NONTRADITIONAL MACHINING AND THERMAL CUTTING PROCESSES

1. Mechanical Energy Processes
2. Electrochemical Machining Processes
3. Thermal Energy Processes
4. Chemical Machining

1

NonTraditional Processes (NTP)

- Conventional Machining Processes (cutting, milling, drilling & grinding) use a sharp cutting tool
- NTP - A group of processes that remove excess material without a sharp cutting tool by various techniques involving mechanical, thermal, electrical, or chemical energy (or combinations) developed since World War II (1940's).
- Motivations in Aerospace and Electronics Industries
  - to machine new (harder, stronger & tougher) **materials** difficult or impossible to machine conventionally
  - for unusual & **complex geometries** that cannot easily machined conventionally
  - to achieve stringent **surface** (finish & texture) requirements not possible with conventional machining

2

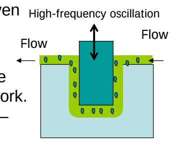
Classification

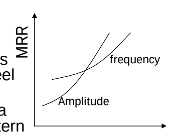
- ***Mechanical*** - Erosion of work material by a high velocity stream of abrasives and/or fluid
  - Ultrasonic machining, Water jet cutting (WJC), Abrasive water jet cutting (AWJC) and Abrasive jet machining (AJM)
- ***Electrical*** - Electrochemical energy to remove material
  - Electrochemical machining (ECM), Electrochemical deburring (ECD) and Electrochemical grinding (ECG)
- ***Thermal*** - Thermal energy applied to small portion of work surface, removing by fusion and/or vaporization
  - Electric Discharge Machining (EDM), Wire EDM, Electron Beam, Laser Beam, Arc Cutting
- ***Chemical*** - chemical etchants selectively - using a mask - remove a portion of a workpart
  - Chemical Milling, Blanking, Engraving and Photochemical Machining

3

1. Mechanical Energy Processes

- Ultrasonic Machining (USM)
  - Abrasives (20-60 volume %) in a slurry are driven at high velocity by the tool vibrating at low amplitude (0.05-0.125mm) and high frequency (20kHz).
  - Tool oscillation is perpendicular to work surface
  - Tool: soft and stainless steels fed slowly into work.
  - Abrasives (Grit size 100 (rough) to 2000(fine)) – BN, BC, Al_2O_3, SiC & Diamond
  - The vibration amplitude equals to grit size, which also determines the resulting surface finish.
  - Time of contact: 10-100μs
  - Shape of tool is formed into a part
  - Work materials – Hard, brittle materials such as ceramics, glass and carbides and stainless steel and titanium
  - Shapes include non-round holes (holes along a curved axis) and "Coining operations" (the pattern on tool is imparted to a flat work surface).

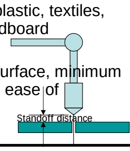




4

Water Jets

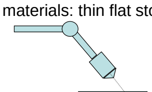
- **Water Jet Cutting (WJC)** or Hydrodynamic machining – use a fine, high-pressure and high velocity stream of water.
  - A small nozzle (made of sapphire, ruby or diamond) opening of diameter (0.1 to 0.4 mm)
  - Pressure up to 400MPa and velocity up to 900m/s.
  - A typical standoff distance is 3.2mm.
  - Feed rates between 5mm/s to 500mm/s depending on material and thickness
  - CNC or industrial robots to cut along desired trajectory
  - Used to cut narrow slits in flat stock such as plastic, textiles, composites, floor tile, carpet, leather, and cardboard
  - Not suitable for brittle materials (e.g., glass)
  - Advantages: no crushing or burning of work surface, minimum material loss, no environmental pollution, and ease of automation



5

Water and Abrasive Jets

- **Abrasive Water Jet Cutting (AWJC)**
  - Use of abrasive particles (grid sizes between 60 and 120) into the jet stream
  - Process parameters: abrasive type, grit size, & flow rate
  - Other parameters: Nozzle office diameter(0.25 to 0.63 mm)
  - Abrasives: aluminum oxide, silicon dioxide & garnet.
  - Standoff distance is ½ and ¼ of those of WJC.
- **Abrasive Jet Machining (AJM)**
  - Usually finishing process (deburring, polishing, cleaning) not cutting
  - Grid size between 15 and 40 μm
  - Usually performed manually by operator who directs nozzle
  - Normally used as a finishing process rather than cutting process
  - Use for deburring, trimming & deflashing, cleaning, and polishing
  - Work materials: thin flat stock of hard, brittle materials



6

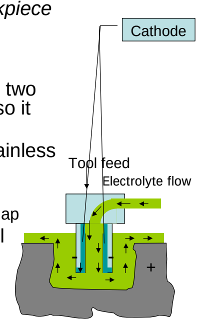
2. Electrochemical Machining Processes

- Electrical energy in combination with chemical reactions to remove material - Work material must be a conductor
- Reverse of electroplating
  - Part is the anode (+) and the tool is the cathode (-)
  - Metal is "pulled" away from work
- Advantage
  - Hard to soft materials made of conductive material can be machined
  - Cutting tool can be made from soft material
  - Low heat generated during process
  - No cutting forces
  - Excellent surface finish
- Processes:
  - Electrochemical machining (ECM)
  - Electrochemical deburring (ECD)
  - Electrochemical grinding (ECG)

7

Electrochemical Machining (ECM)

- Material is deplated from *anode workpiece* (positive pole) and transported to a *cathode tool* (negative pole) in an electrolyte bath
- Electrolyte flows rapidly between the two poles to carry off deplated material, so it does not plate onto tool
- Electrode materials: Cu, brass, or stainless steel
- Tool has inverse shape of part
  - Tool size and shape must allow for the gap
- No surface damage, no burr, low tool wear, high removal rate for hard-to-machine materials



8

Process Physics

IN ECM, Resistance: $R = \frac{gr}{A}$

Current: $I = \frac{E}{R} = \frac{EA}{gr}$

Faraday's First Law: $V = CIt = \frac{CEAt}{gr}$

$\frac{V}{At} = f_r = \frac{CE}{gr}$

Feed rate: $f_r = \frac{CI}{A}$

Material Removal Rate: $MRR = CI\eta$

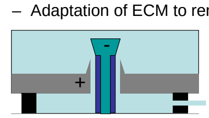
g= gap
r = resistivity of electrolyte
A=surface area between work & tool
V = Volume of metal removed;
C = specific removal rate depending on work material (mm^3/amp-s);
t = time (s)
E=voltage
η = the current efficiency (0.9-1)

Work material	C(mm^3/amp-sec)
Al	3.44×10^{-2}
Cu	7.35×10^{-2}
Fe	3.67×10^{-2}
Steel	$3\text{-}2.5 \times 10^{-2}$
Ni	3.42×10^{-2}
Ti	2.73×10^{-2}

9

Electrochemical Machining

- ElectroChemical Machining (ECM)
  - Gap distance needed to be controlled without touching.
  - Water with salts is used as electrolyte
    - Remove debris, heat and hydrogen bubbles
  - Disadvantages
    - Disposal of the electrolyte
    - Large amounts of electric power required
  - Advantages:
    - Used on very hard or difficult to machine
    - Die sinking, multiple holes, irregular holes and deburring
- ElectroChemical Deburring (ECD)
  - Adaptation of ECM to remove burrs and round sharp corners

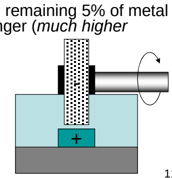


10

Electrochemical Grinding (ECG)

Special form of ECM in which a grinding wheel with conductive bond material is used to augment anodic dissolution of metal part surface

- Applications:
  - Sharpening of cemented carbide tools
  - Surgical needles, other thin wall tubes, and fragile parts
- Advantages:
  - Deplating removes 95%, and abrasives remaining 5% of metal removal - grinding wheel lasts much longer (*much higher grinding ratio, less frequent dressing)*



11

3. Thermal Energy Processes

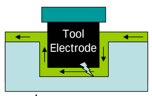
Very high local temperatures remove material by fusion or vaporization. Physical and metallurgical damage to the new work surface

- Electric Discharge Processes
  - Electric Discharge Machining (EDM)
    - Wire EDM
  - Electron Beam Machining
- Laser Beam Machining
- Arc Cutting Processes
  - Plasma Arc Cutting
  - Air Carbon Arc Cutting
  - Other Arc Cutting Processes
- Oxyfuel Cutting Processes

12

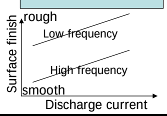
Electric Discharge Machining (EDM)

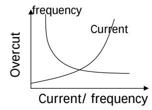
- Most widely used among nontraditional processes
- Sparks (lightening: 500 - 5,000 sparks per second) across a small gap between tool and work to remove material, thus slow (MRR= 1 in^3 to 15 in^3 per hr.)
- Electrode (made of Brass, Copper and Graphite) is (+) and the part is (-)
- Requires dielectric fluid, which creates a path for each discharge as fluid becomes ionized in the gap
- Dielectric fluids: hydrogen oil, kerosene and water



$$MRR = \frac{KI}{T_m^{1.23}}$$

$$\text{where } K = 39.86 \text{ in SI units}$$





13

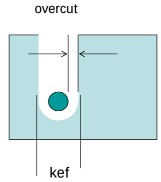
Work Materials and Applications

- Only **electrically conducting work materials**
- Hardness and strength of the work material are not factors in EDM
- Material removal rate is related to melting point of work material
- Tooling for many mechanical processes: molds for plastic injection molding, extrusion dies, wire drawing dies, forging and heading dies, and sheetmetal stamping dies
- Production parts: delicate parts not rigid enough to withstand conventional cutting forces, hole drilling where hole axis is at an acute angle to surface, and machining of hard and exotic metals

14

Wire EDM

- A special form of EDM that uses small diameter wire as electrode to cut a narrow kerf in work
- Wire diameter range from 0.076 to 0.3mm
- Overcut in a range of 0.02 to 0.051mm



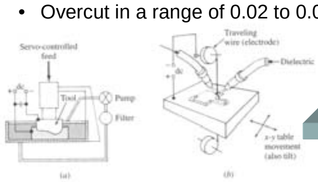
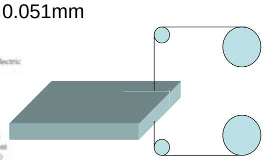


Figure 17-3 Electrodischarge machining is practiced with (a) form tools in ram-EDM and (b) traveling wire in wire-EDM.



From Schey [

15

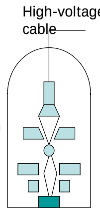
Operations and Applications

- Work is fed slowly past wire along desired cutting path, like a bandsaw operation
- CNC used for motion control
- While cutting, wire is continuously advanced between supply spool and take-up spool to maintain a constant diameter
- Dielectric required, using nozzles directed at tool-work interface or submerging workpart
- Ideal for stamping die components
  - Since kerf is so narrow, it is often possible to fabricate punch and die in a single cut
- Other tools and parts with intricate outline shapes, such as lathe form tools, extrusion dies, and flat templates

16

Thermal Energy Processes

- Electron Beam Machining
  - Uses a high-velocity stream of electrons capable to remove any material
  - EB gun accelerates a continuous stream of electrons to about 75% of light speed.
  - Kinetic energy of electrons is converted to thermal energy of extremely high density which vaporizes material in a very localized area
  - Beam focused through electromagnetic lens.
  - Very precise – drill holes less than 0.05mm and depth to height ratio up to 100
  - Small depth (0.25-6.3mm),
  - Vacuum chamber, high energy, expensive equipment



17

Laser and Its Applications

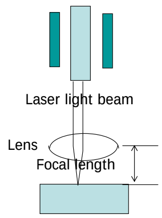
*L*ight *a*mplification by *s*timulated *e*mission of *r*adiation

- A laser converts electrical energy into a highly coherent light beam with the following properties:
  - Monochromatic (theoretically, single wave length)
  - Highly collimated (light rays are almost perfectly parallel)
- These properties allow laser light to be focused, using optical lenses, onto a very small spot with resulting high power densities

18

Laser Beam Machining

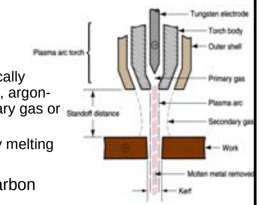
- Drilling, slitting, slotting, scribing, and marking
- Drilling small diameter holes - down to 0.025 mm on thin stock
- Work materials: metals with high hardness and strength, soft metals, ceramics, glass and glass epoxy, plastics, rubber, cloth, and wood
- Applies high power density to a small spot.
- Unlimited range of work materials



19

Thermal Energy Processes

- Arc Cutting Processes
  - Plasma arc cutting (PAC)
    - A plasma – a superheated, electrically ionized gas (Primary gas: nitrogen, argon-hydrogen or mixtures and secondary gas or water for shielding).
    - Cut flat metal sheets and plates by melting
    - High productivity
  - Air carbon arc cutting - Arc from carbon electrode
  - Other arc cutting processes
    - Gas metal arc cutting, shielded metal arc cutting, gas tungsten arc cutting and carbon arc cutting
- Oxyfuel cutting processes – flame cutting



PAC

20

Plasma Arc Cutting (PAC)

- *Plasma* = a superheated, electrically ionized gas
- PAC temperatures: 10,000°C to 14,000°C (18,000°F to 25,000°F)
- Plasma arc generated between electrode in torch and anode workpiece
- The plasma flows through water-cooled nozzle that constricts and directs stream to desired location
- Cutting flat metal sheets and plates and hole piercing and cutting along a defined path operated by hand-held torch or automated by CNC
- Can cut any electrically conductive metals such as carbon steel, stainless steel, aluminum

21

Air Carbon Arc Cutting

Arc is generated between a carbon electrode and metallic work, and high-velocity air jet blows away melted portion of metal

- Can be used to form a kerf to sever a piece, or to gouge a cavity to prepare edges of plates for welding
- Work materials: cast iron, carbon steel, alloy steels, and various nonferrous alloys
- Spattering of molten metal is a hazard
- Other Similar Processes
  - Gas metal arc cutting
  - Shielded metal arc cutting
  - Gas tungsten arc cutting
  - Carbon arc cutting

22

Oxyfuel Cutting (OFC) Processes

Use heat of combustion of fuel gases combined with exothermic reaction of metal with oxygen

- Popularly known as *flame cutting*
- Cutting torch delivers a mixture of fuel gas and oxygen and directs a stream of oxygen to cutting region
- Fuel
  - Acetylene (C_2H_2)
    - Highest flame temperature
    - Most widely used but hazardous
  - MAPP (methylacetylene-propadiene - C_3H_4) -
  - Propylene (C_3H_6)
  - Propane (C_3H_8)

23

Operation and Applications

- Primary mechanism of material removal is chemical reaction of oxygen with base metal
  - Especially in cutting ferrous metals
- Purpose of oxyfuel combustion is to raise the temperature to support the reaction
- Commonly used to cut ferrous metal plates
- Performed manually or by machine
- Manual operation, examples of applications:
  - Repair work
  - Cutting scrap metal
  - Trimming risers from sand castings
- Machine flame cutting allows faster speeds and greater accuracies
  - Machine operation often CNC controlled to cut profiled shapes

24

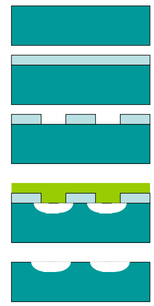
Chemical Machining (CHM)

Material removal through contact with a strong chemical etchant (controlled etching process)

- Processes include:
  - Chemical milling
  - Chemical blanking
  - Chemical engraving
  - Photochemical machining
- All utilizing the same mechanism of material removal
- Applications
  - Remove material from aircraft wing and fuselage panels for weight reduction
  - Applicable to large parts where substantial amounts of metal are removed
  - Cut and peel maskant method is used

25

Chemical Milling: Processing Steps



Clean - to insure uniform etching

Apply maskant - a maskant (chemically resistant to etchant) to portions of work surface not to be etched
  Materials: neoprene, polyvinylchloride, polyethylene, and other polymers
  Three Masking methods: **Cut and peel, Photographic resist, Screen resist**

Selectively remove maskant

Etch - Part is immersed in etchant which chemically attacks those portions not masked

Remove maskant and clean - maskant is removed

26

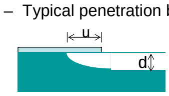
Masking Methods

- Cut and Peel Maskant
  - Maskant is applied over entire part by dipping, painting, or spraying
  - After maskant hardens, it is cut by hand using a scribing knife and peeled away in areas of work surface to be etched
  - Used for large workparts, low production quantities, and where accuracy is not a critical factor
- Photographic Resist Method
  - Masking materials contain photosensitive chemicals
  - Maskant is applied to work surface and exposed to light through a negative image of areas to be etched
  - These areas are then removed using photographic developing techniques
    - Remaining areas are vulnerable to etching
  - Applications:
    - Small parts are produced in high quantities
    - Fabrication of integrated circuits and printed circuit cards
- Screen Resist Method
  - Maskant applied by "silk screening" methods
  - Maskant is painted through a silk or stainless steel mesh containing stencil onto surface areas that are not to be etched
  - Applications:
    - Between other two masking methods
    - Fabrication of printed circuit boards

27

Etchant

- Factors in selection of etchant:
  - Work material
  - Depth and rate of material removal
  - Surface finish requirements and
  - matched with the type of maskant not chemically attacked
- Undercut: Etches downward & sideways under maskant
- Material Removal Rate
  - Generally indicated as penetration rates, mm/min (in/min), since rate of chemical attack is directed into surface
  - Penetration rate is *unaffected by surface area*.
  - Typical penetration between 0.020 and 0.050 mm/min



Etch factor: $F_e = \frac{u}{d}$

28

Work Materials and Etchants

Work Material	Etchant	Penetration rate(mm/min)	Etch Factor
Al Al alloys	$FeCl_3$ NaOH	0.02 0.025	1.75 1.75
Cu & alloys	$FeCl_3$	0.05	2.75
Mg & alloys	H_2SO_4	0.038	1.0
Si	HNO_3:HF:H_2O	Very slow	NA
Mild Steel	HCl:HNO_3 $FeCl_3$	0.025 0.025	2.0 2.0
Ti alloy	HF HF:HNO_3	0.025 0.025	1.0 1.0

29

Chemical Blanking

Uses chemical erosion to cut very thin sheetmetal parts - down to 0.025 mm (0.001 in) thick and/or for intricate cutting patterns

- Conventional punch and die does not work because *stamping forces damage the thin sheetmetal*, or tooling cost is prohibitive, or both
- Maskant methods are either photoresist or screen resist

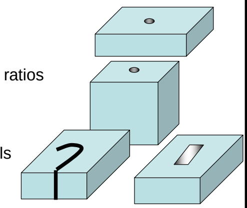
30

Photochemical Machining (PCM)

- Uses photoresist masking method
- Applies to chemical blanking and chemical engraving when photographic resist method is used
- Used extensively in the electronics industry to produce intricate circuit designs on semiconductor wafers
- Also used in printed circuit board fabrication

31

5. Application consideration



- Workpart Geometry Features
  - Very small holes
  - Holes with large depth to diameter ratios
  - Holes that are not round
  - Narrow slots
  - Microscale
  - Shallow pockets and surface details
  - Special contoured shapes
- Work materials
  - Metals and non-metals. However, certain processes are not suited to certain work materials
  - Several processes can be used on metals but not nonmetals:
    - ECM
    - EDM and wire EDM
    - PAM

32

Work Material Compatibility

Work Material	Nontraditional Process								Conventional Machining	
	Mech		Elec		Thermal			Chem		
	USM	WJC	ECM	EDM	EBM	LBM	PAC	CHM	Milling	Grinding
Al	C	C	B	B	B	B	A	A	A	A
Steels	B	D	A	A	B	B	A	A	A	A
Super Alloys	C	D	A	A	B	B	A	B	B	B
Ceramics	A	D	D	D	A	A	D	C	D	C
Glass	A	D	D	D	B	B	D	B	D	C
Silicon			D	D	B	B	D	B	D	B
Plastics	B	B	D	D	B	B	D	C	B	C
Cardboard	D	A	D	D			D	D	D	D
Textiles	D	A	D	D			D	D	D	D

A=good, B=Fair, C=Poor and D=Not Applicable

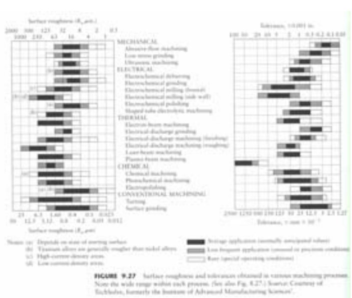
33

Characteristics

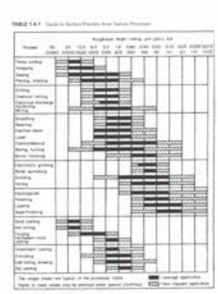
Characteristics	Nontraditional								Conventional Processes	
	Mech		Elec		Thermal			Chem		
	USM	WJC	ECM	EDM	EBM	LBM	PAC	CHM	Milling	Grinding
MRR	C	C	B	C	D	D	A	B-D	A	B
Dimension Control	A	B	B	A-D	A	A	D	A-B	B	A
Surface Finish	A	A	B	B-D	B	B	D	B	B-C	A
Surface Damage	B	B	A	D	D	D	D	A	B	B-C

A=Excellent, B=Good, C=Fair and D=Poor

34



Schey [2000]



Design for Manufacturability Handbook [Bralla,1999]

35

Machining Nonmetallic Materials

- Ceramics
  - Typically using harder abrasives (e.g.: grinding, polishing, USM, AWJC etc.)
  - Chemical as a ceramic can susceptible to a certain chemical attack.
  - EDM if resistivity is less than 300Ω–cm.
- Plastics
  - Less stiff - stability
  - Viscoelastic effect – large relief angle
  - Low thermal conductivity - High thermal gradient
  - Low strength ->Reduce cutting energy ->Large rake angle
  - Twist drill – usually wide, polished flutes, low helix angle (<30°) and 60-90° point angle.
- Composites
  - Delamination, poor edge finish and fiber or resin pull-out - NTP such as abrasive water jet and laser.

36