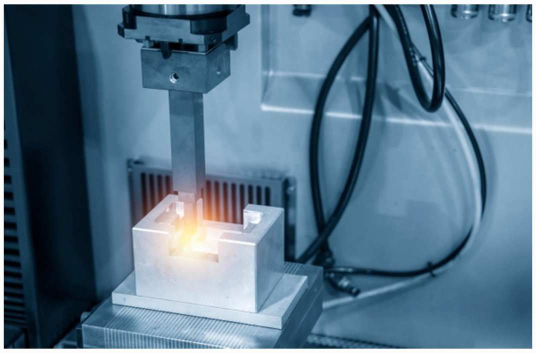
SUBJECT- Advanced Manufacturing Processes

UNIT-01 Non-Conventional Machining Processes

1. Electrical Discharge Machining (EDM)

Working Principle

EDM removes metal by generating continuous, rapid-fire **electrical spark discharges** between a shaped tool and a conductive workpiece. Both are submerged in a dielectric fluid.
When the voltage across the small **spark gap** (0.01 to 0.5 mm) reaches the breakdown voltage of the fluid, the fluid ionizes, forming a plasma channel. A spark jumps across, producing localized temperatures up to 10,000°C that melt and vaporize a microscopic pocket of metal. When the current is turned off, the plasma channel collapses, and the dielectric fluid flushes away the molten metal debris.



Industrial EDM Setup.

Equipment Setup

- **DC Pulse Generator:** Converts AC power into high-frequency, pulsed DC power.
- **Tool (Cathode):** Formed to the inverse shape of the desired cavity; made of graphite, copper, or brass.

- **Workpiece (Anode):** Must be an electrically conductive material.
- **Servo Feed System:** Automatically maintains a constant spark gap between the tool and the workpiece.
- **Dielectric System:** Contains dielectric fluid (kerosene or deionized water), a pump, and a filter to circulate and flush the gap.

Process Parameters

- **Discharge Current (Ip):** Determines spark energy; higher current increases Material Removal Rate (MRR) but roughens surface finish.
- **Pulse-on Time (Ton):** The duration for which the spark is active.
- **Pulse-off Time (Toff):** The cooling period allowing the dielectric to de-ionize and flush away debris.
- **Spark Gap Voltage (V):** Usually ranges between 40V and 400V.

Advantages & Limitations

- **Advantages:** Machining of complex internal cavities; handles ultra-hard materials like tungsten carbide; completely burr-free.
- **Limitations:** Only works on conductive materials; low material removal rate compared to conventional methods; tool wear requires periodic replacement.

Applications

- Manufacturing of injection molding dies and punching dies.
- Drilling micro-holes or complex profiles in aerospace components (turbine blades).

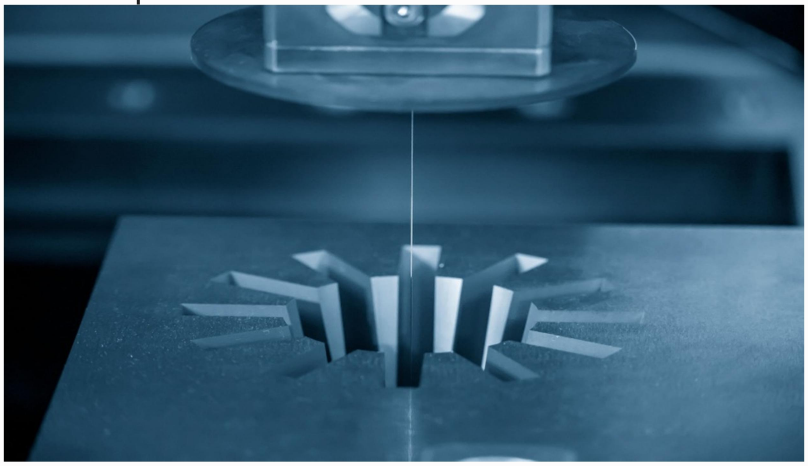
Safe Practices

- Maintain proper dielectric fluid levels to prevent ignition from exposed sparks.
- Ensure adequate ventilation to clear toxic hydrocarbon vapors generated by thermal vaporization.
- Ground all electrical casing structures to minimize electric shock risks.

2. Wire Electrical Discharge Machining (WEDM)

Working Principle

WEDM utilizes the same thermo-electric erosion principle as conventional EDM. However, instead of a formed tool electrode, it utilizes a continuously moving, thin, spool-fed **conductive wire** (usually brass or zinc-coated copper, 0.1 to 0.3 mm diameter) as the electrode to slice through a workpiece along a CNC-programmed 2D or 3D path.



CNC Wire EDM Operation.

Equipment Setup

- **Wire Drive & Guide System:** Consists of a supply spool, tension rollers, precise diamond guides, and a take-up spool to keep the wire taut and moving constantly.
- **CNC Worktable:** Moves the workpiece in X, Y, U, and V directions relative to the wire.
- **Dielectric Fluid Supply:** Uses deionized water jets sprayed directly along the wire axis.
- **Pulsed Power Supply:** Connects negative polarity to the wire and positive polarity to the work.

Process Parameters

- **Wire Feed Rate:** The speed at which the wire unravels; must be optimal to prevent wire breakage.

- **Wire Tension:** Keeps the wire perfectly straight to ensure geometric accuracy.
- **Pulse Frequency & Current:** Governs the cutting speed and the kerf width (width of the cut gap).

Advantages & Limitations

- **Advantages:** No specialized tool shapes required; can cut sharp, intricate profiles and thin slots; negligible mechanical force on the workpiece.
- **Limitations:** Materials must be electrically conductive; slow linear cutting speeds; risk of wire rupture if feed or tension is misconfigured.

Applications

- Fabrication of stamping dies, extrusion dies, and gears.
- Precision sectioning of expensive or hardened metallurgical specimens.

Safe Practices

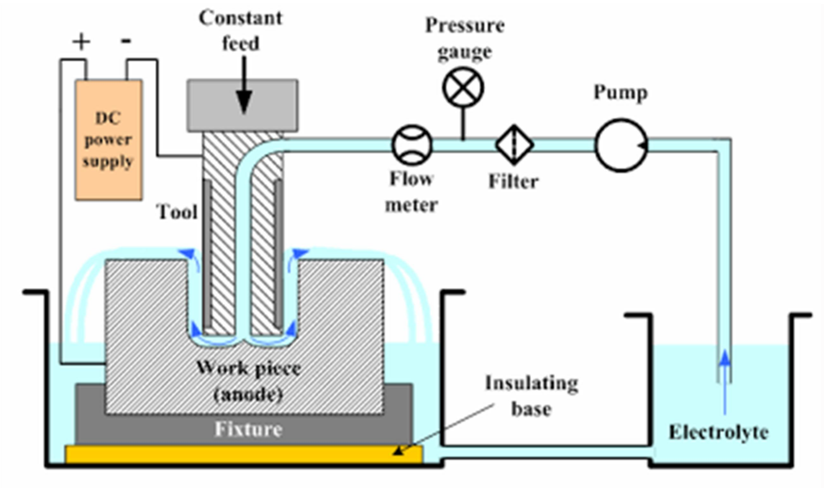
- Ensure interlock doors remain closed during high-frequency cycles to block splashing deionized water.
- Handle spent wire safely using integrated wire choppers to avoid lacerations.

3. Electrochemical Machining (ECM)

Working Principle

ECM can be described as **reverse electroplating**. It operates on **Faraday's Laws of Electrolysis**.

The conductive workpiece acts as the anode (+) and the shaped tool acts as the cathode (-). A highly conductive electrolyte solution is pumped under high pressure through a microscopic gap (0.1 to 0.6 mm) between them. When a low-voltage, high-amperage DC current passes through, atomic-level dissolution occurs on the workpiece surface, accurately replicating the tool's geometry.



ECM System Mechanics. Source: ResearchGate

Equipment Setup

- **DC Power Supply:** High current (up to 10,000 A) and low voltage (5V to 30V).
- **Tool Feeding System:** Advances the tool continuously into the work at a steady rate to maintain a constant gap.
- **Electrolyte System:** Includes a reservoir, pump, high-pressure filters, and heat exchangers to maintain electrolyte temperature and pressure (normally sodium chloride or sodium nitrate solutions).

Process Parameters

- **Current Density:** Higher current density increases the material dissolution rate.
- **Electrolyte Flow Velocity:** Must be high (15 to 60 m/s) to flush away metal hydroxides and heat before boiling occurs.
- **Electrolyte Concentration & Temperature:** Directly influences electrical conductivity.

Advantages & Limitations

- **Advantages: Zero tool wear** (no physical contact); high MRR independent of material hardness; pristine, mirror-like surface finish with zero residual stress.
- **Limitations:** Only works on conductive materials; high initial capital cost; corrosive electrolytes require specialized rust-resistant machine components; challenging to handle chemical sludge disposal.

Applications

- Machining complex turbine blades and blisks (machined blade-disks) for aerospace engines.
- Internal profiling of gun barrels and deep, non-circular blind holes.

Safe Practices

- Ensure proper hydrogen gas ventilation, as hydrogen gas accumulates at the cathode and poses an explosion risk.
- Operators must wear chemical-resistant personal protective equipment (PPE) to avoid direct contact with corrosive salts and acids.

4. Plasma Arc Machining (PAM)

Working Principle

PAM relies on intense thermal energy. A gas (like argon, nitrogen, or hydrogen) is passed through a confined direct-current arc striking between a tungsten electrode and the nozzle or workpiece.

The arc ionizes the gas particles, raising temperatures up to **20,000°C to 30,000°C**, transforming it into a high-velocity **plasma jet**. This concentrated thermal beam melts the target metal instantly, and the high-speed gas stream blows the molten puddle away from the cut kerf.

Equipment Setup

- **Plasma Torch:** Houses the tungsten electrode, inner gas swirler, and a water-cooled copper constricting nozzle.
- **Power Supply:** Heavy-duty DC straight polarity source (electrode negative).
- **Gas Supply:** Regulated cylinders for primary plasma gases and secondary shielding gases.
- **Cooling Water System:** High-capacity loops to keep the copper nozzle from melting under extreme arc heat.

Process Parameters

- **Arc Current:** Controls the total heat input and penetration capacity.
- **Gas Flow Rate:** High flow velocity helps blow away molten dross, clean cuts require precise balance.

- **Stand-off Distance:** The distance between the torch tip and the workpiece surface.

Advantages & Limitations

- **Advantages:** Cuts extremely thick plates (up to 150 mm); exceptionally fast cutting speeds; works on any material that conducts electricity (including stainless steel and aluminum).
- **Limitations:** Produces a large Heat Affected Zone (HAZ); cut edges usually feature a slight taper; generates intense noise, glare, and toxic fumes.

Applications

- Heavy structural fabrication shops for profile cutting of stainless steel, carbon steel, and aluminum plates.
- Rough trimming of castings and forgings.

Safe Practices

- Operators must wear auto-darkening welding helmets with high shade values to shield eyes from blinding UV radiation.
- Heavy-duty industrial exhaust hoods or specialized water tables must be used to collect fine particulate smoke and dross fumes.

5. Abrasive Jet Machining (AJM)

Working Principle

AJM is a mechanical material removal process. A focused stream of fine, abrasive grains (typically aluminum oxide or silicon carbide, 10 to 50 microns) is mixed into a clean, pressurized carrier gas and propelled through a convergent-divergent nozzle at near-sonic speeds (150 to 300 m/s). When this jet strikes the workpiece, material is chipped away gradually via **micro-brittle fracturing**.

Equipment Setup

- **Gas Delivery System:** Air compressor or bottled nitrogen equipped with pressure regulators and moisture separators.

- **Mixing Chamber:** Creates a uniform, vibrating suspension of abrasive particles in the carrier gas stream.
- **Nozzle:** Made from hyper-wear-resistant materials like sapphire or tungsten carbide to withstand constant inner abrasion.
- **Machining Enclosure:** A sealed glove box with a clear view window and vacuum extraction to safely trap airborne dust.

Process Parameters

- **Abrasive Mass Flow Rate:** Grams of abrasive delivered per minute.
- **Nozzle Tip Distance (NTD):** Distance from nozzle tip to work (typically 0.5 to 5 mm). Affects both cut width and material removal rate.
- **Gas Pressure:** Controls jet velocity.

Advantages & Limitations

- **Advantages:** Zero thermal distortion or heat damage; easily cuts ultra-brittle materials (glass, ceramics, quartz); minimal tooling infrastructure costs.
- **Limitations:** Low material removal rate; abrasive particles tend to become embedded in soft metals; nozzles wear out frequently.

Applications

- Etching, frosting, and deburring fragile glass panels, electronic wafers, and ceramics.
- Cleaning internal oxides, scales, or industrial residues out of precision molds.

Safe Practices

- Use a fully closed dust collection cabinet to prevent inhaling fine abrasive dust, which can cause respiratory damage (silicosis).
- Wear safety goggles during setup to protect eyes from high-velocity stray particles.

6. Ultrasonic Machining (USM)

Working Principle

USM is a mechanical machining process that uses a combination of ultrasonic vibrations and abrasive slurry. A tool vibrating at an ultra-high frequency (20 to 30 kHz) with a low amplitude (15 to 50 microns) presses down on an abrasive slurry (fine abrasive grains mixed in water) flowing over the workpiece. The vibrating tool drives the abrasive grains directly into the work surface, eroding material through thousands of microscopic impacts per second.

Equipment Setup

- **Ultrasonic Generator:** Converts conventional 50 Hz electrical power into high-frequency (20 kHz+) electrical signals.
- **Transducer:** Converts high-frequency electrical signals into mechanical vibrations (using magnetostrictive or piezoelectric crystals).
- **Concentrator (Horn):** Amplifies the mechanical vibration amplitude and transmits it to the attached tool.
- **Slurry System:** Continuously pumps and recirculates a slurry of boron carbide or silicon carbide particles over the cutting zone.

Process Parameters

- **Vibration Frequency & Amplitude:** Higher values accelerate the material removal rate.
- **Abrasive Grain Size:** Larger grains cut faster but leave a rougher surface finish.
- **Static Feed Force:** The downward pressure applied to the tool.

Advantages & Limitations

- **Advantages:** Non-thermal, non-chemical, and non-electrical process; leaves no thermal stress or chemical changes; ideal for non-conductive, brittle materials (glass, ceramics, gemstones).
- **Limitations:** Extremely low material removal rate; high tool wear rate caused by reverse abrasive impact; limited to relatively small cutting depths.

Applications

- Drilling precise, non-circular holes or slots in glass, quartz, and advanced structural ceramics.
- Sectioning and dicing silicon wafers for semiconductor manufacturing.

Safe Practices

- Wear ear defenders or acoustic shielding to prevent fatigue and hearing strain from high-frequency airborne sub-harmonics.
- Maintain proper containment systems to prevent slippery abrasive slurries from leaking onto the workshop floor.

7. Electron Beam Machining (EBM)

Working Principle

EBM is a high-energy thermal process conducted within a high-vacuum chamber. A heating filament releases a stream of electrons, which are accelerated to nearly **$2/3$ the speed of light** using a high-voltage anode.
Electromagnetic lenses focus these electrons into a concentrated beam focused directly onto the workpiece. When the high-velocity electrons impact the material, their kinetic energy instantly converts into intense thermal energy, melting and vaporizing the localized zone.

Equipment Setup

- **Electron Gun:** Houses the cathode tungsten filament, grid cup, and accelerating anode.
- **Vacuum Chamber:** Maintains an ultra-low vacuum (10^{-4} to 10^{-5} torr) to prevent electron collisions with gas molecules and avoid filament burnout.
- **Electromagnetic Focusing & Deflection Coils:** Lenses that focus and steer the electron beam along computer-guided coordinates.
- **CNC Table:** Moves the workpiece inside the vacuum chamber.

Process Parameters

- **Accelerating Voltage:** Typically ranges from 50 kV to 150 kV to govern electron velocity.
- **Beam Current:** Controls the total heat energy delivered to the target zone.
- **Pulse Duration:** Determines the depth of penetration and helps minimize the size of the heat-affected zone.

Advantages & Limitations

- **Advantages:** Extremely high accuracy; can drill tiny micro-holes (down to 0.002 mm); zero atmospheric contamination due to the high-vacuum environment.
- **Limitations:** High initial investment; limited workpiece dimensions due to vacuum chamber size; requires substantial cycle time to pull vacuum before operation.

Applications

- High-precision micro-hole drilling for jet engine cooling passages and synthetic fiber spinnerets.
- Wire-mesh slotting operations for specialized filters.

Safe Practices

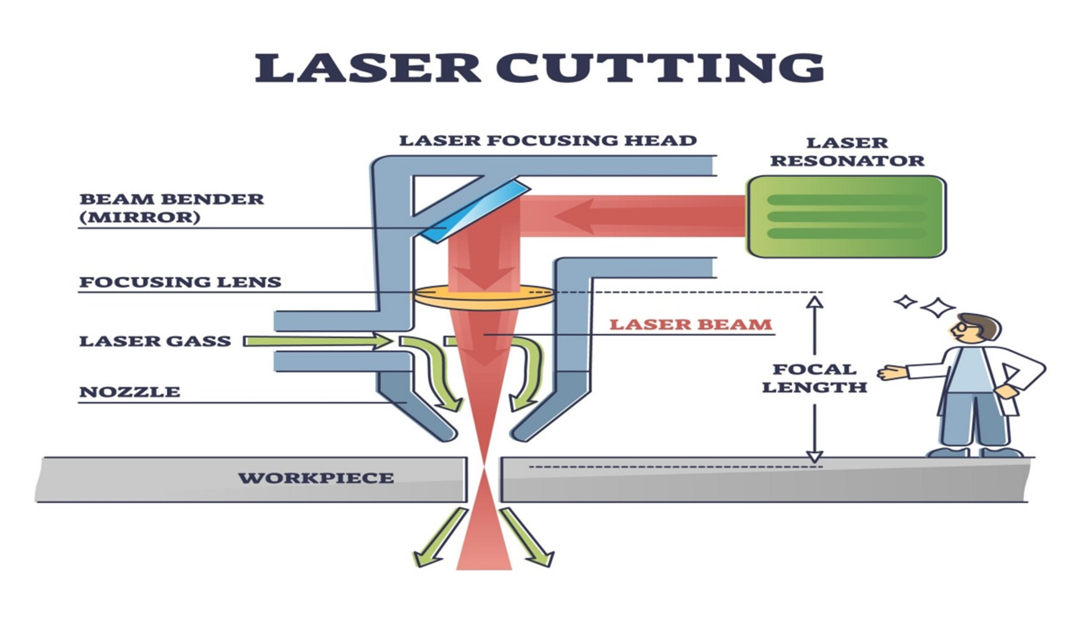
- Ensure the vacuum chamber is properly shielded with lead lining to protect operators from secondary X-ray radiation.
- Ensure all high-voltage power networks are fully insulated and safety-interlocked.

8. Laser Beam Machining (LBM)

Working Principle

LBM is a thermal non-contact manufacturing process that cuts material using a highly focused, monochromatic, and coherent light beam called a **laser**.

The laser source generates a raw light beam that is amplified and focused through a lens onto a tiny spot on the workpiece. The material absorbs this highly concentrated light energy, which causes it to quickly melt, vaporize, and burn away. A coaxial assist gas jet blown through the nozzle helps eject the molten dross from the cut path.



Laser Beam Machining Principles. Source: Vecto

Equipment Setup

- **Laser Source:** Typically solid-state lasers (Nd:YAG, Fiber) or gas-based lasers (CO_2).
- **Optical Delivery System:** Uses high-reflectivity mirrors or flexible fiber-optic cables to guide the laser beam safely.
- **Focusing Lens:** A convex optical lens that focuses the laser beam onto a precise spot.
- **Nozzle & Assist Gas System:** Delivers a coaxial stream of oxygen, nitrogen, or argon gas to protect the lens optics and blow away molten metal.

Process Parameters

- **Laser Power & Mode:** Determines the maximum thickness the beam can cut. Can operate in continuous or pulsed modes.
- **Cutting Speed:** Must be balanced; cutting too fast results in incomplete penetration, while cutting too slow widens the kerf.
- **Focal Position:** Position of the focal spot relative to the workpiece surface (above, on, or below).

Advantages & Limitations

- **Advantages:** No physical tool wear; cuts almost any material (metals, polymers, ceramics, wood); high cutting speeds with minimal mechanical force.
- **Limitations:** High power consumption; can create a heat-affected zone (HAZ) and thermal cracking in sensitive metals; high initial equipment cost.

Applications

- Precision sheet metal profiling, profile cutting, and micro-hole drilling in automotive and electronic housings.
- Etching tracking barcodes, functional serial numbers, and industrial text marks.

Safe Practices

- Operators must wear specialized laser safety glasses rated for the machine's specific laser wavelength to prevent permanent blindness from stray reflections.
- Use localized enclosure exhaust systems to clear hazardous chemical vapors and fine metal dust generated during material vaporization.

1. Electrical Discharge Machining (EDM)

Working Principle

EDM removes metal by generating continuous, rapid-fire **electrical spark discharges** between a shaped tool and a conductive workpiece. Both are submerged in a dielectric fluid.

When the voltage across the small **spark gap** (0.01 to 0.5 mm) reaches the breakdown voltage of the fluid, the fluid ionizes, forming a plasma channel. A spark jumps across, producing localized temperatures up to 10,000°C that melt and vaporize a microscopic pocket of metal. When the current is turned off, the plasma channel collapses, and the dielectric fluid flushes away the molten metal debris.

Equipment Setup

- **DC Pulse Generator:** Converts AC power into high-frequency, pulsed DC power.
- **Tool (Cathode):** Formed to the inverse shape of the desired cavity; made of graphite, copper, or brass.
- **Workpiece (Anode):** Must be an electrically conductive material.
- **Servo Feed System:** Automatically maintains a constant spark gap between the tool and the workpiece.
- **Dielectric System:** Contains dielectric fluid (kerosene or deionized water), a pump, and a filter to circulate and flush the gap.

Process Parameters

- **Discharge Current (Ip):** Determines spark energy; higher current increases Material Removal Rate (MRR) but roughens surface finish.
- **Pulse-on Time (Ton):** The duration for which the spark is active.
- **Pulse-off Time (Toff):** The cooling period allowing the dielectric to de-ionize and flush away debris.
- **Spark Gap Voltage (V):** Usually ranges between 40V and 400V.

Advantages & Limitations

- **Advantages:** Machining of complex internal cavities; handles

Summary Comparison

Process	**Mechanism**	**Material Constraints**	**Medium**	**Tool Wear**
EDM	Spark Erosion (Thermal)	Electrically Conductive	Dielectric Fluid	High
WEDM	Spark Erosion (Thermal)	Electrically Conductive	Deionized Water	Continuous Spool
ECM	Electrochemical Dissolution	Electrically Conductive	Salt Electrolyte	**Zero**
PAM	High-Temp Ionized Jet (Thermal)	Electrically Conductive	Plasma Gas	Medium (Nozzle)
AJM	Mechanical Erosion/Chipping	Brittle Materials Preferred	Pressurized Gas	Medium (Nozzle)
USM	Mechanical Impact / Abrasion	Hard & Brittle Materials	Abrasive Slurry	High
EBM	Vaporization (Electron Kinetic)	All Materials	High Vacuum	**Zero**
LBM	Vaporization (Coherent Light)	All Materials	Assist Gas Jet	**Zero**

UNIT-02 Advanced casting processess

The Gating System

The gating system refers to the channels through which molten metal travels from the pouring basin into the mold cavity. A well-designed gating system ensures smooth, laminar flow to prevent air entrainment and sand erosion.

- **Pouring Basin:** The reservoir at the top that receives the molten metal directly from the ladle. It helps reduce turbulence.
- **Sprue:** The vertical passage that moves metal downward. It is tapered to prevent air aspiration (drawing in air bubbles).
- **Runner:** The horizontal channel that distributes the liquid metal to the gates.
- **Ingate:** The final entry point where molten metal enters the mold cavity.

Riser Design

Metals shrink when changing from liquid to solid. A **riser** (or feeder) is a temporary extra reservoir of molten metal attached to the mold cavity.

- **Working Principle:** The riser must stay liquid *longer* than the main casting. As the casting solidifies and shrinks, it draws liquid metal directly from the riser to fill the shrinkage voids.
- **Chvorinov's Rule:** To ensure the riser solidifies last, its solidification time (Ts) must be greater than the casting's solidification time.

$$Ts = Cm\left(\frac{V}{A}\right)^2$$

Where Cm is the mold constant, V is the volume, and A is the cooling surface area. Therefore, a good riser must have a high volume-to-surface-area ratio (which is why cylindrical or spherical risers are preferred).

2. Evaporative Pattern Casting Process (EPC)

Working Principle

Also known as **Lost Foam Casting**. The process utilizes a pattern made of expanded polystyrene (EPS) foam.

When molten metal is poured into the mold, the intense heat instantly vaporizes (evaporates) the foam pattern. The liquid metal takes the exact place of the vaporized foam, replicating its shape precisely.

Equipment Setup

- **Foam Pattern Production:** EPS foam beads are molded into the desired shape.
- **Refractory Coating:** The foam pattern is coated with a ceramic slurry to provide a smooth surface and withstand the hot metal.
- **Flask and Unbonded Sand:** The coated pattern is placed into a molding box (flask), and dry, binderless sand is packed around it using a vibration table.

Process Parameters

- **Pouring Temperature:** Must be high enough to instantly vaporize the foam without leaving unburned carbon residue.
- **Sand Compaction Frequency:** Vibration frequency must safely pack the dry sand around complex geometries without distorting the fragile foam pattern.

Advantages & Limitations

- **Advantages:** No parting lines, drafts, or core shifts; permits highly complex internal geometries; sand is reusable since it contains no chemical binders.
- **Limitations:** Patterns are destroyed during each pour (high pattern production costs); foam vaporization can release toxic smoke; prone to porosity if the foam doesn't vaporize fully.

Applications

- Automotive engine blocks, cylinder heads, crankshafts, and intricate pump housings.

3. Hybrid EPC & Vacuum EPC Processes

Hybrid EPC Process

- **Working Principle:** Combines traditional investment casting (wax) or sand casting techniques with the evaporative foam method. It often uses a multi-material pattern (e.g., a wax gating system joined to a foam pattern body) to optimize fluid flow and reduce carbon defects.
- **Advantages:** Better control over surface finishes on critical areas while utilizing the cost efficiency of foam for bulk sections.
- **Applications:** Complex aerospace valves and customized structural brackets.

Vacuum EPC Process (V-EPC)

- **Working Principle:** A modification of standard EPC. The foam pattern is surrounded by unbonded sand in a specialized flask. Before pouring, a **vacuum** is applied through internal mesh walls in the flask.

The vacuum tightly locks the dry sand grains in place by pressure differential. When the metal is poured, the vacuum pulls the foam vaporization gases away instantly, ensuring zero gas entrapment.

Advantages & Limitations

- **Advantages:** Excellent dimensional stability; eliminates gas defects completely; thin-walled castings can be poured easily because the vacuum helps pull the metal along.
- **Limitations:** Requires a constant vacuum pump system and specialized sealed flasks; higher equipment cost.

4. Centrifugal Casting Processes

Working Principle

Centrifugal casting forces molten metal against the inner walls of a mold using **centrifugal force** generated by high-speed rotation.

The heavier liquid metal is thrown to the outside walls, while lighter impurities, dross, and slag collect near the hollow center axis, where they can be machined out later.

Equipment Setup

- **Rotating Mold:** A cylindrical steel, iron, or graphite mold mounted on drive rollers.
- **Drive Motor:** Rotates the mold horizontally or vertically at high speeds.
- **Pouring Spout:** An elongated trough used to inject molten metal directly into the spinning core.

Process Parameters

- **Rotational Speed (RPM):** Must be precisely calculated based on G-factor (G = $\frac{V^2}{r.g}$).If too slow, the metal slips or rains down inside the mold; if too fast, it can cause hot tearing.
- **Pouring Speed:** Must match the solidification front of the spinning cylinder.

Advantages & Limitations

- **Advantages:** Forms hollow cylindrical parts **without using sand cores**; uniform grain structure with high mechanical strength; low scrap rates because there are no runners or risers.
- **Limitations:** Limited strictly to axisymmetric cylindrical geometries; inner diameter dimensions can be inaccurate and require post-machining.

Applications

- Cast iron water pipes, hollow tubes, gun barrels, bushing sleeves, and large rings.

5. Pressure Die Casting

Working Principle

Pressure die casting is a permanent mold process where molten metal is forced into a split steel mold (called a die) under **high pressure** (7 to 350 MPa). The metal is held under pressure until it solidifies, after which the die opens and ejector pins push the part out. It has two variations:

1. **Hot Chamber:** The injection mechanism is submerged directly in the molten metal bath (used for low-melting alloys like Zinc, Lead, and Magnesium).
2. **Cold Chamber:** Molten metal is ladled manually or automatically into an injection sleeve before the ram forces it into the die (used for high-melting alloys like Aluminum and Copper to prevent component erosion).

Equipment Setup

- **Die Halves:** Movable and stationary steel dies with internal cooling channels.

- **Injection Mechanism:** Hydraulic ram, piston, and goose-neck or cold cylinder.
- **Ejector Pins:** Mechanical pins that push the solidified part out of the mold cavity.

Process Parameters

- **Injection Pressure:** High pressures ensure completely filled, thin-walled cavities.
- **Die Temperature:** Dies must be kept within an optimal temperature window to avoid premature freezing or thermal cracking of the steel tooling.

Advantages & Limitations

- **Advantages:** Extremely high production rates; excellent dimensional tolerances and smooth surface finish; allows for thin-walled sections (< 1mm).
- **Limitations:** High tooling and equipment costs; limited primarily to non-ferrous metals; air entrapment can cause internal porosity, making heat treatment difficult.

Applications

- Engine components, transmission cases, carburetor bodies, camera bodies, and toys.

6. Slush Casting

Working Principle

Slush casting is a variation of permanent mold casting used to produce **hollow parts without using a core**.

Molten metal is poured into a metal mold, and heat quickly escapes through the cold mold walls, forming a thin shell of solidified metal. Before the center freezes, the mold is inverted (turned upside down), allowing the remaining liquid metal to drain out.

Equipment Setup

- **Split Metal Mold:** Typically made of bronze, brass, or iron.
- **Inverting/Tilting Rig:** A mechanical pivot system used to quickly invert the mold and drain the liquid core.

Process Parameters

- **Dwell Time:** The length of time the metal sits inside the mold before inversion. Longer dwell times create thicker shell walls.

- **Mold Initial Temperature:** Controls the initial rate of shell formation.

Advantages & Limitations

- **Advantages:** Produces hollow parts with no internal cores; simple equipment footprint; excellent reproduction of external details.
- **Limitations:** The internal wall thickness is highly uneven; mechanical strength is low; limited strictly to decorative or low-stress hollow parts.

Applications

- Hollow statues, ornamental lamp bases, candlesticks, and hollow toys made from low-melting-point metals like zinc, lead, or tin.

7. Shell Molding Process

Working Principle

Shell molding is a sand casting variant that uses a thin-walled, hardened shell of sand bonded with a thermosetting resin to form the mold cavity.

A heated metal pattern is covered with a mixture of sand and thermosetting resin. The heat melts the resin, binding the sand grains together into a thin, hardened crust (shell). The shell is baked, stripped away from the pattern, and clamped together with a matching half to receive the molten metal.

Equipment Setup

- **Metal Pattern Plate:** Usually made of cast iron or aluminum, equipped with ejector pins and internal heaters.
- **Dump Box:** A container holding the sand and thermosetting resin mixture (typically $3\text{ to }6\%$ phenolic resin).
- **Curing Oven:** Used to heat and fully polymerize the green shell crust.

1.Pattern Heating: Prerequisite.

The metal pattern is heated to approximately 200°C to 300°C and coated with a silicone release agent.

2.Investment (The Dump): Shell Formation.

The heated pattern is clamped upside down over the dump box. The box is inverted, dropping the sand-resin mix onto the hot pattern. Heat melts the resin, forming a partially cured shell (6 mm thickness) within 30 seconds.

3.Curing: Hardening.

The dump box is rotated back. The pattern along with the soft shell is placed into an oven at 300°C for a few minutes to fully cure and harden the resin bond.

4.Stripping & Assembly: Final Pour.

Ejector pins strip the rigid shell from the pattern. Two matching halves (cope and drag shells) are clamped together, placed in a flask with backing shot, and poured.

Process Parameters

- **Pattern Temperature:** Must be uniform to ensure consistent shell thickness.
- **Resin Percentage:** Balanced to provide adequate mold strength while preserving gas permeability.

Advantages & Limitations

- **Advantages:** High dimensional accuracy and smoother surface finish than green sand casting; low defect rates; molds can be stored indefinitely without absorbing moisture.
- **Limitations:** High cost of metal patterns makes it uneconomical for low-volume production; resin binders generate characteristic odors during pouring; limited weight capacity.

Applications

- High-precision automotive parts like camshafts, crankshafts, slider brackets, and small cylinder heads.

Summary sheet

Process	**Mold Material**	**Reusable Mold?**	**Core Required for Hollow Parts?**	**Primary Target Material**
EPC (Lost Foam)	Unbonded Sand / Foam	No (Pattern) / Yes (Sand)	No	Ferrous & Non-Ferrous
Centrifugal	Steel / Cast Iron	Yes	**No** (Centrifugal Force)	Cast Iron, Bronzes
Die Casting	Hardened Tool Steel	Yes	Yes (Steel/Sand)	Aluminum, Zinc, Magnesium
Slush Casting	Metal (Bronze/Iron)	Yes	**No** (Drained core)	Zinc, Lead, Tin
Shell Molding	Silica Sand + Resin	No	Yes (Shell Cores)Steels, Cast Irons	Steels, Cast Irons

Unit 3.0 Advanced Welding and Forming Processes

1. Orbital TIG Welding

Working Principle

Orbital TIG (Tungsten Inert Gas) welding is an automated variant of conventional TIG welding. The process establishes an electric arc between a non-consumable tungsten electrode and the cylindrical workpiece (such as pipes or tubes).

While the workpiece remains rigidly stationary, the welding torch is mounted on a mechanized track system that rotates mechanically **360°C around the joint**. An inert gas shield (usually Argon) continuously protects the weld pool from atmospheric oxidation.

Equipment Setup

- **Orbital Weld Head:** A specialized clamp-on mechanism that houses the torch body, gas lines, and a motorized rotor to drive the electrode smoothly around the pipe circumference.
- **Programmable Power Source:** A microprocessor-controlled DC power supply that dynamically adjusts welding parameters based on the torch's angular clock position (0°C to 360°C).
- **Gas Delivery System:** Supplies high-purity argon or helium shielding gas to the torch head and to the interior of the pipe (backing gas/purge gas) to prevent interior oxidation.

Process Parameters

- **Welding Current (Amperage):** Often modulated across four or more positional sectors to counteract gravity pulling on the molten weld puddle during overhead versus down-hand segments.
- **Travel Speed:** The rotational velocity of the torch around the pipe axis.
- **Purge Gas Flow Rate:** Must be precisely regulated to prevent internal concave or convex root defects.

Advantages & Limitations

- **Advantages:** Produces flawless, X-ray-quality welds; eliminates operator fatigue; exceptionally high consistency across repetitive manufacturing runs.
- **Limitations:** High initial capital cost for equipment setup; restricted strictly to circular geometries (pipes, tubes, cylinders); requires skilled technicians to program and configure the controller.

Applications

- High-purity pharmaceutical and food-processing tubing networks.
- Aerospace hydraulic lines and high-pressure oil/gas pipeline manifolds.

2. Electron Beam Welding (EBW)

Working Principle

Electron Beam Welding is a high-energy-density fusion welding process conducted inside an ultra-high vacuum chamber.

A heated tungsten filament generates a stream of electrons that are accelerated to high velocities by a high-voltage anode. Electromagnetic lenses focus these high-speed electrons into a concentrated beam aimed at the weld joint. Upon impact, the kinetic energy of the electrons instantly converts into intense thermal energy. This creates a **"keyhole" effect**, vaporizing a narrow channel through the metal, which fills with molten material as the beam advances, resulting in a deep, narrow weld profile.

Equipment Setup

- **Electron Gun:** Houses the cathode filament, grid cup, and accelerating anode under a high-voltage network.
- **Vacuum Chamber & Pumping System:** Encloses the entire workspace to maintain a vacuum level of 10^{-3} to10^{-5} torr. This prevents electrons from scattering due to collisions with gas molecules.
- **Magnetic Optical System:** Electromagnetic focusing lenses and deflection coils used to sharpen and manipulate the beam path.
- **CNC Work Table:** Moves the workpiece beneath the stationary electron gun assembly.

Process Parameters

- **Accelerating Voltage:** Typically ranges from 30to 150 kV, which determines the depth of beam penetration.
- **Beam Current:** Controls the total heat energy input delivered to the joint.
- **Welding Speed:** Linear speed of the work table; dictates the final shape and width of the weld bead.

Advantages & Limitations

- **Advantages:** Tremendous depth-to-width ratio (up to 20:1); exceptionally narrow Heat Affected Zone (HAZ) with minimal thermal distortion; welds dissimilar or reactive metals cleanly without atmospheric contamination.
- **Limitations:** Very high initial investment cost; workpiece size is strictly limited by the physical dimensions of the vacuum chamber; pulling a vacuum for each cycle increases production turnaround times.

Applications

- Joining heavy aerospace structures, titanium components, and aircraft turbine rotors.
- High-precision nuclear reactor vessels and medical implant assemblies.

3. Laser Beam Welding (LBW)

Working Principle

Laser Beam Welding is a non-contact, high-energy-density fusion process that utilizes a highly focused, coherent, and monochromatic light beam (laser) to fuse materials together.

The laser beam is directed and focused through an optical lens assembly onto the joint interface. The workpiece material absorbs the concentrated light energy, causing it to melt and vaporize rapidly. Like EBW, LBW can operate in **keyhole mode** for deep, narrow welds, or in **conduction mode** for shallow, cosmetic surface welds. An inert shielding gas jet protects the hot weld pool from environmental contamination.

Equipment Setup

- **Laser Source:** Typically solid-state lasers (Fiber, Nd:YAG) or gas-based lasers (Co_2).
- **Fiber Optic Cable or Mirrors:** Transmits the raw laser beam safely from the generator source to the focal head assembly.
- **Focusing Optics:** High-precision convex lenses that concentrate the beam down to a microscopic focal spot diameter.
- **Shielding Gas Nozzle:** Supplies a coaxial stream of protective argon, helium, or nitrogen gas.

Process Parameters

- **Laser Power:** Measured in kilowatts; determines maximum penetration depth and processing capabilities.
- **Focal Position:** Position of the focal point relative to the workpiece surface (above, on, or below).
- **Welding Speed:** The rate of linear travel; must be optimized to balance penetration against root drop-through or undercutting.

Advantages & Limitations

- **Advantages: Does not require a vacuum chamber** (unlike EBW); high processing speeds; can be easily integrated with multi-axis robotic arms; minimal distortion due to low heat input.
- **Limitations:** High initial capital and maintenance costs; materials with high reflectivity (such as copper and aluminium) can reflect the laser beam, requiring specialized laser types; requires tight joint fit-up tolerances because the beam spot is extremely small.

Applications

- High-volume automated assembly lines in the automotive sector (roof panels, tailored blanks).
- Hermetic sealing of electronic micro-packages, batteries, and medical pacemakers.

4. Ultrasonic Welding (USW)

Working Principle

Ultrasonic Welding is a **solid-state welding process** that joins materials without melting them.

The two workpieces are held together under a static clamping force. A welding tip (sonotrode) introduces high-frequency mechanical vibrations (typically 20 to 40kHz) parallel to the mating surface. These rapid oscillatory movements break up surface oxide layers and cause localized plastic deformation through friction. This allows atoms from both surfaces to interdiffuse, creating a solid-state molecular bond **without reaching the melting point** of the materials.

1.Clamping Force: Positioning.

The two overlapping workpieces are placed between a stationary anvil and the movable welding tip (sonotrode). A pneumatic force clamps them firmly together.

2.Ultrasonic Activation: Frictional Heating.

The transducer generates high-frequency vibrations that move the sonotrode back and forth across the joint line. This action shears away surface contaminants and generates localized frictional heat.

3.Intermolecular Bonding: Interdiffusion.

Under combined pressure and dynamic motion, localized plastic flow occurs. This allows metal lattices to interlock and diffuse across the boundary layer.

4.Hold & Release: Solidification.

The ultrasonic vibrations stop, but the clamping pressure is held briefly to let the joint consolidate. The tool then retracts, completing the process.

Equipment Setup

- **Ultrasonic Generator:** Converts standard 50Hz electrical power into high-frequency (20 kHz or higher) electrical energy.
- **Transducer (Piezoelectric):** Converts the high-frequency electrical signals into mechanical linear oscillations.
- **Booster & Horn (Sonotrode):** Amplifies the mechanical vibration amplitude and delivers it directly to the weld zone.
- **Anvil:** A rigid, heavy fixture that supports the workpieces and resists the downward clamping force.

Process Parameters

- **Vibration Frequency:** Typically fixed at 20 kHz,30 kHz}, or 40kHz}.
- **Vibration Amplitude:** The distance the sonotrode moves during each oscillation cycle (typically 10 to 50mu m).
- **Clamping Pressure:** The static force pressing the pieces together.
- **Weld Time:** The duration of the ultrasonic vibration pulse.

Advantages & Limitations

- **Advantages:** Extremely fast cycle times (often under one second); no filler metals, fluxes, or shielding gases required; excellent for joining dissimilar metals; safe for heat-sensitive materials since no melting occurs.
- **Limitations:** Limited primarily to lap joints and thin sheets or wires; not suitable for thick structural components; high-frequency vibrations can cause resonance issues in fragile internal electronic components.

Applications

- Wire bonding and tab attachments in lithium-ion batteries and microelectronics.
- Assembly of automotive wire harnesses and terminal connections.
- Sealing plastic containers, tubes, and medical packaging blistpacks.

Summary sheet

Process	**Bond Mechanism**	**Operating Environment**	**Heat Affected Zone (HAZ)**	**Material Capabilities**
Orbital TIG	Fusion (Electric Arc)	Atmospheric (Gas Shield)	Moderate to Large	Conductive Metals (Pipes/Tubes)
EBW	Fusion (Kinetic Electron Beam)	**High Vacuum Required**	Exceptionally Narrow	Refractory, Reactive, & Heavy Metals
LBW	Fusion (Coherent Light Beam)	Atmospheric (Gas Shield)	Very Narrow	Metals and Diverse Polymers
Ultrasonic	**Solid-State** (Acoustic Friction)	Atmospheric	**None (No Melting)**	Thin Foils

Introduction to High-Energy Rate Forming (HERF)

Conventional forming methods use mechanical or hydraulic presses to shape metal at relatively low velocities. HERF processes, by contrast, utilize explosive chemical energy, high-voltage electrical discharges, or powerful electromagnetic fields to deform sheet metal at extremely high velocities (10 to 300 m/s).

Major Advantages of HERF

- **Reduced Springback:** Due to high-velocity plastic deformation, the metal retains its shape more accurately.
- **Improved Formability:** Metals display increased ductility at very high strain rates, allowing for more complex shapes.
- **Low Tooling Cost:** Most HERF setups require only a single female die half rather than a matching male/female die set.

1. Electromagnetic Forming (EMF)

Working Principle

Electromagnetic Forming is a solid-state, non-contact HERF process that operates on **Lorentz's Force** and **Faraday's Law of Induction**.

A massive electrical energy charge is stored in a capacitor bank and discharged rapidly through an induction coil placed near a conductive metal workpiece. This high-frequency current pulse generates an intense, transient magnetic field around the coil. This magnetic field induces powerful **eddy currents** in the conductive workpiece. The interaction between the coil's magnetic field and the induced eddy currents creates a massive repulsive force (Lorentz force) that rapidly drives the workpiece against the die cavity

Equipment Setup

- **Capacitor Bank:** Stores a massive electrical charge at high voltages (2 to 20kV).
- **High-Energy Discharging Switch:** A specialized switch (like a thyratron or ignitron) that dumps the stored energy into the coil in microseconds.
- **Forming Coil (Actuator):** A heavy, insulated copper coil shaped to match the application (e.g., a compression coil for shrinking tubes, an expansion coil for expanding tubes, or a flat coil for sheet metal).
- **Die Cavity:** The single-sided mold structure that defines the final shape of the part.

Process Parameters

- **Discharge Voltage and Capacitance:** Determines the total kinetic energy delivered ($E = 1/2\ CV^2$).
- **Electrical Conductivity of the Workpiece:** Highly conductive materials (like copper or aluminum) react efficiently. Poor conductors (like stainless steel) require a thin conductive "driver sheet" wrapped around them.
- **Discharge Time Pulse:** Usually completes within 10 to 100 microseconds.

Advantages & Limitations

- **Advantages:** Non-contact process (no tool marks or surface scratches); highly repeatable; safe and clean environment suitable for automation; no lubricants required.
- **Limitations:** Limited strictly to highly conductive metals (or requires a driver sheet); cannot form very thick plates; magnetic coils experience high mechanical stress and can deform over time.

Applications

- Crimping, fastening, and swaging metal bands onto rubber hoses, cables, and ceramic insulators.

- Expanding or bulging aluminum and copper tubing profiles for aerospace conduits.

2. Explosive Forming

Working Principle

Explosive forming uses the detonation of a chemical explosive to generate a high-pressure shockwave through a fluid medium (typically water) to deform a metal sheet into a mold cavity.

There are two primary configurations:

1. **Standoff Method:** The explosive charge is placed at a calculated distance (standoff distance) from the workpiece inside a water tank. The detonation creates a shockwave that travels through the water, uniforming transferring kinetic energy to press the metal sheet into the die.
2. **Contact Method:** The explosive charge is held in direct physical contact with the metal plate. This method produces extremely high pressure and is used primarily for high-density hardening or cutting rather than conventional sheet shaping.

Equipment Setup

- **Explosive Charge:** Chemical explosives such as TNT, RDX, or dynamite.
- **Die Assembly:** A heavy-duty female die made of cast iron, tool steel, or reinforced concrete.
- **Water Tank:** Acts as the pressure-transmitting medium, confining the energy and distributing the shockwave evenly.
- **Hold-Down Ring:** Clamps the perimeter of the sheet metal blank securely over the die.
- **Vacuum System:** Extracts air trapped *beneath* the metal sheet in the die cavity to prevent compressed air pockets from burning or dimpling the metal.

Process Parameters

- **Type and Weight of Charge:** Determines the peak pressure generated.
- **Standoff Distance:** The distance between the charge and the metal blank; balancing this prevents tearing while ensuring complete die filling.
- **Water Depth:** Must be sufficient to confine the explosive energy without excessive venting into the atmosphere.

Advantages & Limitations

- **Advantages:** Virtually no limit to the size of the component; very low tooling cost since only a female die is required; ideal for low-volume prototype manufacturing.
- **Limitations:** Slow cycle times (unsuitable for mass production); strict safety regulations regarding handling and storing explosives; requires outdoor operation or specialized bunker facilities.

Applications

- Shaping large-diameter aerospace rocket nose cones, parabolic radar dishes, and marine ship hull panels.

3. Electrohydraulic Forming (EHF)

Working Principle

Electrohydraulic Forming (also known as **Electro-spark Forming**) converts electrical energy into mechanical shockwave energy inside a liquid medium.

Two electrodes are submerged in a water tank directly above a clamped metal blank. A large capacitor bank releases a high-voltage flash discharge across the electrode gap. This sudden electrical arc causes instantaneous vaporization of the surrounding water, creating a high-temperature plasma bubble. As this plasma bubble expands rapidly, it creates a powerful hydraulic shockwave that travels through the water and forces the sheet metal into the die cavity.

Equipment Setup

- **Energy Storage Bank:** High-voltage capacitor banks similar to those used in electromagnetic forming.
- **Submerged Electrodes:** A pair of adjustable electrodes positioned inside a water chamber. A thin initiating wire is sometimes bridged between them to guide the spark arc.
- **Water Chamber:** A closed or semi-confined vessel that directs the hydraulic shock pulse downward onto the workpiece.
- **Female Die and Vacuum Line:** Supports the metal blank and extracts trapped air to ensure a crisp impression.

Process Parameters

- **Spark Gap Distance:** The distance between the electrode tips; determines the breakdown voltage threshold.
- **Discharge Energy Level:** Governs the magnitude and velocity of the water shockwave front.
- **Standoff Distance:** The height of the electrodes relative to the metal blank surface.

Advantages & Limitations

- **Advantages:** Offers better control of energy delivery compared to chemical explosives; safe for indoor factory use; can form complex shapes with sharp details.

- **Limitations:** Limited to small and medium-sized workpieces due to electrical equipment scaling limits; cycle time is slow because the water must be managed and components loaded manually; electrode tips erode rapidly.

Applications

- Fabricating small commercial appliance panels, embossed decorative sheets, and precision industrial manifolds.
- Bulging or venting thin-walled non-ferrous metal tubes.

Unit 4.0 Gear Manufacturing

Major Types of Gears

- **Spur Gears:** Straight teeth parallel to the gear axis. Used for parallel shafts. Simple but noisy at high speeds.
- **Helical Gears:** Teeth cut at an angle (helix angle) to the axis. Provides smoother, quieter operation due to gradual tooth engagement. Introduces axial thrust.
- **Bevel Gears:** Cone-shaped gears used to transmit power between intersecting shafts (usually at 90°). Includes straight, spiral, and hypoid variants.
- **Worm & Worm Gears:** A screw (worm) meshes with a gear (worm wheel). Delivers high gear ratios in a compact space and features self-locking capabilities.
- **Rack and Pinion:** A circular gear (pinion) meshes with a linear tooth bar (rack) to convert rotational motion into linear motion.

Overview of Manufacturing Methods

Industrial gear manufacturing falls into two main categories: **Forming** (shaping material without cutting) and **Machining** (material removal).

```
                            Gear Manufacturing
                                    │
         ┌──────────────────────────┴──────────────────────────┐
         ▼                                                     ▼
   Forming Methods                                     Machining Methods
  (No Material Cut)                                    (Material Cut)
   ├── Casting (Sand/Die)                              ├── Gear Forming
(Milling/Broaching)
   ├── Forging (Drop/Precision)                        └── Gear Generation
   ├── Extrusion & Rolling                                  ├── Gear Hobbing
   └── Powder Metallurgy                                    └── Gear Shaping
```

- **Casting:** Used for massive gears or low-precision, low-cost applications.
- **Forging:** Refines grain structure, yielding high strength for heavy-duty automotive and industrial gears.
- **Powder Metallurgy:** Fine metal powder is compacted and sintered. Excellent for high-volume, small, low-load components (like toys or appliances).
- **Extrusion & Plastic Molding:** Ideal for non-metallic gears requiring lightweight properties and low operating noise.

4.2 Gear Hobbing

Gear hobbing is a continuous, high-speed material-removal generation process where the cutting tool and blank rotate simultaneously in a fixed relationship.

Working Principle

The cutting tool, called a **hob**, is essentially a multipoint cutter shaped like a worm screw with helical gashes that form cutting edges.

During operations, the gear blank and hob are geared together mechanically or via CNC software. As the hob rotates, it plunges axially into the spinning gear blank. Every rotation of the hob advances the blank by a precise angular distance corresponding to one or more teeth, generating the correct involute tooth profile continuously.

Types of Gear Hobbing

1. **Axial Hobbing:** The hob feeds parallel to the axis of the gear blank. This is the standard method for producing conventional spur and helical gears.
2. **Radial Hobbing:** The hob feeds perpendicularly (radially) into the blank until the full tooth depth is reached. Used primarily for cutting worm wheels.
3. **Tangential Hobbing:** The hob feeds tangentially across the face of the blank. Used for high-precision worm gears with steep helix angles.

Process Characteristics

Feature	**Description**
Advantages	High production rates; highly versatile (one hob can cut any number of teeth of the same module); exceptional dimensional uniformity across large batches.

Feature	Description
Limitations	Cannot cut internal gears; restricted by clear clearance zones (cannot cut teeth directly adjacent to a larger shoulder or flange).
Applications	High-volume production of external spur gears, helical gears, splines, sprockets, and worm wheels.

4.3 Gear Shaping

Gear shaping is a generating method based on a reciprocating cutting motion, replicating the kinematics of two gears meshing together.

Gear Shaping by Pinion Cutter

The tool is a hardened steel gear (pinion) with cutting clearances ground into its teeth.

- **Working Principle:** The pinion cutter reciprocates rapidly along its vertical axis to cut the material while both the cutter and gear blank rotate slowly together at a synchronized pitch-circle velocity. The cutter backs away slightly on the return stroke to prevent friction and tool wear.

Gear Shaping by Rack Cutter

The tool is a segment of a linear rack with cutting edges.

- **Working Principle:** The rack cutter reciprocates vertically across the blank face. Simultaneously, the blank rotates and translates linearly across the face of the rack. Because a rack cutter has a finite length, the machine must periodically halt cutting to index and reset the blank back to its starting position.

Advantages, Limitations & Comparison

- **Advantages (Pinion):** Can cut **internal gears** and close-to-shoulder gears where hobs cannot physically fit.
- **Advantages (Rack):** Highly accurate tooth profiles, as grinding a straight-sided rack profile is easier than grinding a complex pinion form.
- **Limitations:** Slower production rates compared to hobbing due to the non-cutting return stroke. Rack shaping is further slowed by indexing resets.

Direct Comparison: Hobbing vs. Shaping

Parameter	**Gear Hobbing**	**Gear Shaping**
Process Kinematics	Continuous rotary cutting motion.	Reciprocating cutting motion + indexing rotation.
Production Speed	Much higher; highly efficient for batches.	Slower due to lost time on the return stroke.
Internal Gears	Impossible.	Highly capable (using a pinion cutter).
Interference Constraints	Requires clear run-out space; fails near shoulders.	Excellent for close-clearance cluster gears.
Tool Versatility	One hob cuts any tooth count of a given module.	One cutter cuts any tooth count of a given module.

4.4 Gear Finishing Methods

The Need for Gear Finishing

Rough-machined gears (from hobbing or shaping) retain surface irregularities, micro-geometry errors, and minor distortions caused by heat treatment. Left unfixed, these flaws cause stress concentrations, premature wear, and severe noise. Finishing ensures precise tooth spacing, profile accuracy, and an optimized surface finish.

a) Gear Shaving

A fast, chip-removing process used on **unhardened (green) gears** before heat treatment.

- **Method:** The gear meshes closely with a high-precision cutter shaped like a gear, featuring micro-grooves along its tooth flanks. The axes of the tool and workpiece are intentionally crossed at an angle (typically 10° to 15°). As they rotate under pressure, the axial sliding motion causes the cutter blades to shave tiny, hair-like chips off the gear flanks.

b) Gear Grinding

An abrasive process used on **hardened gears** to correct distortions caused by heat treatment.

- **Method:** A rotating abrasive grinding wheel removes material from the tooth flanks. This is done using form grinding (where the wheel profile matches the tooth space) or generation grinding (where a threaded wheel mimics a hob). It yields exceptional dimensional accuracy but operates at a higher cycle cost.

c) Gear Burnishing

A **non-cutting, plastic deformation** process for unhardened gears.

- **Method:** The workpiece gear is cold-rolled under high pressure between two or three hardened, master burnishing gears. This flattens microscopic peaks, cold-works the surface layer, and improves wear resistance without removing chips.

d) Gear Lapping

An abrasive correction process used primarily for **hardened bevel and worm gear sets**.

- **Method:** The gear and its mating pinion are run together under load while a fluid containing fine abrasive grit (like silicon carbide) is pumped into the mesh. The compound corrects minor pitch errors and custom-fits the pair, ensuring smooth running characteristics as a matched set.

e) Gear Honing

A high-precision abrasive process used on **hardened gears** to reduce noise.

- **Method:** The gear meshes with a plastic or ceramic bonding tool impregnated with fine abrasive grains, running at crossed axes. Honing removes the "heat-treat scale," refines the surface finish to a mirror-like quality, and corrects high-frequency distortions.

f) Gear Tooth Rounding

A specialized machining operation targeting the **axial ends** of the teeth.

- **Method:** A small, high-speed milling cutter profiles the tips of the gear teeth into rounded or chamfered edges. This process is essential for manual automotive transmissions, preventing the teeth from chipping or jamming during gear shifts.

Summary

Process	**Applicable Hardness**	**Material Removal Mechanism**	**Primary Objective**
Shaving	Pre-hardened (Soft)	Cutting (Micro-chips)	Rapid pre-heat-treat profile correction.
Grinding	Post-hardened (Hard)	Grinding (Abrasive wheel)	Ultimate geometric precision, corrects distortion.
Burnishing	Pre-hardened (Soft)	Plastic deformation (No chips)	Surface hardening and peak flattening.
Lapping	Post-hardened (Hard)	Loose abrasive slurry	Mating adjustment for quiet running (Gear sets).
Honing	Post-hardened (Hard)	Bonded abrasive tool	Removes scale, minimizes gear whine noise.
Rounding	Pre-hardened (Soft)	Milling cutter	Prevents tooth clashing during engagement.

Unit 5.0 Recent trends in CAM

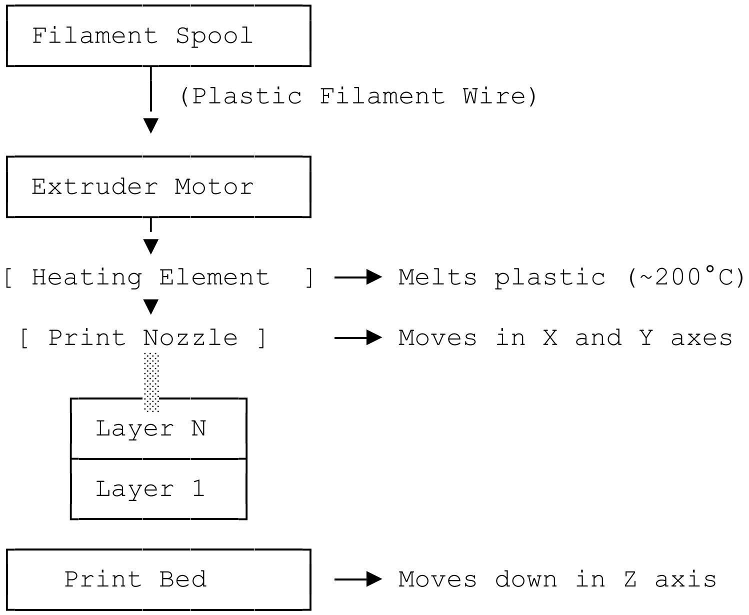
5.1 to 5.3 Additive Manufacturing & 3D Printing

1. Core Concepts

- **Additive Manufacturing (AM):** A process of joining materials to make objects from 3D model data, usually **layer upon layer**, as opposed to subtractive manufacturing methodologies (like milling or turning).
- **Rapid Prototyping (RP):** The quick fabrication of a physical part or assembly using 3D computer-aided design (CAD) data. It allows engineers to see, touch, and test a concept model before mass production.

2. Construction and Working of a 3D Printer (Fused Deposition Modeling - FDM)

FDM is the most common 3D printing technology taught in polytechnic courses.



- **Core Construction Elements:**
  1. **Filament Spool:** Holds the raw thermoplastic wire.
  2. **Extruder Mechanism:** A stepper motor pushes the filament forward into the hot end.
  3. **Heating Element (Hot End):** Melts the solid plastic filament into a semi-liquid state.
  4. **Nozzle:** Deposits the melted material accurately onto the build platform.

5. **Print Bed (Build Plate):** The flat surface where the part is built. It is often heated to prevent the plastic from warping.
6. **Gantry System:** Stepper motors and belts that move the nozzle in the **X and Y axes**, and the bed or nozzle assembly in the **Z axis** (vertical layer steps).

- **Working Principle:**

  The printer reads a layer-by-layer instruction file. The raw plastic filament is pushed into the heated nozzle, where it melts. The nozzle traces the geometry of the first layer onto the print bed, depositing thin tracks of plastic that cool and solidify instantly. Once a layer is complete, the print bed moves down (or the nozzle moves up) by one layer thickness (Z-increment), and the next layer is extruded directly on top of the previous one. This continues until the part is complete.

3. Materials for 3D Printing & Rapid Prototyping

Material	**Type**	**Key Properties**	**Applications**
PLA (Polylactic Acid)	Thermoplastic	Biodegradable (corn-starch based), easy to print, very low warping, brittle.	Conceptual prototypes, educational models, non-functional mockups.
ABS (Acrylonitrile Butadiene Styrene)	Thermoplastic	Tough, high impact resistance, heat resistant, smells bad when printed, prone to warping.	Automotive trim elements, functional mechanical prototypes, Lego bricks.
PETG (Polyethylene Terephthalate Glycol)	Thermoplastic	Combines the ease of PLA with the strength of ABS; chemical resistant, flexible, food-safe.	Functional brackets, snap-fit components, containers.
Photopolymer Resins	Liquid Resin (UV curable)	Extremely high geometric resolution, smooth surface finish, brittle after curing.	Jewelry models, dental models, high-detail miniature parts (used in

Material	Type	Key Properties	Applications
			SLA printers).

5.4 & 5.5 File Formats & Software Workflow

1. STL (Stereo Lithography) File Format

- **Definition:** The universal file format used by almost all 3D printers.
- **Concept:** It converts a smooth 3D CAD model into a mesh of thousands of tiny, interconnected **triangles** (tessellation).
- **Limitation:** It only describes the *surface geometry* of a 3D object. It does not store information regarding color, material, texture, or internal structures.

2. 3D Printer Software Workflow (The "Slicing" Process)

Before an STL file can be printed, it must be compiled into machine instructions called **G-code** via a tool known as a "Slicer" (e.g., Cura, PrusaSlicer).

```
   [ Import STL ] → [ Orient Part ] → [ Process / Slice ] → [ Export G-code ]
```

1. **Part Import:** The user loads the digital .STL file into the slicing software workspace.
2. **Orientation:** Rotating and positioning the model on the virtual print bed. Proper orientation minimizes the need for support material, avoids weak grain directions, and improves surface finish.
3. **Processing (Slicing Configuration):** The user sets the physical build parameters:
    - *Layer Height:* Controls the vertical printing resolution (e.g., 0.2 mm).
    - *Infill Density:* The internal grid structure (0% is hollow, 100% is completely solid; 15-20% is typical for general use).
    - *Supports:* Sacrificial structures generated underneath overhanging features that would otherwise collapse during printing.
    - *Temperature:* Setting the appropriate heat levels for the nozzle and bed based on the material used.
4. **Printing:** The slicer slices the 3D model into thousands of horizontal 2D planes, writes them into numerical code (**G-code**), and sends it to the printer via USB, SD Card, or Wi-Fi.

5.6 Computer Integrated Manufacturing (CIM)

1. Concept & Definition

CIM is the complete integration of all enterprise manufacturing functions using computer systems. It is not a single manufacturing process; it is an overarching business philosophy where design, production, testing, and business operations share a single digital database.

2. Areas Covered by CIM

CIM bridges the gap between factory floor operations and corporate business tasks:

```
                                   ┌────────────────────────┐
                                   │  Shared CIM Database   │
                                   └────────────────────────┘
                                               │
                                      │
┌────────────────────┬────────────────┴────────────────┬───────────────────┐
         ▼                    ▼                                 ▼
▼
    Design (CAD)      Planning (CAM/CAP)               Production (CNC/AM)
Business (ERP/MRP)
  - 3D Modeling       - Process Planning               - Machining Cells
- Order Tracking
  - FEA Analysis      - Tooling Selection              - Assembly Robots
- Inventory Control
```

3. Key Benefits of CIM

- **Reduced Lead Time:** Speeds up the path from initial design concept to final physical delivery.
- **Fewer Errors:** A single database ensures that updates to a design automatically propagate to the factory floor, minimizing rework.
- **Lower Inventory Levels:** Real-time production tracking enables Just-In-Time (JIT) material delivery.
- **Higher Machine Utilization:** Schedules manufacturing equipment efficiently, reducing idle downtime.

5.7 & 5.8 Automation Concepts & Types

1. Definition & Need for Automation

- **Definition:** Automation is the application of mechanical, electronic, and computer-based systems to operate and control production processes without direct human intervention.
- **The Need for Automation:**
  - To increase labor productivity and throughput.
  - To lower total labor costs.

    - To mitigate the effects of labor shortages.
    - To improve worker safety by removing personnel from hazardous manufacturing environments.
    - To achieve consistent, high-precision product quality.

2. Low-Cost Automation (LCA) vs. High-Cost Automation

- **Low-Cost Automation (LCA):** Upgrading existing manual machines and processes using inexpensive mechanical, pneumatic, hydraulic, or simple electrical components.
    - *Example:* Adding a pneumatic cylinder with a limit switch to automatically clamp parts into a manual drill press fixture.
- **High-Cost Automation:** Implementing advanced, capital-intensive technology from the ground up.
    - *Example:* Installing an autonomous robotic arm integrated with an artificial vision system to sort, pick, and pack items on a high-speed conveyor line.

3. The Three Main Types of Automation

Feature	**Fixed (Hard) Automation**	**Programmable Automation**	**Flexible (Soft) Automation**
Production Volume	Exceptionally High	Low to Medium	Medium
Product Variety	Very Low (Single design)	High (Batches of different designs)	Low to Medium (Variations on a family)
Changeover Flexibility	Poor (Requires rebuilding mechanical cams/fixtures)	Hard (Requires stopping to re-program and swap tooling)	Excellent (Instant changeover via software instructions)
Investment Cost	High initial cost	Medium initial cost	Very high initial cost

Feature	Fixed (Hard) Automation	Programmable Automation	Flexible (Soft) Automation
Examples	Automotive transfer lines, beverage bottling plants.	CNC milling batch runs, industrial weaving looms.	Flexible Manufacturing Systems (FMS), robotic assembly cells.

5.9 Group Technology (GT) & Cellular Manufacturing

1. Concept of Group Technology

Group Technology is a manufacturing philosophy where similar parts are identified and grouped together to take advantage of their design similarities and manufacturing process efficiencies.

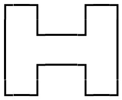
2. Basis for Developing Part Families

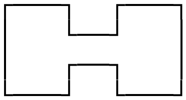
Parts are grouped into **Part Families** based on two main criteria:

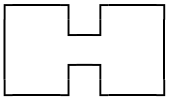
1. **Design Attributes:** Geometric shape, dimensions, tolerances, and material type.
2. **Manufacturing Attributes:** The sequence of machining steps, required tooling, cutting feeds, and machine tools used.

```
                  Part Family Example (Different Shapes, Same Steps)

     Part A: Cylindrical Ring      Part B: Stepped Shaft      Part C: Flanged
Sleeve
```







```
     [All parts belong to the same family because they require turning,
drilling, and facing]
```

3. Part Classification and Coding Systems

To easily group parts into families, factories assign a digital code to every component. There are three structural types:

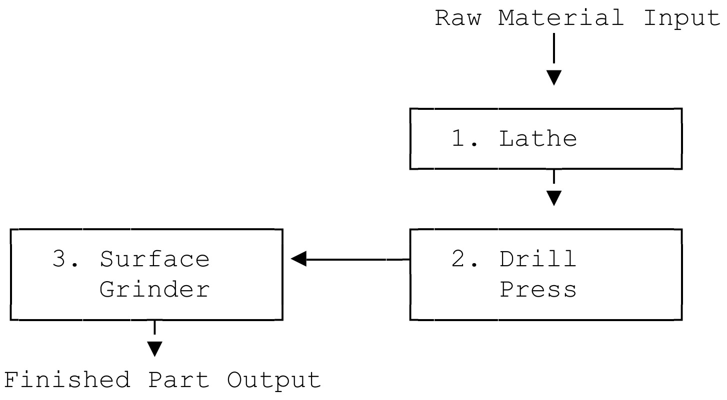
- **Opitz System:** The most famous classification system. It uses a sequence of digits to define shape, process parameters, and production requirements.

- **Monocode (Hierarchical Code):** Each digit's meaning depends on the value of the digit before it. Deep information density, but highly complex to design.
- **Polycode (Attribute Code):** Each digit represents a completely independent physical attribute. Easy to interpret and search database files.

4. Cellular Manufacturing

- **Concept:** Disassembling a traditional functional layout (where all drills are in one room, and all lathes are in another) and rearranging the shop floor into dedicated **Manufacturing Cells**.
- **Cell Design:** A cell is a collection of different machine tools arranged typically in a **U-shape**. This layout allows a single part family to be processed completely from start to finish within a localized area, dramatically reducing material transport times.

Typical U-Shaped Manufacturing Cell



5. Advantages and Limitations of Group Technology

- **Advantages:**
  - **Reduced Setup Times:** Because similar parts are processed sequentially, machines require fewer tooling changeovers.
  - **Less Material Handling:** Parts move short distances within a single localized cell rather than traveling across an entire factory floor.
  - **Reduced Work-in-Progress (WIP):** Parts flow quickly through the cell instead of sitting in storage stacks between departments.
- **Limitations:**
  - **High Setup Expense:** Re-arranging a traditional factory layout into cellular formations requires significant capital and downtime.
  - **Imbalanced Machine Utilization:** A machine inside a specific cell might sit idle if the demand for that particular part family drops.

5.10 Flexible Manufacturing Systems (FMS)

1. Concept & Definition

An **FMS** is an automated, mid-volume production system consisting of interconnected processing workstations (typically CNC machines) linked by an automated material handling system, all operating under centralized computer control.

It is "Flexible" because it can process a variety of different part styles simultaneously without stopping for changeovers.

2. Main Elements and Their Functions

An FMS is built on three core pillars:

```
                                   ┌─────────────────────────┐
                                   │   Central Controller    │
                                   └────────────┬────────────┘
                                                │ (Instructs and monitors)
┌────────────────────────────────────┼────────────────────────────────────┐
         ▼                                      ▼
▼
┌───────────────────┐                ┌───────────────────┐
┌───────────────────┐
│ Workstations      │                │ Material Handling│                  │
Computer Control │
│ - CNC Mills       │ ◄────────────► │ - AGVs            │ ◄────────────► │ -
Part Routing   │
│ - Robot Assembly │  (Transports)   │ - AS/RS Systems   │  (Data Sync)   │ -
Tool Monitoring│
└───────────────────┘                └───────────────────┘
└───────────────────┘
```

1. **Processing Workstations:** CNC machine tools, automated inspection stations, or washing machines that perform the actual physical work.
2. **Automated Material Handling & Storage System:** Transports workpieces and tooling between stations. Common hardware includes:
   - *AGV (Automated Guided Vehicle):* Driverless carts that move parts along floor tracks.
   - *AS/RS (Automated Storage and Retrieval System):* Computerized high-density racking warehouses that store raw blanks and finished parts.
3. **Centralized Computer Control System:** The brain of the FMS. It downloads CNC programs to individual machines, routes AGVs along transport pathways, monitors tool wear, and updates scheduling schedules.

3. FMS Layout Types

The physical arrangement of workstations depends on production routing needs:

- **Inline Layout:** Workstations are arranged in a straight line. Parts move sequentially from one machine to the next.
- **Loop Layout:** Workstations are arranged in an enclosed ring track. Parts can bypass certain machines, allowing for variation in processing steps.
- **Ladder Layout:** Features cross-tracks between parallel lines, cutting down transport times for complex, non-sequential routing paths.
- **Open Field Layout:** The most complex configuration. Uses multiple AGVs to move parts freely across a sprawling grid of distinct workstations.

5.11 & 5.12 Industrial Robotics

1. Definition & Core Terminology

- **Definition:** An industrial robot is an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes.
- **Key Terminology:**
    - **Manipulator:** The main articulated body of the robot (the arm linkage assembly).
    - **End Effector:** The specialized tool attached to the robot's wrist to perform specific tasks (e.g., mechanical grippers, welding torches, paint spray guns).
    - **Degrees of Freedom (DOF):** The number of independent directional movements a robot arm can make (typically 6 axes for standard industrial work).
    - **Work Envelope (Workspace):** The complete physical space volume that a robot's manipulator can reach.
    - **Payload:** The maximum weight the robot can lift and manipulate accurately at full speed.

2. Classification of Robots (By Coordinate Configurations)

```
       Cartesian (XYZ)                  Cylindrical (R-θ-Z)
Spherical / Polar
             ┌───┐                        ┌─┐
      ┌──────┼───┼───▶ X                  │ │
//\
      │      └───┘                        │ ├───▶ R                    //
\ ──▶ Extend
      ▼ Z                                 └─┘                       //
\
                                           (Rotates θ)
(Rotates Base & Tilt)
```

1. **Cartesian Configuration (Linear/Gantry):**
    - *Movements:* Three linear axes of motion (**X, Y, Z**).
    - *Work Envelope:* Rectangular box.
2. **Cylindrical Configuration:**
    - *Movements:* One rotational axis at the base, and two linear translation axes.
    - *Work Envelope:* Cylinder space.
3. **Spherical (Polar) Configuration:**

    - *Movements:* Two rotational axes (base rotation and vertical tilt) and one linear extension axis.
    - *Work Envelope:* Spherical section.
4. **Articulated Configuration (Jointed Arm):**
    - *Movements:* Built with rotary joints that mimic a human arm (shoulder, elbow, wrist). Offers maximum maneuverability.
    - *Work Envelope:* Irregular spherical space.
5. **SCARA Configuration:**
    - *Definition:* Selective Compliance Assembly Robot Arm. It features two parallel rotary joints providing flexibility in a horizontal plane, while remaining rigid vertically. Excellent for high-speed pick-and-place assembly lines.

3. Structural Components of an Industrial Robot

- **Manipulator:** The physical structure of links and joints that moves through space.
- **End Effectors:** Tools mounted to the wrist interface. Divided into *Grippers* (vacuum cups, magnetic pads, mechanical jaws) and *Process Tools* (welding nozzles, routing spindles, sprayers).
- **Actuators:** The motors that drive movement at the joints. Mostly brushless **AC Servomotors** combined with precision gearboxes for highly accurate positioning.
- **Sensors:** Gather internal and external system data:
    - *Internal:* Encoders and resolvers that track joint angles and rotation speeds.
    - *External:* Limit switches, vision cameras, and force/torque sensors that detect part location and contact forces.
- **Controller:** The hardware enclosure that reads software code, processes sensor inputs, and calculates the electrical drive power needed for individual joint motors.
- **Processor:** The computer microprocessor chip within the controller that solves real-time kinematics equations.
- **Software:** The interface where engineers program trajectories, configure safety boundaries, and code logic operations.

4. Typical Industrial Applications

- **Material Handling:** Moving heavy parts between automated conveyors and CNC machine chucks (machine tending).
- **Spot & Arc Welding:** Used extensively across automotive assembly plants for consistent, high-strength welds.
- **Spray Painting:** Eliminates human exposure to toxic vapors while laying down highly uniform coating layers.
- **Assembly & Inspection:** High-speed positioning of small electronic parts on circuit boards, paired with camera verification.

Summary Table

Technology	**Core Keyword**	**Primary Advantage**
Additive Manufacturing	Layer-by-layer build	Unmatched geometric freedom; minimal material waste.
STL File Format	Triangular mesh	Universal compatibility between CAD software and slicers.
CIM	Shared enterprise database	Bridges the gap between business planning and factory floor.
Flexible Automation	Soft changeovers	Perfect for producing part variations without mechanical downtime.
Group Technology	Part Families	Eliminates redundant design work and optimizes machine setups.
FMS	Central Computer Control	Combines mass-production speeds with custom batch flexibility.
SCARA Robot	Compliant horizontal plane	Ideal choice for rapid pick-and-place electronics assembly.