Metal Removal Processes

Dr. N S Mahesh
Session Objectives

• At the end of the session delegates should have understood
  – Classification material removal processes
  – Principles of operation of conventional machining processes
  – Need, process principle, application of non-conventional machining processes
  – Machining process selection guidelines
Machining Processes

- Conventional
  - Turning
  - Drilling
  - Milling
  - Other

- Abrasive
  - Grinding
  - Lapping
  - Polishing
  - Other

- Nontraditional
  - Mechanical Energy
  - Electrochemical
  - Thermal Energy
  - Chemical Machining
INTRODUCTION

• Components for FITs require accurate mating dimensions and surfaces
• Most of the primary processes can not meet these requirements
• Metal removal processes are the most common route for generating acceptable dimensional accuracies and surface texture
• Machining is costlier route because of material wastage, time and energy spent for removal of excess material
To reduce machining costs

- Avoid excess machining allowances during primary processing
- Achieve rough shape as “near net” as possible eg. Die casting a piston instead of sand casting reduces machining
- Optimize initial shaping and final machining regarding the aspects like machine tools, cutting tools and cutting parameters
Single - Point Tools

Surface of revolution
(Job rotating)

Feed parallel to axis of rotation
(Cylindrical surfaces)
- External turning, screw cutting
- Internal boring
  - Internal screw cutting

Feed not parallel to axis of rotation

Tool reciprocates
- Shaping
- Slotting

Job reciprocates
- Planing

At any angle
(Conical surfaces)
- External taper turning, facing
- Internal Taper boring

Simultaneous two axes motion
- Contouring
- Copy turning
Multi – Point Tools

Cylindrical Surface

- Two edge Cutting
- Drilling

- Multi edge cutting

- Sizeable Chips (Milling, Gear cutting)
  - Spiral milling
  - Gear hobbing

Plane Surfaces

- Sizeable Chips (Milling)
- Plane milling
- Broaching
- Gear shaping

- Small Chips (Grinding)
- Surface grinding
- Lapping

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<table>
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<tr>
<th>Operation</th>
<th>Block diagram</th>
<th>Most commonly used machines</th>
<th>Machines less frequently used</th>
<th>Machines seldom used</th>
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<tr>
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<td><img src="image" alt="Diagram" /></td>
<td>Lathe&lt;br&gt;NC lathe machining center</td>
<td>Boring mill</td>
<td>Turret lathe</td>
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<tr>
<td>Grinding</td>
<td><img src="image" alt="Diagram" /></td>
<td>Cylindrical grinder</td>
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<td>Lathe (with special attachment)</td>
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<tr>
<td>Sawing (of plates and sheets)</td>
<td><img src="image" alt="Diagram" /></td>
<td>Contour or band saw</td>
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<td>Drilling</td>
<td><img src="image" alt="Diagram" /></td>
<td>Drill press&lt;br&gt;Machining center (nc)&lt;br&gt;Vert. milling machine</td>
<td>Lathe&lt;br&gt;Horizontal boring machine</td>
<td>Horizontal milling machine&lt;br&gt;Boring mill</td>
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<td>Boring</td>
<td><img src="image" alt="Diagram" /></td>
<td>Lathe&lt;br&gt;Boring mill&lt;br&gt;Horizontal boring machine&lt;br&gt;Machining center</td>
<td></td>
<td>Milling machine&lt;br&gt;Drill press</td>
</tr>
</tbody>
</table>
Reaming

Grinding

Sawing

Broaching

Lathe
Drill press
Boring mill
Horizontal boring machine
Machining center

Milling machine

Cylindrical grinder

Lathe (with special attachment)

Contour or band saw

Broaching machine
Arbor press (keyway broaching)

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<table>
<thead>
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<th>Block diagram</th>
<th>Most commonly used machines</th>
<th>Machines less frequently used</th>
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<tbody>
<tr>
<td>Facing</td>
<td><img src="#" alt="Facing Diagram" /></td>
<td>Lathe</td>
<td>Boring mill</td>
<td></td>
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<tr>
<td>Broaching</td>
<td><img src="#" alt="Broaching Diagram" /></td>
<td>Broaching machine</td>
<td>Turret broach</td>
<td></td>
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<tr>
<td>Grinding</td>
<td><img src="#" alt="Grinding Diagram" /></td>
<td>Surface grinder</td>
<td></td>
<td>Lathe (with special attachment)</td>
</tr>
<tr>
<td>Sawing</td>
<td><img src="#" alt="Sawing Diagram" /></td>
<td>Cutoff saw</td>
<td>Contour saw</td>
<td></td>
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</tbody>
</table>
Shaping

Planing

Milling

Shaper

Planer

Milling machine

Lathe with special milling tools

Drill press (light cuts)
BASIC RULES OF METAL CUTTING

• Strong cutting tools with good support
• Strong m/c to avoid bending / twisting
• Strong dovetail slide ways to give good support
• Non excessive depth of cut
• Secured work piece holding
• Cutting force application to avoid work piece deformation
WORK PIECE HOLDING
CONSIDERATIONS

• Chip removal
• Access for cutting tool
• Design the components to facilitate holding during machining
• Avoid / reduce frequency of work removal and re-setting
• Use correct Fixtures and Jigs (if need be)
Advanced Machining Processes
Session Objectives

• At the end of the session the delegates should have understood
  – Different Non traditional Machining processes viz. USM, EDM, WEDM, WJM, ECM, CM, etc.
  – Their operating principles and parameters for machining
  – Applications
Energy consumption for surface generation

- Specific energy [J/mm³]
- Speed of surface generation [mm/s]

- Forming
- Cutting
- Non-conventional machining processes
Machining features of non-conventional machining:

- High speed of surface generation,
- High specific energy,
- Atomic scale processing,
- Metal removal is based on several complex physical and chemical phenomena,
- Their development and applications are still increasing,
- They are suitable for machining hard, brittle and the so called ‘exotic’ materials,
- They are suitable for workpieces with high shape complexity,
- They are suitable for automation of data communication,
- They fulfill high surface integrity and precision requirements,
- They meet miniaturization requirements.
Introduction

• Advanced Machining Processes or NTM can be used when mechanical methods are not satisfactory, economical or possible due to:
  – High strength or hardness
  – Too brittle or too flexible
  – Complex shapes
  – Special finish and dimensional tolerance requirements
  – Temperature rise and residual stresses
Introduction

• These advanced methods began to be introduced in the 1940's.
• Removes material by chemical dissolution, etching, melting, evaporation, and hydrodynamic action.
• These requirements led to chemical, electrical, laser, and high-energy beams as energy sources for removing material from metallic or non-metallic workpieces.
NTM Classification

• Mechanical processes
  – Ultrasonic machining
  – Ultrasonically assisted machining
  – Rotary ultrasonically assisted machining
  – Abrasive jet machining
  – Water jet cutting
  – Abrasive water jet cutting

• Electrical processes
  – Electrochemical machining
  – Electrochemical grinding
  – Electrochemical deburring
  – Electrochemical honing
  – Shaped tube electrolytic machining
NTM Classification

• Thermal processes
  – Electron beam machining
  – Laser beam machining
  – Electric discharge machining
  – Electric discharge wire cutting
  – Plasma arc machining
  – Plasma-assisted machining
  – Thermal deburring

• Chemical processes
  – Chemical material removal
  – Chemical milling
  – Chemical blanking
  – Chemical engraving
Overview of basic non-conventional machining processes

MECHANICAL PROCESSES

ULTRASONIC MACHINING (USM)

WATER JET MACHINING (WJM)

ABRASIVE JET MACHINING (AJM)

CHEMICAL PROCESSES

CHEMICAL MACHINING (CHM)

ELECTRO-CHEMICAL PROCESSES

ELECTRO-CHEMICAL MACHINING (ECM)

ELECTRO-THERMAL PROCESSES

ELECTRICAL DISCHARGE MACHINING (EDM)

LASER BEAM MACHINING (LBM)

ELECTRON BEAM MACHINING (EBM)

ION BEAM MACHINING (IBM)

PLASMA ARC CUTTING (PAC)
Mechanical Processing
Ultra Sonic Machining (USM)

• Hard materials like stainless steel, glass, ceramics, carbide, quartz and semi-conductors are machined by this process.

• It has been efficiently applied to machine glass, ceramics, precision minerals stones, tungsten.

• Brittle materials
Principle of Ultrasonic Machining

• Material removal due to combination of four mechanisms
  – Hammering of abrasive particles in the work surface by the tool
  – Impact of free abrasive particles on the work surface
  – Cavitation erosion
  – Chemical action associated with the fluid employed
Principle of Ultrasonic Machining

• In USM process, the tool, made of softer material than that of the workpiece, is oscillated by the Booster and Sonotrode at a frequency of about 20 kHz with an amplitude of about 25.4 µm (0.001 in).

• The tool forces the abrasive grits, in the gap between the tool and the workpiece, to impact normally and successively on the work surface, thereby machining the work surface.
Principle of Ultrasonic Machining

This is the standard mechanism used in most of the universal Ultrasonic machines

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Principle of Ultrasonic Machining

• During one strike, the tool moves down from its most upper remote position with a starting speed at zero, then it speeds up to finally reach the maximum speed at the mean position.
• Then the tool slows down its speed and eventually reaches zero again at the lowest position.
• When the grit size is close to the mean position, the tool hits the grit with its full speed.
• The smaller the grit size, the lesser the momentum it receives from the tool.
• Therefore, there is an effective speed zone for the tool and, correspondingly there is an effective size range for the grits.
• In the machining process, the tool, at some point, impacts on the largest grits, which are forced into the tool and workpiece.
• As the tool continues to move downwards, the force acting on these grits increases rapidly, therefore some of the grits may be fractured.
• As the tool moves further down, more grits with smaller sizes come in contact with the tool, the force acting on each grit becomes less.
• Eventually, the tool comes to the end of its strike, the number of grits under impact force from both the tool and the workpiece becomes maximum.
• Grits with size larger than the minimum gap will penetrate into the tool and work surface to different extents according to their diameters and the hardness of both surfaces.
Various work samples machined by USM

A plastic sample that has inner grooves that are machined using USM

A plastic sample that has complex details on the surface

A coin with the grooving done by USM
Mechanism

Abraasive Slurry

• The abrasive slurry contains fine abrasive grains. The grains are usually boron carbide, aluminum oxide, or silicon carbide ranging in grain size from 100 for roughing to 1000 for finishing.

• It is used to microchip or erode the work piece surface and it is also used to carry debris away from the cutting area.
Mechanism

Tool holder

- The shape of the tool holder is cylindrical or conical, or a modified cone which helps in magnifying the tool tip vibrations.
- In order to reduce the fatigue failures, it should be free from nicks, scratches and tool marks and polished smooth.
Mechanism

Tool

• Tool material should be tough and ductile. Low carbon steels and stainless steels give good performance.
• Tools are usually 25 mm long; its size is equal to the hole size minus twice the size of abrasives.
• Mass of tool should be minimum possible so that it does not absorb the ultrasonic energy.
Applications

It is mainly used for

- Drilling
- Grinding,
- Profiling
- Coining
- Piercing of dies
Advantages of USM

- Machining any materials regardless of their conductivity
- USM apply to machining semi-conductor such as silicon, germanium etc.
- USM is suitable to precise machining brittle material.
- USM does not produce electric, thermal, chemical abnormal surface.
- Can drill circular or non-circular holes in very hard materials
- Less stress because of its non-thermal characteristics
Disadvantages of USM

- USM has low material removal rate.
- Tool wears fast in USM.
- Machining area and depth is restraint in USM.
## USM Characteristics

<table>
<thead>
<tr>
<th>Principle</th>
<th>Oscillating tool in water-Abrasive slurry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrasive</td>
<td>B4C, Al2O3, SiC</td>
</tr>
<tr>
<td></td>
<td>100 to 800 grit size</td>
</tr>
<tr>
<td>Frequency</td>
<td>15-30KHz</td>
</tr>
<tr>
<td>Amplitude</td>
<td>0.03 to 0.10mm</td>
</tr>
<tr>
<td>Tool material</td>
<td>Soft tool steel</td>
</tr>
<tr>
<td>Stock removal</td>
<td>WC=1.5in (38mm)</td>
</tr>
<tr>
<td></td>
<td>Glass=100in (254cm)</td>
</tr>
<tr>
<td>Critical parameters</td>
<td>Frequency, amplitude, tool holder shape, grit size, hole depth, slurry</td>
</tr>
<tr>
<td>Material application</td>
<td>Metals and alloys (particularly hard metals)</td>
</tr>
<tr>
<td></td>
<td>Non-metallic</td>
</tr>
<tr>
<td>Part applications</td>
<td>Round and irregular holes</td>
</tr>
<tr>
<td>Limitations</td>
<td>Low metal removal rate</td>
</tr>
<tr>
<td></td>
<td>Tool wear</td>
</tr>
<tr>
<td></td>
<td>Hole depth</td>
</tr>
</tbody>
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Water Jet Machining

• Also known as hydrodynamic machining
• The water jet acts as a saw and cuts a narrow groove in the material
• Pressures range from 60ksi to 200ksi (1500-4000 MN/m²)
• Jet velocity > 900m/s
Water Jet Machining

(a) Schematic illustration of water-jet machining. (b) A computer-controlled, water-jet cutting machine cutting a granite plate. (c) Example of various nonmetallic parts produced by the water-jet cutting process.
Water Jet Machining

• Process capabilities
  – Can be used on any material up to 1” thick
  – Cuts can be started at any location without predrilled holes
  – No heat produced
  – No flex to the material being cut
    • Suitable for flexible materials
  – Little wetting of the workpiece
  – Little to no burr produced
  – Environmentally safe
Pros and Cons

• Pros:
  – No work hardening of pieces
  – Faster than EDM or Laser
  – Initial cost is less

• Cons:
  – Accuracy is poor (0.003 inch)
  – Nozzle life is short (40 hours)
Abrasive Jet Machining

- Uses high velocity dry air, nitrogen, or carbon dioxide containing abrasive particles
- Supply pressure is on the order of 125psi
- The abrasive jet velocity can be as high as 100 ft/sec
- Abrasive size is approximately 400-2000 micro-inches
Abrasive Jet Machining

Schematic illustration of Abrasive Jet Machining

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Abrasive Water Jet Machining

- Very similar to water jet machining
  - Water contains abrasive material
    - Silicon carbide
    - Aluminum oxide
  - Higher cutting speed than that of conventional water jet machining
    - Up to 25 ft/min (7.5 m/min) for reinforce plastics
  - Minimum hole diameter thus far is approximately 0.12 inches (3 mm)
  - Maximum hole depth is approximately 1 inch (25 mm)
Chemical Process

Chemical machining

– Uses chemical dissolution to dissolve material from the workpiece.
– Can be used on stones, most metals and some ceramics.
– Oldest of the advanced machining processes.
(a) Missile skin-panel section contoured by chemical milling to improve the stiffness-to weight ratio of the part.

(b) Weight reduction of space launch vehicles by chemical milling aluminum-alloy plates.

These panels are chemically milled after the plates have first been formed into shape by processes such as roll forming or stretch forming. The design of the chemically machined rib patterns can be modified readily at minimal cost.
Chemical milling

• Chemical milling - shallow cavities are produced on plates, sheets, forgings, and extrusions, generally for the overall reduction of weight.
  – Can be used with depths of metal removal as large as 12 mm.
  – Masking is used to protect areas that are not meant to be attacked by the chemical.
(a) Schematic illustration of the chemical machining process. Note that no forces or machine tools are involved in this process.
(b) Stages in producing a profiled cavity by machining; not the undercut.
Chemical Blanking

• Similar to the blanking of sheet metals with the exception that the material is removed by chemical dissolution rather than by shearing.
  – Printed circuit boards.
  – Decorative panels.
  – Thin sheet-metal stampings.
  – Complex or small shapes.
# Surface Roughness and Tolerance Table

## Surface Roughness ($R_a$ $\mu$m)

<table>
<thead>
<tr>
<th>Surface Roughness ($R_a$ $\mu$m)</th>
<th>2000</th>
<th>500</th>
<th>125</th>
<th>32</th>
<th>8</th>
<th>2</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000</td>
<td>250</td>
<td>63</td>
<td>16</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

### Mechanicale
- Abrasive-flow machining
- Low-stress grinding
- Ultrasonic machining

### Electrical
- Electrochemical deburring
- Electrochemical grinding
- Electrochemical milling (frontal)
- Electrochemical milling (side wall)
- Electrochemical polishing
- Shaped tube electrolytic machining

### Thermal
- Electron-beam machining
- Electrical-discharge grinding
- Electrical-discharge machining (finishing)
- Electrical-discharge machining (roughing)
- Laser-beam machining
- Plasma-beam machining

### Chemical
- Chemical machining
- Photochemical machining
- Electropolishing

### Conventional Machining
- Turning
- Surface grinding

## Tolerance, $\pm 0.001$ in.

<table>
<thead>
<tr>
<th>Tolerance, $\pm$ $\text{mm} \times 10^{-3}$</th>
<th>100</th>
<th>50</th>
<th>20</th>
<th>10</th>
<th>5</th>
<th>2</th>
<th>1</th>
<th>0.5</th>
<th>0.2</th>
<th>0.1</th>
<th>0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2500</td>
<td>1250</td>
<td>500</td>
<td>250</td>
<td>125</td>
<td>50</td>
<td>25</td>
<td>12.5</td>
<td>5</td>
<td>2.5</td>
<td>1.25</td>
</tr>
</tbody>
</table>

### Notes:
- (a) Depends on state of starting surface.
- (b) Titanium alloys are generally rougher than nickel alloys.
- (c) High current density areas.
- (d) Low current density areas.

- **Black**: Average application (normally anticipated values)
- **Light Grey**: Less frequent application (unusual or precision conditions)
- **White**: Rare (special operating conditions)
• Photochemical blanking/machining
  – Modification of chemical milling.
  – Can be used on metals as thin as .0025 mm.

• Applications
  – Fine screens.
  – Printed circuit boards.
  – Electric-motor laminations.
  – Flat springs.
  – Masks for color televisions

(i) Clean    (ii) Apply resist    (iii) UV exposure    (iv) Development    (v) Etching    (v) Stripping
Chemical Machining Design Considerations

• No sharp corners, deep or narrow cavities, severe tapers, folded seam, or porous workpiece materials.
• Undercuts may develop.
• The bulk of the workpiece should be shaped by other processes prior to chemical machining.
Electrical processes
Electrochemical Machining

• An electrolyte acts as a current carrier which washes metal ions away from the workpiece (anode) before they have a chance to plate on the tool (cathode).
• The shaped tool is either solid or tubular.
• Generally made of brass, copper, bronze or stainless steel.
• The electrolyte is a highly conductive inorganic fluid.
• The cavity produced is the female mating image of the tool shape.
$V = CIT$  \\
$R = \frac{gr}{A}$  \\
$I = \frac{EA}{gr}$  \\
$V = \frac{C(EA\tau)}{gr}$  \\
$\frac{V}{At} = f_r = \frac{CE}{gr}$  \\
$f_r = \frac{CI}{A}$

$V$: Volume of Metal Removed; $C$: Specific Removal Rate  
$R$: Resistance; $g$: Gap between Electrode and Work  
$r$: Resistivity of Electrode; $E$: Applied Voltage  
$I$: Current; $t$: Time; $f_r$: Feed Rate
Electrochemical Machining

• Process capabilities
  – Generally used to machine complex cavities and shapes in high strength materials.

• Design considerations
  – Not suited for producing sharp square corners or flat bottoms.
  – No irregular cavities.
Typical parts made by electrochemical machining. (a) Turbine blade made of a nickel alloy, 360 HB; note the shape of the electrode on the right. (b) Thin slots on a 4340-steel roller-bearing cage. (c) Integral airfoils on a compressor disk.
• **Pulsed electrochemical machining (PECM)**
  – Refinement of ECM.
  – The current is pulsed instead of a direct current.
  – Lower electrolyte flow rate.
  – Improves fatigue life.
  – Tolerance obtained 20 to 100 micro-meters.

(a) Two total knee replacement systems showing metal implants (top pieces) with an ultrahigh molecular weight polyethylene insert (bottom pieces) (b) Cross-section of the ECM process as applied to the metal implant.
**Electrochemical grinding (ECG)**

- Combines ECM with conventional grinding.
- Similar to a conventional grinder, except that the wheel is a rotating cathode with abrasive particles.
  - The abrasive particles serve as insulators and they remove electrolytic products from the working area.
- Less then 5% of the metal is removed by the abrasive action of the wheel.

*Schematic illustration of the electrochemical – grinding process. (b) Thin slot produced on a round nickel – alloy tube by this process.*
• Electrochemical honing
  – Combines the fine abrasive action of honing with electrochemical action.
  – Costs more than conventional honing.
  – 5 times faster than conventional honing.
  – The tool lasts up to 10 times longer.

• Design considerations for ECG
  – Avoid sharp inside radii.
Thermal processes
Electric Discharge Machining (EDM)

• Principle of operation
  – Based on the erosion of metal by spark discharge

• Components of operation
  – Shaped tool
    • Electrode
  – Workpiece
    • Connected to a DC power supply
  – Dielectric
    • Nonconductive fluid
(a) Schematic illustration of the electrical-discharge machining process. This is one of the most widely used machining processes, particularly for die-sinking operations.

(b) Examples of cavities produced by the electrical-discharge machining process, using shaped electrodes. Two round parts (rear) are the set of dies for extruding the aluminum the aluminum piece shown in front.

(c) A spiral cavity produced by ECM using a slowly rotating electrode, similar to a screw thread.
Electric Discharge Machining

• When the potential difference is sufficiently high, the dielectric breaks down and a transient spark discharges through the fluid, removing a very small amount of material from the workpiece

• Capacitor discharge
  – 200-500 kHz

• This process can be used on any electrically conductive material
Electric Discharge Machining

Example

A certain alloy whose melting point = 1100 °C is to be machined in an EDM operation. If discharged current = 25 amps, what is the expected metal removal rate?

Use Equation \( MRR = \frac{KI}{T_m^{1.23}} \), the anticipated metal removal rate is \( MRR = 664 \frac{(25)}{(1100^{1.23})} = 3.01 \text{ mm}^3/\text{s} \)

\[
    MRR = \frac{KI}{T^{1.23}}
\]
Electric Discharge Machining

• Movement in the X&Y axis is controlled by CNC systems
• Overcut (in the Z axis) is the gap between the electrode and the workpiece
  – Controlled by servomechanisms
  – Critical to maintain a constant gap
Electric Discharge Machining

• **Dielectric fluids**
  – Act as a dielectric
  – Provide a cooling medium
  – Provide a flushing medium

• **Common fluids**
  – Mineral oils
  – Distilled/Deionized water
  – Kerosene
  – Other clear low viscosity fluids are available which are easier to clean but more expensive
Electric Discharge Machining

• Electrodes
  – Graphite
  – Brass
  – Copper-tungsten alloys
  – Formed by casting, powder metallurgy, or CNC machining
  – On right, human hair with a 0.0012 inch hole drilled through
Electric Discharge Machining

• Electrode wear
  – Important factor in maintaining the gap between the electrode and the workpiece
  – Wear ratio is defined as the amount of material removed to the volume of electrode wear
    • 3:1 to 100:1 is typical
  – No-wear EDM is defined as the EDM process with reversed polarity using copper electrodes
Electric Discharge Machining

• Process capabilities
  – Used in the forming of dies for forging, extrusion, die casting, and injection molding
  – Typically intricate shapes
Electric Discharge Machining

• Material removal rates affect finish quality
  – High removal rates produce very rough surface finish with poor surface integrity
  – Finishing cuts are often made at low removal rates so surface finish can be improved

• Design considerations
  – Design so that electrodes can be simple/economical to produce
  – Deep slots and narrow openings should be avoided
  – Conventional techniques should be used to remove the bulk of material
Examples of EDM

Stepped cavities produced with a square electrode by the EDM process. The workpiece moves in the two principal horizontal directions (x-y), and its motion is synchronized with the downward movement of the electrode to produce these cavities. Also shown is a round electrode capable of producing round or elliptical cavities.

Schematic illustration of producing an inner cavity by EDM, using a specially designed electrode with a hinged tip, which is slowly opened and rotated to produce the large cavity.
Wire EDM

- Similar to contour cutting with a bandsaw
- Typically used to cut thicker material
  - Up to 12” thick
  - Also used to make punches, tools and dies from hard materials

Schematic illustration of the wire EDM process.
As much as 50 hours of machining can be performed with one reel of wire, which is then discarded.
Wire EDM

• Wire
  – Usually made of brass, copper, or tungsten
  – Range in diameter from 0.012 – 0.008 inches
  – Typically used at 60% of tensile strength
  – Used once since it is relatively inexpensive
  – Travels at a constant velocity ranging from 6-360 in/min
  – Cutting speed is measured in cross sectional area per unit time (varies with material)
    • 18,000 mm^2/hour
    • 28 in^2/hour
Wire EDM

• Multiaxis EDM
  – Computer controls for controlling the cutting path of the wire and its angle with respect to the workpiece plane
  – Multiheads for cutting multiple parts
  – Features to prevent and correct wire breakage
  – Programming to optimize the operation
Electric Discharge Grinding

• Similar to the standard grinder
• Grinding wheel is made of graphite or brass and contains no abrasives
• Material is removed by spark discharge between the workpiece and rotating wheel
• Typically used to sharpen carbide tools and dies
• Can also be used on fragile parts such as surgical needles, thin-wall tubes, and honeycomb structures
• Process can be combined with electrochemical discharge grinding
• Material removal rate is similar to that of EDM
  – \[ \text{MRR} = K I \] where \( K \) is the workpiece material factor in \( \text{mm}^3/A\text{-min} \)
Laser Beam Machining

• The source of the energy is the laser
  – Light Amplification by Stimulated Emission of Radiation

• The focus of optical energy on the surface of the workpiece melts and evaporates portions of the workpiece in a controlled manner
  – Works on both metallic and non-metallic materials

• Important considerations include the reflectivity and thermal conductivity of the material

• The lower these quantities the more efficient the process
• The cutting depth can be calculated using the formula \( t = \frac{CP}{vd} \) where
  - \( t \) is the depth
  - \( C \) is a constant for the process
  - \( P \) is the power input
  - \( v \) is the cutting speed
  - \( d \) is the laser spot diameter

• The surface produced is usually rough and has a heat affected zone.

(a) Schematic illustration of the laser-beam machining process. (b) and (c) Examples of holes produced in nonmetallic parts by LBM.
Laser Beam Machining

- Lasers may be used in conjunction with a gas such as oxygen, nitrogen, or argon to aid in energy absorption
  - Commonly referred to as laser beam torches
  - The gas helps blow away molten and vaporized material
- Process capabilities also include welding, localized heat treating, and marking
- Very flexible process
  - Fiber optic beam delivery
  - Simple fixtures
  - Low setup times
Laser Beam Machining

• Design considerations
  – Sharp corners should be avoided
  – Deep cuts will produce tapered walls
  – Reflectivity is an important consideration
    • Dull and unpolished surfaces are preferable
  – Any adverse effects on the properties of the machined materials caused by the high local temperatures and heat affected zones should be investigated
Electron Beam Machining

- Energy source is high velocity electrons which strike the workpiece
- Voltages range from 50-200kV
- Electron speeds range from 50-80% the speed of light
- Requires vacuum
Electron Beam Machining

Schematic illustration of the electron-beam machining process. Unlike LBM, this process requires a vacuum, so workpiece size is limited to the size is limited to the size of the vacuum chamber.
Plasma Arc cutting

- Ionized gas is used to rapidly cut ferrous and nonferrous sheets and plates
- Temperatures range from 9400-17,000 F (> 10000°C)
- The process is fast, the kerf width is small, and the surface finish is good
- Parts as thick as 6” can be cut
- Much faster than the EDM and LBM process
- Design considerations
  - Parts must fit in vacuum chamber
  - Parts that only require EBM machining on a small portion should be manufactured as a number of smaller components
Laser cutting

Light Amplification by Stimulated Emission of Radiation

- High energy density (small focus area)
- Uses: Cutting, welding, precision holes
- Common lasers: CO$_2$, Nd:YAG
- Continuous power or Pulsed (more precise)
Cost of Machining/Surface Finish Required

Increase in the cost of machining and finishing a part as a function of the surface finish required.
Summary

• Material removal processes have been classified based on principle of operation
• A Review of conventional machining operations has been done
• Non traditional processing has been classified depending on the source of energy such as mechanical, electrical, chemical and thermal energy.
• Advanced machining processes have been discussed with respect to process principles, parameters, application examples
• The economic production run for a particular process depends on the costs of tooling, equipment, operating costs, material removal rate required, level of operator skill required, and necessary secondary and finishing operations