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Advanced Manufacturing Techniques

Course Code: 23BTMEL407
B. Tech - VII Semester

Prepared by:
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Teaching and Evaluation Scheme

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Course Title: **Advanced Manufacturing Techniques**										
Semester	VII	Teaching Scheme				Evaluation Scheme				
						Theory			Practical	
Term	Odd	Th	Tu	Pr	Credits	TAE	CAE	ESE	INT	EXT
Course Category	PEC 4	4 Hrs	-	-	04	10	15	50	-	-
Course Code	23BTMEL407									
Teaching Mode	Offline	3 Hrs.			Total	75			-	
Duration of ESE	3 Hrs.					75				

Course Objectives and Outcomes

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Course Objectives	1. To understand various material characterization techniques.
	2. To analyze and identify applications of advanced joining processes.
	3. To understand and analyze the basic mechanisms of hybrid non-conventional machining techniques and identify applications of special forming processes.
	4. To understand various applications and methods of micro and nano fabrication techniques.
	5. To understand advanced Additive Manufacturing (AM) technology for innovations in product development.
Course Outcomes	Upon successful completion of this course, student shall be able to:
	CO1: Interpret the fundamental principles and applications of various advanced forming processes.
	CO2: Apply advanced joining techniques to solve engineering challenges
	CO3: Apply knowledge of hybrid, micro- machining processes, their mechanisms, process parameters, and applications to solve manufacturing problems.
	CO4: Apply additive manufacturing techniques and process steps in product development.
	CO5: Analyze the effects of chemical composition, composition variation, crystal structure, etc.by using material characterization technique.

Mapping of Course Outcomes with Program Outcomes and Program Specific Outcomes:

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Following mapping is only for reference

Course Outcomes	Program Outcomes and Program Specific Outcomes														
	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO 10	PO 11	PO12	PSO 1	PSO 2	PSO 3
CO1	3	3	3	2		3	1	1	--	--	--	2	3	2	2
CO2	3	3	3	2		2	1	1	--	--	--	2	3	2	2
CO3	3	3	3	3		2	1	1	--	--	--	2	3	2	2
CO4	3	3	3	3		2	1	1	--	--	--	2	3	2	2
CO5	3	3	3	3		2	1	1	--	--	--	2	3	2	2

Syllabus

Unit	Contents
Unit 1	**Special Forming Processes:** Principle, machines, process variables, characteristics, advantages, limitations and application of High Energy Rate Forming process (HERF), High Velocity Forming (HVF), Explosive forming, Magnetic pulse forming, Electro hydraulic forming, Metal spinning, Flow forming, Stretch forming, Incremental sheet metal forming, Petro-forge forming, Micro forming, Micro coining, Micro extrusion, Micro bending/laser bending, fine blanking.
Unit 2	**Advanced Joining Processes:** Friction stir welding, Electron Beam welding, Laser beam welding, Ultrasonic welding, Under water welding, Cryogenic welding, Thermal spray coatings, Welding of plastics and composites, Explosive joining, Adhesive bonding.
Unit 3	**Hybrid Non-conventional Machining Techniques:** Introduction to hybrid processes, Abrasive flow finishing, Magnetic abrasive finishing, Abrasive water-jet machining, Wire electric discharge machining, Electrochemical grinding (ECG), Electrochemical Deburring (ECD), Shaped tube electrolytic machining (STEM), Electro-jet Machining (EJM), Electrolytic In-process dressing (ELPD), Ultrasonic assisted EDM, Rotary EDM, Electrochemical discharge Machining (ECDM), Laser surface treatments. micro and nano machining, Machine/setup, Process parameters, Mechanism of material removal, Applications, Advances of the Diamond Turn machining, Ultrasonic micro-machining, Focused Ion Beam Machining, Lithography, photochemical machining, Challenges in micro and nano-fabrication techniques.

Syllabus

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Unit	Contents
Unit 4	**Additive Manufacturing Processes** Introduction and principle of the additive manufacturing process; Generalized additive manufacturing process chain; Classification of additive manufacturing processes and its principle, process steps and materials; Post-processing of parts manufactured by Additive Manufacturing (AM) processes, Software issues in AM, Design For Additive Manufacturing (DFAM), Applications of Additive Manufacturing in Medical and Aerospace technologies.
Unit 5	**Material Characterization Techniques** Introduction: Material Characterization. Microscopy: Electron Microscopes, Scanning Electron Microscope (SEM), Transmission Electron Microscope (TEM), Scanning Tunneling Microscope (STM), Atomic Force Microscope (AFM), Field Ion Microscope(FIM); Spectroscopy: Energy-dispersive X-ray spectroscopy (EDX), X-Ray Diffraction (XRD), X-Ray Photoelectron Spectroscopy (XPS), Nuclear Magnetic Resonance Spectroscopy (NMR), Electron Backscatter Diffraction (EBSD).

Study Material

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Text Books	1	Groover M. P., Fundamentals of modern manufacturing: materials, processes, and systems. John Wiley & Sons; 2020.
	2	Mallik A.K., Ghosh A. and Dittrich G., Kinematic analysis and synthesis of mechanisms. CrcPress; 2021.
	3	Ghosh A, Mallik A. K. Manufacturing science. Ellis Horwood, 1986.
	4	Ebnesajjad S., Surface and material characterization techniques. In Handbook of Adhesives and Surface Preparation; William Andrew Publishing. 2011.
E-Books	1	Jain V K. Advanced machining processes. Allied publishers; 2009.
Reference Books	1	Welding E.B., and Handbook A.S., Welding, brazing, and soldering. ASM Int. 1993.
	2	Muldoon K, Marquard E, Lampman H, Karcher C, Musgrove B, Dragolich K, and Schaefer M. ASM Handbook. 2005.
	3	Balasubramaniam R, Sarepaka R.V., and Subbiah S., Diamond turn machining: Theory and practice. CRC press; 2017.
	4	Kumar L. J., Pandey P.M., and Wimpenny D. I., 3D printing and additive manufacturing technologies. Berlin, Germany: Springer; 2019.

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Unit 1

Unit 1
High Energy Rate Forming (HERF) Processes

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Important features of HERF processes:

1. The energy of deformation is delivered at a much higher rate than in conventional practice.
2. Larger energy is applied for a very short interval of time.
3. High particle velocities are produced in contrast with conventional forming process.
4. The velocity of deformation is also very large and hence these are also called High Velocity Forming (HVF) processes.
5. Many metals tend to deform more readily under extra fast application of force.
6. Large parts can be easily formed by this technique.
7. For many metals, the elongation to fracture increases with strain rate beyond the usual metal working range, until a critical strain rate is achieved, where the ductility drops sharply.
8. The strain rate dependence of strength increases with increasing temperature.
9. The yield stress and flow stress at lower plastic strains are more dependent on strain rate than the tensile strength.
10. High rates of strain cause the yield point to appear in tests on low carbon steel that do not show a yield point under ordinary rates of strain.

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Advantages of HERF Processes

1. Production rates are higher, as parts are made at a rapid rate.
2. Die costs are relatively lower.
3. Tolerances can be easily maintained.
4. Versatility of the process – it is possible to form most metals including difficult to form metals.
5. No or minimum spring back effect on the material after the process.
6. Production cost is low as power hammer (or press) is eliminated in the process. Hence it is economically justifiable.
7. Complex shapes / profiles can be made much easily, as compared to conventional forming.
8. The required final shape/ dimensions are obtained in one stroke (or step), thus eliminating intermediate forming steps and pre forming dies.
9. Suitable for a range of production volume such as small numbers, batches or mass production.

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Limitations:

i) Highly skilled personnel are required from design to execution.

ii) Transient stresses of high magnitude are applied on the work.

iii) Not suitable to highly brittle materials

iv) Source of energy (chemical explosive or electrical) must be handled carefully.

v) Governmental regulations/ procedures / safety norms must be followed.

vi) Dies need to be much bigger to withstand high energy rates and shocks and to prevent cracking.

vii) Controlling the application of energy is critical as it may crack the die or work.

viii) It is very essential to know the behavior or established performance of the work metal initially.

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Applications:

i) In ship building – to form large plates / parts (up to 25 mm thick).

ii) Bending thick tubes/ pipes (up to 25 mm thick).

iii) Crimping of metal strips.

iv) Radar dishes

v) Elliptical domes used in space applications.

vi) Cladding of two large plates of dissimilar metals.

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Explosive Forming

Introduction:

A punch in conventional forming is replaced by an explosive charge.

Explosives used can be:

- High energy chemicals like TNT, RDX, and Dynamite.
- Gaseous mixtures
- Propellants.

Types of explosive forming:

1) Unconfined type or Stand off technique

2) Confined type or Contact technique

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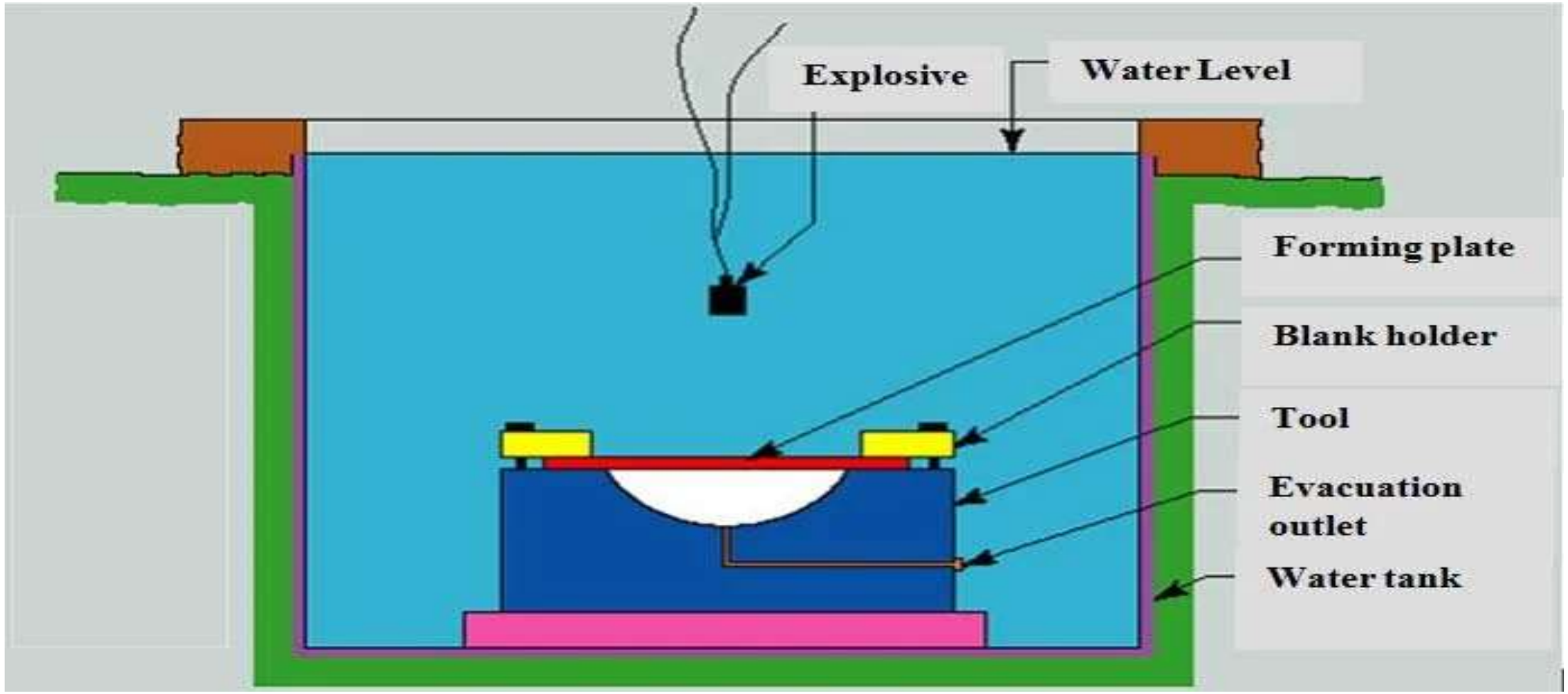
Factors to be considered while selecting an HERF process:

1. Size of work piece
2. Geometry of deformation
3. Behavior of work material under high strain rates
4. Energy requirements/ source
5. Cost of tooling / die
6. Cycle time
7. Overall capital investment
8. Safety considerations.

Explosive Forming

(Unconfined type (or Stand off technique))

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Principle:

The work is firmly supported on the die and the die cavity is evacuated. A definite quantity of explosive is placed suitably in water medium at a definite stand off distance from the work. On detonation of the explosive charge, a pressure pulse (or a shock wave) of very high intensity is produced.

A gas bubble is also produced which expands spherically and then collapses. When the pressure pulse impinges against the work (plate or sheet0, the metal is deformed into the die with a high velocity of around 120 m/s (430km/h). The vacuum is necessary in the die to prevent adiabatic heating of the work which may lead to oxidation or melting.

Role of water in Explosive Forming:

i) Acts as energy transfer medium

ii) Ensures uniform transmission of energy

iii) Muffles the sound of explosion

iv) Cushioning/ smooth application of energy on the work without direct contact.

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Process Variables of Explosive forming process

i) Type and amount of explosive: wide range of explosive sis available.

ii) Stand off distance – SOD- (Distance between work piece and explosive): Optimum SOD must be maintained.

iii) The medium used to transmit energy: water is most widely used.

iv) Work size

v) Work material properties

vi) Vacuum in the die

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Advantages

i) Shock wave is efficiently transmitted through water and energy is transmitted effectively on the work

ii) Less noise

iii) Less probability of damage to work.

iv) Large and thick parts can be easily formed

v) Economical, when compared to a hydraulic press

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Limitations:

i) Optimum SOD is essential for proper forming operation.

ii) Vacuum is essential and hence it adds to the cost.

iii) Dies must be larger and thicker to withstand shocks.

iv) Not suitable for small and thin works.

v) Explosives must be carefully handled according to the regulations of the government.

Applications:

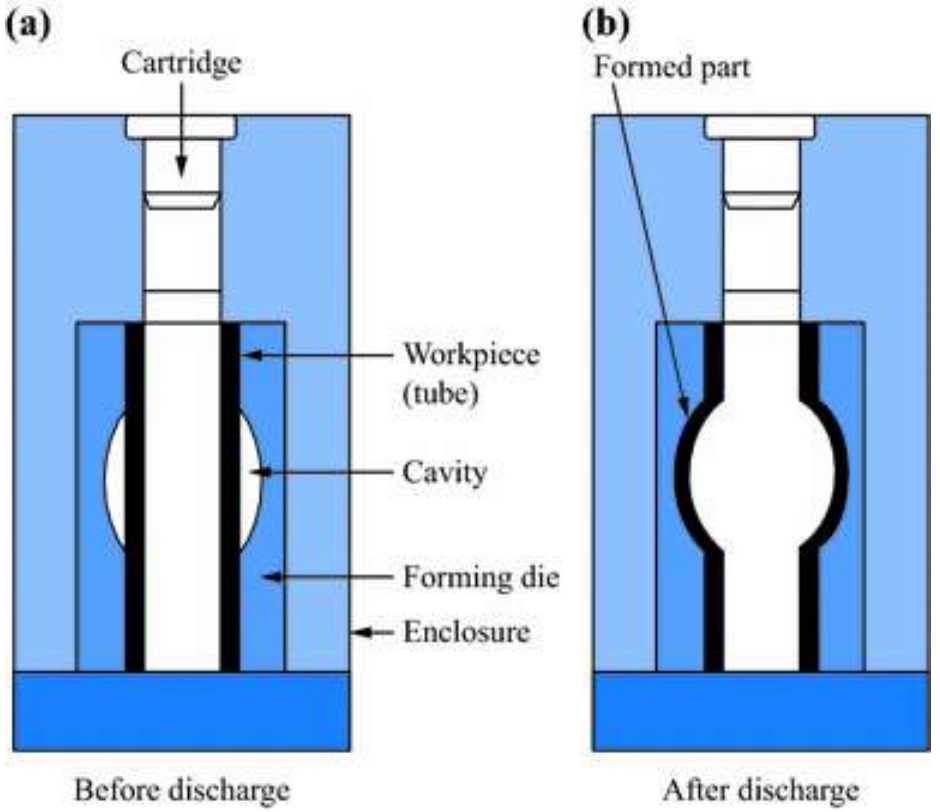
- Ship building,
- Radar dish,
- Elliptical domes in space applications

2) Confined System (or Contact Technique)

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Principle:

The pressure pulse or shock wave produced is in direct contact with the work piece (usually tubular) and hence the energy is directly applied on the work without any water medium. The tube collapses into the die cavity and is formed. It is used for bulging and flaring operations.



Advantages:

i) Entire shock wave front is utilized as there is no loss in water.

ii) More efficient as compared to unconfined type.

Disadvantages:

i) More hazard of die failure

ii) Vacuum is required in the die

iii) Air present in the work piece (tube) is compressed leading to heating.

iv) Not suitable for large and thick plates.

Applications

Bulging and flaring of tubes.

Electro hydraulic Forming

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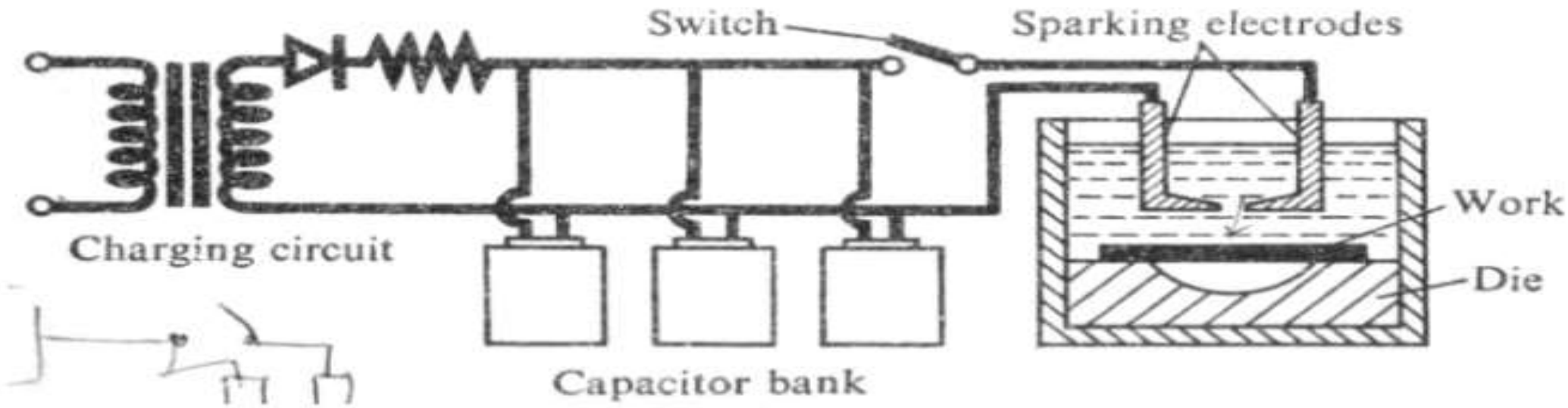


Fig. Electro Hydraulic Forming

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Working Principle of electro-hydraulic forming process

A sudden electrical discharge in the form of sparks is produced between electrodes and this discharge produces a shock wave in the water medium. This shock wave deforms the work plate and collapses it into the die.

The characteristics of this process are similar to those of explosive forming. The major difference, however, is that a chemical explosive is replaced by a capacitor bank, which stores the electrical energy. The capacitor is charged through a charging circuit. When the switch is closed, a spark is produced between electrodes and a shock wave or pressure pulse is created. The energy released is much lesser than that released in explosive forming.

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Process Characteristics:

i) Stand off distance: It must be optimum.

ii) Capacitor used: The energy of the pressure pulse depends on the size of capacitor.

iii) Transfer medium: Usually water is used.

iv) Vacuum: the die cavity must be evacuated to prevent adiabatic heating of the work due to a sudden compression of air.

v) Material properties with regard to the application of high rates of strain.

Advantages:

i) Better control of the pressure pulse as source of energy is electrical- which can be easily controlled.

ii) Safer in handling than the explosive materials.

iii) More suitable if the work size is small to medium.

iv) Thin plates can be formed with smaller amounts of energy.

v) The process does not depend on the electrical properties of the work material.

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Limitations:

i) Suitable only for smaller works

ii) Need for vacuum makes the equipment more complicated.

iii) Proper SOD is necessary for effective process.

Applications:

They include smaller radar dish, cone and other shapes in thinner and small works.

Electromagnetic forming

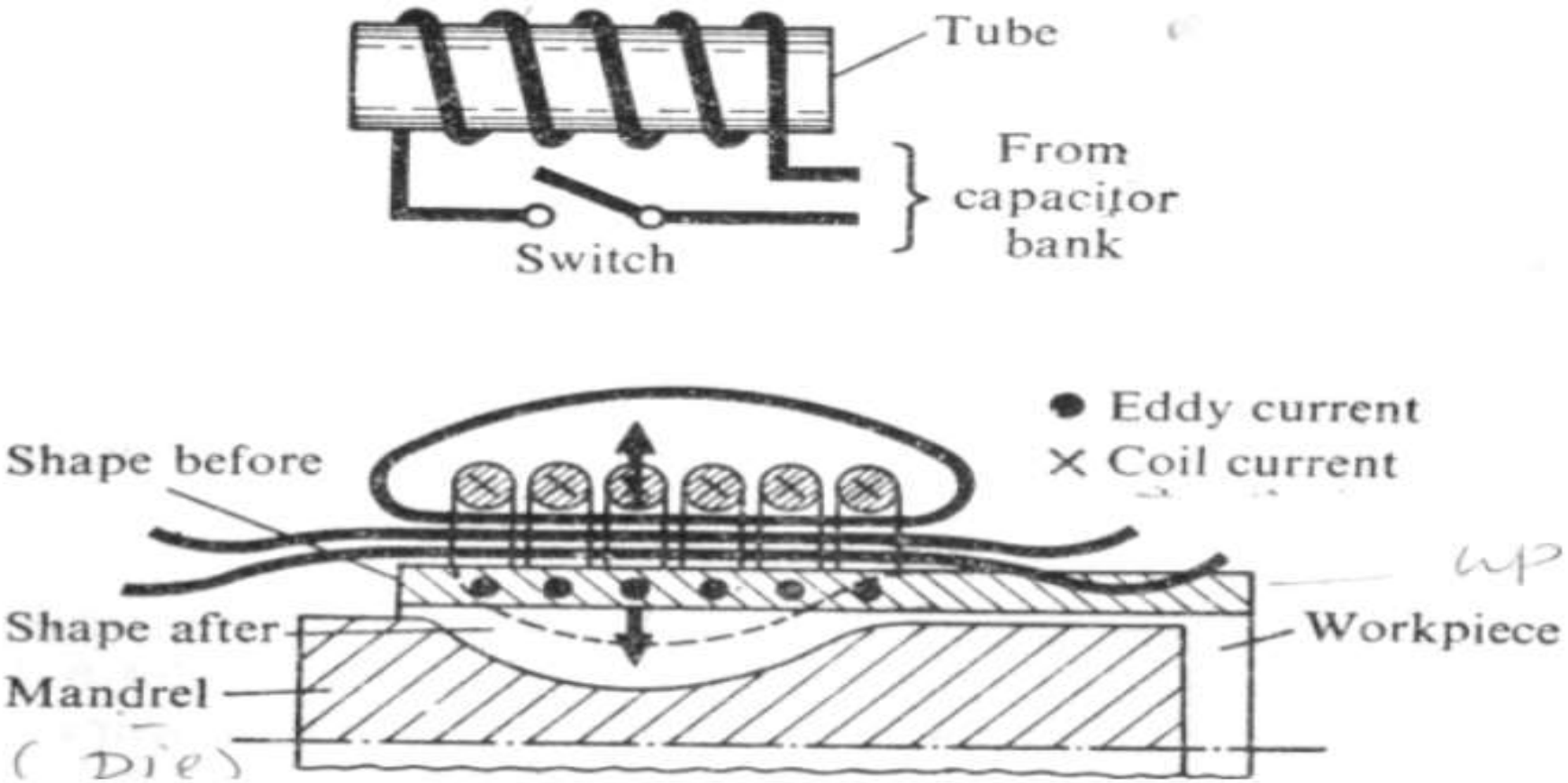


Fig. Electro Magnetic Forming

The electrical energy stored in a capacitor bank is used to produce opposing magnetic fields around a tubular work piece, surrounded by current carrying coils. The coil is firmly held and hence the work piece collapses into the die cavity due to magnetic repelling force, thus assuming die shape.

Process details/ Steps:

i) The electrical energy is stored in the capacitor bank

ii) The tubular work piece is mounted on a mandrel having the die cavity to produce shape on the tube.

iii) A primary coil is placed around the tube and mandrel assembly.

iv) When the switch is closed, the energy is discharged through the coil

v) The coil produces a varying magnetic field around it.

vi) In the tube a secondary current is induced, which creates its own magnetic field in the opposite direction. The directions of these two magnetic fields oppose one another and hence the rigidly held coil repels the work into the die cavity.

viii) The work tube collapses into the die, assuming its shape.

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Process parameters:

i) Work piece size

ii) Electrical conductivity of the work material.

iii) Size of the capacitor bank

iv) The strength of the current, which decides the strength of the magnetic field and the force applied.

v) Insulation on the coil.

vi) Rigidity of the coil.

Advantages:

i) Suitable for small tubes

ii)Operations like collapsing, bending and crimping can be easily done.

iii) Electrical energy applied can be precisely controlled and hence the process is accurately controlled.

iv) The process is safer compared to explosive forming.

v) Wide range of applications.

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Limitations:

i) Applicable only for electrically conducting materials.

ii) Not suitable for large work pieces.

iii) Rigid clamping of primary coil is critical.

iv) Shorter life of the coil due to large forces acting on it.

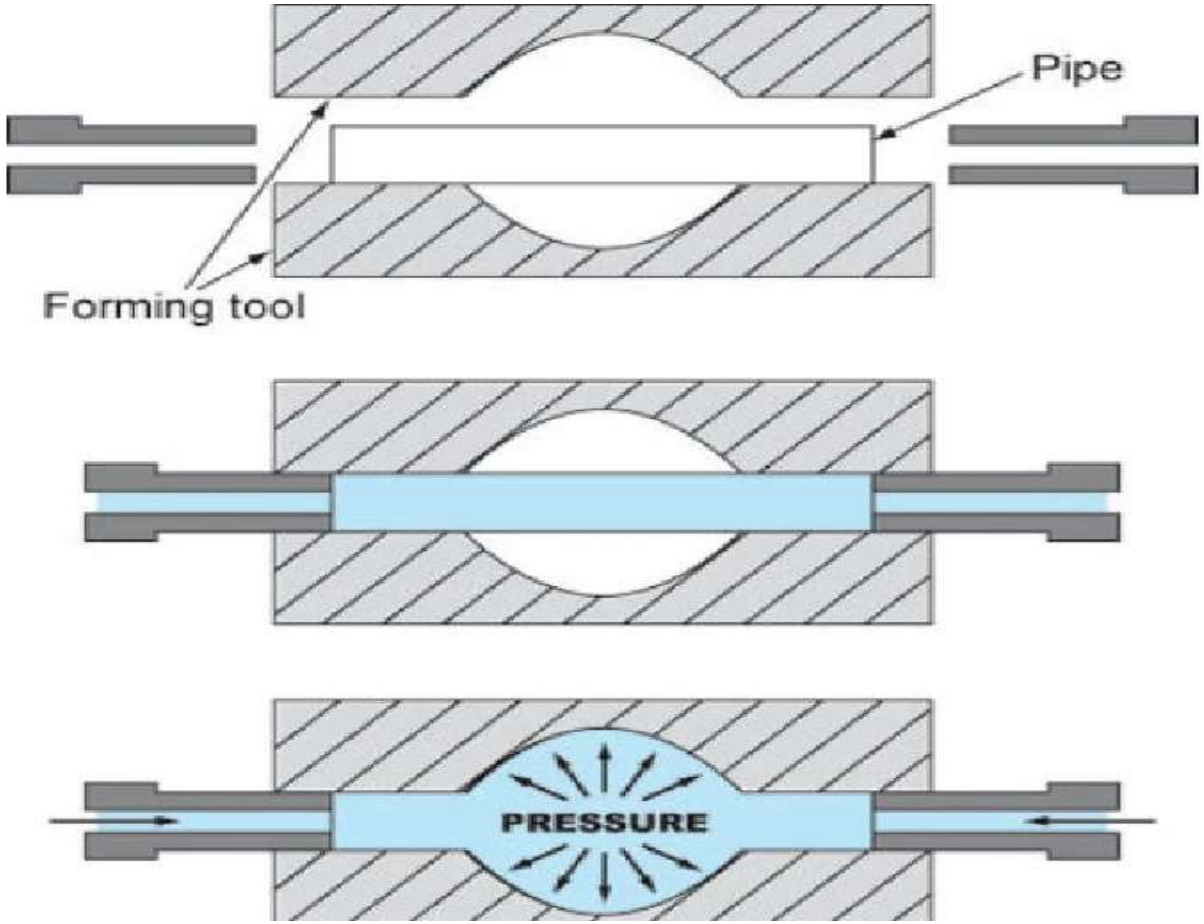
Applications:

i) Crimping of coils, tubes, wires

ii) Bending of tubes into complex shapes

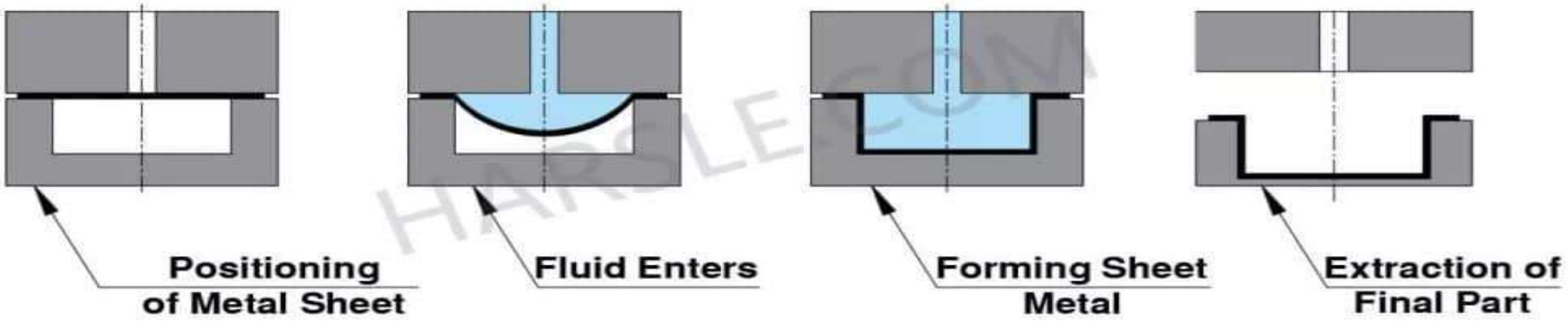
iii) Bulging of thin tubes.

High Velocity Hydroforming (Tube)



Sheet hydroforming (process steps)

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High-velocity hydroforming (HVH) is an advanced manufacturing technique that uses high-pressure fluid, often activated by shockwaves (e.g., electro-hydraulic forming), to shape metals at high speeds. It allows for forming, complex, lightweight, and high-strength parts—especially from aluminum and titanium—with improved material distribution, increased forming limits, and reduced springback compared to conventional methods.

Key Aspects of High-Velocity Hydroforming

Mechanisms: Techniques include electro-hydraulic forming (EHF), where a spark discharges between electrodes in a fluid, creating a shockwave that drives the material into a die.

Types:

1. Tube Hydroforming: Expands tubes into complex shapes.

2. Sheet Hydroforming: Forms sheets using fluid counter-pressure.

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Advantages:

High Precision & Quality: Produces parts with complex shapes, high strength, and tighter tolerances.

Material Efficiency: Enhanced, uniform material thickness, reducing scrap.

Production Speed: Rapid, high-speed forming suitable for high-volume production, with some techniques incorporating direct quenching.

Applications:

Widely used in the automotive and aerospace industries for structural components.

Techniques & Benefits

High-velocity techniques allow for improved formability and reduced material thinning, particularly beneficial for complex automotive components and aircraft parts. The process can be integrated with hot stamping to enhance productivity, allowing the material to be shaped within milliseconds before cooling.

Limitations

While advantageous, these techniques often require skilled personnel, specialized equipment, and incur higher initial costs.

Metal spinning

Metal spinning is a highly efficient, often computerized, cold-forming process used to shape metal discs or tubes into symmetrical, hollow, axisymmetric parts by rotating them at high speeds against a mandrel. It is widely used in aerospace, automotive, and lighting industries for creating durable, seamless components like cones and cylinders.

Key Aspects of Metal Spinning

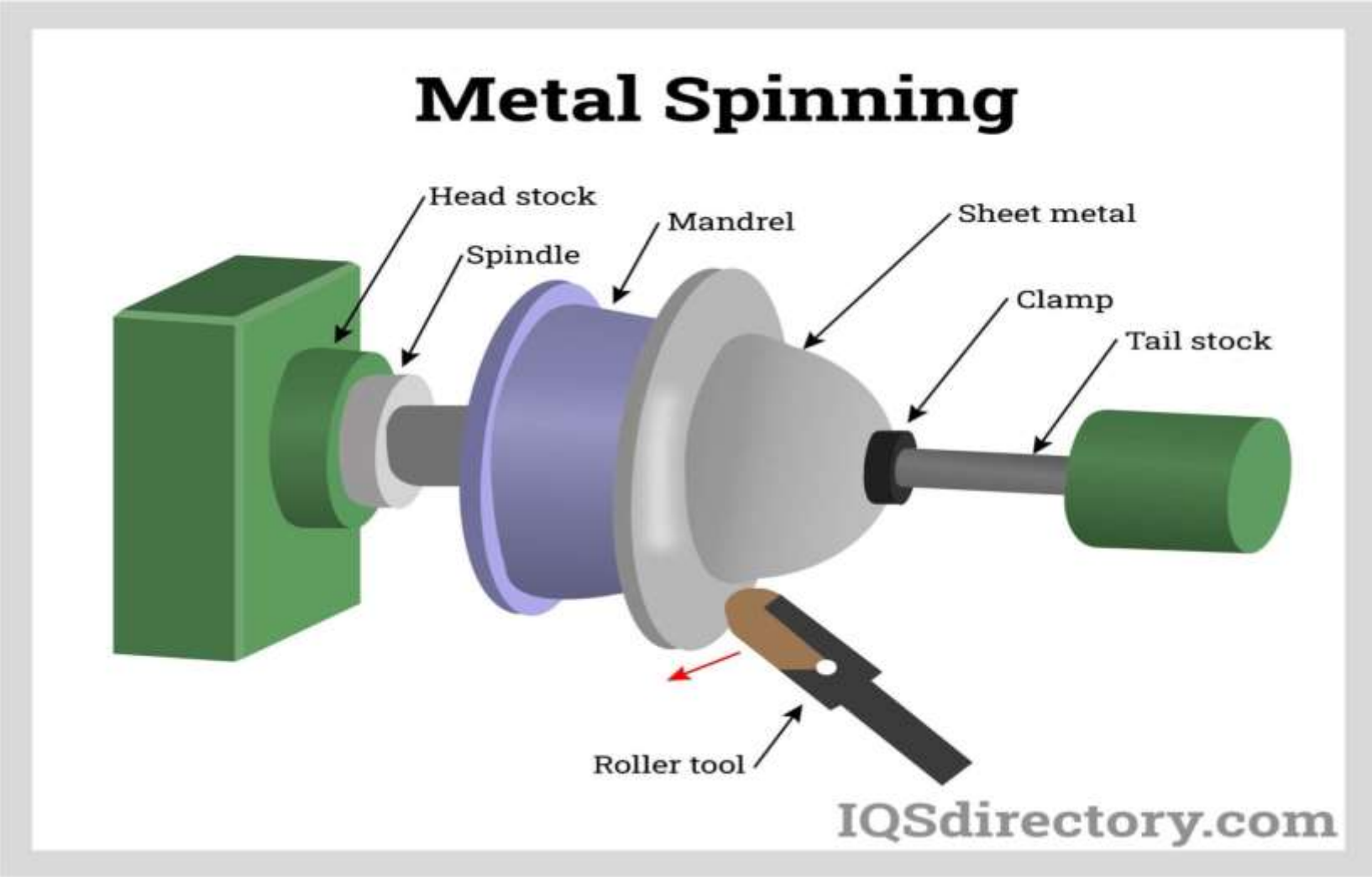
Process: A metal blank is clamped onto a rotating mandrel (or chuck) on a lathe. A roller tool, operated by hand or CNC, applies localized pressure to form the metal over the mandrel.

Types: The three main types are conventional spinning, shear spinning, and tube spinning, which can be performed hot or cold.

Materials: Virtually any ductile metal can be formed, including aluminum, stainless steel, and high-strength alloys.

Versatility: Capable of producing a variety of shapes, including hemispherical, conical, and parabolic forms.

Metal spinning



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Advantages:

Cost-Effective: Low tooling costs make it ideal for prototypes and small-to-large production runs. Material Strength: The process compresses the grain structure, increasing the tensile strength and toughness of the part.

Common Applications

Metal spinning is utilized in various industries for both functional and decorative, axially symmetric parts:

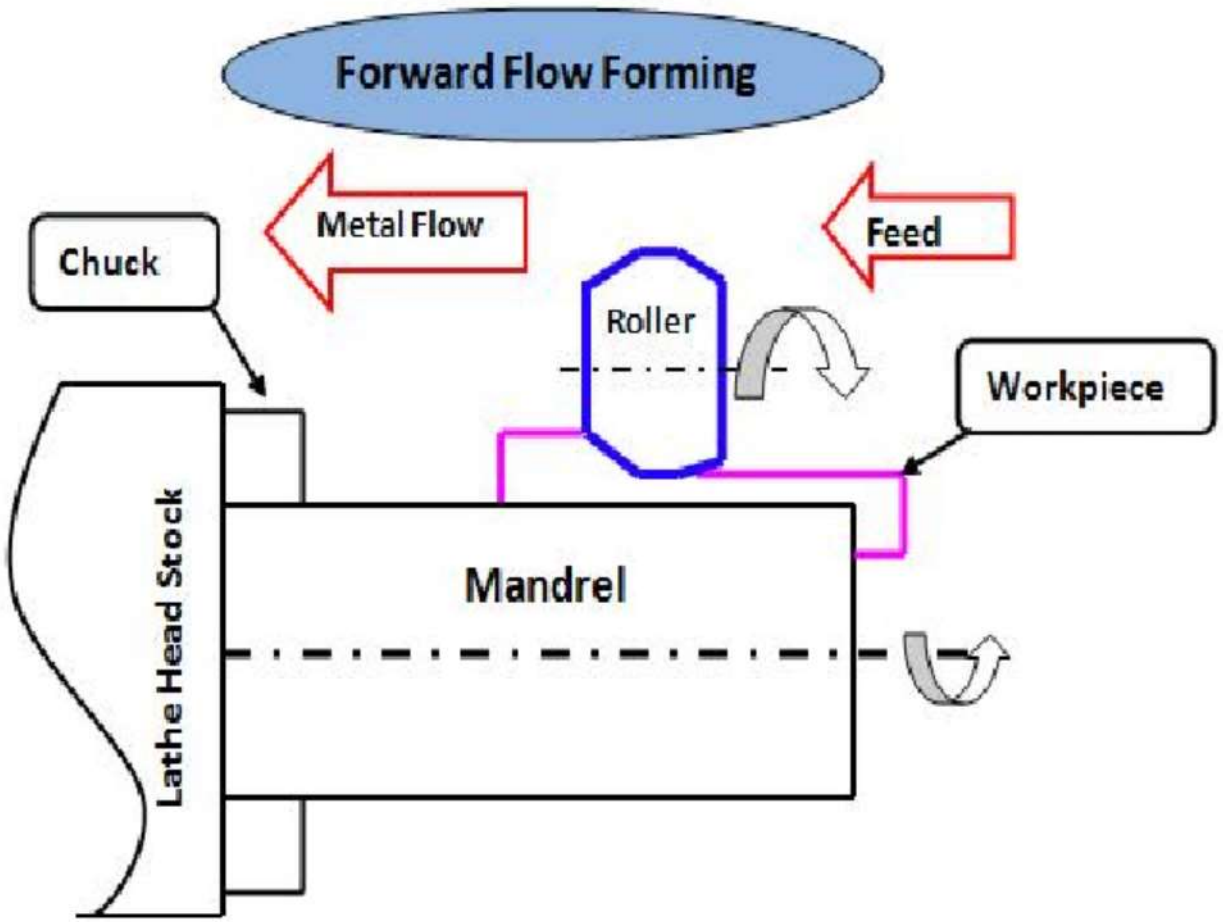
✓Aerospace: Nose cones, rocket components.

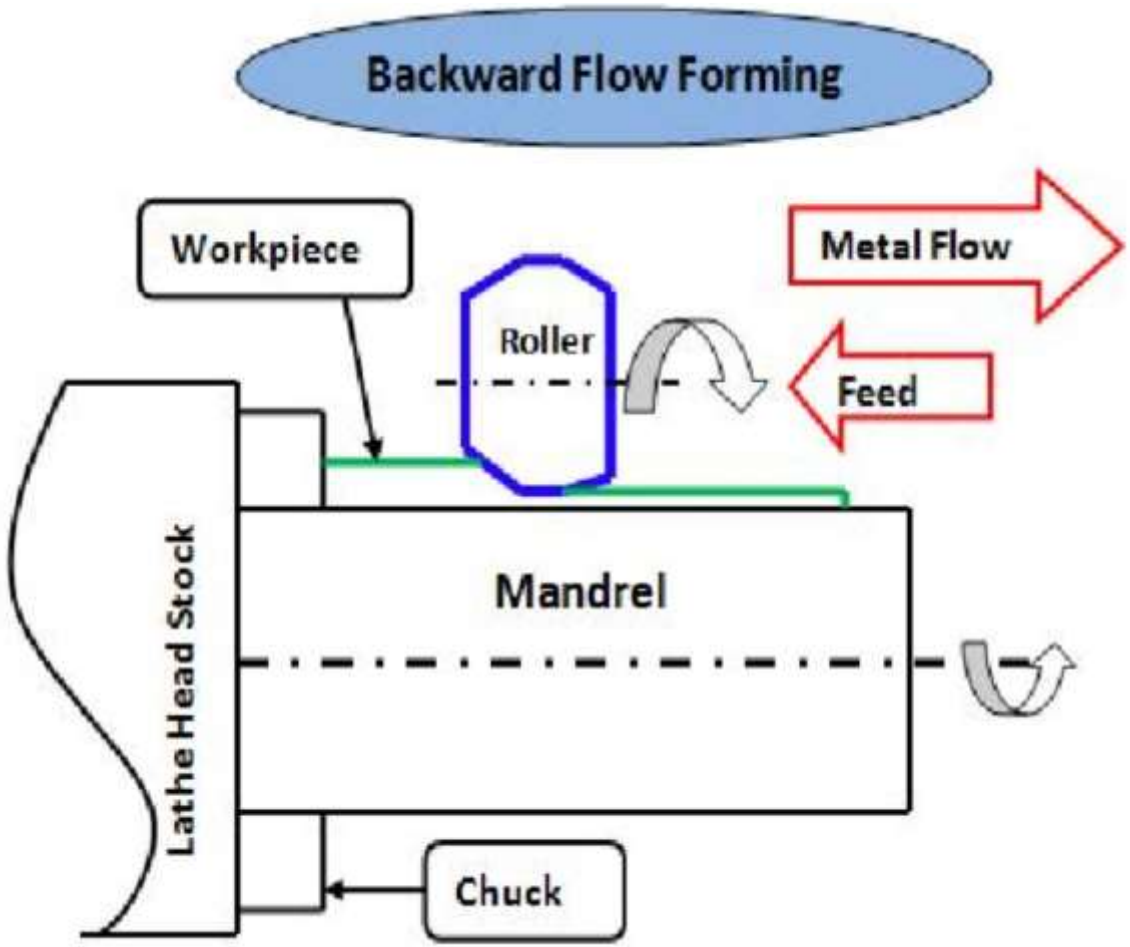
✓Lighting: Reflectors, fixtures.

✓Automotive: Wheels, housings.

✓Industrial/Commercial: Tanks, containers, roof ventilators.

The technique is often preferred for its ability to produce high-quality, lightweight components with little material waste.


Forward Flow Forming
Metal Flow
Feed
Chuck
Roller
Workpiece
Lathe Head Stock
Mandrel


Backward Flow Forming
Workpiece
Metal Flow
Roller
Feed
Lathe Head Stock
Mandrel
Chuck

Forward and Backward Tube Spinning

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- Forward tube spinning (flow forming) and backward tube spinning are chipless metal forming processes that reduce wall thickness and increase length by rotating a mandrel-mounted tube against forming rollers. Forward spinning moves material with the roller direction, often causing flaring. Backward spinning moves material opposite to roller direction, requiring no tube base.

Key Differences Between Forward and Backward Tube Spinning:

Material Flow Direction:

1. Forward Spinning: The material flows in the same direction as the rollers' axial movement.
2. Backward Spinning: The material flows opposite to the direction of the rollers.

Method of Holding the Blank:

1. Forward Spinning: The blank is usually clamped at one end (e.g., with a mandrel and tailstock), suitable for preforms with a base.
2. Backward Spinning: The blank is pushed onto the mandrel and held against the headstock, allowing for open-ended, thin-walled components.

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Application and Advantages:

1. Forward Spinning: Commonly used to produce long, thin-walled precision components like rocket motor cases and pressure vessels.
2. Backward Spinning: Often used when the starting tube has no pre-formed base and for high-precision, thin-walled cylindrical parts.

Key Parameters:

1. **Thickness Reduction:** Higher reduction increases axial length.
2. **Mandrel Type:** Can be performed over an external mandrel, allowing for precise control of internal diameter.
3. **Roller Configuration:** Often uses three or more rollers, spaced equidistantly around the tube for balanced loading.

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Incremental Sheet Metal Forming (ISF)

ISF is a die-less manufacturing process that shapes metal sheets into 3D forms using a CNC-controlled, hemispherical tool, skipping the need for traditional dies. Ideal for prototyping and small-batch production, this method provides high flexibility, low tooling costs, and can produce complex, customized geometries.

Key Aspects of Incremental Sheet Forming:

Process Types: The two main types are Single-Point Incremental Forming (SPIF), which uses only a tool and a backing plate, and Two-Point Incremental Forming (TPIF), which uses a partial or full die for better accuracy.

Key Advantages: High customization, low set-up costs, ability to create complex shapes, and quick design changes.

Disadvantages: Slow processing speeds compared to conventional stamping, lower accuracy, and potential for high tool wear.

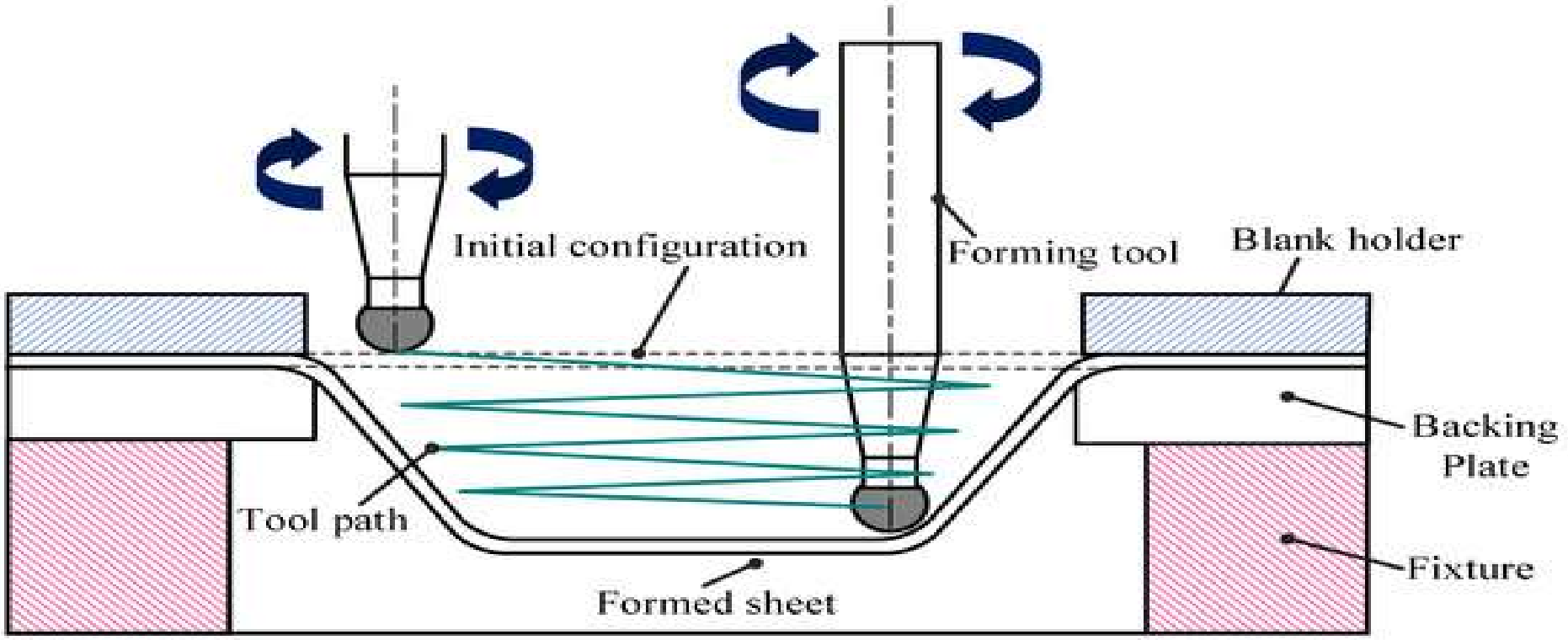


Fig. Schematic diagram of the incremental forming process.

Applications: Commonly used in aerospace for complex, lightweight structures, as well as in the automotive and medical industries for rapid prototyping.

Materials: Suitable for forming various metals, often used with aluminum, steel, and advanced alloys.

Commonly Used Tools:

Hemispherical tools/dapping tools (e.g., 12mm tools) Titanium ball bearings

Robotic systems (often used for modern, AI-driven applications)

This method is rapidly growing due to the demand for customized, complex, and small-batch metal parts, allowing for "design for manufacture" strategies without the expense of traditional dies

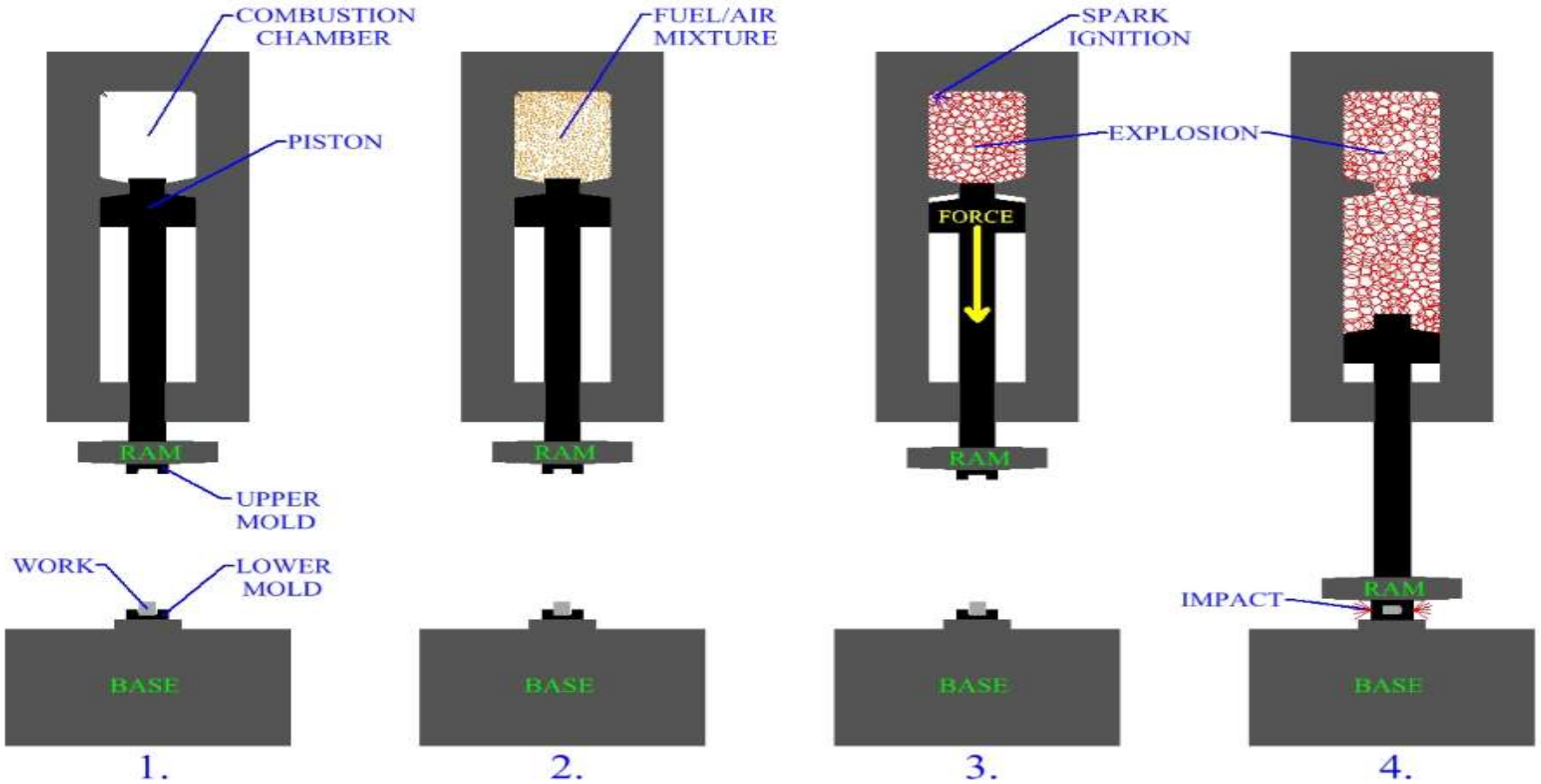
Petro forge forming

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High energy rate forging, is a metal forging process in which the actual forging of the work occurs in a few thousandths of a second. This type of manufacturing technique is very useful for hard to forge metals. As discussed in isothermal forging, there may be reasons that the cooling of a part during the process may create problems. Such as, mechanical properties of some metals can vary considerably over a short temperature range, some metals are difficult to form at lower temperatures, or parts may have thin, complex sections. Isothermal forging was developed specifically to deal with the problems associated with cooling of the metal at the work-die interface. High energy rate forging also solves that same problem, but by a different method. Since the part is forged so fast, there is no time for cooling to occur during the forging of the work. With high energy rate forging, hard to forge materials, and thin, complicated parts can be forged with a single stroke.

Figure.207

HIGH ENERGY RATE FORGING



A petro forge is a machine designed to perform high energy rate forging operations. The petro forge bears some similarities to the engine in a car, in that it does employ an internal combustion chamber for its working energy. The upper die of the mold is attached to the ram, that is a part of a piston that is located under a combustion chamber.

Basically, the combustion chamber is filled with a fuel-air mixture. The mixture is then ignited by a spark plug, creating an explosion in the chamber. This explosion forces the piston, ram, and upper die downward with tremendous power. The upper apparatus accelerates towards the work, striking it with a great velocity, forging the part in a few milliseconds. Back pressure is then used to raise the apparatus, returning it to its position, this also occurs rapidly.

During industrial manufacture, forging die can strike the work at velocities of 750 feet per second. The power and velocity employed during this process raises many concerns with regard to safety.

Laser bending

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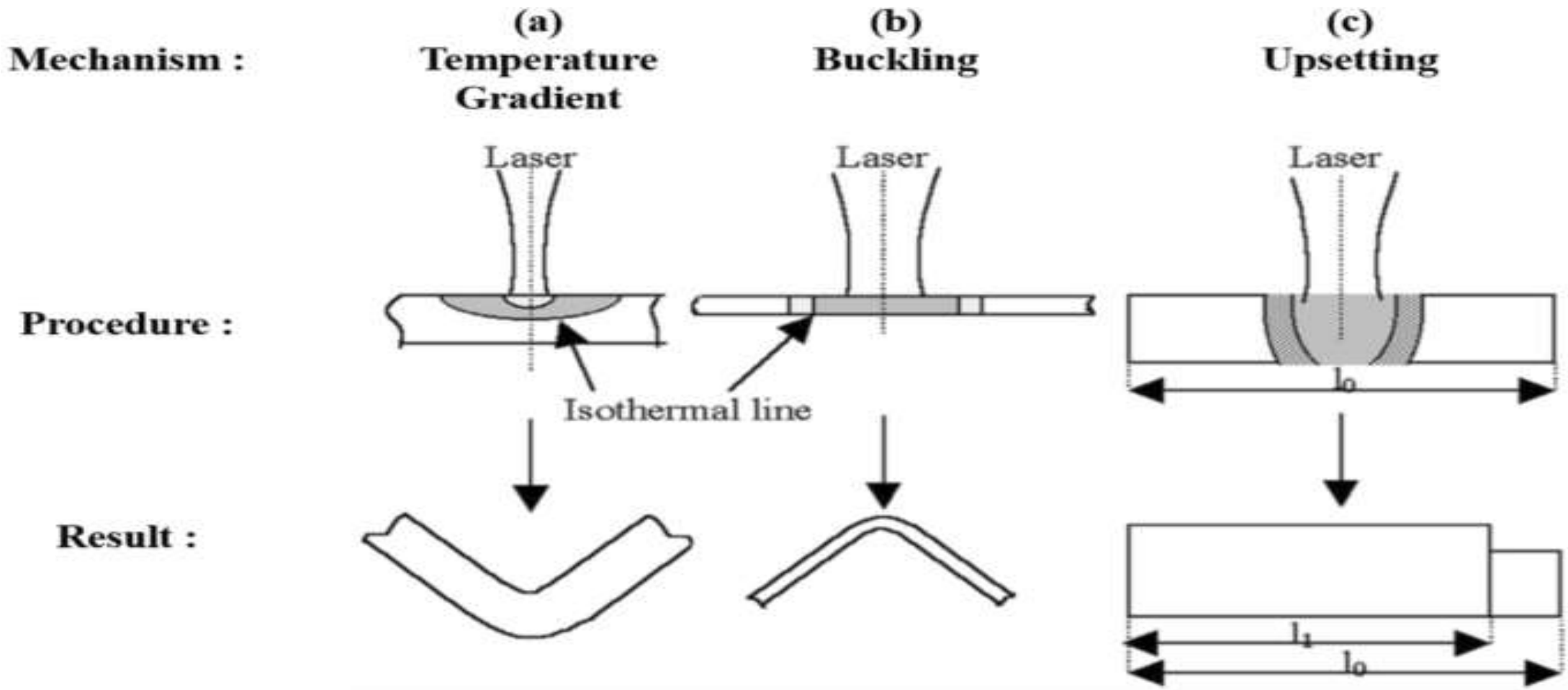
Laser bending, or laser forming, is a non-contact manufacturing process that shapes metal sheets, tubes, and foils by inducing thermal stresses with a laser beam rather than mechanical force. It eliminates spring-back, allowing high-precision, automated shaping, particularly for brittle or complex 3D parts. Key mechanisms include temperature gradients and buckling.

Key Aspects of Laser Bending:

1. Mechanisms: Primarily uses the Temperature Gradient Mechanism (TGM), where rapid surface heating creates compressive stress, causing the material to bend toward the laser beam upon cooling.

Laser bending

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2. Advantages:

No Spring-back: Because it is a thermal process, it lacks the elastic recovery (spring-back) associated with mechanical bending.

No Tooling: No dies or punches are required, making it ideal for rapid prototyping and small batches.

Precision & Complexity: Highly controllable, suitable for complex 3D shapes and micro-parts.

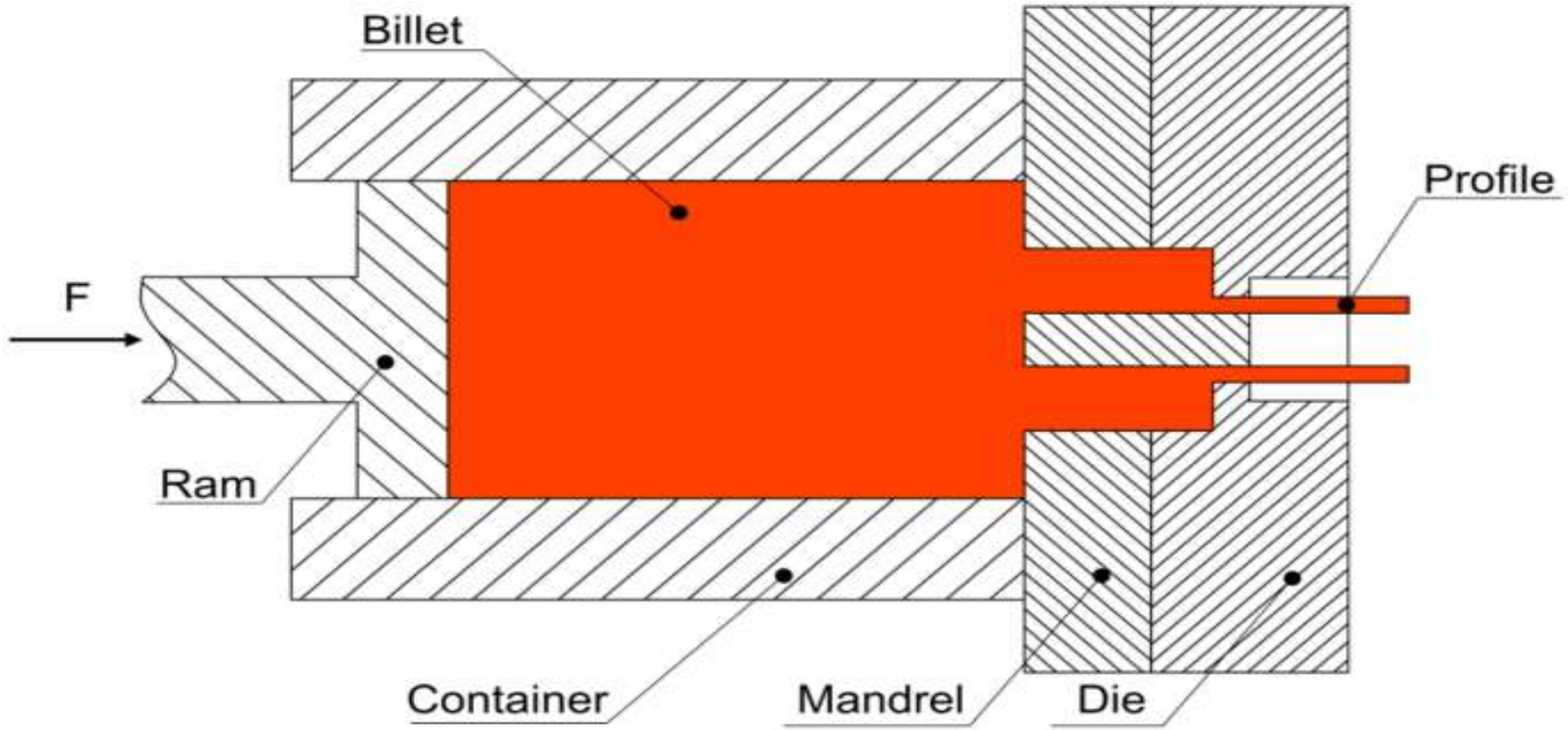
3. **Process Parameters**: The bending angle depends on laser power, scanning speed, beam diameter, material properties, and the number of passes.

Applications: Commonly used in automotive, shipbuilding, and microelectronics for adjusting components, prototyping, and creating V-shapes, domes, or tubes.

4. Limitations: Slower than conventional mechanical bending and requires specialized knowledge of material behavior under heat.

Micro extrusion

Micro-extrusion is a precision manufacturing process that produces components with submillimeter features, where at least one dimension fits within a square. It operates as a micro-forming technique for metals or specialized plastics to create complex, high-accuracy parts, often used in medical, electronics, and aerospace industries to achieve superior surface quality and dimensional control.



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Key Aspects of Micro-Extrusion:

1. Process Characteristics: It involves pressing materials (like copper or polymers) through a micro-die, offering high production efficiency, material savings, and near-net-shape components.

2. Aplications: Used for creating medical devices (micro-catheters), electronic components, micro-surgical instruments, and aerospace parts.

3. **Material Capabilities**: Common materials include aluminum alloys, copper, and polymers such as PEEK, Nylon, and Polycarbonate.

4. Advantages: Provides excellent dimensional accuracy, improved mechanical properties, and high-quality, lightweight components.

5. Challenges: The process is highly affected by the "size effect," where lower ram speeds and careful control of grain size in the material are required to avoid defects in the microscopic structure.

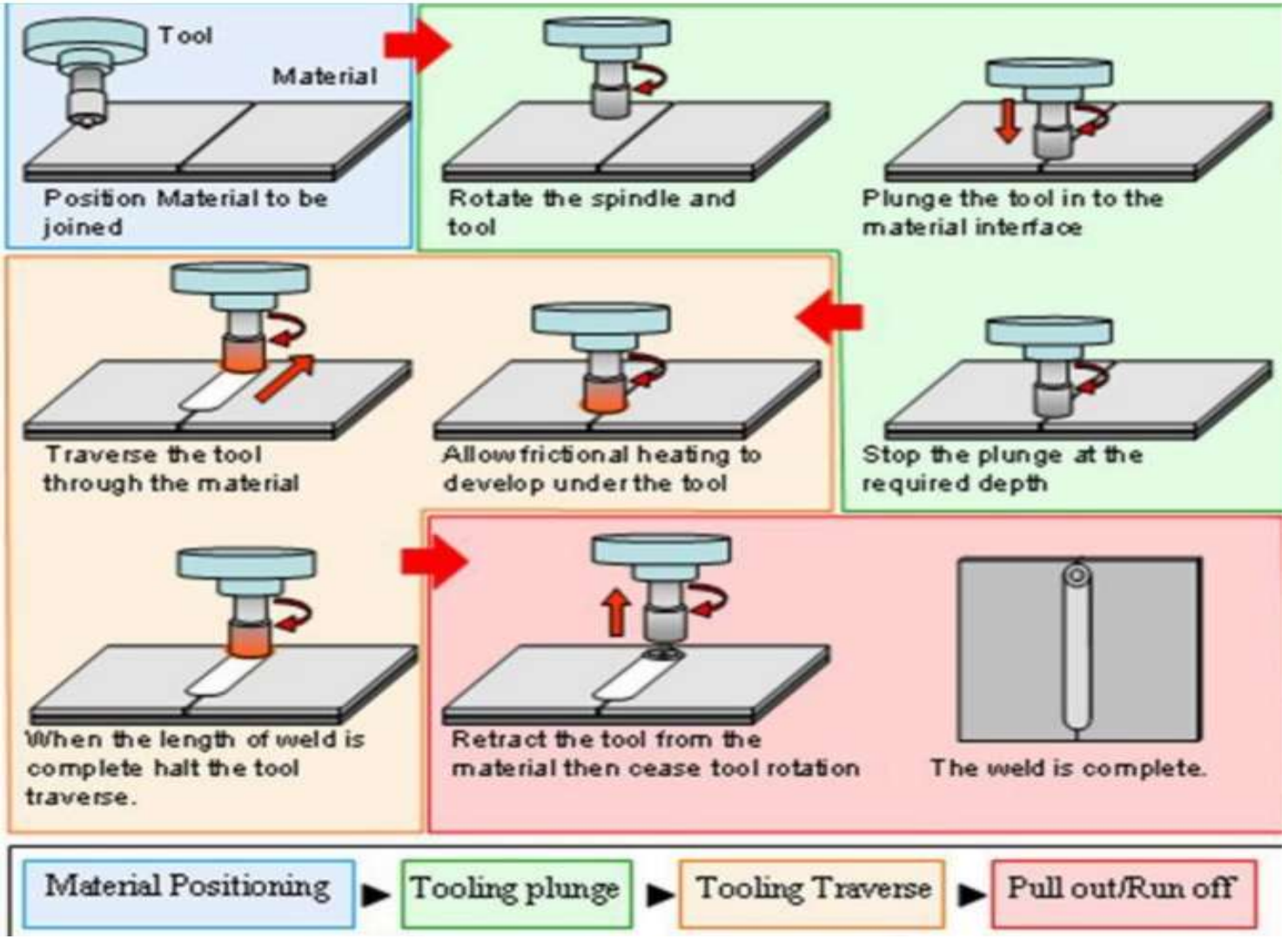
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Unit 2

Unit II
Advanced Joining Processes

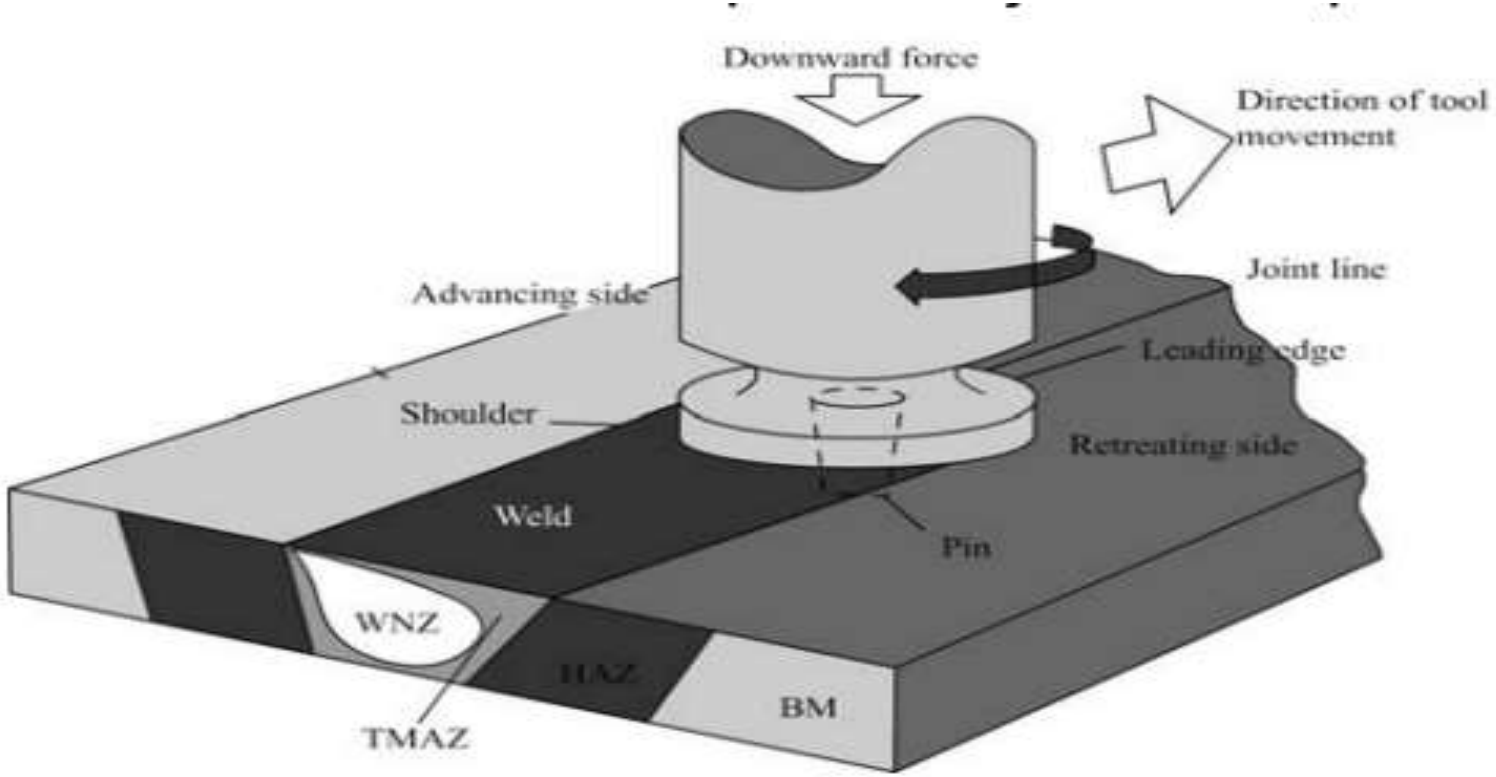
Friction Stir Welding process steps

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Friction stir welding

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The friction stir welding is a comparatively new solid state joining process developed by the Welding Institute U.K. in 1991. This process is based on the simple principle of thermal softening of metal followed by sever plastic deformation to develop a weld joint. The thermal softening is facilitated by heat generation from two sources a) friction between tool and base metal and b) plastic deformation. The development of weld joints is facilitated by transport of metal from one side to another followed by consolidation by forging action To ensure proper performance of tool, its material must be strong and heat and wear resistant. The typical solid state joining feature of this process lowers undesirable effects of common fusion weld thermal cycle. This process is common applied for developing butt joints. The friction stirwelding has been applied in many ways for producing other weld configuration like T joints and Lap joints. Friction stir spot welding is one of the typical variant of friction stir welding used for producing lap joints. The strength of friction stir spot weld jointsis found comparable or even better than spot weld joints in lap weld configuration.

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Advantages

1. Superior Joint Quality: Because it is a solid-state process (no melting), it eliminates defects like porosity and solidification cracks.
2. Minimal Distortion: Lower heat input results in reduced warping and shrinkage compared to traditional welding.
3. Versatility: Capable of joining complex alloys (e.g., 2xxx and 7xxx aluminum series) and dissimilar metals (e.g., aluminum to steel).
4. Environmental & Cost-Effective: No filler materials, shielding gas, or flux required. The process generates no fumes or smoke.
5. Automation-Friendly: Easily automated, yielding high repeatability and requiring less operator skill.

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Limitations

1. High Initial Cost: Machinery and specialized tooling are expensive.
2. Exit Hole/Tool Removal: Leaving a hole when the tool is withdrawn is a significant drawback, often requiring a "runoff" tab or specialized techniques.
3. High Clamping Forces: Requires robust clamping and heavy-duty jigs to hold parts in place against the high traversing forces.
4. Speed & Geometry: Generally slower than conventional arc welding, and it is limited in creating complex, multi-axis or non-linear joints.

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Key Applications by Industry:

1. Aerospace: Widely utilized for manufacturing spacecraft components, satellite launch vehicle fuel tanks, rocket fairings, and structural airframe components.
2. Automotive: Crucial for producing lightweight components to improve fuel efficiency, including electric vehicle (EV) battery enclosures, chassis components, fuel tanks, wheel rims, and engine cradles.

1. Marine & Shipbuilding: Used to join large aluminum panels for ship decks, hull sections, and offshore platforms requiring high corrosion resistance.

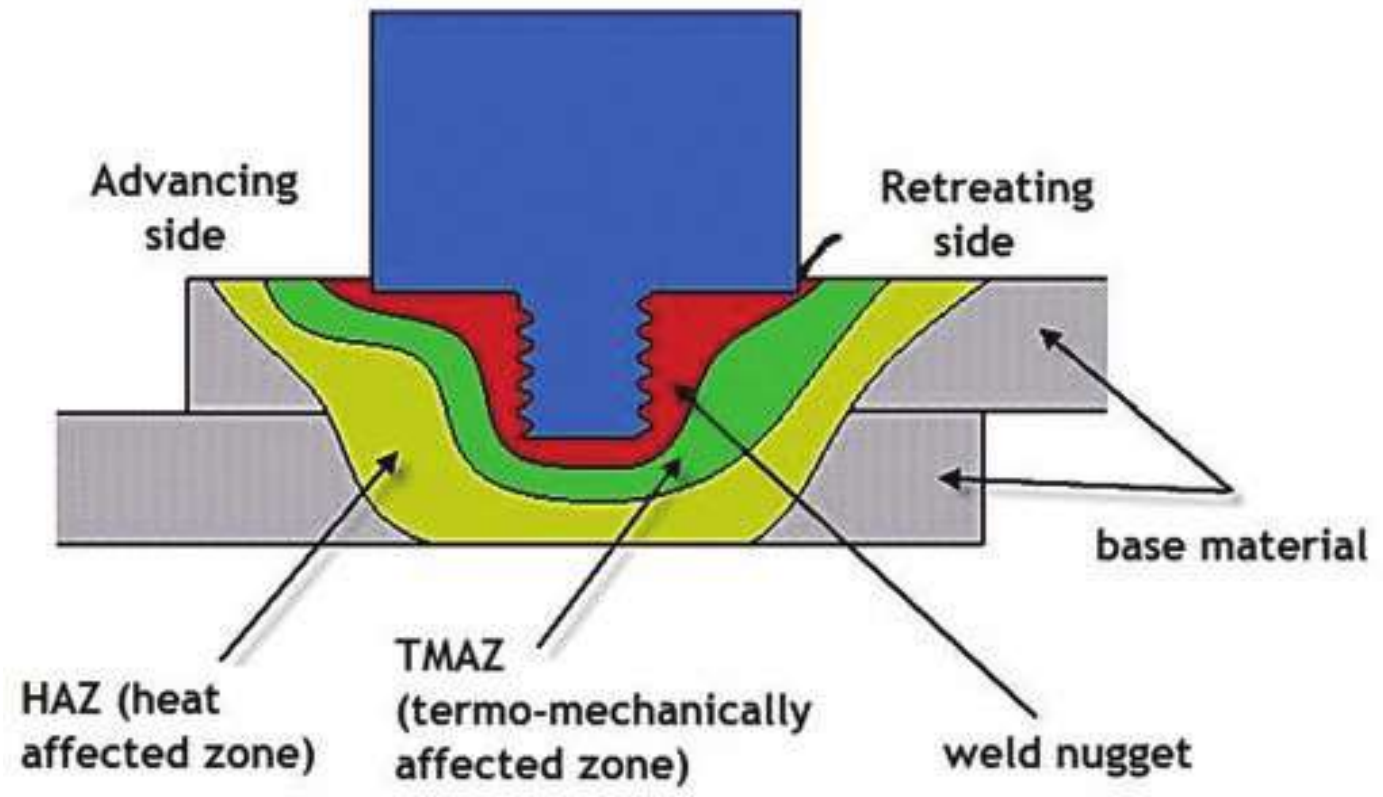
1. Railway & Transportation: Employed in fabricating high-speed train bodies, railway carriages, and freight wagons, often using long aluminum extrusions.
2. Electronics & Manufacturing: Used for heat sinks, cooling plates, and power electronics housings due to its ability to create leak-tight, structurally sound joints

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Main Advantages in Applications:

1. Dissimilar Materials: Capable of joining incompatible alloys (e.g., aluminum to steel).
2. Quality: Produces high-strength, pore-free, and crack-free welds.
3. Efficiency: Environmentally friendly, energy-efficient, and easily automated.

The Heat Affected Zone (HAZ) in friction stir welding (FSW) is a distinct region subjected to a thermal cycle but no plastic deformation, often forming the weakest point in the weld due to grain coarsening or precipitate dissolution. Situated between the base material and the Thermomechanically Affected Zone (TMAZ), it shows lower hardness, typically forming a "W"-shaped hardness profile across the weld.



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Key Aspects of HAZ in FSW:

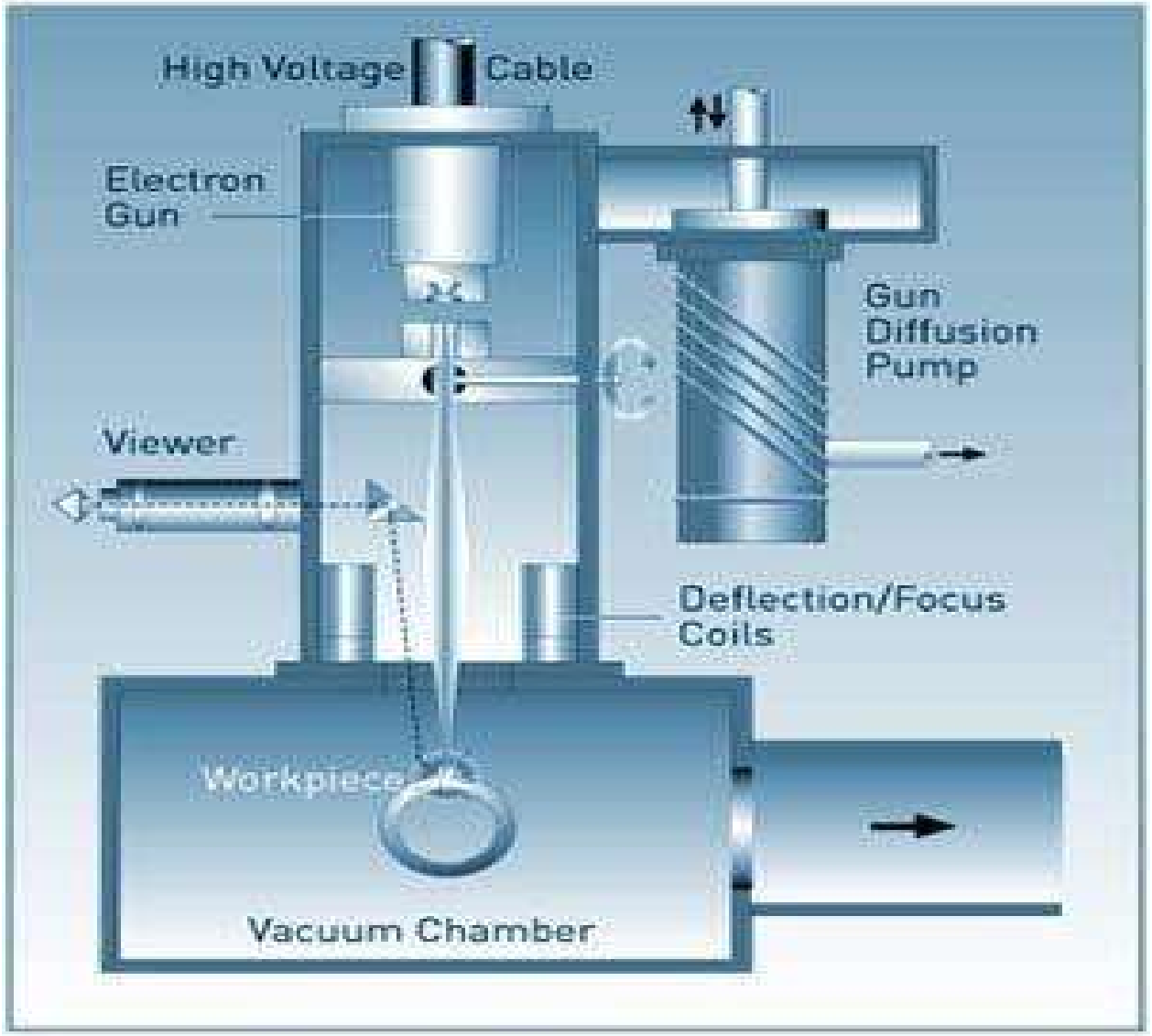
1. **Structure:** The HAZ is located outside the thermomechanically affected zone (TMAZ) and experiences thermal cycles without plastic deformation.
2. **Microstructural Changes:** In heat-treatable alloys (e.g., AA6061-T6), the heat causes coarsening or dissolution of strengthening precipitates, often creating a weak, low-hardness zone.
3. **Characteristics:** Compared to fusion welding, FSW produces a much narrower HAZ, which significantly reduces distortion and improves structural integrity.
4. **Heat Input Impact:** High heat input during FSW increases the grain size within the heat-affected area and decreases overall strength, while lower heat input limits these effects.

Residual Stresses: Residual stress profiles across the FSW joint, including the HAZ, often display an M-shape, with stress levels dependent on welding parameters like tool rotation and translation speed.

The HAZ is typically the region of lowest hardness and tensile strength in FSW aluminum joints. Optimized welding parameters (rotational speed and welding speed) are crucial to minimize HAZ degradation and avoid defects like tunnel holes.

Electron Beam Welding

Electron beam welding (EBW) is a high-precision fusion process using a focused beam of high-velocity electrons in a vacuum to produce deep, narrow, and clean welds with minimal distortion. Advantages include joining dissimilar and refractory metals, high welding speeds, and no filler metal required. Main limitations are high capital cost, vacuum chamber size restrictions, and strict safety requirements.



Electron Beam Welding

Key Aspects of Electron Beam Welding

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1. Vacuum Requirement: Usually conducted within a vacuum chamber to prevent the electron beam from scattering, which improves weld quality and prevents contamination.
2. Mechanism: An electron gun generates, accelerates, and focuses electrons (via magnetic fields) onto the workpiece, turning kinetic energy into heat.
3. Precision and Quality: The process is highly automated and computer-controlled, ensuring high repeatability and deep penetration with minimal heat-affected zones.
4. Applications: Commonly used in aerospace, automotive, medical, and defense industries for components requiring extreme accuracy and structural integrity.
5. Materials: Suitable for welding a wide range of metals, including stainless steel, titanium, aluminum, copper, and refractory metals.

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Key Advantages of Electron Beam Welding

1. High Precision and Quality: Minimal Heat Affected Zone (HAZ) leads to exceptionally low distortion and shrinkage, ideal for finished or delicate parts.
2. Deep Penetration: Capable of welding thick materials in a single pass, typically with a high depth-to-width ratio (up to 40:1).
3. Vacuum Environment: Performing the weld in a vacuum eliminates contamination, preventing oxides and nitrides, which is crucial for welding metals like titanium, zirconium, and columbium.
4. Dissimilar Metal Joining: Capable of joining metals with different thermal properties.
5. High Speed and Efficiency: Generally faster and more energy-efficient than traditional welding methods, with minimal need for filler materials.

Limitations of Electron Beam Welding

1. High Initial Investment: Equipment is very expensive to purchase, install, and maintain.
2. Size Constraints: Components must fit inside a vacuum chamber, limiting the size of workpieces.
3. Set-up Time & Skilled Operation: Requires skilled operators for high-level vacuum technology and programming; not suitable for quick, on-site repairs.
4. Safety Hazards: The process generates X-rays, necessitating specialized shielding and safety measures.
5. Joint Preparation: Requires precise edge preparation for fitting parts together.

Laser Beam Welding

Laser beam welding (LBW) is a high-precision fusion welding process that uses a concentrated, coherent light beam to join metals or thermoplastics. It offers rapid welding speeds, narrow, deep welds with low thermal distortion, and can be automated, making it ideal for electronics, automotive, and medical manufacturing.

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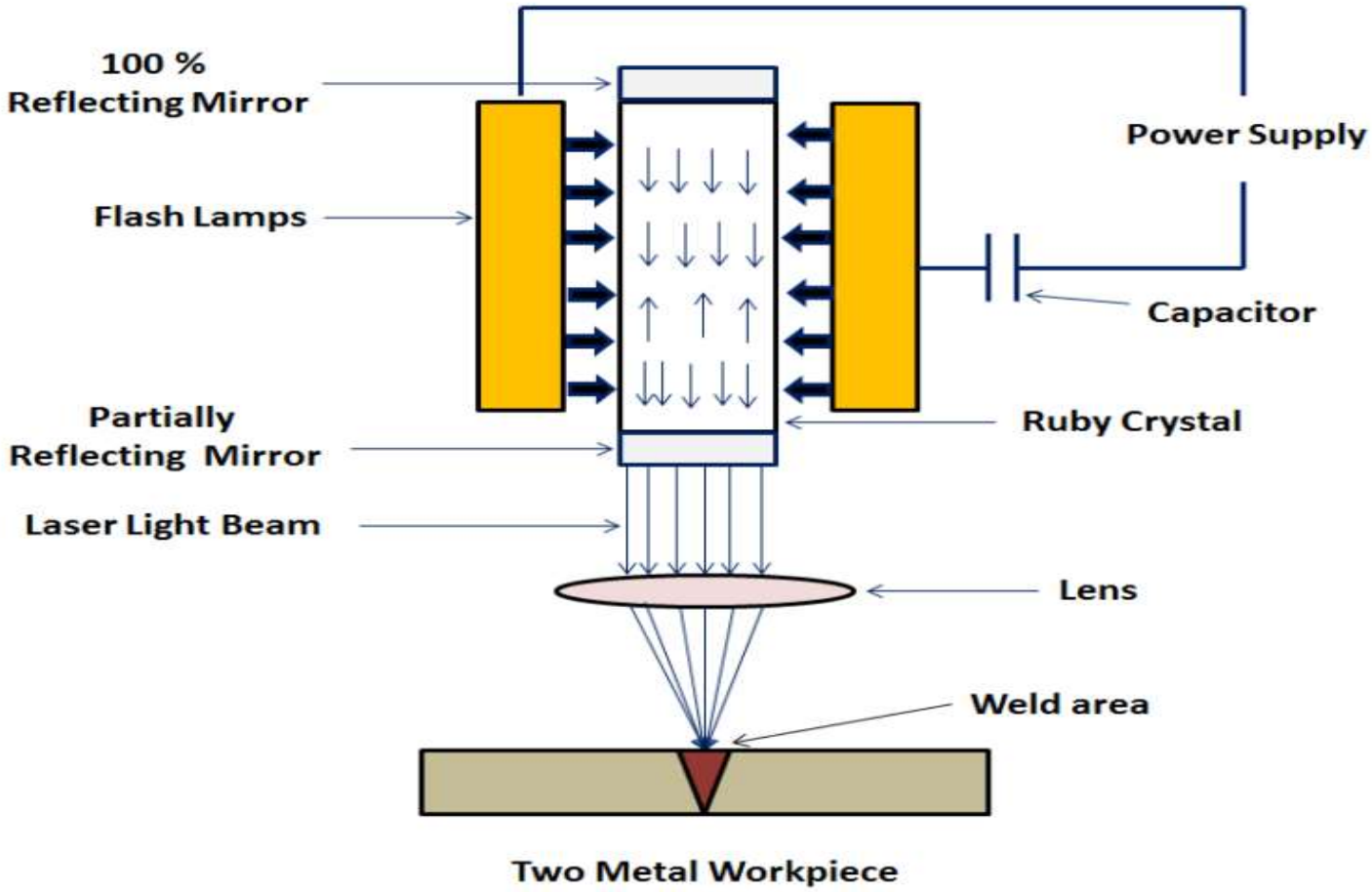
Key Aspects of Laser Beam Welding:

Mechanism: A laser beam, often from fiber or CO_2 lasers, melts the edges of the workpiece, creating a weld through high-power density.

Modes of Welding:

a. Keyhole Welding: At very high power densities the laser penetrates the material, creating a vapor-filled keyhole that produces narrow, deep welds.

b. Conduction Welding: At lower power (below 500W). it is used for shallow, aesthetic, and smooth welds.



Laser Beam Welding

Key Advantages:

Low heat-affected zone (HAZ) prevents deformation of sensitive parts, and it can operate without filler materials.

Applications:

Commonly used in the automotive industry (components, batteries), medical devices (implants, tools), and electronics, say EB Industries and Laserline.

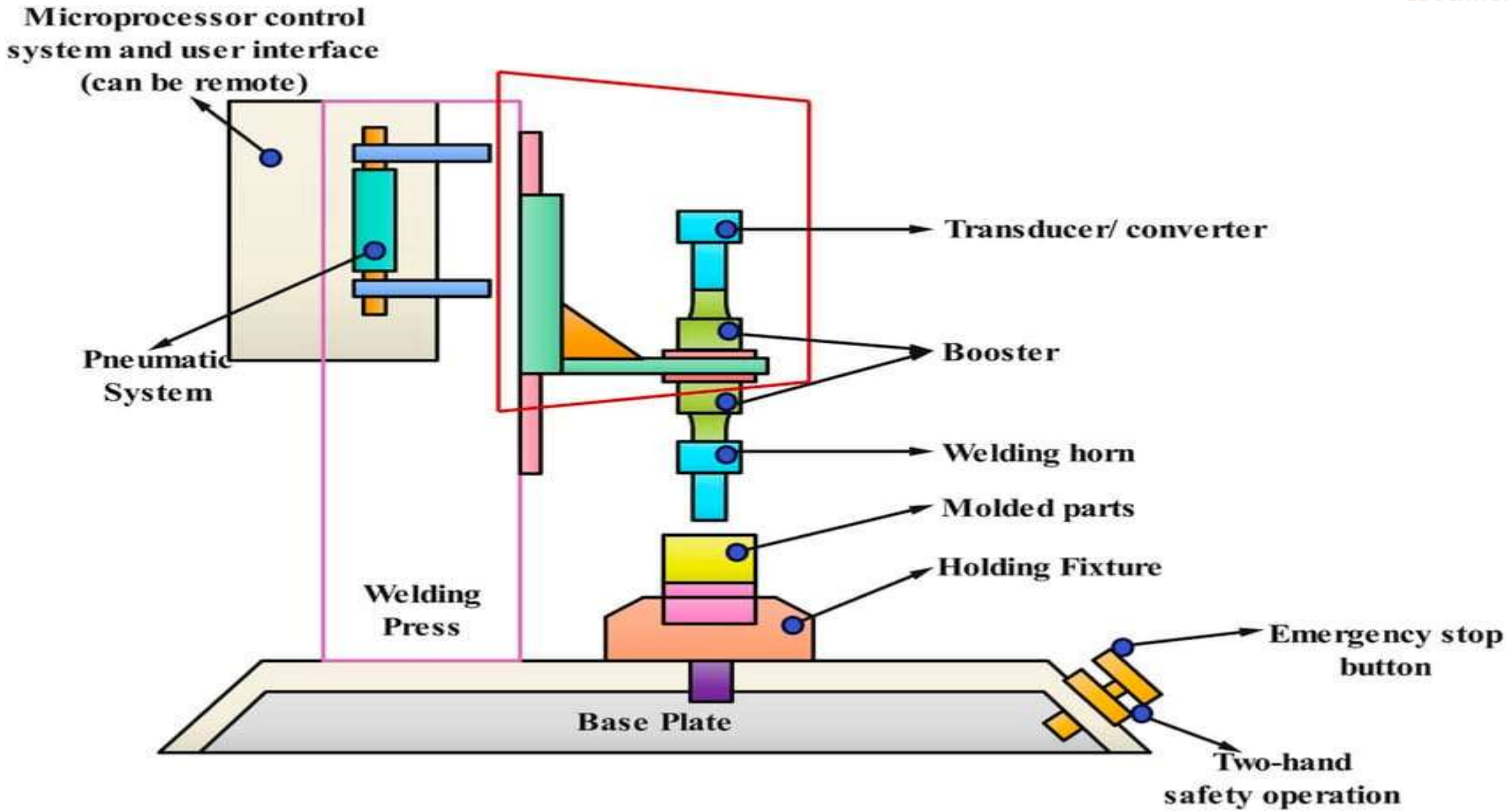
Limitations:

High initial equipment costs, limited penetration (up to ~20 mm, but generally less), and high joint precision requirements.

Common Laser Types:

1. Solid-state lasers: Nd:YAG or fiber lasers, often used for metal joining.
2. CO_2 lasers: Commonly used for higher power applications.
3. Diode lasers: Suitable for plastics or lower-power applications

Ultrasonic welding



Ultrasonic Welding

Ultrasonic welding is a fast, clean industrial process that joins materials (plastics or metals) by applying high-frequency ultrasonic vibrations (under pressure. A converter transforms electrical energy into mechanical vibrations, which a horn transmits to the parts, causing friction and localized heat at the joint interface, creating a solid-state weld without melting the entire material.

Ultrasonic welding is a fast, industrial joining technique that uses high-frequency ultrasonic acoustic vibrations (typically 20–40 kHz) to create solid-state welds. It fuses materials—primarily thermoplastics and soft metals like aluminum or copper—under pressure without melting the base material, completing joints in under a second.

Key Aspects of Ultrasonic Welding:

1. Process: A transducer converts electrical energy into mechanical vibrations, which are amplified by a booster and delivered by a horn (sonotrode) to the workpiece. The high-frequency movement creates frictional heat at the joint interface.

1. Applications: Commonly used in automotive (battery foils), electronics, medical devices (catheters, filters), and packaging.

1. Materials: Ideal for thermoplastics, but also used for joining thin, soft metals and dissimilar materials.

1. Advantages: Clean, fast, energy-efficient, and does not require adhesives, screws, or solvents.

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Typical Steps in Ultrasonic Welding:

1. Placement: Parts are secured in a fixture (anvil).
2. Contact: A horn contacts the upper workpiece, applying pressure.
3. Vibration: The horn vibrates vertically at high frequency, usually for less than one second.
4. Cooling: The pressure is maintained briefly to allow the part to solidify.
5. Release: The horn retracts, leaving a finished, strong joint.

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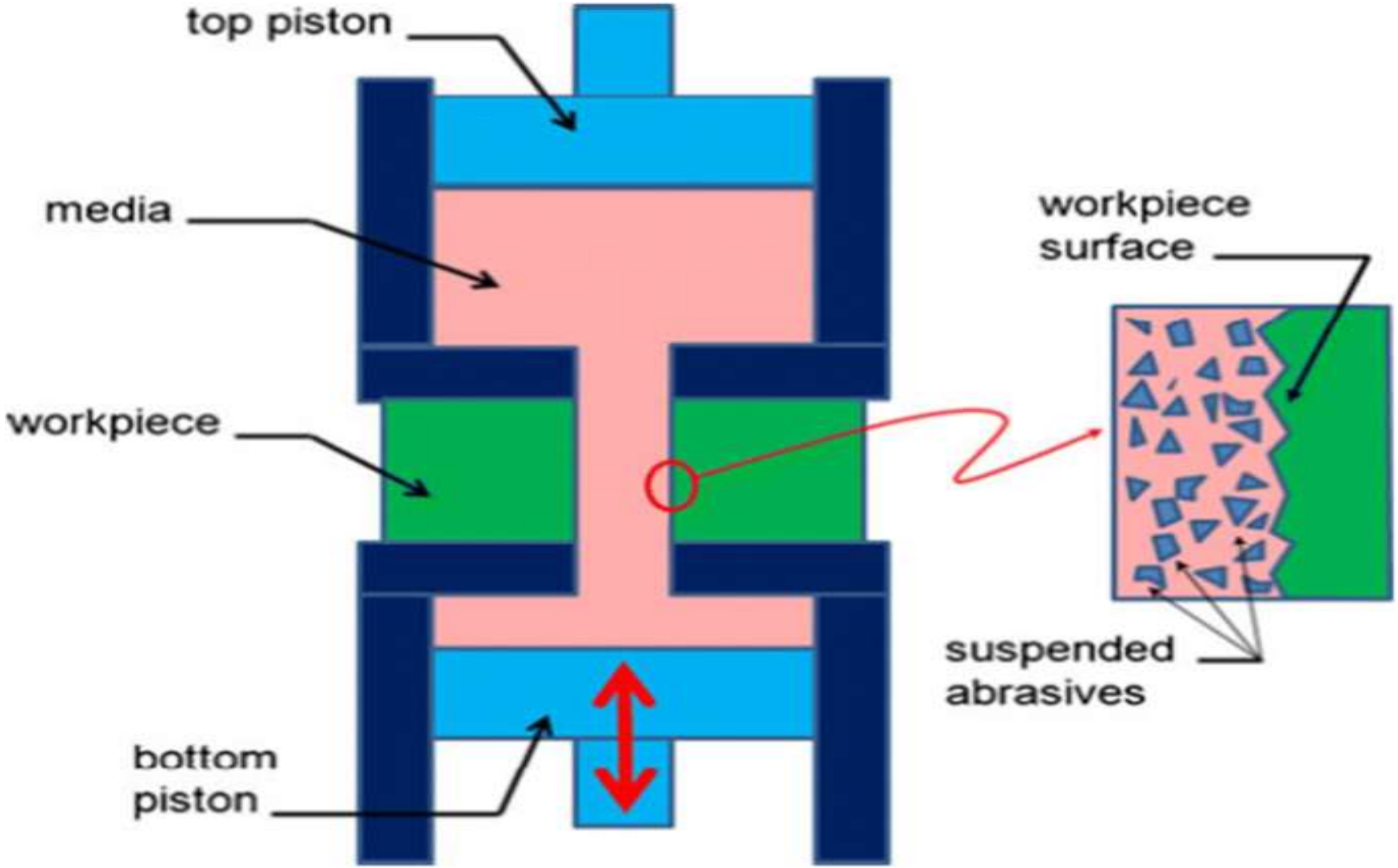
Unit 3

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Unit III
Hybrid Non-conventional Machining Techniques

Abrasive flow finishing

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Abrasive Flow Finishing (AFF), or abrasive flow machining (AFM), is a non-conventional, precision process that uses a viscous, abrasive-laden, putty-like medium to polish, deburr, and radius complex internal surfaces. It is ideal for hard-to-reach areas, improving surface finish to under by forcing the medium through or around the workpiece.

Key Aspects of Abrasive Flow Finishing:

Process Principle: A viscoelastic carrier filled with abrasive particles (e.g., silicon carbide, diamond) is extruded back and forth through a workpiece held in a fixture.

Applications: Widely used in aerospace, medical implants, automotive (fuel injectors), and die-casting industries for finishing, deburring, and polishing complex, intricate passages.

Key Parameters: Performance is controlled by media viscosity, extrusion pressure, number of cycles, and abrasive grit size.

Hybrid Methods: Modern techniques include Magnetorheological Abrasive Flow Finishing (MRAFF), which uses magnetic fields to control the media's stiffness and improve efficiency on harder materials.

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Key Advantages:

1. Precision: Achieves superior surface finish and high geometric accuracy, often reducing surface roughness ( ) by 75–90%.
2. Complex Geometries: Effectively finishes surfaces that are impossible to reach by conventional methods.
3. Uniformity: Produces uniform, repeatable results across multiple surfaces simultaneously.
4. Material Versatility: Suitable for finishing ceramics, plastics, and various metals.

Key Limitations:

1. Lower Material Removal Rate: Generally inefficient for heavy bulk material removal.
2. Cost: The viscoelastic abrasive media is expensive.
3. Setup Complexity: Requires specialized fixture and tooling for each unique component.

applications of Abrasive Flow Finishing:

1. Aerospace: Polishes turbine blades and fuel nozzles to improve airflow and combustion efficiency.
2. Automotive: Smooths intake manifolds and fuel injectors to optimize engine performance and reduce emissions.
3. Medical: Finishes delicate heart stents and surgical tools to ensure ultra-smooth, biocompatible surfaces.
4. Dies & Molds: Provides a mirror-like finish to complex internal cavities in extrusion and injection molds.
5. Additive Manufacturing: Removes surface roughness and "stair-stepping" from 3D-printed metal parts and internal channels.

Magnetic Abrasive Finishing (MAF):

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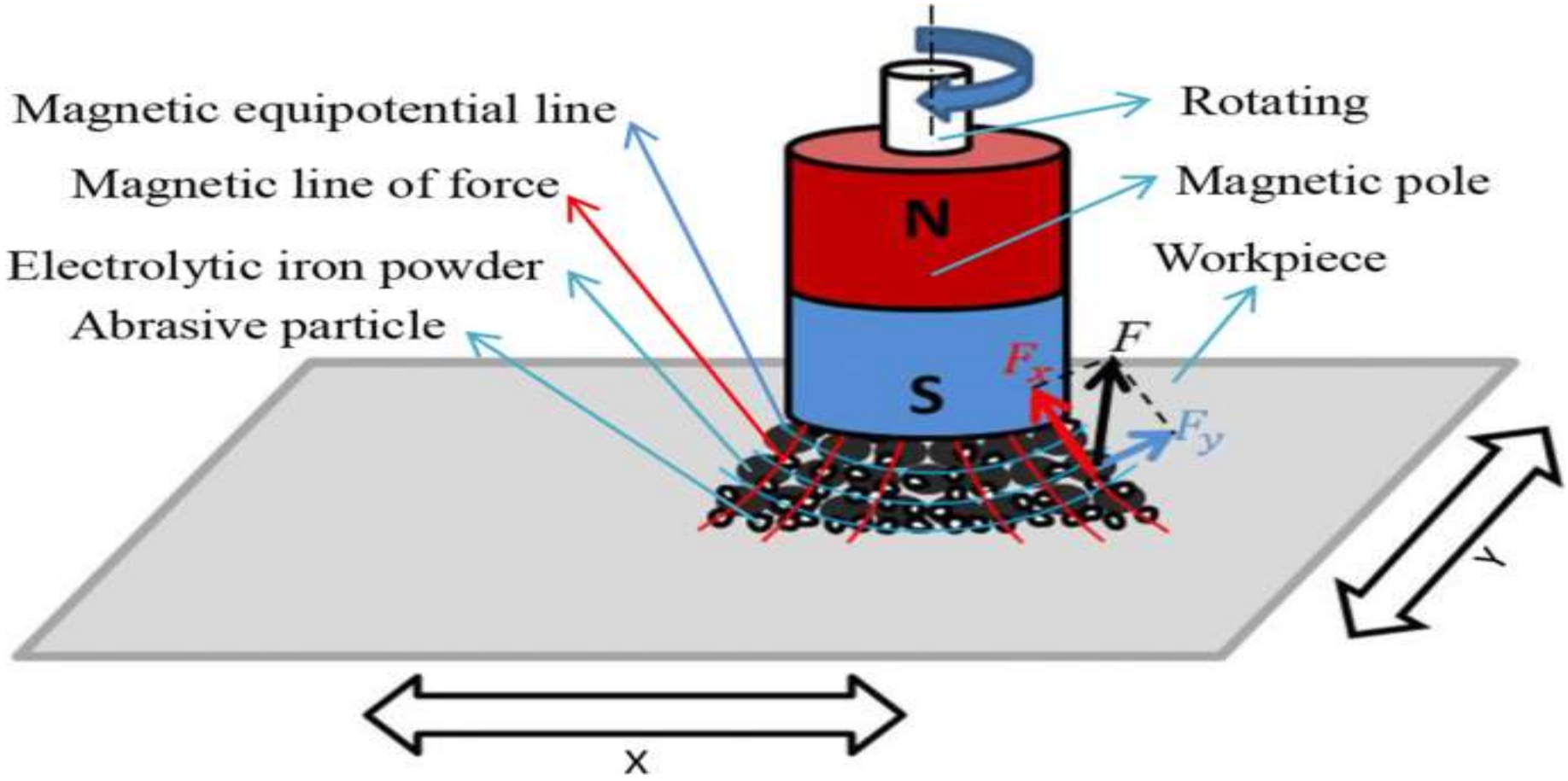
Key points

- **Magnetic Force:** It uses a magnetic field to manipulate a mixture of magnetic particles and abrasive grains to finish a surface.
- **Flexible Brush:** The magnetic field forms a "flexible abrasive brush" that conforms perfectly to the shape of the workpiece.
- **Nano-Precision:** It is capable of achieving extremely high surface quality, reaching nanometer-level smoothness with minimal heat.
- **Applications:** Commonly used for polishing medical implants, optical lenses, and high-precision semiconductor components.
- **Efficiency:** It offers a fast, non-contact finishing method that prevents surface damage or stress on delicate parts.

Magnetic Abrasive Finishing (MAF):

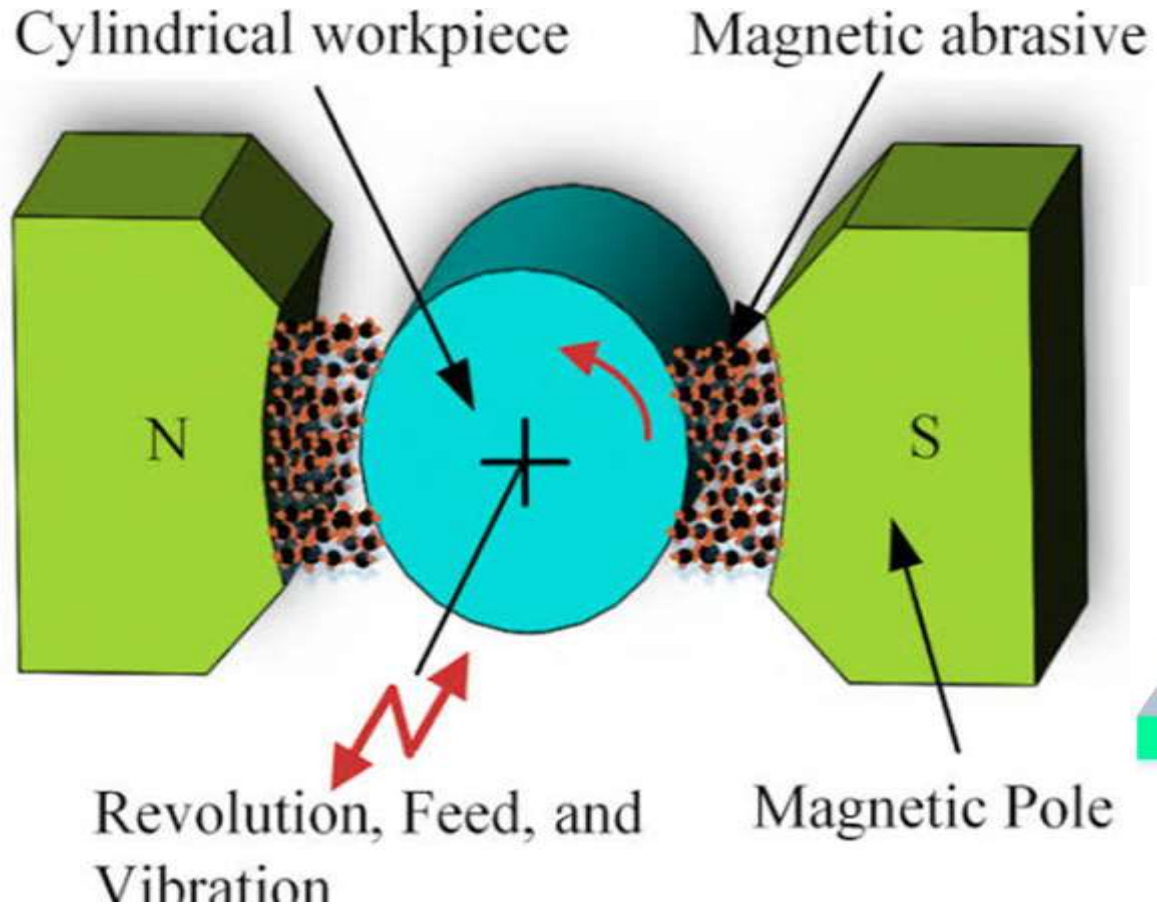
Magnetic Abrasive Flow Finishing (MAFF) is an advanced, non-conventional finishing process that uses a magnetic field to control a specialized abrasive medium, creating a flexible "brush" to polish internal and complex surfaces. This hybrid technique enhances surface roughness (reducing it to nanometer levels) and removes material from hard-to-reach areas, commonly used in automotive, aerospace, and medical device manufacturing.

MAFF

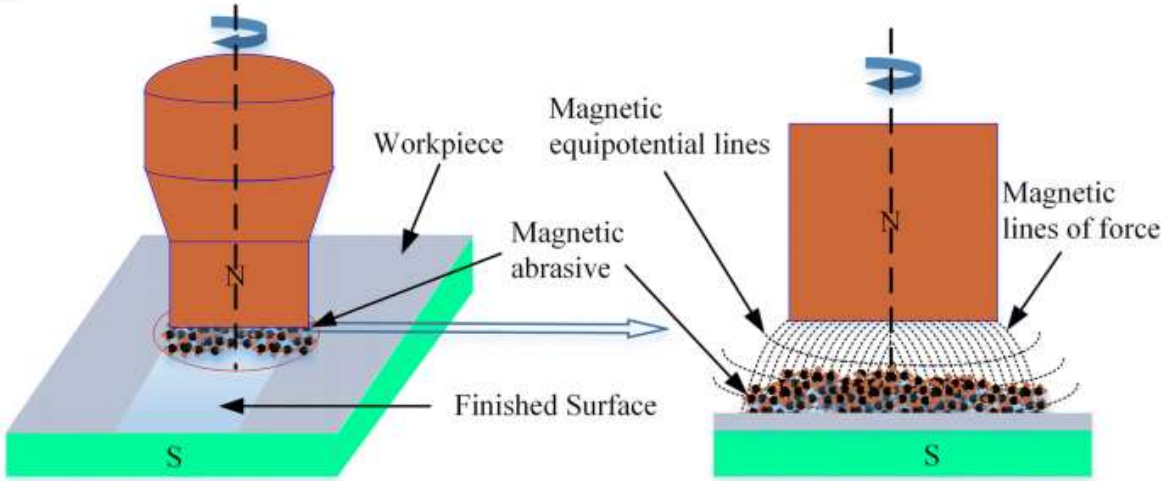


Magnetic Abrasive Finishing (MAF):

Magnetic Abrasive Finishing (MAF):



For Cylindrical workpiece



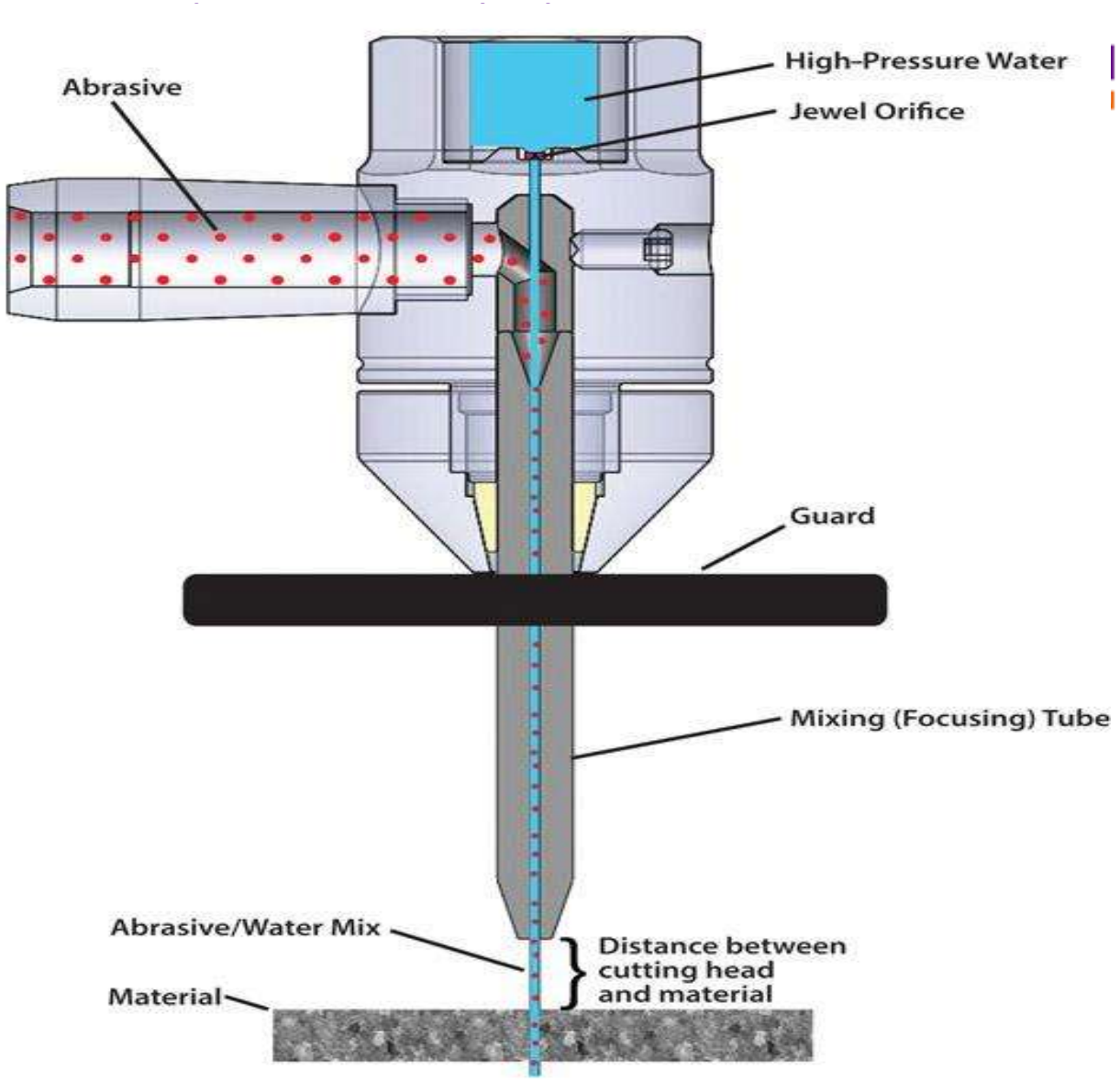
For Flat workpiece

MAFF vs. Other Techniques:

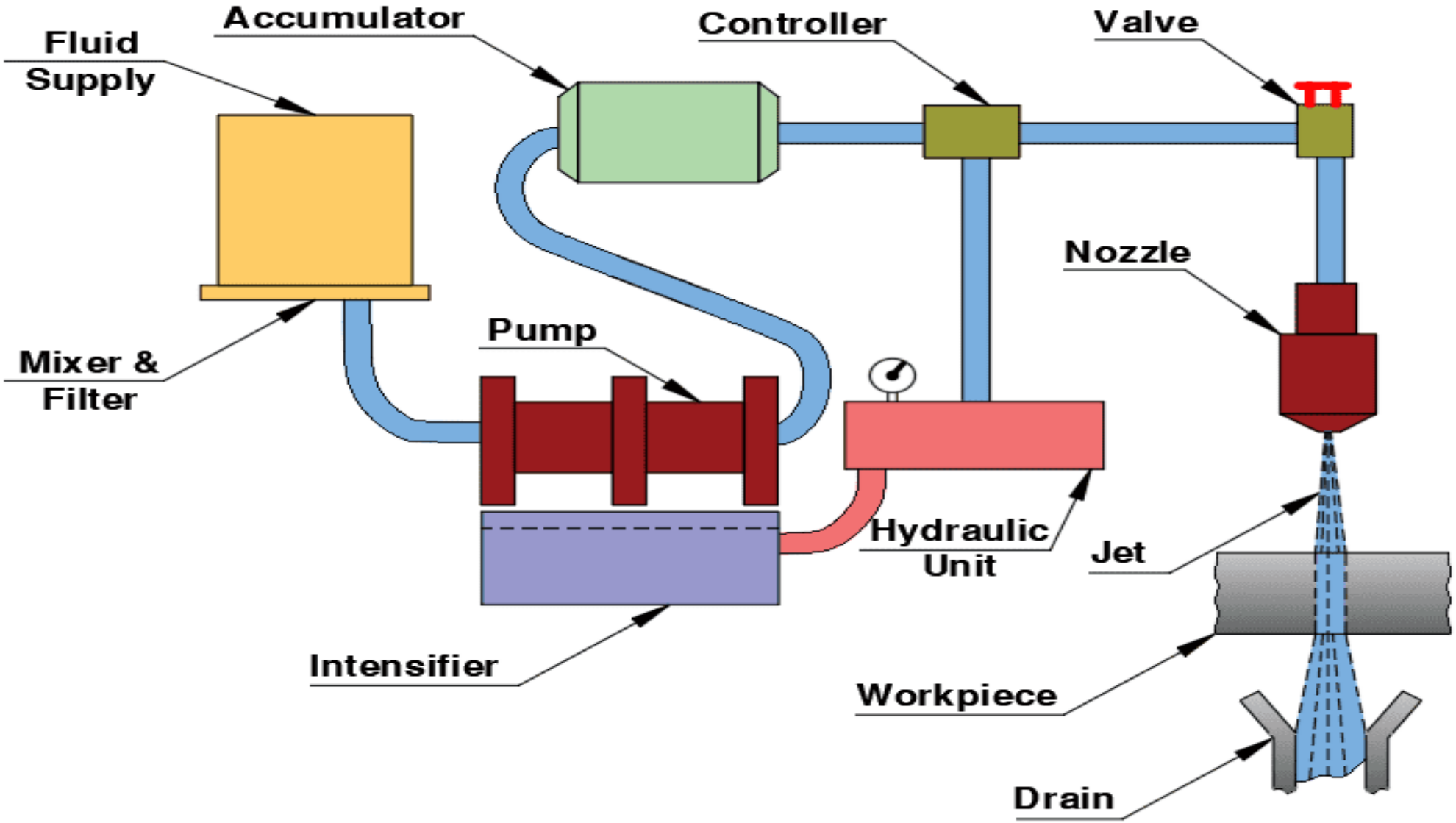
1. AFM: Uses a viscous medium for polishing but is less precise and slower compared to MAFF.
2. MAF (Magnetic Abrasive Finishing): Focuses on external or simple internal surfaces, whereas MAFF is generally used for internal complex geometries.

Abrasive

Abrasive Water Jet Machining (AWJM) is a cold-cutting, non-traditional process that uses high-pressure water (often >2000 bar) mixed with abrasive particles (like garnet) to erode and cut through materials. It cuts thick, hard materials—such as metals, composites, and ceramics—without creating a Heat Affected Zone (HAZ).



Water Jet Machining



Key Components of AWJM

1. High-Pressure Pump/Intensifier: Boosts water pressure to 1500–4000+ MN/cm².
2. Nozzle/Orifice: Sapphire or diamond nozzles convert water pressure into a high-velocity jet (often faster than the speed of sound).
3. Abrasive Feed System: Delivers abrasives (e.g., garnet, aluminum oxide) into the water stream.
4. Mixing Chamber/Tube: Combines the abrasive and water to form a focused, cutting slurry.

Working Principle

1. Pressurization: Water is pressurized to extreme levels.
2. Mixing: Abrasive particles are introduced to the water jet.
3. Erosion: The high-velocity jet impacts the workpiece, removing material through micro-cutting actions.
4. Cutting: The jet cuts through the material via, effectively, a controlled, high-pressure, erosive action.

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Advantages

1. **No Thermal Distortion:** As a "cold" cutting process, it leaves no heat-affected zone or, with excellent edge quality, eliminates the need for secondary finishing.
2. **Versatility:** Cuts almost any material, including thick metals, glass, ceramics, and composites.
3. **Low Force:** Minimal contact force reduces the need for heavy fixturing.
4. **Environmentally Friendly:** Uses no hazardous materials and creates minimal dust.

Limitations

1. Cost: High initial capital investment and high costs for abrasives.
2. Noise: The supersonic jet produces significant noise.
3. Nozzle Wear: High velocity causes short nozzle life, requiring regular maintenance.
4. Abrasive Embedment: Risk of abrasive particles sticking to ductile materials.

Typical Applications

1. Cutting thick metallic plates (up to 10+ inches).
2. Machining fragile/brittle materials (glass, quartz, ceramics).
3. Intricate, precise shaping in aerospace, automotive, and industrial applications.
4. Deburring and cleaning.

Wire EDM

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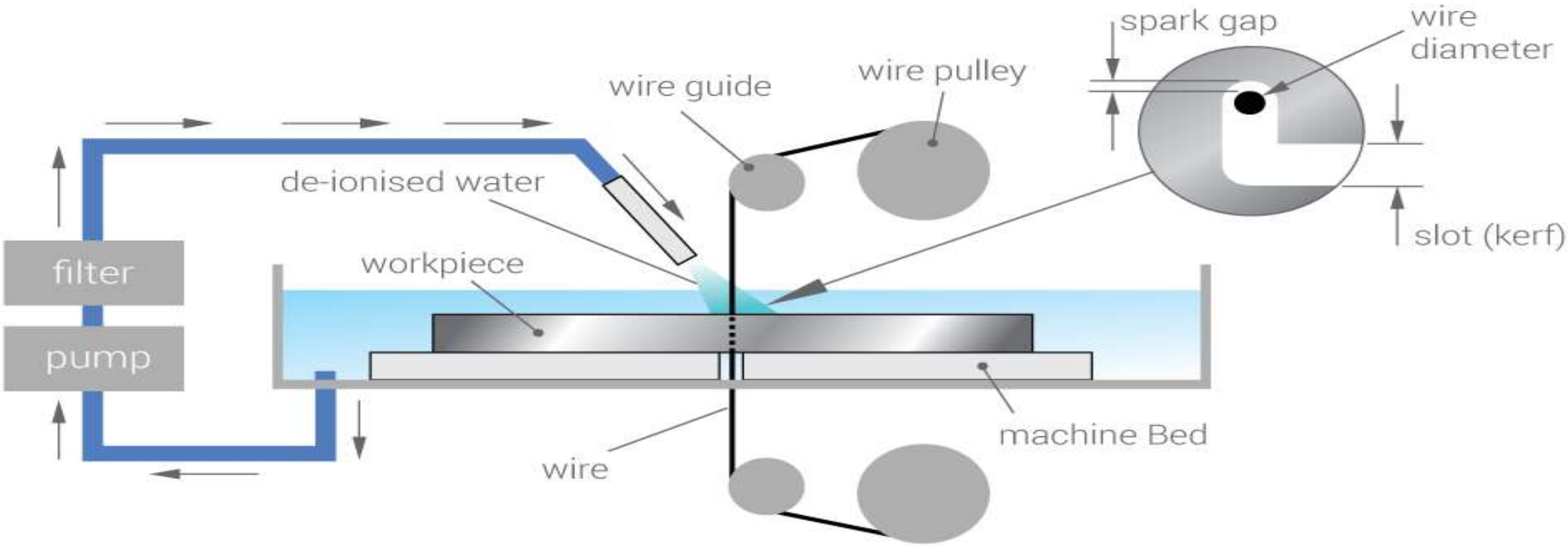


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Wire EDM

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Wire Electrical Discharge Machining (WEDM) is a non-contact manufacturing process that cuts complex, hardened conductive materials by using electrical sparks to erode material between a thin, continuously moving wire electrode and a workpiece, usually submerged in a dielectric fluid. It offers high-precision, intricate contouring with minimal stress, commonly used in aerospace, medical, and die-making industries.

Working Principle: A thin wire—typically brass or copper , acts as an electrode. High-frequency sparks erode the material, creating a small spark gap, often with ionized water acting as the dielectric fluid.

Non-Contact & Precision: Because the wire does not touch the material, there is minimal stress, allowing for, delicate, intricate shapes.

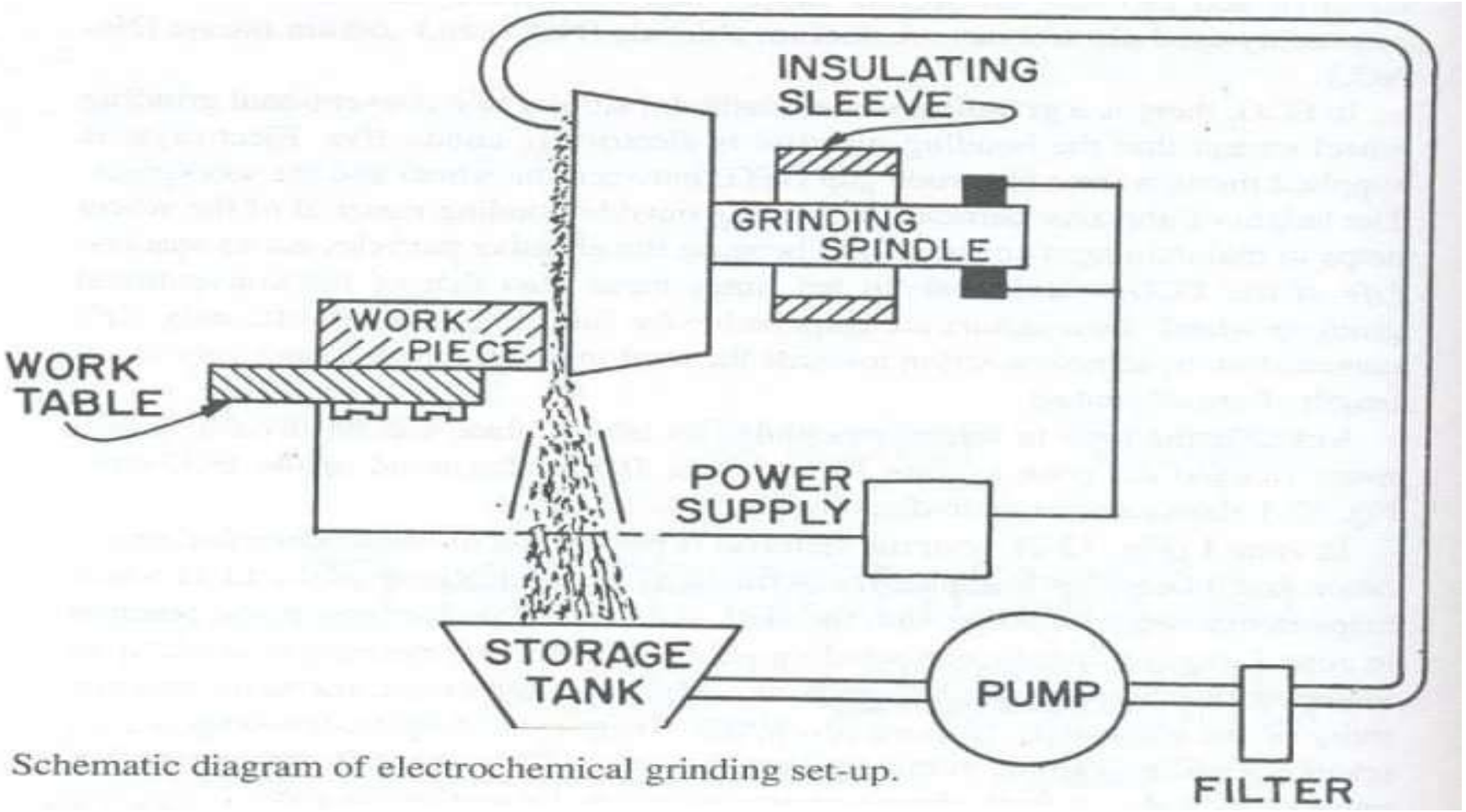
Key Features & Applications:

1. Versatility: Capable of cutting hardened steels, titanium, and conductive ceramics.
2. Taper Cutting: Machines can move along four independent axes to produce complex, changing tapers (e.g., in extrusion dies).
3. Automation: Wires are constantly fed from a spool, ensuring consistent, high-precision cuts.
4. Limitations: The process is generally slower than conventional machining and is limited to conductive materials.

Applications: Widely used for creating extrusion dies, tools, intricate aerospace components, medical devices, and high-precision electronics.

Electrochemical grinding

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Schematic diagram of electrochemical grinding set-up.

Electrochemical grinding

This figure provides a schematic diagram of an Electrochemical Grinding (ECG) setup. ECG is a hybrid machining process that combines conventional abrasive grinding with electrochemical machining (ECM) to remove material from a workpiece

Key Components and Their Functions

Based on the diagram, here is how the system works:

1. Power Supply: A DC power source is used to create an electrical circuit.

The Workpiece (connected to the positive terminal) acts as the Anode.

2. The Grinding Wheel (connected via the spindle and sleeve to the negative terminal) acts as the Cathode

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3. Grinding Spindle & Insulating Sleeve: The spindle rotates the grinding wheel. The insulating sleeve is crucial because it prevents the electrical current from short-circuiting through the machine frame, ensuring it flows only through the electrolyte between the wheel and the workpiece.

4. Electrolyte System (Storage Tank, Pump, Filter):

5. Electrolyte: A conductive fluid (like sodium chloride or sodium nitrate) is pumped into the gap between the wheel and the workpiece.

6. Pump & Filter: The pump circulates the electrolyte, while the filter removes metal chips and sludge to maintain the fluid's conductivity and prevent clogging.

7. Work Table: Holds the workpiece securely in place during the machining process.

How it Works

In this process, material is removed through two simultaneous actions:

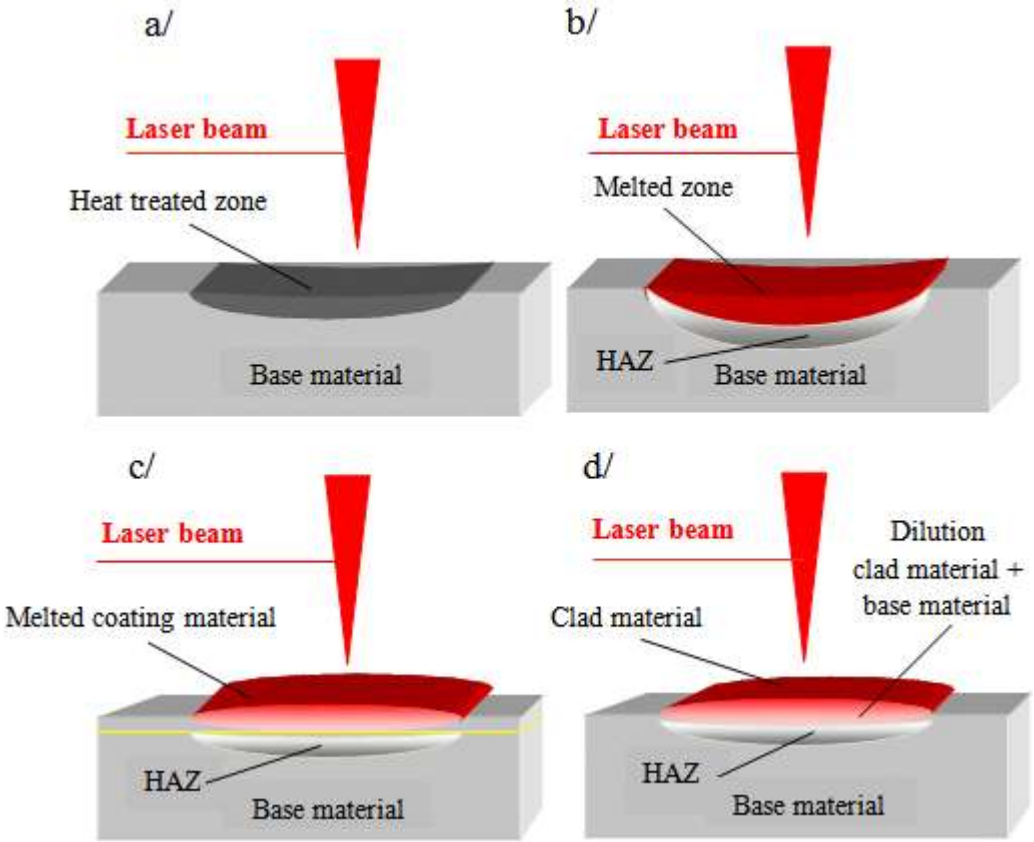
1. Electrolytic Dissolution (~90%): The electrical current flowing through the electrolyte causes the surface of the metal workpiece to dissolve into ions.
2. Mechanical Abrasion (~10%): The abrasive grains on the grinding wheel (often diamond or aluminum oxide) physically scrape away the oxide film formed by the chemical reaction, exposing "fresh" metal for further dissolution.

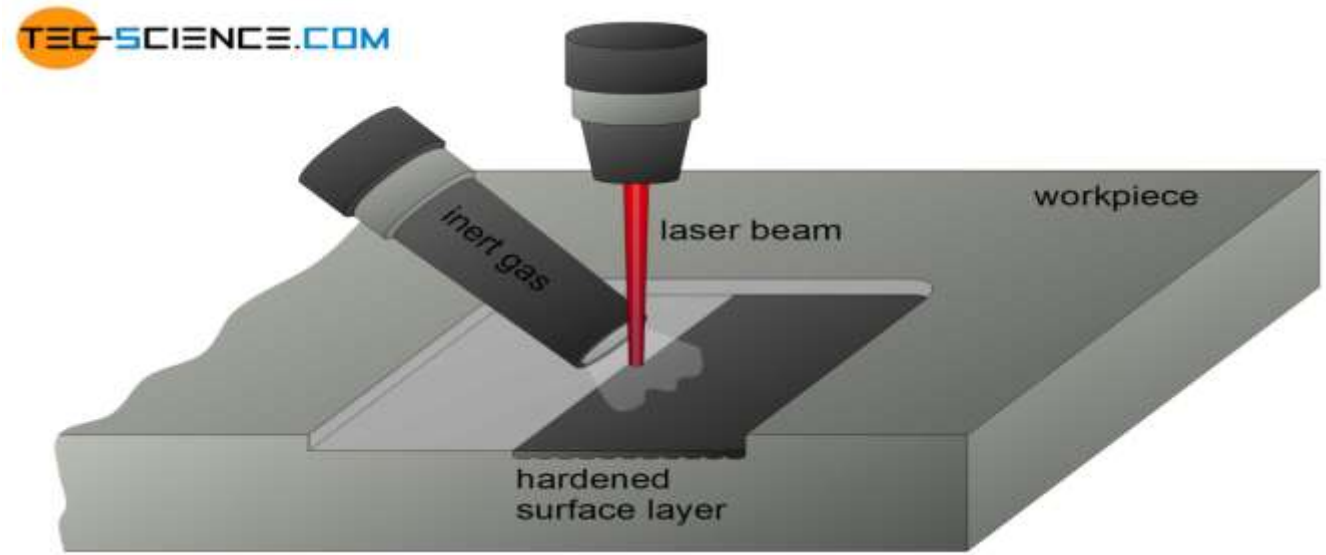
Main Advantages

1. Low Heat: Since most material is removed chemically, there is very little heat generated, preventing thermal damage to the part.
2. No Burrs: It produces a very smooth, burr-free finish.
3. Hard Material Machining: It is ideal for extremely hard or fragile materials that are difficult to grind using conventional methods, such as tungsten carbide or thin-walled tubing.

Laser surface treatments

Laser surface treatment is a precise, non-contact engineering process that uses high-energy laser beams to modify the surface properties of materials—mostly metals—without affecting the bulk material. Common methods include laser hardening, melting, alloying, and cladding to improve wear, corrosion resistance, and hardness through localized, rapid heating and cooling.





Key Laser Surface Treatment Techniques

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1. **Laser Hardening** (Transformation Hardening): Rapid heating (below melting point) followed by cooling to create a hard martensite layer for improved wear resistance.
2. **Laser Surface Melting/Remelting**: Melts a thin top layer that solidifies quickly, creating a refined, homogeneous microstructure and a smoother, sealed surface.
3. **Laser Alloying/Cladding**: Adds a new material (powder or wire) into the laser-melted surface pool to change the surface composition, improving corrosion resistance or repairing parts.
4. **Laser Cleaning/Ablation**: Uses laser energy to remove impurities, rust, or paint from a surface without damaging the base material.
5. **Laser Texturing/Structuring**: Creates precise micro-scale patterns or roughness to enhance friction properties, bonding, or appearance.

Key Advantages

1. Minimal Distortion: Because the heating is localized, the bulk part stays cool and retains its structural integrity, according to ScienceDirect.com.
2. High Precision: Allows for treatment of specific, difficult-to-reach areas with micrometer accuracy.
3. High Speed & Automation: Easily automated for industrial production lines and robotics.
4. Environmentally Friendly: Chemical-free and reduces waste compared to traditional coating or treatment methods.

Industrial Applications

Laser surface treatment is widely used in automotive, aerospace, and power generation industries to enhance parts like gears, camshafts, and turbine blades to reduce wear and extend service life.

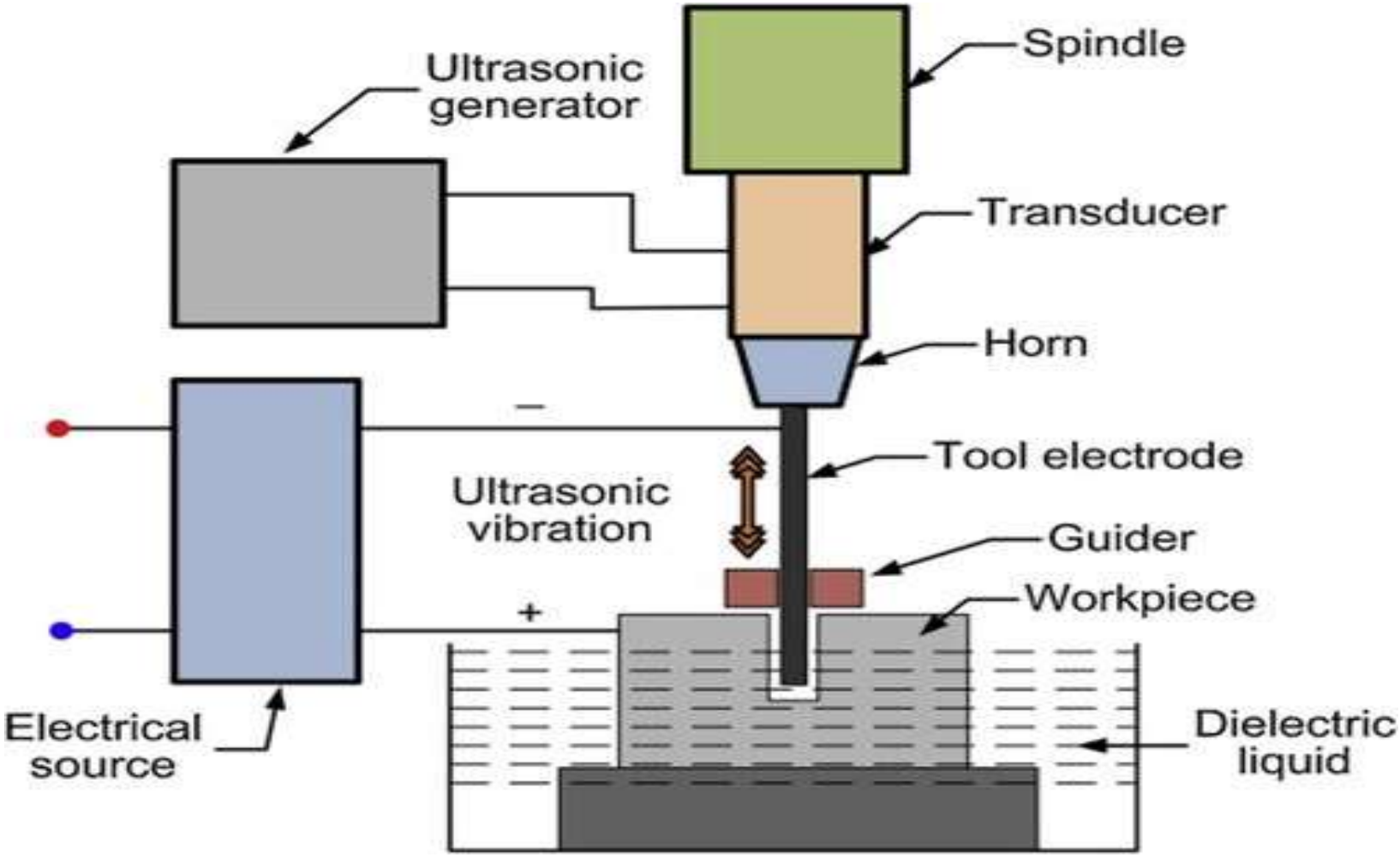
Ultrasonic assisted EDM

Ultrasonic-assisted Electrical Discharge Machining (UA-EDM) is a hybrid manufacturing process that combines the thermal energy of Electrical Discharge Machining (EDM) with high-frequency mechanical vibrations from Ultrasonic Machining (USM).

In standard EDM, material is removed through localized melting and vaporization caused by electric sparks. By adding ultrasonic vibrations (typically above 20 kHz), the process significantly improves material removal rates (MRR) and surface quality, especially in challenging applications like deep micro-hole drilling.

Ultrasonic assisted EDM

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How It Works

1. The core principle involves applying ultrasonic vibrations to one of the following components:
2. Tool Electrode: The most common method, where a piezoelectric transducer vibrates the tool. This creates a "pumping action" that forces dielectric fluid into and out of the spark gap.
3. Workpiece: The workpiece is vibrated, often horizontally or vertically, to help disperse sparks across a wider area and prevent localized arcing.
4. Dielectric Fluid: Vibrations applied to the liquid itself create turbulence and cavitation, which helps break up and carry away debris.

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Key Advantages

UA-EDM addresses several major limitations of conventional EDM:

1. Superior Debris Removal: The high-frequency vibrations effectively flush out eroded particles (debris) from the narrow spark gap, preventing "short circuits" and unstable sparking.
2. Increased Machining Speed: By maintaining a stable spark gap, UA-EDM can achieve a reduction of up to 58% in machining time for high-aspect-ratio holes.
3. Reduced Tool Wear: Improved flushing prevents secondary discharges on the tool, which reduces electrode wear and extends tool life.
4. Higher Aspect Ratios: It enables the drilling of extremely deep, small-diameter holes (aspect ratios >40) that would be impossible with standard EDM due to poor flushing

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Main Applications

1. This technology is primarily used in industries requiring high precision in hard-to-machine materials:
2. Aerospace & Medical: Manufacturing turbine blades, fuel injector nozzles, and surgical implants.
3. Micro-Manufacturing: Creating micro-holes (8 µm to 400 µm) and complex micro-grooves in superalloys.
4. Difficult Materials: Machining titanium alloys (Ti-6Al-4V), Inconel 718, and even some non-conductive ceramics using an assisting electrode.

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Unit 4

Unit IV
Additive Manufacturing Processes

Introduction

Additive manufacturing is a process in which materials are built up, layer by layer, to create three-dimensional parts from 3D model data. The manufacturing process, also known as 3D printing, has its industrial origins in the mid-1980s. Patented by U.S. physicist Chuck Hall, the stereolithography process used a laser beam to harden liquid plastic layer by layer. This allowed the industry to produce material mechanically. Any component with complex shapes and internal structures could be produced from a 3D CAD model.

Since then, the limitless design freedom of additive manufacturing has inspired researchers around the world and continues to inspire the development of new processes and material applications. Plastic is no longer the only material used. Ceramics, organic tissues, and a variety of metals are also utilized. The possibilities of additive manufacturing are far from exhausted and there is every reason to believe that the use of additive processes will be on the rise in all areas of industrial

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Introduction to Additive Manufacturing

Definition: The official, industry-standard term for 3D printing, defined by creating objects by joining materials, usually layer upon layer, rather than removing material.

Process Origin: The technology originated in the mid-1980s with stereolithography (SLA), allowing for the creation of complex, high-precision industrial parts.

Significance: It is a key technology for rapid prototyping, customized medical implants, lightweight aerospace components, and automotive manufacturing.

Fundamental Principles of AM

The additive manufacturing process follows a structured, iterative approach:

1. CAD Modeling: The process begins by creating a 3D digital model of the object using Computer-Aided Design (CAD) software.
2. Conversion to STL/Slicing: The CAD model is converted to a stereolithography (.stl) file and "sliced" into hundreds or thousands of 2D horizontal layers by specialized software.
3. Layer-by-Layer Fabrication: The machine creates the object, adding material layer upon layer based on the 3D data. These layers are joined using methods like lasers, binders, or extrusion.
4. Post-Processing: Once completed, the object often requires post-processing, such as curing, removing support structures, sintering, or surface finishing

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Advantages

Complex Geometries: Enables designs that are impossible with traditional manufacturing.

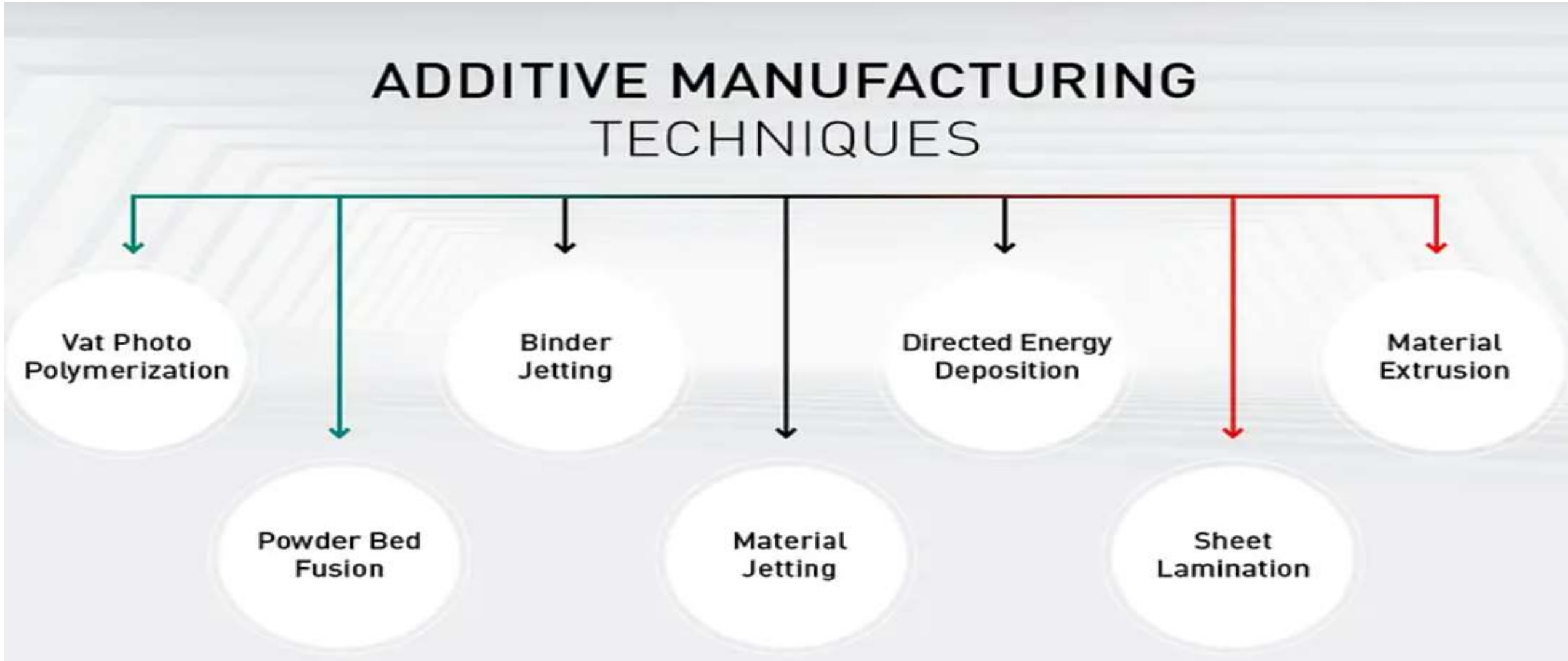
Material Efficiency: Reduces material waste because only the necessary material is used.

Customization: Allows cost-effective, personalized production, from dental implants to personalized consumer products.

Reduced Assembly: Permits part consolidation, reducing the need for assembly and improving structural integrity.

L21

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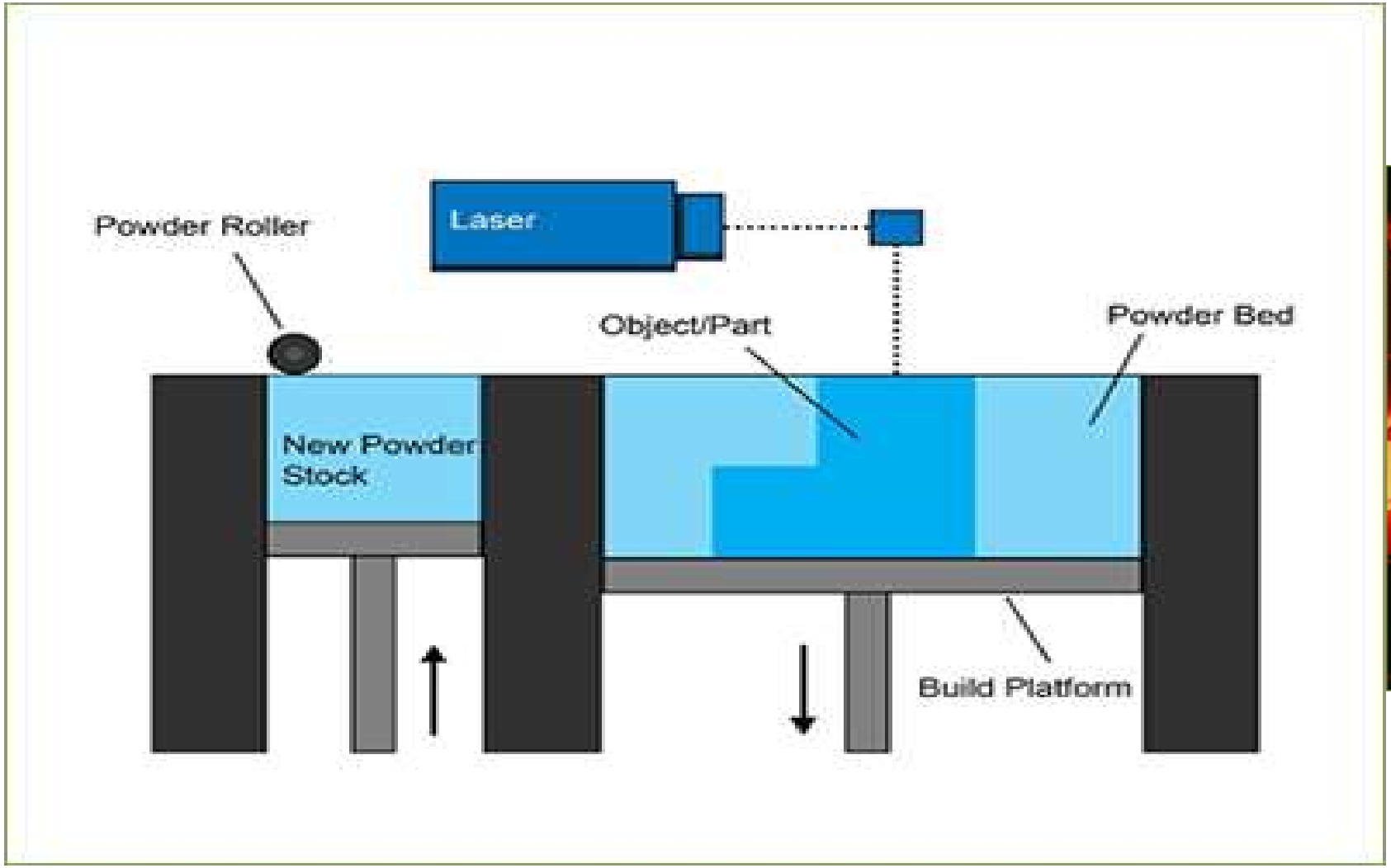
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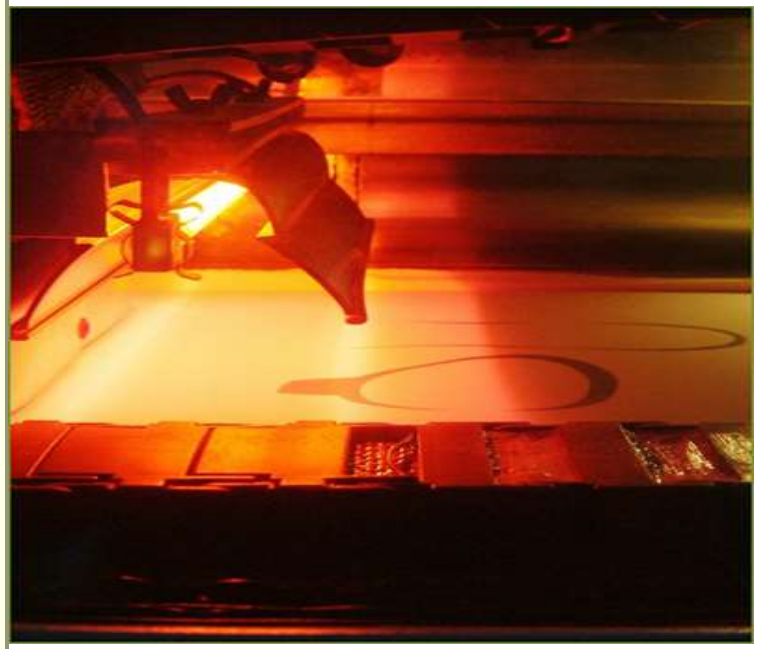
Powder Bed Fusion (PBF)

Powder bed fusion (DIN: powder bed-based fusion) is the dominant process in the metals industry. Components are produced by building up material layer by layer. The individual layers correspond to horizontal "slices" of a three-dimensional CAD image of the part to be produced. These layers are then used to calculate a control program that directs a laser or electron beam across these cuts with high precision to fuse the material over their entire surface. The area adheres to the previous layer and solidifies as the material cools. Once the layer has melted, a new layer of powder is applied. DMG MORI is successfully represented in the market with the LASERTEC SLM series.

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- The Powder Bed Fusion process includes the following commonly used printing techniques: Direct metal laser sintering (DMLS), Electron beam melting (EBM), Selective heat sintering (SHS), Selective laser melting (SLM) and Selective laser sintering (SLS).
- Powder bed fusion (PBF) methods use either a laser or electron beam to melt and fuse material powder together. Electron beam melting (EBM), methods require a vacuum but can be used with metals and alloys in the creation of functional parts. All PBF processes involve the spreading of the powder material over previous layers. There are different mechanisms to enable this, including a roller or a blade. A hopper or a reservoir below of aside the bed provides fresh material supply. Direct metal laser sintering (DMLS) is the same as SLS, but with the use of metals and not plastics. The process sinters the powder, layer by layer. Selective Heat Sintering differs from other processes by way of using a heated thermal print head to fuse powder material together. As before, layers are added with a roller in between fusion of layers. A platform lowers the model accordingly.





Powder Bed Fusion

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Powder Bed Fusion – working procedure

1. A layer, typically 0.1mm thick of material is spread over the build platform.
2. A laser fuses the first layer or first cross section of the model.
3. A new layer of powder is spread across the previous layer using a roller.
4. Further layers or cross sections are fused and added.
5. The process repeats until the entire model is created. Loose, unfused powder is remains in position but is removed during post processing.

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Advantages:

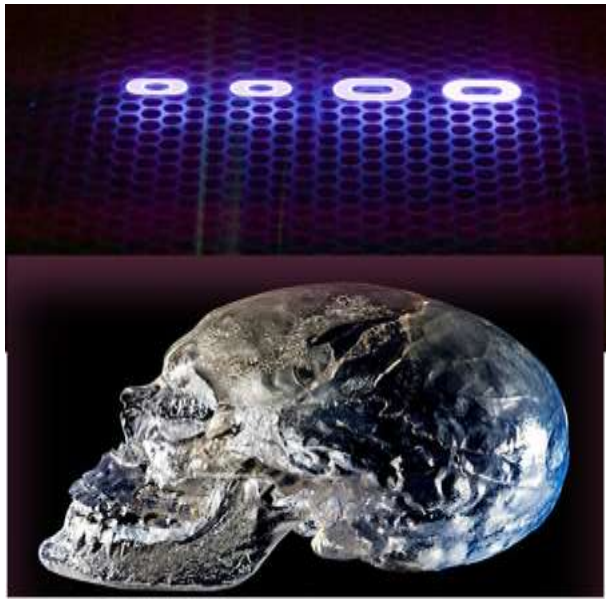
1. Relatively inexpensive
2. Suitable for visual models and prototypes
3. (SHS) Ability to integrate technology into small scale, office sized machine
4. Powder acts as an integrated support structure
5. Large range of material options

Disadvantages:

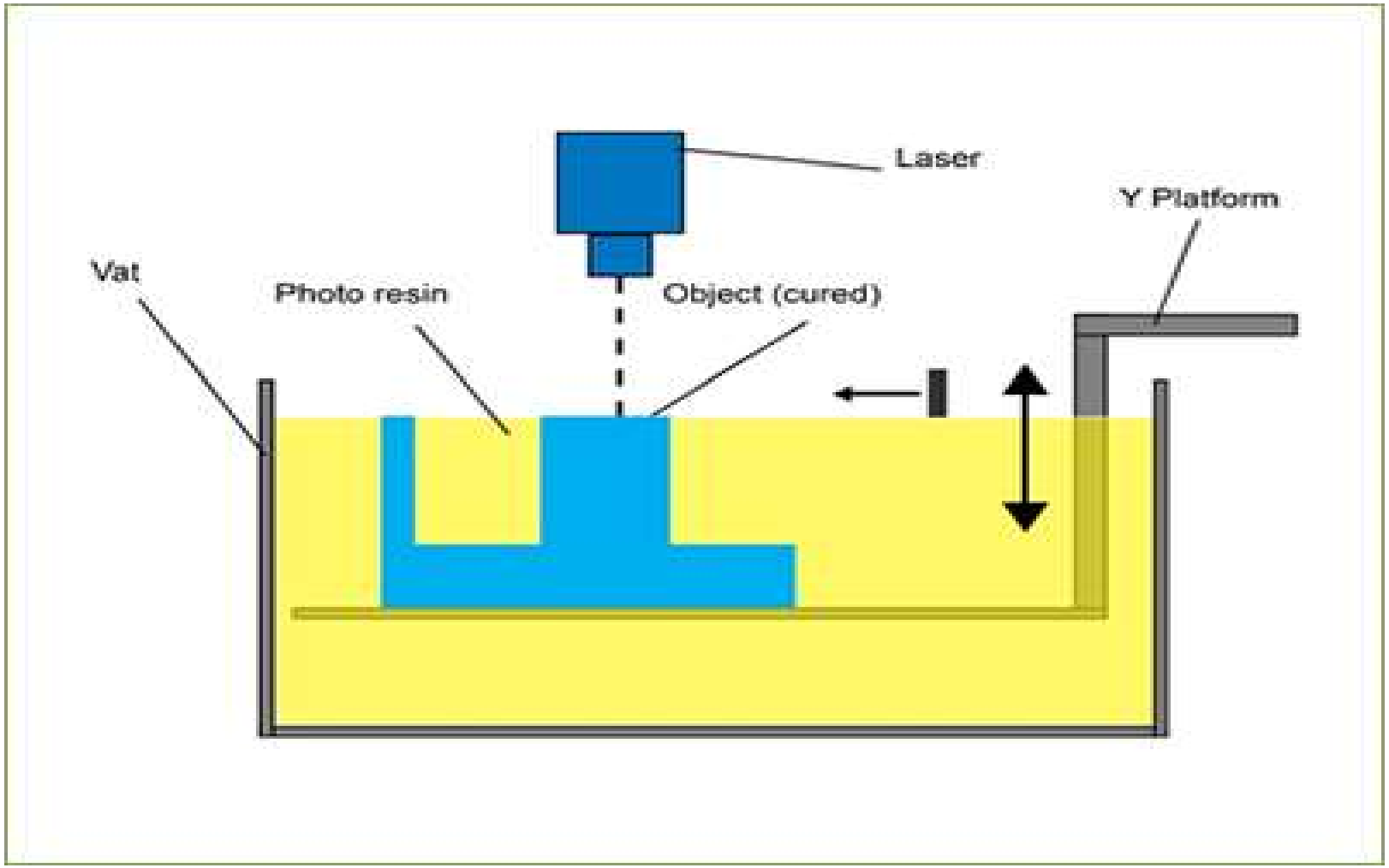
1. Relatively slow speed (SHS)
2. Lack of structural properties in materials
3. Size limitations
4. High power usage
5. Finish is dependent on powder grain size

VAT Photopolymerisation

Vat polymerisation uses a vat of liquid photopolymer resin, out of which the model is constructed layer by layer. An ultraviolet (UV) light is used to cure or harden the resin where required, whilst a platform moves the object being made downwards after each new layer is cured.



As the process uses liquid to form objects, there is no structural support from the material during the build phase., unlike powder based methods, where support is given from the unbound material. In this case, support structures will often need to be added. Resins are cured using a process of photo polymerisation (Gibson et al., 2010) or UV light, where the light is directed across the surface of the resin with the use of motor controlled mirrors (Grenda, 2009). Where the resin comes in contact with the light, it cures or hardens.



VAT
Photopolymerisation

Photopolymerisation –

Working Procedure

1. The build platform is lowered from the top of the resin vat downwards by the layer thickness.
2. A UV light cures the resin layer by layer. The platform continues to move downwards and additional layers are built on top of the previous.
3. Some machines use a blade which moves between layers in order to provide a smooth resin base to build the next layer on.
4. After completion, the vat is drained of resin and the object removed.

Advantages:

1. High level of accuracy and good finish
2. Relatively quick process
3. Typically large build areas: objet 1000: 1000 x 800 x 500 and max model weight of 200 kg

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Disadvantages:

1. Relatively expensive
2. Lengthly post processing time and reomval from resin
3. Limited material use of photo-resins
4. Often requires support structures and post curing for parts to be strong enough for structural use

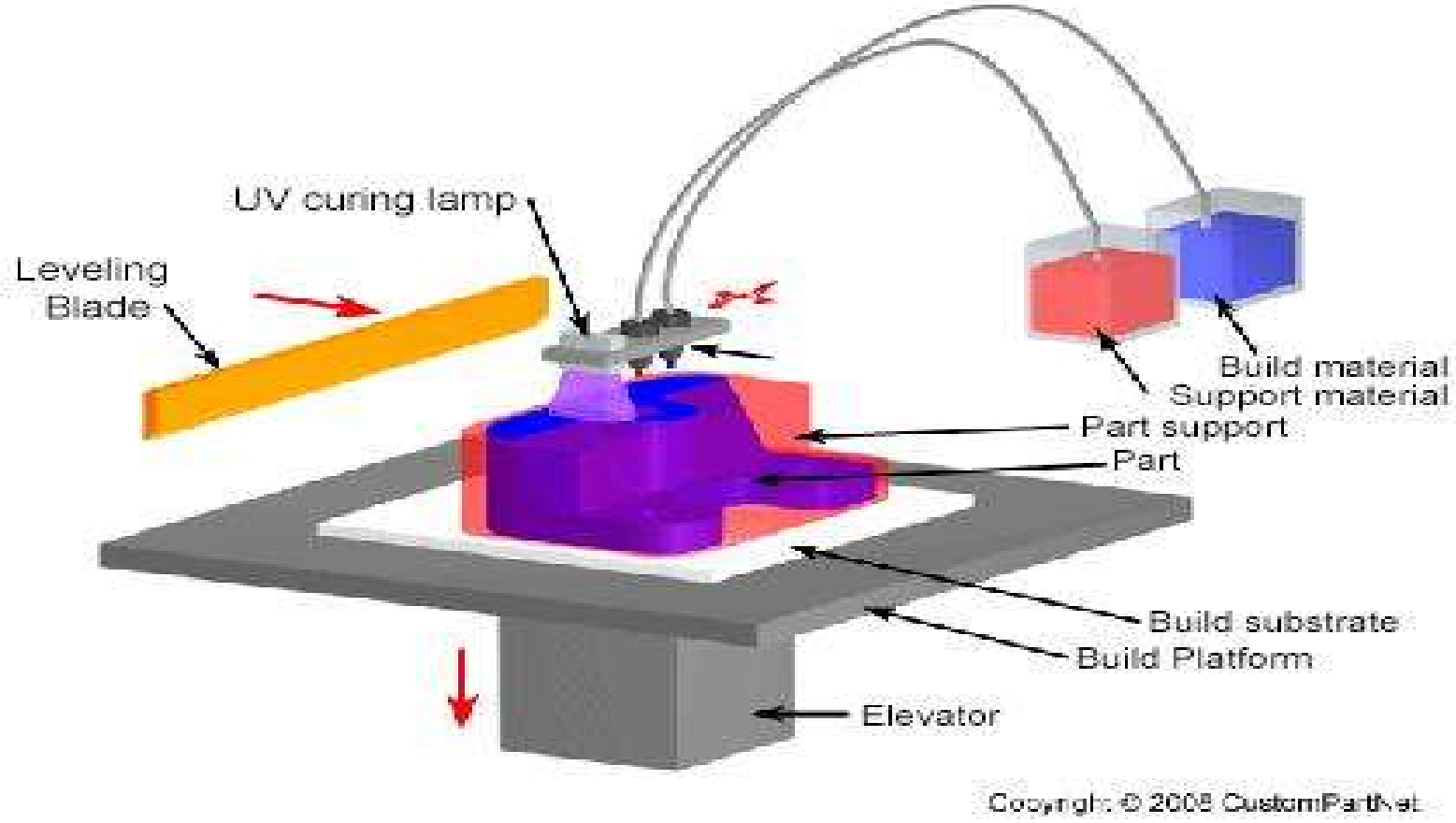
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Material Jetting

1. Material jetting creates objects in a similar method to a two dimensional ink jet printer. Material is jetted onto a build platform using either a continuous or Drop on Demand (DOD) approach.
2. Material is jetted onto the build surface or platform, where it solidifies and the model is built layer by layer. Material is deposited from a nozzle which moves horizontally across the build platform. Machines vary in complexity and in their methods of controlling the deposition of material. The material layers are then cured or hardened using ultraviolet (UV) light.
3. As material must be deposited in drops, the number of materials available to use is limited. Polymers and waxes are suitable and commonly used materials, due to their viscous nature and ability to form drops.

Material Jetting

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Material Jetting

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Material Jetting – working procedure

1. The print head is positioned above build platform.
2. Droplets of material are deposited from the print head onto surface where required, using either thermal or piezoelectric method.
3. Droplets of material solidify and make up the first layer.
4. Further layers are built up as before on top of the previous.
5. Layers are allowed to cool and harden or are cured by UV light. Post processing includes removal of support material.

Advantages:

1. The process benefits from a high accuracy of deposition of droplets and therefore low waste
2. The process allows for multiple material parts and colours under one process

Disadvantages:

1. Support material is often required
2. A high accuracy can be achieved but materials are limited and only polymers and waxes can be used

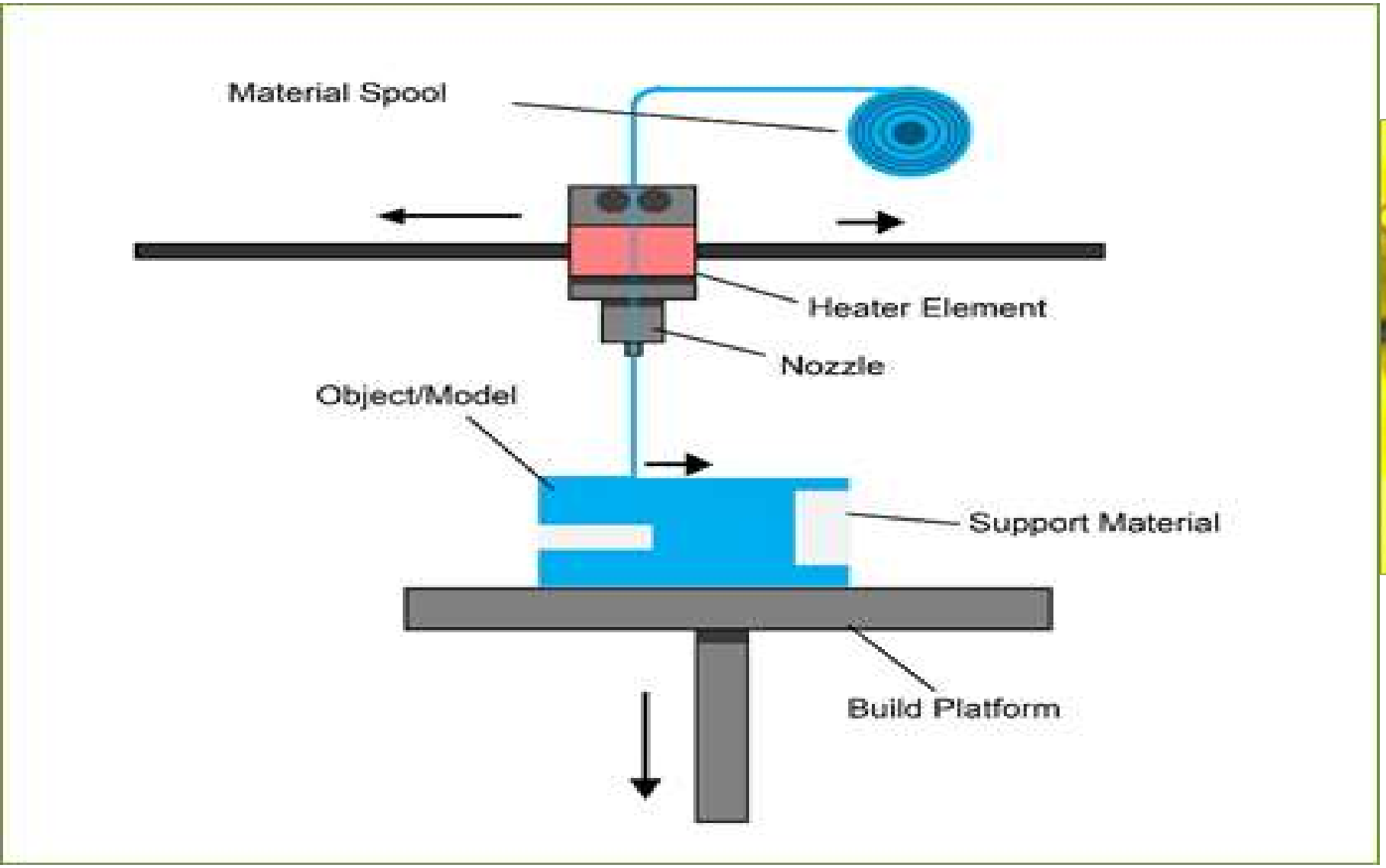
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Material Extrusion

- Fuse deposition modelling (FDM) is a common material extrusion process and is trademarked by the company Stratasys. Material is drawn through a nozzle, where it is heated and is then deposited layer by layer. The nozzle can move horizontally and a platform moves up and down vertically after each new layer is deposited. It is a commonly used technique used on many inexpensive, domestic and hobby 3D printers.
- The process has many factors that influence the final model quality but has great potential and viability when these factors are controlled successfully. Whilst FDM is similar to all other 3D printing processes, as it builds layer by layer, it varies in the fact that material is added through a nozzle under constant pressure and in a continuous stream. This pressure must be kept steady and at a constant speed to enable accurate results (Gibson et al., 2010). Material layers can be bonded by temperature control or through the use of chemical agents. Material is often added to the machine in spool form as shown in the diagram.

Material Extrusion

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Material Extrusion –

working steps

1. First layer is built as nozzle deposits material where required onto the cross sectional area of first object slice.
2. The following layers are added on top of previous layers.
3. Layers are fused together upon deposition as the material is in a melted state.

Advantages:

1. Widespread and inexpensive process
2. ABS plastic can be used, which has good structural properties and is easily accessible

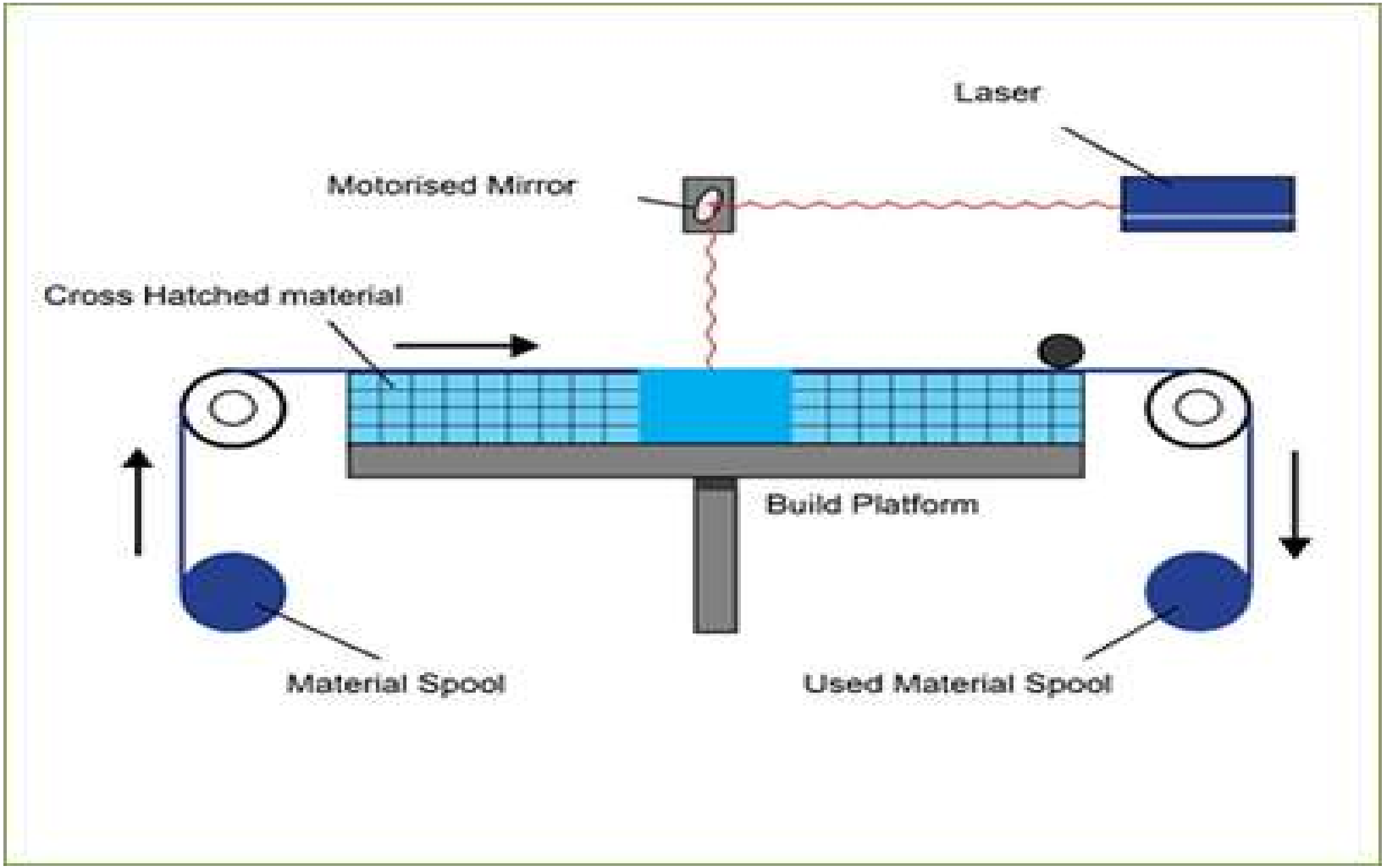
Disadvantages:

1. The nozzle radius limits and reduces the final quality
2. Accuracy and speed are low when compared to other processes and accuracy of the final model is limited to material nozzle thickness
3. Constant pressure of material is required in order to increase quality of finish

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Sheet Lamination

Sheet lamination processes include ultrasonic additive manufacturing (UAM) and laminated object manufacturing (LOM). The Ultrasonic Additive Manufacturing process uses sheets or ribbons of metal, which are bound together using ultrasonic welding. The process does require additional cnc machining and removal of the unbound metal, often during the welding process. Laminated object manufacturing (LOM) uses a similar layer by layer approach but uses paper as material and adhesive instead of welding. The LOM process uses a cross hatching method during the printing process to allow for easy removal post build. Laminated objects are often used for aesthetic and visual models and are not suitable for structural use. UAM uses metals and includes aluminium, copper, stainless steel and titanium (Ultrasonic Additive Manufacturing Overview, 2014). The process is low temperature and allows for internal geometries to be created. The process can bond different materials and requires relatively little energy, as the metal is not melted.



Sheet Lamination

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Sheet Lamination –

working steps

1. The material is positioned in place on the cutting bed.
2. The material is bonded in place, over the previous layer, using the adhesive.
3. The required shape is then cut from the layer, by laser or knife.
4. The next layer is added.
5. Steps two and three can be reversed and alternatively, the material can be cut before being positioned and bonded.

Advantages:

1. Benefits include speed, low cost, ease of material handling, but the strength and integrity of models is reliant on the adhesive used (Krar and Gill, 203)
2. Cutting can be very fast due to the cutting route only being that of the shape outline, not the entire cross sectional area

Disadvantages:

1. Finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect
2. Limited material use
3. Fusion processes require more research to further advance the process into a more mainstream positioning

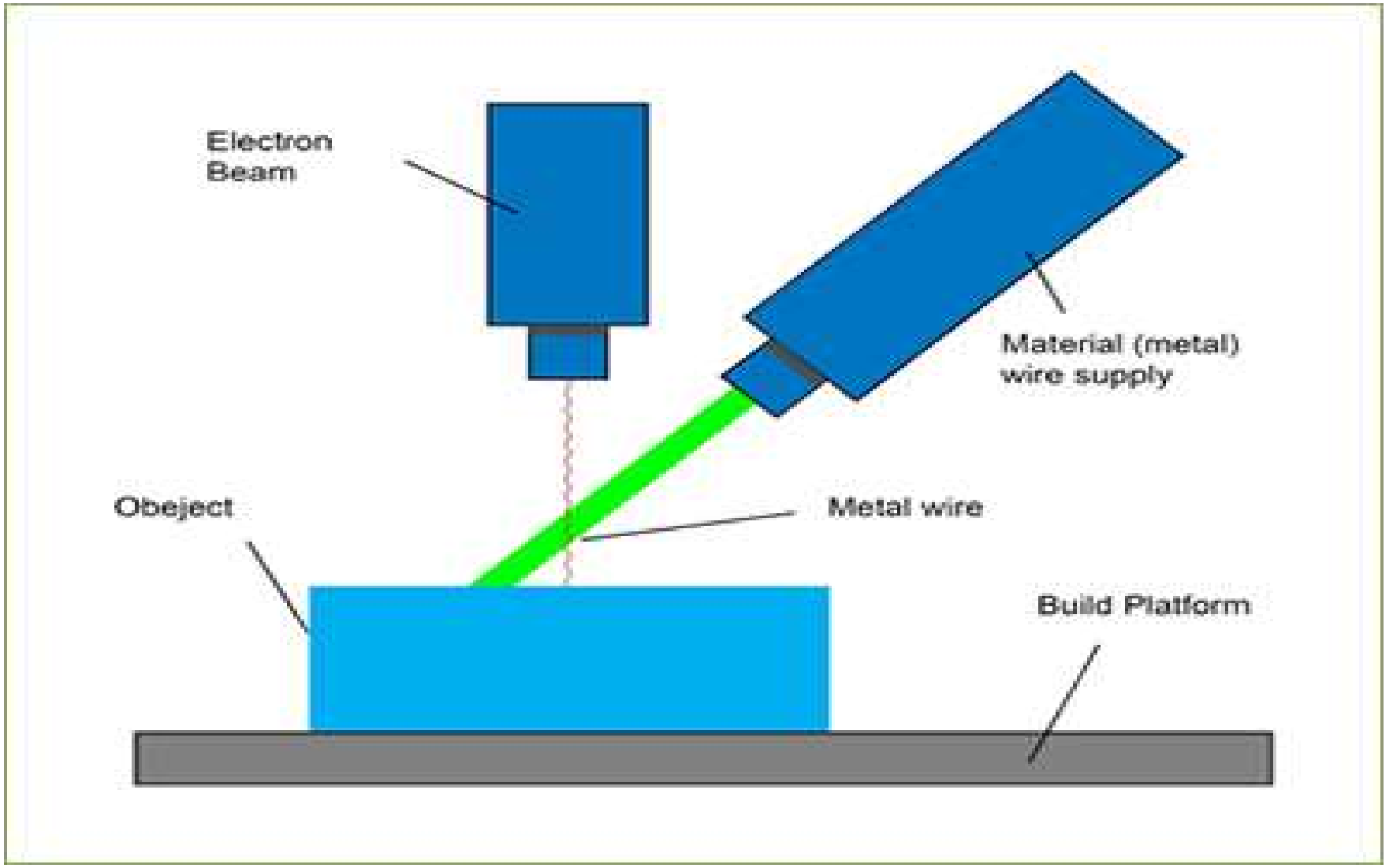
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Directed Energy Deposition

Directed Energy Deposition (DED) covers a range of terminology: ‘Laser engineered net shaping, directed light fabrication, direct metal deposition, 3D laser cladding’ It is a more complex printing process commonly used to repair or add additional material to existing components (Gibson et al., 2010).

A typical DED machine consists of a nozzle mounted on a multi axis arm, which deposits melted material onto the specified surface, where it solidifies. The process is similar in principle to material extrusion, but the nozzle can move in multiple directions and is not fixed to a specific axis. The material, which can be deposited from any angle due to 4 and 5 axis machines, is melted upon deposition with a laser or electron beam. The process can be used with polymers, ceramics but is typically used with metals, in the form of either powder or wire.

Typical applications include repairing and maintaining structural parts.



Directed Energy Deposition

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Direct Energy Deposition –

Step by Step procedure

1. A4 or 5 axis arm with nozzle moves around a fixed object.
2. Material is deposited from the nozzle onto existing surfaces of the object.
3. Material is either provided in wire or powder form.
4. Material is melted using a laser, electron beam or plasma arc upon deposition.
5. Further material is added layer by layer and solidifies, creating or repairing new material features on the existing object.

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Advantages:

1. Advantages of DED
2. Ability to control the grain structure to a high degree, which lends the process to repair work of high quality, functional parts
3. A balance is needed between surface quality and speed, although with repair applications, speed can often be sacrificed for a high accuracy and a pre- determined microstructure

Disadvantages:

1. Finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect
2. Limited material use
3. Fusion processes require more research to further advance the process into a more mainstream positioning

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Post-processing in additive manufacturing (AM) is a critical, multi-stage, third step in the production workflow, transforming as-printed "slugs" into functional, high-quality, customer-ready parts. It removes support structures and excess material, improves surface finish, and optimizes mechanical properties through thermal or chemical treatments.

- **Key post-processing techniques and objectives include:**

1. **Support Structure Removal:** Using manual tools (cutters, pliers), thermal, or chemical dissolution to remove supports used to prevent deformation during printing.
2. **Surface Finishing:** Techniques like bead blasting, sanding, chemical smoothing, and polishing are used to reduce surface roughness, enhancing aesthetics and reducing friction.

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3. Powder Removal: Critical for metal powder bed fusion (PBF) to remove trapped powder from intricate internal cavities.

4. **Coatings and Finishing:** Painting, plating, or anodizing are applied for corrosion resistance, aesthetics, or conductivity.

5. The extent of post-processing is highly dependent on the print technology (e.g., polymer vs. metal) and the part's intended application, and it can account for a significant portion of the total production cost.

6. **Heat Treatment/Material Improvement:** Processes like annealing or Hot Isostatic Pressing (HIP) are applied to reduce residual stresses, close internal pores, increase density, and improve fatigue life.

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Unit 5

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Unit V
Material Characterization Techniques

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Material characterization is the process of measuring and determining the physical, chemical, and structural properties of materials using techniques like microscopy, spectroscopy, and diffraction. It is essential for understanding microstructure-property relationships, ensuring quality, and facilitating new material development, spanning scales from atomic levels up to millimeters.

Key techniques include:

1. **Microscopy (Imaging):** Optical microscopy, Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Atomic Force Microscopy (AFM) are used to study surface topography, morphology, and atomic structure.
2. **Spectroscopy (Composition):** Mass spectrometry, nuclear spectroscopy, and X-ray diffraction (XRD) are used to analyze elemental composition and identify crystal structures, distinguishing between crystalline and amorphous materials.
3. **Thermal Analysis (Behavior):** Thermogravimetric analysis (TGA) and differential thermal analysis measure weight changes and chemical transformations in response to temperature variations.
4. **Mechanical Testing (Performance):** Tensile and hardness tests are used to determine mechanical properties such as strength, elasticity, and durability.

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Key Benefits & Applications:

1. **Improved Performance:** Enables the development of more durable and efficient materials.
2. **Failure Analysis:** Helps identify the root causes of material failure in engineering applications.
3. **Quality Control:** Verifies that materials meet required structural specifications.

Common applications include alloy aging in aerospace, semiconductor manufacturing, and examining additive manufacturing materials.

Electron Microscope

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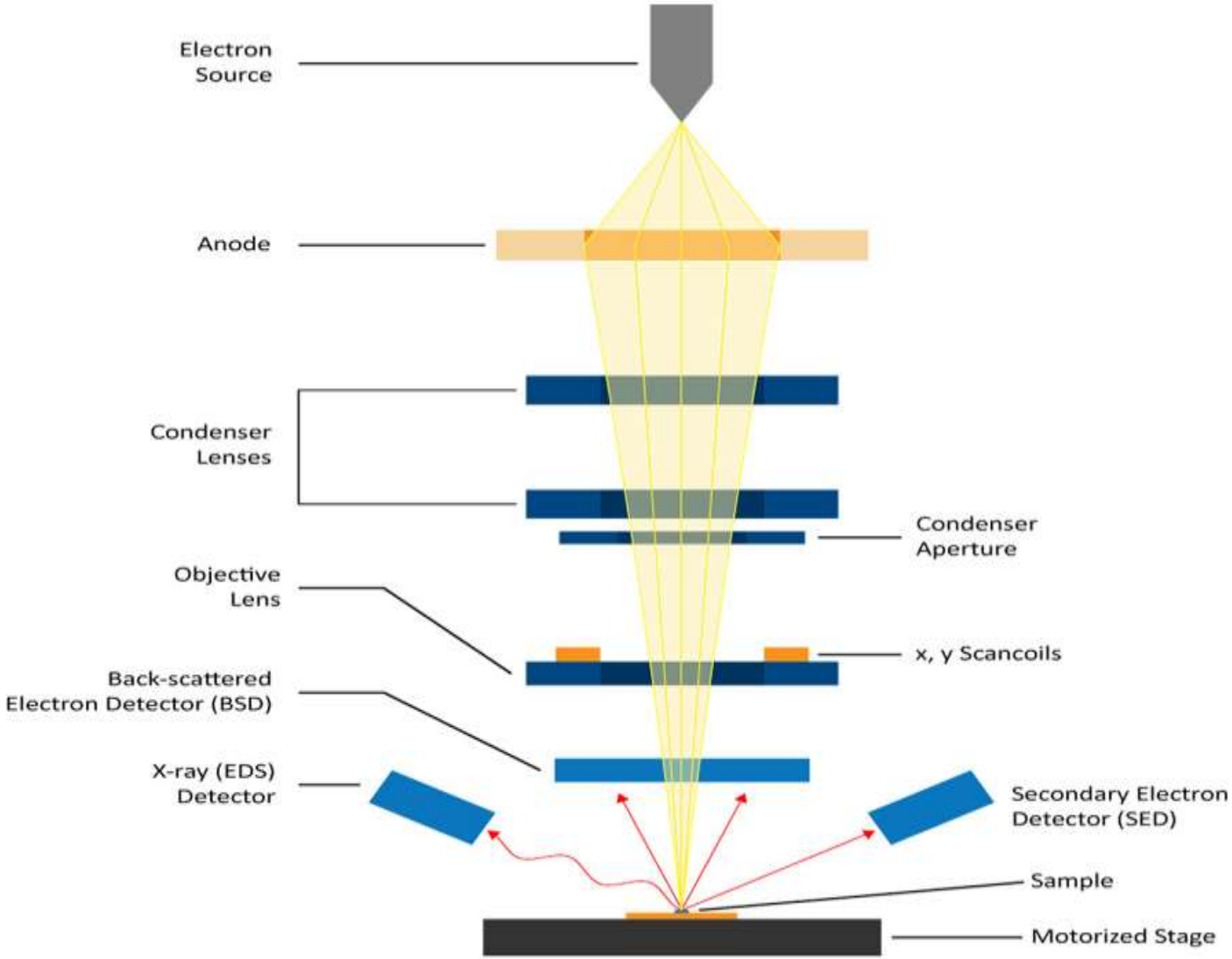
An electron microscope is a high-powered scientific instrument that uses accelerated electron beams instead of light to image objects at the nanoscale, achieving up to 2,000,000x magnification. Invented in 1931, it uses electromagnetic lenses to focus electrons, revealing detailed structural, compositional, and 3D topographic information.

Key Types and Functions:

1. Transmission Electron Microscope (TEM): Transmits electrons through ultra-thin specimens to provide detailed, 2D internal structural images.
2. Scanning Electron Microscope (SEM): Scans a focused electron beam over the surface, detecting secondary electrons to create detailed 3D, high-resolution topographic images of surfaces.

Scanning Electron Microscope (SEM)

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1. Beam Generation & Focus

I. **Electron Source:** Also known as the electron gun (typically a tungsten filament or field emission tip), it generates the electron beam.

II. **Anode:** Negatively charged electrons are accelerated toward the positively charged anode to form a high-energy beam.

III. **Condenser Lenses:** These electromagnetic lenses converge the beam and control the "spot size" (how many electrons hit the sample).

IV. **Condenser Aperture:** A small hole that limits the beam spread and helps define the final resolution.

V. **Objective Lens:** The final lens that focuses the electron beam into a very fine spot on the sample surface.

VI. **x, y Scancoils:** These coils deflect the beam in a grid pattern (rastering) across the sample. This "scanning" is what allows the microscope to build an image.

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Detection & Interaction

1. When the beam hits the Sample on the Motorized Stage, it interacts with the atoms of the specimen, producing different signals:
2. Secondary Electron Detector (SED): Collects low-energy electrons knocked out of the sample's surface atoms. This is the primary method for showing topography (surface texture).
3. Back-scattered Electron Detector (BSD): Collects high-energy electrons that are "reflected" back from deeper within the sample. This provides information on composition (heavier elements appear brighter).
4. X-ray (EDS) Detector: Detects characteristic X-rays emitted during the interaction. This is used for Energy Dispersive Spectroscopy (EDS) to identify the chemical elements present in the sample.

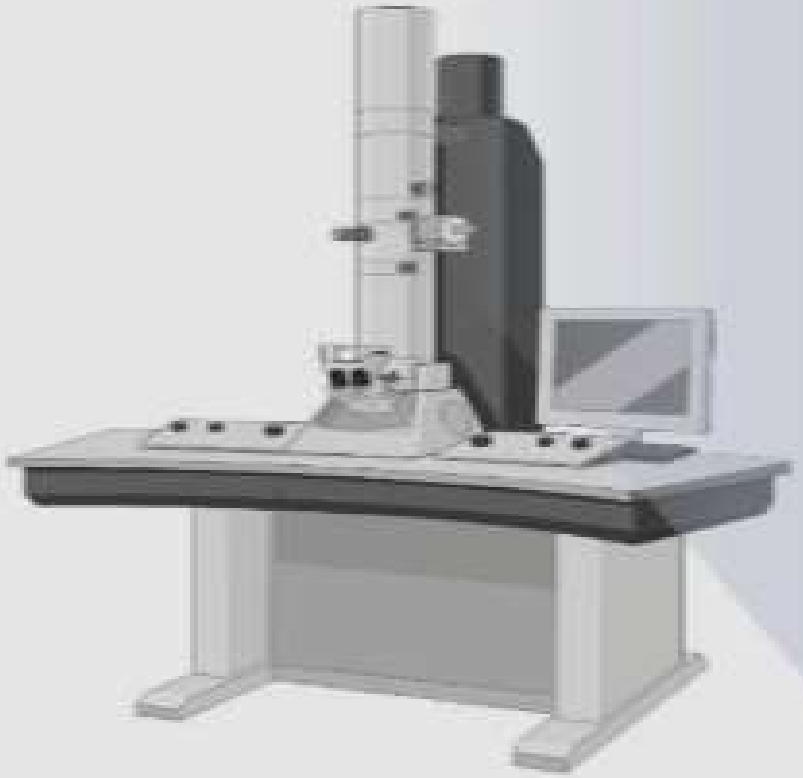
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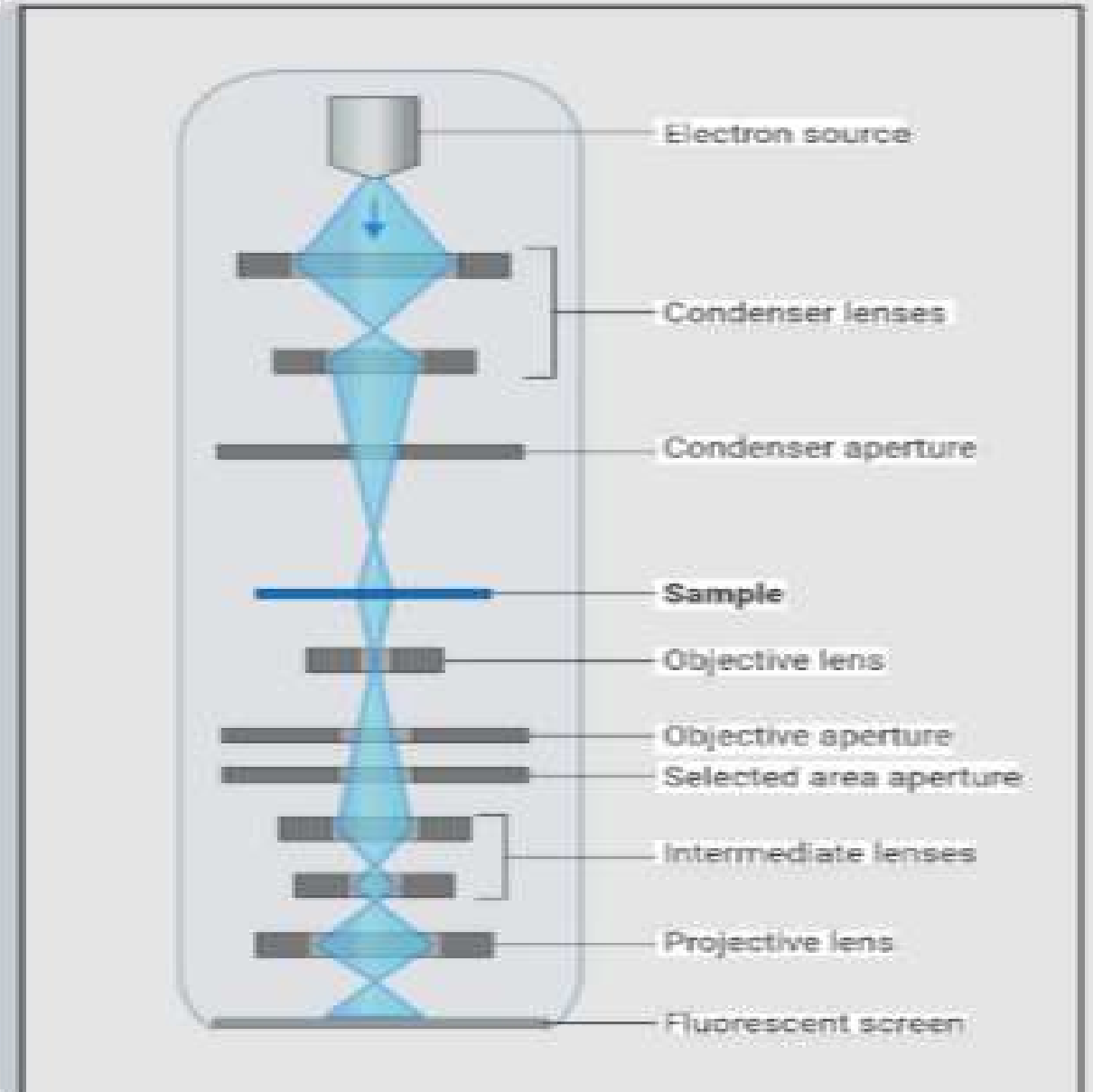
Key applications include:

1. Material Sciences: Characterization of materials, including surface morphology and structure.
2. Biology and Medicine: Observing biological samples and structures.
3. Chemistry: Various uses within chemical analysis.
4. Geology: Applications in petroleum exploration and analysis of geological samples.
5. Archaeology and Justice: Used in fields such as archaeology and forensic analysis.
6. Elemental Analysis: The integrated X-ray (EDS) Detector allows for the identification of the elemental composition of a sample.

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Transmission Electron Microscopy (TEM)





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A Transmission Electron Microscope (TEM) is an imaging tool that differs significantly in principle and design from the Scanning Electron Microscope (SEM) shown in the image.

Principle of Operation: In the SEM shown, a focused electron beam scans the surface of a sample, and secondary or back-scattered electrons are detected to form an image of the surface topography. In contrast, a TEM works much like a traditional light microscope, but uses electrons that are transmitted through an extremely thin specimen (typically 20–100 nm thick).

Image Formation: The image in a TEM is formed due to varying opacity in different parts of the specimen, which can be enhanced by staining with heavy metals. The electrons that pass through are focused by electromagnetic lenses to create a highly magnified image on a screen or detector.

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Components: While both use an electron source and lenses, the arrangement and types of detectors differ. The diagram provided shows detectors (SED, BSD, EDS) positioned around the sample surface, which is characteristic of an SEM. A TEM has its detector below the sample, capturing the transmitted beam.

Resolution and Use: TEMs offer much higher resolution and magnification (up to 1,000,000x) than SEMs, allowing for the visualization of internal structures, crystal lattices, and even individual atoms, whereas SEMs are typically used for surface morphology and composition.

Scanning Tunneling Microscopy (STM)

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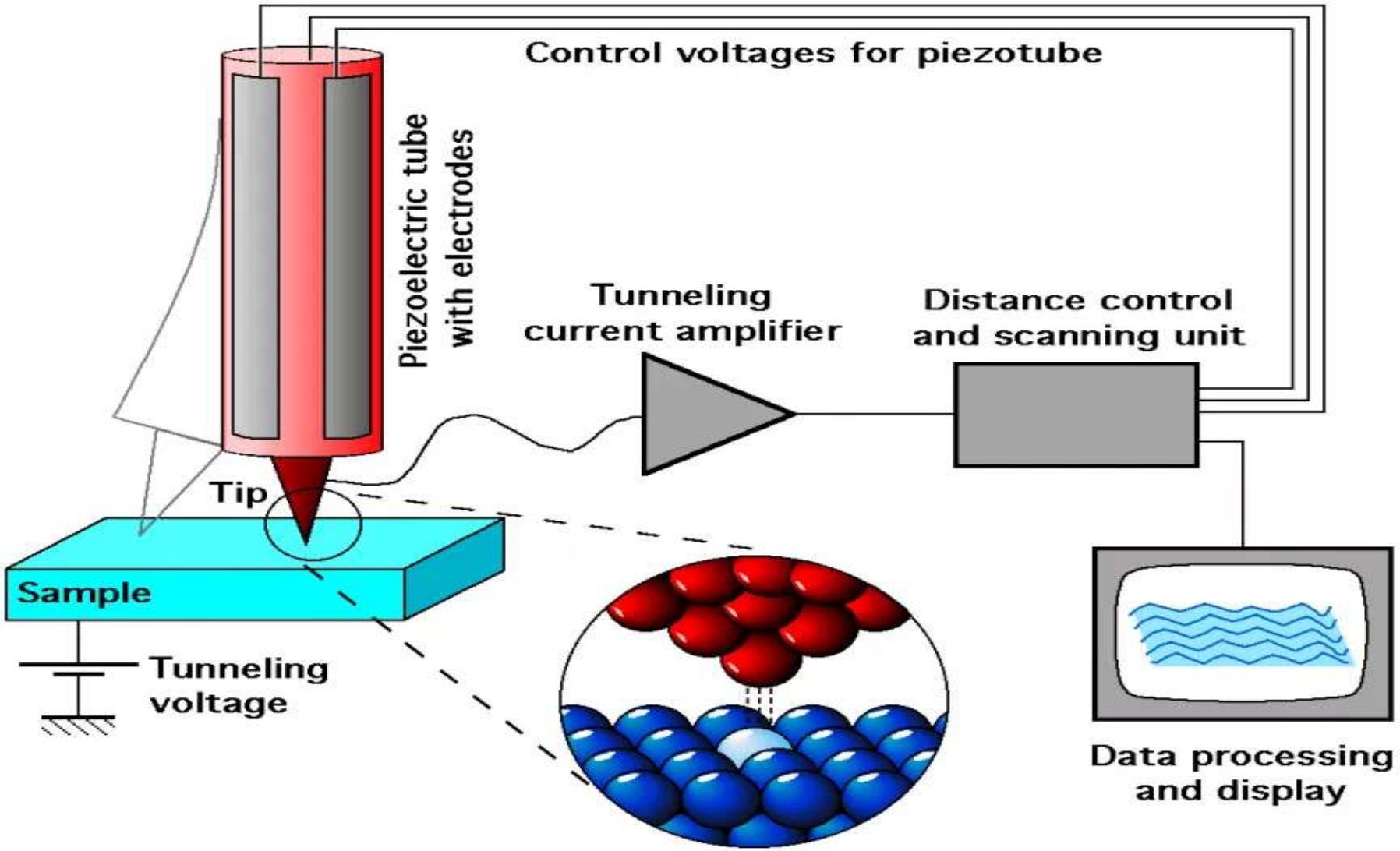
Scanning Tunneling Microscopy (STM) is an atomic-resolution imaging technique that maps surface topographies of conductive materials by measuring a quantum mechanical tunneling current between a sharp metallic tip and the sample. Invented in 1981, it allows visualization and manipulation of individual atoms, playing a crucial role In nanotechnology.

Key Principles & Operation

1. **Quantum Tunneling**: A sharp conductive tip (e.g., tungsten, platinum-iridium) is brought within angstroms of a conductive sample. When a bias voltage is applied, electrons "tunnel" across the barrier, creating a measurable current.
2. **Piezoelectric Control**: The tip is moved in the plane and adjusted in the direction with sub-angstrom precision using piezoelectric actuators.
3. **Feedback Loop**: The system keeps the current constant by adjusting the tip height, mapping the surface shape to create 3D topographies

STM

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Key Features & Applications

1. Atomic Resolution: Provides imaging at the atomic scale, enabling the visualization of individual atoms and surface atomic structures.
2. Surface Spectroscopy: Beyond imaging, STM can provide information about the local electronic density of states.
3. Atomic Manipulation: Tips can be used to move and place individual atoms on a surface, enabling the creation of novel nano-structures.
4. Applications: Essential in solid-state physics, materials science, and surface chemistry to study semiconductors, catalysts, and thin films.
5. Components
6. Scanning Tip: A sharp metallic needle (often sharpened to a single atom at the tip).
7. Piezoelectric Scanner: For precise, high-resolution movement control.
8. Vibration Isolation: Crucial to eliminate noise, allowing the instrument to operate in ultra-high vacuum (UHV) environments.

Key Components & Their Functions

1. Piezoelectric Tube with Electrodes: This is the "motor" of the microscope. Piezoelectric materials change shape when a voltage is applied. This tube can move the tip with sub-atomic precision in three dimensions
2. The Tip: Usually made of tungsten or platinum-iridium, the tip is chemically etched or mechanically formed to ideally end in a single atom.
3. Tunneling Current Amplifier: Because the tunneling current is extremely small (typically in the nanoampere range), it must be amplified and converted into a voltage to be processed.
4. Distance Control and Scanning Unit: This is the brain of the feedback loop. It monitors the tunneling current. If the current changes (meaning the distance to the surface changed), it sends control voltages back to the piezotube to move the tip up or down.
5. Tunneling Voltage: A small bias voltage applied between the tip and the sample to drive the flow of electrons.
6. Data Processing and Display: The computer records the vertical movements of the tip as it scans across the surface and These movements are then translated into a 3D topographic map of the atoms on the sample surface.

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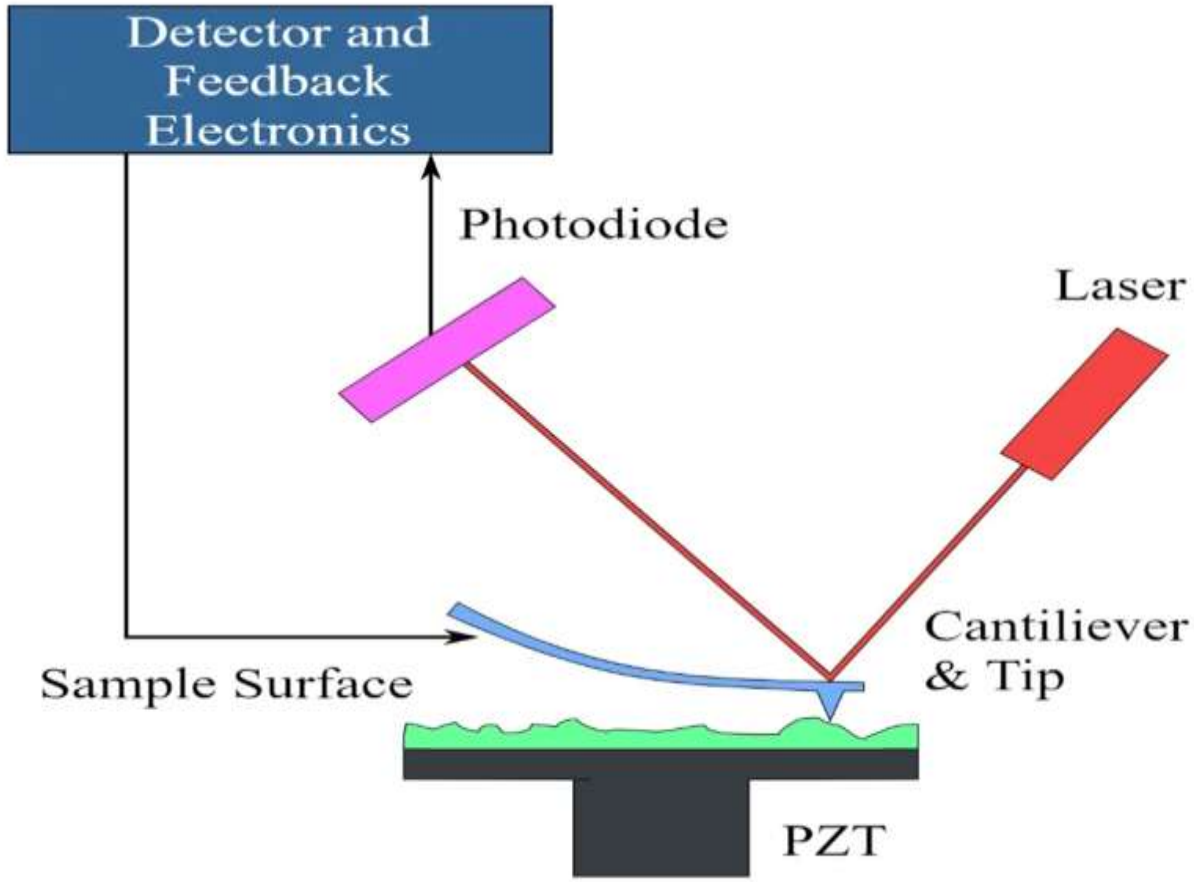
How an Image is Formed

The most common method is Constant Current Mode. As the tip scans across the sample, the feedback loop adjusts the height of the tip to keep the tunneling current constant. If the tip encounters an atom (a "bump"), it moves up to maintain the distance; if it finds a "valley," it moves down. The path the tip takes mimics the electronic contours of the surface, which we see as the final image.

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Atomic Force Microscope





The image provides a clear look at the setup and internal working principles of an Atomic Force Microscope (AFM). This powerful tool is used to "feel" surfaces at the atomic level, providing 3D topographic images with incredibly high resolution.

The Components

1. Cantilever & Tip: The heart of the AFM. The tip is extremely sharp (often only a few nanometers wide) and is attached to a flexible cantilever. As the tip moves over the sample, it deflects based on the forces between the tip and the surface.
2. Laser: A laser beam is aimed at the back of the cantilever.
3. Photodiode: The laser reflects off the cantilever onto a position-sensitive photodiode. Small movements of the cantilever cause the reflected laser spot to shift on the detector.
4. PZT (Piezoelectric Transducer): This moves the sample (or the tip) in the X, Y, and Z directions with sub-nanometer precision using electrical signals.
5. Detector and Feedback Electronics: This unit monitors the photodiode signal. If the tip moves up or down due to surface features, the feedback loop adjusts the PZT to maintain a constant force or distance.

How It Works

1. Scanning: The PZT moves the Sample Surface under the tip in a raster pattern (back and forth).
2. Interaction: As the Tip encounters "hills" or "valleys" on the surface, the Cantilever bends.
3. Detection: The Laser reflects off the bending cantilever. Even a tiny movement in the cantilever causes a large change in the laser's position on the Photodiode.
4. Feedback Loop: The Feedback Electronics sense this change and instantly move the PZT up or down to keep the cantilever's deflection constant.
5. Imaging: The computer records these vertical adjustments (Z-axis movements) and uses them to map the 3D topography of the surface.

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Key Advantages

Nanoscale Resolution: It can see features much smaller than what a traditional optical microscope can resolve (down to fractions of a nanometer).

Versatility: Unlike Electron Microscopes (which often require a vacuum), AFM can operate in air or even submerged in liquids, making it ideal for studying biological samples like DNA or living cells.

True 3D Data: It provides actual height information, not just a 2D "photo."

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Spectroscopy

is a scientific technique that involves measuring the interaction of energy, such as electromagnetic radiation, with matter to determine its composition, structure, and properties.

Principle: Spectroscopic techniques typically pass a beam of energy through a sample and analyze the results. Atoms or molecules in the sample absorb or emit radiation at specific wavelengths, which are characteristic to each substance.

Purpose: The resulting spectrum (a graph of absorbance/transmittance versus wavelength/frequency) is used to identify and quantify the components of the sample.

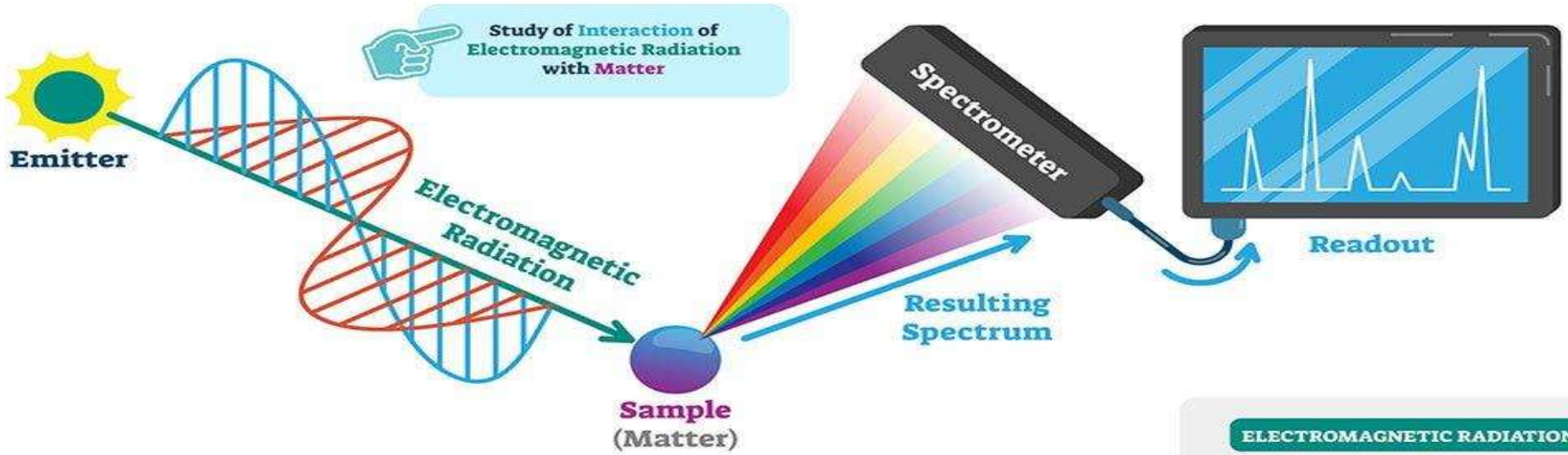
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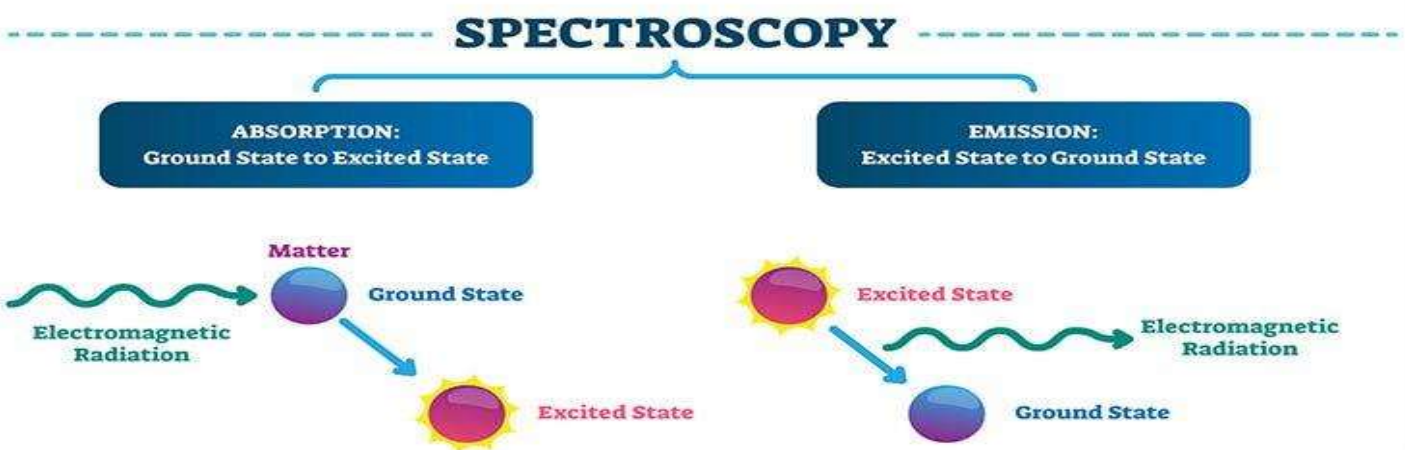
Types: Different types of energy are used depending on the application, including visible light, infrared (IR), ultraviolet, and X-rays. Examples include atomic spectroscopy, infrared spectroscopy, and force spectroscopy, which can be applied using instruments like the Atomic Force Microscope (AFM) shown in the image.

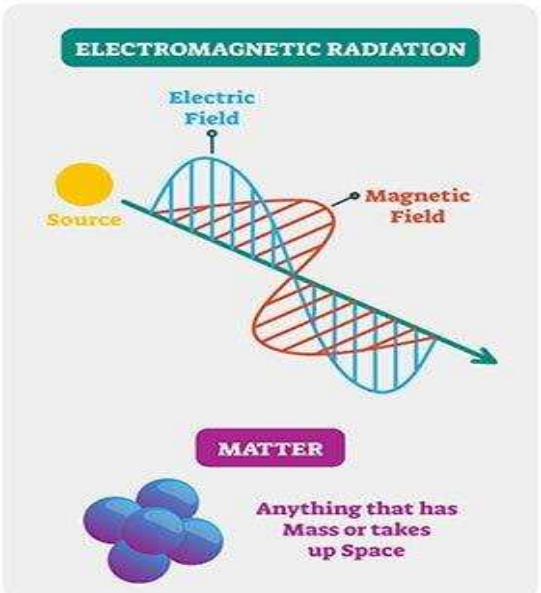
Applications: These methods are widely used across various fields, including environmental chemistry, materials science, biology, geology, and medicine.

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SPECTROSCOPY







What is EDX (Energy Dispersive X-Ray Spectroscopy)?

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EDX systems are attachments to Electron Microscopy instruments (Scanning Electron Microscopy (SEM) or Transmission Electron Microscopy (TEM)) where the imaging capability of the microscope identifies the specimen of interest. The data generated by EDX analysis consist of spectra showing peaks corresponding to the elements making up the true composition of the sample being analyzed.

In a multi-technique approach EDX becomes very powerful, particularly in contamination analysis and industrial forensic science investigations. The technique can be qualitative, semi-quantitative, quantitative and also provide spatial distribution of elements through mapping. The EDX technique is non-destructive and specimens of interest can be examined in situ with little or no sample preparation.

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An electron beam is focused on the sample in either a scanning electron microscope (SEM) or a transmission electron microscope (TEM). The electrons from the primary beam penetrate the sample and interact with the atoms from which it is made. Two types of X-rays result from these interactions: Bremsstrahlung X-rays, which means 'braking radiation' and are also referred to as Continuum or background X-rays, and Characteristic X-rays.

The X-rays are detected by an Energy Dispersive detector which displays the signal as a spectrum, or histogram, of intensity (number of X-rays or X-ray count rate) versus X-ray energy. The energies of the Characteristic X-rays allow the elements making up the sample to be identified, while the intensities of the Characteristic X-ray peaks allow the concentrations of the elements to be quantified.

How does EDX work?

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When the sample is bombarded by the SEM's electron beam, electrons are ejected from the atoms comprising the sample's surface. The resulting electron vacancies are filled by electrons from a higher state, and an x-ray is emitted to balance the energy difference between the two electrons' states. The x-ray energy is characteristic of the element from which it was emitted.

The EDS x-ray detector measures the relative abundance of emitted x-rays versus their energy. The detector is typically a lithium-drifted silicon, solid-state device. When an incident x-ray strikes the detector, it creates a charge pulse that is proportional to the energy of the x-ray. The charge pulse is converted to a voltage pulse (which remains proportional to the x-ray energy) by a charge-sensitive preamplifier. The signal is then sent to a multichannel analyzer where the pulses are sorted by voltage. The energy, as determined from the voltage measurement, for each incident x-ray is sent to a computer for display and further data evaluation. The spectrum of x-ray energy versus counts is evaluated to determine the elemental composition of the sampled volume.

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Key Principles and Components

1. Mechanism: An electron beam knocks an inner-shell electron out of an atom, leaving a vacancy. A higher-energy electron fills this hole, emitting a characteristic X-ray with energy equivalent to the difference between the electron shells.
2. Detector: Modern systems use a Silicon Drift Detector (SDD) to measure the energy and count of these X-rays, allowing fast, high-throughput analysis.
3. Data Representation: Data is displayed as a spectrum of X-ray counts versus energy (keV), with peaks identifying specific elements present.

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Key Features and Capabilities

1. Elemental Mapping: Visualizes the spatial distribution of elements within a sample's microstructure.
2. Sensitivity: Can detect elements at concentrations as low as 100 ppm, although typically used for bulk analysis.
3. Resolution: When used with an SEM, the spatial resolution is typically on the order of 1 µm,whereas TEM can achieve 0.1 µm
4. Limitations: Generally, standard EDX cannot detect elements lighter than beryllium

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Applications

1. Material Analysis: Identification of metals, polymers, and failures in materials research.
2. Geology: Mineral identification and petrography.
3. Biological Studies: Element mapping in tissues and cells.
4. Archaeology: Analysis of artifacts for conservation.