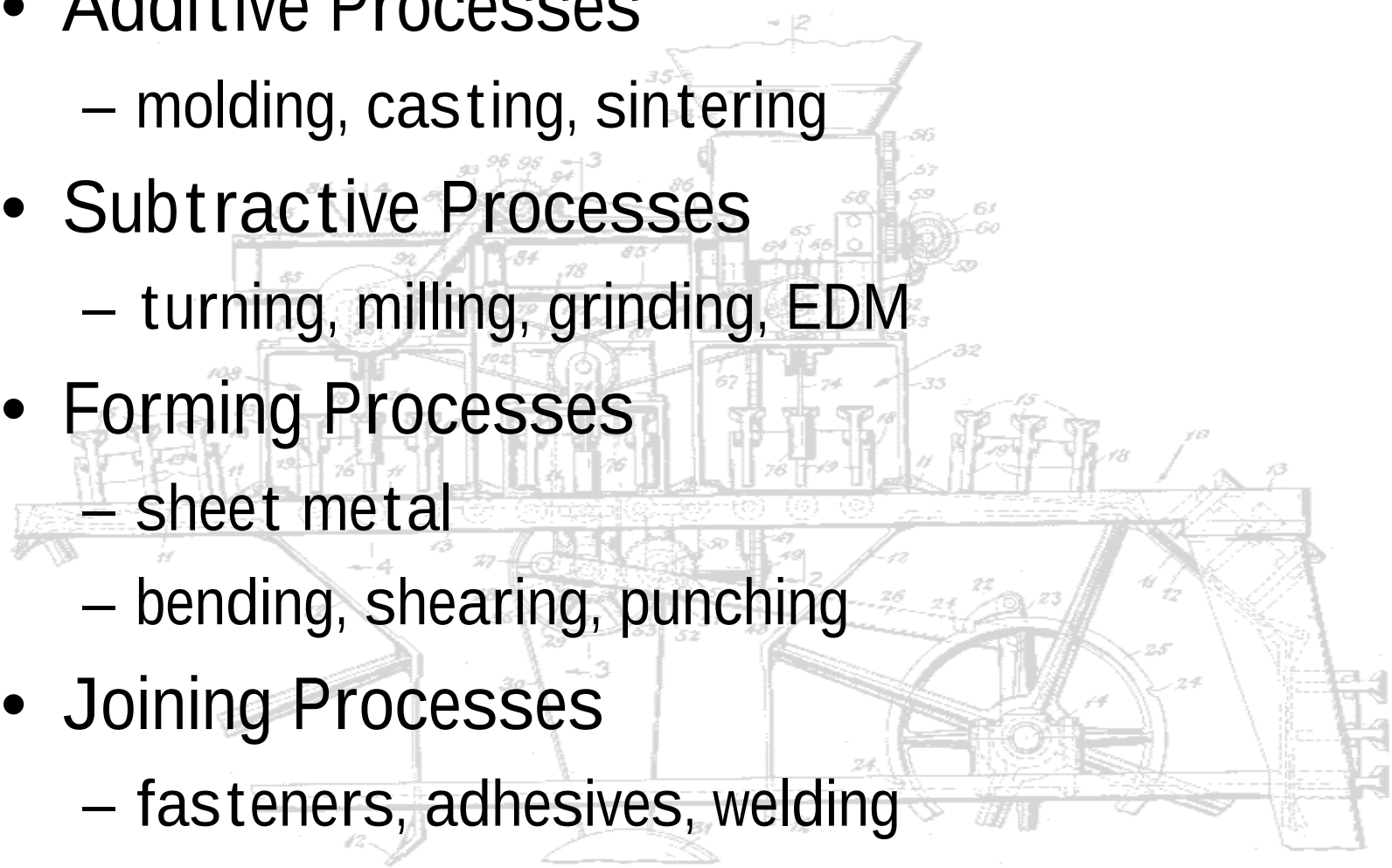
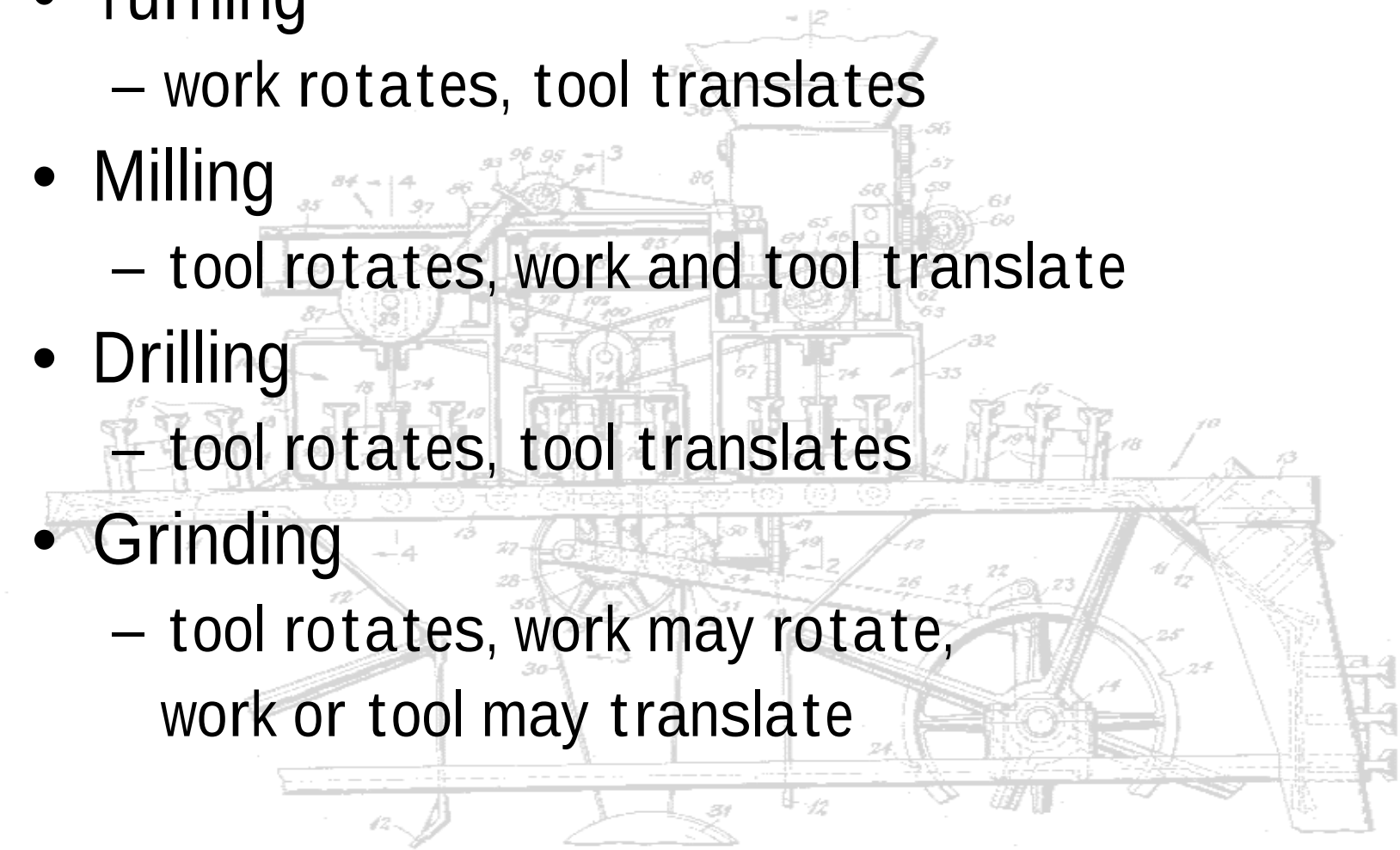
Part Fabrication

- Additive Processes
  - molding, casting, sintering
- Subtractive Processes
  - turning, milling, grinding, EDM
- Forming Processes
  - sheet metal
  - bending, shearing, punching
- Joining Processes
  - fasteners, adhesives, welding

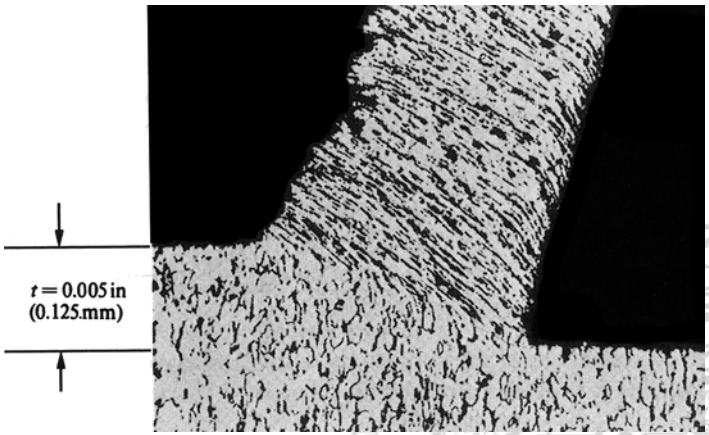


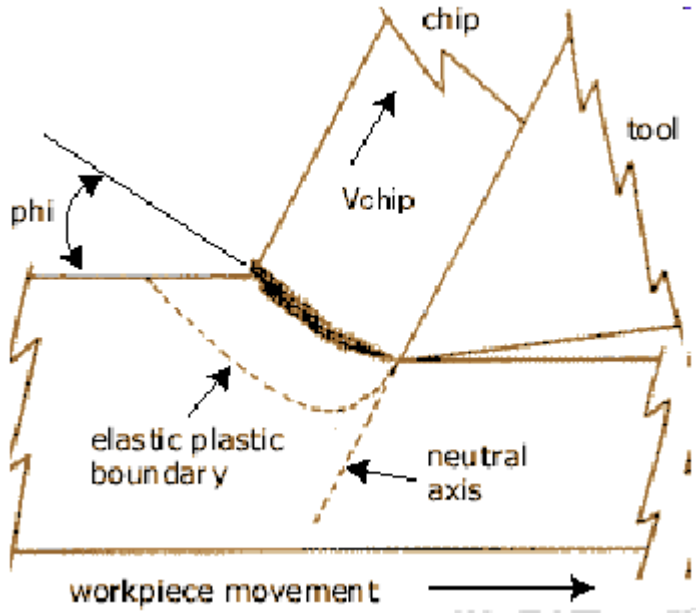
Material Removal Processes

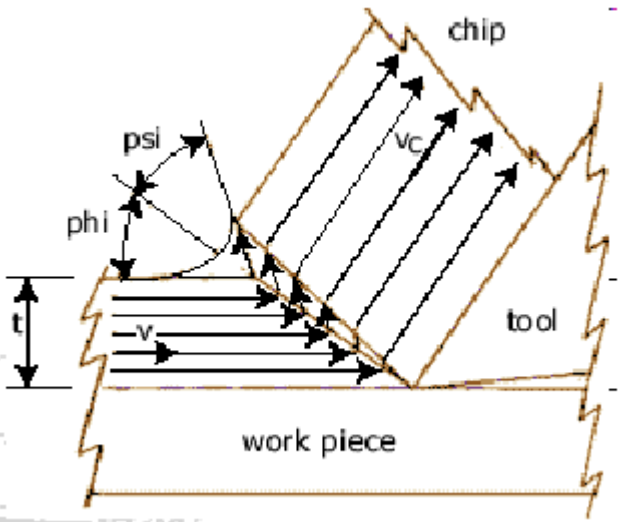
- Turning
  - work rotates, tool translates
- Milling
  - tool rotates, work and tool translate
- Drilling
  - tool rotates, tool translates
- Grinding
  - tool rotates, work may rotate, work or tool may translate



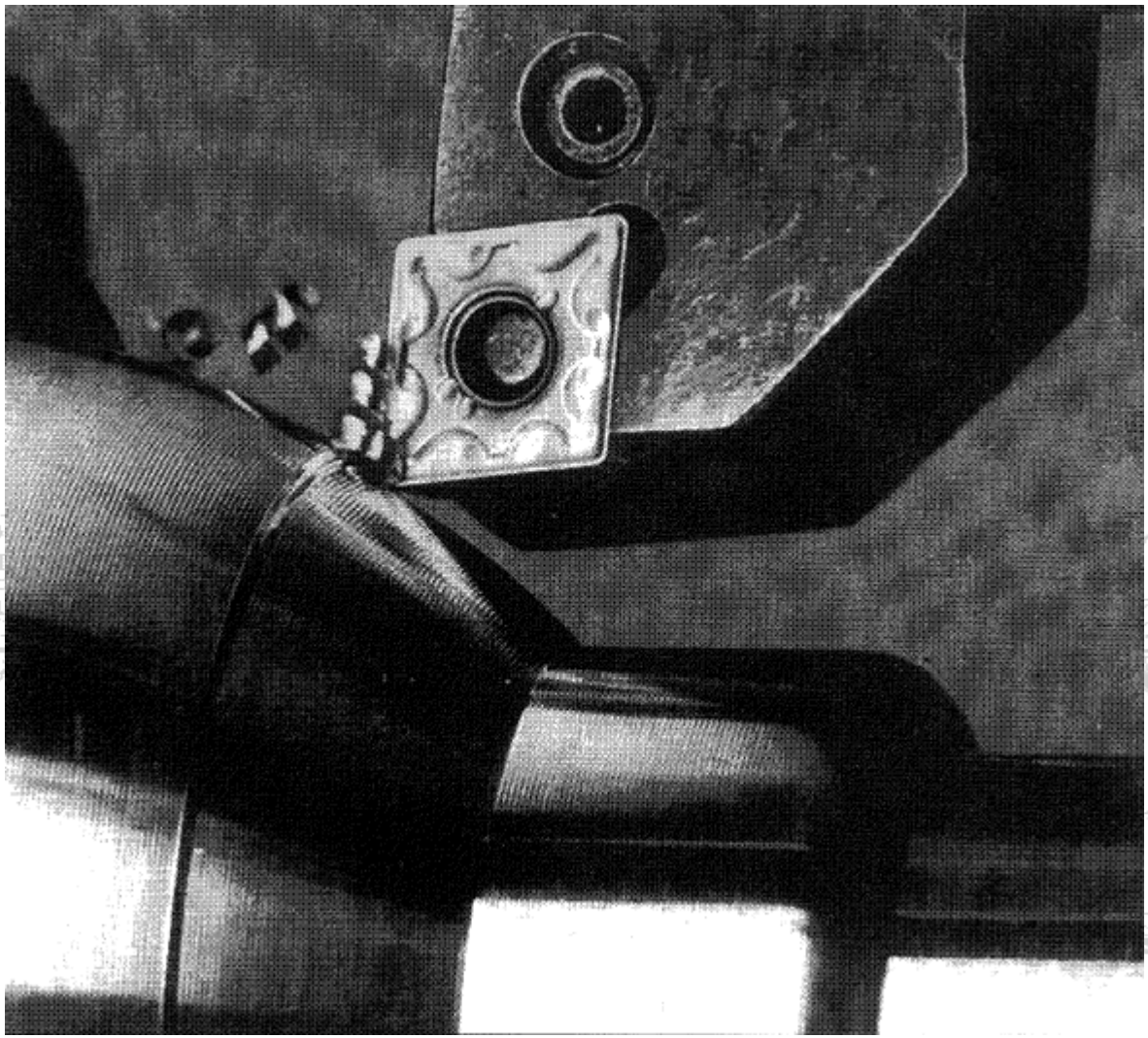
Chip Formation



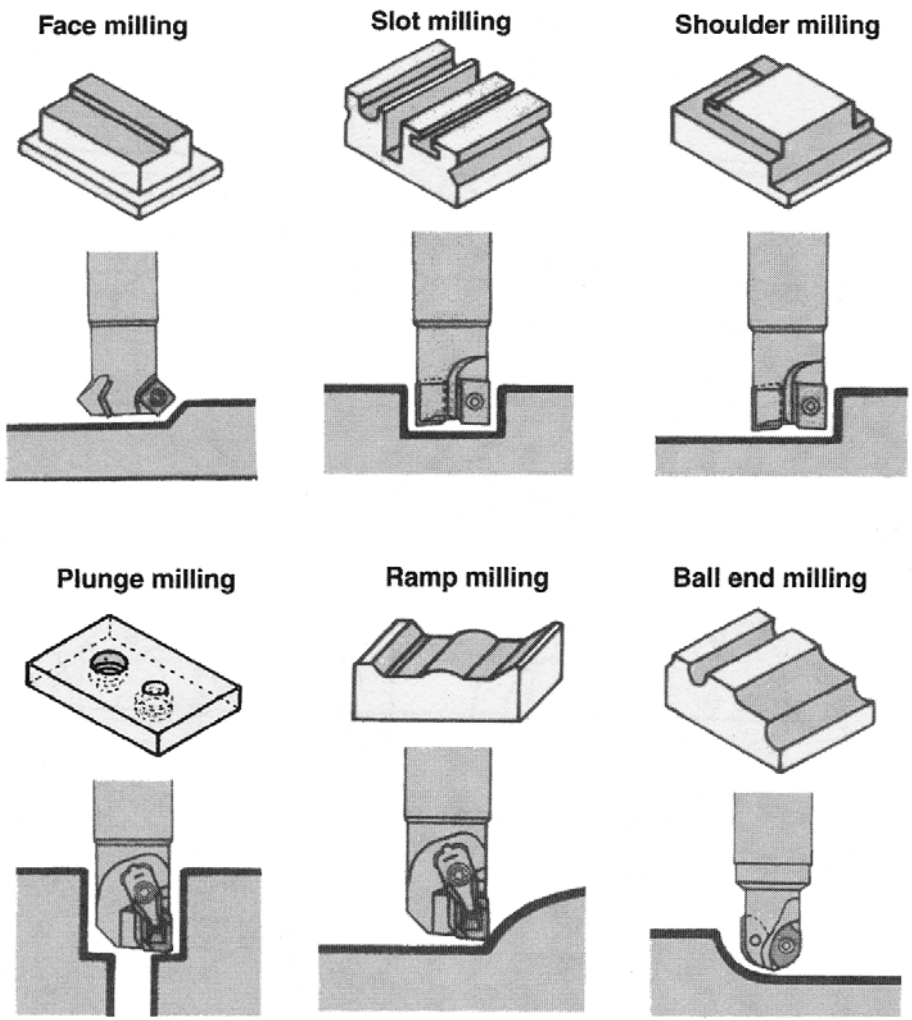




Turning



Milling Operations



Geometry of Milling Process

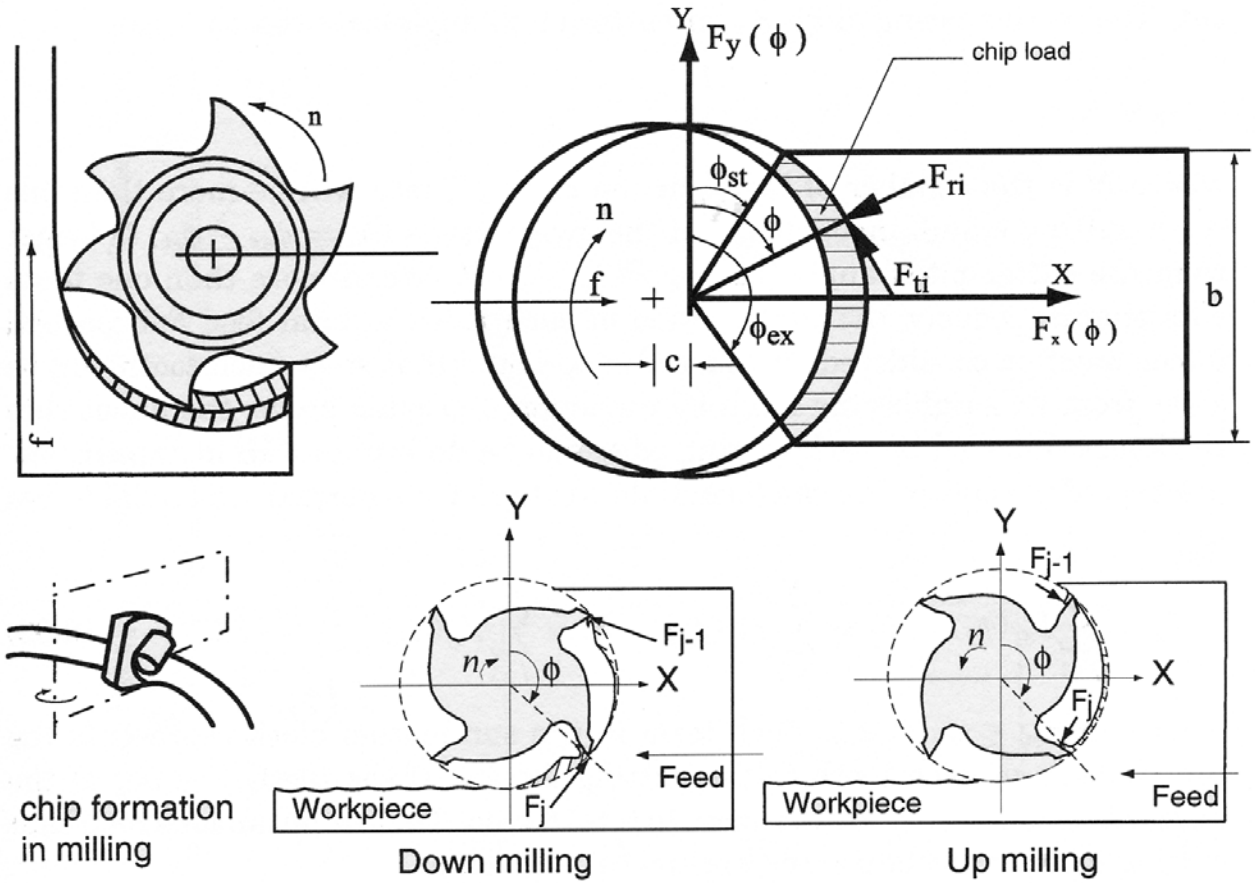
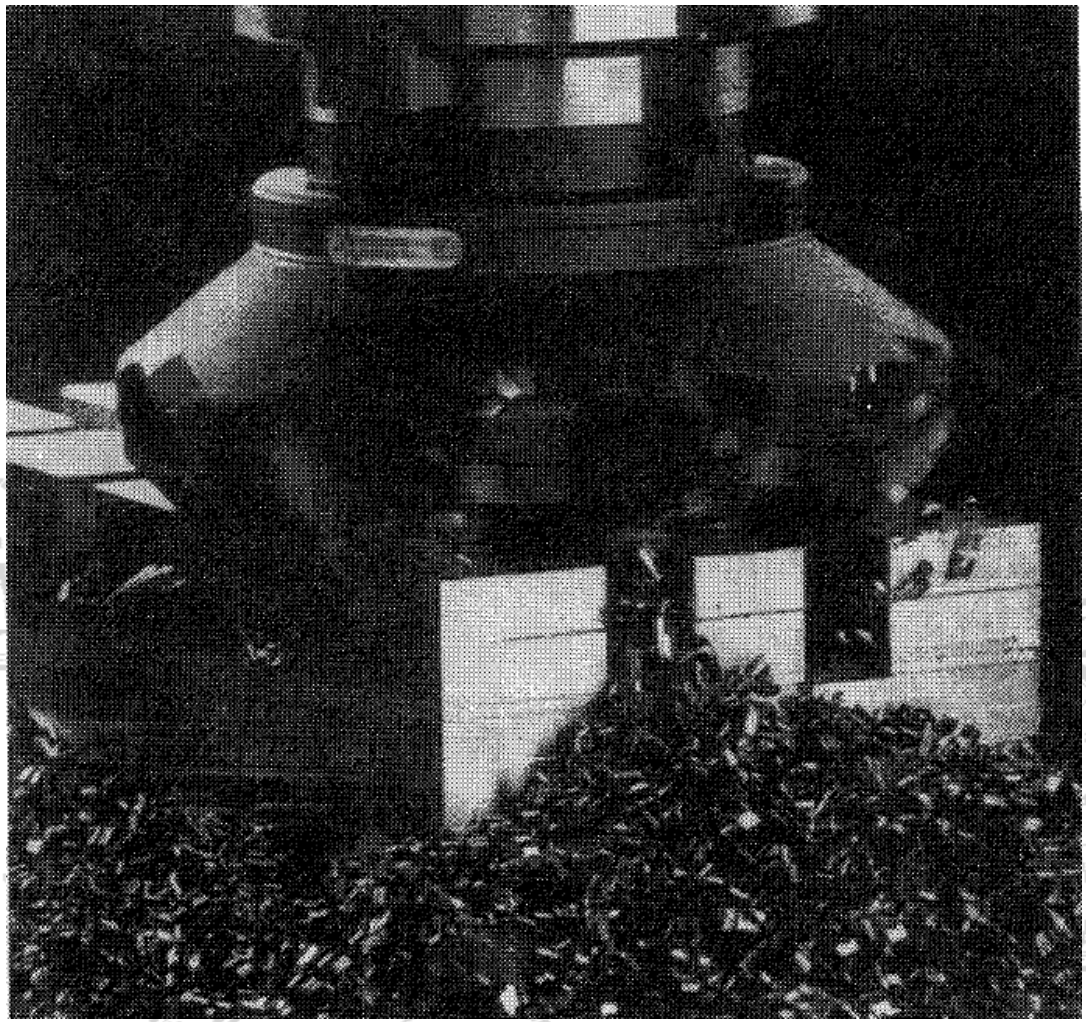
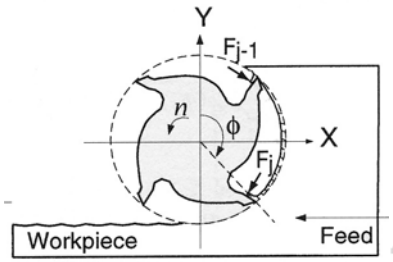


Figure 2.19: Geometry of milling process.

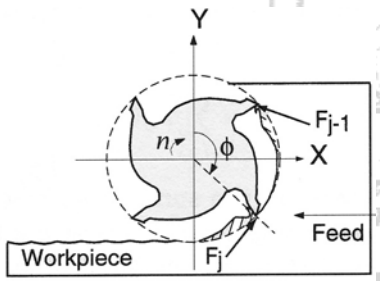
Face Milling



Milling Forces

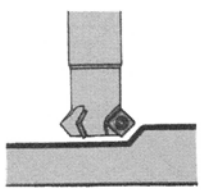


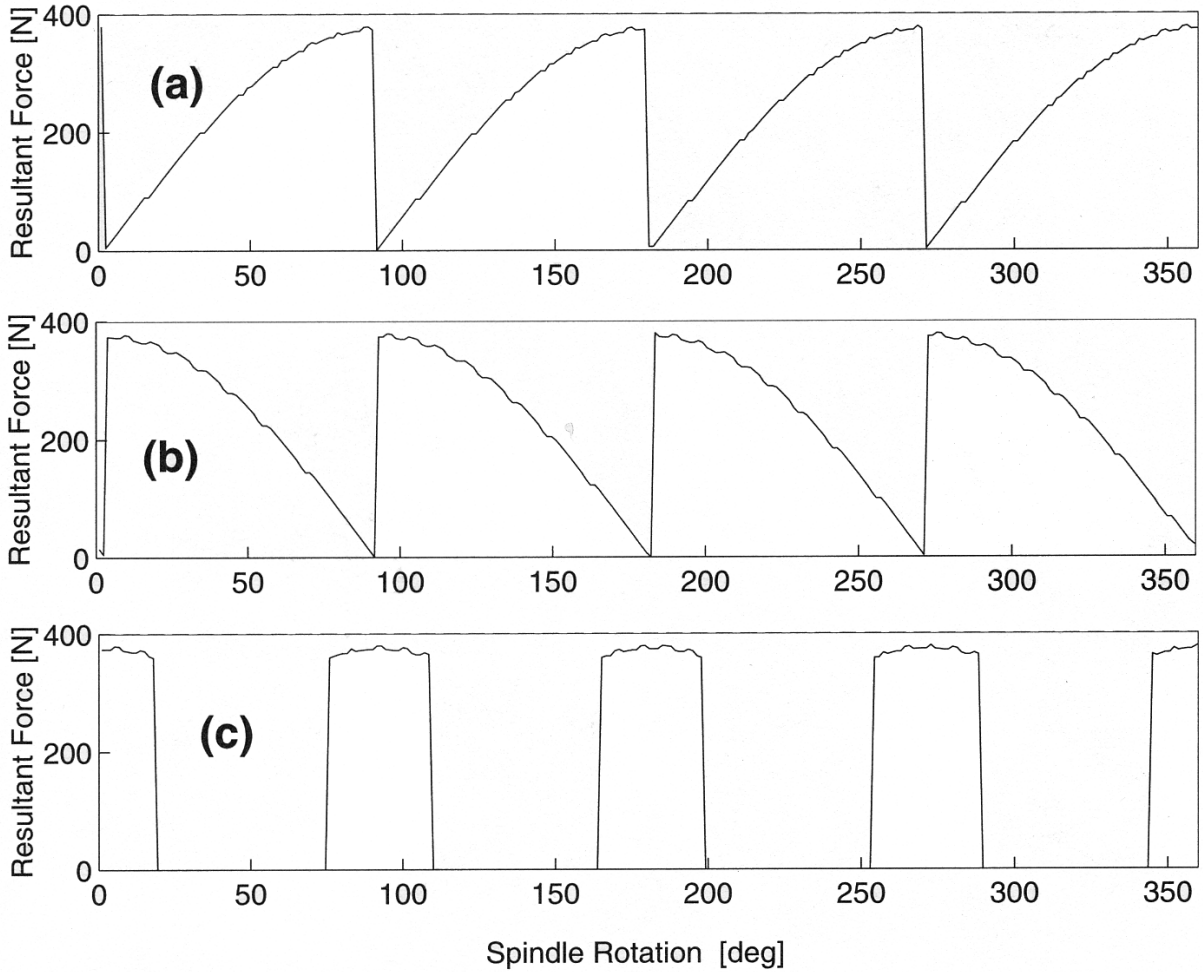
Up milling



Down milling

Face milling

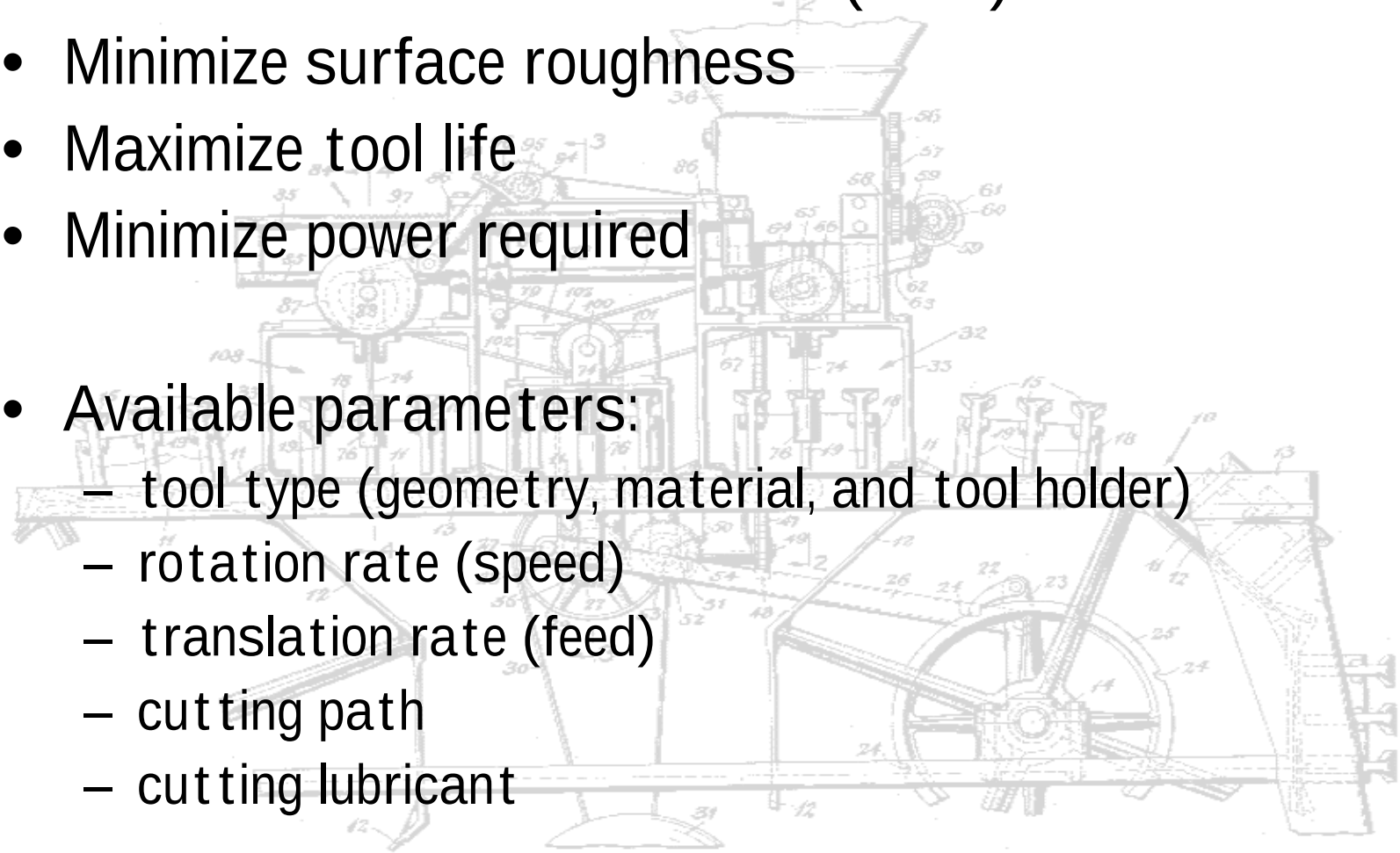




Machinability

- Maximize metal removal rate (MRR)
- Minimize surface roughness
- Maximize tool life
- Minimize power required

- Available parameters:
  - tool type (geometry, material, and tool holder)
  - rotation rate (speed)
  - translation rate (feed)
  - cutting path
  - cutting lubricant



Feed & Speed Charts

COBALT HSS AND HSS END MILLS

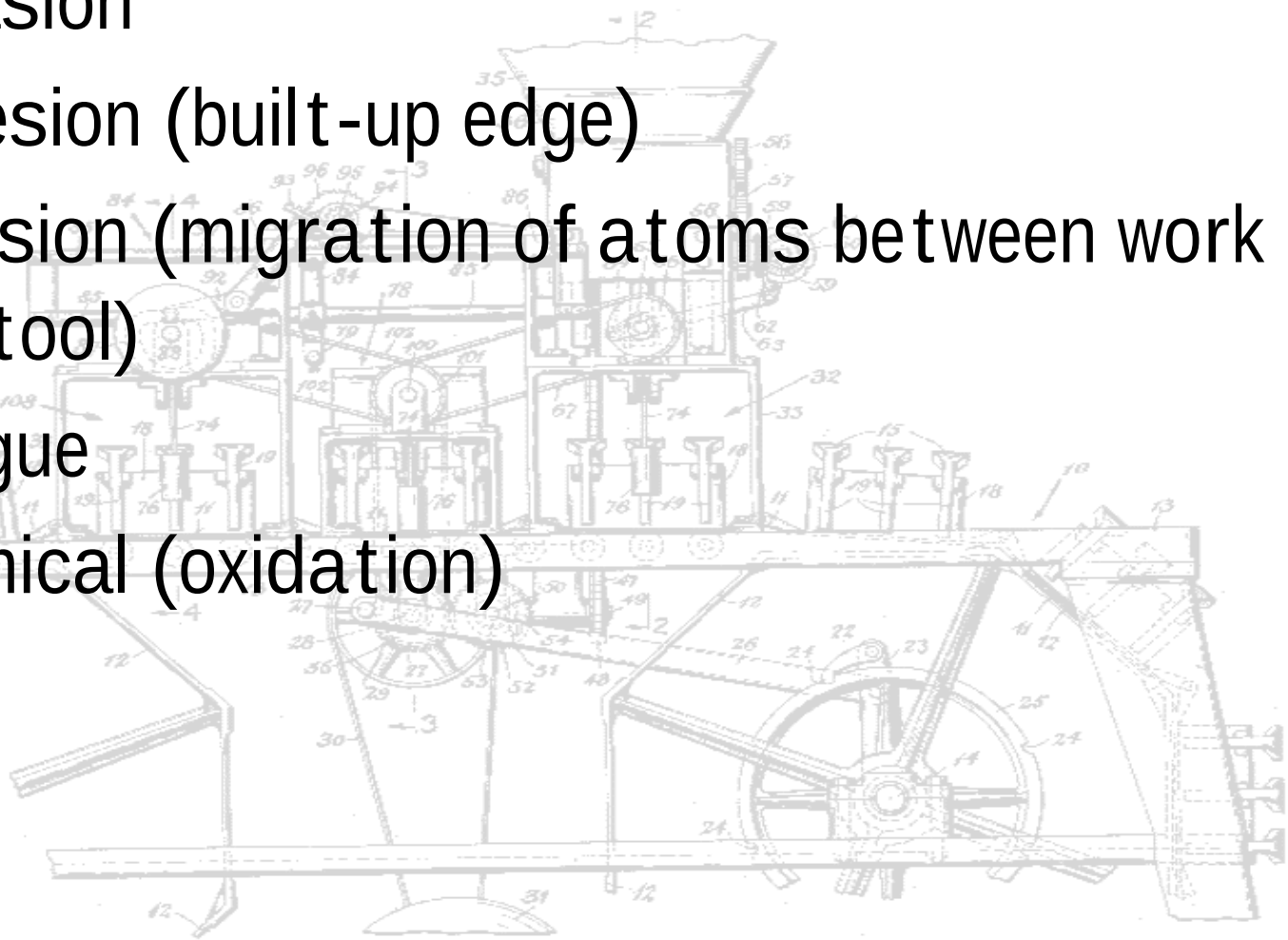
Speed and Feed Data - Applications in Various Materials

MATERIAL	HEAT-RESISTANT COBALT BASE ALLOYS, HIGH TENSILE STEELS (50-55 C)		HEAT-RESISTANT AUSTENITIC ALLOYS, HIGH TENSILE STEELS (46-50 C)		HEAT-RESISTANT NICKEL BASE ALLOYS, HIGH STRENGTH STAINLESS STEELS, HIGH STRENGTH TITANIUM ALLOYS		HIGH STRENGTH STAINLESS STEELS, HIGH TENSILE STEELS (40-60 C) MEDIUM STRENGTH TITANIUM ALLOYS		HEAT RESISTANT FERRITIC BASE ALLOYS MEDIUM STRENGTH STAINLESS STEELS UNALLOYED TITANIUM TOOL STEELS (30-40 C)		MACHINE STEEL, HARD BRASS AND BRONZE, ELECTROLYTIC COPPER MILD STEEL FORGINGS (20-30 C)		CAST IRON, MILD STEEL, HALF-HARD BRASS AND BRONZE		BRASS, BRONZE, ALLOYED ALUMINUM, ABRASIVE PLASTICS		ALUMINUM, PLASTICS, WOOD	
	SPEED 5-10 SFM	FEED	SPEED 10-15 SFM	FEED	SPEED 15-20 SFM	FEED	SPEED 20-40 SFM	FEED	SPEED 40-60 SFM	FEED	SPEED 60-80 SFM	FEED	SPEED 80-100 SFM	FEED	SPEED 100-200 SFM	FEED	SPEED 200-600 SFM	FEED
DIA. OF END MILLS	RPM	CHIP LOAD PER TOOTH	RPM	CHIP LEAD PER TOOTH	RPM	CHIP LEAD PER TOOTH	RPM	CHIP LEAD PER TOOTH	RPM	CHIP LEAD PER TOOTH	RPM	CHIP LEAD PER TOOTH	RPM	CHIP LEAD PER TOOTH	RPM	CHIP LEAD PER TOOTH	RPM	CHIP LEAD PER TOOTH
1/16	-	-	-	-	-	-	1222-2444	.0002-.0005	2444-3667	.0002-.005	3667-4888	.0002-.0005	4888-6111	.0002-.0005	6111-12222	.0002-.0005	12222 UP	.0002-.0005
3/32	-	-	-	-	611-815	.0002-.0005	815-1629	.0002-.0005	1629-2750	.0002-.005	2750-3259	.0002-.0005	3259-4073	.0002-.0005	4073-8146	.0002-.0005	8146 UP	.0002-.0005
1/8	-	-	-	-	456-611	.0002-.0005	611-1222	.0002-.0005	1222-1833	.0002-.005	1833-2440	.0002-.001	2440-3056	.0002-.001	3056-6112	.0002-.001	6112 UP	.0002-.001
3/16	-	-	204-306	.0002-.0005	306-407	.0002-.0005	407-815	.0002-.0005	815-1222	.0002-.005	1222-1625	.0002-.001	1625-2037	.0002-.001	2037-4074	.0002-.001	4074-12222	.0002-.001
1/4	76-153	.0002-.001	153-230	.0002-.001	229-306	.0002-.001	306-611	.0002-.001	611-917	.0002-.001	917-1222	.0005-.002	1222-1528	.0005-.002	1528-3056	.0005-.002	3056-9168	.0005-.002
5/16	61-122	.0002-.001	122-183	.0002-.001	183-244	.0002-.001	244-489	.0002-.001	489-733	.0002-.001	733-978	.0005-.002	978-1222	.0005-.002	1222-2444	.0005-.002	2444-7332	.0005-.002
3/8	51-102	.0002-.001	102-153	.0002-.001	153-203	.0002-.001	203-407	.0005-.002	408-611	.0005-.002	611-815	.001-.003	815-1019	.001-.003	1019-2038	.0005-.003	2038-6114	.0005-.002
7/16	44-88	.0005-.001	88-132	.0005-.001	131-175	.0005-.002	175-349	.0005-.002	349-524	.0005-.002	524-698	.001-.003	698-873	.001-.003	873-1746	.0005-.003	1746-5238	.0005-.002
1/2	38-76	.0005-.001	76-115	.0005-.001	115-153	.0005-.002	153-306	.0005-.003	306-458	.001-.003	458-611	.001-.003	611-764	.001-.003	764-1528	.0005-.003	1528-4584	.0005-.002
9/16	34-68	.0005-.002	68-104	.0005-.002	104-136	.0005-.002	136-272	.0005-.003	272-412	.001-.003	412-543	.001-.004	543-678	.001-.004	678-1356	.0005-.004	1356-4071	.0005-.003
5/8	31-61	.0005-.002	61-92	.0005-.002	92-122	.0005-.002	122-244	.001-.004	244-367	.001-.004	367-489	.001-.004	489-611	.001-.004	611-1222	.0005-.004	1222-3666	.0005-.003
11/16	28-56	.0005-.002	56-84	.0005-.002	84-111	.0005-.002	111-222	.001-.004	222-337	.001-.004	337-444	.001-.004	444-555	.001-.004	555-1110	.0005-.004	1110-3330	.0005-.003
3/4	26-51	.0005-.002	51-76	.0005-.002	76-102	.001-.004	102-203	.001-.004	203-306	.001-.004	306-407	.001-.004	407-509	.002-.006	509-1018	.001-.006	1018-3054	.001-.004
13/16	24-47	.001-.003	47-71	.001-.003	71-94	.001-.004	94-189	.001-.004	189-284	.001-.004	284-379	.002-.006	379-469	.002-.006	469-938	.001-.006	938-2814	.001-.004
7/8	22-44	.001-.003	44-65	.001-.003	65-87	.001-.004	87-175	.001-.004	175-262	.002-.006	262-349	.002-.006	349-436	.002-.006	436-872	.001-.006	872-2616	.001-.004
15/16	20-40	.001-.003	40-62	.001-.003	62-81	.001-.004	81-163	.001-.004	163-246	.002-.006	246-326	.002-.006	326-407	.002-.006	407-814	.001-.006	514-2442	.001-.004
1	19-38	.001-.003	38-58	.001-.003	58-76	.001-.004	76-153	.002-.006	153-229	.002-.006	229-306	.002-.006	306-382	.002-.006	382-764	.002 UP	764-2292	.002 UP
1 1/8	34	.0015-.004	34-51	.0015-.004	51-68	.0015-.005	68-136	.002-.006	136-204	.002-.006	204-272	.002-.006	272-340	.003 UP	340-680	.002 UP	680-2040	.002 UP
1 1/4	31	.0015-.004	31-46	.0015-.004	46-61	.0015-.005	61-122	.002-.006	122-183	.002-.006	183-244	.003 UP	244-306	.003 UP	306-612	.002 UP	612-1836	.002 UP
1 3/8	28	.0015-.004	28-42	.0015-.004	42-55	.0015-.005	55-111	.002-.006	111-167	.003 UP	167-222	.003 UP	222-278	.003 UP	278-556	.002 UP	556-1668	.002 UP
1 1/2	26	.0015-.004	26-38	.0015-.004	38-51	.002 UP	51-102	.003 UP	102-153	.003 UP	153-204	.003 UP	204-255	.003 UP	255-510	.003 UP	510-1530	.002 UP
1 5/8	24	.002 UP	35	.002 UP	35-47	.002 UP	47-94	.003 UP	94-141	.003 UP	141-188	.003 UP	188-235	.003 UP	235-470	.003 UP	470-1410	.002 UP
1 3/4	22	.002 UP	32	.002 UP	32-43	.002 UP	43-87	.003 UP	87-131	.003 UP	131-175	.003 UP	175-218	.003 UP	218-436	.003 UP	436-1308	.002 UP
1 7/8	20	.002 UP	30	.002 UP	30-40	.003 UP	40-81	.003 UP	81-122	.003 UP	122-163	.003 UP	163-204	.003 UP	204-408	.003 UP	408-1224	.003 UP
2	19	.002 UP	29	.003 UP	29-38	.003 UP	38-76	.003 UP	76-115	.003 UP	115-153	.003 UP	153-191	.003 UP	191-382	.003 UP	382-1146	.003 UP
2 1/8	18	.003 UP	26	.003 UP	36	.003 UP	36-72	.003 UP	72-106	.003 UP	106-144	.003 UP	144-179	.003 UP	179-358	.003 UP	358-1074	.003 UP
2 1/4	17	.003 UP	26	.003 UP	34	.003 UP	34-68	.003 UP	68-102	.003 UP	103-136	.003 UP	136-170	.003 UP	170-340	.003 UP	340-1020	.003 UP
2 3/8	16	.003 UP	25	.003 UP	32	.003 UP	32-64	.003 UP	64-97	.003 UP	97-128	.003 UP	128-161	.003 UP	161-322	.003 UP	322-966	.003 UP
2 1/2	15	.003 UP	23	.003 UP	30	.003 UP	30-61	.003 UP	61-92	.003 UP	92-122	.003 UP	122-153	.003 UP	153-306	.003 UP	306-918	.003 UP
2 5/8	15	.003 UP	22	.003 UP	29	.003 UP	29-58	.003 UP	58-88	.003 UP	88-116	.003 UP	116-145	.003 UP	145-290	.003 UP	290-870	.003 UP
2 3/4	14	.003 UP	21	.003 UP	28	.003 UP	28-56	.003 UP	56-83	.003 UP	83-111	.003 UP	111-139	.003 UP	139-278	.003 UP	278-834	.003 UP
2 7/8	14	.003 UP	20	.003 UP	27	.003 UP	27-53	.003 UP	53-80	.003 UP	80-106	.003 UP	106-132	.003 UP	132-264	.003 UP	264-792	.003 UP
3	13	.003 UP	19	.003 UP	26	.003 UP	26-51	.003 UP	51-76	.003 UP	76-102	.003 UP	102-127	.003 UP	127-154	.003 UP	254-762	.003 UP

Note: All speed and feed data are suggested starting points. They may be increased or decreased depending on machine condition, depth of cut, finish required, coolant, etc.

Tool Wear

- Abrasion
- Adhesion (built-up edge)
- Diffusion (migration of atoms between work and tool)
- Fatigue
- Chemical (oxidation)



Tool Wear

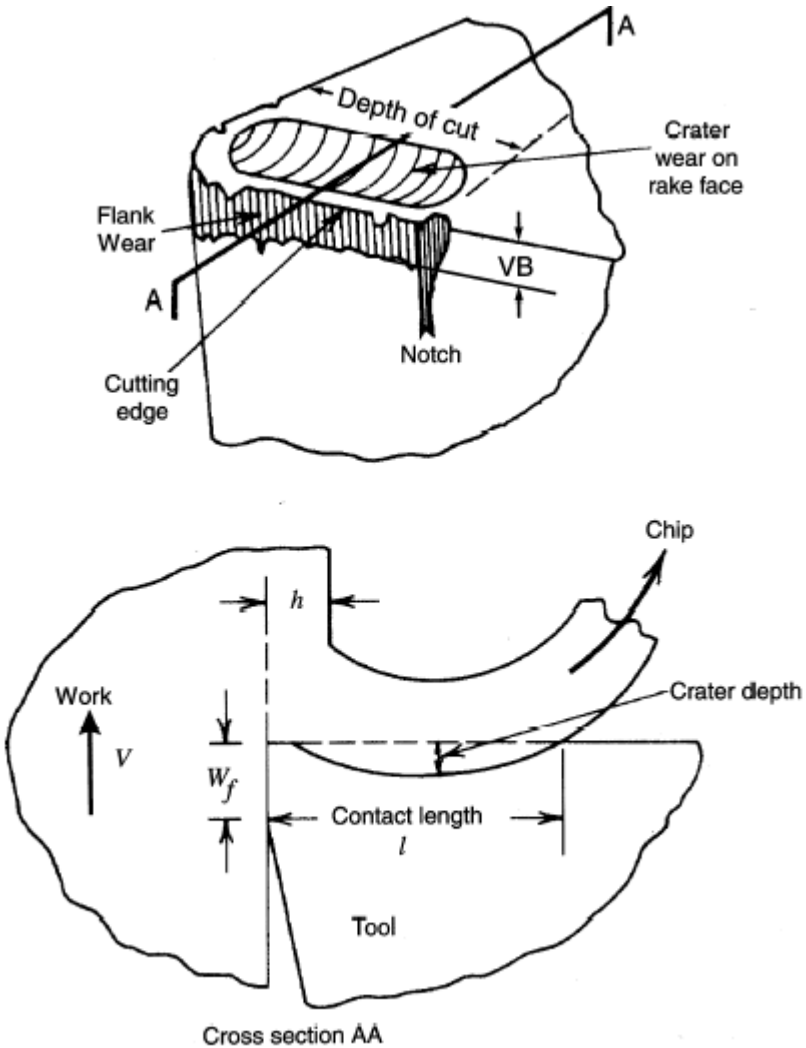
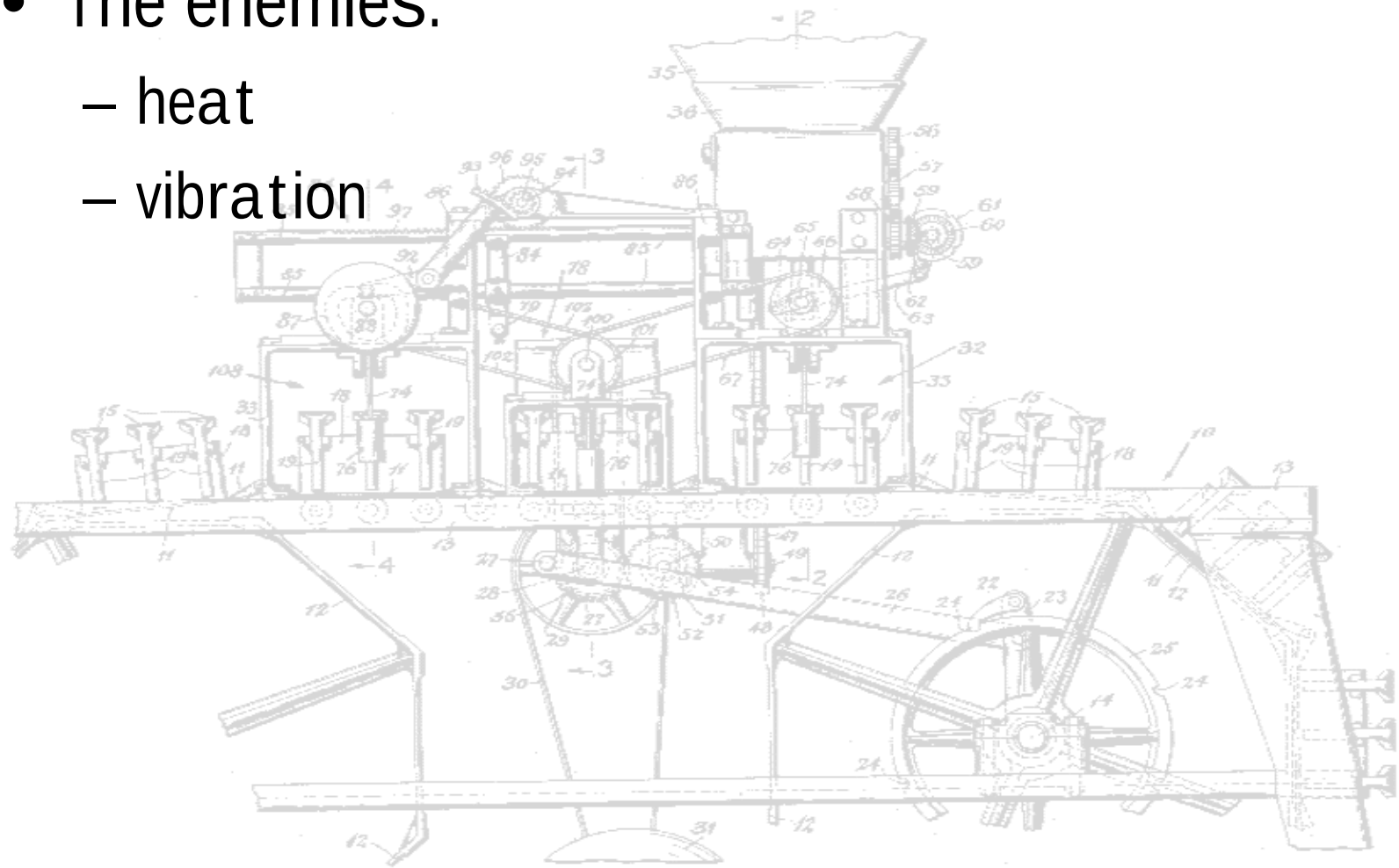


Figure 2.28: The types of tool wear and breakage.

Machinability

- The enemies:
  - heat
  - vibration

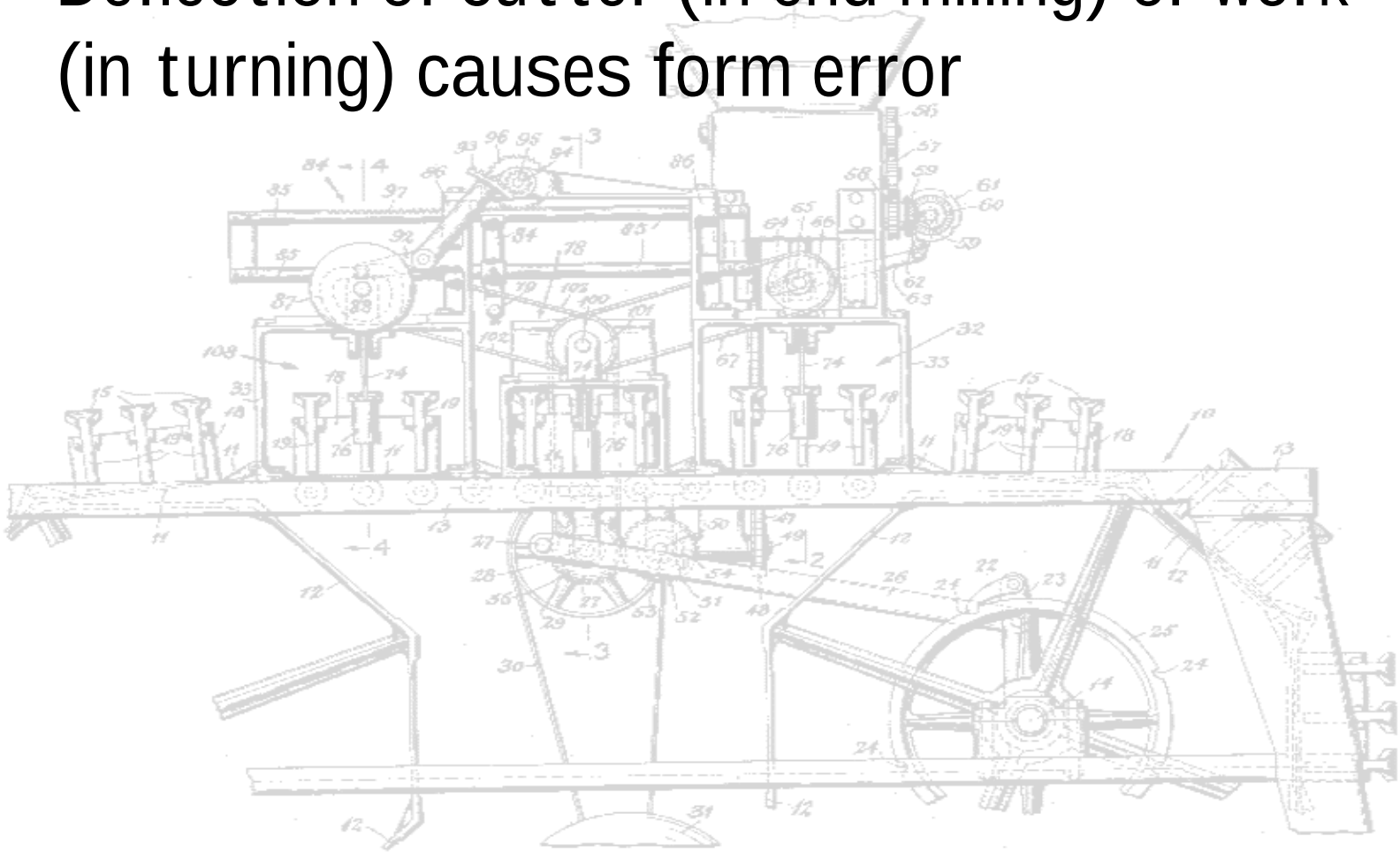


Process

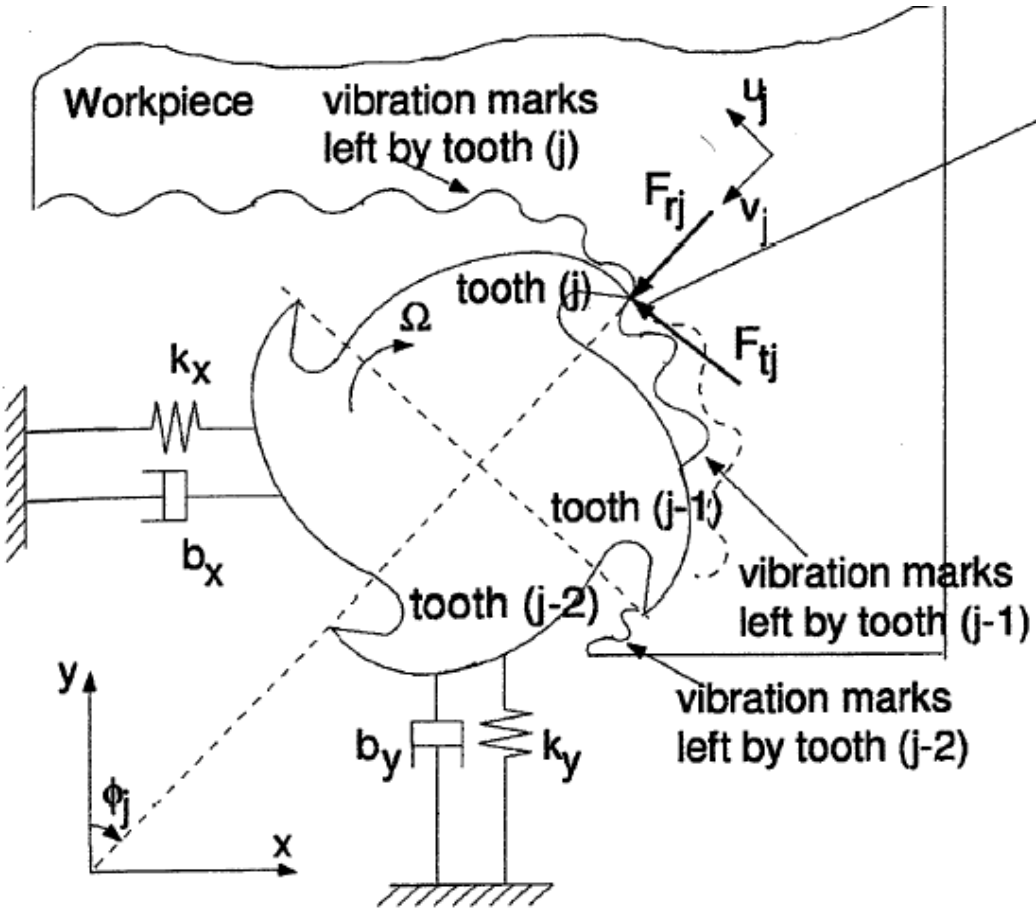
- Rigidity:
  - use shortest tool and tool holder
  - keep workpiece firmly clamped
  - avoid speed/feed/depth combos that chatter
- Heat:
  - use coated tools when heat is a problem
  - keep chips cleared (liquid or air coolant)
    - hard chips get harder
    - soft chips stick to tool
  - don't go too fast OR too slow
- Chip load:
  - keep volume removed constant!
  - especially watch tool entry, exit, corners

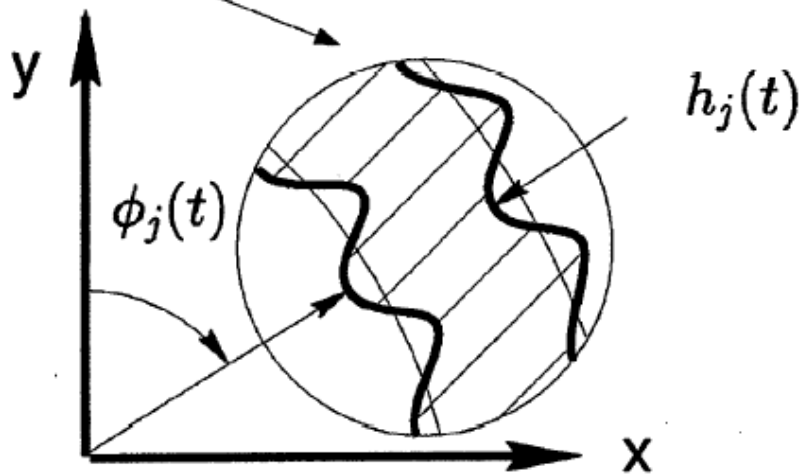
Form Errors

- Deflection of cutter (in end milling) or work (in turning) causes form error



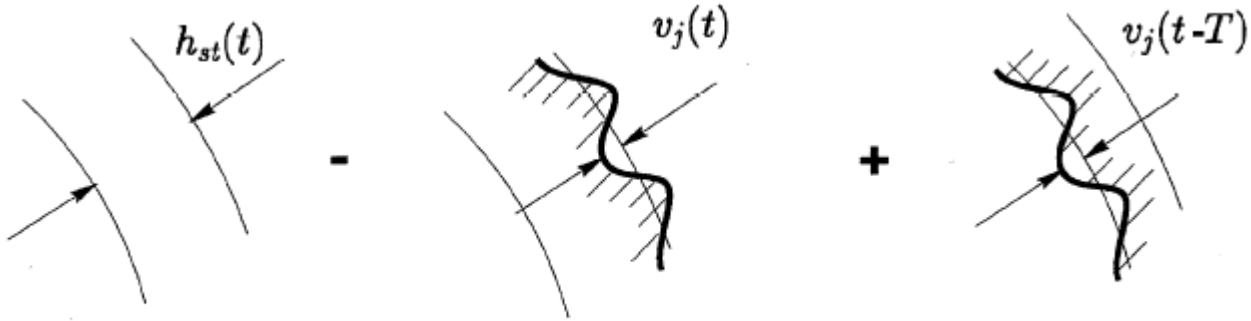
Vibration (chatter)



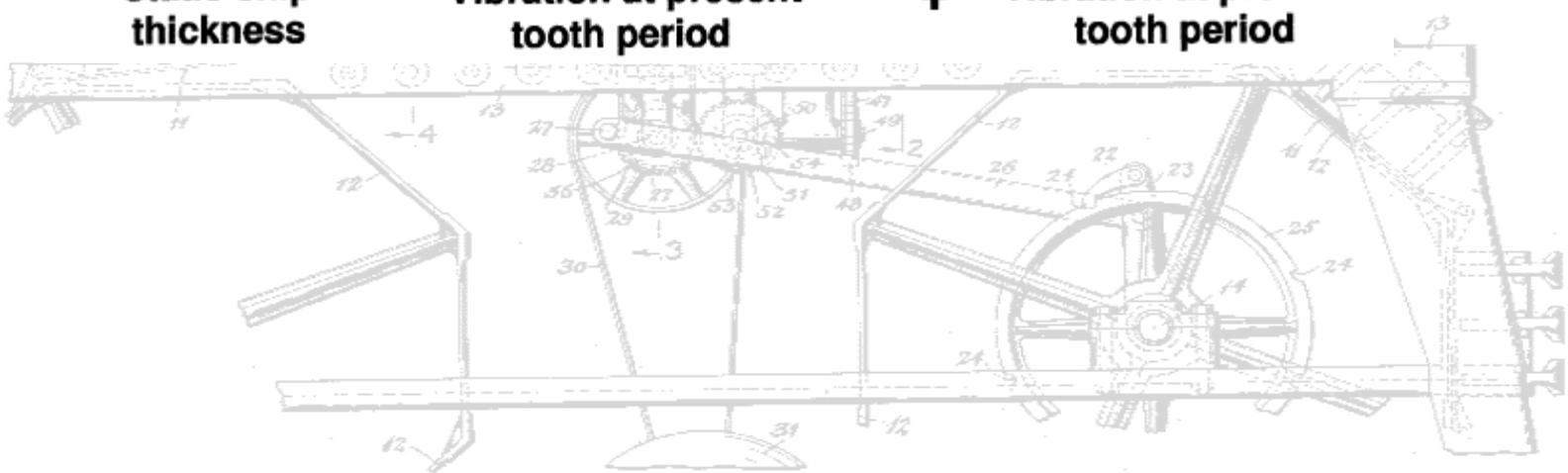


Dynamic chip thickness

Vibration

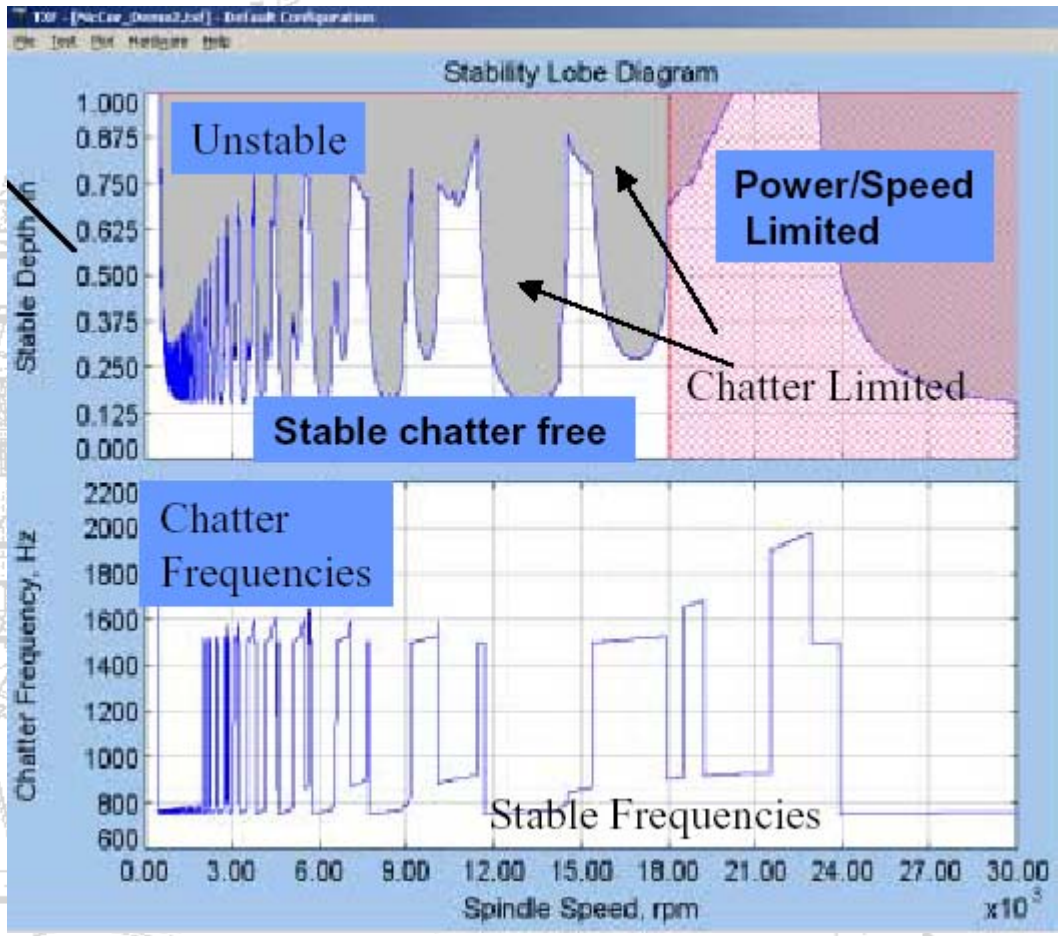


Static chip thickness - **Vibration at present tooth period** + **Vibration at previous tooth period**

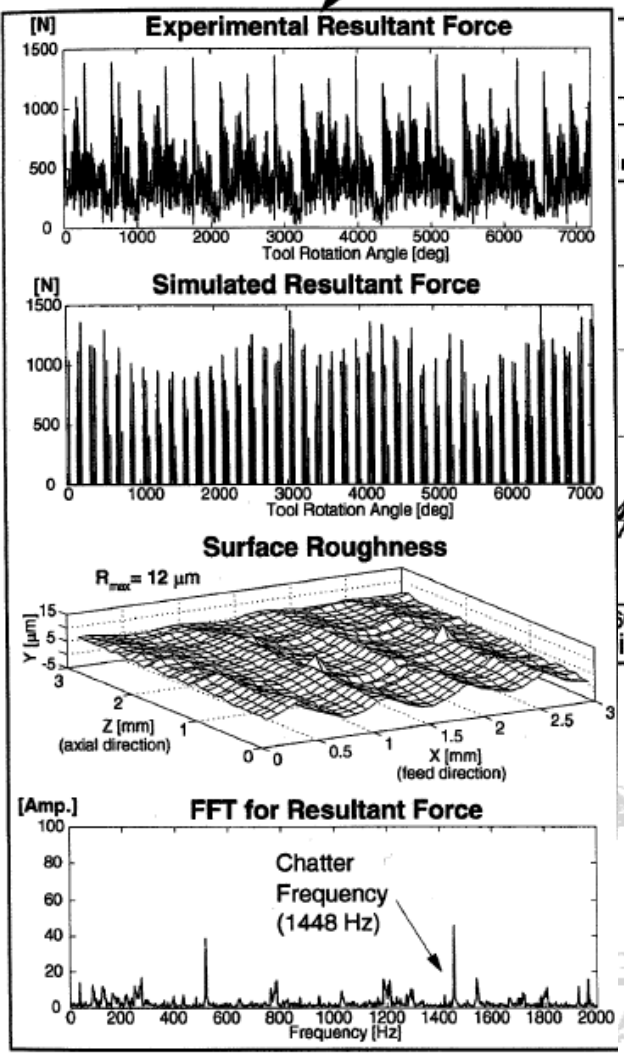


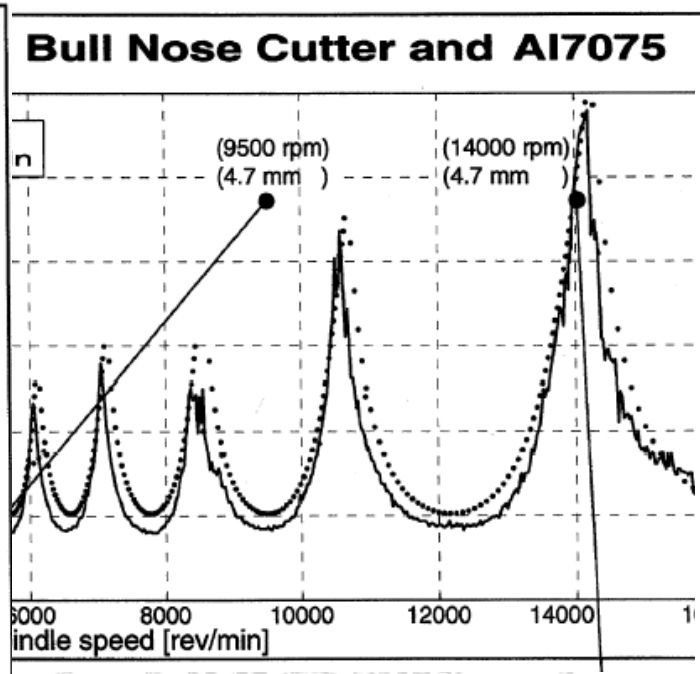
Vibration

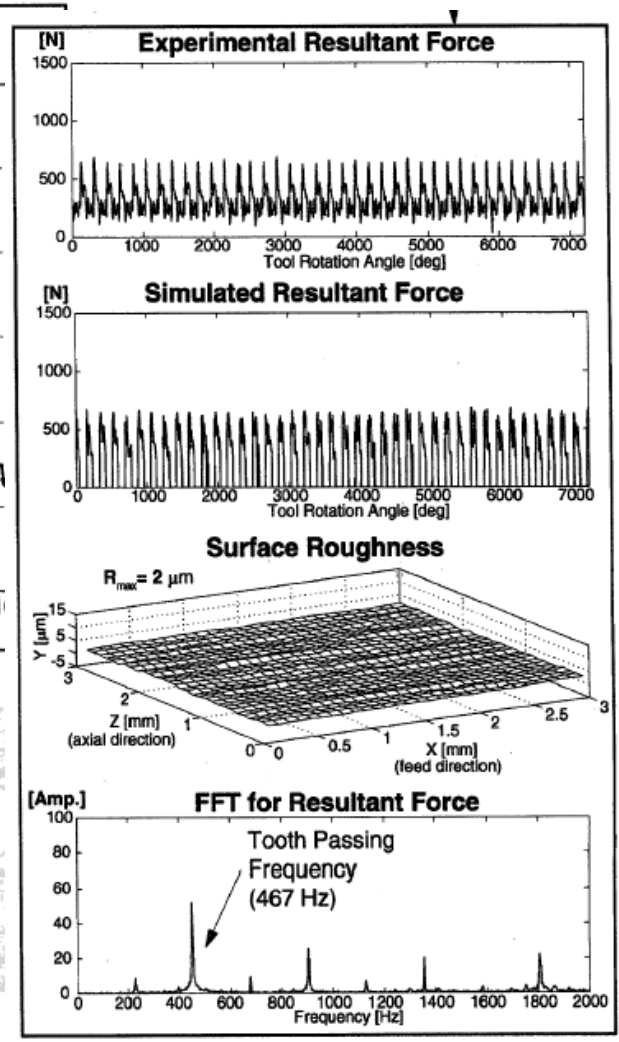
- Choose highest spindle RPM
- Tune tool length to stay in a stable lobe at top spindle RPM



Vibration


[N]
Experimental Resultant Force
Tool Rotation Angle [deg]
[N]
Simulated Resultant Force
Tool Rotation Angle [deg]
Surface Roughness
R_max = 12 μm
Y [μm]
Z [mm] (axial direction)
X [mm] (feed direction)
[Amp.]
FFT for Resultant Force
Chatter Frequency (1448 Hz)
Frequency [Hz]


Bull Nose Cutter and Al7075
(9500 rpm)
(4.7 mm)
(14000 rpm)
(4.7 mm)
indle speed [rev/min]


[N]
Experimental Resultant Force
Tool Rotation Angle [deg]
[N]
Simulated Resultant Force
Tool Rotation Angle [deg]
Surface Roughness
R_max = 2 μm
Y [μm]
Z [mm] (axial direction)
X [mm] (feed direction)
[Amp.]
FFT for Resultant Force
Tooth Passing Frequency (467 Hz)
Frequency [Hz]