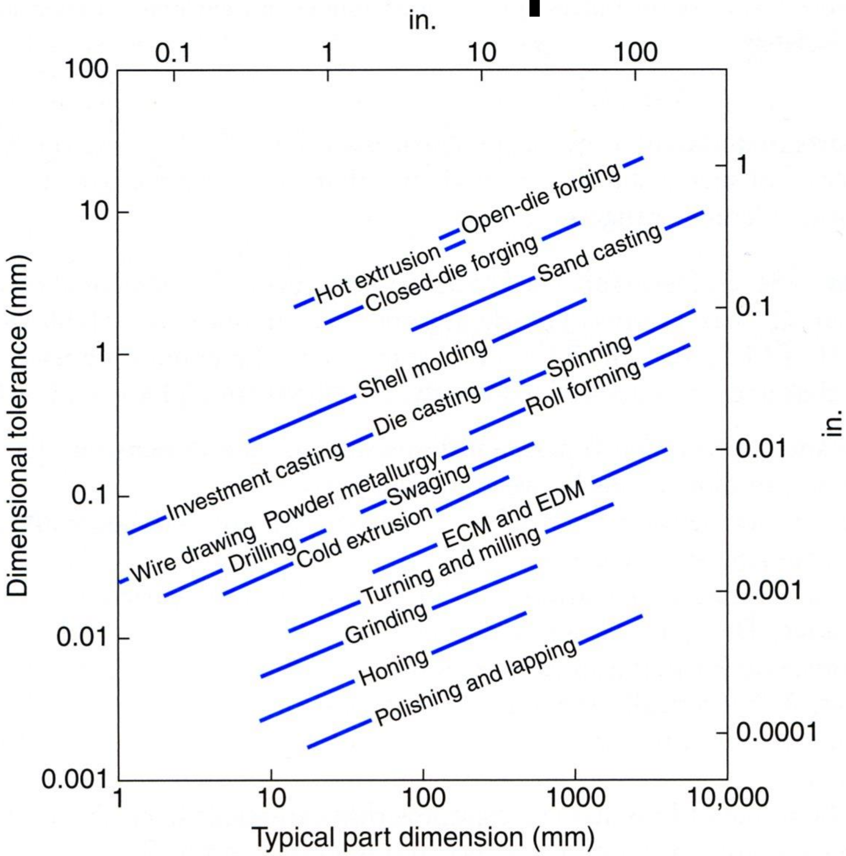


FIGURE 35.20 Dimensional tolerances as a function of part size for various manufacturing processes; note that because many factors are involved, there is a broad range for tolerances.

Why machining is still important

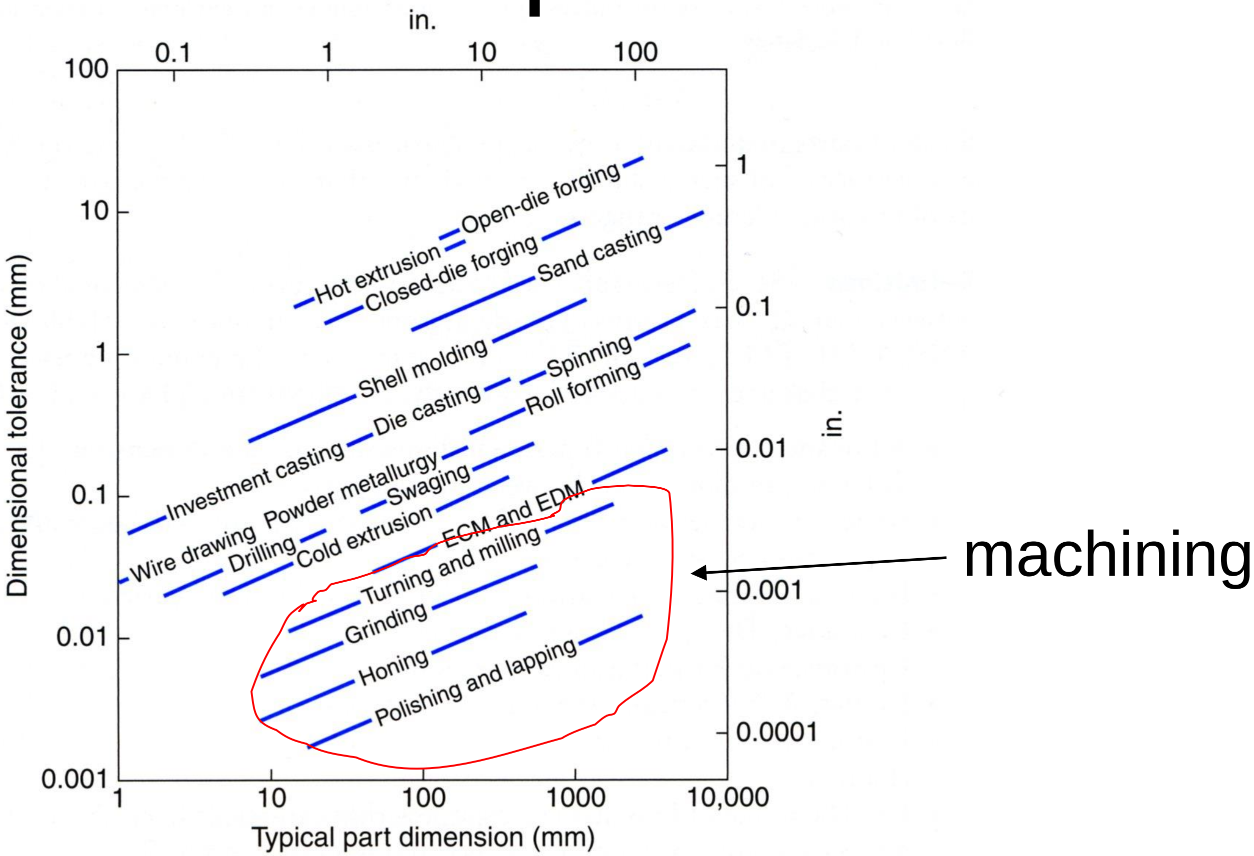


FIGURE 35.20 Dimensional tolerances as a function of part size for various manufacturing processes; note that because many factors are involved, there is a broad range for tolerances.

Kalpakjian & Schmid

Compared to Additive

Table 4: Overview of IT-classes for various manufacturing processes according to FRITZ [42]

Process	IT-Classes (DIN EN ISO 286-1)											
	5	6	7	8	9	10	11	12	13	14	15	16
Casting							■	■	■	■	■	■
Sintering					■	■	■	■				
Drop forging								■	■	■	■	■
Precision forging						■	■	■				
Cold extrusion			■	■	■	■	■	■				
Milling				■	■	■	■					
Cutting								■	■	■		
Turning			■	■	■	■						
Drilling								■	■	■		
Face milling			■	■	■	■	■	■				
Planing				■	■	■	■	■				
Stripping			■	■	■	■						
Circular grinding	■	■	■	■	■							
Additive manufact.							■	■	■	■	■	■
FDM							xyz	xyz	xyz	z		
LS									xyz	xyz	xyz	
LM							xy	xy	xy	xy	z	z

Ref Lienke et al, U. Paderborn, Germany (DIN German Standard for part tolerance)

What prevents machining from being a fully digital technology?

1. Large cutting forces require
   - Secure fixturing
   - Robust tools & tool holders
   - Limiting geometrical access
   - Requiring repeated fixturing

Basic Mechanics Issues

– Shear strain

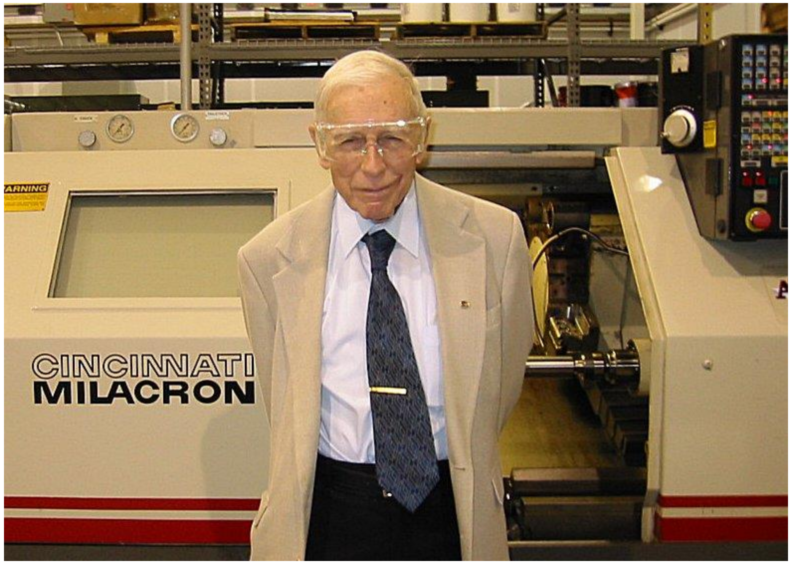
– Power, plastic work

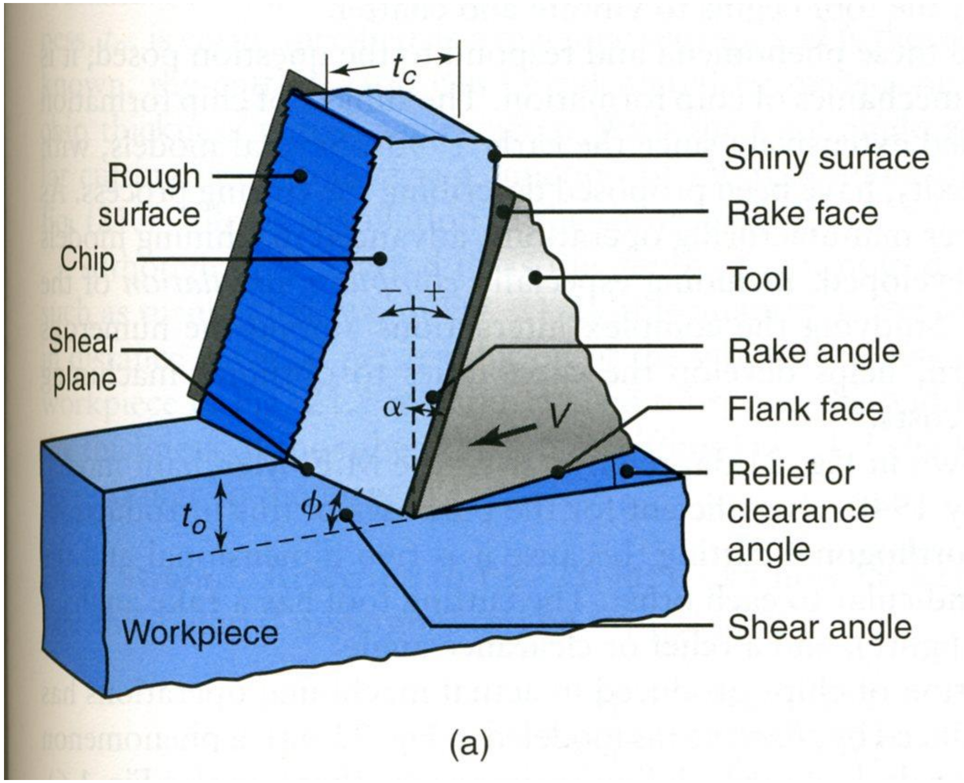
– Friction, forces

– Temperature rise

– Heat, Tool materials, Rate limits

Basic Machining Mechanism

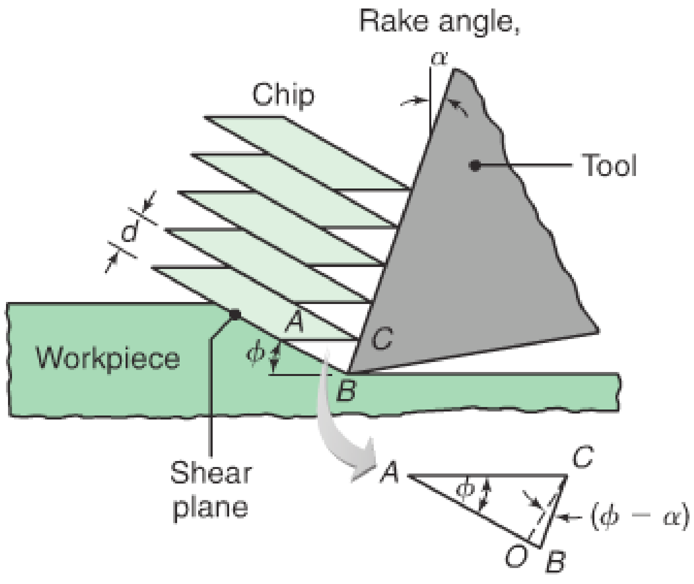




Eugene Merchant's model for orthogonal cutting

Video on plastic deformation in machining

Basic Machining Mechanism



(a)

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,

$$\gamma = \cot(\phi) + \tan(\phi - \alpha)$$

$$\text{Shear strain, } \gamma = \frac{AB}{OC} = \frac{AO}{OC} + \frac{OB}{OC}$$

γ becomes large for small ϕ
$\rightarrow$small or negative α

Observation for Video

- $\phi \cong 25°$ shear angle
- $\alpha \cong 10°$ rake angle
- Therefore,
- $\gamma \cong \frac{1}{tan25°} + tan15°$=2.41 Shear Strain

Basic Machining Mechanism

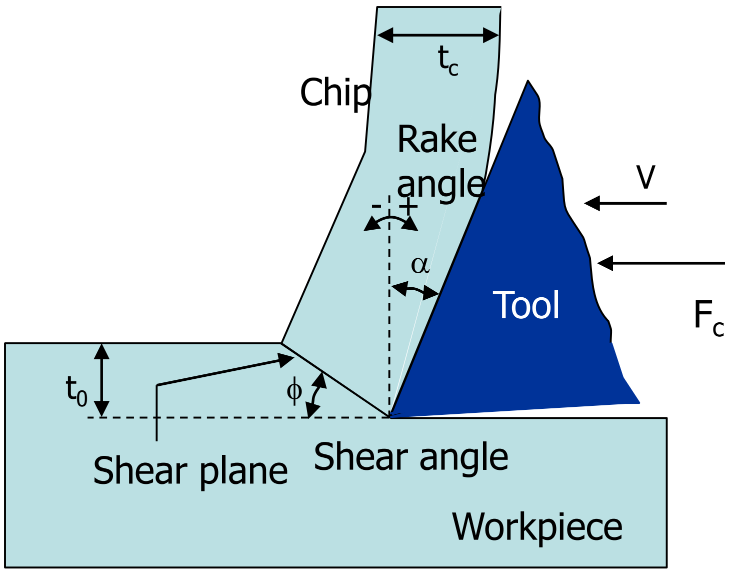
TABLE 2.4

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}

Kalpakjian & Schmid

Basic Machining Mechanism



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

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

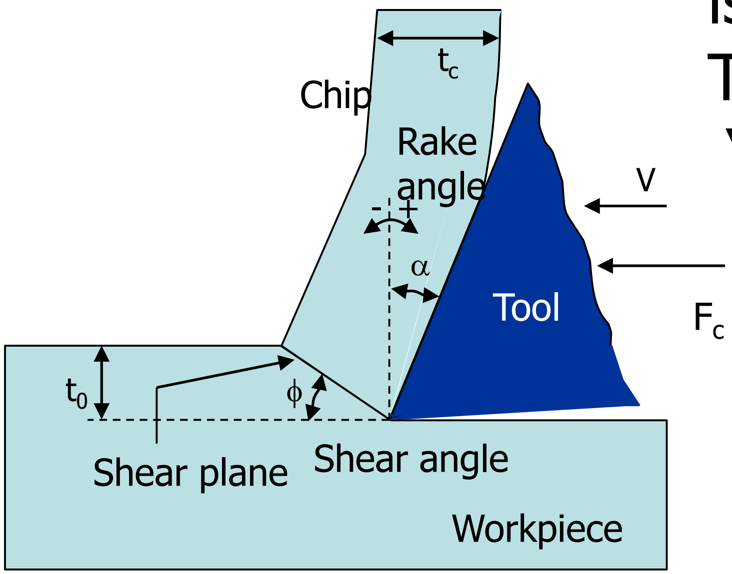
$$u_S = u_{\text{plastic work}} + u_{\text{friction}}$$

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

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

Friction?

Basic Machining Mechanism



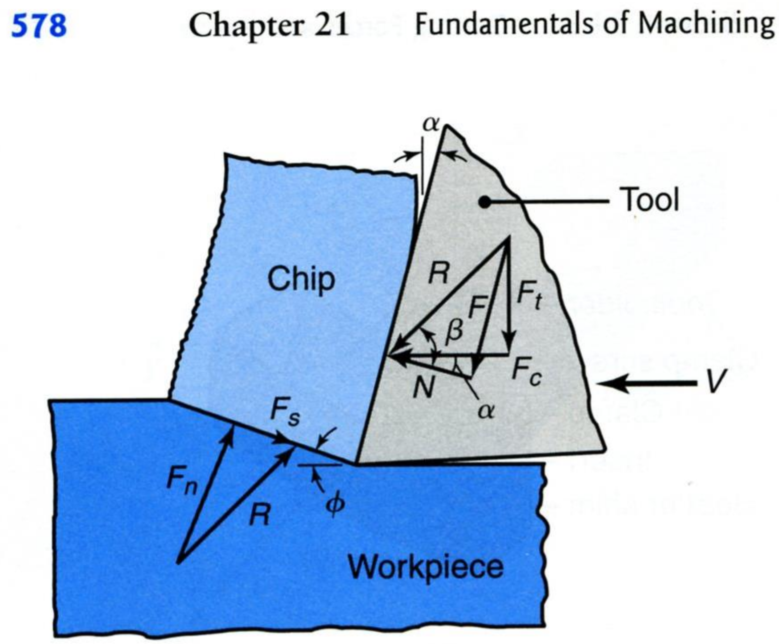
If friction work u_f
is about 0.25 to 0.5 of u_p *(Ref Cook)*
Then specific cutting work (the total)
"u_s" is about 9/16 x Hardness "H"

Approximate scaling:

$u_s \sim H$ (Hardness)

We will use tabulated values for specific energy
See tables 21.2 for cutting and Table 26.2 for grinding

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

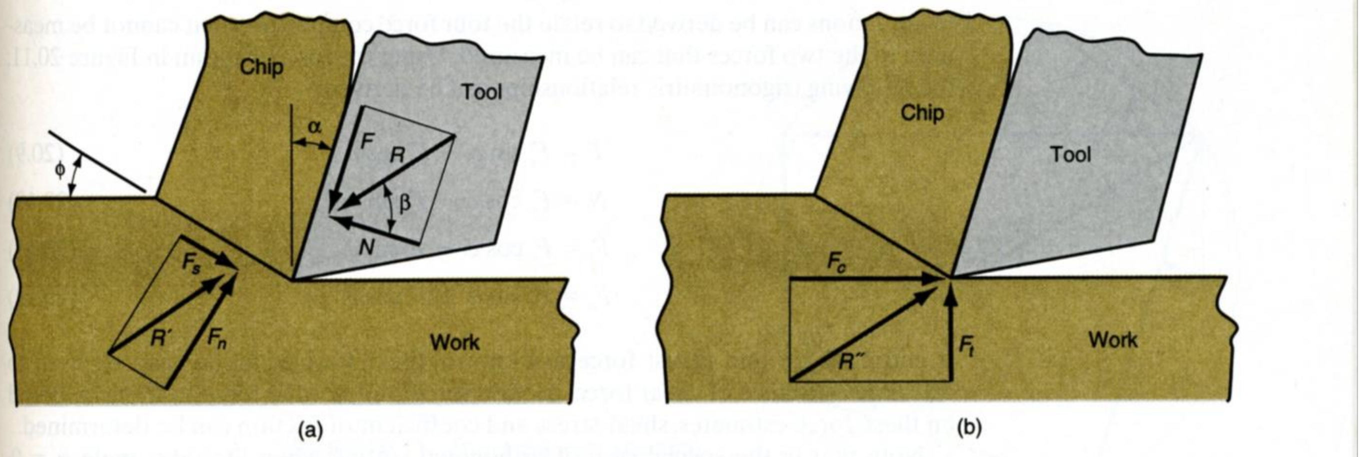


FIGURE 20.10 Forces in metal cutting: (a) forces acting on the chip in orthogonal cutting, and (b) forces acting on the tool that can be measured.

- $\tau_s = \frac{F_s}{A_s} = \frac{F_c cos\phi - F_t sin\phi}{t_o w / sin\phi}$; taking $\frac{d\tau_s}{d\phi} = 0$
- Gives: $\phi = 45° + \frac{\alpha}{2} - \frac{\beta}{2}$

Ref. Groover

The Merchant Equation

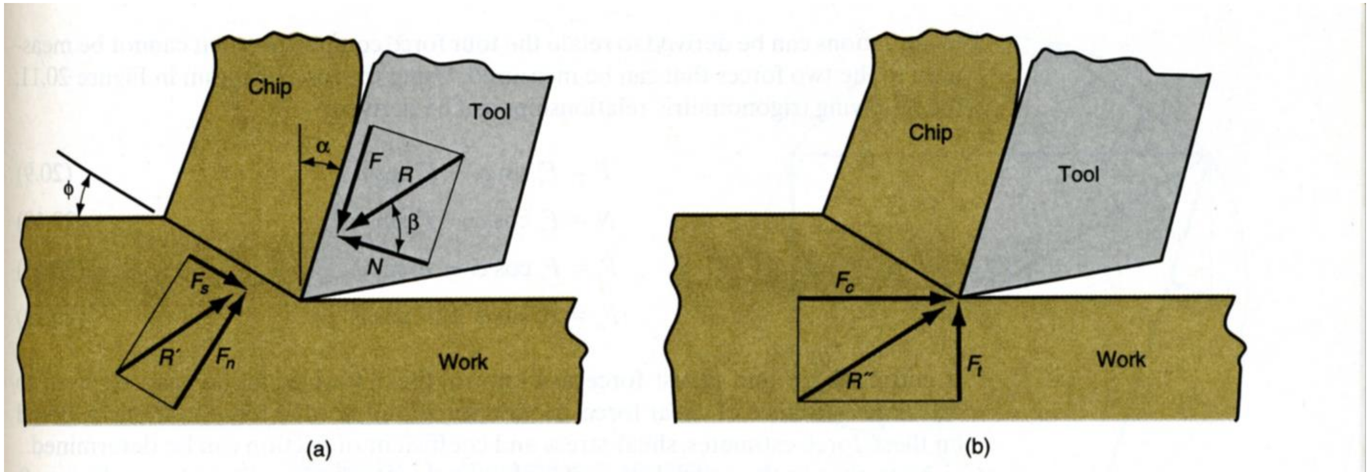
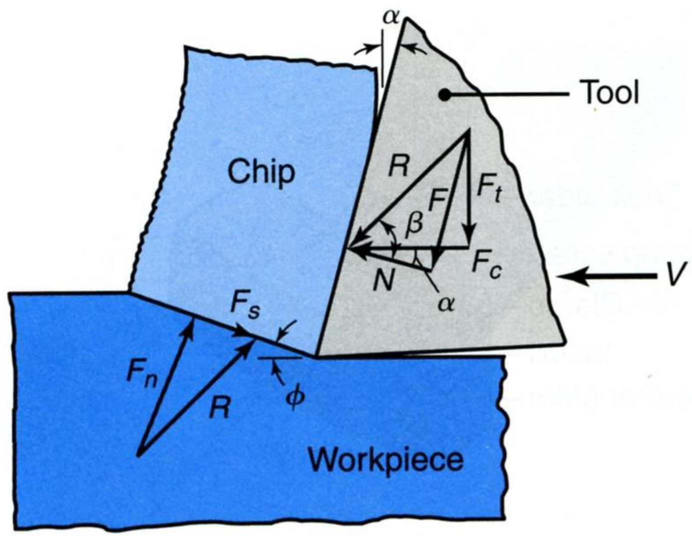


FIGURE 20.10 Forces in metal cutting: (a) forces acting on the chip in orthogonal cutting, and (b) forces acting on the tool that can be measured.

- Using values from the video,
- $\phi \cong 25°$ shear angle, $\alpha \cong 10°$ rake angle
- $\phi = 45° + \frac{\alpha}{2} - \frac{\beta}{2}$, gives $\beta = 50°$
- $\mu = tan50° = 1.19$

Ref. Groover

The Thrust Force



(a)

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

Again from our example:

$$F_t = 0.84 F_c$$

Ref. Kalpakjian & Schmid

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 W · s/mm³	Specific energy hp · min/in³
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

Specific energy, u_S

Cutting

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)

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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

Grinding

TABLE 26.2

Approximate Specific-Energy Requirements for Surface Grinding

Workpiece material	Hardness	Specific energy $W \cdot s/mm^3$	Specific energy $hp \cdot min/in^3$
Aluminum	150 HB	7–27	2.5–10
Cast iron (class 40)	215 HB	12–60	4.5–22
Low-carbon steel (1020)	110 HB	14–68	5–25
Titanium alloy	300 HB	16–55	6–20
Tool steel (T15)	67 HRC	18–82	6.5–30

For comparison see Table 26.2 for grinding

See Kalpakjian & Schmid
Chapter 26: Abrasive Machining

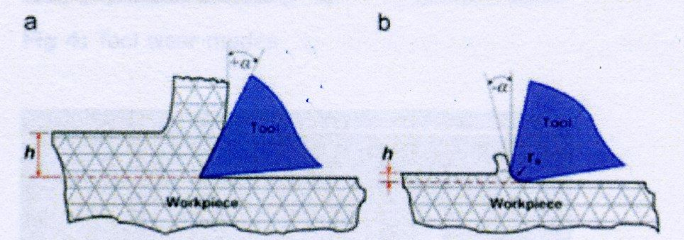
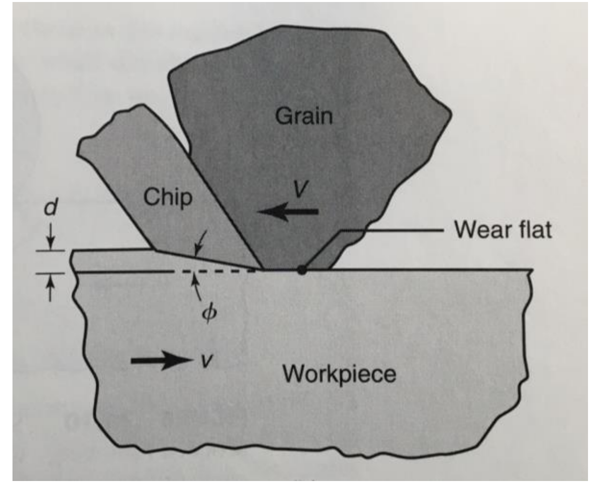


Fig 1: Size effect in (a) macro-scale and (b) micro-scale milling.



Surface Grinding

TABLE 26.2

Approximate Specific-Energy Requirements for Surface Grinding

Workpiece material	Hardness	Specific energy W · s/mm^3	Specific energy hp · min/in^3
Aluminum	150 HB	7–27	2.5–10
Cast iron (class 40)	215 HB	12–60	4.5–22
Low-carbon steel (1020)	110 HB	14–68	5–25
Titanium alloy	300 HB	16–55	6–20
Tool steel (T15)	67 HRC	18–82	6.5–30

Approximations:

Hence we have the approximation;

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

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

Since Power is

$$P = F_c * V$$

and MRR can be written as,

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

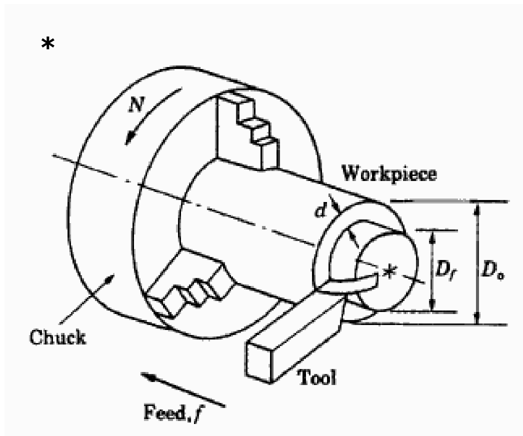
Where A is the cross-sectional area of the undeformed chip, we can get an estimate for the cutting force as,

$$F_c \approx u_s \times A$$

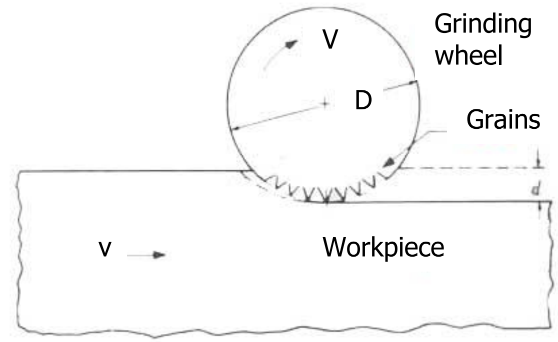
Note that this approximation is the cutting force in the cutting direction.

Basic Machining Processes

Turning

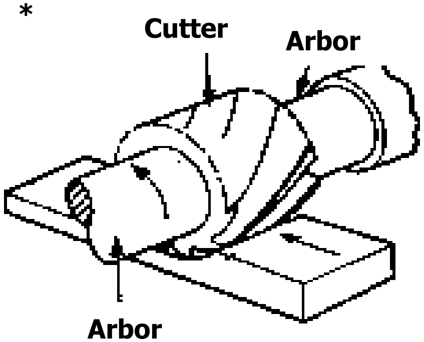


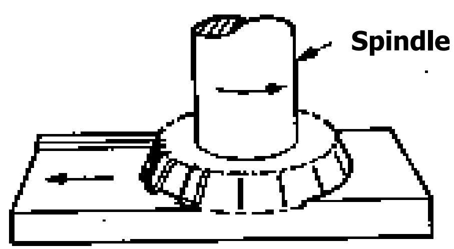
Grinding

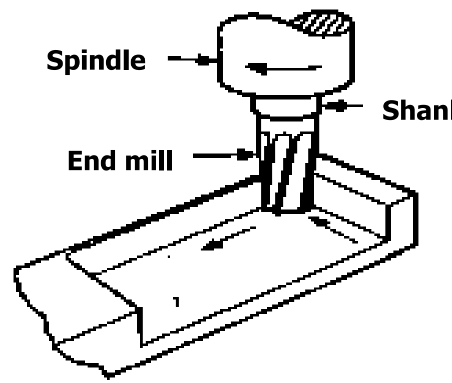


Milling

*





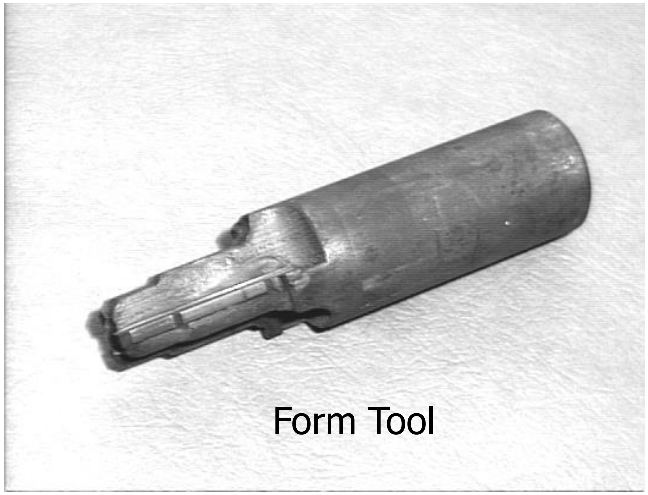


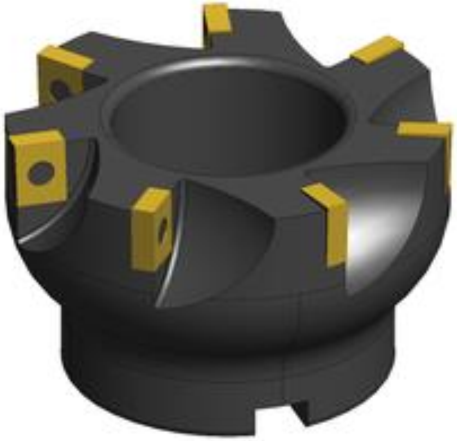
Horizontal Slab milling **Face milling** **End milling**

* Source: Kalpakjian, "Manufacturing Engineering and Technology"

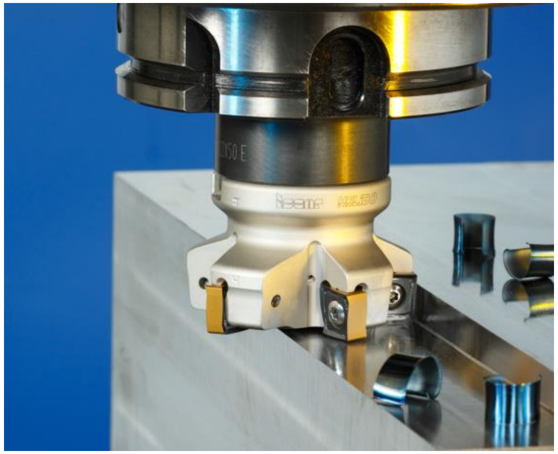
Cutter Geometries

End Mills

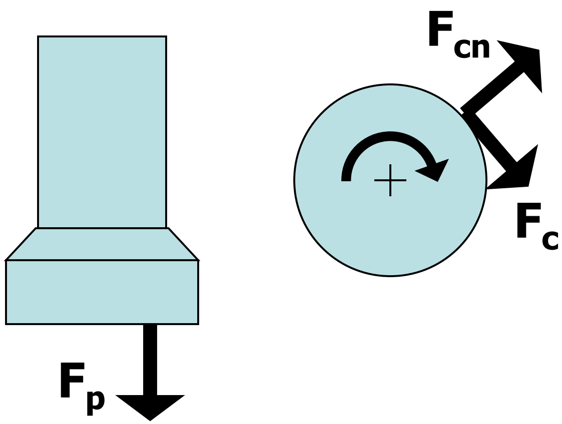

Form Tool

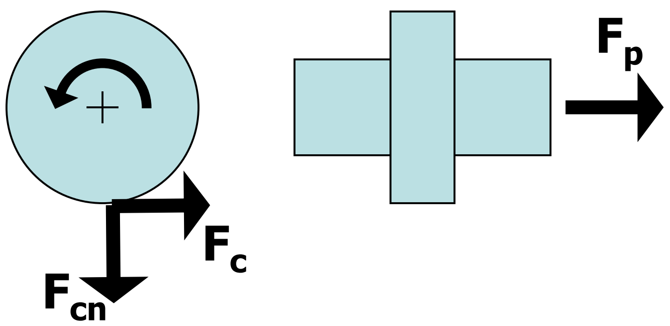


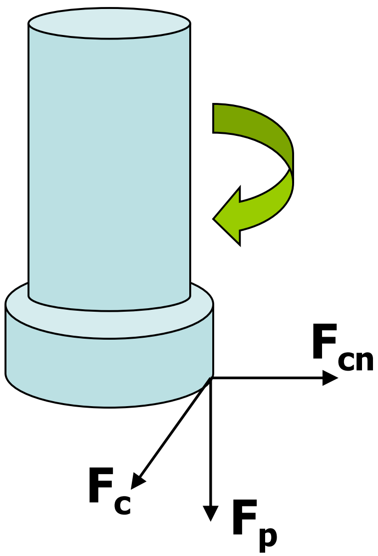
Face
Mill

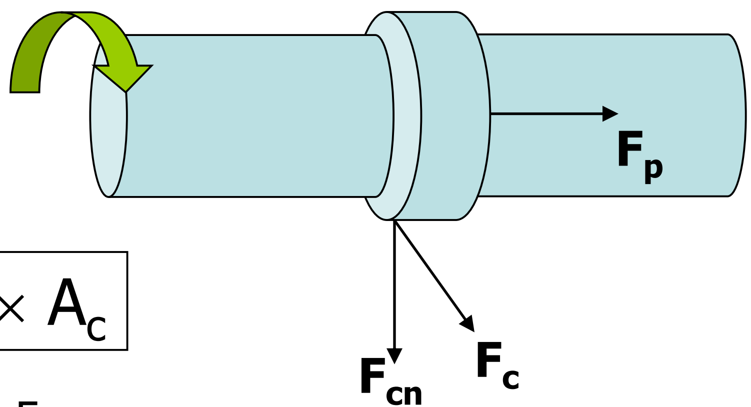


Cutting Force Directions in Milling





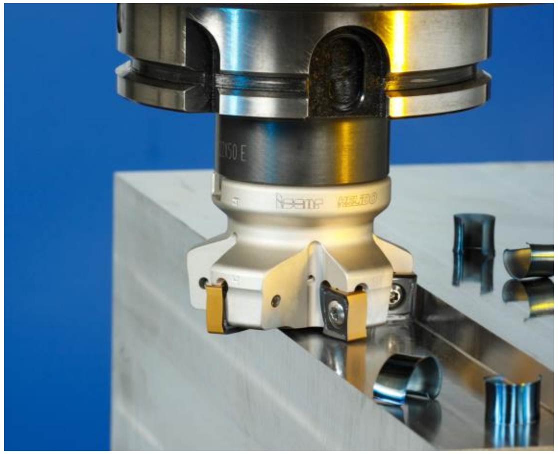


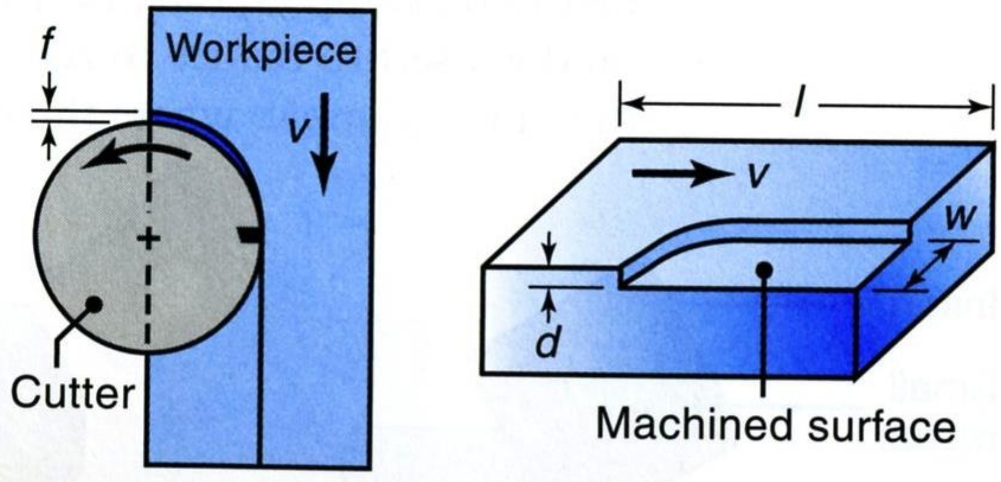


$$F_c \sim H \times A_c$$

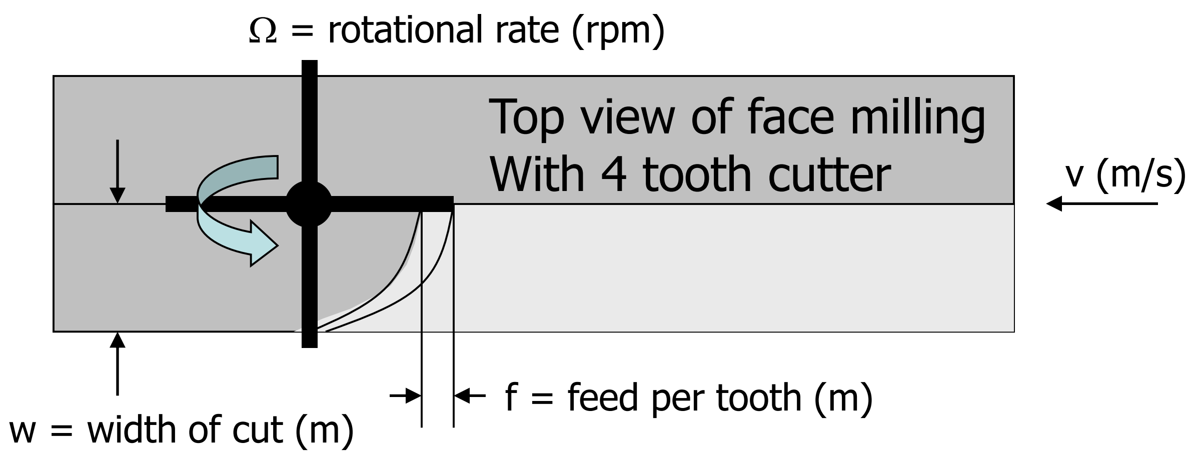
(Tangential Cutting Force ~
Chip Cross-section × Hardness)

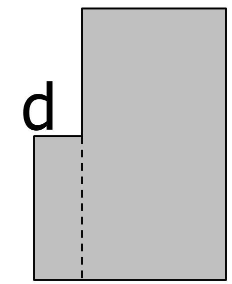
Face Milling





Feed per Tooth and MRR





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 **$f = v/4\Omega$.** In general, a cutter may have "N" teeth, so the ***feed per tooth*** is

$$f = v / N\Omega$$

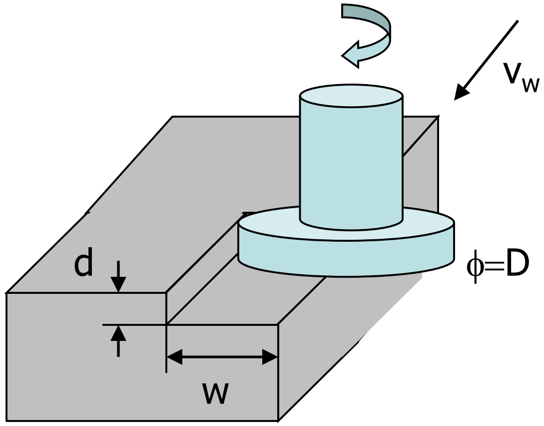
The material removal rate (MRR) is,

$$Force \approx f\, d\, u_s$$

$$MRR = v\, w\, d = f\, d \times w N\Omega$$

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

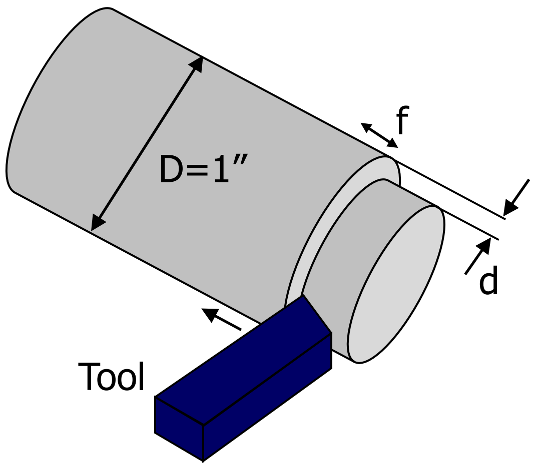
General Recommendations for Milling Operations

Material	Cutting tool	General-purpose starting conditions: Feed mm/tooth (in./tooth)	General-purpose starting conditions: Speed m/min (ft/min)	Range of conditions: Feed mm/tooth (in./tooth)	Range of conditions: 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]

Consequences of large forces

- Secure fixturing
- Robust tools & tool holders
- Limiting geometrical access
- Requiring repeated fixturing
- Heat Rise, Cutting tool requirements

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 $v\, f / \alpha$ = Pé = convection/conduction

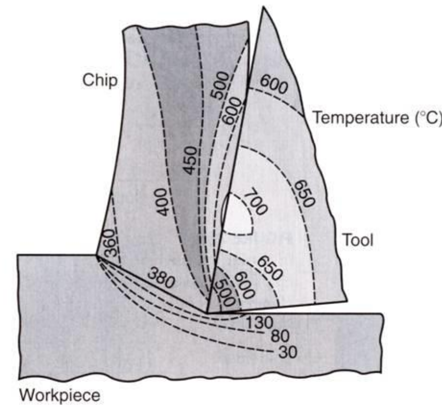


FIGURE 21.12 Typical temperature distribution in the cutting zone. Note the severe temperature gradients within the tool and the chip, and that the workpiece is relatively cool. *Source:* After G. Vieregge.

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

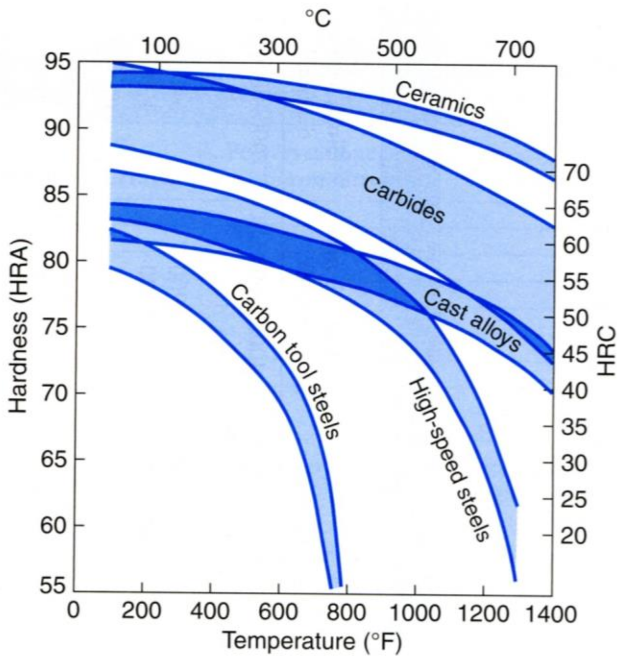


FIGURE 22.1 The hardness of various cutting-tool materials as a function of temperature (hot hardness); the wide range in each group of materials is due to the variety of tool compositions and treatments available for that group.

Section 22.7 Cubic Boron Nitride 613

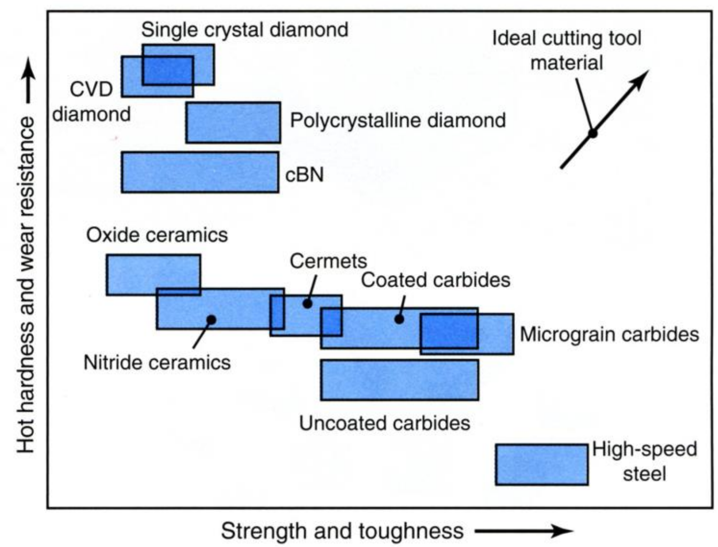


FIGURE 22.9 Ranges of mechanical properties for various groups of tool materials. HIP = hot isostatically pressed. (See also Tables 22.1–22.5.)

Tool Life

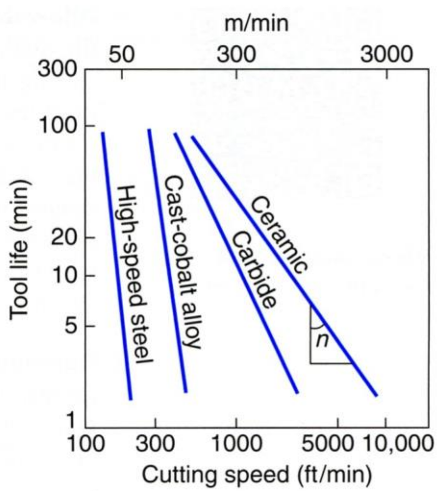


FIGURE 21.17 Tool-life curves for a variety of cutting-tool materials. The negative reciprocal of the slope of these curves is the exponent n in the Taylor tool-life equation (21.25), and C is the cutting speed at $T = 1$ min, ranging from about 200 to 10,000 ft/min in this figure.

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

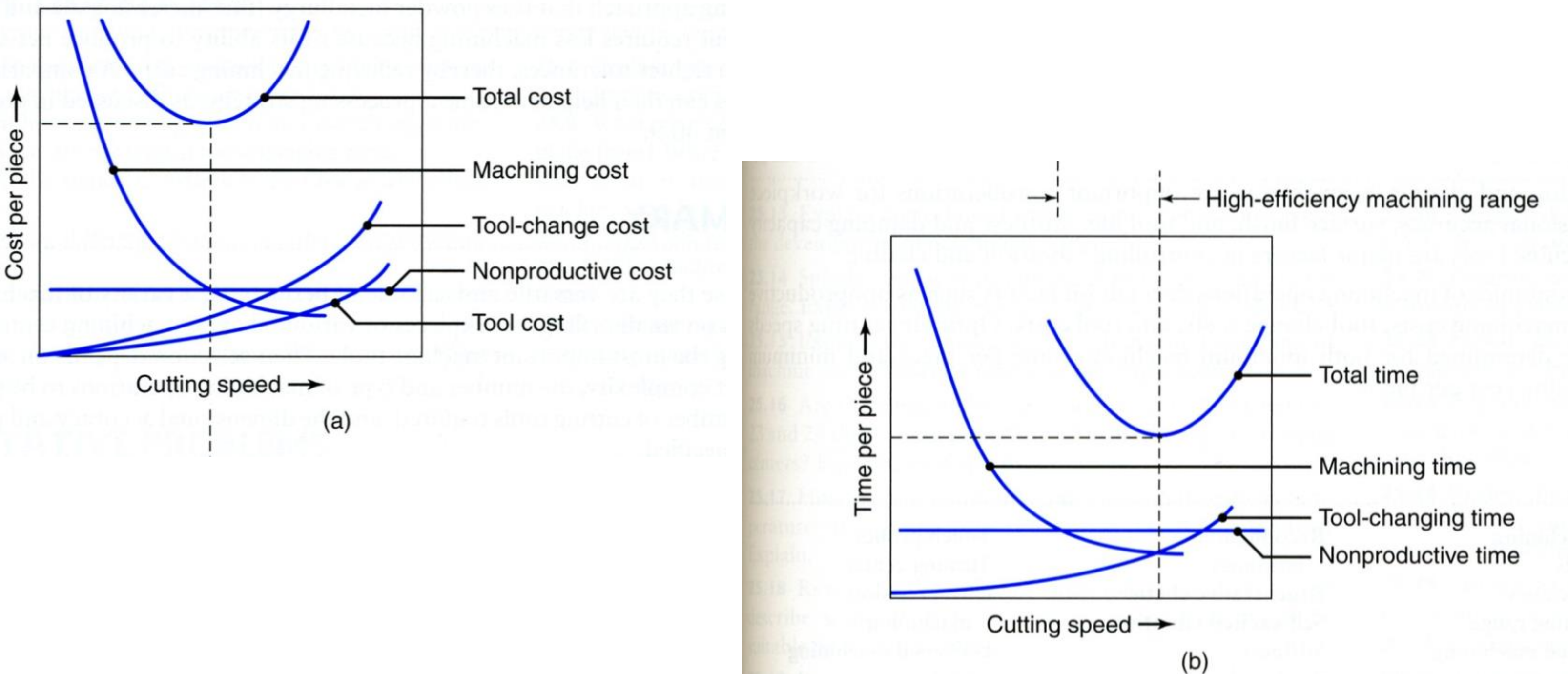


FIGURE 25.17 Graphs showing (a) cost per piece and (b) time per piece in machining; note the optimum speeds for both cost and time. The range between the two is known as the *high-efficiency machining range*.

New Tooling Materials and their effect on Productivity

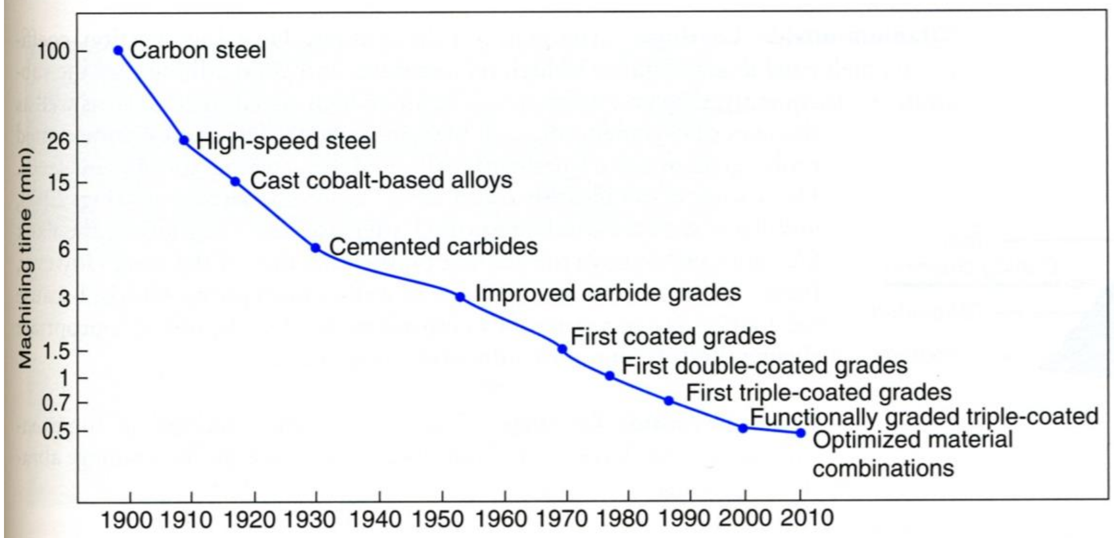


FIGURE 22.6 Relative time required to machine with various cutting-tool materials, indicating the year the tool materials were first introduced; note that machining time has been reduced by two orders of magnitude within a 100 years. *Source:* Courtesy of Sandvik.

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 poor surface finish, excessive work hardening, “welding”; can be reduced with cutting fluid
- Economics - tool changes

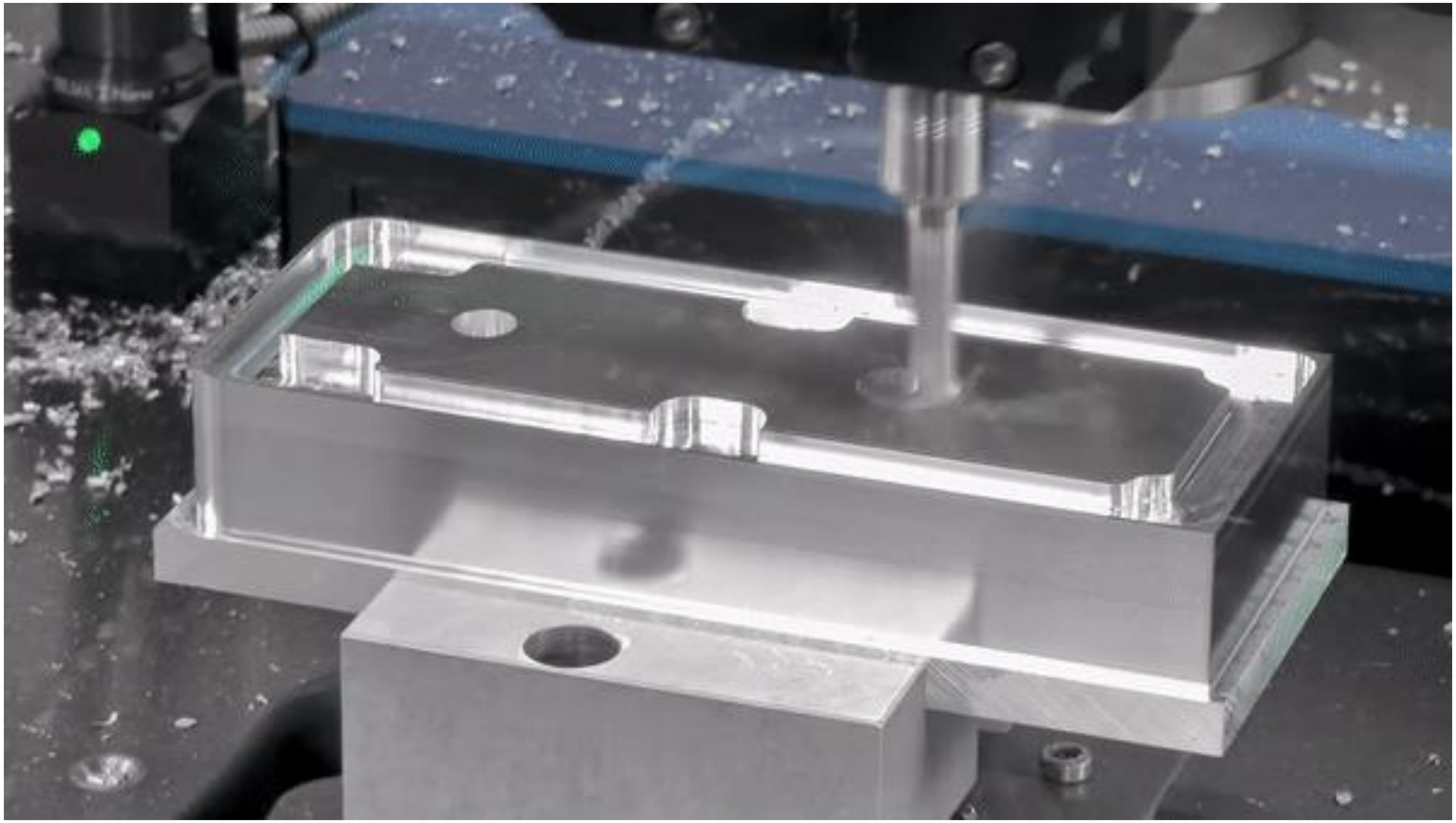
See Video on Rate Limits In Machining

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.

$$MRR = f\,d * N\,\Omega\,w$$

High Speed Machining



https://www.youtube.com/watch?v=3YzAl29Ag78

Machine tool configurations

- Machine tool

  number of axes, spindles, serial and parallel configurations

- Cutter geometry

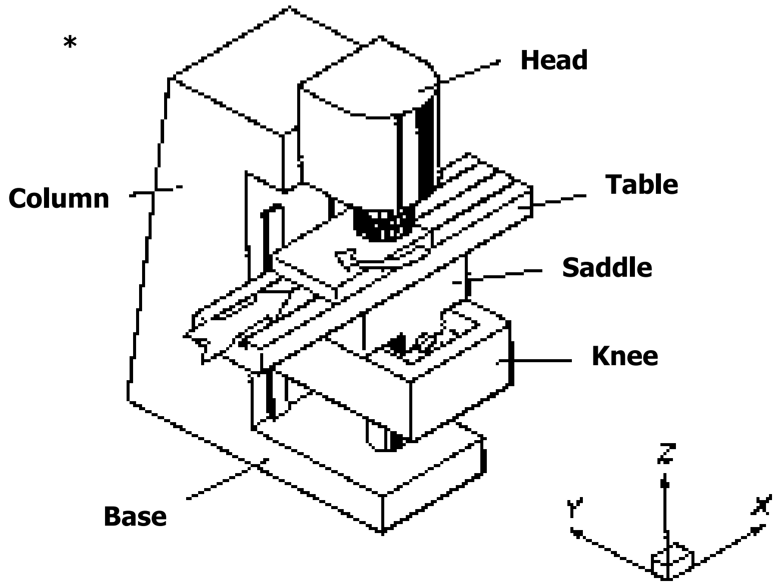
  Form tool, cutter radius, inserts, tool changers

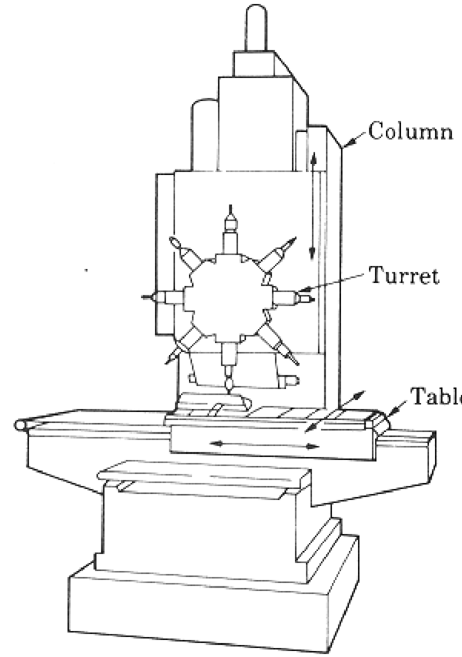
- Software

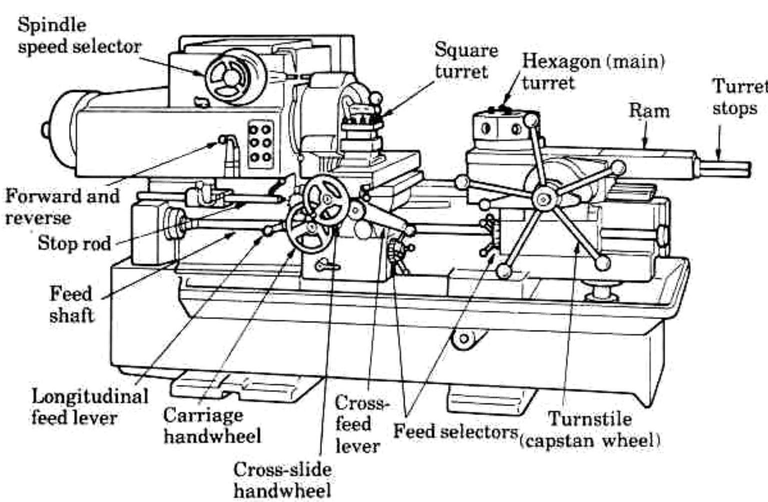
  flexibility, geometrical compensation, “look ahead” dynamics compensation

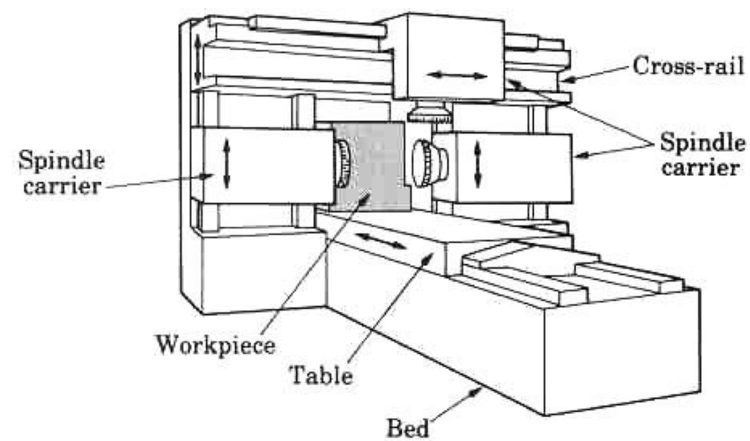
Various Machine Tool Configurations

*



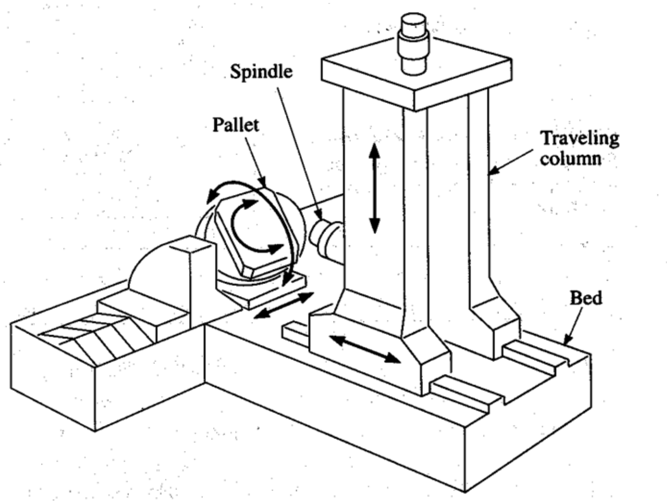


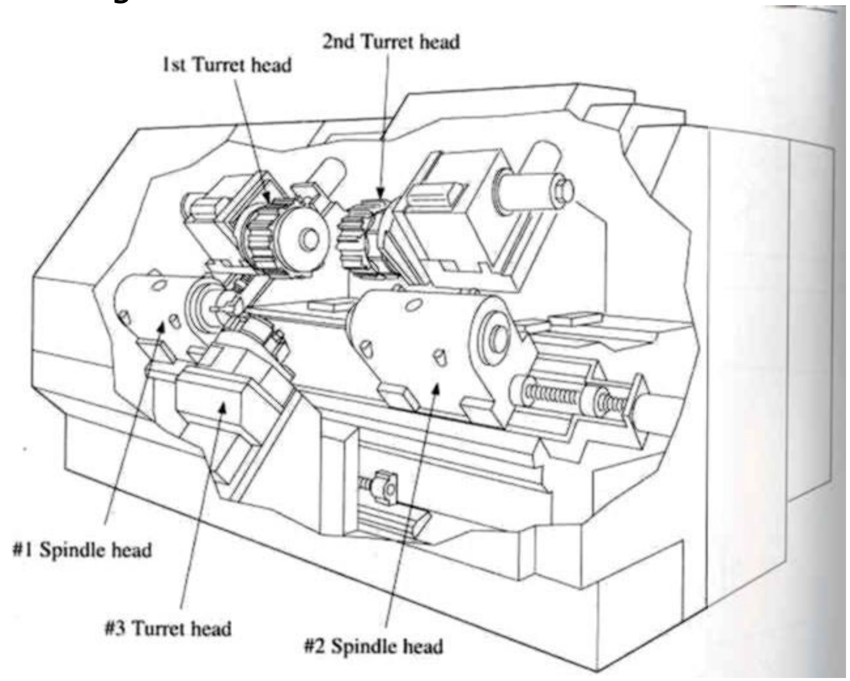




* Source: Kalpakjian, "Manufacturing Engineering and Technology"

Various Machine Tool Configurations





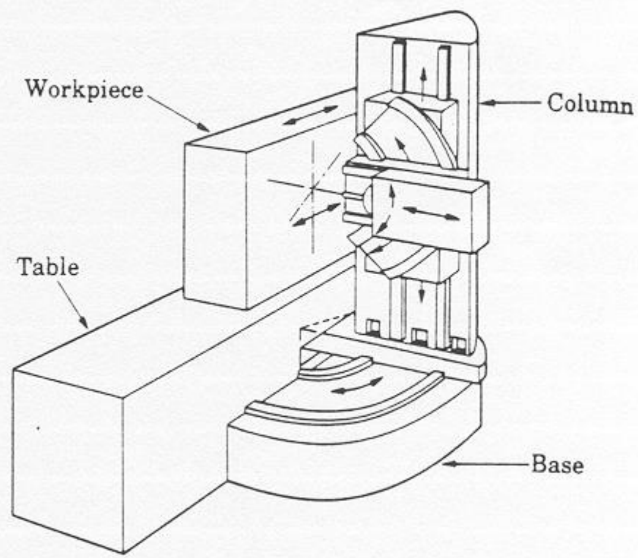
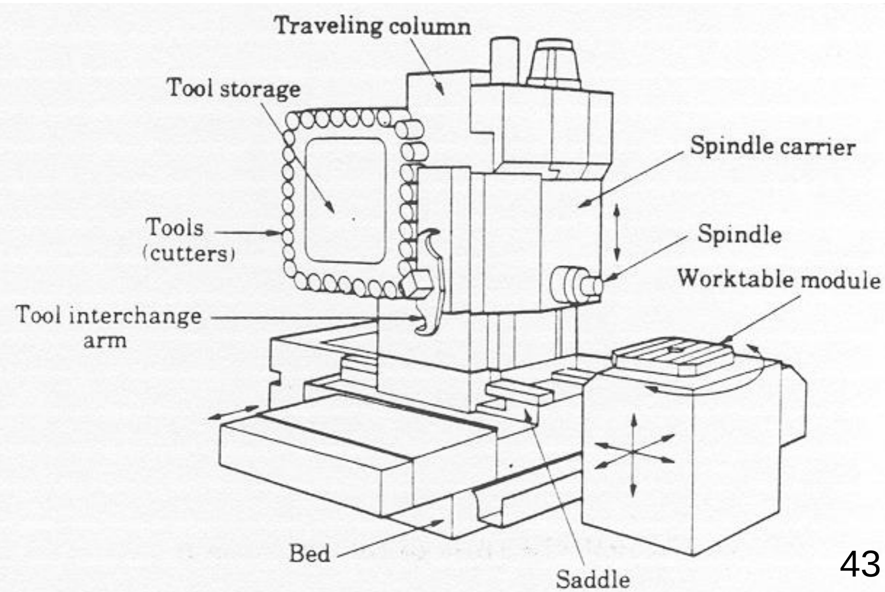


FIGURE 23.21

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"

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 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,

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

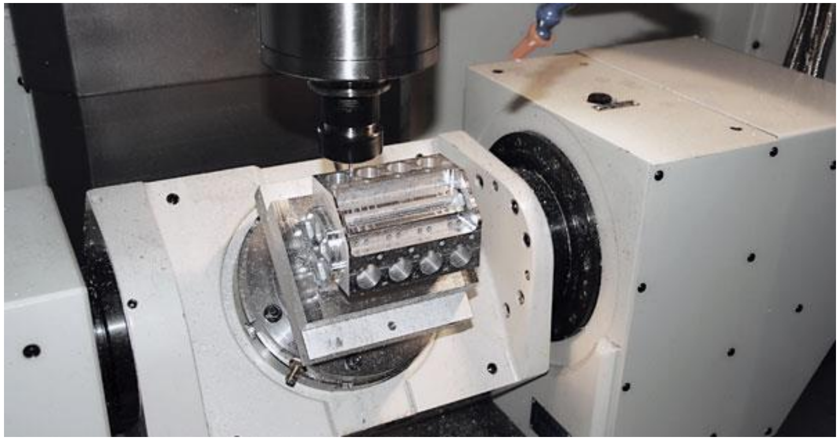
Invar tooling and mandrels produced at Coast Composites are used for the production of various commercial and military aircraft.

Some Machining Developments

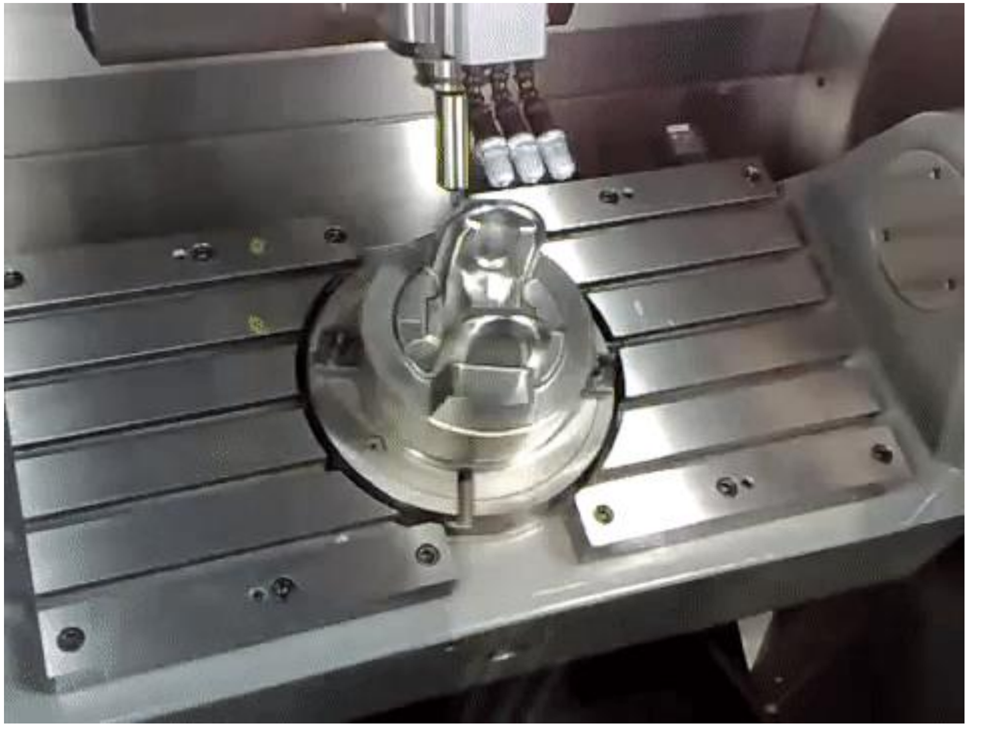
- 5 Axis machining
- Diamond turning
- Micro-machining
- Fast tool server
- Cryogenic cooling

5 Axis Machining

- David Kim



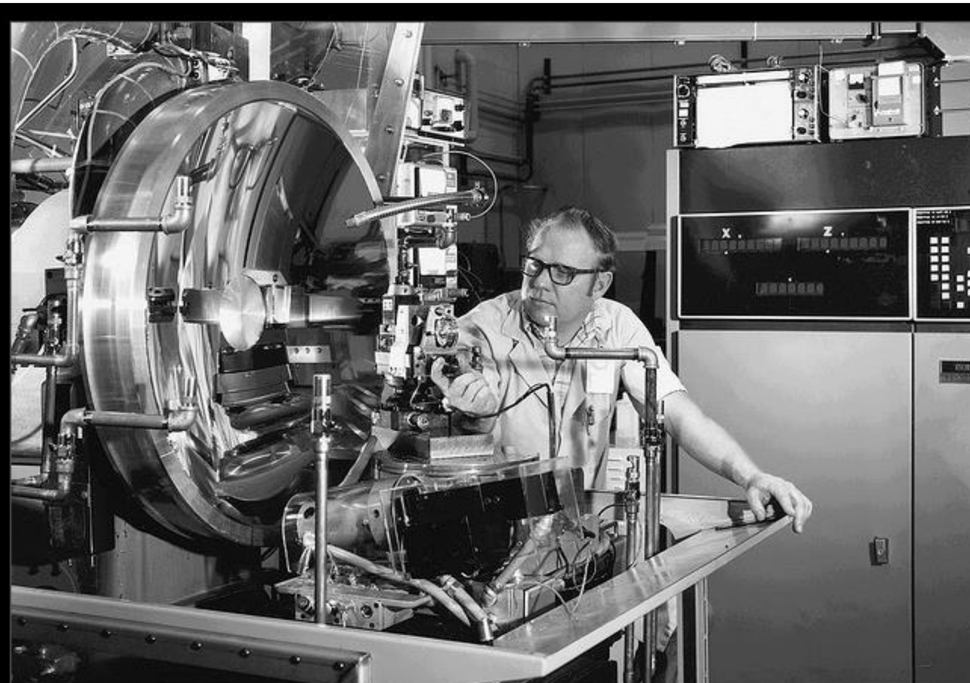
5 axis machining demos



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

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

Diamond Turning



Diamond Turning Machine

A technician finishes a large laser mirror on Lawrence Livermore National Laboratory's Diamond Turning Machine No. 2, one of the precision tools developed to meet demanding programmatic needs. The machine was later commercialized. Livermore's
state-of-the-art diamond turning machines have often been used by other agencies and private organizations when the required accuracy was not available elsewhere.

Bob Donaldson ?
LLNL

Optical surfaces (400-700nm) surface finish ~1nm, temp control ±0.01°F

Diamond Turning

Empire Precision

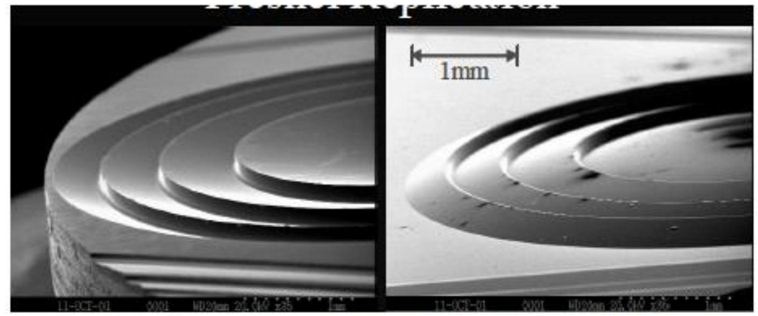
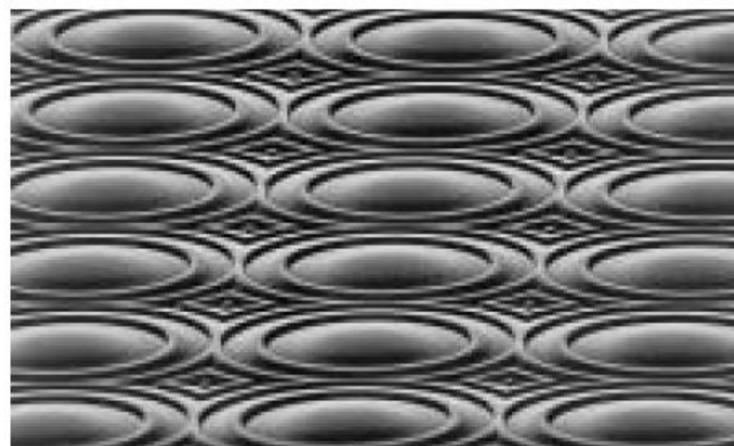
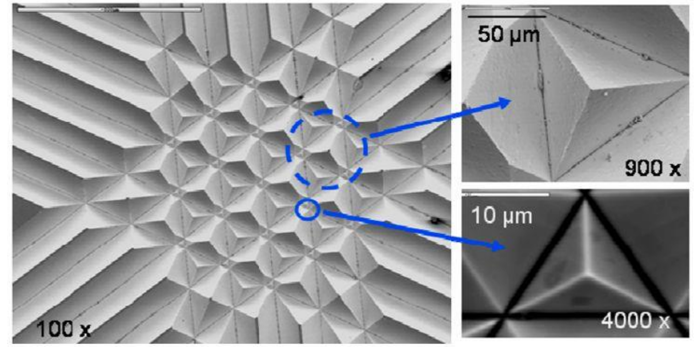


Figure 11: (a) Diamond machined mold and (b) molded PMMA Fresnel optic.



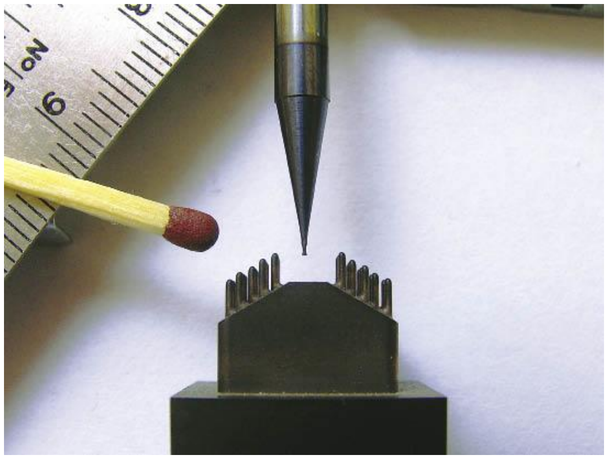
Davies et al

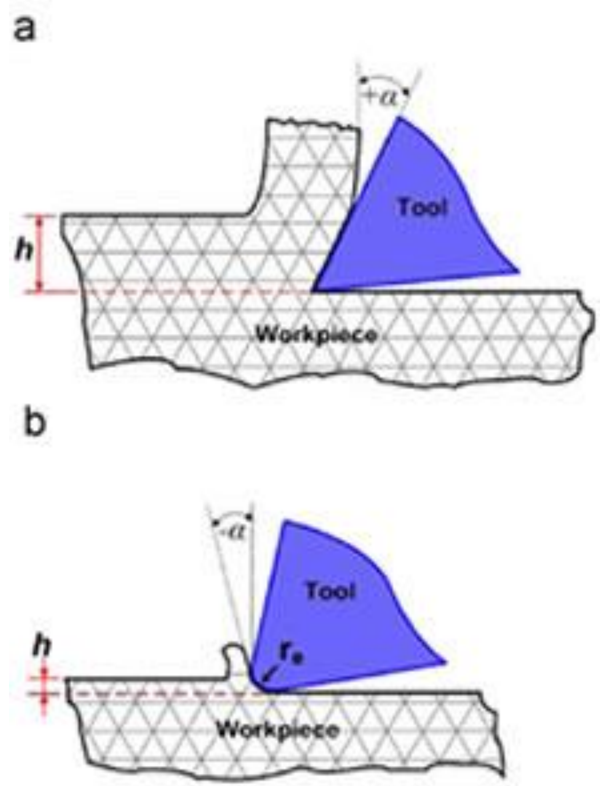
Micro machining



Diamond turning
& micro-milling

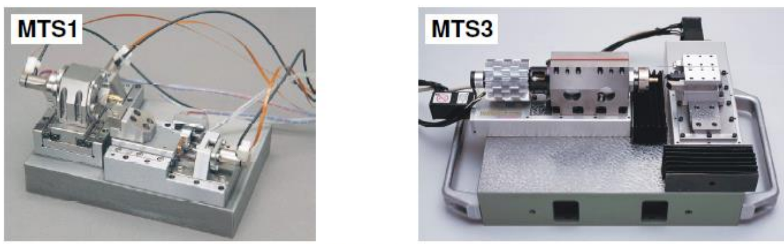
Micro machining





Micro Machines & Factories

Micro machines

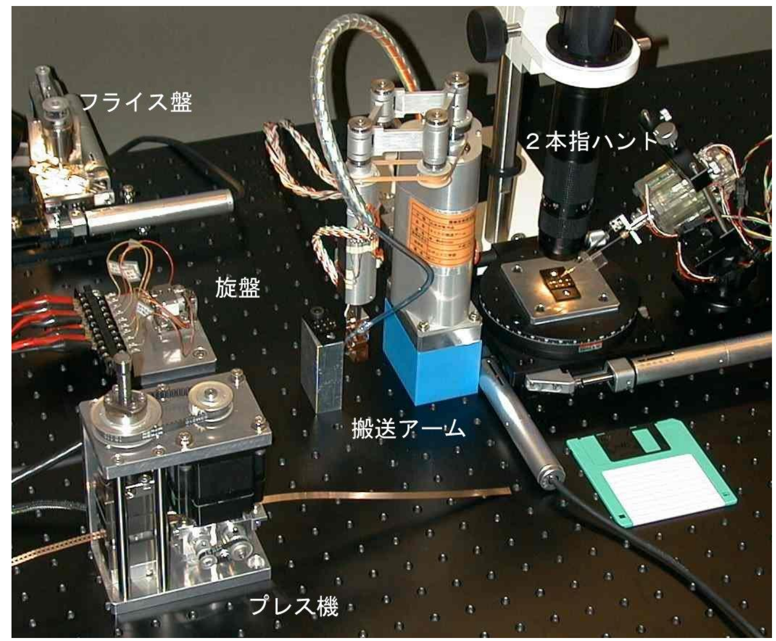


Nano Corporation MTS1, MTS3, MTS5

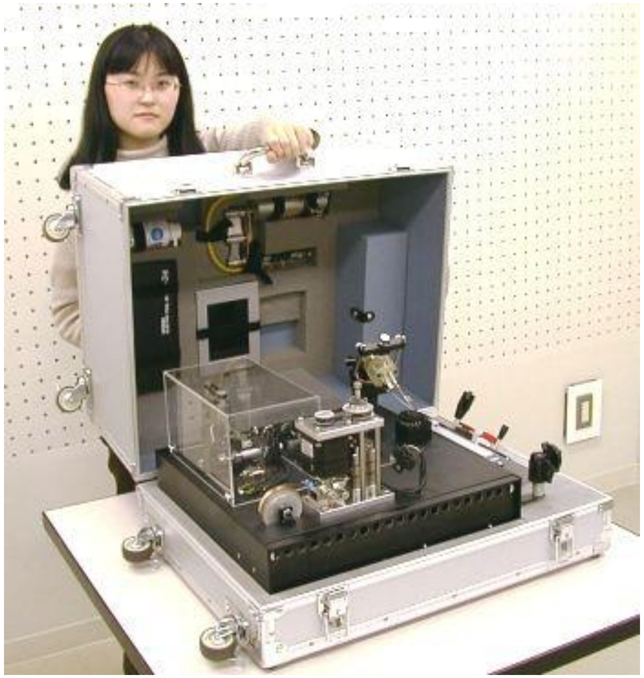
	MTS2	MTS3	MTS4	MTS5
Footprint [mm^2]	100 x 150	200 x 300	220 x 320	260 x 324
Spindle drive P_s [W]	11 DC	30 AC	30 AC	260 DC
Speed n_{max} [min^{-1}]	10,000	3,000	3,000	20,000
Feed drive P_f [W]	3 AC	30 AC	30 AC	30 AC

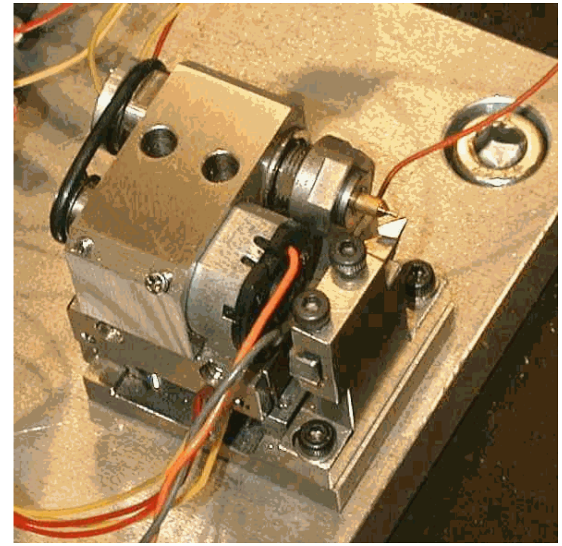
Source [NANO07]

Figure 3.14: Nano Corporation micro machines



Micro Factory developed at Mech Eng Lab AIST Japan





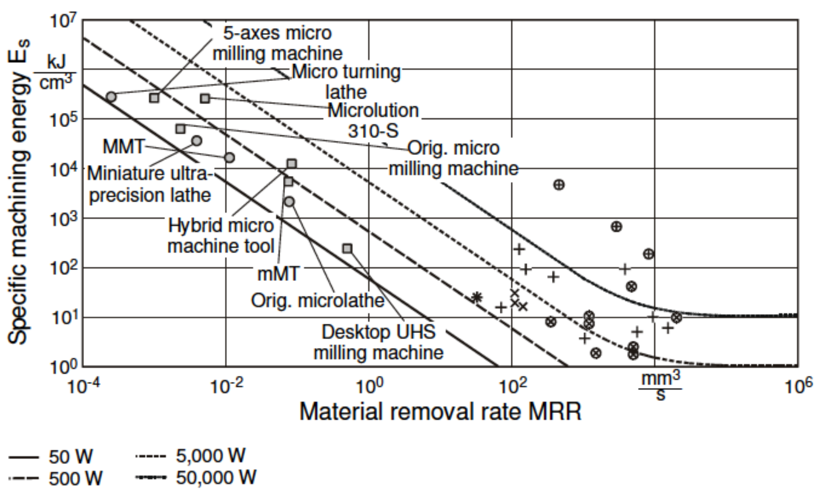


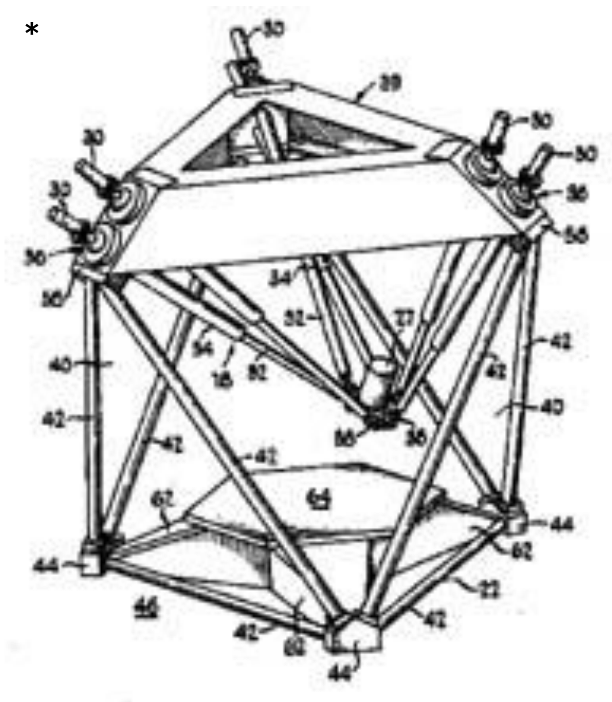
Figure 5.2: Specific machining energy and the material removal rate

MS Thesis Thilo Grove

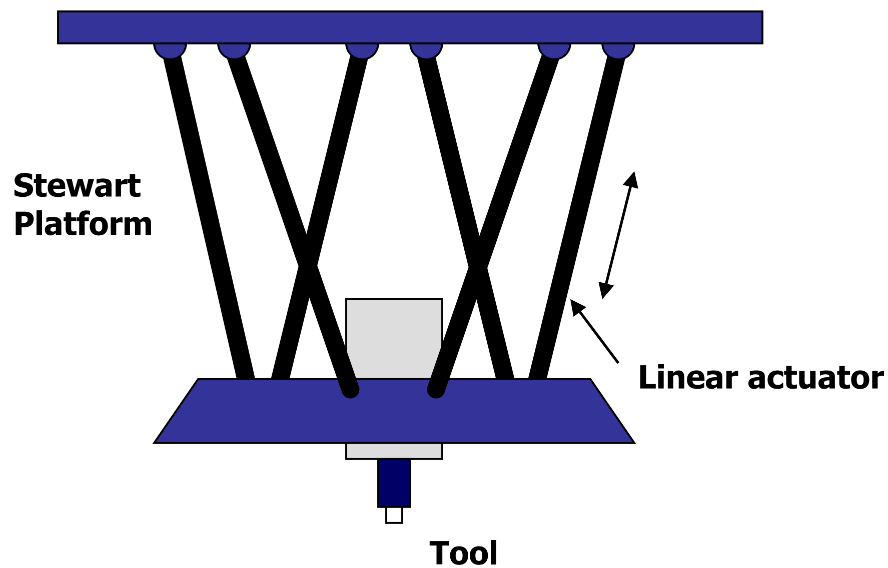
Part available on Alibaba

Hexapod Milling Machines

*



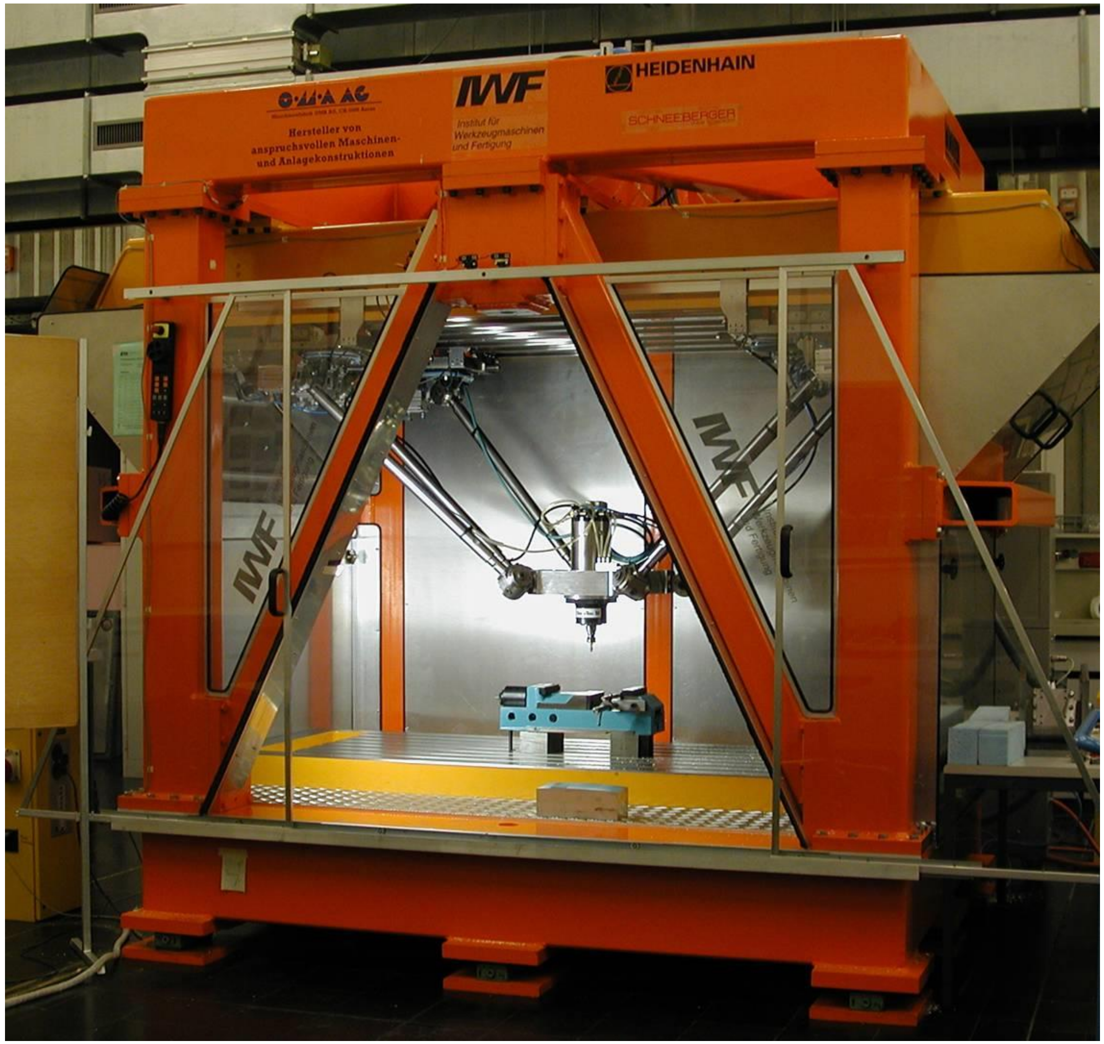
Hexapod machining center (Ingersoll, USA)



Schematics

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

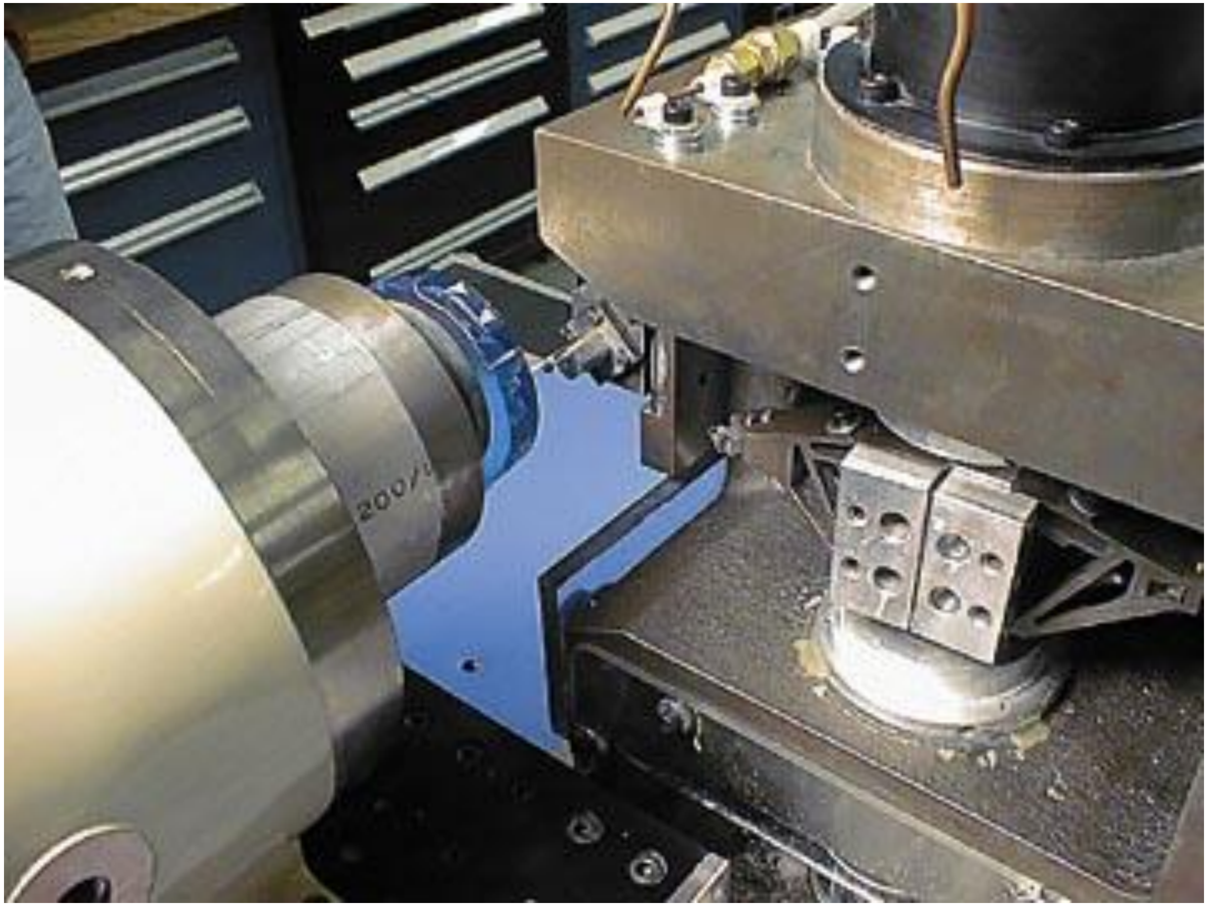
Institut für Werkzeugmaschinen und Fertigung
Hexaglide from Zurich (ETH)

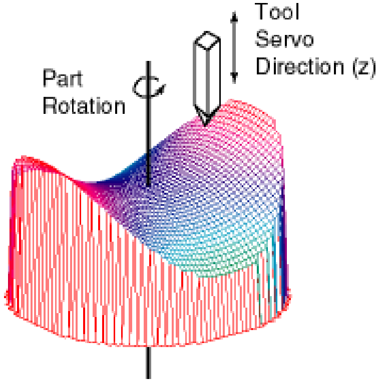


www.iwf.mavt.ethz.ch/

Fast Tool Servo

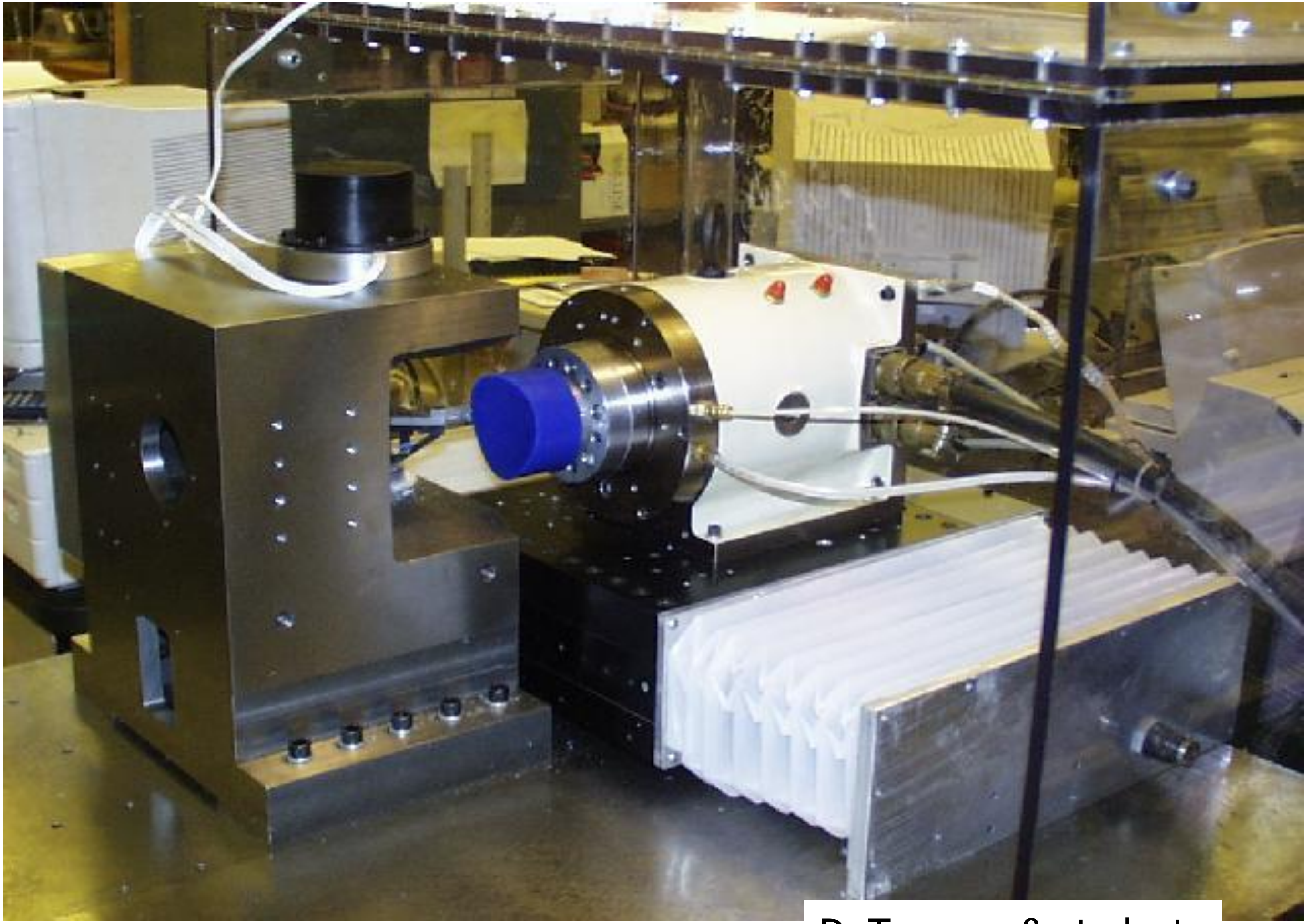
http://web.mit.edu/pmc/www/index.html





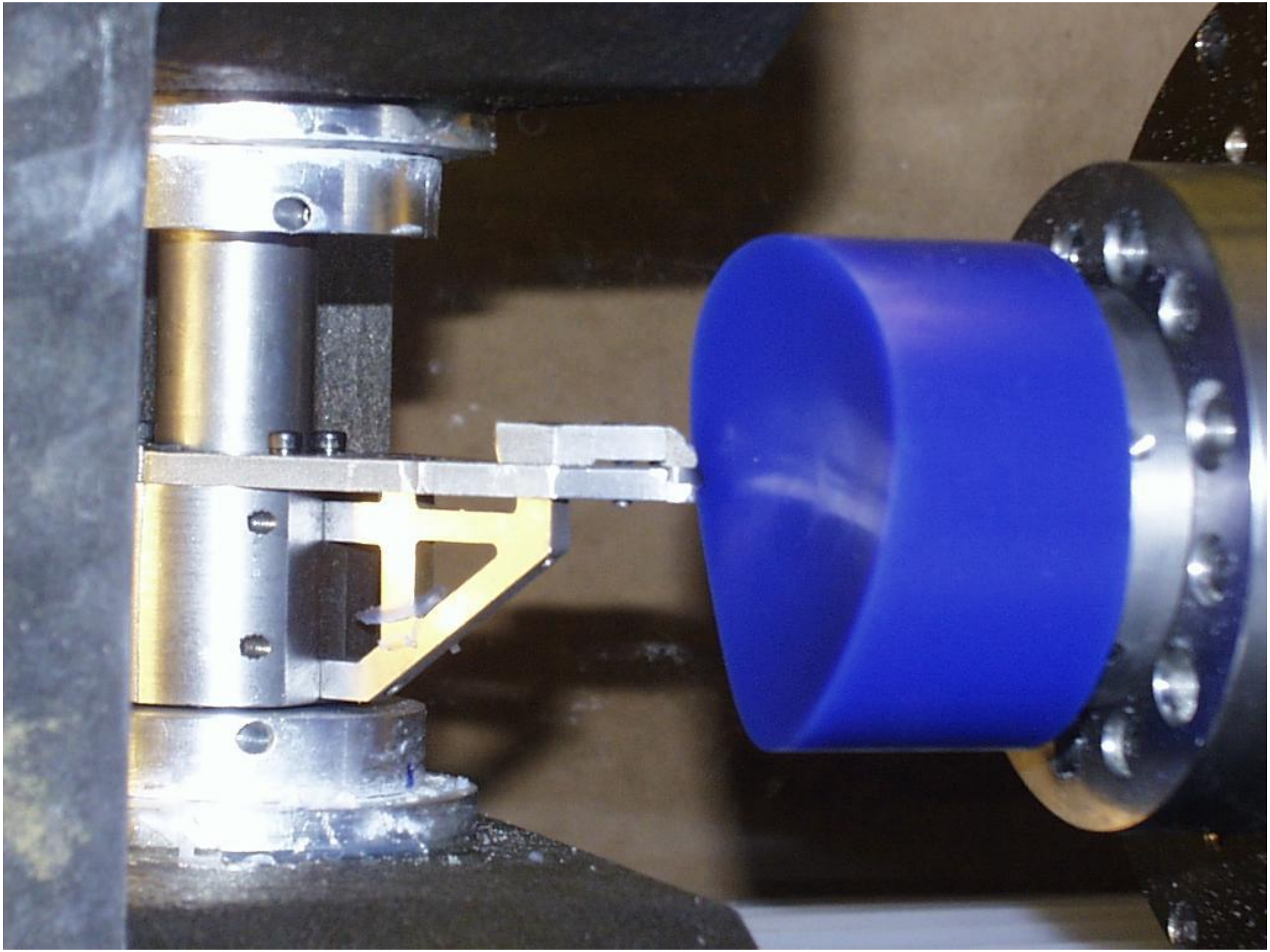
Ref D. Trumper

Rotary Fast Tool Servo Machine for Eyeglass Lenses



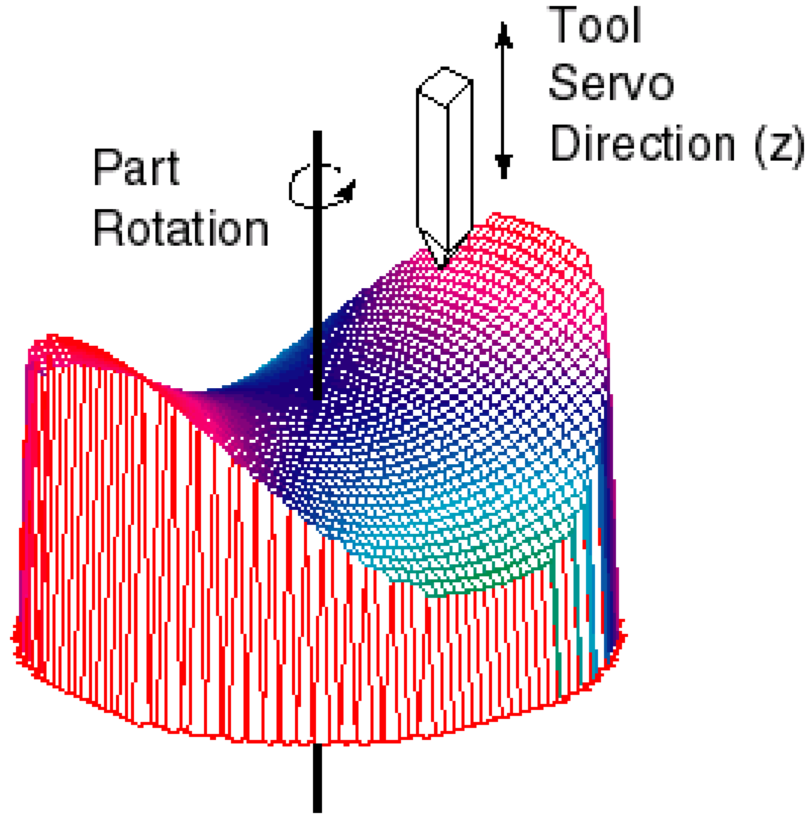
D. Trumper & students

Tool at end of arm rotates about vertical axis



Asymmetric Turning Operation

- Spectacle lenses
- Contact lenses
- Human lens implants
- Elements for laser vision correction surgery
- Camera lenses
- Image train elements in semiconductor processing
- Camshafts
- Not-round pistons

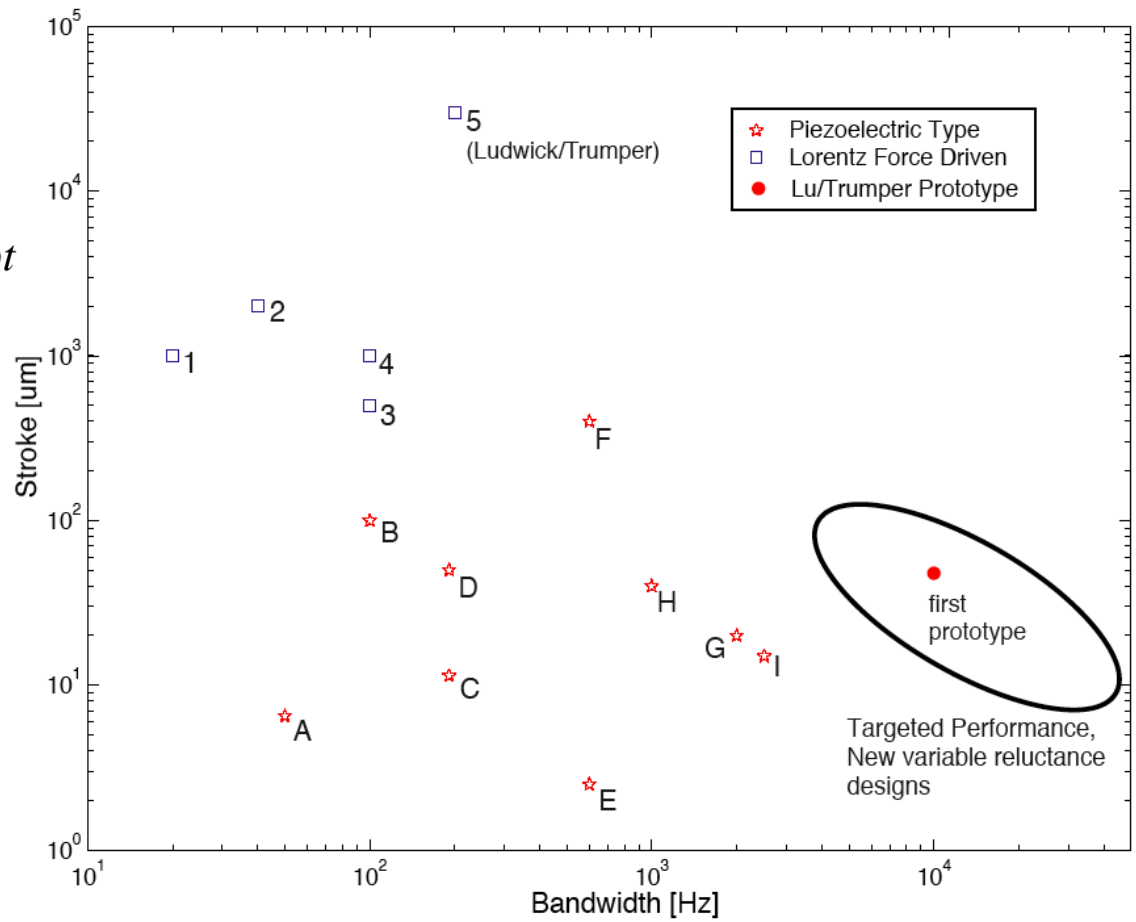


Fast Tool Servo State of the Art

$$x = A\sin\omega t$$

$$\ddot{x} = -A\omega^2 \sin\omega t$$

$$F = m\ddot{x}$$



<u>Lu/Trumper</u>

Bandwidth 23 kHz

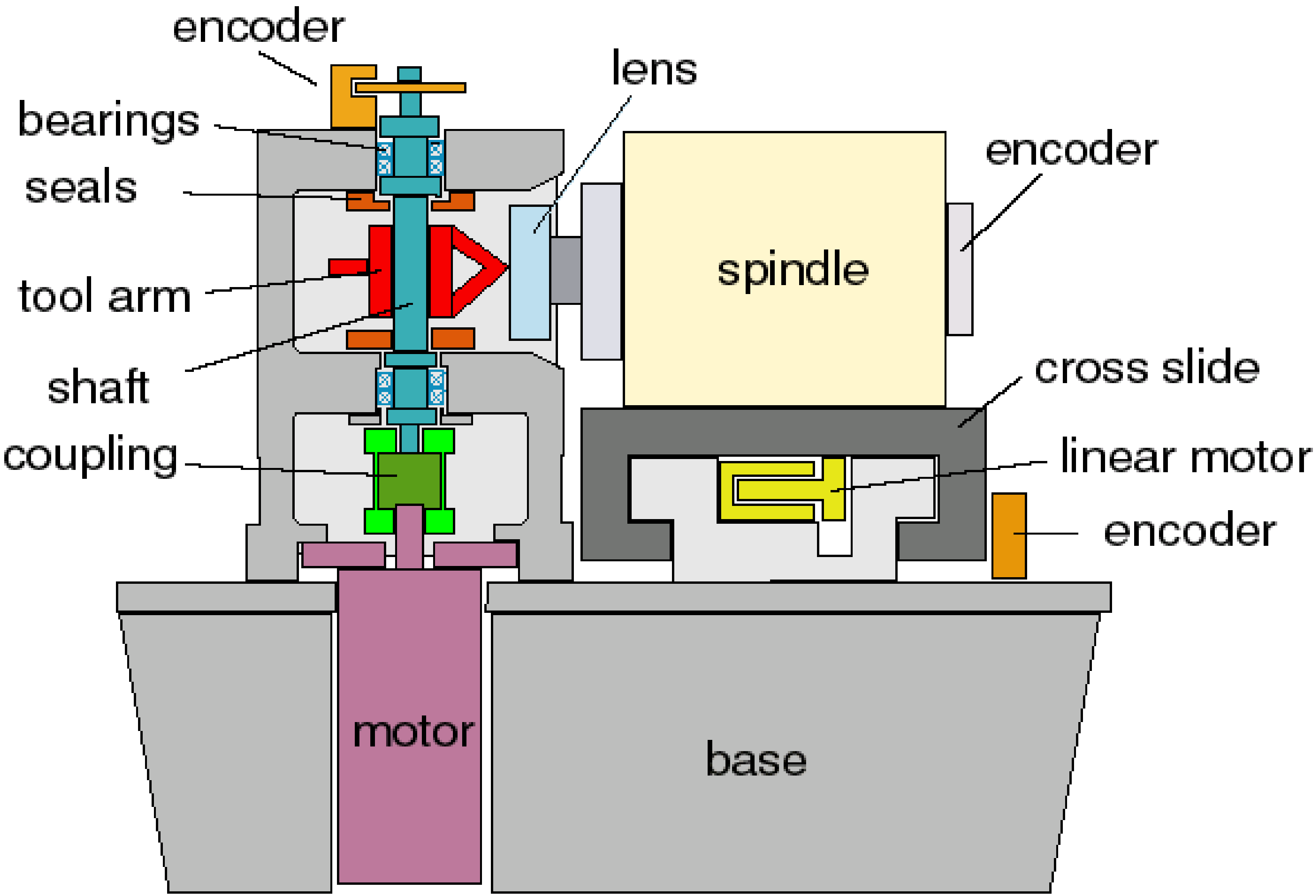
Stroke 30 μm

RMS tracking error: 1.7 nm

Peak acceleration: 500g

Lorentz FTS		*Piezoelectric FTS*			
1	Todd and Cuttino [19]	A	Kuuno [4]	F	Falter and Youden [10]
2	Weck [17]	B	Cuttino [13]	G	Dow [7]
3	Douglass [16]	C	Jared and Dow [9]	H	Weck [17]
4	Greene and Shinstock [18]	D	Rasmussen [5], [6]	I	Okazaki [12]
5	Ludwick and Trumper [20]	E	Patterson and Magrab [3]		

Diamond Turning Machine Cross Section

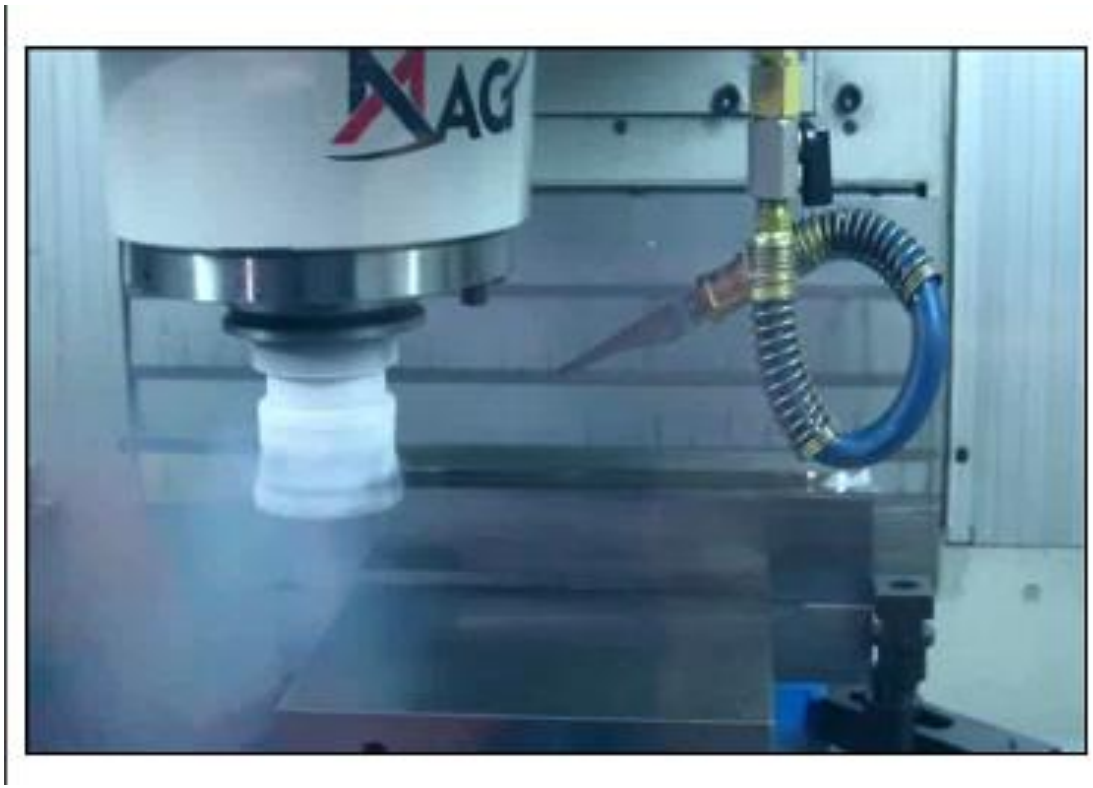


Satisloh

http://www.satisloh.com/usa-canada/ophthalmic/generating/vft-orbit/

Cryogenic Machining

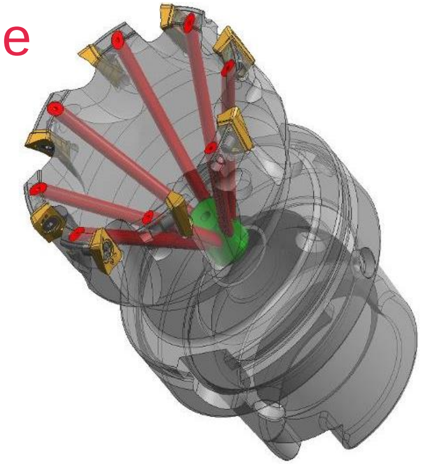
http://www.youtube.com/watch?v=GFOXbb7P2jc

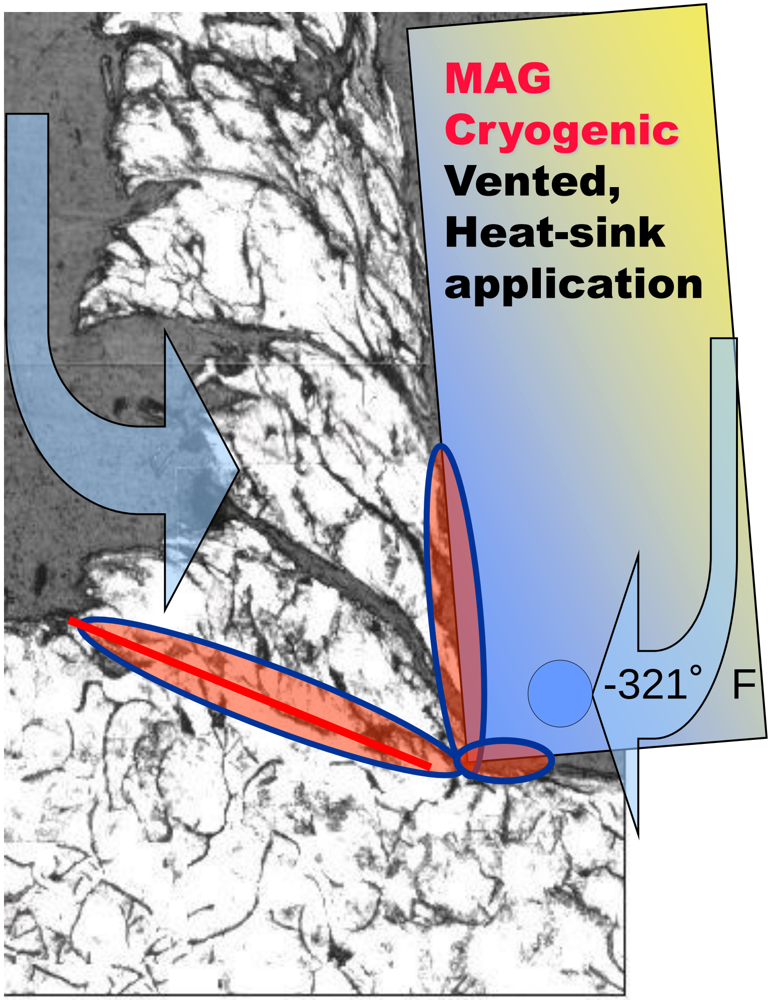


Cryogenic Cutting Tools

CYCLO CUT ® Brand

- Cryogen to the cutting edge
- Solid carbide end mills and drills
- Index end mills, face mills, turning and boring tools





Cryogenic Cutting Tools

CYCLO CUT ® Brand

- Cryogen to the cutting edge
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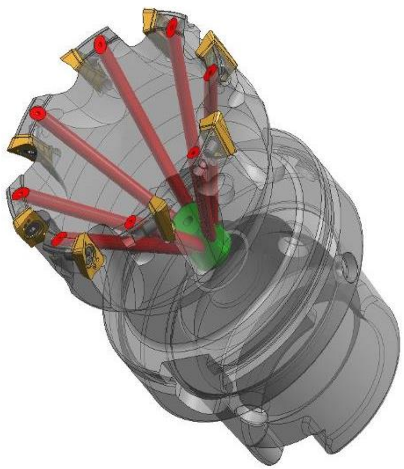
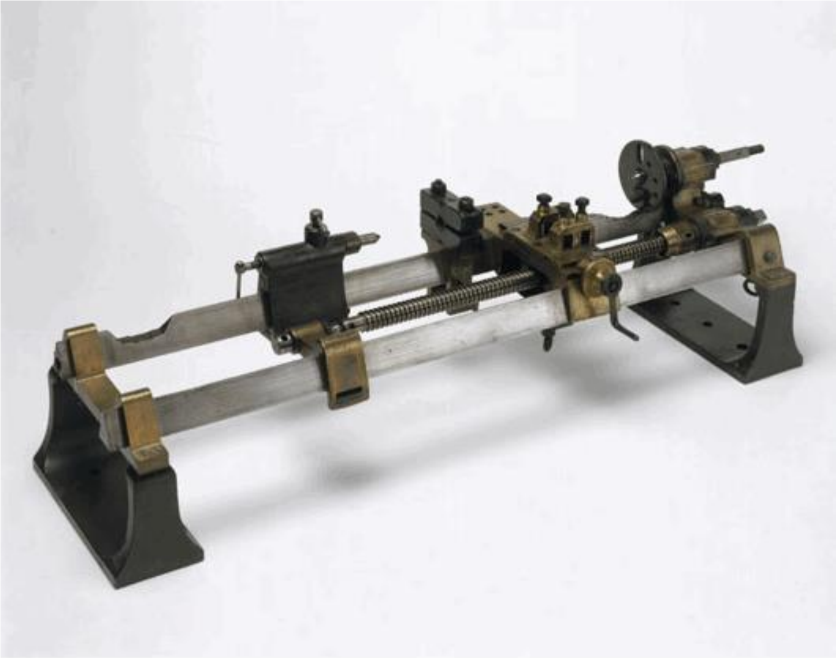


LN_2 through tool
77K (-321 ° F)
$0.06/liter

Claims:
30% - 50% higher feed rate (up to 2X)
60% tool life
No cleaning of part
Easy disposal

Historical Development of Machine Tools



Henry Maudslay, and screw cutting lathe circa 1797

Early paper on cutting mechanics

Prof Milt Shaw

Prof Nate Cook

M.I.T., LMP

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)

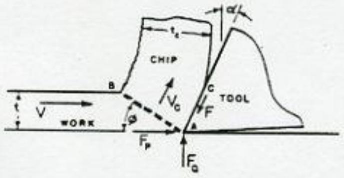


Fig. 1 Conditions at Point of Cutting Tool During Continuous Cutting. Width of Cut Along Cutting Edge = b

Fig. 2 Actual Surfaces in Contact at Very High Magnification

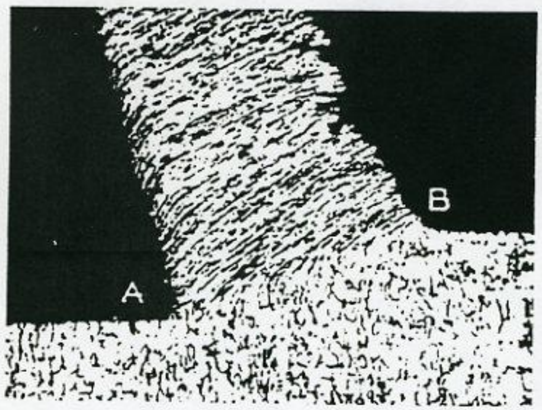


Fig. 1. In the process of metal cutting, tool tip, A, produces chips above the line AB with no deformation of the metal below this line.

NC machine tool developed at MIT mid 1950's

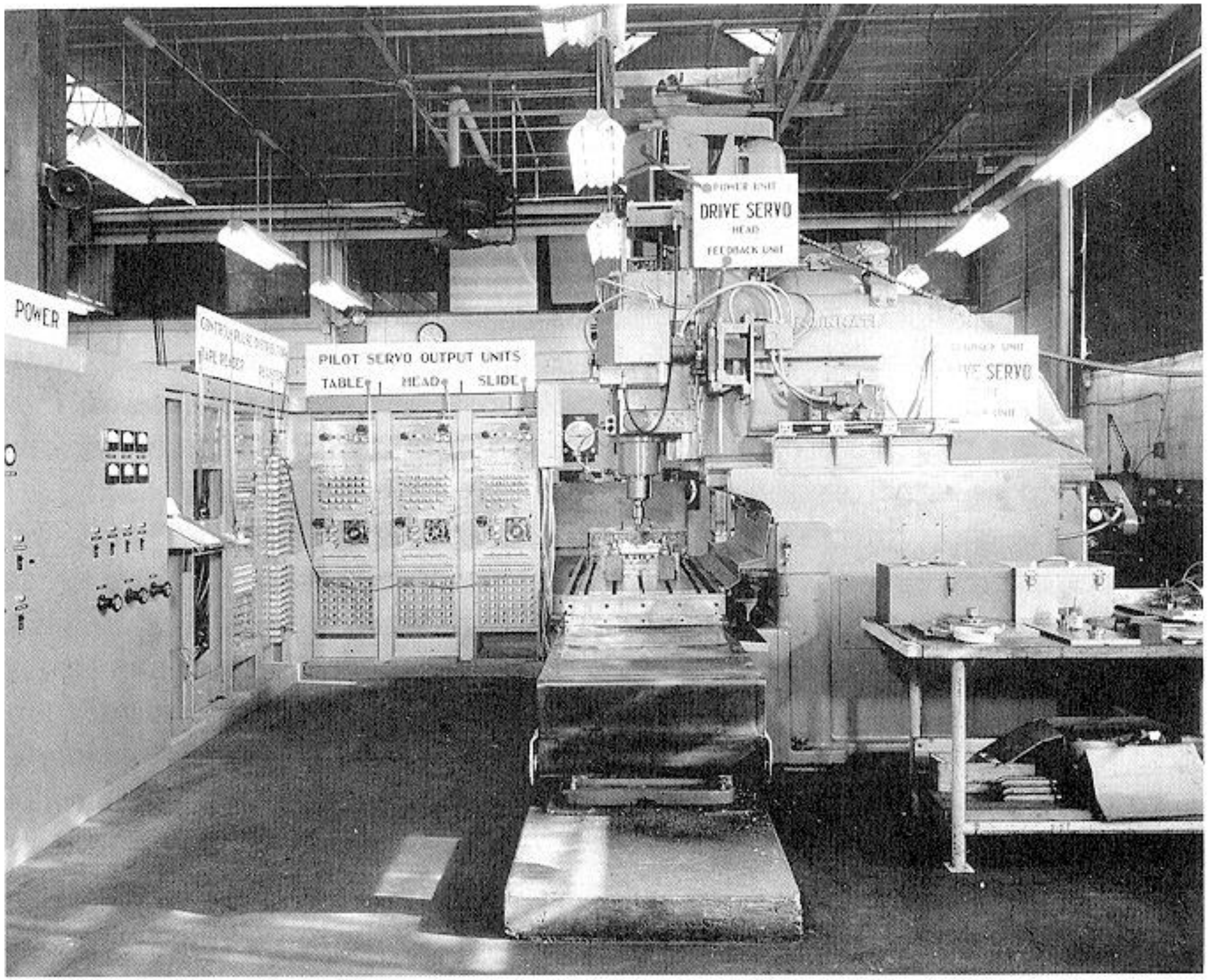
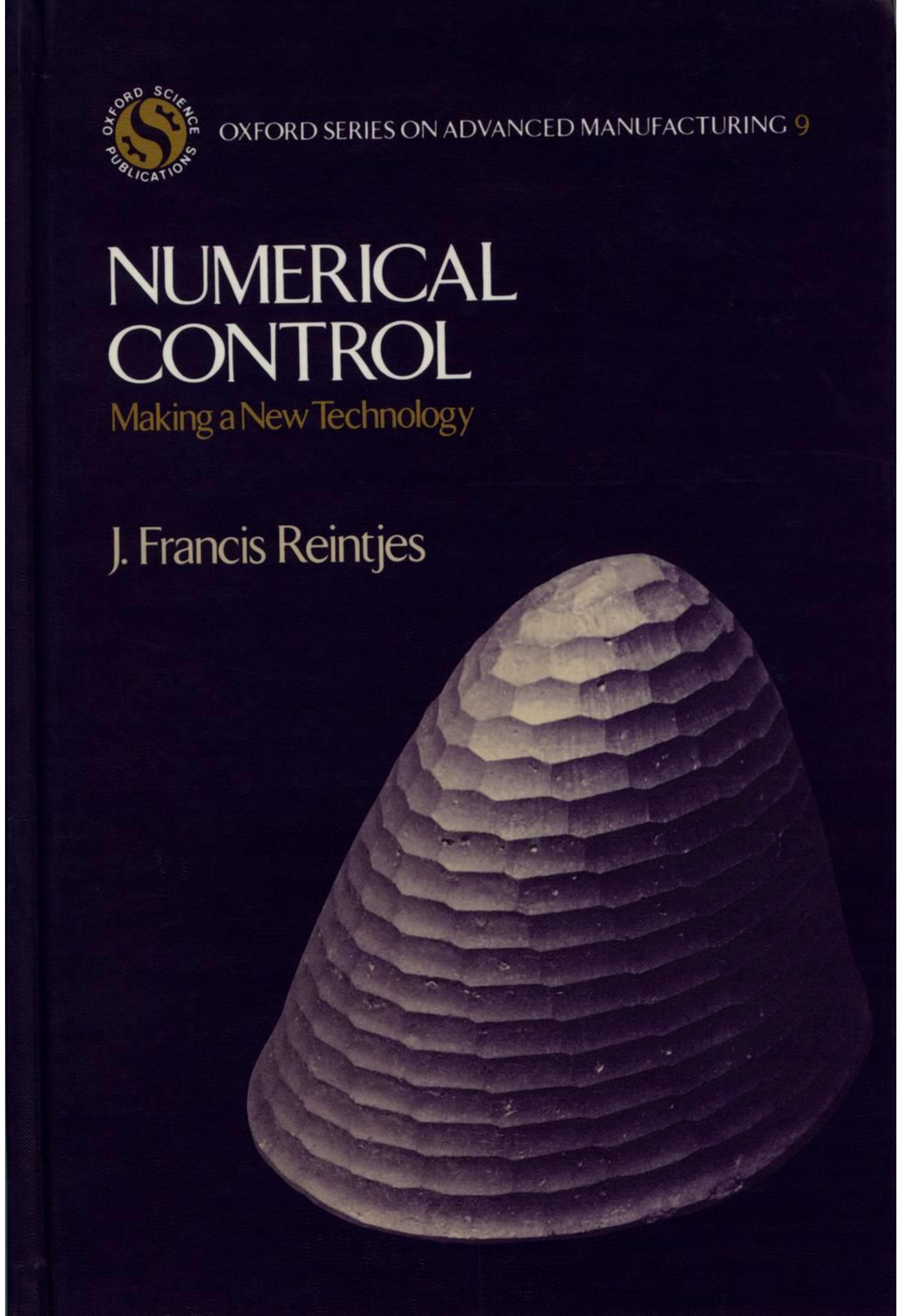


FIG. 2.2. The MIT numerically controlled milling machine.

* Source: Reintjes, "Numerical Control 1991"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NUMERICAL CONTROL
Making a New Technology
J. Francis Reintjes

Readings

- Kalpakjian & Schmid Machining chapters are extensive: Ch 21-27
- Design for Machining handout
- AM tolerances paper available but not required (i.e. Lienke et al U. Paderborn)