Manufacturing Engineering - III

DI05019011

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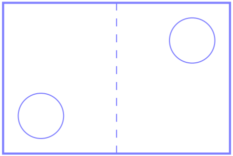
Course: Manufacturing Engineering - III (DI05019011)

Unit 1: Production Tooling: Jigs, Fixtures & Press Tools

Lecture 1: Need for Jigs and Fixtures - Part 1

Agenda

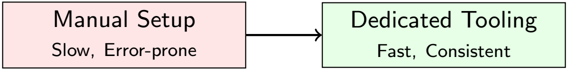
- Introduction to Production Tooling
- What are Jigs?
- What are Fixtures?
- Key Differences Between Jigs and Fixtures
- Basic Elements of Jigs and Fixtures
- Summary & Q&A



Blueprint

Introduction to Production Tooling

- Mass production requires high precision, consistency, and speed.
- Manual alignment and clamping of workpieces are time-consuming.
- Production tooling refers to the specialized tools designed to facilitate manufacturing operations.
- Primary goal: Maximize productivity while maintaining quality and minimizing costs.
- Includes jigs, fixtures, press tools, dies, gauges, and molds.

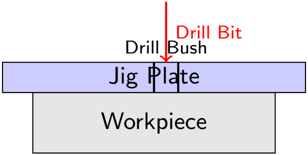


Challenges in Conventional Machining

- Marking out the workpiece is required for each part.
- Positioning the tool accurately relative to the workpiece is manual and error-prone.
- Clamping relies on standard vices or clamps which may not hold complex shapes securely.
- Requires highly skilled labor for setup and operation.
- High cycle time per part, leading to higher unit costs.

What is a Jig?

- A jig is a custom-made tool used to control the location and/or motion of another tool.
- Primary function: Holds, supports, and locates the workpiece and GUIDES the cutting tool.
- Used primarily in drilling, reaming, tapping, and boring operations.
- Eliminates the need for marking out and center punching.
- Ensures interchangeability and high accuracy of parts.



Key Features of a Jig

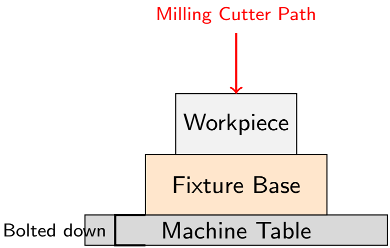
- Typically lighter in construction compared to fixtures.
- Not always secured to the machine table (can be hand-held for small drilling jobs).
- Contains guide bushes (e.g., drill bushes) for the cutting tools.
- Reduces operator skill requirements.
- Significantly speeds up multi-hole drilling operations.

Jig Advantage

By providing direct guidance for the tool, jigs make complex operations much more repeatable without marking out.

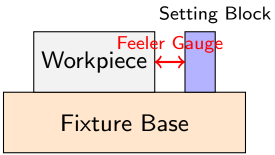
What is a Fixture?

- A fixture is a production tool that securely locates and supports the workpiece.
- Primary function: Holds the part firmly in a specific orientation during machining.
- DOES NOT guide the cutting tool. Tool movement is controlled by the machine.
- Used in milling, turning, grinding, welding, and assembly operations.
- Often heavier in construction to withstand cutting forces.



Key Features of a Fixture

- Must be securely fastened to the machine table (e.g., using T-slots).
- Includes locating pins/blocks to ensure precise positioning.
- Requires setting blocks or feeler gauges to establish the initial tool position.
- Designed to withstand heavy dynamic cutting forces.
- Enables faster loading and unloading of workpieces.



Jigs vs. Fixtures: A Comparison

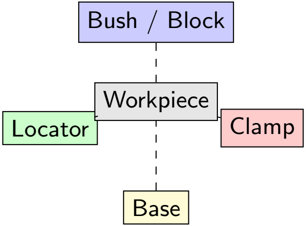
Feature	Jigs	Fixtures
Function	Holds part & guides tool	Holds part only
Application	Drilling, reaming, tapping	Milling, turning, grinding, welding
Weight/Build	Generally lighter	Heavier and more rigid
Machine attachment	May be free-standing	Must be bolted to machine table
Tool setting	Uses guide bushes	Uses setting blocks/gauges

Core Difference

Jigs **guide** the tool; Fixtures **hold** the work.

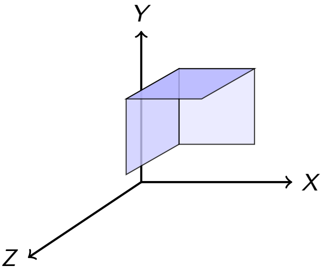
Fundamental Elements of Jigs and Fixtures

- Regardless of type, they consist of similar basic elements:
- **1. Locating Elements:** Position the workpiece accurately.
- **2. Clamping Elements:** Hold the workpiece securely against cutting forces.
- **3. Tool Guiding/Setting Elements:** Bushes (jigs) or setting blocks (fixtures).
- **4. Body/Base (Tool Frame):** The main structure holding everything together.
- **5. Fastening/Positioning Elements:** Keys and bolts to secure to machine table.



The Principle of Location

- Location ensures the workpiece is positioned exactly the same way every time.
- Must restrict the workpiece's movement in space.
- Relies on establishing reference surfaces (datum planes) on the workpiece.
- Improper location leads to dimensional inaccuracies and rejected parts.
- We will discuss degrees of freedom and location principles in detail in Lecture 3.

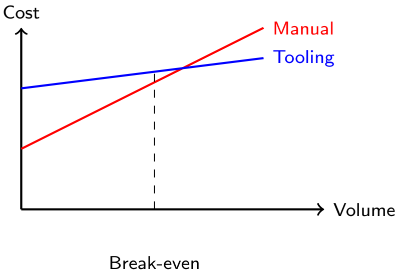


Summary

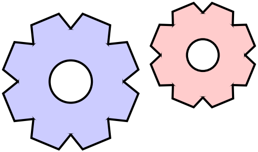
- Production tooling is essential for efficient mass production.
- Jigs hold the part and guide the cutting tool (mainly for drilling operations).
- Fixtures hold the part securely but do not guide the tool (mainly for milling/turning).
- Both require locators, clamps, and a solid base structure.
- They eliminate marking out and reduce reliance on highly skilled operators.

Lecture 2: Need for Jigs and Fixtures - Part 2

- The economics of using jigs and fixtures
- Detailed advantages and disadvantages
- Fundamental design principles to consider when designing a jig or fixture



Need for Jigs and Fixtures - Part 2

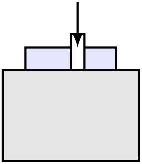


Lecture Info

- Course: Manufacturing Engineering - III (DI05019011)
- Unit 1: Production Tooling: Jigs, Fixtures & Press Tools
- Lecture 2: Economics and Advantages of Jigs & Fixtures

Recap of Lecture 1

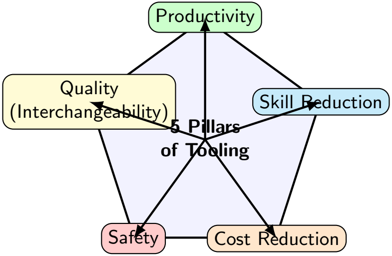
Jig (Guides Tool)



Fixture (Holds Workpiece)

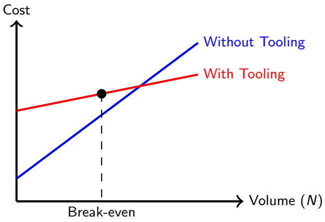
- Jig: Holds the workpiece and guides the cutting tool (e.g., Drill jig).
- Fixture: Securely holds the workpiece; tool is guided by the machine (e.g., Milling fixture).
- Both eliminate manual marking out.
- Both require locators, clamps, and a solid base.

Why Use Jigs and Fixtures? (The 'Need')



- **Productivity**: Reduces idle time by speeding up loading/unloading.
- **Interchangeability**: Ensures all parts are identical within tolerances.
- **Skill Reduction**: Semi-skilled operators can produce high-quality work.
- **Cost Reduction**: Lowers per-unit manufacturing cost in mass production.
- **Safety**: Secure clamping prevents accidents.

Economic Justification



- Jigs/fixtures require initial capital investment.
- Cost recovered through savings in time and labor.
- **Break-even Point**: Production volume where tooling cost equals savings.
- High volume = high tooling investment justified; Low volume = minimal tooling.

Cost Analysis Factors

Total Unit Cost Formula

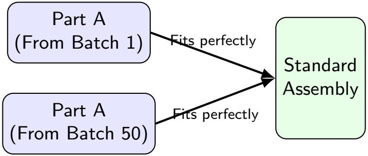
$$\text{Total Unit Cost} = \left(\frac{C_t}{N}\right) + C_u$$

Where C_t = Total Tooling Cost, N = Number of parts, C_u = Unit Machining Cost.

- Cost of the jig/fixture (Design, materials, fabrication).
- Setup cost (Time to mount the tool on the machine).
- Machining cost per part.
- Labor rate (skilled vs. unskilled).
- Overhead costs.

Goal: Minimize total cost as N increases (tooling cost per part becomes negligible).

Advantage: Interchangeability



- **Definition**: Parts are manufactured so precisely that any part can replace another in an assembly without custom fitting.
- Jigs and fixtures guarantee that holes, slots, and faces are in the exact same position on every part.
- Crucial for modern assembly lines (e.g., automotive manufacturing).
- Reduces assembly time and eliminates 'fitting' work.

Advantage: Skill Reduction

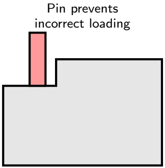
Conventional Machining	Machining with Jigs/Fixtures
Requires a skilled machinist	Operator pushes a button
Measure, mark, align, and cut	Load, clamp, run cycle, unload
Operator dictates accuracy	Tool dictates accuracy
High hourly wages	Semi-skilled labor (lower wages)
Higher chance of human error	Reduced human error & scrap rates

Key Concept

By embedding the 'skill' and accuracy into the hard steel of the fixture, we remove the burden of accuracy from the human operator.

Fundamental Design Principles (Preview)

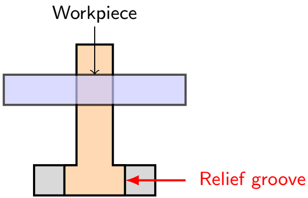
Foolproofing Principle



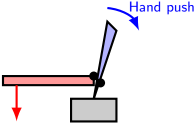
When designing a jig or fixture, engineers must consider:

1. **Rigidity and Stability**: Must absorb cutting vibrations.
2. **Foolproofing**: The part should only fit in the CORRECT orientation.
3. **Clearance**: Allow space for chips to escape and for cleaning.
4. **Clamping Force**: Must oppose cutting forces, but not distort the workpiece.

Design Principles: Chip Clearance



- Machining generates chips (swarf) and uses coolant.
- If chips accumulate on locating surfaces, the part will not seat correctly.
- Leads to dimensional errors in the machined part.
- Design must include **relief grooves**, angled surfaces, and open spaces for chips to wash away.
- Makes cleaning between cycles fast and efficient.



- Operator fatigue leads to mistakes and accidents.
- Clamps should be quick-acting (e.g., toggle clamps, pneumatics).
- Loading and unloading should not require heavy lifting or awkward angles.
- Sharp edges on the fixture should be chamfered.
- All moving parts should be guarded or safely positioned.

Applications across Industries

Industry	Typical Applications of Jigs & Fixtures
Automotive	Engine block machining, chassis welding fixtures.
Aerospace	Assembly fixtures for fuselage panels, precise drilling jigs.
Electronics	PCB testing fixtures, automated assembly nests.
Consumer Goods	Molds and holding fixtures for plastic parts.

Universal Rule

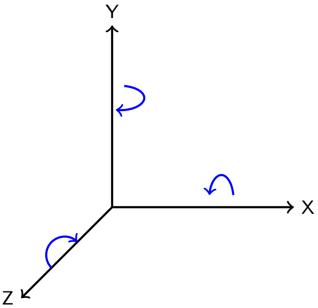
Any industry producing identical parts in large quantities relies on jigs and fixtures.

Summary

Key Takeaways

- Jigs and fixtures are essential for economic mass production.
- They justify their upfront cost by reducing machining time and labor costs.
- Key benefits: Interchangeability, quality control, skill reduction, and safety.
- Good design requires foolproofing, rigidity, chip clearance, and quick clamping.

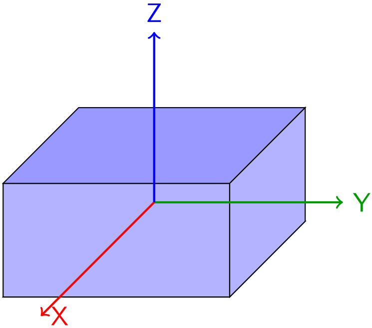
Next Lecture Preview



Lecture 3: Degrees of Freedom and 3-2-1 Location Principle

- Understanding how a workpiece moves in 3D space (12 degrees of freedom).
- How to mathematically restrict all movement.
- The fundamental **3-2-1 rule** used in all fixture design.

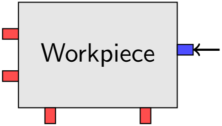
Degrees of Freedom & 3-2-1 Location



- Course: Manufacturing Engineering - III (DI05019011)
- Unit 1: Production Tooling: Jigs, Fixtures & Press Tools
- Lecture 3: Degrees of Freedom and 3-2-1 Location Principle

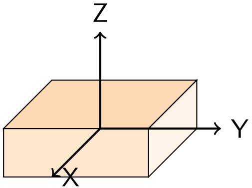
What is 'Location'?

- Location is the process of establishing a precise, reference relationship between the workpiece and the jig/fixture.
- It ensures that every part loaded into the tool is in the exact same physical space.
- Without proper location, accurate machining is impossible.
- The goal of location is to restrict the movement of the workpiece in all necessary directions.



Concept of a Rigid Body in Space

- Imagine a solid block suspended in mid-air.
- It can move in various directions.
- To define its movement, we use the Cartesian coordinate system (X, Y, Z axes).
- The block can **translate** (move in a straight line) along these axes.
- The block can **rotate** (spin) around these axes.

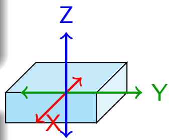


The 12 Degrees of Freedom (DOF)

A rigid body has 6 basic movements, but 12 directional degrees of freedom:

Translation (Linear Movement) - 6 DOF:

1, 2: Positive & Negative along X-axis (+X, -X)
3, 4: Positive & Negative along Y-axis (+Y, -Y)
5, 6: Positive & Negative along Z-axis (+Z, -Z)

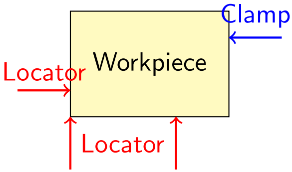


Rotation (Rotary Movement) - 6 DOF:

7, 8: Clockwise & Counter-clockwise around X-axis
9, 10: Clockwise & Counter-clockwise around Y-axis
11, 12: Clockwise & Counter-clockwise around Z-axis

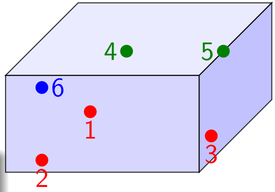
Arresting Degrees of Freedom

- To properly locate a workpiece, we must restrict 9 of these 12 degrees of freedom using locators (pins, pads).
- The remaining 3 degrees of freedom are restricted by the Clamping devices.
- Locators establish the physical boundaries.
- Clamps push the workpiece firmly against these locators.
- If a workpiece is perfectly located, it cannot move or rotate unless unclamped.



The 3-2-1 Principle of Location

- The most widely used method to constrain a prismatic (box-like) part.
- Also known as the Six-Point Location principle.
- It uses 6 locator points to arrest 9 degrees of freedom.



Rule:

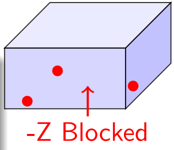
- **3 points** on the Primary Datum plane.
- **2 points** on the Secondary Datum plane.
- **1 point** on the Tertiary Datum plane.

Step 1: The '3' (Primary Location)

- Three locating points (pins) are placed on the largest flat surface (Primary Datum).
- Let's say this is the XY plane (bottom of the block).

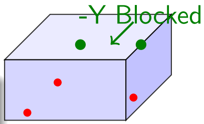
Restricts 5 Degrees of Freedom:

- Linear movement downward (-Z direction).
- Rotation CW around X-axis.
- Rotation CCW around X-axis.
- Rotation CW around Y-axis.
- Rotation CCW around Y-axis.



Step 2: The '2' (Secondary Location)

- Two locating points are placed on the second largest surface, perpendicular to the primary (Secondary Datum).
- Let's say this is the XZ plane (long side of the block).

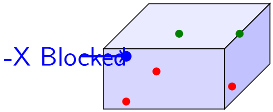


Restricts 3 additional Degrees of Freedom:

- Linear movement backwards (-Y direction).
- Rotation CW around Z-axis.
- Rotation CCW around Z-axis.

Step 3: The '1' (Tertiary Location)

- One locating point is placed on a third surface, perpendicular to both primary and secondary (Tertiary Datum).
- Let's say this is the YZ plane (short end of the block).



Restricts 1 additional Degree of Freedom:

- Linear movement sideways (-X direction).

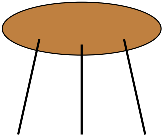
Summary of Restricted DOFs (3-2-1)

Location Plane	**Degrees of Freedom Arrested**	**Total DOF**
Primary (3 points)	1 Translation (-Z) & 4 Rotations (±RotX, ±RotY)	5
Secondary (2 points)	1 Translation (-Y) & 2 Rotations (±RotZ)	3
Tertiary (1 point)	1 Translation (-X)	1
Total Arrested by Locators		**9**

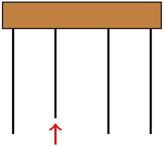
The remaining 3 DOF (+X, +Y, +Z translations) must be opposed by **CLAMPS**.

Why 3 points on the base, not 4?

- **Geometry:** Three points mathematically define a single, distinct plane.
- **Stability:** A three-legged stool never wobbles, even on an uneven surface.
- Four points can cause rocking if the workpiece surface is rough or uneven (hyper-constraint).
- If a 4th support is needed for rigidity under cutting forces, it must be an **ADJUSTABLE** support (e.g., a screw jack), not a fixed locator.



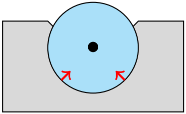
Stable (3 legs)



Wobbly (4 legs)

Cylindrical Part Location (V-Blocks)

- The 3-2-1 rule strictly applies to rectangular/prismatic parts.
- Cylindrical parts (shafts) use different location methods.
- A V-block is typically used for cylinders.
- A single V-block provides 4 points of contact, restricting 4 DOF (2 translations, 2 rotations).
- A stop pin at the end restricts axial movement.



Front View

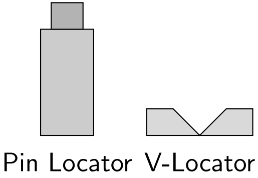
Summary

Key Takeaways

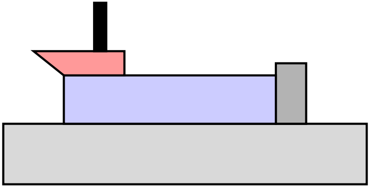
- A free body has 12 directional degrees of freedom in space.
- Proper location arrests 9 of these DOFs; clamps secure the remaining 3.
- The 3-2-1 principle uses 6 locators on 3 mutually perpendicular planes.
- Primary (3 pins), Secondary (2 pins), Tertiary (1 pin).
- It prevents rocking and ensures repeatable part placement.

Next Lecture Preview

- **Lecture 4: Locators and Clamps**
- Practical hardware used to achieve the 3-2-1 location.
- Types of locators: Pin, button, V-locator, nest locator.
- Types of clamps: Strap clamp, C-clamp, and clamping principles.



Locators and Clamps

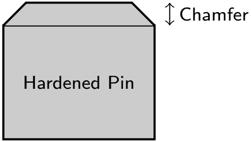


A conceptual setup of Locators and Clamps

- Course: Manufacturing Engineering - III (DI05019011)
- Unit 1: Production Tooling: Jigs, Fixtures & Press Tools
- Lecture 4: Locators and Clamps

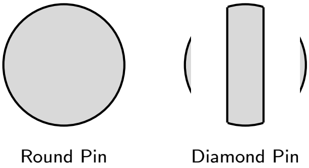
Function of Locators

- Physical components used to correctly orient the workpiece in the jig/fixture.
- They execute the 3-2-1 principle in practice.
- Must be highly wear-resistant (usually made of hardened steel).
- Must facilitate easy loading and unloading (chamfered edges).
- Must not allow chip accumulation (chip clearance).



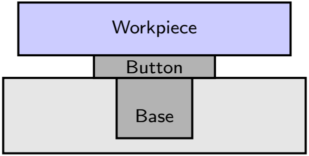
Types of Locators: Pin Locators

- Most common type for internal location (locating from pre-machined holes).
- Cylindrical pins used to locate a part using a previously drilled hole.
- Two pins are often used to locate a part fully: one full cylinder pin, one diamond pin.
- Why a diamond pin? It prevents binding and compensates for center-distance variations between holes.



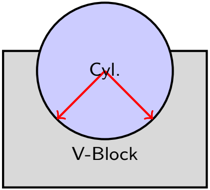
Types of Locators: Button Locators

- Used for external location on flat surfaces.
- Essentially short, flat-headed pins pressed into the fixture base.
- Act as the '3', '2', or '1' resting points in the 3-2-1 principle.
- Provide a small contact area to minimize the risk of chips getting trapped under the workpiece.
- Often replaceable when worn out.



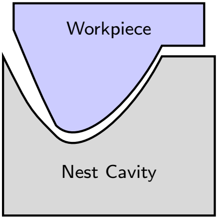
Types of Locators: V-Locators

- Specifically designed for locating cylindrical or spherical workpieces.
- Centralizes the workpiece automatically.
- Can be fixed or sliding.
- A single V-block restrains 4 degrees of freedom.
- Usually has a 90-degree internal angle.



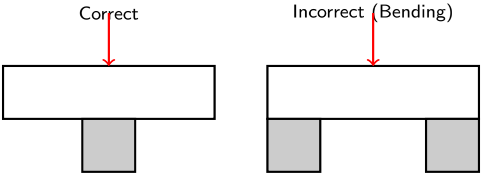
Types of Locators: Nest Locators

- A cavity machined into the fixture base that exactly matches the shape of the workpiece contour.
- Used for complex, irregular shaped parts (e.g., castings, forgings).
- Part is simply dropped into the 'nest'.
- Disadvantage: Extremely prone to chip accumulation and hard to clean.
- Used only when standard pin/button locators are impossible to use.



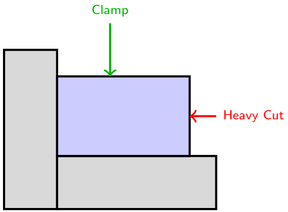
Introduction to Clamping

- Clamping is applying a force to hold the workpiece securely against the locators.
- Resists cutting forces and vibrations during machining.
- Must NOT distort or damage the workpiece.
- Must be quick to operate to minimize non-productive time.
- Should be applied directly opposite to a locator (supported area) to prevent bending.



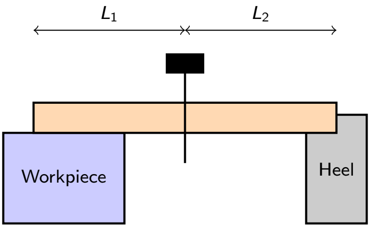
Basic Principles of Clamping

1. **Position**: Clamp should be positioned over the most rigid part of the workpiece.
2. **Direction**: Clamping force should direct the part against the locators, not away.
3. **Cutting Force**: The fixture should be designed so that the heavy cutting forces push the part INTO the solid locators, not against the clamps.
4. Clamps are for holding, not for resisting the primary cutting forces.



Types of Clamps: Strap Clamp

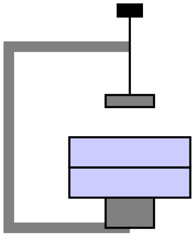
- The simplest and most common type of clamp. Acts as a lever.
- Components: The strap (bar), a T-bolt/nut (applies force), and a heel block (fulcrum).
- Mechanical Advantage: Position the bolt as close to the workpiece as possible for maximum force.
- Classifications: 1st, 2nd, or 3rd class lever arrangements.



To maximize clamping force, L_1 should be less than L_2.

Types of Clamps: C-Clamp

- A simple, portable clamping device shaped like a 'C'.
- Uses a screw mechanism to apply clamping force.
- Usually not permanently attached to the fixture.
- Advantage: Versatile and can accommodate varying sizes.
- Disadvantage: Very slow to operate (requires winding the screw). Not ideal for high-volume mass production.



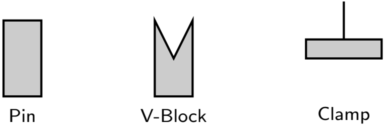
Other Quick-Acting Clamps

While strap and C-clamps are foundational, modern fixtures rely heavily on quick-acting clamps to slash setup times.

Clamp Type	Mechanism & Features	Speed / Cost
Toggle Clamps	Use a linkage mechanism to snap into a locked position instantly. Low operator effort.	Fast / Low
Cam Clamps	Use an eccentric cam to quickly apply force. Can vibrate loose under heavy milling.	Fast / Medium
Hydraulic / Pneumatic	Automated clamping using fluid power. Consistent force, integrated into PLC systems.	Fastest / High

Key Takeaways

- Locators position the part; Clamps secure it.
- Pin and button locators are for holes and flat surfaces; V-locators for cylinders.
- A diamond pin is used with a round pin to prevent binding.
- Clamping force must be directed towards locators, never over unsupported areas.
- Strap clamps act as levers; C-clamps are versatile but slow.

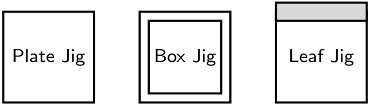


Next Lecture Preview

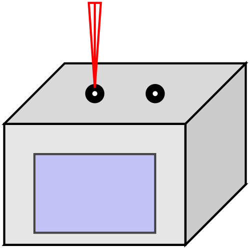
Lecture 5: Types of Jigs

Next lecture we shift our focus entirely to Jigs. We will look at the different structural designs used for drilling operations:

- Plate jig
- Box jig
- Leaf jig
- Channel jig
- Construction and specific applications of each type.



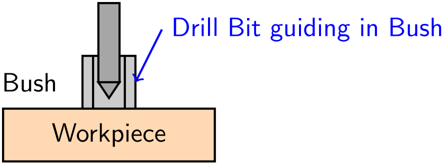
Types of Jigs



Welcome

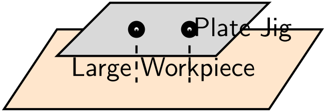
- Course: Manufacturing Engineering - III (DI05019011)
- Unit 1: Production Tooling: Jigs, Fixtures & Press Tools
- Lecture 5: Types, Construction and Applications of Jigs

Recall: What is a Jig?



- A device that holds the workpiece AND guides the cutting tool.
- Most commonly used for drilling, reaming, tapping, and counterboring.
- Contains hardened steel drill bushes to guide the tool.
- Often free-standing on the drill press table, moved around by hand for different holes.
- Jigs are categorized primarily by their physical construction/shape.

1. Plate Jig (Template Jig)

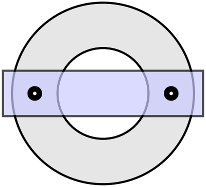


Features

- The simplest type of jig.
- Construction: Consists simply of a flat plate containing drill bushes.
- The plate is clamped directly ON TOP of the workpiece.
- Often, the plate has locating pins projecting downwards that fit into existing holes or edges of the workpiece.
- Sometimes called a 'template jig' if it lacks clamps and is just held by hand.

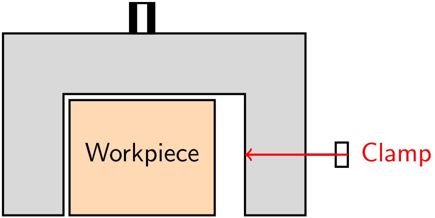
Plate Jig: Applications & Pros/Cons

Drilling Bolt Holes on a Flange



- **Applications:** Drilling holes in large, flat plates, flanges, or structural members where a full enclosing jig is too heavy or expensive.
- **Advantages:** Inexpensive, simple to design, easy to handle, good for large parts.
- **Disadvantages:** Only drills holes from one direction. Clamping can sometimes be slow if independent clamps are used.

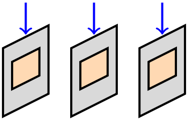
2. Channel Jig



Features

- Construction: Shaped like an inverted 'U' or channel cross-section.
- The workpiece fits inside the channel.
- Drill bushes are located on the top face of the channel.
- Clamping is usually done via a screw acting from the side or bottom, pushing the part against the channel walls.

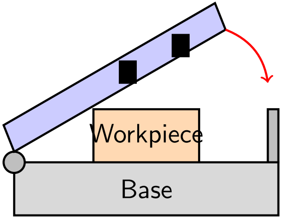
Channel Jig: Applications



Blocks sliding into channel jigs

- **Applications:** Ideal for simple, symmetrical parts like blocks, short shafts, or rectangular bars.
- **Advantages:** Provides built-in location (sides of the channel). Rigid construction. Easy to slide parts in and out.
- **Limitations:** Limited to parts that fit the specific channel profile. Holes generally only drilled from the top face.

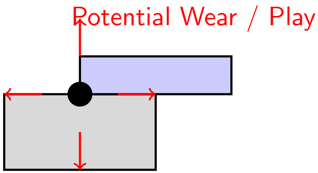
3. Leaf Jig



Features

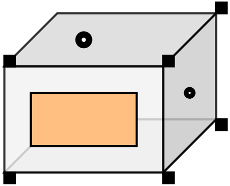
- Construction: Features a hinged cover or 'leaf' that swings open.
- The drill bushes are typically mounted in this swinging leaf.
- The workpiece is placed in the base, and the leaf is swung closed and locked (latched) over the part.
- Often, the closing action of the leaf also acts as the clamp.

Leaf Jig: Applications & Pros/Cons



- **Applications:** Small to medium parts requiring high-speed loading/unloading.
- **Advantages:** Very fast operation. Easy removal of parts and clearing of chips when the leaf is open.
- **Disadvantages:** The hinge pin can wear over time, causing the leaf (and the drill bushes) to lose accuracy. Not ideal for very heavy drilling forces.

4. Box Jig (Tumble Jig)

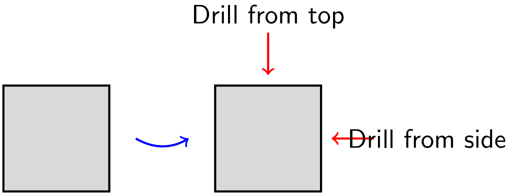


Feet on multiple faces allow tumbling

Features

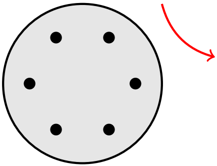
- Construction: A fully enclosed box-like structure that completely surrounds the workpiece.
- Contains drill bushes on multiple faces (top, sides, bottom).
- The jig can be 'tumbled' (rolled over) on the drill press table to drill holes from different directions in a single setup.
- Usually features a hinged door (like a leaf) for loading.

Box Jig: Applications & Pros/Cons

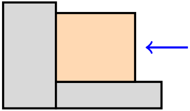


- **Applications:** Complex parts requiring holes drilled from multiple angles (e.g., valve bodies, manifolds).
- **Advantages:** Excellent accuracy (part is never unclamped). Highly versatile.
- **Disadvantages:** Expensive to design and manufacture. Heavy to lift and tumble. Chip removal can be difficult from inside the box.

Other Minor Types of Jigs



Indexing Jig



Angle Plate Jig

- **Angle Plate Jig:** Used to drill holes perpendicular to a machined flange or face (part is clamped to an upright plate).
- **Indexing Jig:** Used for drilling holes in a circular pattern (pitch circle). Features an indexing mechanism to rotate the part accurately.
- **Diameter Jig:** Specifically for drilling transverse holes through cylinders/shafts.

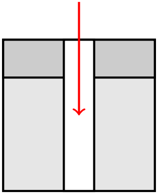
Summary of Jig Types

Jig Type	Description	Application
Plate Jig	Flat, clamps on part.	Best for large plates.
Channel Jig	U-shaped, part slides in.	Good for simple blocks.
Leaf Jig	Hinged lid with bushes.	Fast loading, but hinge wear can affect accuracy.
Box Jig	Fully encloses part.	Used for drilling from multiple directions in one setup.

Key Takeaway

Selecting the right jig balances cost, part complexity, and required production speed.

Next Lecture Preview

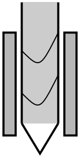


Shiny, Hardened Steel Drill Bush

Lecture 6: Drill Bushes

- The core component of any jig.
- Types of bushes: Fixed, Renewable, Slip, and Liner.
- Materials and applications of drill bushes.

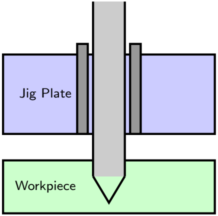
Drill Bushes



- Course: Manufacturing Engineering - III (DI05019011)
- Unit 1: Production Tooling: Jigs, Fixtures & Press Tools
- Lecture 6: Drill Bushes: Types and Applications

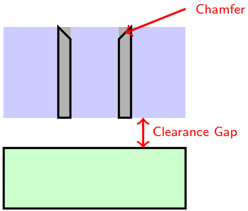
What is a Drill Bush?

- A precision-machined, hardened steel tube inserted into a jig plate.
- **Function 1:** Guides the cutting tool (drill, reamer, tap) accurately into the workpiece.
- **Function 2:** Prevents the tool from wandering or deflecting on the workpiece surface.
- **Function 3:** Protects the softer jig body from wear and damage caused by rotating cutting tools.



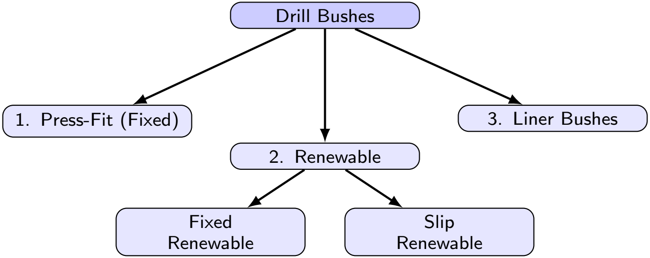
Characteristics of Drill Bushes

- **Material:** Typically case-hardened low-carbon steel, alloy steel, or Tungsten Carbide for high-volume.
- **Hardness:** Usually RC 60-64 to resist the rubbing of high-speed steel tools.
- **Design feature:** Often have a chamfered inner top edge to help the tool enter smoothly.
- **Clearance:** Must have a small gap between the bottom of the bush and the workpiece to allow chips to escape.



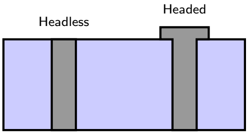
Classification of Drill Bushes

Drill bushes are broadly classified into three main categories based on how they are mounted. Selection depends on the production volume and whether multiple operations are performed on the same hole.



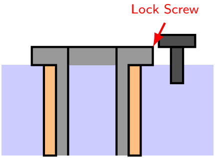
1. Press-Fit Bushes (Fixed)

- Pressed permanently directly into the hole in the jig plate.
- Used for low to medium volume production where the bush is expected to last the life of the jig.
- **Types:**
  - *Headless Press-Fit:* Flush with the jig plate surface (closer spacing allowed).
  - *Headed Press-Fit:* Has a flange (head) to resist heavy downward axial forces.



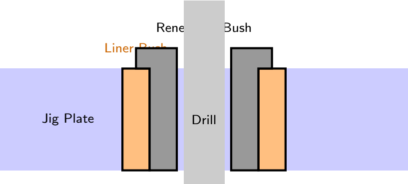
2. Renewable Bushes

- Used for high-volume production where bushes wear out and must be replaced frequently.
- Instead of pressing directly into the jig plate, they slide into a 'Liner Bush'.
- Locked in place using a locking screw or clamp.
- **Two main types of Renewable bushes:**
  - Fixed Renewable
  - Slip Renewable



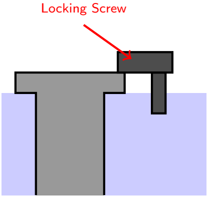
The Role of the Liner Bush

- A Liner Bush is a permanent, headless press-fit bush pressed into the jig plate.
- Its inside diameter (ID) perfectly matches the outside diameter (OD) of a renewable bush.
- It acts as a permanent, hardened socket.
- Prevents the jig plate hole from wearing out during repeated bush replacements.



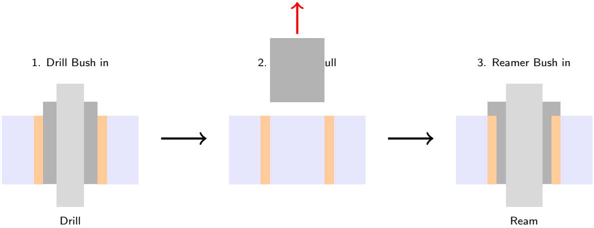
Fixed Renewable Bushes

- Used when only ONE operation (e.g., just drilling) is performed per hole.
- They are meant to stay in place until they wear out, then they are replaced.
- Locked to the jig plate using a simple retaining screw to prevent rotation and upward movement.
- Can be swapped relatively quickly without a press.



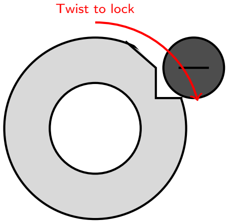
Slip Renewable Bushes

Crucial for holes requiring MULTIPLE operations (e.g., Drilling followed by Reaming or Tapping). A reamer requires a slightly larger guide hole than the drill bit.



Locking Mechanisms for Renewable Bushes

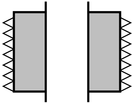
- Renewable bushes must not spin or pull out.
- They feature a milled recess on the head.
- A lock screw is threaded into the jig plate next to the bush.
- **For Slip Bushes:** The recess is shaped like an 'L' (bayonet lock). The operator inserts the bush and twists it under the screw head to lock.



Special Bushes (Mention)

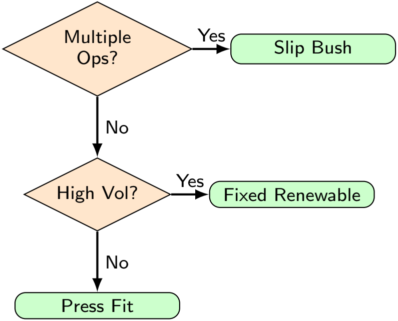
Type	Application
Threaded Bushes	Used when the bush also acts as a clamp (screws down onto the workpiece).
Knurled Bushes	Molded or cast into plastic/resin jigs.
Carbide Bushes	Solid tungsten carbide inserts used for drilling highly abrasive materials (like fiberglass or cast iron) in extreme volumes.

Threaded Bush (Simplified)



Summary

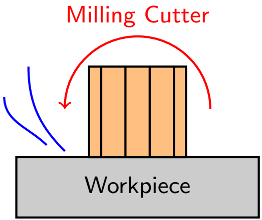
- Drill bushes guide the tool and prevent jig plate wear.
- **Press-fit (fixed):** Permanent installations for lower volumes.
- **Renewable:** Fit inside liner bushes, easily replaced.
- **Slip renewable:** Required for multiple sequential operations.



Next Lecture Preview

Lecture 7: Fixtures for Various Operations

- Milling fixtures (designing for heavy lateral forces)
- Turning fixtures (lathe faceplates and mandrels)
- Welding and assembly fixtures (heat distortion considerations)



Types of Fixtures

Course: Manufacturing Engineering - III (DI05019011)

Unit 1: Production Tooling: Jigs, Fixtures & Press Tools

Lecture 7: Milling, Turning, Welding and Assembly Fixtures

Milling Fixture (Rigid, Machine Guided)	Welding Fixture (Heat Resistant, Clamped)

Recall: Characteristics of Fixtures

- Hold and locate the workpiece securely.
- Do **NOT** guide the cutting tool (no drill bushes).
- Must be physically fastened to the machine tool table (milling) or spindle (turning).
- Generally much heavier and more rigid than jigs to withstand severe cutting forces.

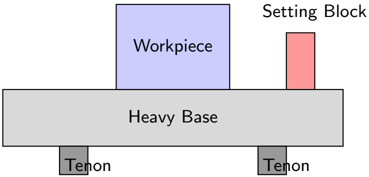
Jigs	**Fixtures**
Lighter construction	Heavy-duty holding device
Guides the cutting tool	Does NOT guide the cutting tool
Usually not fastened to machine	Fastened to machine table or spindle
Lower cutting forces	Massive cutting forces, high rigidity

1. Milling Fixtures

- Used on horizontal and vertical milling machines.
- Subjected to heavy, interrupted cutting forces (vibration).

Key Design Elements

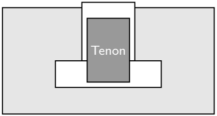
- Heavy cast iron or steel base.
- Tenons (keys) on the base for alignment.
- Setting blocks to position the milling cutter.
- Robust clamping mechanisms.



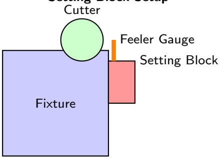
Milling Fixtures: Tenons & Setting Blocks

- **Tenons (Keys):** Metal blocks bolted to the bottom of the fixture base. They fit snugly into the T-slots of the milling machine table. Ensures rapid and perfect alignment.
- **Setting Blocks:** Hardened blocks attached to the fixture. Used with a feeler gauge to set the exact starting depth/position of the tool.

Tenon in T-Slot



Setting Block Setup

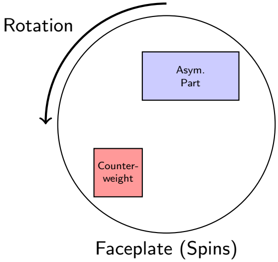


2. Turning Fixtures

- Used on lathes; the fixture and workpiece **ROTATE** together.
- Often mounted on the lathe faceplate or spindle.

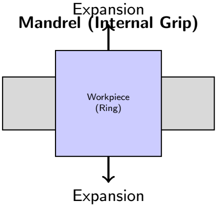
Key Design Elements

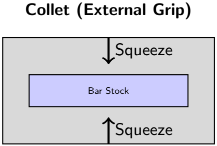
- **Perfect Balance:** Unbalanced rotating fixtures cause severe vibration, destroying accuracy and machine bearings.
- **Counterweights:** Used to balance asymmetrical fixtures.
- No protruding parts that could catch operator clothing.



Turning Fixtures: Mandrels and Collets

- **Mandrel:** Cylindrical fixture holding a part via an existing internal hole. Expanding mandrels grip the inside diameter tightly.
- **Collet:** A slotted sleeve that squeezes around the outside of a cylindrical part when tightened. Highly accurate and fast for round stock.



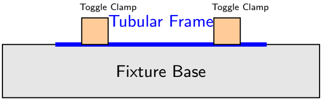


3. Welding Fixtures

- Used to hold parts in correct relation to each other during welding.
- Must withstand extreme heat and prevent thermal distortion (warpage).

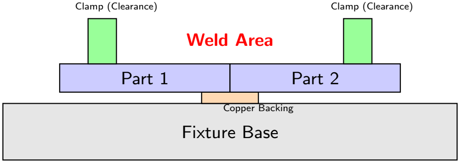
Key Design Elements

- Heat dissipation (copper backing bars).
- Allowance for expansion and shrinkage.
- Spatter protection (shielding threads and clamps from weld spatter).
- Grounding connections.



Welding Fixtures: Design Challenges

- Clamps must be clear of the weld area to allow torch access.
- Tack welding is often done in the fixture, then the part is removed for final heavy welding to prevent overheating.
- Threads and precision locators must be shielded to prevent spatter fusion.

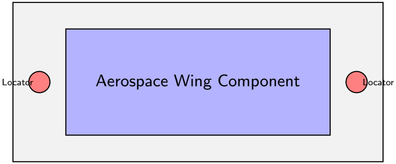


4. Assembly Fixtures

- Used to hold multiple components together in their final configuration for mechanical fastening (riveting, bolting, gluing).
- Common in aerospace (fuselage assembly) and automotive (door panels).

Key Design Elements

- Ergonomics are critical (operators work in/around them for long periods).
- Foolproofing ensures parts cannot be assembled backwards.
- Often large and require structural framing.



Summary of Fixture Types

Milling Heavy, rigid Tenons & Setting blocks	**Turning** Rotates with spindle Dynamic balancing
Welding Manages thermal expansion Spatter protection	**Assembly** Ergonomics, foolproofing Holding multiple parts

End of Jigs and Fixtures Section

We have completed the first half of Unit 1.

You should now be able to:

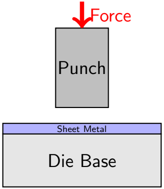
- Differentiate jigs and fixtures.
- Apply the 3-2-1 location principle.
- Select locators, clamps, and drill bushes.
- Understand specific requirements for milling, turning, and welding fixtures.

✓ **Module Completed**

Next Lecture Preview

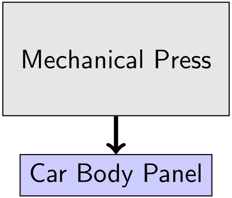
Lecture 8: Introduction to Press Tools

- Transitioning from cutting chips to shearing sheet metal.
- Construction and working of a basic press tool (punch and die).
- Applications of press working in mass production.



Course Information

- Course: Manufacturing Engineering - III (DI05019011)
- Unit 1: Production Tooling: Jigs, Fixtures & Press Tools
- Lecture 8: Construction, Working & Application of Press Tools



What is Press Working?

Definition & Characteristics

- A manufacturing process used to cut or form sheet metal without creating chips (swarf).
- Performed on a machine called a Press (mechanical or hydraulic).
- Uses specialized tooling called Press Tools (Dies).
- Extremely fast; capable of producing hundreds of parts per minute.

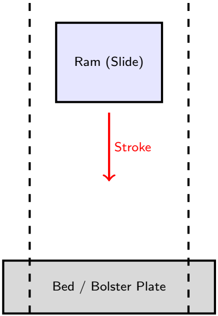
Applications

Car bodies, computer chassis, coins, beverage cans, brackets.

The Machine: The Power Press

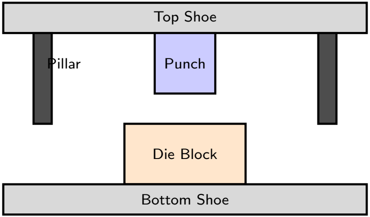
Key Components

- The press provides the force and the motion.
- **Bed/Bolster Plate:** Stationary bottom part where the lower half of the tool is mounted.
- **Ram (Slide):** The moving top part that travels up and down.
- **Stroke:** The distance the ram travels from TDC to BDC.



Basic Components of a Press Tool

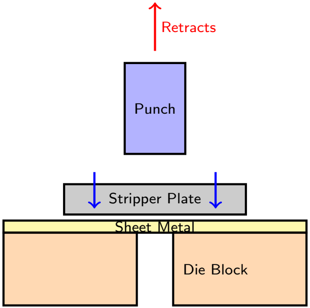
- **Punch:** The male cutting/forming element (upper shoe).
- **Die Block:** The female element matching the punch (lower shoe).
- **Shoes:** Thick steel plates holding punch and die.
- **Guide Pillars & Bushes:** Ensure perfect alignment.



Detailed Component Breakdown

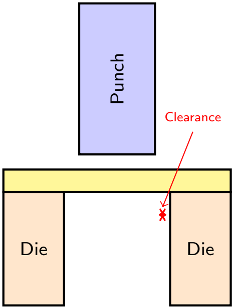
Additional Components

- **Punch Plate:** Holds the punch firmly to the top shoe.
- **Stripper Plate:** Pulls (strips) the sheet metal off the punch as it retracts upward.
- **Stock Guides:** Guide the strip of sheet metal.
- **Stop Pin:** Stops the fed metal strip at the correct pitch.



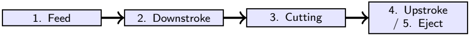
Clearance in Press Tools

- Clearance is the deliberate gap between Punch and Die Block.
- Die opening is slightly larger than punch.
- Determined by thickness (t) and shear strength.
- **Too little:** Excessive cutting force, rapid wear.
- **Too much:** Large burrs, part distortion.



Working Mechanism (The Stroke)

1. **Feed:** Sheet metal strip is fed over the die block.
2. **Downstroke:** Ram descends. Stripper holds metal flat.
3. **Cutting:** Punch contacts metal, exceeding shear strength.
4. **Upstroke:** Ram ascends. Stripper strips scrap off punch.
5. **Ejection:** The cut part falls through die block clearance.



Die Set Architecture

Why use guide pillars in a die set?

- Press tools are built as a complete assembly ('Die Set').
- The press ram itself has some slop/play.
- Punches and dies have very tight clearances (microns).
- Guide pillars in the tool ensure alignment independent of the machine's condition.
- Allows the tool to be setup quickly and safely.

Materials Used in Press Tools

Component	Material & Properties
Punches & Die Blocks	HCHC or Tool Steel. Hardened for impact/wear.
Shoes (Top/Bottom)	Cast iron or mild steel (rigidity, shock absorption).
Guide Pillars/Bushes	Case-hardened steel for wear resistance.
Stripper plates	Mild steel or tool steel depending on forces.

Applications and Advantages

Applications

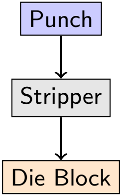
Automotive panels, electronics housings, washers, hinges, aerospace skins.

Advantages

- Extremely high production rates.
- Low cost per part in high volume.
- Excellent dimensional accuracy and interchangeability.
- Good surface finish without secondary operations.

Summary

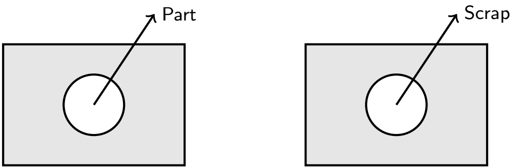
- Press working shapes sheet metal without chip removal.
- The press tool (Die Set) contains the intelligence and shape.
- **Key parts:** Punch (male), Die block (female), Stripper, Guide pillars.
- Clearance is critical for clean cutting and tool life.



Next Lecture Preview

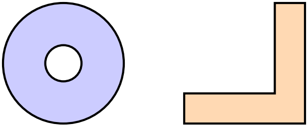
Lecture 9: Sheet Metal Operations

- The difference between Shearing, Blanking, and Piercing.
- Bending operations and springback.
- How to calculate cutting forces.



Blanking (Disk kept)   Piercing (Hole kept)

Sheet Metal Operations

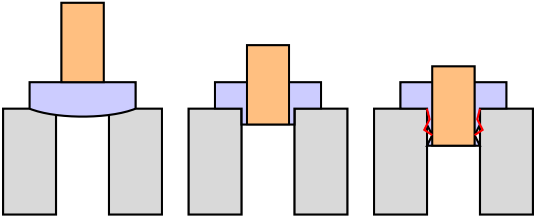


Details

- Course: Manufacturing Engineering - III (DI05019011)
- Unit 1: Production Tooling: Jigs, Fixtures & Press Tools
- Lecture 9: Sheet Metal Operations (Shearing, Blanking, Piercing & Bending)

Mechanics of Cutting Sheet Metal

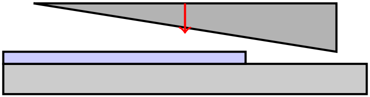
- Cutting in press work is technically called 'Shearing'.
- It happens in three distinct stages:



1. Deformation 2. Penetration 3. Fracture

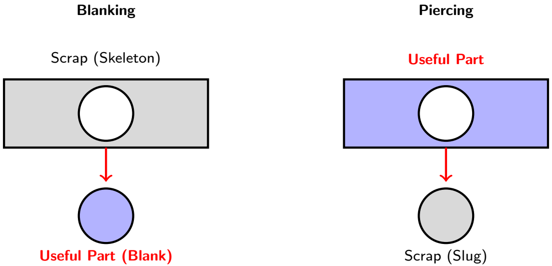
1. Shearing

- Definition: Cutting sheet metal along a straight line.
- Similar to using a pair of scissors on paper, but on a massive scale.
- Usually the first step in press working to cut large sheets down into smaller strips that can be fed into a die.
- Performed on a machine called a Squaring Shear or Guillotine.



Blanking vs. Piercing

- Both involve cutting a closed shape out of a sheet. Difference is WHICH piece you keep.



Clearance Allocation (Important!)

- Because of clearance, the hole made is the size of the Punch, and the piece that falls out is the size of the Die.

Blanking (We want an accurate blank)

Die size = Blank size

Clearance applied to Punch (Punch is made smaller)

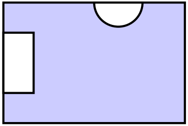
Piercing (We want an accurate hole)

Punch size = Hole size

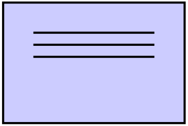
Clearance applied to Die (Die is made larger)

Other Cutting Operations

- **Notching:** Cutting shapes out of the edge of a strip.
- **Trimming:** Cutting away excess material from periphery of a drawn part.
- **Lancing:** Cutting a slit in the metal without completely separating the piece.
- **Parting/Severing:** Cutting a strip into individual parts by shearing.



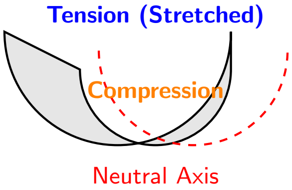
Notching



Lancing

Bending Operations

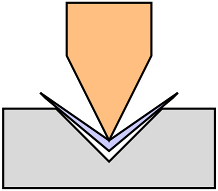
- Straining sheet metal around a straight axis to take a permanent set.
- Used to create V-shapes, U-shapes, or flanges.



Types of Bending

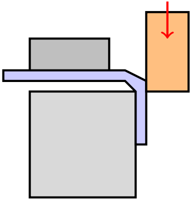
V-Bending

- Metal pressed into V-die by V-punch.
- Common for low production.



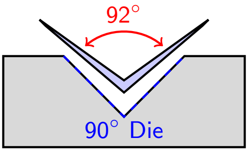
Edge Bending (Wiping)

- Punch wipes metal over edge of a die block.
- Requires pressure pad.



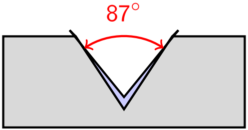
The Problem of Springback

- When bending force is removed, elastic strain recovers.
- Metal 'springs back', angle becomes larger.
- Depends on: Material strength, Bend radius, Material thickness.



Overcoming Springback

- **Overbending:** Punch and die are machined to, e.g., 87°. Metal springs back 3° to settle at 90°.
- **Coining:** Applying massive pressure at bottom of stroke to plastically compress bending zone, destroying elastic recovery.



Summary

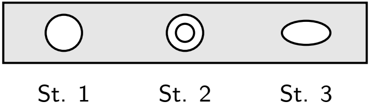
- Blanking keeps the cut-out piece; Piercing keeps the sheet with the hole.
- Clearance is applied to the Punch for blanking, and to the Die for piercing.
- Cutting involves plastic deformation followed by fracture.
- Bending causes inner compression and outer tension.
- Springback must be compensated for by overbending.

Cutting Operations

Bending Operations

Next Lecture Preview

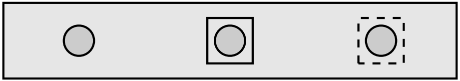
- Lecture 10: Types of Dies
  - Simple dies (one operation per stroke).
  - Compound dies (multiple operations at one station).
  - Progressive dies (multiple operations across multiple sequential stations).



Course: Manufacturing Engineering - III (DI05019011)

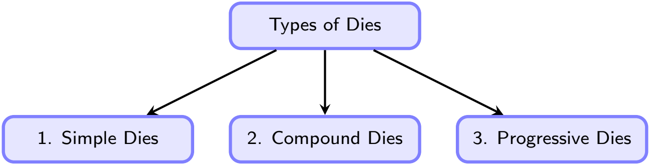
Unit 1: Production Tooling: Jigs, Fixtures & Press Tools

Lecture 10: Types of Dies (Simple, Compound, Progressive)



Classification of Dies

- Dies are classified based on how many operations they perform per stroke of the press, and where those operations occur.
- Choice depends on part tolerance, production rate required, and tool budget.

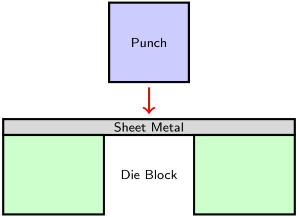


1. Simple Dies

Definition

Performs only ONE operation per stroke of the press ram.

- **Examples:** A simple blanking die, or a simple piercing die.
- **Workflow for a washer:**
  - Machine 1 (Die 1): Pierces the inner hole.
  - Machine 2 (Die 2): Operator manually aligns the hole, then blanks the outer diameter.
- **Pros:** Cheap to build, easy to maintain.
- **Cons:** Very slow, high labor cost, poor concentricity between operations.

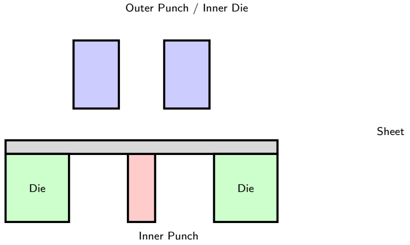


2. Compound Dies

Definition

Performs TWO OR MORE cutting operations at a SINGLE STATION per stroke of the press.

- **Example:** Piercing the center hole AND blanking the outside of a washer simultaneously in one hit.
- **Mechanics:** The tool uses a 'Blanking Die' which also acts as the 'Piercing Punch' internally.
- Both operations happen concurrently on the exact same piece of metal.



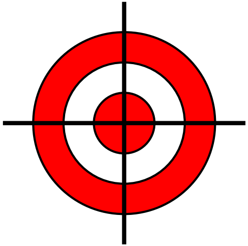
Compound Dies: Pros and Cons

Advantages:

- Perfect accuracy and concentricity (since the part doesn't move between piercing and blanking).
- High production rate compared to simple dies.

Disadvantages:

- Limited to cutting operations (cannot easily incorporate bending).
- Tool design is highly complex and crowded.
- High cost to manufacture the tool.



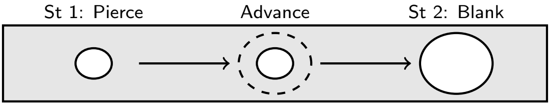
Perfect Concentricity

3. Progressive Dies

Definition

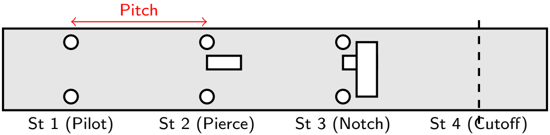
Performs multiple operations at DIFFERENT STATIONS in a single tool.

- The sheet metal strip moves (progresses) through the die from station to station with each press stroke.
- **Station 1:** Pierce hole. $\rightarrow$ Strip advances.
- **Station 2:** Blank outside profile (part drops out).
- A finished part is produced with every single stroke of the press, but each part took multiple strokes to create.



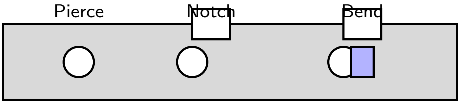
Progressive Dies: Strip Layout

- The most critical part of progressive die design is the **'Strip Layout'**.
- Engineers map out exactly what happens at each station.
- **Pitch:** The exact distance the strip must advance each stroke.
- **Pilots:** Bullet-nosed pins on the punches that enter previously pierced holes to align the strip perfectly before the next cut.



Progressive Dies: Capabilities

- Unlike compound dies, progressive dies can easily mix cutting AND forming operations.
- **Typical sequence:** Pierce → Notch → Form (Bend) → Cutoff (Blank).
- Can have anywhere from 2 to 20+ stations.
- Used for highly complex parts like electrical terminals, clips, and brackets.



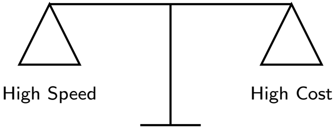
Progressive Dies: Pros and Cons

Advantages:

- Extremely high production rates (hundreds of parts per minute).
- Combines cutting and forming in one tool.
- Minimal operator intervention (coil fed automatically).

Disadvantages:

- Most expensive type of die to design and build.
- Hard to set up.
- Concentricity is slightly less perfect than compound dies (due to strip indexing).

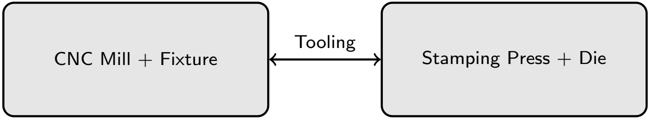


Comparison Summary

Die Type	Operations/Stroke	Stations	Part Complexity	Tool Cost
Simple	One	One	Low	Low
Compound	Multiple (Cut only)	One	Medium	High
Progressive	Multiple (Cut/Form)	Multiple	High	Very High

Unit 1 Conclusion

- We have covered Production Tooling comprehensively.
- **Jigs and Fixtures:** Essential for holding and guiding in chip-machining (milling, drilling).
- **Press Tools:** Essential for high-speed sheet metal forming and cutting.
- Both represent massive upfront investments that are justified entirely by the economics of Mass Production and Interchangeability.



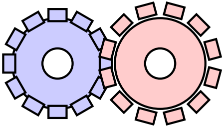
Congratulations on completing Unit 1: Production Tooling.

UNIT COMPLETE

- Please review the 3-2-1 principle, jig types, press tool components, and die classifications for your assessments.
- **Next Unit:** Gear Manufacturing Processes.

Manufacturing Engineering - III

DI05019011

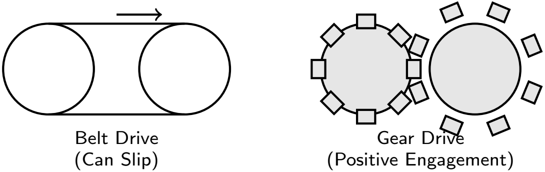


Agenda

- Introduction to Gears
- Classification of Gears
- Parallel Axes Gears (Spur, Helical, Herringbone)
- Intersecting Axes Gears (Bevel Gears)
- Non-Intersecting, Non-Parallel Axes Gears (Worm, Spiral)
- Summary and Applications

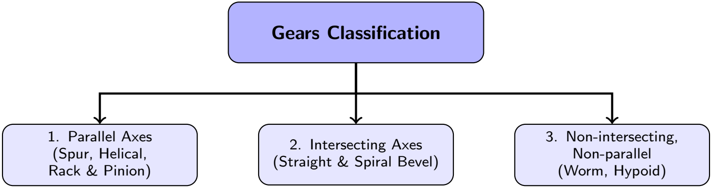
Introduction to Gears

- Gears are toothed, mechanical transmission elements used to transfer motion and power between machine components.
- They ensure positive drive (no slip) compared to belt drives.
- Capable of changing the speed, magnitude, and direction of a power source.
- Widely used in automotive transmissions, industrial machinery, and precision instruments.



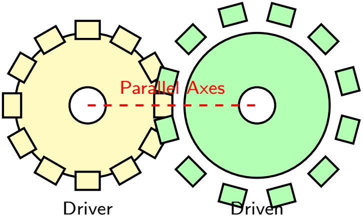
Classification of Gears

Gears are primarily classified based on the orientation of the axes of the mating shafts:



Spur Gears

- Teeth are straight and parallel to the axis of rotation.
- Most common, simplest to manufacture, and cost-effective.
- Used for transmitting power between parallel shafts.
- Produce no axial thrust forces.
- Limitation: Can be noisy at high speeds due to sudden contact of teeth.



Applications of Spur Gears

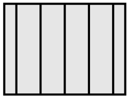
- Clocks and mechanical watches.
- Washing machines and household appliances.
- Material handling equipment (conveyors).
- Machine tool gearboxes for speed variation.

Low Speed Applications

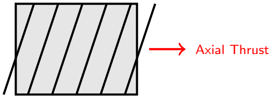
Cost-Effective Mechanisms

Helical Gears

- Teeth are cut at an angle (helix angle) to the axis of rotation.
- Gradual engagement of teeth results in smoother and quieter operation.
- Can carry higher loads than spur gears of the same size.
- Drawback: Generates axial thrust force, requiring thrust bearings.



Spur Gear (Straight Teeth)



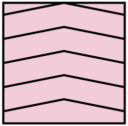
Helical Gear (Angled Teeth)

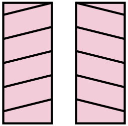
Applications of Helical Gears

- Automotive manual transmissions (for smooth, high-speed power transfer).
- High-speed industrial gearboxes.
- Steam and gas turbine drives.
- Applications requiring high load capacity and quiet operation.

Herringbone and Double Helical Gears

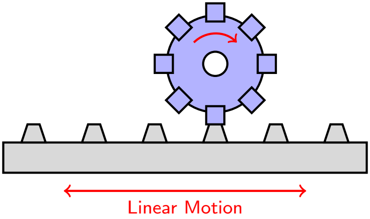
- Consist of two helical gears of opposite hands placed side-by-side.
- The opposite thrust forces cancel each other out.
- Eliminates the need for heavy thrust bearings.
- Herringbone has no gap between the two helices; double helical has a center groove for tool runout.





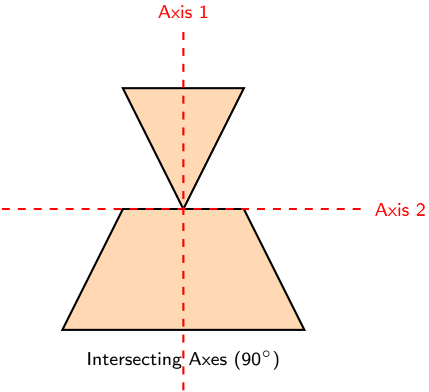
Rack and Pinion

- A special case of spur/helical gears where one gear (rack) has an infinite radius.
- Converts rotational motion into linear motion, or vice versa.
- The small gear is called the pinion, and the straight bar is the rack.



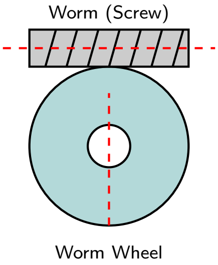
Bevel Gears

- Used for intersecting shafts, typically at a 90-degree angle.
- Pitch surface is a cone rather than a cylinder.
- Types include Straight Bevel (straight teeth), Spiral Bevel (curved teeth), and Zerol Bevel.
- Spiral bevel gears offer smoother operation similar to helical gears.



Worm and Worm Wheel

- Used for non-intersecting, non-parallel shafts (typically perpendicular).
- Worm resembles a screw, meshing with a worm wheel (similar to a spur/helical gear).
- Provides very high speed reduction ratios (up to 100:1 or more) in a single step.
- Often self-locking (cannot be back-driven), which is useful for hoisting.

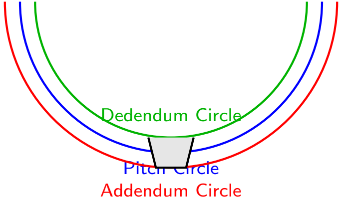


Summary of Gear Types

Gear Type	Axes Orientation	Advantages	Applications
Spur	Parallel	Simple, no axial thrust	Clocks, low-speed drives
Helical	Parallel	Smooth, quiet, high load	Automotive transmissions
Bevel	Intersecting	Changes power direction (90°)	Differentials, hand drills
Worm	Skew (Non-parallel/intersecting)	High reduction, self-locking	Hoists, lifts, conveyors

Next Lecture Preview

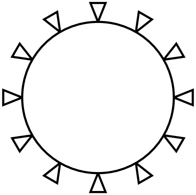
- In the next lecture, we will dive into:
- Gear Terminology
- Key parameters like Pitch Circle, Module, Addendum, and Dedendum
- Understanding these terms is crucial for gear design and manufacturing.



Gear Terminology

Course: Manufacturing Engineering - III (DI05019011)
Unit 2: Gear & Thread Manufacturing Processes
Lecture 12

DI05019011



Agenda

- Importance of Gear Terminology
- Pitch Circle and Pitch Diameter
- Module, Circular Pitch, and Diametral Pitch
- Addendum and Dedendum
- Clearance and Backlash
- Pressure Angle and Tooth Profile

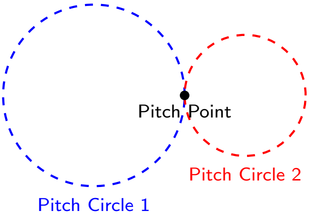
Why Learn Gear Terminology?

- **Standardization:** Ensures gears from different manufacturers can mesh properly.
- **Design & Manufacturing:** Provides the exact dimensions required to set up machines like hobbers and shapers.
- **Inspection:** Serves as the reference points for checking gear quality and tolerances.
- **Communication:** Common language for engineers worldwide.

Standards | Manufacturing | Inspection | Communication

Pitch Circle & Pitch Diameter

- **Pitch Circle:** An imaginary circle that by pure rolling action would give the same motion as the actual gear.
- **Pitch Diameter (D):** The diameter of the pitch circle.
- The size of a gear is usually specified by its pitch diameter.
- When two gears mesh, their pitch circles are tangent to each other at the pitch point.



Module (m)

- Module is the ratio of the pitch diameter (in mm) to the number of teeth.
- **Formula:** $m = \frac{D}{Z}$ (where D is pitch diameter, Z is number of teeth).
- It is the standard metric system measure of gear tooth size.
- Gears must have the same module to mesh together properly.
- Standard modules are defined by ISO to reduce tooling costs.

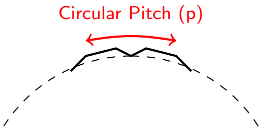
Formula

$$m = \frac{D}{Z}$$

Standard Modules	1	1.25	1.5	2	2.5	3

Circular Pitch (p)

- The distance measured along the circumference of the pitch circle from a point on one tooth to the corresponding point on the adjacent tooth.
- **Formula:** $p = \frac{\pi \times D}{Z} = \pi \times m$
- It includes one tooth thickness and one tooth space.
- Used mostly in older systems, largely replaced by Module in metric countries.



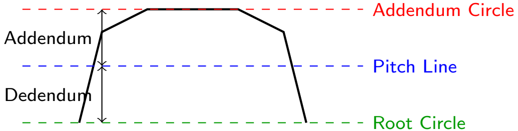
Diametral Pitch (P)

- The ratio of the number of teeth to the pitch diameter in inches.
- **Formula:** $P = \frac{Z}{D}$ (where D is in inches).
- It is the imperial equivalent of module.
- Note that $P = \frac{1}{m}$ (when m is in inches).
- Like module, gears must have the same diametral pitch to mesh.

Feature	Module (Metric)	Diametral Pitch (Imperial)
Definition	D/Z	Z/D
Units	mm / tooth	teeth / inch
Relation	$m = \frac{25.4}{P}$	$P = \frac{25.4}{m}$

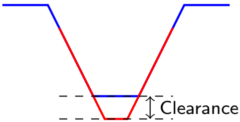
Addendum and Dedendum

- **Addendum (a):** The radial distance from the pitch circle to the top of the tooth. Standard $a = 1 \times m$.
- **Dedendum (b):** The radial distance from the pitch circle to the bottom of the tooth space (root circle). Standard $b = 1.25 \times m$.
- Dedendum is always slightly larger than the addendum to provide clearance.



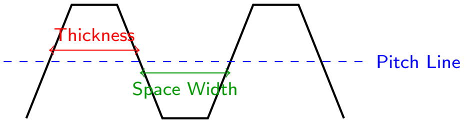
Clearance and Working Depth

- **Clearance (c):** The radial distance between the top of a tooth and the bottom of the mating tooth space.
  $c = \text{Dedendum} - \text{Addendum} = 0.25 \times m$.
- **Working Depth:** The radial distance from the addendum circle to the clearance circle. It is the depth of engagement of two mating gears ($2 \times m$).
- **Whole Depth:** The total depth of the tooth space (Addendum + Dedendum).



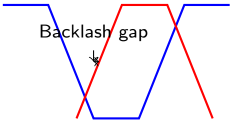
Tooth Thickness and Space Width

- **Tooth Thickness:** The width of the tooth measured along the pitch circle.
- **Space Width:** The width of the space between two adjacent teeth measured along the pitch circle.
- Ideally, Tooth Thickness = Space Width = $p/2$.
- In practice, space width is slightly larger to prevent jamming.



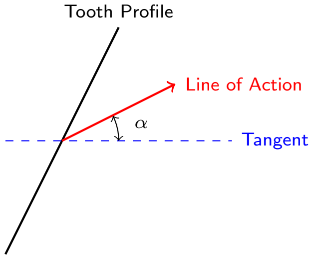
Backlash

- Backlash is the difference between the tooth space and the tooth thickness of mating gears.
- It is the amount of 'play' or lost motion between mating gears.
- **Purpose:** Prevents gears from jamming due to thermal expansion, manufacturing errors, or lubrication needs.
- Excessive backlash causes noise and inaccuracy, especially upon reversing direction.



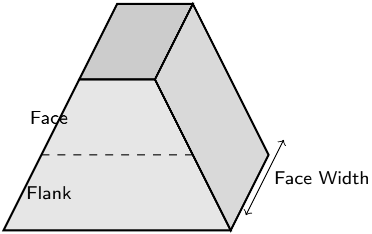
Pressure Angle (α)

- The angle between the line of action and the common tangent to the pitch circles.
- Standard pressure angles are 14.5° (obsolete), 20° (most common), and 25° (high load).
- Higher pressure angle means a wider tooth base, making it stronger.
- Gears must have the same pressure angle to mesh properly.



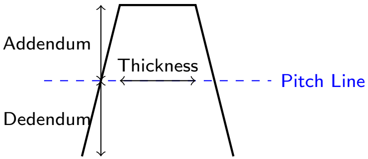
Face Width and Flank

- **Face:** The working surface of the gear tooth above the pitch surface.
- **Flank:** The working surface of the gear tooth below the pitch surface.
- **Face Width:** The width of the gear tooth measured parallel to its axis.
- A wider face width can transmit more power but requires better alignment.



Summary of Key Terms

- **Module (m)** defines the size. Matching module is mandatory.
- **Addendum and Dedendum** define the depth of the tooth.
- **Clearance and Backlash** prevent jamming.
- **Pressure angle** determines the force transmission direction and tooth strength.



Next Lecture Preview

In the next lecture, we will explore:

- Classification of Gear Manufacturing Processes.
- Forming vs. Generating processes.
- An overview of casting, stamping, and machining gears.

Casting & Stamping

Machining (Hobbing/Shaping)

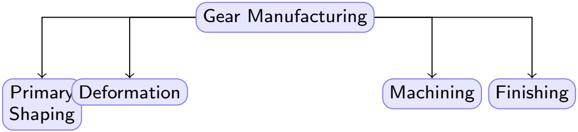
Classification of Gear Manufacturing Processes

- Course: Manufacturing Engineering - III (DI05019011)
- Unit 2: Gear & Thread Manufacturing Processes
- Lecture 13: Classification of Gear Manufacturing

Agenda

- Overview of Gear Manufacturing
- Casting and Molding Processes
- Metal Forming Processes (Stamping, Drawing)
- Machining Processes: Forming vs. Generating
- Gear Finishing Processes (Introduction)
- Selection Criteria for Manufacturing

Overview of Gear Manufacturing



- Gears can be made by many processes depending on the required accuracy, material, and production volume.
- Processes are broadly divided into:
- 1. Primary shaping (Casting, Molding)
- 2. Deformation (Forging, Extrusion, Stamping)
- 3. Material Removal / Machining (Milling, Hobbing, Shaping)
- 4. Finishing (Shaving, Grinding, Lapping)

Casting Processes

- Sand Casting: Used for very large, slow-moving gears (e.g., mill gears). Poor surface finish and accuracy.
- Die Casting: Used for high-volume production of small to medium gears in zinc, aluminum, or brass. Good accuracy.
- Investment Casting: Offers better precision and surface finish for complex shapes.

Plastic Molding

- Injection Molding is used extensively for producing polymer/plastic gears.
- Materials: Nylon, Delrin (Acetal), Polycarbonate.
- Advantages: Very low cost in high volumes, lightweight, self-lubricating, quiet operation.
- Limitations: Low load-carrying capacity, poor thermal resistance.

Metal Forming: Stamping

- Fine Blanking and Stamping are used to produce thin, flat gears from sheet metal.
- Advantages: Extremely fast, cheap for mass production.
- Applications: Watches, clocks, timers, light mechanisms.
- Limitations: Only suitable for thin gears; limited to low-torque applications.

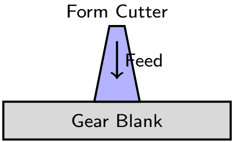
Metal Forming: Powder Metallurgy (Sintering)

- Metal powder is compacted in a die and then heated (sintered) to fuse the particles.
- Advantages: Near-net shape, minimizes machining, porosity can hold lubricating oil.
- Applications: Automotive oil pump gears, power tools.
- Limitations: Tooling is expensive; mechanical properties are slightly lower than solid steel.

Machining Processes: The Standard for Precision

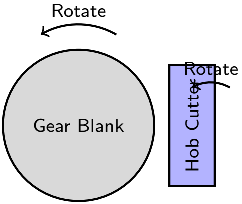
- For most industrial applications, gears must be machined from solid metal blanks.
- Machining provides the highest accuracy, load capacity, and surface finish.
- Gear machining is classified into two fundamental principles:
- 1. Gear Forming Principle
- 2. Gear Generating Principle

Gear Forming Principle



- The cutting tool has the exact inverse shape of the gear tooth space.
- The tool plunges or feeds into the blank, cutting one space at a time.
- After one space is cut, the blank is indexed (rotated) to the next position.
- Examples: Gear Milling, Broaching.

Gear Generating Principle



- The gear tooth shape is formed as an envelope of successive tool positions.
- The tool and the blank rotate together in a continuous meshing action, simulating two gears running together.
- Examples: Gear Hobbing, Gear Shaping.
- A single tool can cut any number of teeth for a given module.

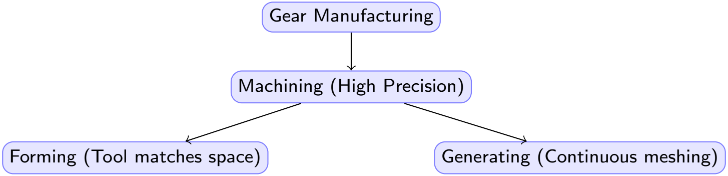
Forming vs. Generating

Forming	**Generating**
Lower machine cost, uses standard milling machines	High accuracy, faster continuous cutting
Lower accuracy, slower (indexing required)	Same tool cuts any tooth number of that module
Tool specific to tooth number range	Requires specialized, expensive machines

Gear Finishing (Brief Overview)

- Machining processes (forming/generating) leave tool marks and slight inaccuracies.
- Heat treatment (hardening) often causes distortion.
- Finishing processes are used post-hardening to correct errors and improve surface finish.
- Common methods: Gear Shaving, Gear Grinding, Lapping, and Honing.

Summary



- Gears can be cast, molded, formed, or machined depending on requirements.
- Machining is essential for high-precision, heavy-duty metal gears.
- Machining is divided into Forming and Generating.
- Generating processes are the industry standard for mass production.

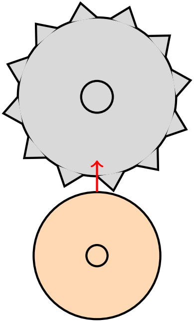
Next Lecture Preview

- In the next lecture, we will focus deeply on Gear Forming Processes.
- Specifically, Gear Milling using a form milling cutter.
- We will learn about the indexing mechanism and the advantages/limitations of this specific process.

Gear Forming Processes: Gear Milling

Manufacturing Engineering - III (DI05019011)

DI05019011

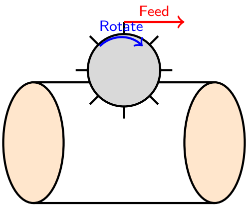


Agenda

- Principle of Gear Forming
- The Form Milling Cutter
- Machine Setup (Universal Milling Machine)
- The Role of Indexing
- Simple Indexing Calculation
- Advantages and Limitations

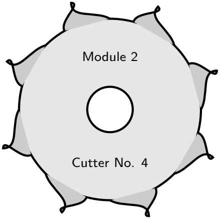
Principle of Gear Forming by Milling

- Gear forming is a machining process where the cutting tool geometry exactly matches the intended shape of the gear tooth space.
- A rotating multi-point cutter (form milling cutter) is fed parallel to the axis of the gear blank.
- It removes metal to create one complete tooth space per pass.
- After one pass, the tool returns, the blank is rotated (indexed), and the next space is cut.



The Form Milling Cutter

- The cutter is basically a specialized disc milling cutter.
- Its profile is a negative of the involute curve of the gear tooth gap.
- Issue: The shape of an involute gear gap changes depending on the number of teeth on the gear, even if the module is the same.
- A 20-tooth gear has a different gap shape than a 50-tooth gear.



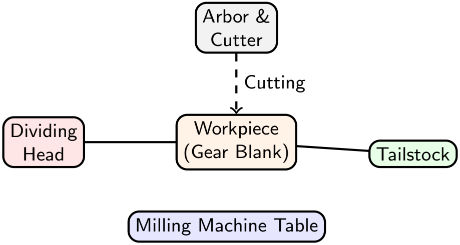
Standard Cutter Sets

- To solve the varying gap shape problem, cutters are sold in standardized sets for each module.
- A standard set typically consists of 8 cutters.
- This is an approximation; only the lowest number of teeth in the range is perfectly accurate.

Cutter No.	Number of Teeth Cut
1	135 to Rack
2	55 to 134
3	35 to 54
4	26 to 34
5	21 to 25
6	17 to 20
7	14 to 16
8	12 to 13

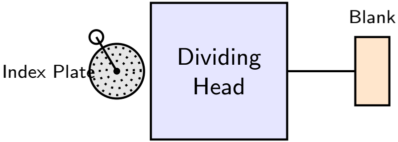
Machine Setup

- Machine Used: Usually a Horizontal or Universal Milling Machine.
- The gear blank is mounted on a mandrel between centers.
- The cutter is mounted on the machine arbor.
- A Dividing Head (Indexing Head) is attached to one end of the workpiece to control rotation.



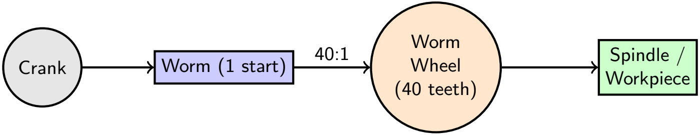
The Need for Indexing

- Indexing is the process of dividing the periphery of a workpiece into any number of equal parts.
- Since gear milling cuts one tooth gap at a time, we must rotate the blank by exactly $(360^\circ\ /\ Z)$ after every cut.
- Manual rotation is not precise enough; a dividing head uses a worm gear mechanism for high precision.



How Indexing Works

- The dividing head typically has a worm and worm wheel with a ratio of 40:1.
- 40 turns of the index crank = 1 full turn of the spindle/workpiece.
- To cut Z teeth, the required crank rotation = 40 / Z.
- An Index Plate with multiple circles of holes is used to achieve fractional turns.



Simple Indexing Example

Task: Cut a gear with 30 teeth ($Z = 30$)

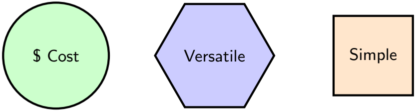
- Index Crank Movement $= 40/Z = 40/30 = 1$ and $1/3$ turns.
- We need to turn the crank 1 full revolution, plus $1/3$ of a revolution.

Solution

- Use an index plate circle divisible by 3 (e.g., 21 holes).
- $1/3$ of $21 = 7$ holes.
- Action: Turn 1 full revolution + 7 holes on the 21-hole circle.

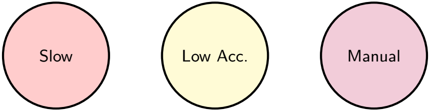
Advantages of Gear Milling

- Low Machine Cost: Uses standard milling machines available in most job shops.
- Versatility: The same machine can do regular milling when not cutting gears.
- Simple Setup: Easy to understand and configure for small batches.
- Good for large module/heavy gears if specialized machines are unavailable.



Limitations of Gear Milling

- Low Accuracy: The cutter profile is an approximation for most gears in the set.
- Slow Production: Cutting one tooth at a time, plus retraction and indexing time, makes it unsuitable for mass production.
- Operator Skill: Indexing requires careful attention; a miscount ruins the part.
- Thermal issues: Interrupted cutting can cause localized heating and distortion.



Summary

Principle & Setup

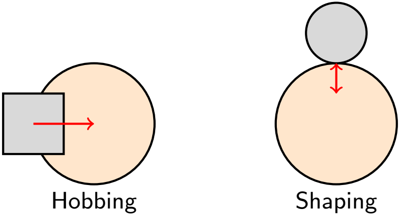
- Gear milling is a forming process using a profile cutter.
- Cutters come in standard sets (usually 8) to approximate involute shapes.
- Indexing via a dividing head (40:1 ratio) is essential for tooth spacing.

Pros & Cons

- **Pros:** Low cost, highly versatile, uses standard milling machine.
- **Cons:** Slow, approximate accuracy, manual indexing errors.
- Ideal for repair work and low volume; not suitable for mass production.

Next Lecture Preview

- In the next lecture, we transition to **Gear Generating Processes**.
- We will study **Gear Hobbing** and **Gear Shaping**.
- We will see how continuous cutting overcomes the speed and accuracy limitations of milling.



Gear Forming Processes: Gear Milling

Manufacturing Engineering - III (DI05019011)

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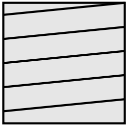
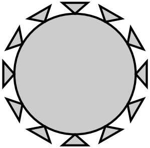


Hob Cutter



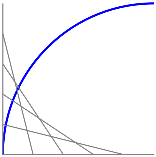
Pinion Shaper

Agenda

- The Generating Principle Recap
- Gear Hobbing: Working Principle
- The Hob Tool Geometry
- Advantages and Limitations of Hobbing
- Gear Shaping (Pinion Cutter): Working Principle
- Advantages and Limitations of Shaping
- Comparison: Hobbing vs Shaping

The Generating Principle

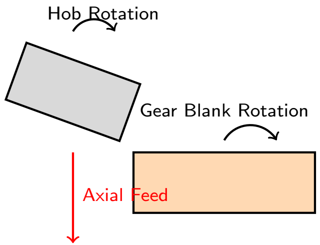
- Unlike forming, the tool does not have the exact shape of the tooth space.
- The tool and workpiece rotate in a synchronized motion, simulating two gears meshing.
- The cutting edges of the tool remove material in successive passes.
- The involute profile is 'generated' as the envelope of these successive cuts.
- One tool can cut gears with any number of teeth (of the same module).



Straight cuts enveloping into involute curve

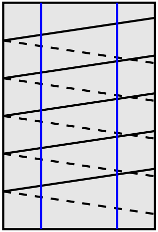
Gear Hobbing: Principle

- A continuous generating process.
- The tool (Hob) is essentially a threaded worm with gashes (flutes) cut across the threads to create cutting edges.
- The hob and the gear blank rotate simultaneously at a strict gear ratio.
- As they rotate, the hob is slowly fed axially across the face width of the blank.
- It continuously cuts all teeth simultaneously without needing indexing.



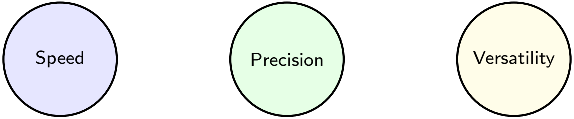
The Hob Tool Geometry

- Shape: Cylindrical with helical threads.
- Flutes: Longitudinal gashes cut across the threads to form the cutting faces and provide chip clearance.
- Relief: The teeth are backed off (relieved) to provide clearance angles behind the cutting edge.
- Profile: In an axial section, the hob teeth look like a basic rack profile (straight sides).



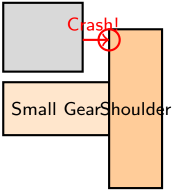
Advantages of Hobbing

- High Productivity: Continuous cutting without the idle return/index time of milling.
- High Accuracy: Synchronized motion prevents spacing errors.
- Versatility: The same hob cuts any number of teeth for a given module and pressure angle.
- Can cut spur gears, helical gears, splines, and sprockets.



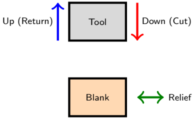
Limitations of Hobbing

- Cannot cut internal gears.
- Cannot cut gears that are close to a shoulder (stepped gears/cluster gears) due to tool run-out space requirements.
- Requires specialized, expensive hobbing machines.
- Hob tools are expensive to manufacture and sharpen.



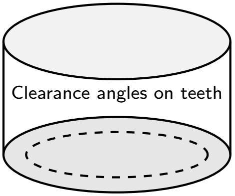
Gear Shaping (Pinion Cutter): Principle

- Also a generating process, but uses reciprocating (up and down) motion.
- The tool is a Pinion Cutter (looks like a gear with cutting edges).
- Motions:
  1. Cutting (downward stroke).
  2. Relief (blank retracts slightly on upward stroke to prevent rubbing).
  3. Rotary feed (tool and blank rotate slightly after each stroke, simulating meshing).



Pinion Cutter Geometry

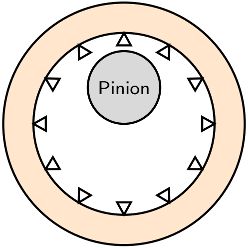
- It resembles a standard spur or helical gear.
- Bottom face is dished to create a cutting rake angle.
- Teeth have side and top clearance (relief angles) to avoid rubbing during the cut.
- Like the hob, one cutter can cut any number of teeth for the same module.



Dished bottom for rake angle

Advantages of Gear Shaping

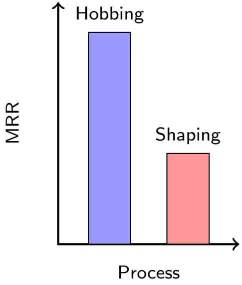
- Can cut Internal Gears (which hobbing cannot do).
- Can cut cluster gears or gears close to a shoulder (requires very little run-out space).
- Can cut herringbone gears without a center groove.
- High accuracy due to the generating principle.



Internal Gear Shaping

Limitations of Gear Shaping

- Slower than hobbing because the return stroke is idle (non-cutting time).
- Machine kinematics are complex (requires a relieving mechanism on the return stroke).
- Length of stroke limits the face width of the gear that can be cut.
- Helical gear shaping requires a special helical guide on the machine spindle.



Hobbing vs. Shaping

Parameter	Gear Hobbing	Gear Shaping
Speed	Faster (continuous)	Slower (reciprocating)
Internal Gears	Cannot be cut	Can be cut
Cluster Gears	Requires large clearance	Requires minimal clearance
Tool Cost	Hobs are more expensive	Pinion cutters are cheaper
Tool Life	Longer	Shorter
Process Type	Continuous generating	Interrupted generating

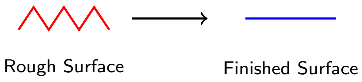
Summary

- Generating processes yield better accuracy and speed than forming.
- Hobbing uses a threaded tool for continuous cutting (great for external, high volume).
- Shaping uses a reciprocating pinion tool (essential for internal and shoulder gears).
- Both processes use one tool for any number of teeth of a given module.

Generating	**Hobbing**	**Shaping**
Better Accuracy	External, High Volume	Internal, Shoulders

Next Lecture Preview

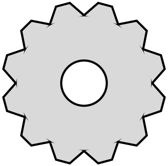
- Machining processes leave tool marks and slight distortions.
- In the next lecture, we will look at Gear Finishing Processes.
- We will understand why finishing is needed and explore various finishing types.



Gear Forming Processes: Gear Milling

Manufacturing Engineering - III (DI05019011)

DI05019011



Course: Manufacturing Engineering - III (DI05019011)

Unit 2: Gear & Thread Manufacturing Processes

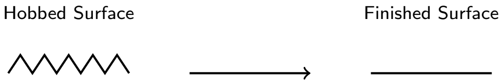
Lecture 16: Gear Finishing (Need and Types)

Agenda

- Why do we need Gear Finishing?
- Sources of Inaccuracies in Gears
- The Role of Heat Treatment
- Classification of Finishing Processes
- Finishing Unhardened Gears
- Finishing Hardened Gears
- Overview of Common Methods

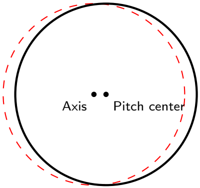
Need for Gear Finishing

- Machining processes (hobbing, shaping, milling) are roughing operations in the context of high-precision gears.
- They leave tool marks (scallops), small geometric errors, and poor surface finish.
- High-speed and heavy-load applications require perfect tooth profiles.
- Without finishing, gears will experience: High noise, vibration, rapid wear, and reduced fatigue life.



Sources of Errors in Gear Cutting

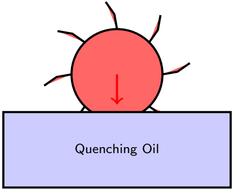
- Profile Error: Deviation from the perfect involute curve.
- Pitch Error: Unequal spacing between teeth.
- Runout: The pitch circle is eccentric to the axis of rotation.
- Lead Error: The tooth flank is not perfectly aligned with the axis (especially in helical gears).
- Surface Roughness: Scallop marks from the cutting tool feed.



Runout Error

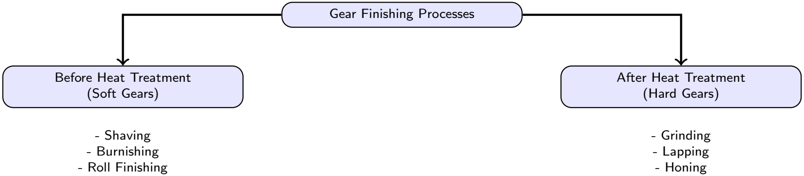
The Impact of Heat Treatment

- Steel gears must be hardened (carburized, quenched) to resist wear and carry high loads.
- Problem: The intense heating and rapid cooling cycle causes thermal distortion and warping.
- A perfectly hobbed gear will lose its accuracy after heat treatment.
- Therefore, finishing operations are often required *after* hardening to correct this distortion.



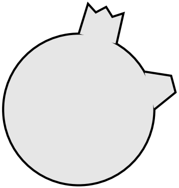
Classification of Finishing Processes

- Gear finishing processes are broadly classified based on the state of the material when finished:
- 1. Finishing Unhardened (Soft) Gears (e.g., Gear Shaving, Gear Burnishing, Gear Roll Finishing).
- 2. Finishing Hardened Gears (e.g., Gear Grinding, Gear Lapping, Gear Honing).



Finishing Soft Gears: Gear Shaving (Overview)

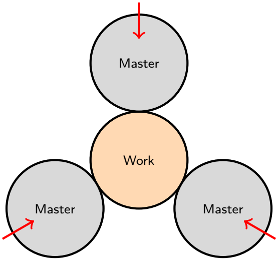
- Performed BEFORE heat treatment.
- Removes tiny amounts of metal (0.02 - 0.1 mm) to correct profile and improve finish.
- Uses a cutter that looks like a gear but has serrations on its teeth.
- Fast and highly effective, but cannot correct severe pitch errors.



Shaving Cutter with Serrated Teeth

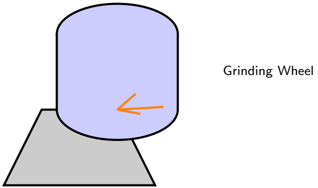
Finishing Soft Gears: Gear Burnishing

- A cold-working plastic deformation process (no metal removal).
- The soft gear is rolled under high pressure between three hardened, highly polished master gears.
- The pressure flattens the peaks of the tool marks into the valleys.
- Improves surface finish and induces beneficial compressive stresses.



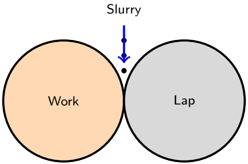
Finishing Hardened Gears: Gear Grinding (Overview)

- Performed AFTER heat treatment.
- The only way to correct heat treatment distortion with high precision.
- Uses abrasive grinding wheels to remove hardened material.
- Produces the highest accuracy and best surface finish.
- Limitation: Very slow and expensive.



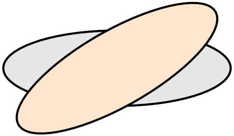
Finishing Hardened Gears: Gear Lapping

- An abrasive finishing process used after heat treatment.
- The hardened gear is run in mesh with a cast-iron master gear (lap).
- An abrasive compound (slurry of fine grit and oil) is pumped between them.
- Removes minute amounts of material to correct minor distortions and improve quietness.



Finishing Hardened Gears: Gear Honing

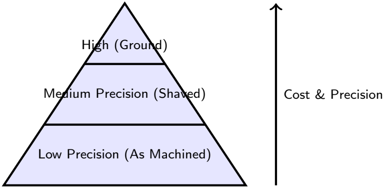
- Similar to lapping, but uses a solid abrasive-impregnated plastic tool instead of loose slurry.
- The honing tool meshes with the gear at a crossed axis angle.
- Fast process used to remove nicks, burrs, and minor heat treat distortion.
- Leaves a favorable cross-hatch surface pattern for lubrication retention.



Crossed Axis Meshing

Selecting the Right Process

- Low-speed, low-load gears: As hobbed/machined (No finishing).
- Medium precision (Automotive): Hobbed → Shaved → Heat Treated → Honed (optional).
- High precision (Aerospace, High-speed turbines): Hobbed → Heat Treated → Ground.



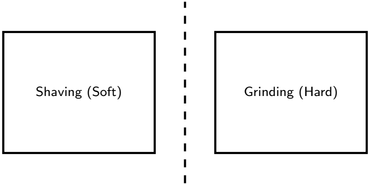
Summary

- Gear finishing corrects machining errors, improves surface finish, and eliminates heat treatment distortion.
- Pre-hardening processes (Soft): Shaving, Burnishing.
- Post-hardening processes (Hard): Grinding, Lapping, Honing.
- The choice depends on the required precision, application, and cost constraints.

Process	**Material State**	**Primary Function**
Shaving	Soft (Pre-Heat Treat)	Fast profile correction
Burnishing	Soft (Pre-Heat Treat)	Surface finish, compressive stress
Grinding	Hard (Post-Heat Treat)	Ultimate precision, fix distortion
Lapping	Hard (Post-Heat Treat)	Smooth running, pair matching
Honing	Hard (Post-Heat Treat)	Remove nicks, surface pattern

Next Lecture Preview

- In the next lecture, we will look closely at the two most important finishing processes.
- Gear Shaving (for soft gears).
- Gear Grinding (for hard gears).
- We will study their principles, specific applications, and achievable accuracies.



Gear Forming Processes: Gear Milling

Manufacturing Engineering - III (DI05019011)

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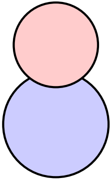
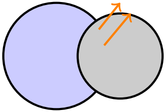


Gear Shaving



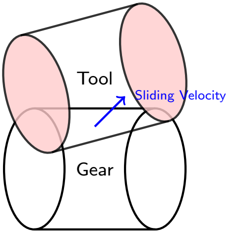
Gear Grinding

Agenda

- Gear Shaving: Principle and Kinematics
- Types of Gear Shaving
- Applications and Accuracy of Shaving
- Gear Grinding: Principle and Need
- Form Grinding vs. Generation Grinding
- Applications and Accuracy of Grinding
- Comparison: Shaving vs. Grinding

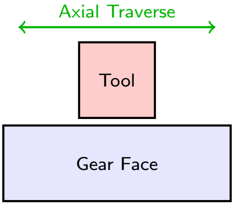
Gear Shaving: Principle

- A pre-heat treatment finishing process.
- The tool is a high-speed steel gear with serrations (grooves) cut into the flanks of its teeth.
- These serrations act as multiple cutting edges.
- The shaving tool and the gear blank mesh at crossed axes (typically 10 to 15 degrees).
- This crossed-axis arrangement causes a sliding action between the mating teeth.



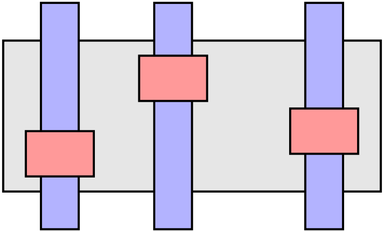
Kinematics of Gear Shaving

- The tool drives the workpiece (or vice versa).
- Because of the crossed axes, the contact point slides across the face of the gear tooth.
- The tool is traversed axially back and forth across the gear face.
- The machine is reversed after a few strokes to shave the opposite flank of the teeth.
- Removes very little material (0.02 to 0.1 mm).



Applications of Gear Shaving

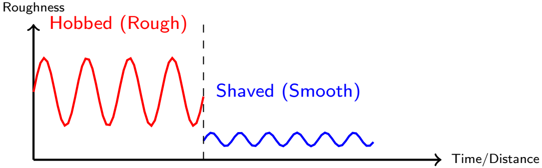
- Extensively used in the automotive industry for transmission gears.
- Suitable for medium to high volume production.
- Ideal for gears that will undergo heat treatment where some minor distortion is acceptable.
- Usually applied to spur and helical gears.



Automotive Gearbox Assembly (Conceptual)

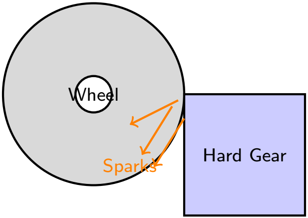
Achievable Accuracy of Shaving

- Surface finish: Can achieve 0.4 to 0.8 μm Ra.
- Profile Accuracy: Excellent, can correct minor involute profile errors from hobbing.
- Limitation: Cannot correct large index (pitch) errors or significant runout.
- Final accuracy is ultimately dependent on the subsequent heat treatment distortion.



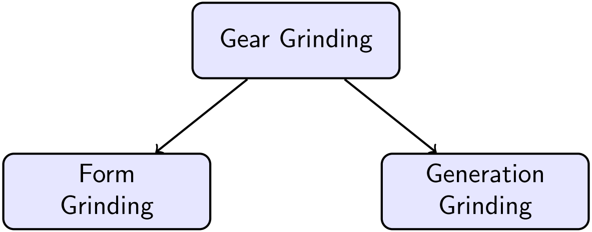
Gear Grinding: Principle

- A post-heat treatment finishing process using abrasive wheels.
- Used when the material is too hard to be cut with steel tools (e.g., after carburizing and quenching).
- Removes heat treatment scale and distortion.
- Produces the highest dimensional accuracy and finest surface finish.



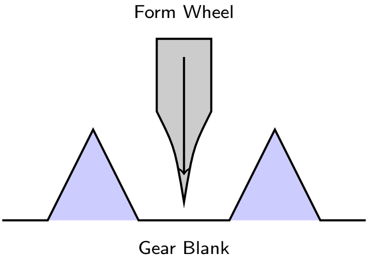
Methods of Gear Grinding

- There are two primary methods of gear grinding:
- 1. Form Grinding (Non-generating)
- 2. Generation Grinding
- The choice depends on the required accuracy, gear size, and production volume.



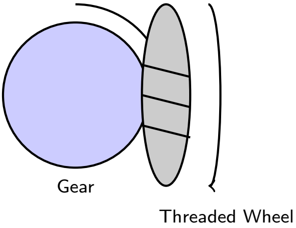
Form Grinding

- The grinding wheel is dressed to the exact inverse profile of the gear tooth space.
- The wheel passes through the tooth space, grinding both adjacent flanks simultaneously.
- After one pass, the wheel retracts, and the gear is indexed to the next tooth.
- Requires a special diamond dresser to accurately shape the grinding wheel.



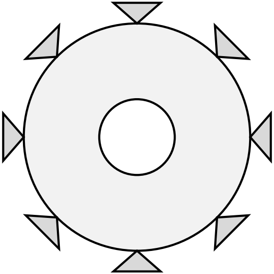
Generation Grinding (Continuous)

- Works on the same kinematic principle as gear hobbing.
- The grinding wheel is shaped like a worm (a threaded wheel).
- The threaded wheel and the gear blank rotate in synchronization.
- The wheel continuously grinds all teeth without the need for indexing.
- Fastest method of gear grinding.



Applications of Gear Grinding

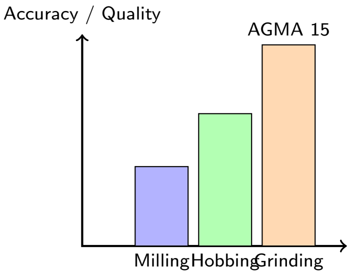
- Aerospace industry (helicopter transmissions, jet engine gearboxes).
- High-speed industrial turbines and compressors.
- Machine tool spindles (where zero backlash and runout are critical).
- Master gears used for inspection.



Aerospace Gearbox Element

Achievable Accuracy of Grinding

- Surface finish: Can achieve 0.2 to 0.4 μm Ra (mirror-like).
- Profile & Pitch Accuracy: Exceptional. Eliminates all heat treat distortion and index errors.
- Can hold tolerances to AGMA Quality Class 12-15 (DIN Class 2-4).
- Drawbacks: High risk of grinding burn (thermal damage to the hardened surface) and very high cost.



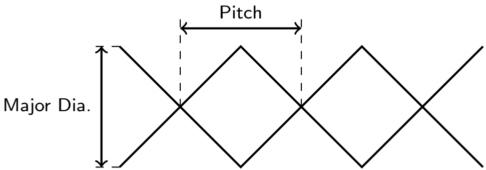
Summary: Shaving vs. Grinding

- Shaving: Pre-heat treat, uses a serrated steel cutter, crossed-axes sliding action. Cheap, fast, automotive use.
- Grinding: Post-heat treat, uses abrasive wheels (form or generation). Expensive, slow, but provides ultimate precision for aerospace.
- Both improve surface finish and correct profile errors from initial machining.

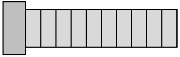
Feature	**Gear Shaving**	**Gear Grinding**
Stage	Pre-heat treatment (Soft)	Post-heat treatment (Hard)
Tool	Serrated HSS gear	Abrasive wheel
Accuracy	High (limited by heat treat)	Ultimate Precision
Cost	Economical	Very High
Primary Application	Automotive transmissions	Aerospace, high-speed turbines

Next Lecture Preview

- We have concluded Gear Manufacturing.
- In the next lecture, we begin Thread Manufacturing.
- We will start with Thread Terminology and Applications.
- Understanding pitch, lead, major/minor diameters, and thread forms.



Course: Manufacturing Engineering - III (DI05019011)
Unit 2: Gear & Thread Manufacturing Processes
Lecture 18: Thread Terminology and Application

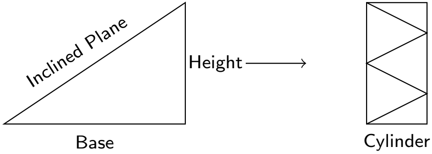


Agenda

- Introduction to Threads
- Functions of Threads
- Standard Thread Terminology
- Pitch vs. Lead (Multi-start threads)
- Common Thread Forms (Profiles)
- Applications of Different Thread Forms

Introduction to Threads

- A screw thread is a continuous helical ridge of uniform section cut on a cylinder or cone.
- It can be formed on the external surface (e.g., a bolt) or internal surface (e.g., a nut).
- Threads act as an inclined plane wrapped around a cylinder.
- They provide a massive mechanical advantage, converting rotational force into linear clamping force or motion.



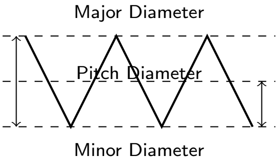
Functions of Threads

1. **Fastening:** Holding parts together (Bolts, screws, nuts).
2. **Power Transmission / Motion:** Converting rotary motion to linear motion (Lead screws in lathes, screw jacks).
3. **Measurement:** Providing precise linear adjustments (Micrometers).
4. **Fluid Sealing:** Connecting pipes tightly (Tapered pipe threads).

Function	Example
Fastening	Bolt and Nut
Power Transmission	Lead Screw
Measurement	Micrometer
Fluid Sealing	Pipe Fitting

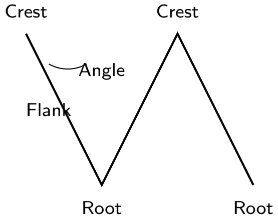
Thread Terminology: Diameters

- **Major Diameter:** The largest diameter of the thread. (Also known as outside diameter on a bolt).
- **Minor Diameter (Root Diameter):** The smallest diameter of the thread.
- **Pitch Diameter:** The theoretical diameter where the thread thickness equals the thread space.
- Most thread strength calculations and manufacturing measurements rely on the Pitch Diameter.



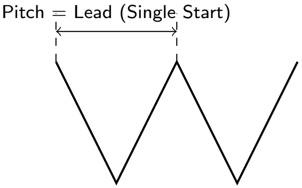
Thread Terminology: Anatomy

- **Crest:** The top surface joining the two sides of a thread.
- **Root:** The bottom surface joining the sides of two adjacent threads.
- **Flank:** The straight side of the thread connecting crest and root.
- **Thread Angle:** The angle included between the flanks of the thread (e.g., 60° for Metric and Unified threads).



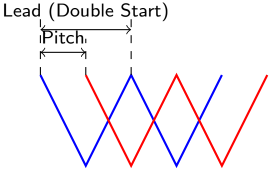
Pitch and Lead

- **Pitch (p):** The distance measured parallel to the axis from a point on one thread to the corresponding point on the adjacent thread.
- **Lead (l):** The linear distance the nut advances along the screw in one complete revolution (360°).
- In a single-start thread, Pitch = Lead.
- Lead determines the speed of linear motion.



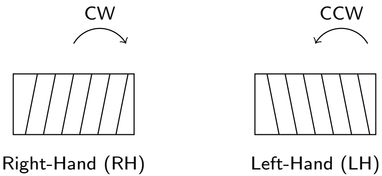
Multi-Start Threads

- A thread can consist of two or more independent helical ridges running side-by-side.
- Double-start: Lead $= 2 \times$ Pitch.
- Triple-start: Lead $= 3 \times$ Pitch.
- Formula: Lead (l) $=$ n $\times$ Pitch (p), where n is the number of starts.
- Purpose: Provides rapid linear motion without making the thread too deep (which would weaken the shaft).



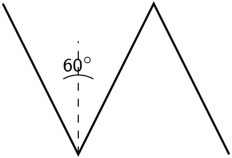
Handedness of Threads

- **Right-Hand (RH) Thread:** Advances (tightens) when turned clockwise. Standard for almost all applications.
- **Left-Hand (LH) Thread:** Advances when turned counter-clockwise.
- **LH Thread Applications:**
  - Rotating shafts where a RH thread would unscrew (e.g., bicycle left pedals).
  - Turnbuckles (uses one RH and one LH thread to draw two cables together).



Thread Forms: V-Threads

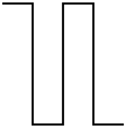
- **Profile:** Triangular shape, typically with a 60° angle (ISO Metric, Unified National).
- **Advantages:** High friction between threads prevents loosening; strong roots.
- **Applications:** Universal standard for fasteners (bolts, nuts, screws).
- Not ideal for power transmission due to high friction.

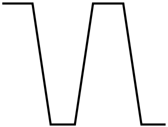


Standard V-Thread Profile

Thread Forms: Square and Acme

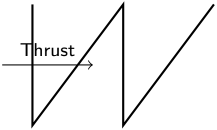
- **Square Thread:** Flanks are perpendicular to the axis. Highest efficiency, zero radial thrust. Very difficult to machine.
- **Acme Thread:** Trapezoidal profile (29° angle).
- Acme is slightly less efficient than Square but much easier to machine using single-point tools.
- **Applications:** Lead screws on lathes, screw jacks, CNC machines.



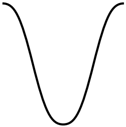


Thread Forms: Buttress and Whitworth

- **Buttress Thread:** One flank is almost vertical (pushing face), the other is angled.
- Designed to transmit extreme power in ONE direction only (e.g., heavy presses, vice screws).
- **Whitworth (BSW):** British standard with a 55° angle and rounded crests/roots for better fatigue resistance.



Buttress Thread



Whitworth (55°)

Summary

- Pitch is the distance between teeth; Lead is the advance per revolution.
- Major, Minor, and Pitch diameters define the thread size.
- V-threads (60°) are used for fastening due to high friction.
- Acme and Square threads are used for power transmission.
- Multi-start threads provide fast motion without weakening the shaft.

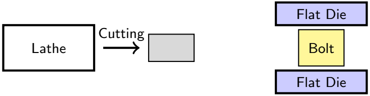
Thread Form	**Primary Application**
V-Thread	Fastening (Bolts, Screws)
Acme/Square	Power Transmission
Buttress	Unidirectional Power/Thrust

Next Lecture Preview

- In the next lecture, we will learn how to make these threads.
- **Thread Cutting:** Using single-point tools on a lathe, and using Taps & Dies.
- **Thread Rolling:** A chipless, mass-production forming process.
- We will compare cutting vs. rolling.

Thread Cutting and Thread Rolling

- Course: Manufacturing Engineering - III (DI05019011)
- Unit 2: Gear & Thread Manufacturing Processes
- Lecture 19: Thread Manufacturing Processes

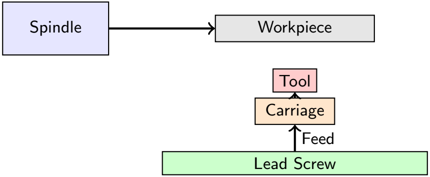


Agenda

- Thread Manufacturing Classification
- Thread Cutting on a Lathe (Single-point tool)
- Thread Cutting with Taps (Internal)
- Thread Cutting with Dies (External)
- Introduction to Thread Rolling
- Flat-Die Thread Rolling
- Cylindrical-Die Thread Rolling
- Comparison: Cutting vs. Rolling

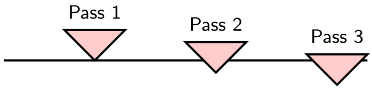
Thread Cutting: Single-Point Tool on a Lathe

- The most versatile method for generating threads.
- A single-point cutting tool (ground to the thread profile angle, e.g., 60°) is mounted on the lathe carriage.
- The carriage is driven linearly by the lathe's Lead Screw.
- Kinematics: The rotation of the spindle must be strictly synchronized with the linear feed of the carriage.



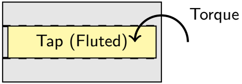
Lathe Threading Process

- For a thread with a Pitch 'p', the tool must advance exactly 'p' mm for every 1 revolution of the workpiece.
- The thread cannot be cut in a single pass. It requires multiple passes, feeding the tool deeper each time.
- A threading dial or half-nut lever is used to engage the carriage at the correct point for each pass.
- Advantage: Can cut very large diameters, square/acme profiles, and multi-start threads.



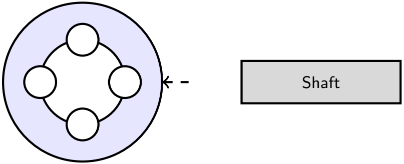
Thread Cutting: Taps (Internal Threads)

- Tapping is the process of cutting internal threads (in a pre-drilled hole).
- A Tap is a cylindrical tool with threads and flutes (grooves) cut into it to provide cutting edges and chip clearance.
- Typically done in sets by hand (Taper, Plug, Bottoming taps) or using a machine tap.
- Pre-drilled hole size (Tap Drill Size) is critical: Drill Size $\approx$ Major Dia - Pitch.



Thread Cutting: Dies (External Threads)

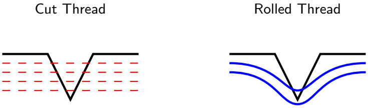
- Dies are used to cut external threads on cylindrical shafts.
- A Die is essentially a nut with flutes cut into it to create cutting edges.
- Thread Chasing: Using a self-opening die head on a turret lathe allows for high-speed external thread cutting.
- Often used for repair work or small batch production of bolts.



Threading Die Cross-section

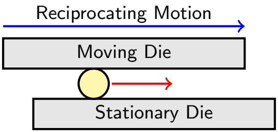
Thread Rolling: Principle

- A cold-forming (plastic deformation) process, NOT a cutting process.
- The thread profile is pressed into the blank cylinder using hardened steel dies.
- The material is displaced (pushed from the roots into the crests).
- Blank Diameter is critical: It must equal the Pitch Diameter of the final thread, not the Major Diameter.



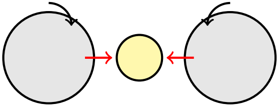
Flat-Die Thread Rolling

- Uses two rectangular, flat hardened steel dies with the thread profile machined into their faces.
- One die is stationary, the other reciprocates.
- The blank is inserted between the dies; the moving die rolls the blank across the stationary die.
- The thread is completely formed in a single pass.

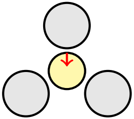


Cylindrical-Die Thread Rolling

- Uses two or three rotating cylindrical dies.
- Two-die machines: Blank rests on a blade between two rotating dies that plunge inward.
- Three-die machines: Blank is self-centered between three rotating dies (used for hollow tubes to prevent crushing).
- Can roll continuous threads on long rods (e.g., all-thread rods).



Two-Die Setup



Three-Die Setup

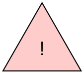
Advantages of Thread Rolling

- 1. Superior Strength: Cold working hardens the material, and unbroken grain flow increases fatigue life by up to 100%.
- 2. Material Savings: No chips are produced. Blank size is smaller than a cut bolt blank.
- 3. High Speed: Mass production rates far exceed any cutting method.
- 4. Excellent Surface Finish: The burnishing action creates a smooth, wear-resistant surface.

Strength | Zero Waste | Speed | Finish

Limitations of Thread Rolling

- Material Constraints: The workpiece must be ductile enough to cold-form (cannot roll cast iron or brittle hardened steels).
- Internal Threads: Very difficult to roll (though thread-forming taps exist, cutting is more common).
- Tooling Cost: Dies are expensive; only economical for large production runs.



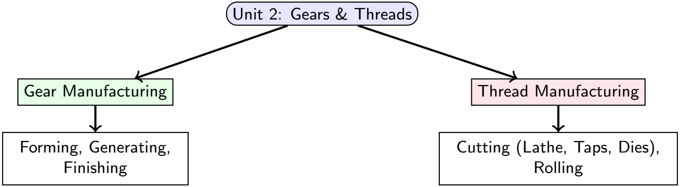
High Ductility Needed
High Setup Cost

Comparison: Cutting vs. Rolling

Feature	**Thread Cutting**	**Thread Rolling**
Strength	Weaker (broken grains)	Stronger (continuous grains)
Waste	Produces chips (waste)	Zero waste
Speed	Slower	Extremely fast
Materials	Any machinable material	Ductile materials only
Economics	Low volume (economical)	High volume (economical)

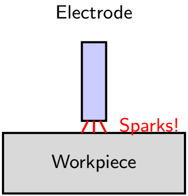
Summary of Unit 2

- We covered Gear Types, Terminology, and Manufacturing (Forming, Generating, Finishing).
- We covered Thread Terminology and Manufacturing (Cutting via Lathe/Taps/Dies and Rolling).
- Manufacturing processes are always selected based on the balance of required strength, precision, volume, and cost.



Next Lecture Preview

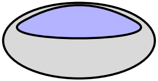
- In the next unit (Unit 3), we will begin our study of Non-Conventional Machining Processes.
- We will explore how to machine materials using electrical sparks, lasers, water jets, and chemicals.
- Starting with an introduction and classification of modern machining.



Gear Forming Processes: Gear Milling

Manufacturing Engineering - III (DI05019011)

DI05019011



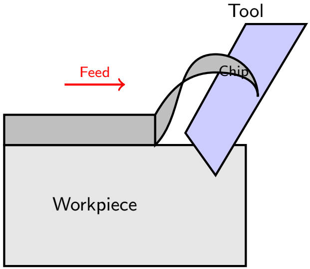
Complex Component

Unit 3 Overview

- Need and comparison of non-conventional machining
- Classification and principles (ECM, EDM, USM, LBM, AJM, PAM, WJM)
- Selection criteria for various processes
- Introduction to MEMS and micro-fabrication

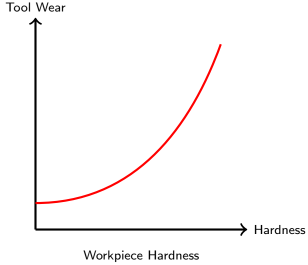
What is Conventional Machining?

- Relies on physical contact between a harder tool and a softer workpiece.
- Material is removed in the form of chips via plastic deformation.
- Examples: Turning, Milling, Drilling, Shaping, Grinding.
- Requires relative motion and significant cutting forces.



Limitations of Conventional Machining

- Tool hardness constraint: Tool must be harder than the workpiece.
- Tool wear: Rapid wear occurs when machining high-strength materials.
- Cutting forces: High forces induce residual stresses and distortions.
- Heat generation: High temperatures can alter the metallurgical structure of the workpiece.

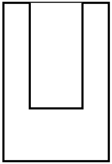


The Rise of Advanced Materials

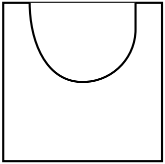
- Industries like aerospace, nuclear, and medical demand high-performance materials.
- Examples: Titanium alloys, Nimonic alloys, Tungsten carbides, High-strength temperature resistant (HSTR) alloys.
- Properties: High hardness, high strength-to-weight ratio, high temperature resistance.
- These properties make them extremely difficult to machine conventionally.

Complex Geometries and Features

- Conventional machining is limited to specific shapes (e.g., cylindrical, flat).
- Modern applications require intricate shapes, non-circular holes, and complex cavities.
- Examples: Cooling holes in turbine blades, blind non-circular holes, micro-features.
- Tool accessibility is a major constraint in conventional methods.



Simple Drilled Hole



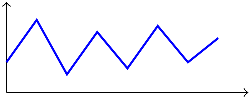
Non-circular Curved Cavity

Delicate and Fragile Workpieces

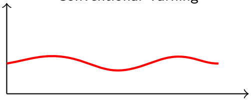
- Conventional methods exert significant macroscopic forces on the workpiece.
- Thin sections, delicate structures, and brittle materials (glass, ceramics) easily crack or deform.
- Non-conventional processes often exert zero or minimal physical force.
- Enables machining of honeycomb structures and extremely thin foils.

Requirement for High Surface Finish & Precision

- Certain applications demand mirror-like surface finishes (e.g., optical components, dies).
- Conventional grinding can leave micro-cracks and residual stresses.
- Advanced methods like ECM provide stress-free surfaces with excellent finish.
- Tolerances in the micron and sub-micron range are achievable.



Conventional Turning



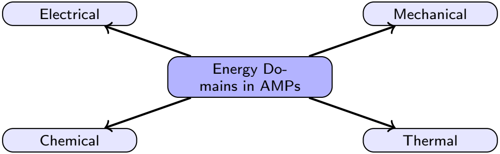
ECM Surface

Miniaturization and Micro-Machining

- Growing trend towards miniaturization in electronics and medical devices.
- Requires micro-holes, micro-channels, and features smaller than traditional tools.
- Conventional tools become too weak at micro-scales and break easily.
- Necessitates the use of energy beams (Laser, Electron beam) or micro-EDM.

What are Non-Conventional Machining Processes?

- Also known as Unconventional or Advanced Machining Processes (AMPs).
- Do not employ a conventional physical cutting tool.
- Utilize direct energy (mechanical, electrical, thermal, or chemical) to remove material.
- Performance is generally independent of the workpiece's physical hardness.



Primary Energy Sources Used

Mechanical Erosion by high-velocity abrasive particles (e.g., AJM, USM)	**Electrical/Thermal** Melting & vaporization via sparks or beams (e.g., EDM, LBM)
Chemical Controlled chemical dissolution (e.g., CHM)	**Electrochemical** Anodic dissolution using electricity (e.g., ECM)

Summary of the Need

Key Drivers for AMPs

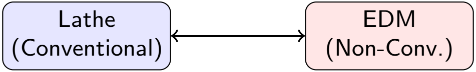
- ✓ Conventional machining fails with very hard or tough materials.
- ✓ Complex and intricate geometries are impossible to machine with solid tools.
- ✓ Fragile parts require zero-force machining.
- ✓ Advanced industries require stress-free, high-precision manufacturing.
- ✓ Non-conventional processes fill this gap using alternative energy forms.

Next Lecture Preview

- Detailed comparison between conventional and non-conventional machining.
- Cost, environmental impact, and production rate comparisons.
- When NOT to use non-conventional machining.

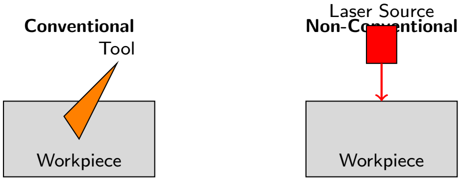
Comparison between Conventional & Non-conventional Machining

Course: Manufacturing Engineering - III (DI05019011)
Unit 3: Non-conventional and Advanced Methods of Machining
Lecture 21



Fundamental Difference: Tool and Workpiece Interaction

- Conventional: Physical contact is mandatory. Tool penetrates workpiece.
- Non-conventional: No physical contact required. Tool acts as an energy director.
- Conventional requires tool hardness $>$ workpiece hardness.
- Non-conventional is independent of workpiece hardness.



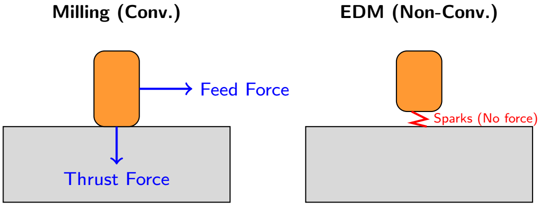
Material Removal Mechanism

- Conventional: Macroscopic shear deformation leading to chip formation.
- Non-conventional: Various mechanisms depending on the energy type.
- Thermal: Melting and vaporization (EDM, LBM).
- Chemical/Electrochemical: Ion-by-ion dissolution (ECM).
- Mechanical Erosion: Micro-chipping (USM, AJM).

Process Category	**Primary Mechanism**
Conventional	Macroscopic Shear
Non-Conventional (Thermal)	Melting & Vaporization
Non-Conventional (Chemical)	Ion-by-ion Dissolution
Non-Conventional (Mechanical)	Erosion (Micro-chipping)

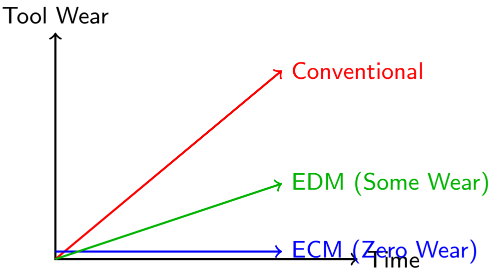
Forces and Residual Stresses

- Conventional: High cutting forces. Induces significant residual stresses. Requires heavy, rigid machine tools and strong fixtures.
- Non-conventional: Minimal or zero cutting forces. Allows machining of fragile parts. Minimal induced macroscopic residual stresses (though thermal processes may cause microscopic stress).



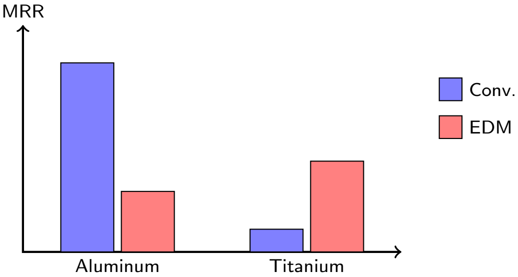
Tool Wear and Maintenance

- Conventional: Tool wear is inevitable and significant. Tools must be frequently sharpened or replaced.
- Non-conventional: Tool wear varies. Zero wear in LBM/ECM. Some wear in EDM/USM.
- Tool geometry in non-conventional (like ECM) remains perfectly intact, ensuring long-term precision.



Material Removal Rate (MRR)

- Conventional: High MRR for standard materials (aluminum, mild steel). Very low MRR for superalloys.
- Non-conventional: Generally lower MRR compared to conventional turning/milling of soft metals.
- However, for superalloys, Non-conventional MRR often exceeds Conventional MRR.
- Non-conventional is generally NOT used for bulk material removal if conventional is possible.



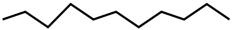
Accuracy and Surface Finish

- Conventional: Good accuracy, but affected by tool wear and deflection. Surface finish is directional (tool marks).
- Non-conventional: Extremely high precision. Complex shapes replicated perfectly.
- Surface finish is often non-directional (matte in EDM, smooth in ECM).
- Capable of achieving nanometer surface roughness in specific processes.

Milled Surface

Directional Marks

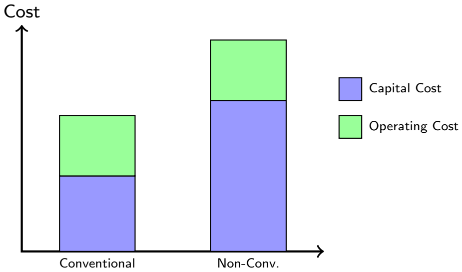
EDM Surface



Random Craters (Matte)

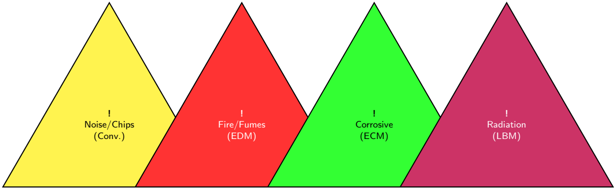
Capital Cost and Operating Cost

- Conventional: Lower initial capital cost (standard lathes/mills). Lower operating costs.
- Non-conventional: High initial investment (generators, lasers, specialized equipment).
- High energy consumption and expensive consumables (dielectric fluids, electrolytes, lenses).
- Maintenance requires specialized technicians.



Environmental and Safety Aspects

- Conventional: Noise, flying chips, cutting fluid disposal.
- Non-conventional: Specific hazards depending on process.
- EDM: Fumes, risk of fire with dielectrics.
- ECM: Corrosive electrolytes, hydrogen gas generation.
- LBM: Radiation hazards, need for strict safety enclosures.



Summary Comparison Table (Part 1)

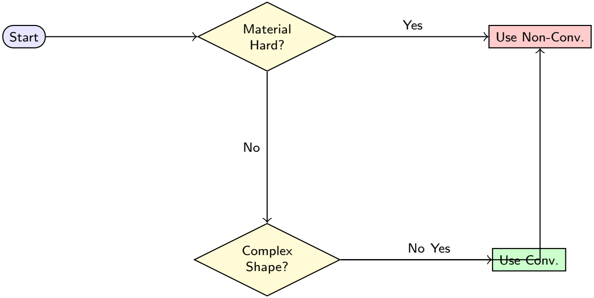
Parameter	Conventional	Non-Conventional
Tool/Work contact	Yes	No (usually)
Workpiece hardness	Must be less than tool	Irrelevant
Mechanics	Macroscopic shear	Melting, erosion, dissolution
MRR	Generally High	Generally Low

Summary Comparison Table (Part 2)

Parameter	Conventional	Non-Conventional
Tool Wear	High	Varies (Zero to Medium)
Capital Cost	Low to Medium	Very High
Complexity of setup	Simple	Complex (fluids, powers)
Energy Consumption	Low	High

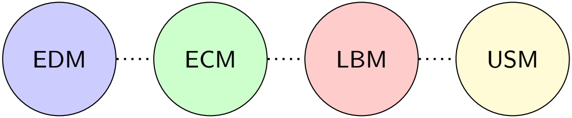
When to choose Non-Conventional?

- Material is too hard or brittle (e.g., > 400 HB).
- Shape is too complex for standard tools (e.g., non-circular blind holes).
- Workpiece is too fragile to withstand cutting forces.
- Ultra-high precision or specific surface integrity is required.
- Rule of thumb: If it can be done conventionally, do it conventionally (it's cheaper!).



Next Lecture Preview

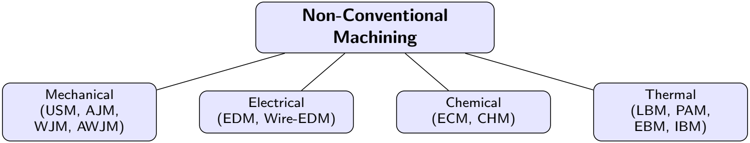
- Deep dive into specific processes.
- Classification of Non-conventional Machining.
- Working principles of ECM, EDM, USM, LBM, AJM, PAM, WJM.



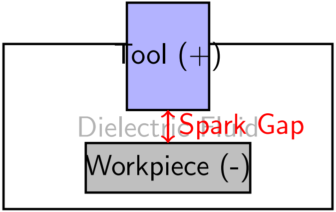
Classification and Principles of Non-conventional Methods

Course: Manufacturing Engineering - III (DI05019011)
Unit 3: Non-conventional and Advanced Methods of Machining
Lecture 22: Classification and Principles of Major Processes

Classification of Non-Conventional Machining

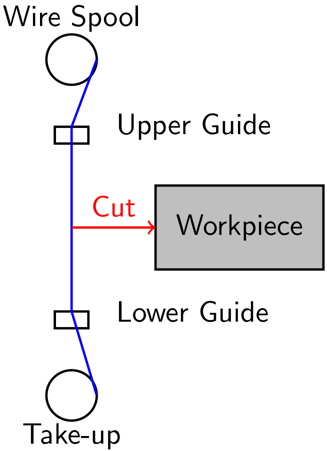


- Mechanical Processes: USM, AJM, WJM, AWJM (Erosion/abrasion).
- Electrical/Electro-Thermal Processes: EDM, Wire-EDM (Melting/vaporization).
- Chemical/Electrochemical Processes: ECM, CHM (Ion displacement/dissolution).
- Thermal/High-Energy Beam Processes: LBM, PAM, EBM, IBM (Intense localized heating).



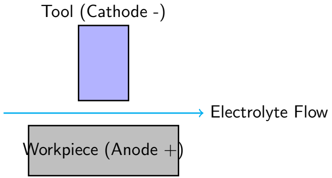
- Principle: Controlled electrical sparks between tool and workpiece melt and vaporize material.
- Requires conductive workpieces.
- Submerged in dielectric fluid (flushes debris, concentrates spark).
- Parameters: Discharge current, pulse ON/OFF time, gap voltage.
- Applications: Die sinking, mould making, very hard conductive materials.

Wire-Cut EDM (WEDM)



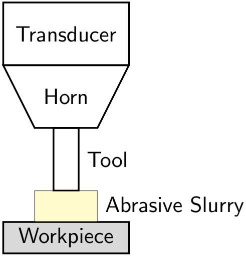
- Variant of EDM using a continuously traveling thin wire (brass or copper) as the tool.
- Acts like an electrical bandsaw cutting complex 2D and 3D contours.
- Uses deionized water as dielectric.
- Applications: Extrusion dies, blanking punches, intricate shapes in hard metals.

Electro Chemical Machining (ECM)



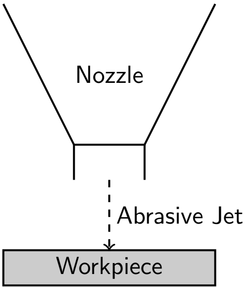
- Principle: Reverse electroplating. Anodic dissolution of workpiece.
- Tool is cathode, workpiece is anode, separated by flowing electrolyte (NaCl solution).
- Zero tool wear, extremely high MRR for superalloys, stress-free finish.
- Parameters: Voltage, current density, electrolyte flow rate and concentration.
- Applications: Aerospace turbine blades, jet engine parts.

Ultrasonic Machining (USM)



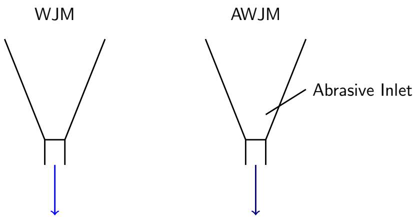
- Principle: Tool vibrating at ultrasonic frequency (20-30 kHz) drives abrasive slurry into workpiece.
- Mechanism: Micro-chipping and erosion.
- Ideal for hard and brittle materials (glass, ceramics, quartz). Does NOT require workpiece to be conductive.
- Parameters: Amplitude, frequency, abrasive grit size, slurry concentration.
- Applications: Coining, drilling holes in glass/ceramics.

Abrasive Jet Machining (AJM)



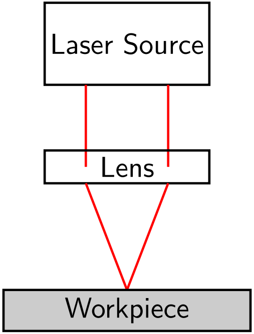
- Principle: High-velocity stream of gas carrying fine abrasive particles hits the workpiece.
- Mechanism: Erosion via micro-cutting action.
- Used for cleaning, frosting, and cutting delicate/brittle materials.
- Parameters: Gas pressure, nozzle stand-off distance, abrasive type/size.
- Applications: Deflashing small parts, frosting glass, cutting fragile components.

Water Jet Machining (WJM) & AWJM



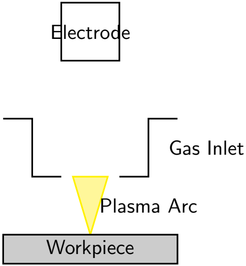
- WJM Principle: Extremely high-pressure water jet (up to 400 MPa) cuts through soft materials (rubber, foam, food).
- AWJM (Abrasive WJM): Abrasives added to water jet to cut hard metals, rock, and thick plates.
- Cold cutting process – no thermal damage (Heat Affected Zone).
- Parameters: Water pressure, jet diameter, traverse speed, abrasive feed rate.
- Applications: Cutting thick steel profiles, aerospace composites, marble.

Laser Beam Machining (LBM)



- Principle: Highly focused monochromatic light beam melts and vaporizes material.
- Non-contact process, works in atmospheric conditions, cuts almost any material.
- Can drill incredibly small holes (micro-machining).
- Parameters: Laser power, pulse duration, focal length, cutting gas.
- Applications: Micro-drilling, cutting sheet metal profiles, medical device manufacturing.

Plasma Arc Machining (PAM)



- Principle: High-velocity jet of high-temperature ionized gas (plasma) melts the metal.
- Temperatures can reach 10,000 to 30,000 $^{\circ}$C.
- Fastest cutting speed for thick conductive plates (stainless steel, aluminum).
- Parameters: Arc voltage, plasma gas flow rate, cutting speed.
- Applications: Heavy industry, shipbuilding, cutting thick metal plates.

Key Characteristics Summary

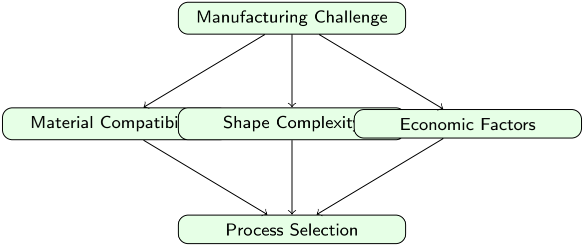
Process	Conductivity Required	Material Type	Typical Application
EDM / ECM	Yes	Hard	Die making, Aerospace parts
USM	No	Hard & Brittle	Glass/Ceramics drilling
LBM / AWJM	No	Various	Profile cutting
PAM	Yes	Thick Plates	Rough cutting
AJM	No	Fragile/Brittle	Light erosion, Surface treatment

- EDM/ECM: Requires conductive materials. High accuracy.
- USM: Best for non-conductive, brittle materials.
- LBM/AWJM: Excellent for profile cutting of various materials.
- PAM: High MRR rough cutting for thick plates.
- AJM: Light erosion and surface treatment.

Summary

- Non-conventional processes use electrical, chemical, mechanical, or thermal energy.
- ECM and EDM are widely used for hard metals and die making.
- USM handles glass and ceramics.
- LBM and AWJM offer versatile profiling capabilities without physical tooling.
- Understanding the specific parameters of each process is vital for successful application.

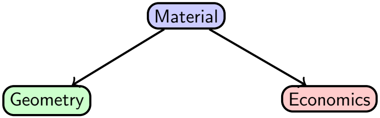
Next Lecture Preview



- How do we choose between these processes?
- Criterion for selection of non-conventional machining methods.
- Material compatibility, shape complexity, and economic factors.

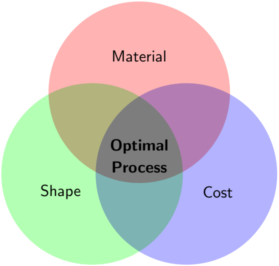
Selection Criteria for Non-conventional Machining (Part 1)

- Course: Manufacturing Engineering - III (DI05019011)
- Unit 3: Non-conventional and Advanced Methods of Machining
- Lecture 23: Selection Criteria - Materials and Geometry



The Selection Challenge

- No single non-conventional process is universally optimal.
- Choosing the wrong process leads to excessive costs, poor quality, or outright failure.
- Selection is a multi-parameter optimization problem.
- Primary decision pillars: Material, Geometry, Surface requirements, Economics.

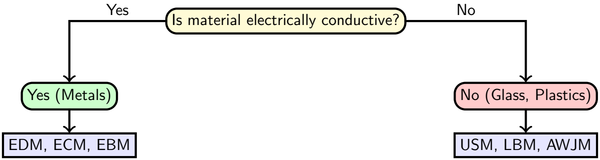


Criterion 1: Material Properties

- The first and most restrictive filter is the workpiece material.
- **Electrical Conductivity**: Is the material a conductor, semiconductor, or insulator?
- **Thermal Properties**: Melting point, thermal conductivity.
- **Mechanical Properties**: Hardness, brittleness, toughness.
- **Chemical Properties**: Reactivity, corrosion resistance.

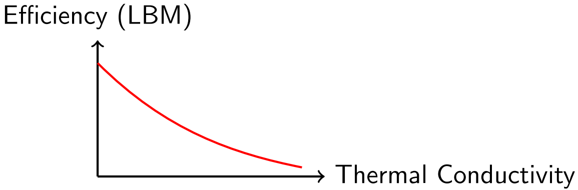
Material: Electrical Conductivity

- Conductive Materials (Metals, Alloys): Can use EDM, ECM, PAM, EBM.
- Non-Conductive Materials (Glass, Ceramics, Plastics): EDM and ECM are impossible.
- Must use USM, LBM, AWJM, or AJM for non-conductors.
- Semiconductors: May require specialized processes or careful parameter tuning in EDM.



Material: Thermal Properties

- Thermal processes (EDM, LBM, PAM, EBM) rely on melting and vaporization.
- High Melting Point materials require more energy.
- High Thermal Conductivity materials dissipate heat rapidly, reducing process efficiency.
- Materials sensitive to thermal damage should avoid thermal processes.



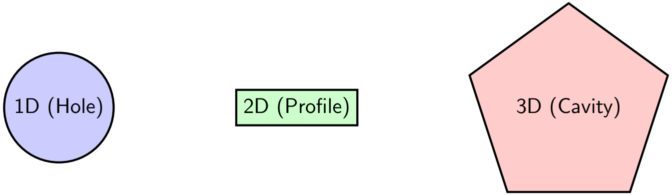
Material: Hardness and Brittleness

- Non-conventional processes are largely independent of material hardness.
- Extremely brittle materials (glass, quartz) may crack under localized thermal stress (LBM).
- USM thrives on brittle materials due to its micro-chipping mechanism.
- Ductile materials are poorly machined by USM but machine well with ECM.

Material Type	**Preferred Process**
Brittle (Glass, Ceramics)	USM, AWJM
Ductile/Hard (Metals)	ECM, EDM

Criterion 2: Shape and Geometry Requirements

- What is the final shape of the part?
- 1D features: Small/micro holes.
- 2D features: Through-cutting, profiling, slotting.
- 3D features: Blind cavities, complex dies, 3D contouring.
- Different processes excel at different dimensionalties.



Geometry: 1D - Micro-Hole Drilling

- Requires deep, small diameter holes (high aspect ratio).
- LBM: Excellent for very small, rapid hole drilling (e.g., cooling holes in turbine blades).
- EDM (Micro-EDM): Good for accurate holes in conductive materials.
- USM: Good for drilling holes in non-conductive brittle materials.
- ECM (STEM drilling): Used for deep, stress-free holes.

Geometry: 2D - Profiling and Through-Cutting

- Cutting shapes out of sheet metal or thick plates.
- Wire-EDM: Extremely accurate, tight corners, conductive materials only.
- LBM: Very fast, precise, for thin to medium sheets.
- AWJM (Waterjet): Can cut almost any material, thick plates, no heat affected zone.
- PAM: Fast rough cutting for thick metal plates.

Geometry: 3D - Blind Cavities and Sinking

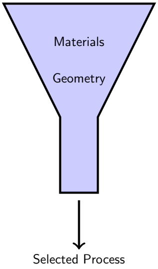
- Forming complex 3D shapes without breaking through the material (e.g., forging dies, injection molds).
- Die-Sinking EDM: The most common process. Tool shape is replicated in the workpiece.
- ECM: Also replicates tool shape, faster than EDM, but tooling is more expensive.
- LBM and AWJM are generally NOT suitable for precision 3D blind cavities.

Process Capabilities Matrix (Material & Geometry)

Process	Mat. Limits	1D Holes	2D Profiling	3D Cavities
EDM	Conductive	Good	Excellent (Wire)	Excellent
ECM	Conductive	Good	Poor	Excellent
LBM	Reflectivity	Excellent	Excellent	Poor
USM	Brittle Only	Good	Poor	Fair
AWJM	None	Fair	Excellent	Poor

Summary of Part 1

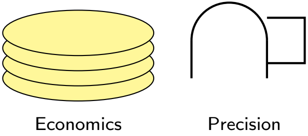
- Process selection begins with filtering by material properties (conductivity, thermal, mechanical).
- Geometry requirements (1D, 2D, 3D) further narrow down the options.
- EDM/ECM dominate conductive 3D work.
- LBM/AWJM dominate 2D profiling.
- USM specializes in non-conductive brittle materials.



Next Lecture Preview

- Selection Criteria Part 2: Process Capabilities and Economics.
- Surface finish, tolerance, MRR, and cost considerations.
- Final decision making frameworks.

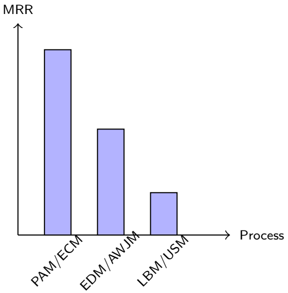
Selection Criteria for Non-conventional Machining (Part 2)



- Course: Manufacturing Engineering - III (DI05019011)
- Unit 3: Non-conventional and Advanced Methods of Machining
- Lecture 24: Selection Criteria - Quality and Economics

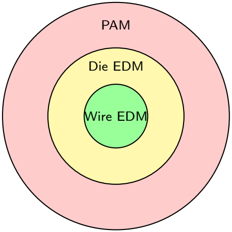
Criterion 3: Process Capabilities - MRR

- Material Removal Rate (MRR) dictates production speed.
- **High MRR:** PAM, ECM. Used when volume removal is prioritized.
- **Medium MRR:** EDM, AWJM.
- **Low MRR:** LBM, USM, AJM. Typically used for finishing or micro-features.
- Trade-off: Higher MRR usually results in poorer surface finish and lower accuracy.



Criterion 4: Tolerance and Accuracy

- How precisely must the part be made?
- **High Accuracy** ($\pm$ 5 to 10 μm): Wire-EDM, LBM, Micro-EDM.
- **Medium Accuracy** ($\pm$ 25 to 50 μm): Die-sinking EDM, ECM.
- **Low Accuracy** ($\pm$ 100+ μm): PAM, AWJM.
- Over-specifying tolerance restricts process choice and exponentially increases cost.



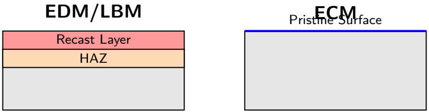
Criterion 5: Surface Finish

- Required surface roughness (Ra) varies by application.
- Note: ECM can produce mirror finishes as it dissolves material atom by atom.

Category	Ra Value	Typical Processes
Excellent	$< 0.5\mu$m	ECM, Wire-EDM (trim passes)
Good	$0.5 - 2\mu$m	Die-sinking EDM, LBM
Rough	$> 5\mu$m	PAM, AWJM

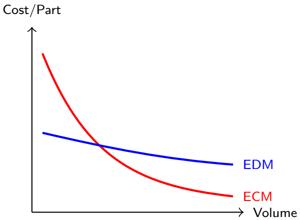
Criterion 6: Surface Integrity and Damage

- It's not just about roughness; it's about sub-surface damage.
- **Thermal** (EDM, LBM): Recast Layer and Heat Affected Zone (HAZ). May induce micro-cracks.
- **Mechanical** (USM, AWJM): Compressive residual stresses, no HAZ.
- **Chemical/Electrochemical** (ECM): Stress-free surface, no HAZ.



Criterion 7: Economic Considerations

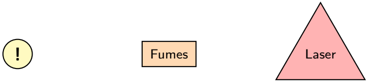
- **Capital Cost:** LBM and ECM are very expensive. EDM and AWJM are moderate.
- **Tooling Cost:** ECM tooling is expensive. EDM electrodes wear out. LBM/AWJM have zero physical tooling cost.
- **Operating Cost:** Consumables (power, gas, wire, abrasives).
- **Production Volume:** ECM for mass production. EDM/LBM for small batches.



Environmental and Safety Factors

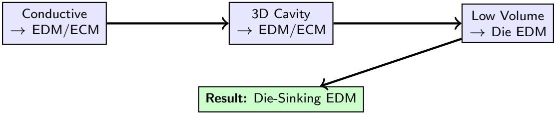
Process selection must account for waste disposal and safety equipment costs.

- **EDM:** Dielectric fluid fumes, fire risk.
- **ECM:** Disposal of metal hydroxide sludge, corrosive electrolytes.
- **LBM:** Fumes from vaporized metal, high-voltage/radiation hazards.
- **AWJM:** Cleanest process, but generates abrasive/metal sludge.



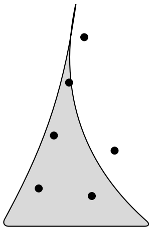
Decision Synthesis: Case Study 1

- **Part:** Forging die for a wrench.
- **Material:** Hardened tool steel (Conductive, Hard).
- **Geometry:** 3D complex cavity.
- **Volume:** Low (Tool room application).



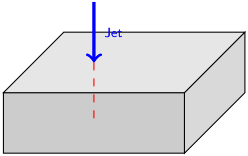
Decision Synthesis: Case Study 2

- **Part:** Cooling holes in turbine blade.
- **Material:** Nickel superalloy (Conductive, Heat resistant).
- **Geometry:** High aspect ratio 1D micro-holes.
- **Requirement:** No micro-cracks allowed.
- **Selection:** LBM leaves HAZ. EDM leaves recast layer. STEM (variant of ECM) leaves a stress-free surface.
- **Result:** ECM (STEM) or specialized ultra-short pulse LBM.



Decision Synthesis: Case Study 3

- **Part:** Complex profile from 50mm Titanium plate.
- **Material:** Titanium (Conductive, hard).
- **Geometry:** 2D through-cut, thick profile.
- **Requirement:** No thermal distortion, good edge quality.
- **Selection:** LBM cannot cut 50mm efficiently. WEDM is slow. AWJM cuts thick materials cold with no HAZ.
- **Result:** Abrasive Water Jet Machining (AWJM).



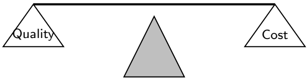
Comprehensive Selection Matrix

A final review table combining Material, Geometry, Surface Finish, and Cost criteria.

Process	Material Req.	Best Geometry	Surface Finish	Tooling Cost
EDM	Conductive	3D Cavities	Good	High
Wire-EDM	Conductive	2D Profiles	Excellent	Low
ECM	Conductive	3D Cavities	Excellent	Very High
LBM	Any	2D Profiles, 1D	Good	Low
AWJM	Any (Thick)	2D Profiles	Rough	Low

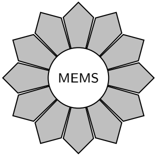
Summary

- Process selection requires balancing physical capabilities against quality and cost.
- Tolerance and surface integrity requirements often dictate the final choice.
- Tooling costs vs. Production volume is the primary economic driver.
- Environmental impacts must be factored into total cost.



Next Lecture Preview

- Shifting gears to the micro-scale.
- Introduction to MEMS (Micro-Electro-Mechanical Systems).
- Characteristics and scaling laws in micro-manufacturing.

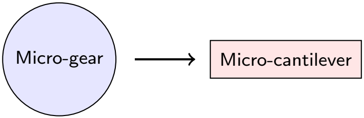


Introduction to MEMS and its Characteristics

Course: Manufacturing Engineering - III (DI05019011)

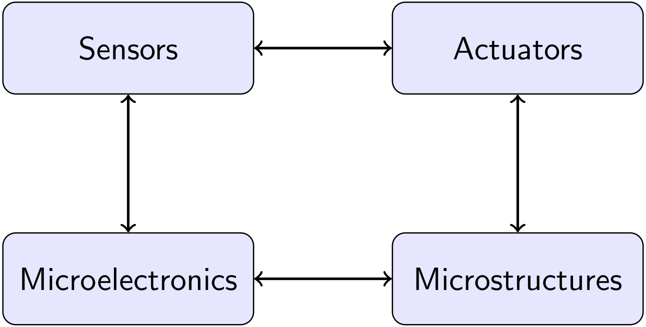
Unit 3: Non-conventional and Advanced Methods of Machining

Lecture 25: Introduction to MEMS



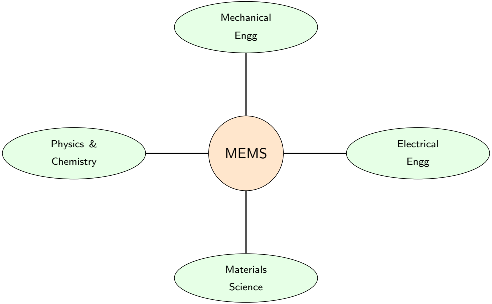
What is MEMS?

- MEMS: Micro-Electro-Mechanical Systems.
- Miniaturized devices that integrate electrical and mechanical components on a single chip.
- Size ranges from a few micrometers to millimeters.
- They are fabricated using techniques derived from the integrated circuit (IC) industry.
- Europe often calls it 'Microsystems Technology (MST)'.



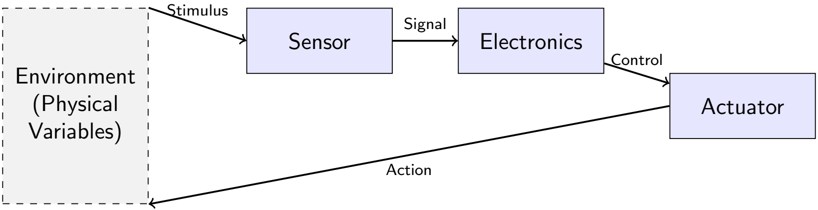
The Multidisciplinary Nature of MEMS

- MEMS is not just mechanical engineering.
- Requires knowledge of:
  - Mechanical Engineering (Structures, kinematics)
  - Electrical Engineering (Circuits, signal processing)
  - Materials Science (Silicon, polymers, thin films)
  - Physics and Chemistry (Micro-fluidics, scaling laws)



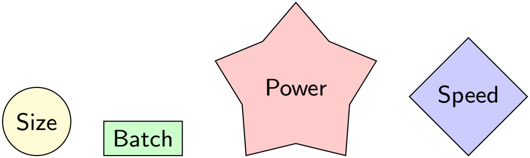
Basic Components of a MEMS Device

- Micro-sensors: Detect changes in the environment (pressure, temperature, acceleration).
- Micro-actuators: Create motion or produce an action (micro-valves, micro-motors, pumps).
- Micro-electronics: Process the sensor signals and control the actuators.
- Micro-structures: The physical housing, beams, and mechanical framework.



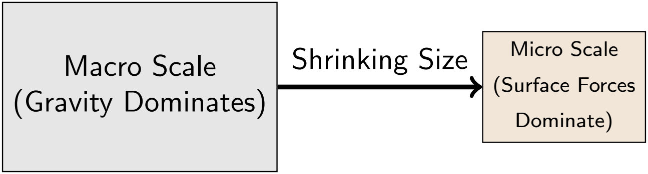
Characteristics of MEMS

- **Miniaturization**: Small size, low weight.
- **Multiplicity**: Batch fabrication allows millions of identical components to be made simultaneously.
- **Microelectronics Integration**: Seamless merging with control circuits.
- **Low Power Consumption**: Due to their small size, they require very little energy.
- **High Performance**: Quick response times due to low mass/inertia.



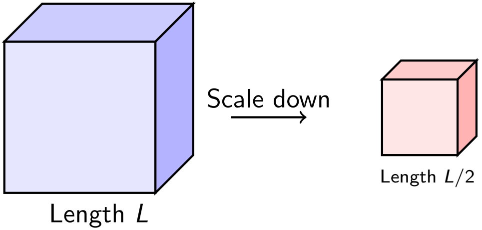
The Physics of the Micro-Scale

- As objects shrink, physical forces scale differently.
- Volume-dependent forces (gravity, inertia) become negligible.
- Surface-area-dependent forces (friction, surface tension, electrostatic forces) dominate.
- This shift in dominant physics is explained by 'Scaling Laws'.



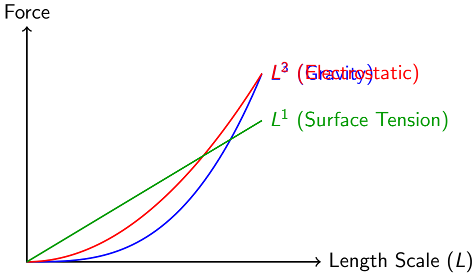
Understanding Scaling Laws (Linear Scaling)

- Let 'L' be the characteristic length of an object.
- If we scale down an object by a factor of 10 (L decreases by 10):
  - Length scales as L^1
  - Area scales as L^2
  - Volume and Mass scale as L^3
- Volume decreases much faster than surface area.



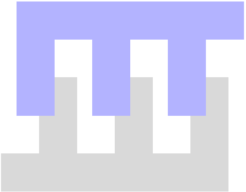
Scaling of Forces

- Gravity (Weight) scales with Volume (L^3).
- Electromagnetic forces scale with Volume (L^3).
- Electrostatic forces scale with Area (L^2).
- Surface tension scales with Length (L^1).
- **Conclusion**: At micro-scales, Electrostatic forces are much stronger than Electromagnetic forces.



Implications of Scaling on MEMS Design

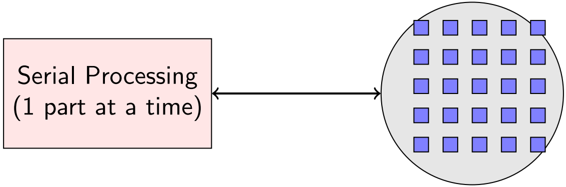
- **Actuation**: Use electrostatic combs instead of electric motors.
- **Stiction**: Surface adhesion forces are so strong that micro-parts can stick together permanently.
- **Friction**: Wear and friction are major failure modes in sliding MEMS parts.
- **Resonance**: Low mass means very high natural frequencies (fast response times).



Electrostatic Comb Drive

Batch Fabrication Advantage

- Unlike macro-machining (turning, milling) which is serial (one part at a time).
- MEMS uses parallel processing (batch fabrication).
- Thousands of devices are built simultaneously on a single silicon wafer.
- Dramatically reduces cost per unit.
- Leverages trillions of dollars of IC industry infrastructure.



Parallel Processing (Thousands per wafer)

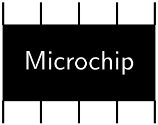
Everyday Examples of MEMS

- Smartphone Accelerometers and Gyroscopes (screen rotation, gaming).
- Automotive Airbag sensors (crash detection).
- Inkjet Printer Heads (piezoelectric micro-pumps).
- DLP Projector chips (millions of micro-mirrors).
- Microphones in cell phones.

Smartphone Sensors	Airbag Sensors	DLP Projectors

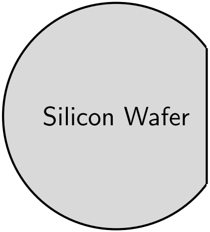
Summary

- MEMS integrates mechanical and electrical components at the micro-scale.
- Devices consist of sensors, actuators, and electronics.
- Scaling laws dictate that surface forces (electrostatic, stiction) dominate over volume forces (gravity, inertia).
- Batch fabrication enables mass production at incredibly low costs.



Next Lecture Preview

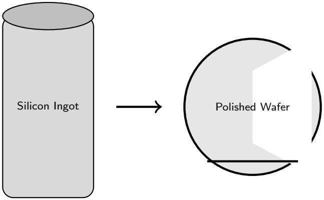
- Materials used in MEMS.
- Why Silicon is the dominant material.
- Role of Polymers, Metals, and Ceramics in micro-manufacturing.



Gear Forming Processes: Gear Milling

Manufacturing Engineering - III (DI05019011)

DI05019011



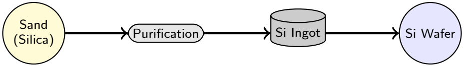
Why Focus on Materials?

- In macro-machining, we have thousands of materials to choose from (steel, brass, aluminum, plastics).
- In micro-machining (MEMS), the material choice is highly restricted.
- The material must act as an electrical component, a mechanical structure, and be compatible with micro-fabrication processes.
- Silicon fulfills all these requirements exceptionally well.

Macro-Materials	**Micro-Materials (MEMS)**
Steel, Brass, Aluminum	Silicon (Dominant)
Diverse properties available	Must be IC-compatible
Machined by cutting tools	Photolithography & Etching

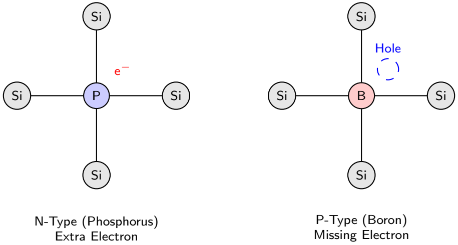
Silicon: The Foundation of MEMS

- Silicon (Si) is the most abundant element in the Earth's crust (after oxygen).
- It is the backbone of the trillion-dollar semiconductor/IC industry.
- MEMS leverages this massive existing infrastructure.
- Because the manufacturing tools already exist for Silicon, it is the cheapest and most reliable material to use for MEMS.



Silicon as an Electrical Material

- Silicon is a semiconductor.
- Its electrical conductivity can be precisely controlled by 'doping' (adding impurities like Boron or Phosphorus).
- Allows integration of transistors, resistors, and control logic directly on the same substrate as the mechanical parts.
- Piezoresistive effect: Silicon's electrical resistance changes significantly when mechanically strained (perfect for sensors).



Silicon as a Mechanical Material

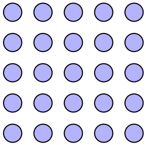
- Surprising fact: Single-crystal Silicon is mechanically superior to most metals at the micro-scale.
- High Strength: Yield strength is higher than stainless steel.
- Low Density: Lighter than aluminum, leading to low inertia and fast response times.
- No Hysteresis: Silicon deforms perfectly elastically until it breaks. It does not permanently bend.
- High fatigue life: Silicon springs can flex billions of times without degrading.

Material	**Yield Strength (GPa)**	**Density (g/cm^3)**
Single-Crystal Silicon	~ 7.0	2.3
Stainless Steel	$\sim 0.2 - 1.0$	7.9
Aluminum	$\sim 0.1 - 0.5$	2.7

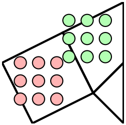
Single-Crystal vs. Polycrystalline Silicon

- Single-Crystal Silicon (Bulk): Used as the substrate/wafer. Atoms are arranged in a perfect, continuous lattice. Anisotropic properties.
- Polysilicon: Deposited as a thin film on top of the wafer. Composed of many small crystals. Isotropic properties.
- Polysilicon is heavily used for the moving parts (surface micro-machining) because it can be deposited over sacrificial layers.

Single-Crystal Silicon
(Aligned Atoms)

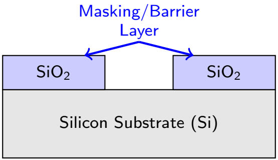


Polycrystalline Silicon
(Random Grains)



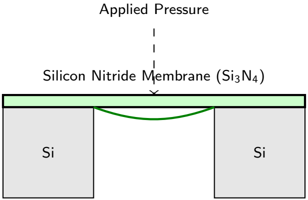
Silicon Compounds: Silicon Dioxide (SiO2)

- Thermally grown or deposited on the silicon wafer.
- Excellent electrical insulator.
- Role in MEMS:
  1. Masking material during etching processes.
  2. Sacrificial material: It provides a temporary support structure that is later dissolved to free moving polysilicon parts.



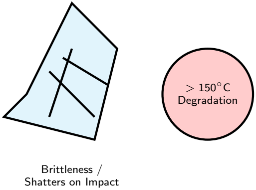
Silicon Compounds: Silicon Nitride (Si3N4)

- Deposited as a thin film.
- Extremely hard and chemically inert.
- Excellent electrical insulator and water/sodium barrier.
- Role in MEMS: Used as a structural membrane material or an isolation layer. Provides excellent wear resistance for moving parts.



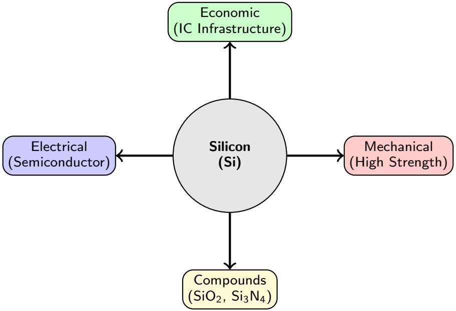
Limitations of Silicon in MEMS

- Brittleness: It does not yield; it shatters under sudden macroscopic impact.
- Optical properties: Opaque to visible light (transparent to IR).
- Bio-compatibility: Bare silicon is not fully bio-compatible for implantable medical devices.
- High-temperature limit: Electronic properties degrade at high temperatures ($> 150^\circ$C).



Summary of Silicon's Dominance

- Abundant and leverages IC industry infrastructure.
- Excellent semiconductor properties (doping, piezoresistivity).
- Exceptional mechanical properties (high strength, perfect elasticity, no fatigue).
- Silicon Dioxide and Nitride provide essential supporting roles in fabrication.

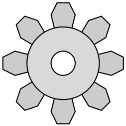


Next Lecture Preview

- Materials Used in MEMS (Part 2).
- Polymers (SU-8, PDMS).
- Metals and Ceramics in MEMS.
- Applications where Silicon fails.

Polymer Micro-Fluidics

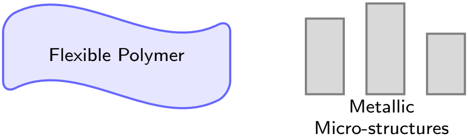
Metal Micro-Gears



Materials Used in MEMS (Part 2 - Polymers & Metals)

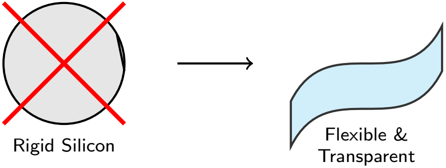
Details

- Course: Manufacturing Engineering - III (DI05019011)
- Unit 3: Non-conventional and Advanced Methods of Machining
- Lecture 27: Alternative Materials in MEMS



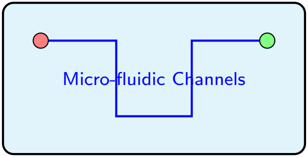
Why Look Beyond Silicon?

- While Silicon is excellent, it has limitations.
- High cost of pure silicon wafers and cleanroom processing.
- Silicon is brittle and inflexible.
- Poor bio-compatibility for implantable devices.
- Opaque to visible light (bad for optical MEMS).
- Therefore, we need Polymers, Metals, and Ceramics.



Polymers in MEMS

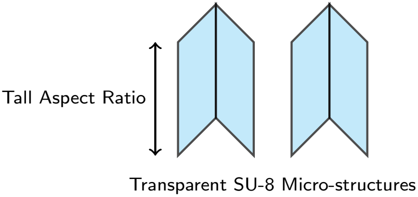
- Polymers are becoming extremely popular, especially in micro-fluidics and Bio-MEMS.
- **Advantages:** Extremely cheap, flexible, transparent, and easy to mass-produce via molding/embossing.
- **Disadvantages:** Poor mechanical strength compared to silicon, lower temperature limits, less precise control over electrical properties.



Transparent Flexible Chip

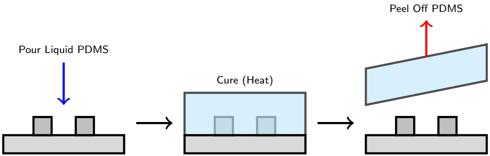
Key Polymer 1: SU-8

- SU-8 is a highly viscous photoresist polymer.
- Unique property: Can be spun into very thick layers (up to hundreds of microns).
- When exposed to UV light, it cross-links and becomes a highly rigid, permanent structure.
- Used to create high-aspect-ratio microstructures (tall, thin walls).
- Often used as a mold for electroplating metals (LIGA process).



Key Polymer 2: PDMS (Polydimethylsiloxane)

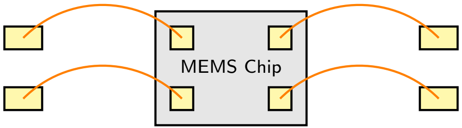
- PDMS is a silicon-based organic polymer (a type of silicone).
- Optically clear, flexible, inert, non-toxic, and bio-compatible.
- The dominant material for Micro-fluidics and Lab-on-a-Chip devices.
- Fabrication is simple: poured as a liquid over a master mold, cured, and peeled off (Soft Lithography).



Soft Lithography Process

Metals in MEMS

- Metals are used primarily for their electrical conductivity and specific physical properties.
- Cannot be easily etched like Silicon, so they are usually deposited (electroplating, sputtering).
- Used for: Electrical interconnects, micro-mirrors, magnetic actuators, and thermal bimorphs.



Metallic Wire Bonds
for Interconnects

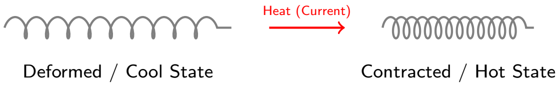
Common Metals Used

- **Gold (Au):** Excellent conductivity, highly resistant to oxidation, excellent for bio-sensing electrodes.
- **Aluminum (Al):** Standard material for electrical interconnects and highly reflective micro-mirrors.
- **Nickel (Ni):** Used in magnetic MEMS actuators and as a strong structural metal in the LIGA process.
- **Platinum (Pt):** Used for micro-heaters and high-temperature sensors.

Au Gold	Al Aluminum	Ni Nickel	Pt Platinum
Bio-sensors	Micro-mirrors	Magnetic Actuators	Micro-heaters

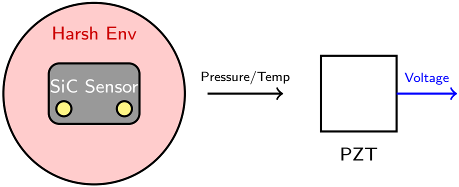
Shape Memory Alloys (SMAs) in MEMS

- Materials like Nitinol (Nickel-Titanium).
- Unique property: Can be deformed, but return to their original shape when heated.
- Used as powerful micro-actuators.
- Provide very high force and large displacement compared to electrostatic actuators.
- Drawback: Slow response time (limited by heating and cooling rates).

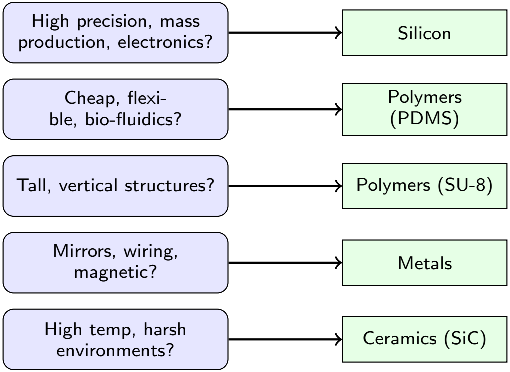


Ceramics in MEMS

- Used when extreme high temperatures or harsh chemical environments are present.
- **Silicon Carbide (SiC):** Excellent for high-temp sensors (e.g., inside jet engines). Can operate at $> 500^\circ$C.
- **Piezoelectric Ceramics (PZT):** Generate a voltage when deformed, or deform when a voltage is applied.
- PZT is crucial for micro-ultrasound transducers and inkjet printer heads.

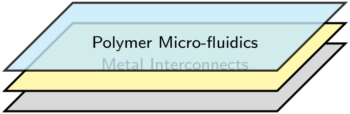


Material Selection Summary for MEMS



Summary

- While Silicon dominates, it is not a panacea.
- Polymers like PDMS and SU-8 enable micro-fluidics and high-aspect-ratio structures.
- Metals provide conductivity, reflectivity, and magnetic properties.
- Ceramics offer high-temperature resilience.
- Modern MEMS devices often integrate multiple materials.

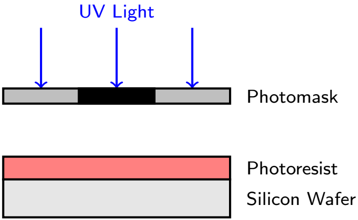


Composite MEMS Device

Next Lecture Preview

Basic Micro-fabrication Techniques

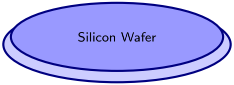
- How do we actually build these tiny devices?
- Photolithography (The core patterning process).
- Etching and Deposition.



Gear Forming Processes: Gear Milling

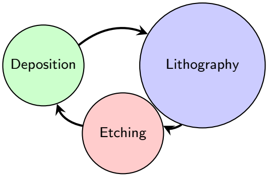
Manufacturing Engineering - III (DI05019011)

DI05019011



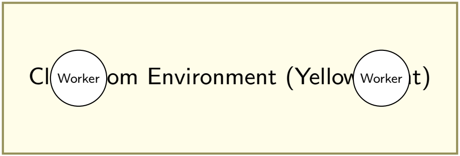
The Micro-fabrication Trinity

- Micro-fabrication relies on three fundamental, repeatable steps:
- 1. Deposition: Adding thin layers of material to the wafer.
- 2. Lithography: Patterning a shape onto the wafer (drawing the blueprint).
- 3. Etching: Selectively removing material based on the pattern.
- By repeating these three steps, complex 3D micro-machines are built layer by layer.



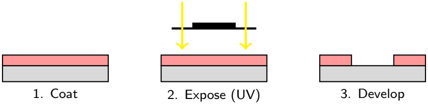
Step 1: Photolithography (The Blueprint)

- Photolithography uses light to transfer a geometric pattern from a mask to a light-sensitive chemical (photoresist).
- It is the optical method that dictates the shape and precision of the MEMS device.
- Done in extremely clean environments (Cleanrooms) using yellow light to prevent accidental exposure.



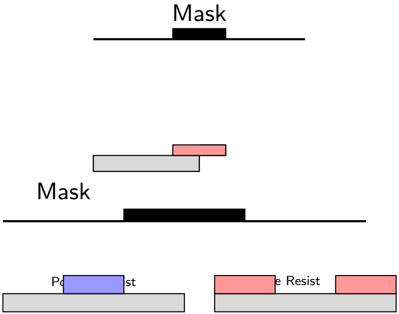
The Photolithography Process Steps

- 1. Coat: Spin a thin layer of liquid Photoresist onto the wafer.
- 2. Expose: Shine UV light through a patterned mask onto the wafer.
- 3. Develop: Wash away the exposed (or unexposed) photoresist using a chemical developer.
- Result: A protective polymer pattern left on the wafer, ready for etching.



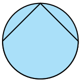
Positive vs. Negative Photoresist

- **Positive Photoresist:** UV light weakens the chemical bonds. Exposed areas become soluble and are washed away. (Pattern is identical to the mask).
- **Negative Photoresist:** UV light strengthens (cross-links) the bonds. Unexposed areas remain soluble and are washed away. (Pattern is the inverse of the mask).
- SU-8 (discussed last lecture) is a famous negative photoresist.

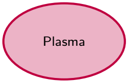


Step 2: Etching (Material Removal)

- Etching removes the material (Silicon, Oxide, Metal) that is NOT protected by the photoresist pattern.
- Two main categories:
- 1. Wet Etching: Using liquid chemicals (acids/bases).
- 2. Dry Etching: Using plasma or reactive gases in a vacuum.



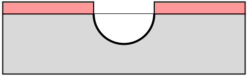
Wet Etching
Liquid chemicals



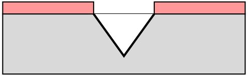
Dry Etching
Plasma/Gas

Wet Etching (Isotropic vs Anisotropic)

- Isotropic Etching: Etches in all directions equally. Creates rounded, bowl-shaped cavities. Often undercuts the photoresist mask.
- Anisotropic Etching: Etches much faster in certain directions based on the crystal structure of Silicon (using chemicals like KOH).
- Anisotropic etching creates precise V-grooves and sharp, angled walls (typically 54.7 degrees in Silicon).



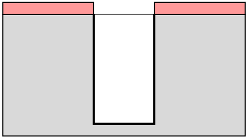
Isotropic (Rounded)



Anisotropic (V-groove)

Dry Etching (Plasma & DRIE)

- Uses ionized gases (plasma) to physically and chemically remove material.
- Highly directional (anisotropic) without relying on crystal orientation.
- DRIE (Deep Reactive Ion Etching): A specialized dry etch process that can carve extremely deep, perfectly vertical trenches in Silicon.
- Crucial for high-aspect-ratio MEMS structures.



DRIE (Deep Vertical Walls)

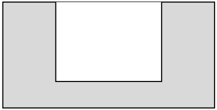
Step 3: Deposition (Adding Material)

- Adding thin films of materials (metals, insulators, polysilicon) onto the wafer.
- Physical Vapor Deposition (PVD): Sputtering or evaporating solid materials in a vacuum so they condense on the wafer. (Mainly used for metals).
- Chemical Vapor Deposition (CVD): Reacting gases at high temperatures so they form a solid film on the wafer. (Used for polysilicon, silicon dioxide, silicon nitride).

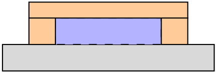
PVD	**CVD**
Target material blasted/evaporated	Reactive gases introduced
Condenses on wafer	Chemical reaction forms film
Mainly for metals	For polysilicon, oxides, nitrides

Bringing it all together: Bulk vs Surface Micromachining

- Bulk Micromachining: Etching deeply into the bulk silicon substrate to form the device (subtracting material).
- Surface Micromachining: Building the device ON TOP of the substrate by sequentially depositing and etching structural layers and sacrificial layers.
- At the end of surface micromachining, the sacrificial layer is etched away, leaving free-moving structures.



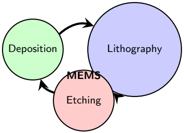
Bulk Micromachining



Surface Micromachining

Summary

- Micro-fabrication is a cycle of Deposition, Lithography, and Etching.
- Photolithography defines the patterns using light and photoresist.
- Etching removes material (wet/chemical vs dry/plasma).
- Deposition adds thin films of functional or structural materials.
- These techniques enable both bulk and surface micro-machining.



Next Lecture Preview

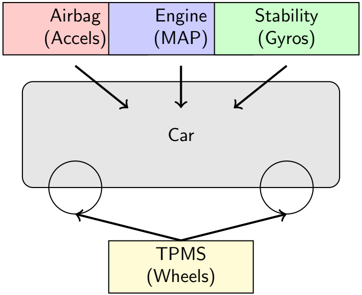
- Applications of MEMS.
- How these micro-fabricated devices are used in engineering and industry.
- Case studies: Accelerometers, inkjet heads, micro-mirrors.

Airbag Sensors	Inkjet Heads	Projector Mirrors

Smartphone | Airbag System | Micro-pump

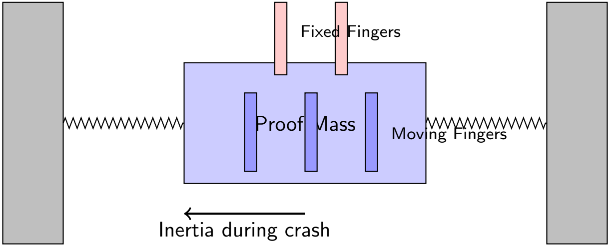
- Course: Manufacturing Engineering - III (DI05019011)
- Unit 3: Non-conventional and Advanced Methods of Machining
- Lecture 29: Real-World MEMS Applications

MEMS in Automotive Engineering



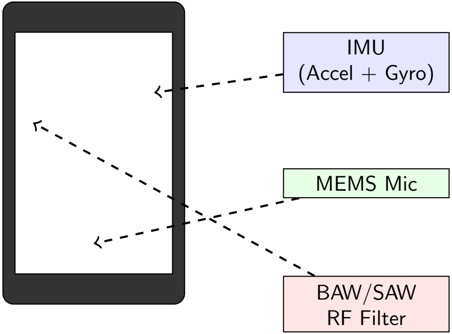
- The automotive industry was an early adopter of MEMS due to the need for cheap, reliable sensors.
- Key Applications:
  - Airbag deployment systems (MEMS accelerometers).
  - Tire Pressure Monitoring Systems (TPMS).
  - Electronic Stability Control (gyroscopes to detect spin/roll).
  - Manifold Absolute Pressure (MAP) sensors for engine management.

Deep Dive: The MEMS Airbag Accelerometer



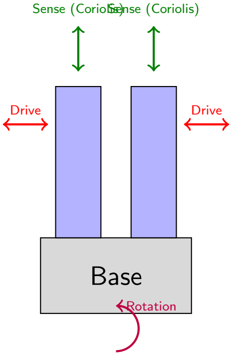
- Replaced bulky, expensive macro-mechanical crash sensors.
- Principle: A tiny proof-mass is suspended by silicon springs.
- During a crash, the car stops, but the proof-mass keeps moving (inertia).
- This movement changes the capacitance between interdigitated 'comb' fingers.
- The micro-circuitry detects this capacitance change and deploys the airbag in milliseconds.

MEMS in Consumer Electronics



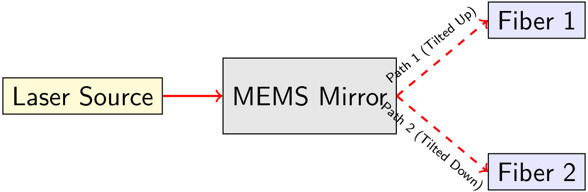
- Smartphones and wearables are the biggest volume drivers for MEMS today.
- Smartphones contain:
  - Inertial Measurement Units (IMUs): Accelerometers + Gyroscopes for screen rotation and gaming.
  - MEMS Microphones: Smaller, lower power, and better noise cancellation than traditional mics.
  - BAW/SAW RF Filters: MEMS filters that allow cell phones to tune into specific 4G/5G frequencies.

Deep Dive: MEMS Gyroscopes (Coriolis Effect)



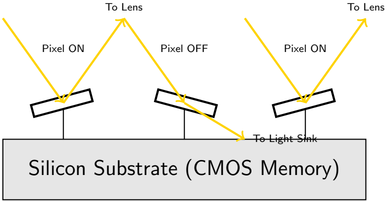
- Macro gyroscopes use heavy spinning wheels. MEMS gyros cannot do this due to friction/stiction.
- Instead, they use vibrating micro-structures.
- When the device rotates, the Coriolis force pushes the vibrating structure perpendicular to its motion.
- This secondary motion is detected capacitively to measure the rate of rotation.
- Crucial for VR headsets, drone stabilization, and smartphone gaming.

MEMS in Optical Systems (MOEMS)



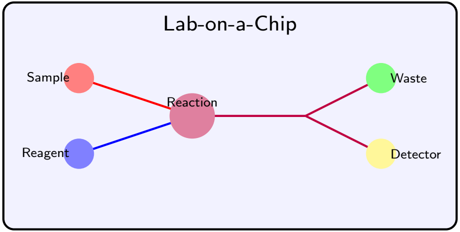
- Micro-Opto-Electro-Mechanical Systems.
- Optical Switches: Used in fiber optic telecom networks to physically redirect beams of light using micro-mirrors.
- Adaptive Optics: Telescopes use MEMS deformable mirrors to correct for atmospheric distortion.
- Displays: Digital Light Processing (DLP) projectors.

Deep Dive: DLP Projectors (DMD Chip)



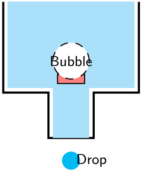
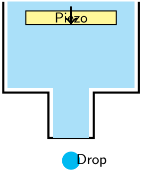
- Digital Micromirror Device (DMD).
- Contains millions of tiny aluminum mirrors on a single silicon chip.
- Each mirror represents one pixel and can tilt electrostatically (on/off).
- When ON, it reflects light through the lens to the screen.
- When OFF, it reflects light into a light-absorbing sink.
- They toggle thousands of times per second to create grayscale and colors.

MEMS in Biomedical Applications (Bio-MEMS)



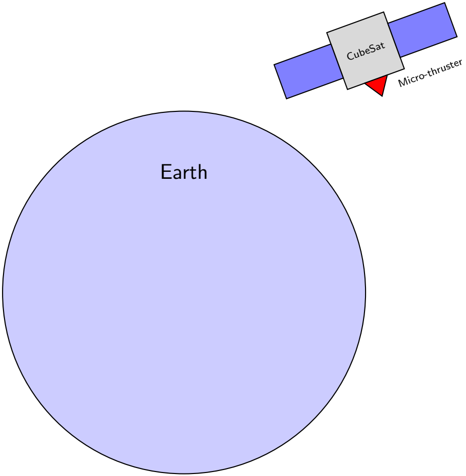
- Micro-fluidics / Lab-on-a-Chip: Manipulating tiny volumes of fluids.
- Applications: Rapid DNA analysis, point-of-care blood testing, drug discovery.
- Advantages: Uses incredibly small sample sizes (drops of blood), fast reaction times, portable.
- Implantable Devices: Micro-pumps for targeted drug delivery (e.g., insulin pumps), retinal implants.

Deep Dive: Inkjet Printer Heads

Thermal Inkjet	**Piezoelectric Inkjet**
	
Micro-resistor boils ink, bubble forces droplet out.	Piezo ceramic deforms with voltage, squeezes ink out.

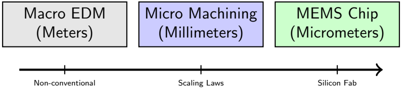
- One of the oldest and most successful MEMS applications.
- Thermal Inkjet: A micro-resistor boils ink, creating a bubble that forces a droplet out of the nozzle.
- Piezoelectric Inkjet: A piezoelectric ceramic deforms when voltage is applied, mechanically squeezing the ink out.
- Millions of precisely formed nozzles are batch-fabricated on a silicon or polymer substrate.

MEMS in Aerospace and Defense



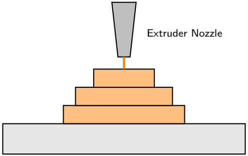
- Miniaturization is critical in aerospace (saving weight saves fuel/money).
- Applications:
  - Micro-thrusters for nano-satellites (CubeSats).
  - High-temp pressure sensors for jet engine monitoring.
  - Precision IMUs for missile guidance and drone navigation.
  - Structural health monitoring (embedding sensors inside composite wings).

Summary of Unit 3



- We started with the need for non-conventional machining for hard materials and complex geometries.
- We explored macro-processes like EDM, ECM, LBM, and AWJM, and how to select them.
- We then shifted to the micro-scale, introducing MEMS, scaling laws, and silicon.
- We covered micro-fabrication (lithography, etching, deposition).
- Finally, we saw how MEMS transforms automotive, consumer, medical, and aerospace industries.

Next Lecture Preview



- Commencement of Unit 4.
- Introduction to Additive Manufacturing (3D Printing).
- Principles, processes, and applications of building parts layer by layer.

Gear Forming Processes: Gear Milling

Manufacturing Engineering - III (DI05019011)

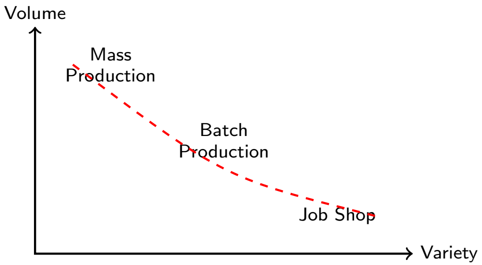
DI05019011

Agenda

- Introduction to Advanced Manufacturing Systems
- What is Group Technology (GT)?
- Definition of Group Technology
- Philosophy of GT
- Traditional Manufacturing Challenges
- How GT Solves these Challenges
- Core Concepts: Similarity in Parts and Processes
- Benefits of Group Technology

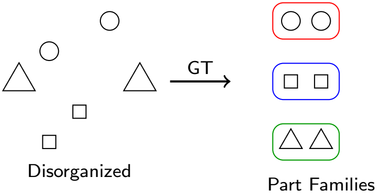
Introduction to Advanced Manufacturing Systems

- Modern manufacturing faces demands for high variety and low volume.
- Traditional systems are inflexible.
- Need systems that combine flexibility of job shops with efficiency of mass production.
- Advanced Manufacturing Systems bridge this gap (GT, FMS, CIM).



What is Group Technology (GT)?

- An approach to maximize production efficiencies.
- Based on grouping similar parts into families.
- Capitalizes on similarities in design and manufacturing attributes.
- Reorganizes factory layout to product-oriented cells.
- Transforms a complex problem into smaller, manageable problems.



Definition of Group Technology

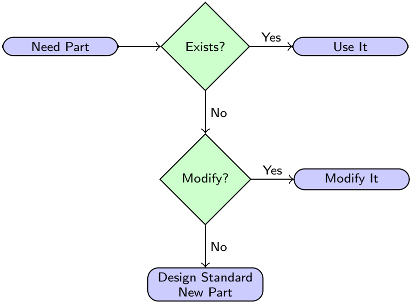
Solaja's Definition

"Group Technology is the realization that many problems are **similar***, and that by* **grouping similar problems***, a single solution can be found...* **saving time and effort***."*

- **In manufacturing:** A strategy of organizing and managing production by clustering parts into families.
- Applies across the entire manufacturing cycle.

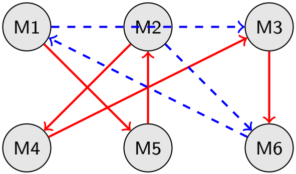
Philosophy of Group Technology

- Never design a new part if an existing one can be used.
- Never design a new part if an existing one can be modified.
- Ensure new parts use standard features.
- Manufacture similar parts using the same processes.
- Standardize tooling, setups, and processes.



Traditional Manufacturing Challenges

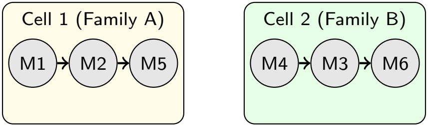
- Batch production uses functional (process) layouts.
- Results in complex material flow.
- High Work-in-Process (WIP) inventory.
- Long setup times.
- Long manufacturing lead times.
- Design duplication.



Spaghetti Flow in Functional Layout

How GT Solves Traditional Challenges

- Parts are grouped into families.
- Machines are grouped into cells dedicated to part families.
- Setup times are drastically reduced.
- WIP is reduced due to faster processing.
- Lead times are shortened.
- Design retrieval prevents reinventing the wheel.



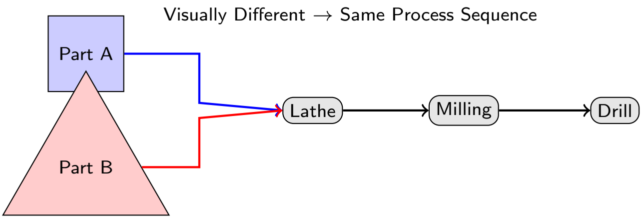
GT Concept: Similarity in Parts

- Design Similarity: Parts share similar shapes, dimensions, and tolerances.
- Material Similarity: Made from similar materials.
- Function Similarity: Serve similar functions.
- Similar parts form a 'Part Family'.
- Recognizing similarities is the first step.

Part Family: Rotational Parts (Gears)

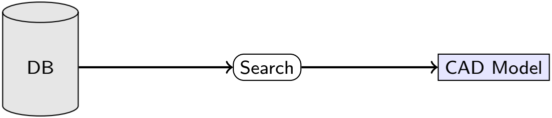
GT Concept: Similarity in Manufacturing

- Manufacturing Similarity: Require the same sequence of machining operations.
- Tooling Similarity: Use the same cutting tools and fixtures.
- Setup Similarity: Machined with the same setup.
- **Note:** Visually different parts might be manufactured similarly.



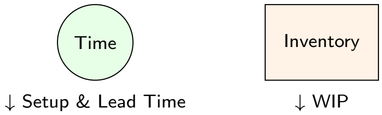
Benefits of Group Technology: Design

- Rapid retrieval of existing designs saves time.
- Promotes design standardization.
- Reduces new parts entering the system.
- Improves cost estimation.
- Facilitates use of standard tooling.



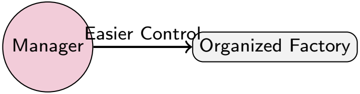
Benefits of Group Technology: Manufacturing

- Significant reduction in setup times.
- Reduced material handling and travel distances.
- Lower Work-in-Process (WIP) inventory.
- Shorter manufacturing lead times.
- Improved product quality.
- Simplified process planning (CAPP).



Benefits of Group Technology: Management

- Simplified production scheduling and control.
- Better space utilization.
- Improved worker morale (cellular teams).
- Easier cost accounting.
- Higher responsiveness to market changes.



Summary

- ✓ GT is a philosophy based on grouping similarities.
- ✓ Applies to part design and manufacturing.
- ✓ Solves inefficiencies of traditional batch production.
- ✓ Benefits span across design, manufacturing, and management.

Next Lecture Preview

- Topic: GT Layout (Cellular Layout)
- Concept and need for Cellular Manufacturing.
- Comparison with conventional layouts.

Coming Up: Cellular Layouts

Gear Forming Processes: Gear Milling

Manufacturing Engineering - III (DI05019011)

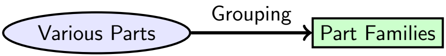
DI05019011

Agenda

- Recap of Group Technology
- Concept of GT Layout (Cellular Manufacturing)
- The Need for GT Layout
- Conventional: Process Layout
- Conventional: Product Layout
- Comparison: GT vs Conventional Layouts
- Examples of GT Layout
- Benefits and Challenges
- Summary

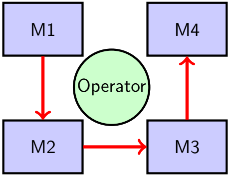
Recap of Group Technology

- GT identifies and groups similar parts into part families.
- Leverages similarities in design and manufacturing.
- Aims to achieve mass production efficiencies in batch production environments.



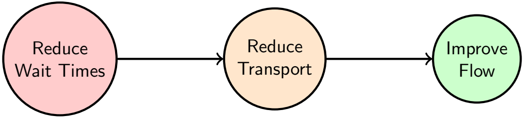
Concept of GT Layout (Cellular Layout)

- Also known as Cellular Manufacturing.
- Equipment and workstations are arranged to facilitate small lot continuous flow production.
- Machines are grouped into 'cells' dedicated to producing a specific part family.
- Cells contain all necessary equipment to complete the part family.

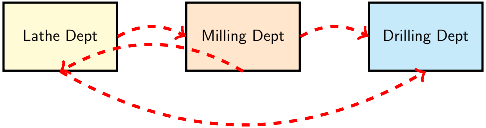


The Need for GT Layout

- To eliminate excessive material handling found in process layouts.
- To reduce long setup times between different batches.
- To improve production flow and reduce WIP inventory.
- To foster teamwork and responsibility among cell operators.



- Machines of the same type are grouped together (e.g., all lathes in one department, all mills in another).
- Parts travel long distances between departments.
- High flexibility but very low efficiency.
- Complex routing and scheduling.

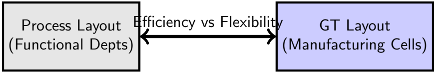


Conventional Layout: Product Layout

- Machines are arranged in a straight line according to the operation sequence (e.g., an assembly line).
- Highly efficient for single, high-volume products.
- Zero flexibility for product variation.
- If one machine breaks, the whole line stops.

GT Layout vs Process Layout

- GT groups different machines into cells; Process groups similar machines into departments.
- GT reduces travel distance and material handling significantly compared to Process layout.
- Process layout has higher flexibility for entirely new parts.
- GT relies on part families; Process layout handles any batch.



GT Layout vs Product Layout

- GT layout handles a family of similar parts; Product handles exactly one part.
- GT is slightly less efficient than a pure product line but vastly more flexible.
- Both aim for continuous or semi-continuous flow.
- GT cells are often U-shaped to allow operator multi-tasking, unlike long product lines.

Comparison Table: Layouts

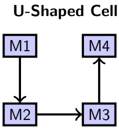
Feature	Process Layout	Product Layout	GT Layout
Volume	Low	High	Medium
Variety	High	Low	Medium
Efficiency	Low	High	High (for part family)
Flexibility	High	Low	Medium
Material Handling	High	Low	Low

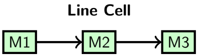
Benefits of GT Layout

- Drastic reduction in material handling and transport time.
- Shorter manufacturing lead times.
- Reduction in Work-In-Process (WIP).
- Simplified routing and scheduling.
- Improved operator expertise (focusing on specific part families).

Examples of GT Layout

- **U-Shaped Cell**: Common for manual operations, allows one operator to tend multiple machines.
- **Line Cell**: Sequential operations for a family with identical routing.
- **Loop Cell**: Parts circulate on a conveyor through various workstations.
- **Virtual Cell**: Machines remain in functional departments but are dedicated to a part family in the planning system.





Challenges in Implementing GT Layout

- High initial cost of rearranging factory floor and duplicating some equipment.
- Difficulty in identifying and grouping part families accurately.
- Resistance to change from workforce accustomed to departmental structures.
- Risk of machine underutilization if demand for a part family drops.

Summary

- GT layout (Cellular Manufacturing) groups machines based on part families.
- It bridges the gap between highly flexible process layouts and highly efficient product layouts.
- Provides benefits like reduced WIP and faster lead times.
- Implementation requires careful planning and overcoming structural challenges.

Next Lecture Preview

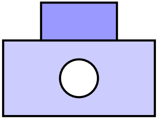
Topic: Part Features

- Concept of part features in design and manufacturing.
- Types of features and examples.

Gear Forming Processes: Gear Milling

Manufacturing Engineering - III (DI05019011)

DI05019011



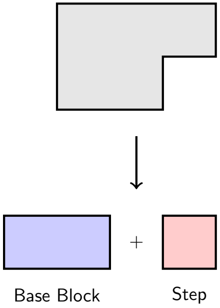
Complex Machined Part Example

Agenda

- Introduction to Part Features
- Concept and Definition of Features
- Importance in Group Technology
- Design Features vs. Manufacturing Features
- Examples of Design Features
- Examples of Manufacturing Features
- Feature Recognition in CAD/CAM
- Summary

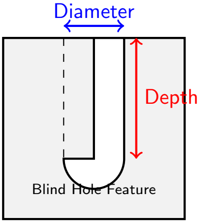
Introduction to Part Features

- To group parts into families, we must define what makes them similar.
- Parts are composed of primitive geometric shapes and functional elements.
- These recognizable elements are called 'Features'.
- Features form the language of modern CAD/CAM systems.



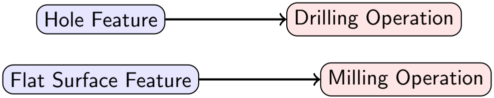
Concept and Definition of Features

- **Definition:** A feature is a generic shape or characteristic of a part that carries engineering meaning.
- Represents a specific region of the part's geometry.
- Contains geometric data (dimensions, tolerances) and non-geometric data (material, finish).
- Provides a higher-level abstraction than basic lines/surfaces.



Importance in Group Technology

- Part families are formed based on feature similarities.
- If two parts share a majority of manufacturing features, they belong in the same family.
- Features dictate the required manufacturing operations, tools, and setups.
- Feature-based coding systems form the backbone of GT classification.



Design Features vs. Manufacturing Features

- Features can be viewed differently depending on the context.
- **Design Features:** Elements relevant to the part's function and aesthetics.
- **Manufacturing Features:** Elements relevant to the processes required to create the part.
- A single design feature might translate to multiple manufacturing features, or vice versa.

Designer's View

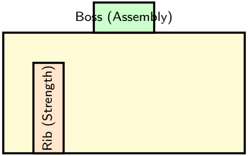
Focuses on end-use:
e.g., Mating surface, strength rib.

Machinist's View

Focuses on material removal:
e.g., Pocket to be milled, drilled hole.

Types of Part Features: Design Features

- Focus on the product's end-use.
- **Form Features:** Basic shapes (bosses, ribs, holes, slots).
- **Material Features:** Material type, heat treatment specifications.
- **Precision/Tolerance Features:** Dimensional tolerances, GD&T.
- **Assembly Features:** Mating surfaces, alignment pins.

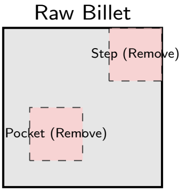


Examples of Design Features

Feature	Description	Visual
Boss	Protruding feature for locating/mounting	
Rib	Thin fin used to strengthen a larger body	
Fillet	Rounded interior corner to reduce stress	
Chamfer	Beveled exterior edge for safety/assembly	
O-ring Groove	Functional slot designed to hold a seal	

Types of Part Features: Manufacturing Features

- Focus on the volume of material to be removed or process applied.
- **Machining Features:** Holes, pockets, slots, steps, turned profiles.
- **Sheet Metal Features:** Bends, punches, hems, louvers.
- **Forming Features:** Draft angles, parting lines (in casting/forging).
- Each manufacturing feature maps to a specific tool/operation.

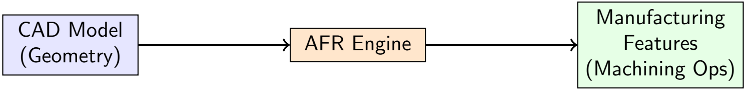


Examples of Manufacturing Features

Feature	Description	Cross-Section
Through Hole	Drilled completely through the part	
Blind Hole	Drilled to a specific depth	
Counterbore	Flat-bottomed cylindrical enlargement	
Countersink	Conical enlargement of a hole	
Pocket	Closed geometric depression milled into surface	

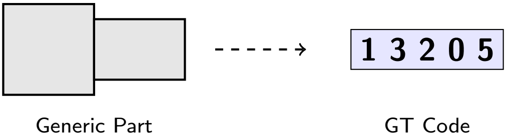
Feature Recognition in CAD/CAM

- Modern CAM systems automatically translate CAD geometry into manufacturing features.
- **Process:** Automatic Feature Recognition (AFR).
- The system identifies a cylindrical void as a 'hole' and suggests a drilling operation.
- Essential for Computer-Aided Process Planning (CAPP) and automated GT coding.



Role of Features in Group Technology

- Parts are coded based on their features (e.g., Opitz coding system).
- A code might specify: rotational part, step on one end, internal thread.
- Sorting parts by these codes automatically groups them into families.
- This leads directly to the design of the manufacturing cell.

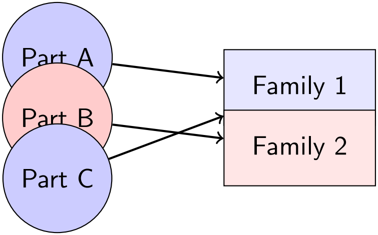


Summary

Key Takeaways

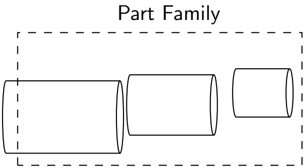
- Features are geometric characteristics with engineering meaning.
- They are the fundamental elements used to evaluate part similarities in GT.
- Design features focus on function; Manufacturing features focus on production processes.
- Feature recognition is key to automating CAD/CAM and CAPP integration.

Next Lecture Preview



- **Topic:** Part Family Concept and Formation
- What exactly is a part family?
- Approaches to forming part families (Visual, Classification/Coding, Production Flow Analysis).

Part Family: Concept & Approach to Form Cells



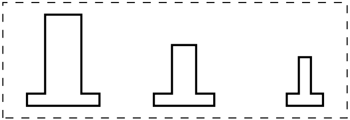
- Course: Manufacturing Engineering - III (DI05019011)
- Unit 4: Advanced Manufacturing Systems
- Lecture 33: Part Family - Concept & Cell Formation

Agenda

- Concept of Part Families
- Visualizing Part Families
- Three Approaches to Forming Part Families
  - 1. Visual Inspection Method
  - 2. Parts Classification and Coding (PC&C)
  - 3. Production Flow Analysis (PFA)
- Forming Manufacturing Cells
- Machine-Part Matrices
- Summary

What is a Part Family?

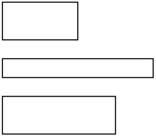
- A Part Family is a collection of parts that are similar either in geometric shape and size or in the manufacturing steps required to produce them.
- Parts within a family don't need to be identical.
- The goal is that the similarities allow them to be processed on the same group of machines (a cell).
- It is the fundamental unit of Group Technology.



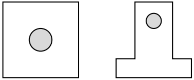
Family of Screws/Bolts

Visualizing Part Families

Family 1: Design Similarity
(e.g., Cylindrical shafts)



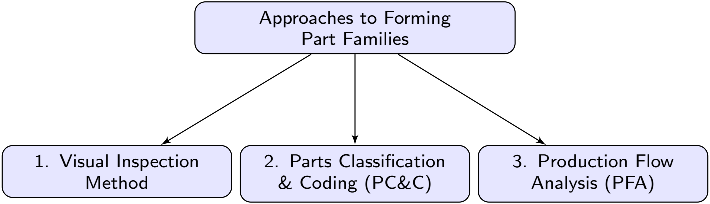
Family 2: Mfg. Similarity
(e.g., Block & flange requiring drilling)



The most useful families for cellular manufacturing are those sharing manufacturing processes.

Approaches to Forming Part Families

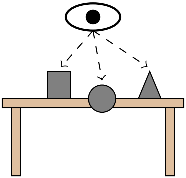
- There are three primary methods used in industry to group parts into families:



- The choice depends on factory size, number of parts, and available data.

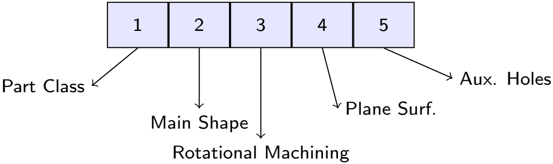
1. Visual Inspection Method

- The simplest and least expensive method.
- Involves physically looking at the parts, photos, or CAD drawings.
- Human experts sort parts into groups based on their knowledge.
- Advantages: Fast, inexpensive, easy to understand.
- Disadvantages: Highly subjective, relies on human memory, unscientific, difficult for very large numbers of parts (> 1000).



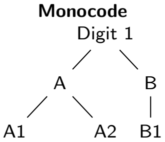
2. Parts Classification and Coding (PC&C)

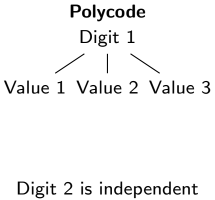
- The most widely used and formalized method.
- Parts are assigned numerical or alphanumeric codes based on design and manufacturing features.
- Similar codes indicate similar parts. Common: Opitz, MICLASS, DCLASS.
- Adv: Objective, computerized, extremely powerful for CAPP.
- Disadv: Time-consuming and expensive to setup.



Structure of Coding Systems

- **Monocode (Hierarchical)**: Each digit's meaning depends on preceding digit.
- **Polycode (Chain)**: Each digit has independent, constant meaning.
- **Mixed-mode (Hybrid)**: Combines both, e.g., Opitz system.





3. Production Flow Analysis (PFA)

- Developed by J.L. Burbidge. Focuses solely on routing sheet (operation sequence).
- Parts with identical/similar operation sequences form a family.
- Advantages: Uses existing production data, directly groups parts by machine usage.
- Disadvantages: Relies on existing routing sheets (may be flawed), no help with design retrieval.

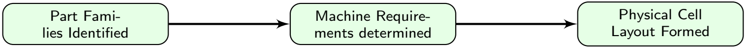
Machines	**Part 1**	**Part 2**	**Part 3**	**Part 4**	**Part 5**
Lathe (M1)	✓		✓		✓
Mill (M2)		✓		✓	
Drill (M3)	✓		✓		✓
Grinder (M4)		✓		✓	

Comparing the Approaches

Feature	Visual Inspection	PC&C	PFA
Cost	Low	High	Medium
Accuracy	Low	High	Medium
Setup Time	Fast	Slow (initial)	Medium
Best For	Small shops	Large enterprises	Quick layout
Data Source	Physical/CAD	Features/Specs	Routing Sheets

Forming Manufacturing Cells

- Once part families are identified, the next step is assigning machines to form a cell.
- The goal is to have the cell complete as many operations for the part family as possible without the part leaving the cell.
- This involves identifying specific machines used by the part family and grouping them physically.



Machine-Part Matrices

- A key tool in PFA and Cell Formation.
- Construct a matrix: Rows = Machines, Columns = Parts.
- Place a '1' if a part requires a machine, '0' otherwise.
- Objective: Rearrange to form clusters of '1's along the diagonal.

Initial Matrix

	P1	P2	P3	P4
M1	1	0	1	0
M2	0	1	0	1
M3	1	0	1	0
M4	0	1	0	1

$\Rightarrow$

Clustered Matrix

	P1	P3	P2	P4
M1	1	1	0	0
M3	1	1	0	0
M2	0	0	1	1
M4	0	0	1	1

Example of Cell Formation (Rank Order Clustering)

- Algorithms like Rank Order Clustering (ROC) sort the matrix.
- Assign binary weights to rows/columns, sort descending iteratively.
- The result is a block-diagonal matrix (exceptions = inter-cell routing).

	P1	P2	P3
M1	1	0	1
M2	0	1	0
M3	1	0	0

Sort Rows

	P1	P2	P3
M1	1	0	1
M3	1	0	0
M2	0	1	0

Sort Cols

	P1	P3	P2
M1	1	1	0
M3	1	0	0
M2	0	0	1

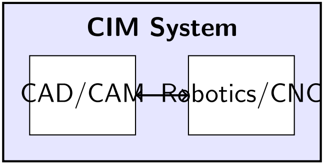
Summary

Key Takeaways

- Part families are groups of parts with design or manufacturing similarities.
- Three main formation methods: Visual, Coding (PC&C), and PFA.
- Coding systems are the most robust but require significant investment.
- Machine-part matrices mathematically group machines into cells.

Next Lecture Preview

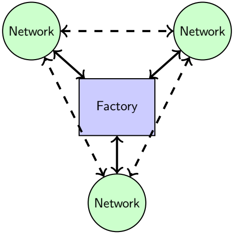
- Topic: Computer Integrated Manufacturing (CIM)
- Moving from cells to the entire factory.
- CIM concept and the need for integration.



Gear Forming Processes: Gear Milling

Manufacturing Engineering - III (DI05019011)

DI05019011



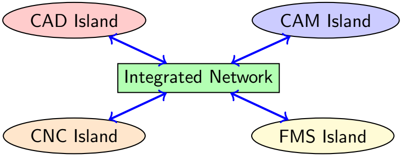
- Course: Manufacturing Engineering - III (DI05019011)
- Unit 4: Advanced Manufacturing Systems
- Lecture 34: CIM Concept & Need

Agenda

- Introduction to CIM
- Evolution of Manufacturing Systems
- What is CIM? (Definitions)
- The Core Philosophy of CIM
- The Need for CIM in Modern Industry
- Market Drivers for CIM
- Technological Drivers for CIM
- Goals and Objectives of CIM
- Summary

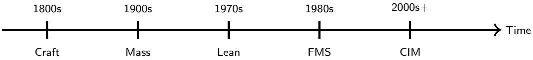
Introduction to CIM

- Manufacturing evolved from craft to mass production to advanced automated systems.
- Modern markets demand high quality, high customization, and rapid delivery.
- Isolated automation (islands of automation) is no longer sufficient.
- CIM represents the integration of all manufacturing enterprise functions using computer networks.



Evolution of Manufacturing Systems

- 1. Craft Production: High customization, low volume, skilled labor.
- 2. Mass Production (Fordism): High volume, low customization.
- 3. Lean Manufacturing (Toyota): Elimination of waste, JIT.
- 4. Flexible Manufacturing (GT, FMS): High variety, mid-volume, automated cells.
- 5. CIM: Total integration of business and manufacturing data across the enterprise.



What is CIM? (Definitions)

Definition 1

The integration of the total manufacturing enterprise through the use of integrated systems and data communications coupled with new managerial philosophies.

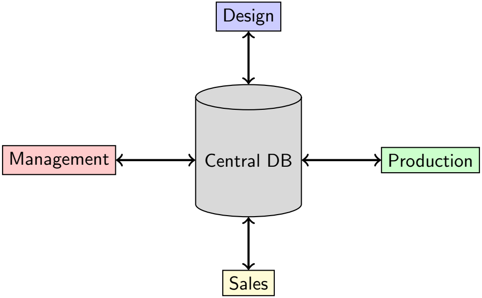
Definition 2 (SME)

Integration of the total manufacturing enterprise... to improve organizational and personnel efficiency.

- In essence: Using computers to tie everything together.

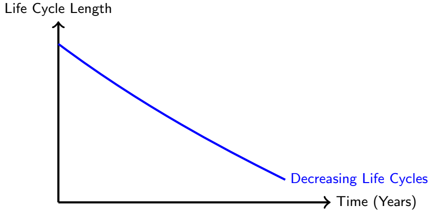
The Core Philosophy of CIM

- CIM is a philosophy, a way of doing business, rather than a specific product.
- It relies on a shared database (single source of truth) for all departments.
- Information flows seamlessly from marketing to design to production to dispatch.
- It breaks down traditional departmental silos.



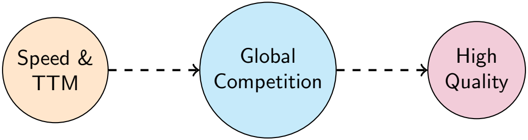
The Need for CIM in Modern Industry

- The manufacturing environment is increasingly competitive and globalized.
- Product life cycles are shrinking dramatically (e.g., electronics).
- Customers demand customized products at mass-production prices.
- Traditional sequential engineering is too slow and error-prone.
- CIM provides the agility required to survive and thrive.



Market Drivers for CIM

- Global competition forces cost reduction and quality improvement.
- Need for faster Time-to-Market (TTM) for new products.
- Demand for product customization (mass customization).
- Stricter quality and regulatory standards requiring traceability.
- Need for rapid response to fluctuating market demands.



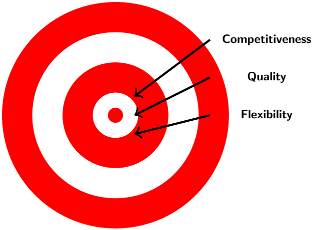
Technological Drivers for CIM

- Explosive growth in computing power and reduction in cost.
- Advancements in networking and communication protocols (LANs, Internet).
- Maturation of CAD, CAM, and CAE software tools.
- Development of robust database management systems (DBMS).
- Availability of advanced CNC machines, robotics, and sensors.

Microchips Networks Software

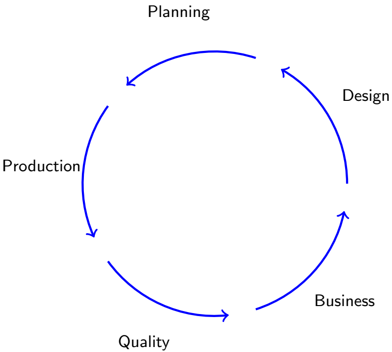
Goals and Objectives of CIM

- Primary Goal: To improve the competitiveness of the manufacturing enterprise.
- Reduce overall costs (direct, indirect, inventory, rework).
- Improve product quality and consistency.
- Decrease lead times and time-to-market.
- Increase manufacturing flexibility and responsiveness.
- Optimize asset utilization and improve management control.



Scope of CIM

- CIM encompasses the entire product life cycle.
- From conceptual design and engineering analysis.
- Through process planning and production scheduling.
- To shop floor control, machining, assembly, and quality inspection.
- Including business functions like purchasing, inventory control, and cost accounting.

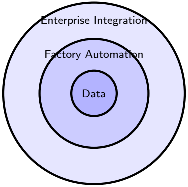


Summary

- CIM is the integration of all manufacturing and business functions using computer networks.
- It is a philosophy driven by market demands for speed, quality, and customization.
- Technological advancements have made CIM implementation possible.
- The core of CIM is shared data and seamless information flow.

Next Lecture Preview

- Topic: CIM Block Diagram and Architecture
- The SME CIM Wheel.
- Understanding the major components of a CIM system.
- Information and physical flow in CIM.



CIM Block Diagram and Architecture

Course: Manufacturing Engineering - III (DI05019011)

Unit 4: Advanced Manufacturing Systems

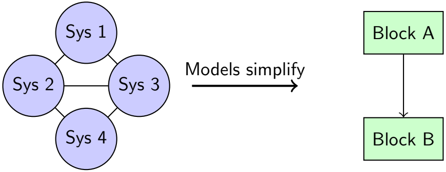
Lecture 35: CIM Block Diagram and Architecture

Agenda

- Introduction to CIM Architecture
- The SME CIM Wheel Model
- General CIM Block Diagram
- Component 1: Business Planning
- Component 2: Product Design (CAD/CAE)
- Component 3: Manufacturing Planning
- Component 4: Manufacturing Control
- Information vs. Physical Flow
- Summary

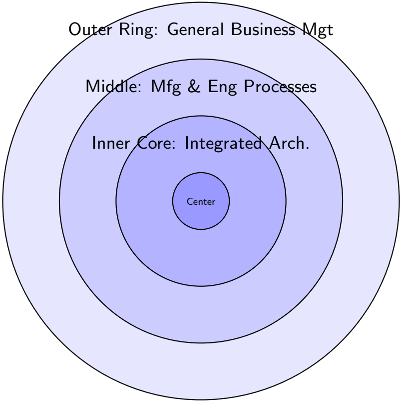
Introduction to CIM Architecture

- A CIM system is incredibly complex, comprising hundreds of sub-systems.
- Architectural models help visualize how these sub-systems interact.
- They show the functional areas and the flow of data between them.
- Different organizations use different models, but core components are similar.



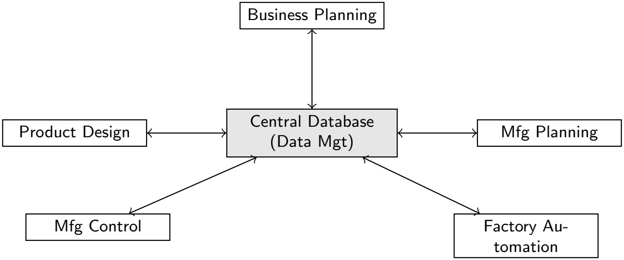
The SME CIM Wheel

- Developed by the Society of Manufacturing Engineers (SME).
- A widely accepted conceptual model for CIM.
- Inner to Outer layers show integration.



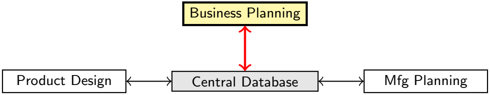
General CIM Block Diagram: Overview

- Typical blocks include 5 main areas linked by a central Data Management System.



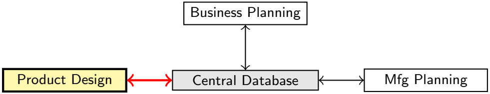
Component 1: Business Planning & Support

- The highest level of planning.
- Includes Sales, Marketing, Finance, and Enterprise Resource Planning (ERP).
- Inputs: Customer orders, market forecasts.
- Outputs: Master Production Schedule (MPS), budget allocations.
- Dictates WHAT to make and WHEN to make it.



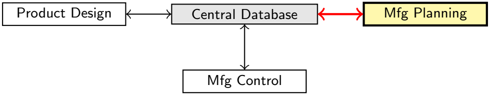
Component 2: Product Design (CAD/CAE)

- Where the product is conceptualized and engineered.
- Computer-Aided Design (CAD) for geometric modeling.
- Computer-Aided Engineering (CAE) for simulation and FEA.
- Output: A complete digital definition of the product (3D model, BOM).



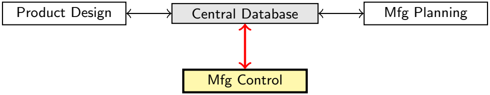
Component 3: Manufacturing Planning

- Translates the design into a method of production.
- CAPP: Determines routing and operations.
- MRP: Determines material needs based on BOM.
- Tool and Fixture design.
- Output: Process plans, NC part programs, material orders.



Component 4: Manufacturing Control

- Execution of the plans on the shop floor.
- Shop Floor Control (SFC) and Manufacturing Execution Systems (MES).
- Scheduling specific machines, dispatching orders, tracking WIP.
- Monitoring machine status and quality data in real-time.
- Output: Production commands, performance data feedback.



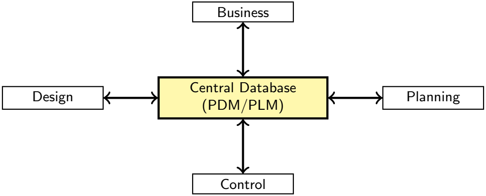
Component 5: Factory Automation

- The physical realization of the manufacturing process.
- CNC machine tools for cutting.
- Industrial Robots for welding, painting, assembly.
- Automated Material Handling Systems (AGVs, conveyors, AS/RS).
- Automated Inspection Systems (CMM).

Automation Area	**Examples**
Machining	CNC Lathe, CNC Mill
Handling	AGV, AS/RS, Conveyors
Assembly	Industrial Robots
Inspection	CMM, Vision Systems

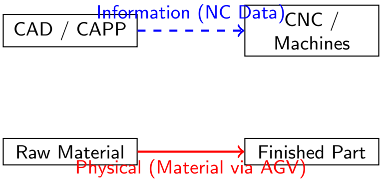
The Central Role of Database Management

- The 'Glue' that holds CIM together (PDM/PLM).
- Ensures all departments are working from the most current, accurate data.
- Eliminates data redundancy and inconsistencies.
- Handles security, access control, and version tracking.



Information Flow vs. Physical Flow

- Information Flow: Data moving through networks (e.g., CAD to CAPP).
- Physical Flow: Raw materials, WIP, and finished goods moving via AGVs.
- CIM optimizes both: information flow drives efficient physical flow.



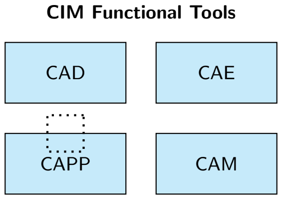
Summary

Key Takeaways

- CIM architecture can be modeled using the SME Wheel or block diagrams.
- Key blocks include Business Planning, Design, Planning, Control, and Automation.
- A central, integrated database is the foundational requirement for CIM.
- CIM manages both information flow and physical materials flow.

Next Lecture Preview

- Topic: Functional Areas Covered in CIM
- Deep dive into CAD, CAM, CAE, CAPP.
- How these specific software tools function within the CIM architecture.



CIM: Functional Areas Covered

CAD　CAM　CAPP　CAE

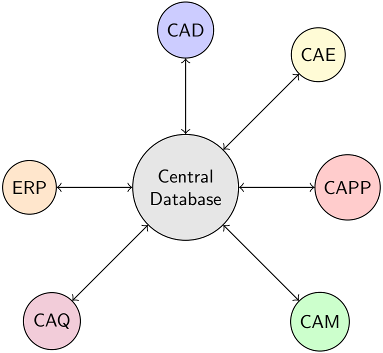
- Course: Manufacturing Engineering - III (DI05019011)
- Unit 4: Advanced Manufacturing Systems
- Lecture 36: Functional Areas Covered in CIM

Agenda

- Overview of Functional Areas
- Product Design (CAD)
- Engineering Analysis (CAE)
- Process Planning (CAPP)
- Manufacturing Engineering (CAM)
- Production Planning & Control (ERP/PPC)
- Quality Assurance (CAQ)
- Summary

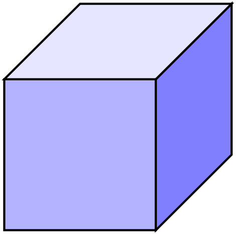
Overview of Functional Areas

- CIM is a collection of computer-based technologies.
- Categorized by their function in the enterprise.
- Commonly known as 'CAx' technologies (Computer-Aided 'X').
- They must communicate seamlessly through the central CIM database.
- We will examine the core functional areas.



Product Design: CAD

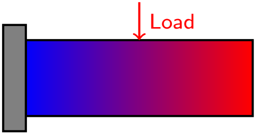
- Computer-Aided Design (CAD).
- Use of computer systems to assist in creation, modification, analysis of a design.
- Creates 2D drawings and 3D solid models.
- Output: Geometric data, Bill of Materials (BOM), mass properties.
- Replaces manual drafting and physical modeling.



3D CAD Model

Engineering Analysis: CAE

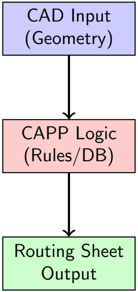
- Computer-Aided Engineering (CAE).
- Use of software to simulate performance to improve product designs.
- Includes Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD).
- Reduces the need for physical prototypes, saving time and cost.



FEA Stress Contour

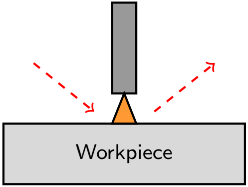
Process Planning: CAPP

- Computer-Aided Process Planning (CAPP).
- The link between CAD and CAM.
- Determines the sequence of operations, machines, and tools required.
- Two types: Variant CAPP (retrieves and modifies based on GT) and Generative CAPP (creates new plans from scratch).
- Ensures consistent manufacturing methods.



Manufacturing Engineering: CAM

- Computer-Aided Manufacturing (CAM).
- Software to control machine tools and machinery.
- Takes CAD geometry and CAPP plans to generate NC part programs.
- Simulates toolpaths to prevent machine crashes.
- Directly drives CNC lathes and mills.



Animated Toolpath

Production Planning & Control: ERP/PPC

- Enterprise Resource Planning (ERP) / Production Planning & Control.
- Manages business and logistical aspects.
- Includes Master Production Scheduling (MPS), MRP, and Inventory Control.
- Ensures raw materials arrive on time.
- Balances machine capacity with order demand.

Order ID	Product	Due Date	Status
ORD-101	Part A	24-Jul	On Time
ORD-102	Part B	25-Jul	Delayed
ORD-103	Part C	26-Jul	Planned
ORD-104	Part D	27-Jul	Planned

Production Schedule Dashboard

Shop Floor Control & Execution (MES)

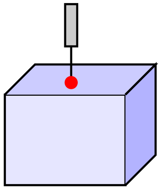
- Manufacturing Execution Systems (MES).
- Monitors and controls physical processes in real-time.
- Tracks Work-In-Process (WIP), downtime, and operator performance.
- Provides real-time feedback to ERP.
- The execution arm of production planning.

Machine	Job ID	Status	Efficiency
CNC-Mill 1	JOB-55	Running	92%
CNC-Lathe 2	–	Idle	–
Robot Arm A	JOB-55	Running	98%
CMM 1	JOB-54	Maintenance	–

Real-Time Machine Status

Quality Assurance: CAQ

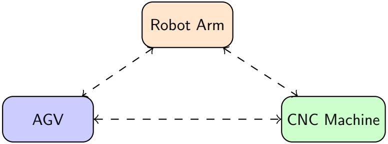
- Computer-Aided Quality (CAQ).
- Integration of quality control into CIM.
- Uses Coordinate Measuring Machines (CMM) programmed via CAD data.
- Automated optical inspection systems.
- Statistical Process Control (SPC) software to prevent defects.



CMM Probing Part

Factory Automation

- The physical hardware executing digital commands.
- CNC Machine Tools: For cutting and forming.
- Industrial Robots: For assembly and material handling.
- Automated Guided Vehicles (AGVs) & AS/RS: For moving and storing materials.
- Programmable Logic Controllers (PLCs).



Summary

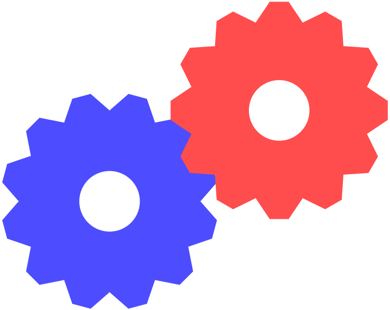
- CIM relies on a suite of CAx tools covering the entire product lifecycle.
- CAD creates the design; CAE verifies it.
- CAPP plans the process; CAM writes the machine code.
- ERP manages logistics; MES executes the schedule.
- CAQ ensures final product meets specifications.

Next Lecture Preview

- Topic: Importance of Functional Areas in CIM
- Why is the integration of these areas so critical?
- Synergy and data flow.
- Benefits of successful integration.

Design	Plan
Make	Control

CIM: Importance of Functional Areas

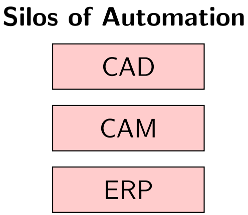


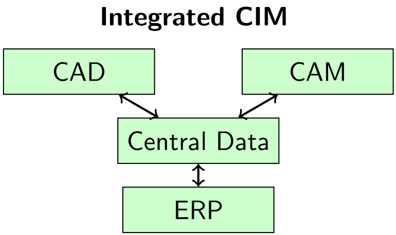
- Course: Manufacturing Engineering - III (DI05019011)
- Unit 4: Advanced Manufacturing Systems
- Lecture 37: Importance of Functional Areas

Agenda

- Integration: The Key to CIM
- Importance of Product Design Integration
- Importance of Process Planning Integration
- Importance of Manufacturing Control Integration
- Importance of Quality Assurance Integration
- Synergy and Concurrent Engineering
- Data Management (PLM) as the Backbone
- Overall Benefits of CIM Integration
- Summary

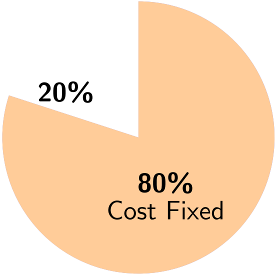
Integration: The Key to CIM





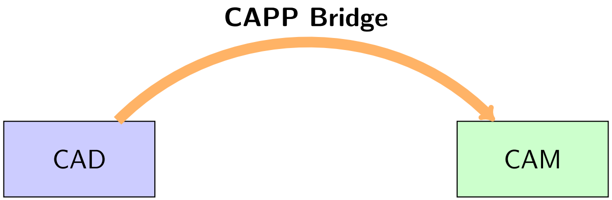
- Having CAD, CAM, and ERP software does not mean a company has CIM.
- If systems operate in silos, data must be re-entered manually, causing errors.
- The true power of CIM lies in seamless, automated transfer of data between areas.
- Integration eliminates redundancy and ensures a single version of the truth.

Importance of Product Design (CAD/CAE) Integration



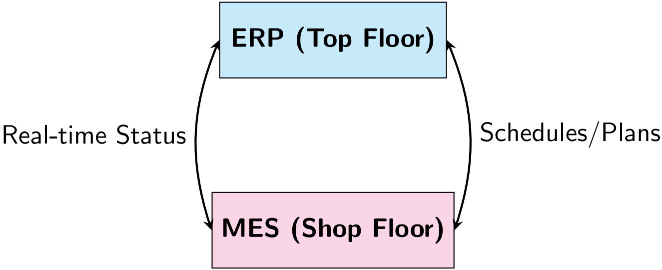
- Design decisions dictate up to 80% of final manufacturing costs.
- Integrated CAD/CAE allows for Design for Manufacturability (DFM).
- Manufacturing constraints are considered during design, not after.
- Reduces costly Engineering Change Orders (ECOs).
- Digital models are instantly available to downstream departments.

Importance of Process Planning (CAPP) Integration



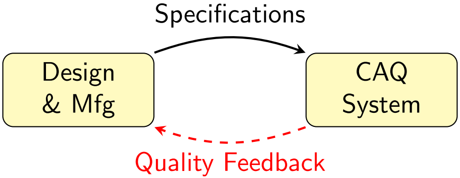
- CAPP is the critical bridge between 'What to make' (CAD) and 'How to make it' (CAM).
- Automates routing creation, ensuring best practices are used.
- Directly reads CAD features, eliminating interpretation errors.
- Provides accurate time estimates to the ERP system.
- Rapidly updates manufacturing plans if design changes.

Importance of Manufacturing Control (CAM/MES) Integration



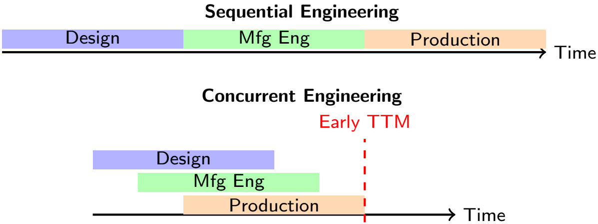
- Integrated CAM ensures NC programs exactly match the approved CAD model.
- Simulation prevents machine crashes.
- MES feeds real-time shop floor data back to ERP.
- Allows management to know exactly where every order is.
- Enables rapid response to machine breakdowns.

Importance of Quality Assurance (CAQ) Integration



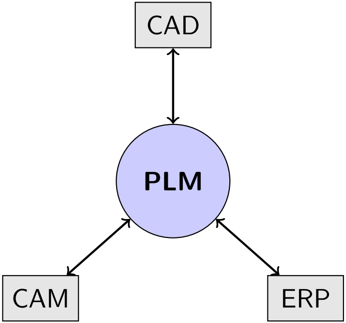
- Quality is integrated into the process, not an afterthought.
- CMMs are programmed directly from CAD tolerance data.
- Real-time SPC data can halt production before scrap is produced.
- Inspection data is fed back to design to identify root causes.
- Ensures comprehensive traceability.

Synergy and Concurrent Engineering



- Integration enables Concurrent Engineering.
- Instead of sequential engineering, departments work simultaneously on a shared digital model.
- Designers, manufacturing engineers, and quality experts collaborate in real-time.
- Dramatically reduces Time-to-Market (TTM).
- The whole is greater than the sum of its parts (Synergy).

Data Management (PLM) as the Backbone



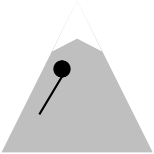
- Product Lifecycle Management (PLM) software is the modern backbone of CIM.
- Manages all data related to the product from cradle to grave.
- Provides version control, ensuring correct models are used.
- Manages access rights, security, and workflows.
- It is the central nervous system connecting all functional areas.

Overall Benefits of CIM Integration

Metric	Trend
Flexibility	$\uparrow$
Lead Times	$\downarrow$
Inventory	$\downarrow$
Quality Yield	$\uparrow$
Labor Prod.	$\uparrow$

- Increased flexibility to handle high variety and small batch sizes.
- Significant reduction in lead times and inventory levels.
- Improved product quality and yield.
- Higher machine utilization and labor productivity.
- Better customer satisfaction.
- Enhanced ability to innovate.

Challenges in CIM Implementation

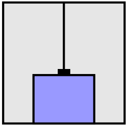


- High initial capital investment.
- Complexity of integrating legacy systems from different vendors.
- Requires a massive culture change and extensive employee training.
- Data security and cybersecurity risks.
- Risk of 'Paralysis by Analysis' if data is not managed properly.

Summary

- Importance of functional areas lies in their integration.
- Integration enables Concurrent Engineering and DFM.
- Data must flow seamlessly between CAD, CAPP, CAM, ERP, and CAQ.
- A central PLM database is essential for managing this complexity.
- Successful CIM provides agility, quality, and speed.

Unit 4 Conclusion

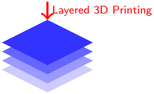


- This concludes Unit 4: Advanced Manufacturing Systems.
- We have covered Group Technology, Cellular Manufacturing, and CIM.
- Next Unit: Unit 5 - Additive Manufacturing.
- Concepts of 3D printing, rapid prototyping, and their applications.

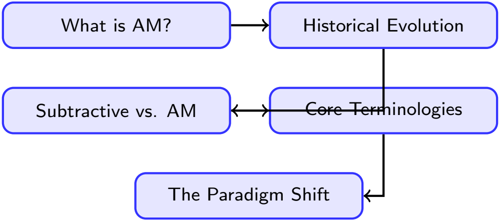
Gear Forming Processes: Gear Milling

Manufacturing Engineering - III (DI05019011)

DI05019011



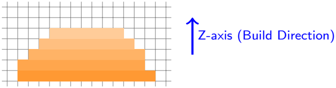
Agenda



- What is Additive Manufacturing?
- Historical Evolution of AM
- Subtractive vs. Additive Manufacturing
- Core Terminologies (Rapid Prototyping, 3D Printing, AM)
- The Paradigm Shift in Manufacturing

What is Additive Manufacturing?

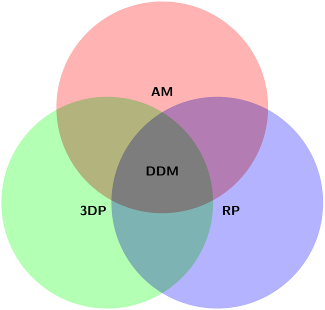
- ASTM F2792 defines AM as: “Process of joining materials to make objects from 3D model data, usually layer upon layer.”
- It is fundamentally different from subtractive manufacturing methodologies (like milling or turning).
- Often interchangeably called 3D Printing, Rapid Prototyping (RP), or Direct Digital Manufacturing (DDM).
- Creates parts with highly complex geometries without tooling.



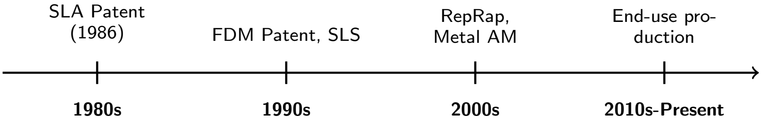
Layer-by-layer Building

Terminology Confusion & Clarity

- **Rapid Prototyping (RP):** The original term; used when AM was primarily for making prototypes quickly.
- **3D Printing (3DP):** Popularized by media; originally referred to a specific binder jetting process invented at MIT.
- **Additive Manufacturing (AM):** The formal, industrial term encompassing all layer-by-layer technologies.
- **Direct Digital Manufacturing (DDM):** Emphasizes the direct link from digital CAD to physical part.



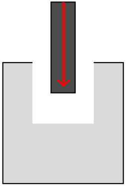
Historical Evolution of AM



- **1980s:** Hideo Kodama files first patent for SLA (abandoned). Charles Hull (3D Systems) patents Stereolithography (1986).
- **1990s:** Fused Deposition Modeling (FDM) patented by Scott Crump (Stratasys). Selective Laser Sintering (SLS) commercialized.
- **2000s:** Open-source RepRap project begins, leading to desktop 3D printing revolution. Metal AM gains traction.
- **2010s-Present:** AM shifts from rapid prototyping to end-use production. Development of new materials and multi-material printing.

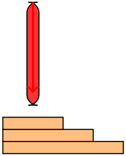
Subtractive vs. Additive Manufacturing

Subtractive (Milling)



Material removed

Additive (3D Printing)

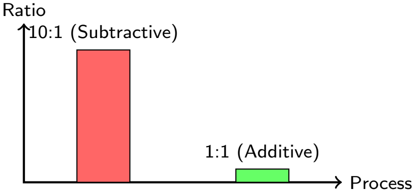


Material added

Subtractive Manufacturing	**Additive Manufacturing**
Starts with a solid block; material is removed (e.g., CNC milling, turning, drilling). High material waste, geometric limitations based on tool access.	Starts with nothing; material is added where needed. Minimal waste, extreme geometric freedom (e.g., internal channels).

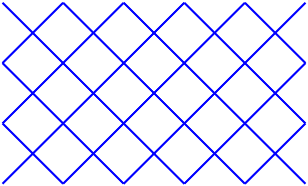
Comparison: Material Utilization

- Buy-to-Fly Ratio: The weight of raw material purchased vs. the weight of the final part.
- Aerospace subtractive parts can have ratios of 10:1 to 20:1.
- AM reduces this ratio to near 1:1, saving immense material costs, especially in exotic alloys like Titanium.
- Sustainable manufacturing aspect of AM.



Comparison: Complexity & Tooling

- **Complexity is Free:** In AM, complex shapes do not cost more to produce than simple shapes.
- **Tool-less Manufacturing:** No need for molds, dies, jigs, or fixtures to create the geometry.
- **Part Consolidation:** Assemblies of many parts can be redesigned into a single AM part.
- **Shorter lead times** from design to physical part.

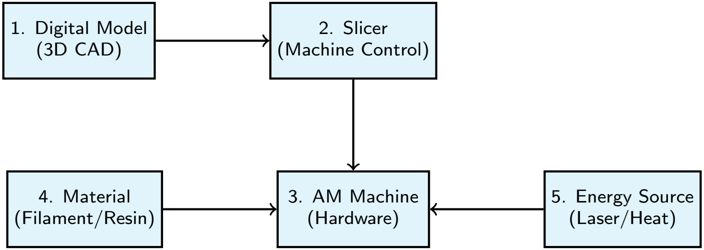


Complex Lattice Structure (Impossible conventionally)

The Paradigm Shift

- Design for Manufacturing → Design for AM (DfAM)
- Mass Production → Mass Customization
- Centralized Factories → Distributed Manufacturing
- Physical Inventory → Digital Inventory (On-demand)

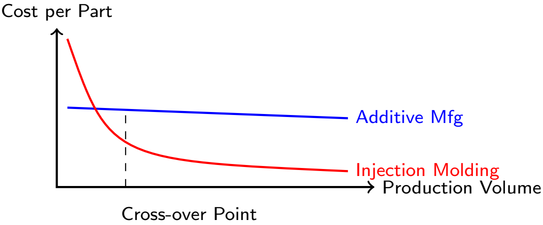
Core Components of any AM System



- Digital Model (3D CAD).
- Machine Control Software (Slicer).
- AM Machine / Hardware.
- Material (Filament, Resin, Powder).
- Energy Source (Laser, Heat, UV Light).

When NOT to use AM

- **High Volume Mass Production:** Injection molding is still faster and cheaper for millions of parts.
- **Simple Geometries:** A simple block or cylinder is better machined.
- **Extreme Tolerance/Finish Requirements:** AM parts often require post-processing to achieve tight tolerances and smooth finishes.

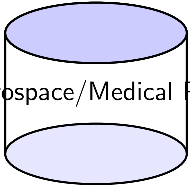


Summary

- AM builds parts layer-by-layer directly from digital CAD data.
- It evolved from rapid prototyping to end-use production.
- AM offers tool-less production and near-zero material waste.
- Provides unprecedented geometric freedom, enabling part consolidation and lightweighting.

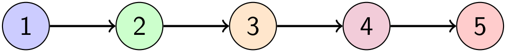
Introduction to Additive Manufacturing - II

- Course: Manufacturing Engineering - III (DI05019011)
- Unit 5: Additive Manufacturing & Modern Trends
- Lecture 39: Introduction to Additive Manufacturing - II



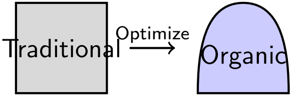
Agenda

- Advantages of AM
- Limitations and Challenges
- Industrial Applications (Aerospace, Medical, Automotive)
- Impact on Supply Chain
- Future Trends in AM



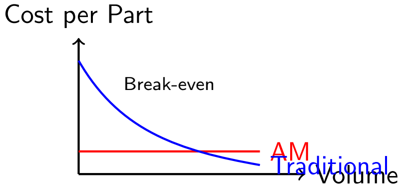
Advantages of AM: Design Freedom

- Ability to create organic shapes, internal cooling channels, and lattice structures.
- Generative Design and Topology Optimization can be fully realized.
- Customization at no extra cost (e.g., patient-specific medical implants).
- Part Consolidation: Combining 20+ parts into a single monolithic printed part.



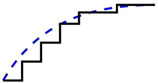
Advantages of AM: Time and Cost

- Rapid Prototyping drastically reduces product development cycles.
- No upfront tooling costs (dies, molds) makes low-volume production economical.
- Reduced material waste (High material utilization).
- Lower inventory costs through 'Print on Demand' capabilities.



Limitations and Challenges

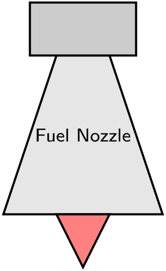
- Slow Production Speed: Not suitable for mass production of millions of parts.
- Material Properties: Anisotropy (weaker in Z-axis due to layer bonding).
- Surface Finish: Stair-stepping effect requires significant post-processing.
- Size Limitations: Constrained by the machine's build volume.
- High Equipment and Material Costs for industrial grades.



Stair-stepping effect on curved surface

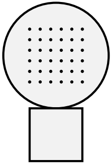
Application: Aerospace Industry

- Focus on lightweighting (Topology optimization).
- Fuel nozzles (e.g., GE LEAP engine nozzle consolidated from 20 parts to 1).
- Complex ducting and brackets.
- High material efficiency for expensive titanium alloys.



Application: Medical and Dental

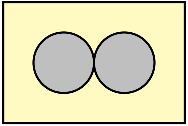
- Mass Customization is key: Every patient's anatomy is unique.
- Dental aligners, crowns, and surgical guides.
- Orthopedic implants (e.g., Titanium hip joints with porous structures for bone ingrowth).
- Bioprinting (experimental printing of tissues and organs).



Hip Implant with Porous Structure

Application: Automotive Industry

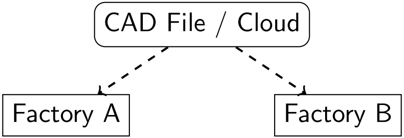
- Rapid prototyping for design iteration (wind tunnel models).
- Jigs, fixtures, and tooling for the assembly line.
- Custom or discontinued spare parts for classic cars.
- High-performance parts in Formula 1 (e.g., complex cooling jackets).



3D Printed Fixture

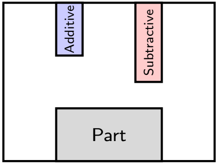
Impact on Supply Chain

- Digital Inventory: Storing CAD files instead of physical spare parts.
- Distributed Manufacturing: Sending a file across the world to print locally.
- Reduced dependence on complex global shipping and warehousing.
- Faster response to disruptions.



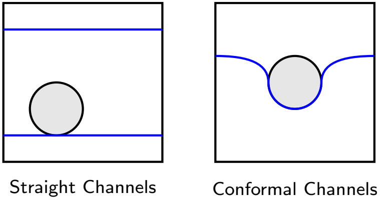
Future Trends in AM

- Multi-material and multi-color printing in a single build.
- 4D Printing: AM parts that change shape or properties over time.
- Hybrid Machines: Combining additive and subtractive processes in one CNC center.
- In-situ monitoring and AI-driven quality control during printing.



Case Study: Rapid Tooling

- Conformal Cooling Channels in Injection Molds.
- Traditional molds use straight drilled cooling lines. AM allows channels that hug the contour of the part.
- Result: Uniform cooling, reduced cycle times by up to 30%, and fewer part defects (warpage).
- Demonstrates AM adding value to traditional mass production.



Summary

- AM excels in low-volume, high-complexity, customized production.
- Major hurdles remain in speed, anisotropic properties, and post-processing.
- Aerospace, Medical, and Automotive are the dominant early adopters.
- AM enables digital supply chains and distributed manufacturing.

Aerospace	**Medical**	**Supply Chain**
Lightweighting	Custom Implants	Digital Inventory
Complex Parts	Bioprinting	Dist. Manufacturing

AM Principle & Process Chain

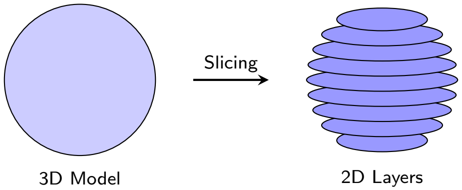
- Course: Manufacturing Engineering - III (DI05019011)
- Unit 5: Additive Manufacturing & Modern Trends
- Lecture 40: AM Principle & Process Chain

Agenda

No.	Topic	Focus
1	Fundamental Principle	Slicing and Layering
2	The Process Chain Overview	8 Generic Steps
3	Step 1: CAD Design	Digital Modeling
4	Step 2: STL Conversion	Mesh Generation
5	Step 3: Transfer & Orientation	Slicer & G-Code
6	Step 4: Machine Setup	Preparation
7	Step 5-8: Build to Application	Execution & Finalization

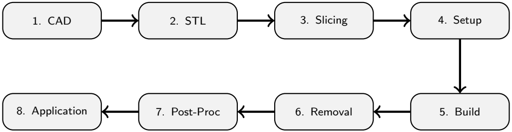
Fundamental Principle of AM

- Slicing: A complex 3D digital model is computationally sliced into 2D cross-sectional layers.
- Layering: The AM machine fabricates the physical part by sequentially depositing or curing material corresponding to each 2D slice.
- Bonding: Each new layer adheres or fuses to the previous layer beneath it.
- Z-Axis Resolution: The thickness of these layers dictates the vertical resolution and surface finish.



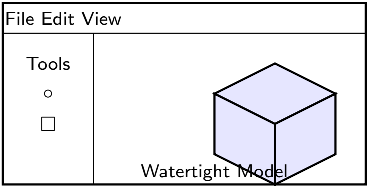
The Generic AM Process Chain

- Regardless of the specific technology (FDM, SLA, SLS), the workflow is generally standard.
- It bridges the digital domain (Software) and the physical domain (Hardware/Materials).
- Consists of 8 generalized steps from concept to final usable part.
- Efficiency in this chain dictates the overall success and cost of the AM project.



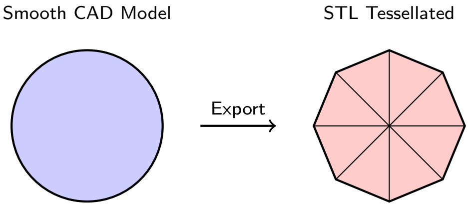
Step 1: Conceptualization & CAD

- The process starts with a 3D software model.
- Created via solid modeling CAD (SolidWorks, CATIA), surface modeling, or 3D scanning/reverse engineering.
- Crucial Requirement: The model must be a 'watertight' solid manifold.
- Design for Additive Manufacturing (DfAM) principles should be applied here (e.g., minimizing overhangs, hollowing out bulk).



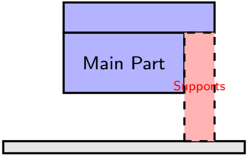
Step 2: Conversion to STL/AMF

- AM machines do not read native CAD files (.prt, .sldprt).
- The CAD model must be exported to an AM-specific format, universally the STL (Standard Tessellation Language) file.
- STL approximates the surfaces of the model using a mesh of triangles.
- Newer formats like 3MF and AMF include color, material, and lattice data.



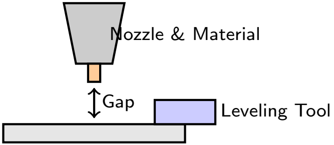
Step 3: Transfer to AM Machine & Slicing

- The STL file is imported into slicer software (e.g., Cura, Magics).
- Part Orientation: Positioning the part in the build envelope for strength, surface finish, and minimal support material.
- Support Generation: Software automatically adds temporary structures to support overhanging features.
- Slicing: The software generates the G-code (toolpath instructions) for the specific machine.



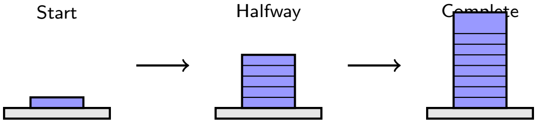
Step 4: Machine Setup

- Physical preparation of the AM machine before starting.
- Material loading (filling powder beds, loading filament spools, or pouring resin).
- Build platform preparation (leveling the bed, applying adhesion promoters like glue or tape).
- Pre-heating the build chamber or platform to prevent thermal warping.



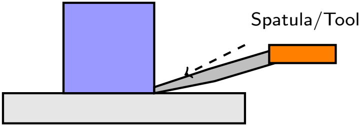
Step 5: The Build Process

- The machine executes the G-code to build the part layer by layer.
- Largely an automated process requiring minimal human intervention.
- Monitoring: Checking for early layer failures, thermal issues, or material run-out.
- Build times can range from a few hours to several days depending on size and resolution.



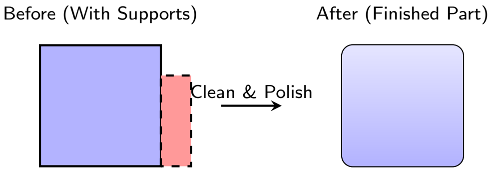
Step 6: Removal and Cleanup

- Removing the completed part from the build platform.
- Can require physical force, spatulas, or EDM wire cutting for metal parts.
- Initial cleanup: Removing excess unfused powder (SLS) or washing away uncured liquid resin (SLA).
- Safety gear (PPE) is often required here for handling powders or resins.



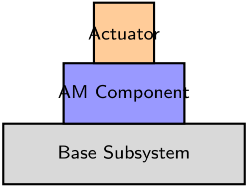
Step 7: Post-Processing

- The most labor-intensive step.
- Support Removal: Manually breaking off supports or dissolving them in chemical baths.
- Thermal Treatments: Stress relieving, sintering, or Hot Isostatic Pressing (HIP) for metal parts.
- Surface Finishing: Sanding, bead blasting, painting, or machining critical tolerances.



Step 8: Application

- The final part is ready for its intended use.
- Inspection and Quality Control (CMM, CT scanning for internal defects) ensure it meets specifications.
- Process Chain Summary: CAD → STL → Slicer → Setup → Build → Removal → Post-Processing → Application.



Gear Forming Processes: Gear Milling

Manufacturing Engineering - III (DI05019011)

DI05019011

Agenda

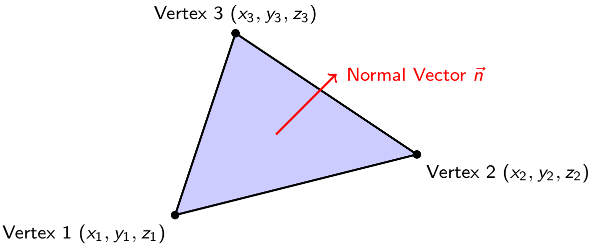
- What is the STL File Format?
- Tessellation Concept
- Chordal Error and Resolution
- Common STL Errors (Non-manifold, Flipped Normals)
- Overview of AM Materials (Polymers, Metals, Ceramics)

The STL File Format

- STL = Standard Tessellation Language (or STereoLithography).
- Created by 3D Systems in 1987; remains the de facto industry standard.
- It strips away all CAD history, parametric data, color, and material properties.
- It only describes the surface geometry of a three-dimensional object.

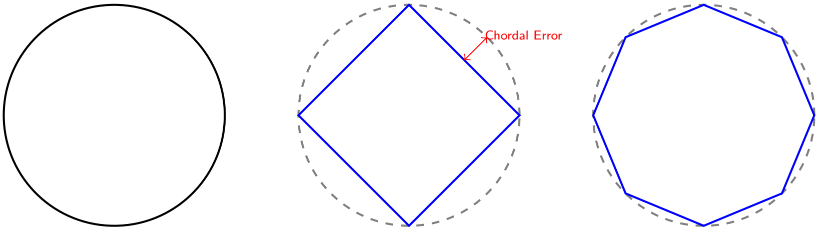
Concept of Tessellation

- Tessellation is the process of tiling a surface with geometric shapes without gaps or overlaps.
- STL files tessellate a 3D surface using exclusively triangles (facets).
- Each triangle is defined by: 3 vertices (X, Y, Z coordinates) and 1 Normal Vector.
- The Normal Vector points OUTWARD, telling the software which side of the triangle is 'outside' and which is 'inside' (solid material).



Resolution and Chordal Error

- Because triangles are flat, they can only approximate curved surfaces.
- **Chordal Error (or Tolerance):** The maximum distance between the true curved CAD surface and the flat triangular facet.
- **Coarse Resolution:** Large triangles, high chordal error, highly faceted/blocky printed surface, small file size.
- **Fine Resolution:** Tiny triangles, low chordal error, smooth surface, massive file size.



True Surface   Coarse (High Error)   Fine (Low Error)

Common STL File Errors

- For slicing to work, the STL must be 'Manifold' or 'Watertight' (a continuous enclosed volume).
- **Gaps/Holes:** Missing triangles leave the model open.
- **Overlapping/Intersecting Facets:** Triangles crossing through each other confusing the slicer.
- **Flipped Normals:** A normal vector pointing 'inwards', making the slicer think a solid section is empty space.

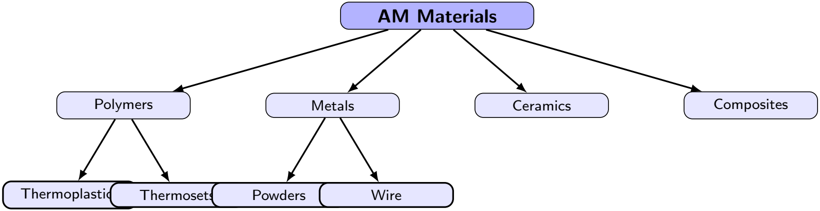
Alternative Formats (AMF, 3MF)

- STL is outdated and inefficient for modern multi-color, multi-material printers.
- **AMF (Additive Manufacturing File Format):** XML-based, supports color, materials, lattices, and curved triangles.
- **3MF (3D Manufacturing Format):** Developed by Microsoft/Consortium, highly compressed, prevents common STL errors, widely adopted in modern slicers.

Feature	STL	AMF	3MF
Data Type	Surface geometry only	Color, Materials	Complete manufacturing data
Curved Triangles	No	Yes	No (supports high res)
File Size	Large (for high res)	Moderate	Highly Compressed
Industry Adoption	Standard	Low	Growing Standard

Overview of AM Materials

- AM technologies are categorized by the state of raw material: Liquid, Solid (Wire/Filament), or Powder.
- The three major classes of materials are Polymers, Metals, and Ceramics.
- Composites (carbon-fiber reinforced polymers) are also rapidly growing.



Polymer AM Materials

- **Thermoplastics:** Melted and extruded (e.g., PLA, ABS, Nylon, PC, ULTEM). Used in FDM/FFF.
- **Thermosets (Photopolymers):** Liquid resins cured by UV light (e.g., Standard resins, tough resins, castable waxes). Used in SLA/DLP.
- Polymers are the most widely used AM materials due to low cost and ease of processing.
- Applications range from rapid prototyping to functional end-use parts.

Metal AM Materials

- Most common form is fine, spherical metallic powder.
- Common metals: Titanium alloys (Ti6Al4V), Aluminum (AlSi10Mg), Stainless Steel (316L), Inconel (superalloys).
- Used primarily in Powder Bed Fusion (SLM/DMLS) and Directed Energy Deposition (DED).
- High cost, requires inert gas environments and extensive safety protocols.

Ceramics and Composites

- **Ceramics:** Extremely difficult to print due to high melting points. Often printed via binder jetting or SLA (resin loaded with ceramic particles), then heavily sintered.
- Biocompatible ceramics (Hydroxyapatite) used for bone scaffolding.
- **Composites:** Chopped or continuous carbon fiber, glass fiber, or Kevlar embedded in a polymer matrix.
- Provides strength-to-weight ratios rivaling aluminum.

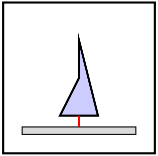
Summary

- STL files describe 3D geometry using a mesh of triangles.
- Chordal error and normal vectors are critical to a valid, printable STL.
- Materials dictate the process: Polymers (Filament/Resin), Metals (Powders), and Ceramics.
- Next-gen formats like 3MF and composite materials are the future.

Gear Forming Processes: Gear Milling

Manufacturing Engineering - III (DI05019011)

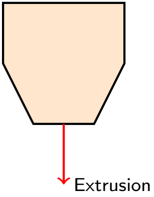
DI05019011



FDM 3D Printer

Agenda

- Introduction to Extrusion-Based AM
- Working Principle of FDM
- Key Hardware Components
- FDM Materials (Thermoplastics)
- Process Parameters (Layer height, Infill, Shells)



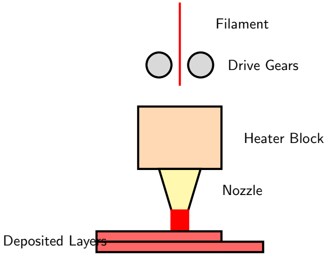
Introduction to FDM

- FDM (Fused Deposition Modelling) was invented by Scott Crump in 1989 (founder of Stratasys).
- Also known as FFF (Fused Filament Fabrication) in open-source/desktop communities to avoid trademarks.
- Falls under the ASTM category of 'Material Extrusion'.
- Most popular AM process due to low cost, safety, and ease of use.

Stratasys (Commercial FDM) ⟷ RepRap (Open-source FFF)

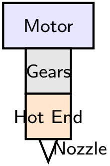
Working Principle of FDM

- Solid thermoplastic filament is fed into a heated extrusion head.
- The heat melts the polymer into a semi-liquid state.
- The print head moves along X and Y axes, depositing the melted polymer onto a build platform.
- The material cools and solidifies immediately, bonding to the layer below.
- The platform drops (or head raises) in the Z-axis, and the next layer is deposited.



Key Hardware Components

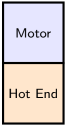
- **Extruder (Cold End):** Stepper motor and gears that grip and push the filament.
- **Hot End:** Consists of a heat break, heater block (melts plastic), and nozzle (typically 0.4mm brass).
- **Motion System:** Stepper motors, belts, and lead screws controlling X, Y, Z movement.
- **Build Platform (Bed):** Often heated to improve part adhesion and prevent warping.
- **Cooling Fans:** Rapidly cool the extruded plastic to maintain shape.



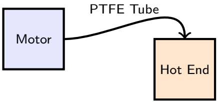
Extruder Configurations

- **Direct Drive:** Extruder motor is mounted directly on the moving print head. Better control for flexible materials, but makes the head heavy.
- **Bowden System:** Extruder motor is mounted on the frame; filament is pushed through a PTFE tube to the hot end. Lighter print head (faster printing), but harder to print flexible filaments.

Direct Drive



Bowden System



FDM Materials (Thermoplastics)

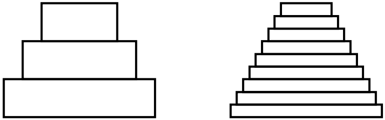
- **PLA (Polylactic Acid):** Biodegradable, easy to print, low warp, brittle. Best for prototyping.
- **ABS (Acrylonitrile Butadiene Styrene):** Durable, impact-resistant, high warp, emits fumes. Used in Lego bricks.
- **PETG:** Combines the ease of PLA with the strength of ABS.
- **TPU (Flexible):** Rubber-like polyurethane.
- **Engineering Plastics:** Nylon, PC, ULTEM (requires high-temperature industrial machines).

Material	Strength	Ease of Printing	Typical Bed Temp.
PLA	Moderate	Very Easy	50–60°C
ABS	High	Difficult (Warps)	90–110°C
PETG	High	Easy	70–80°C

Key Process Parameters: Layer Height

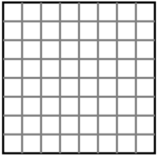
- Dictates the Z-axis resolution.
- Typically ranges from 0.1mm (fine) to 0.3mm (coarse) for a standard 0.4mm nozzle.
- **Trade-off:** Finer layers produce better surface finish and smoother curves, but exponentially increase print time.
- Rule of thumb: Layer height should not exceed 80% of the nozzle diameter.

Coarse (e.g. 0.3mm) Fine (e.g. 0.1mm)



Key Process Parameters: Infill

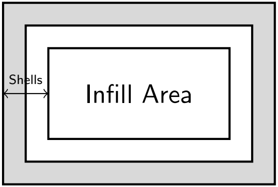
- Unlike subtractive methods, FDM parts do not need to be completely solid.
- **Infill Density:** Percentage of solid material inside the part (0% = hollow, 100% = solid). Usually set between 15-20% for prototypes.
- **Infill Pattern:** Internal geometry (Grid, Honeycomb, Gyroid, Cubic).
- Saves massive amounts of material, weight, and time while maintaining structural integrity.



Grid Infill Pattern

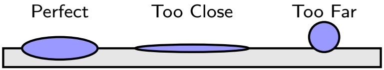
Key Process Parameters: Shells / Perimeters

- **Shells (or Wall Line Count):** The number of solid outer contours printed before laying down the infill.
- **Top/Bottom Layers:** Number of solid layers on horizontal surfaces.
- Increasing the number of shells is the most effective way to increase the mechanical strength of an FDM part, even more than increasing infill density.



Adhesion and the First Layer

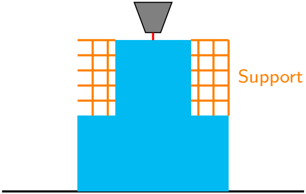
- The first layer is the most critical part of an FDM print.
- If it fails to adhere to the bed, the entire print fails ('spaghetti').
- Bed leveling (tramming) is crucial for a consistent first layer 'squish'.
- Adhesion Aids: Heated bed, PEI sheets, glue stick, painter's tape, or slicer aids like Brims and Rafts.



Summary

- FDM extrudes melted thermoplastic filament layer by layer.
- Key components include the Extruder, Hot End, and XYZ motion system.
- PLA, ABS, and PETG are common materials.
- Process parameters like Layer Height, Infill, and Shells balance speed, strength, and quality.

Polymer AM: Fused Deposition Modelling (FDM) - II



- Course: Manufacturing Engineering - III (DI05019011)
- Unit 5: Additive Manufacturing & Modern Trends
- Lecture 43: Fused Deposition Modelling (FDM) - II

Agenda

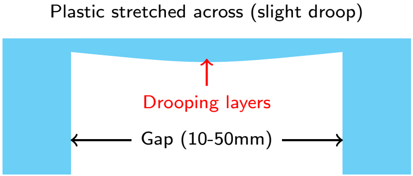
1. The Overhang Problem
2. Support Structures (Standard vs. Soluble)
3. Common FDM Defects (Warping, Stringing, Layer Shifting)
4. Anisotropy in FDM Parts
5. Design for FDM (DfAM Rules)
6. Applications of FDM

The Overhang Problem (The 45-Degree Rule)

Concept

- Because FDM extrudes soft plastic layer-by-layer, each layer must be supported by the one below it.
- You cannot print on thin air.
- **The 45-Degree Rule:** FDM can generally print overhangs up to 45° from the vertical without supports.
- Beyond 45°, the layers overlap too little, causing drooping or failure.

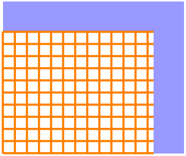
Bridging



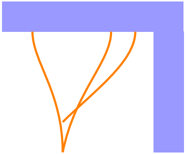
What is Bridging?

- Bridging occurs when plastic is extruded across a horizontal gap between two anchor points.
- With strong part cooling fans, machines can stretch hot plastic across gaps (often 10-50mm) without supports.
- Bridged layers will droop slightly but act as a foundation for subsequent layers.
- Slicers automatically detect bridges and adjust speed and cooling.

Support Structures



Grid/Zigzag Supports



Tree/Organic Supports

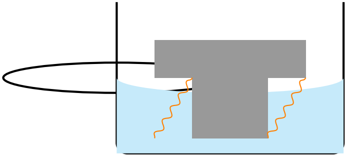
Design Considerations

- For severe overhangs (like the arms of a 'T'), temporary support structures must be printed.
- Supports consume extra material, increase print time, and leave rough surface finish upon removal.
- **Tree Supports:** Advanced slicing feature that generates organic, branch-like supports that use less material and are easier to remove.

Dual Extrusion & Soluble Supports

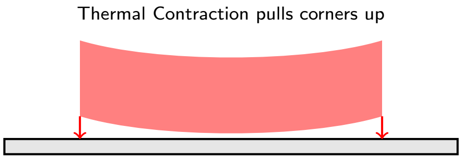
Dual Extrusion

- Industrial FDM machines often have two print heads (Dual Extrusion).
- One head prints the model material (e.g., ABS); the other prints support material.
- **Soluble Supports** (e.g., PVA - Polyvinyl Alcohol, HIPS).
- PVA dissolves in water, leaving a perfect surface finish on complex internal overhangs.



Submerged Part in Water

Common Defect: Warping & Curling

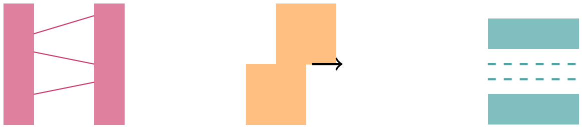


Why it happens and how to fix it

- **Cause:** Uneven cooling. As upper layers cool and contract, they pull on the lower layers.
- Results in corners lifting off the build plate.
- Common in high-temperature materials like ABS and Nylon.
- **Solutions:** Heated build bed, heated enclosure, brims/rafts, draft shields, adjusting cooling fans.

Other Defects: Stringing & Layer Shifting

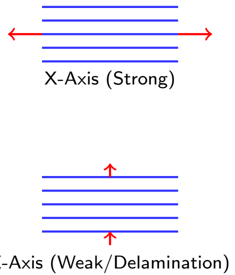
1. Stringing   2. Layer Shifting   3. Under-extrusion



Defects & Causes

- **Stringing (Oozing):** Wispy plastic strings between travel moves. Fixed by tuning ‘Retraction’ settings (pulling filament back slightly during travel).
- **Layer Shifting:** Print layers suddenly step out of alignment. Caused by mechanical issues (loose belts) or stepper motors skipping steps due to collisions.
- **Under-extrusion:** Gaps in the print due to a clogged nozzle or slipping extruder gear.

Anisotropy in FDM

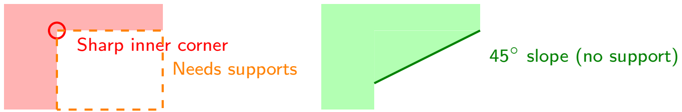


Mechanical Limitation

- FDM parts are highly **Anisotropic**: Mechanical properties vary depending on the direction of measurement.
- **Z-Axis Weakness:** The bond between layers (Z-axis) is weaker than the continuous filament lines in the X-Y plane.
- Parts subjected to tension will snap much easier if pulled perpendicular to the layers (layer delamination).
- **Design Rule:** Orient the part so structural loads run parallel to the X-Y layers.

Design for FDM (DfAM Rules)

Bad Design **Good Design**



Key DfAM Rules

- **Avoid support structures:** Use chamfers (45°) instead of fillets on downward-facing edges. Modify overhangs.
- **Holes and Tolerances:** Horizontal holes often print slightly smaller than designed. Design clearances (0.2 - 0.4mm) for moving assemblies.
- **Flat base:** Ensure the design has a large flat surface for good bed adhesion.
- **Fillet vertical corners:** Sharp vertical corners concentrate thermal stress and warp easily.

Applications of FDM

Application Category	Description / Example
Prototyping	Form, Fit, and Function verification.
Manufacturing Tooling	Custom jigs, fixtures, and tailored assembly aids.
End-use Parts	Low-volume production runs (e.g., drone chassis, custom brackets).
Education & Hobbyist	Ubiquitous in maker communities and student projects.
Medical Models	Anatomical bone models for surgical planning (from CT scans).

Summary

Check	Key Takeaway
✓	Overhangs require support structures, which can be mitigated through good design (45-degree rule).
✓	Thermal contraction causes warping, requiring bed heating and enclosures.
✓	FDM parts are mechanically weakest in the Z-axis (Anisotropic).
✓	FDM is heavily used for rapid prototyping and manufacturing tooling.

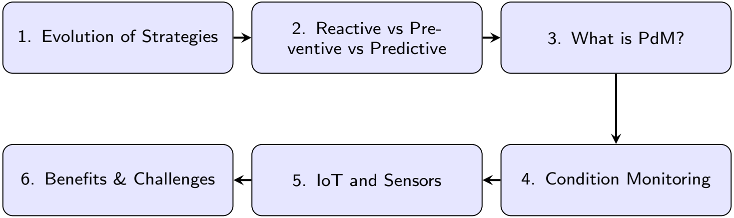
Gear Forming Processes: Gear Milling

Manufacturing Engineering - III (DI05019011)

DI05019011

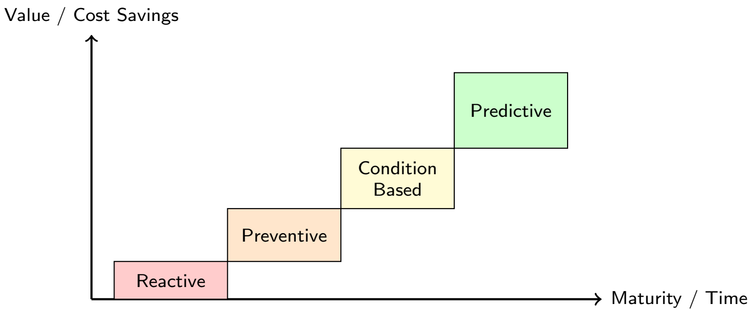
Predictive maintenance, process optimization - introduction

Agenda


1. Evolution of Strategies
2. Reactive vs Preventive vs Predictive
3. What is PdM?
4. Condition Monitoring
5. IoT and Sensors
6. Benefits & Challenges

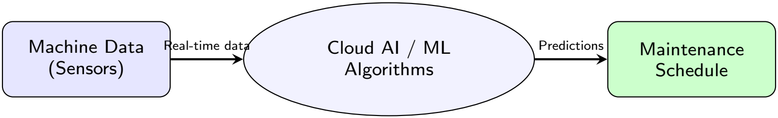
Evolution of Maintenance

- **Run-to-Failure (Reactive):** Fix it only when it breaks. High downtime costs.
- **Time-Based (Preventive):** Scheduled intervals. Unnecessary replacement of healthy parts.
- **Condition-Based:** Based on physical indicators of wear.
- **Predictive (PdM):** Data and algorithms to predict exact failure time.



What is Predictive Maintenance (PdM)?

- Continuously monitors performance/condition during normal operation.
- Reduces the likelihood of unexpected machine failure.
- Relies on Industrial IoT (IIoT), sensor data, and Machine Learning.
- **Goal:** Maximize parts lifetime while minimizing downtime.

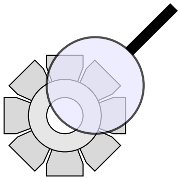


Core Element: Condition Monitoring

Definition

Condition Monitoring is the process of monitoring parameters of condition in machinery to identify significant changes indicative of a developing fault.

- Provides the raw data necessary for predictive algorithms.
- Continuous vs. Periodic monitoring.



Condition Monitoring Techniques

Vibration Analysis	**Infrared Thermography**
Most common. Detects unbalance, misalignment, bearing wear in rotating machinery.	Detects electrical faults, friction, and overheating components.
Acoustic Emission/Ultrasound	**Oil Analysis**
Detects high-frequency friction, leaks, or microscopic cracks.	Checks for wear particles and chemical breakdown in lubricants.

Vibration: Rotating Machinery

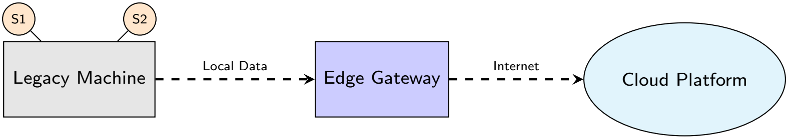
Thermal: Electrical & Friction

Ultrasound: Leaks & Cracks

Oil: Wear & Chemistry

The Role of IoT and Smart Sensors

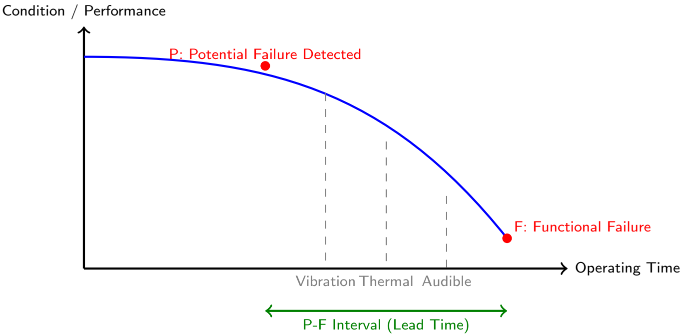
- Sensors: Cheap, wireless, easily retrofitted.
- IIoT networks collect massive amounts of real-time data.
- **Edge Computing:** Initial data processing happens near the machine to reduce latency.
- **Cloud Computing:** Heavy data storage and long-term trend analysis.



The P-F Curve

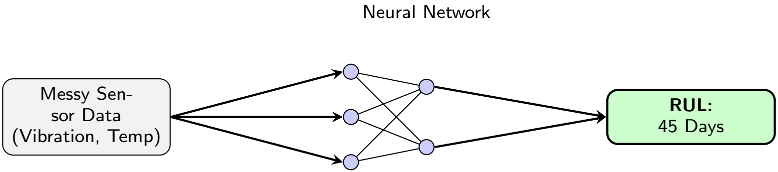
The P-F curve illustrates machine behavior approaching failure.

- **P (Potential Failure):** Defect first detected (ultrasound, vibration).
- **F (Functional Failure):** Machine breaks down.
- **P-F Interval:** Time window between P and F. PdM aims to detect 'P' early.



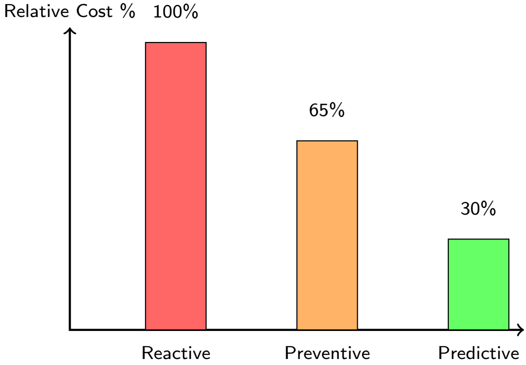
From Data to Prediction (AI/ML)

- ML algorithms learn the 'normal' baseline signature of a machine.
- **Anomaly Detection:** AI flags deviations from the baseline.
- **Predictive Modeling:** Calculates Remaining Useful Life (RUL).



Benefits of Predictive Maintenance

- **Minimized Unplanned Downtime:** Eliminates sudden failures.
- **Maximized Component Life:** Parts used to actual safe limit.
- **Reduced Maintenance Costs:** Less overtime, fewer rush orders.
- **Improved Safety:** Prevents hazardous catastrophic failures.



Challenges in Implementation

- **High setup cost:** Sensors, software, IT infrastructure.
- **Data Quality:** Garbage in, garbage out. Requires accurate baseline data.
- **Skill Gap:** Requires data scientists and reliability engineers.
- **Cultural Shift:** Trusting the algorithm over intuition.

Overcoming Integration
& Cultural Hurdles

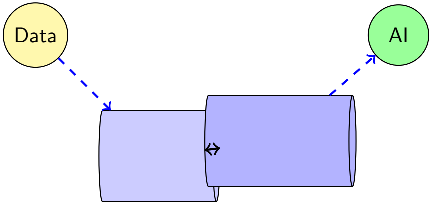
Summary

- ✓ PdM replaces scheduled maintenance with condition-based forecasting.
- ✓ Relies on sensors (vibration, thermal) and IIoT to gather data.
- ✓ Maximizes the P-F interval to plan maintenance without production loss.
- ✓ Reduces costs and downtime, but requires upfront investment in IT and culture.

Key Takeaways

- Predictive maintenance fixes things right before they break.
- IoT and Condition Monitoring provide the required data.
- The P-F curve illustrates the window of opportunity for maintenance.

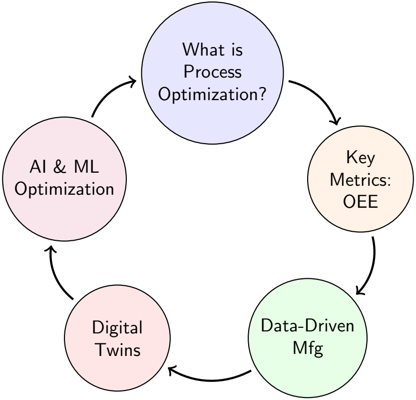
Modern Trends: Process Optimization



Details

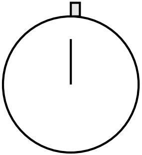
- Course: Manufacturing Engineering - III (DI05019011)
- Unit 5: Additive Manufacturing & Modern Trends
- Lecture 45: Process Optimization - Introduction

Agenda

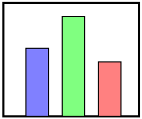


What is Process Optimization?
Key Metrics: OEE
Data-Driven Mfg
Digital Twins
AI & ML Optimization

What is Process Optimization?



Traditional (Stopwatch)



Modern (Dashboard)

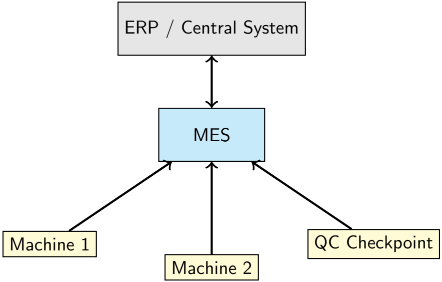
- The discipline of adjusting a process to optimize a specific set of parameters without violating constraints.
- Goals: Minimize cost, maximize throughput, improve quality, reduce energy consumption.
- Traditional optimization relied on Lean Six Sigma, time studies, and trial-and-error.
- Modern optimization relies on big data, real-time analytics, and simulation.

The Gold Standard Metric: OEE

$$\text{OEE} = \text{Availability} \times \text{Performance} \times \text{Quality}$$

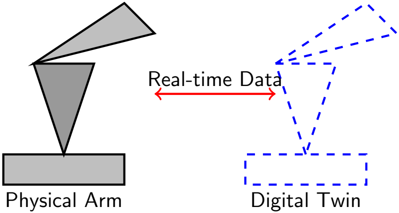
- Overall Equipment Effectiveness (OEE) identifies the percentage of manufacturing time that is truly productive.
- Availability: Uptime vs Downtime (Stops, breakdowns, setups).
- Performance: Actual speed vs Maximum design speed (Slow cycles).
- Quality: Good parts vs Total parts produced (Defects, scrap).

Data-Driven Manufacturing



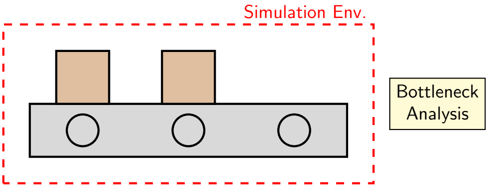
- Traditional factories operate in silos. Data is trapped on paper or isolated machine controllers.
- Smart Factories integrate IT (Information Tech) and OT (Operational Tech).
- Every machine, conveyor, and quality checkpoint feeds data into a central ERP/MES system.
- Allows managers to identify bottlenecks instantly.

Introduction to Digital Twins



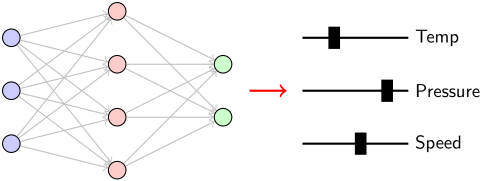
- A Digital Twin is a virtual representation of a physical product, process, or system.
- It is updated with real-time data from sensors on the physical counterpart.
- Levels of Twins: Component Twin, Asset Twin, System Twin.
- Enables 'What-if' simulations without risking real-world production.

How Digital Twins Optimize Processes



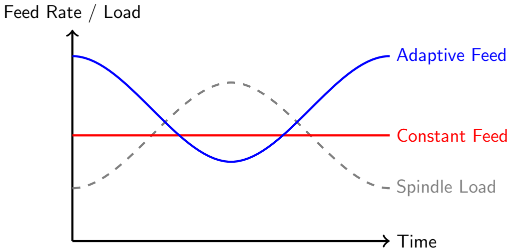
- Virtual Commissioning: Testing and debugging logic in the twin before physical build.
- Bottleneck Analysis: Simulating increased throughput to see where the system fails.
- Energy Optimization: Simulating different schedules to minimize power usage.
- Continuous Feedback: The physical twin learns from the digital twin's simulations.

AI in Process Optimization



- ML algorithms can optimize complex, multi-variable processes.
- AI analyzes historical data to find the optimal combination of variables.
- Closed-Loop Control: Automatically adjusts machine parameters in real-time.
- Computer Vision: Using AI cameras for real-time defect detection.

Example: Adaptive Machining

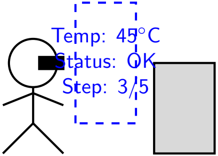


- In traditional CNC, feed rates are programmed conservatively to avoid tool breakage.
- Adaptive machining uses sensors to monitor spindle load in real-time.
- Optimization: System increases feed rate during light cuts, slows down during heavy cuts.
- Result: Reduced cycle times by 10-20% and extended tool life.

Energy Optimization and Sustainability

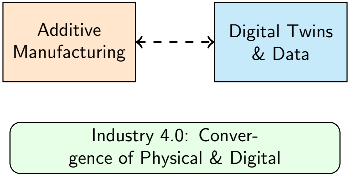
- Modern optimization is not just about speed, but sustainability.
- Smart grids on the factory floor power down inactive equipment.
- Optimizing logistics routes for AGVs to reduce battery usage.
- Reducing scrap rates directly reduces the energy wasted on producing bad parts.

The Human Element in Industry 4.0



- Optimization does not necessarily eliminate operators; it changes their role.
- From manual labor to supervising complex digital systems.
- Augmented Reality (AR): Providing operators with real-time data overlays.
- The operator becomes an 'Augmented Operator'.

Summary of Unit 5



- Additive Manufacturing offers unprecedented design freedom and shifts the paradigm.
- We explored the AM process chain, STL files, and FDM technology in depth.
- Modern trends like Predictive Maintenance use IoT to eliminate unplanned downtime.
- Process Optimization leverages Digital Twins and AI to maximize efficiency and OEE.