Module 4

WELDING, BRAZING, SOLDERING

Metal joining process that uses melted metal as joints

Brazing & soldering: joining two different/similar metals using a third filler material into the joint in liquid state & allowed to solidify.

Brazing differs from soldering →in the melting temp. of the filler

Brazing - only the filler is melted →wets the materials to be joined

- temperature: 430^0 C – 800^0 C

Soldering – same as brazing; temperature range: 100^0 C – 450^0 C

Strength of joint determined by the adhesive quality of the filler

Welding – original materials are melted and joined → solidified

Mainly from Chapter 39:

Arranged according to the subject flow.

Joinability/Weldability

- Wettability: Hydrophobic or Hydrophilic
- Fluidity: Gap, Surface tension, material.
- Cleanliness: Oxide removal, etc.
- Prevention from further oxidation/Contamination

TABLE 37-3. Some Common Solders and Their Properties

Composition (wt %)	Freezing Temperature (°F) Liquidus	Solidus	Range	Applications
Lead–tin solders				
98 Pb–2 Sn	611	601	10	Side seams in three-piece can
90 Pb–10 Sn	576	514	62	Coating and joining metals
80 Pb–20 Sn	531	361	170	Filling and seaming auto bodies
70 Pb–30 Sn	491	361	130	Torch soldering
60 Pb–40 Sn	460	361	99	Wiping solder, radiator cores, heater units
50 Pb–50 Sn	421	361	60	General purpose
40 Pb–60 Sn	374	361	13	Electronic (low temperature)
Silver solders				
97.5 Pb–1 Sn–1.5 Ag	588	588	0	Higher-temperature service
36 Pb–62 Sn–2 Ag	372	354	18	Electrical
96 Sn–4 Ag	430	430	0	Electrical
Other alloys				
45 Pb–55 Bi	255	255	0	Low temperature
43 Sn–57 Bi	281	281	0	Low temperature
95 Sn–5 Sb	464	450	14	Electrical
50 Sn–50 In	257	243	14	Metal-to-glass
37.5 Pb–25 In–37.5 Sn	280	280	0	Low temperature

TABLE 39-4. Some Common Solders and Their Properties

Composition (wt %)	Freezing Temperature (°C) Liquidus	Solidus	Range	Applications
Lead–tin solders				
98 Pb–2 Sn	322	316	6	Side seams in three-piece can
90 Pb–10 Sn	302	268	34	Coating and joining metals
80 Pb–20 Sn	277	183	94	Filling and seaming auto bodies
70 Pb–30 Sn	255	183	72	Torch soldering
60 Pb–40 Sn	238	183	55	Wiping solder, radiator cores, heater units
50 Pb–50 Sn	216	183	33	General purpose
40 Pb–60 Sn	190	183	7	Electronic (low temperature)
Silver solders				
97.5 Pb–1 Sn–1.5 Ag	308	308	0	Higher-temperature service
36 Pb–62 Sn–2 Ag	189	179	10	Electrical
96 Sn–4 Ag	221	221	0	Electrical
Other alloys				
45 Pb–55 Bi	124	124	0	Low temperature
43 Sn–57 Bi	138	138	0	Low temperature
95 Sn–5 Sb	240	234	6	Electrical
50 Sn–50 In	125	117	8	Metal-to-glass
37.5 Pb–25 In–37.5 Sn	138	138	0	Low temperature
95.5 Sn–3.9 Ag–0.6 CO	217	217	0	Electrical

Soldering joints : soft → types:

1. Tin & Lead (60:40, 50:50, 40:60) – $t_f \cong 240^0$ C
2. Lead & Silver (97:3) → $t_f \cong 310^0$ C

For filling → 20/30 % tin – lead composition – cheaper

Cleanliness – Critical to the strength of the joint
Oxide have to be removed from the surfaces before joining

Cleaning methods 1. Using fluxes (chemical action)
2. Abrasive removal (mechanical action)
3. Ultrasonic cleaning (acoustic action)

Fluxless Soldering: Gold coated, Ultrasonic, Inert atmosphere.

Heating:- required to melt the filler (by any method: furnaces, torch, electrical resistance)

•Typical, the use of soldering iron heat is applied from the iron and solder is melted and it adheres to the surface of the joint (usually, as a wire)

•The joined parts should be also heated to improve the joining process

•Ultrasonic soldering →the soldering iron is actuated with 20KHz

SOLDERING JOINTS:

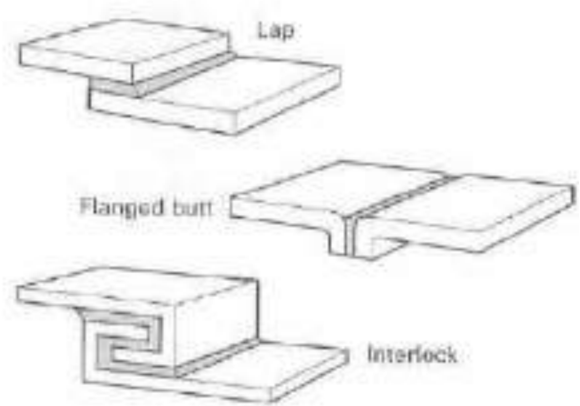


FIGURE 37-8 Some common designs for soldered joints. *(Courtesy of Lead Industries Association.)*

BRAZING: **Similar to soldering but at temp > 450^0 C, still lower than melting temperature of the brazed metal parts.**

Here, the capillary attraction is driving the filler metal into the joint (clearance is very small)

For different fillers →different recommended clearances to improve the strength of the joint

- **Copper → no clearance**
- **silver alloy → 0.04 – 0.05 mm**
- **brass → 0.5 – 0.75 mm**

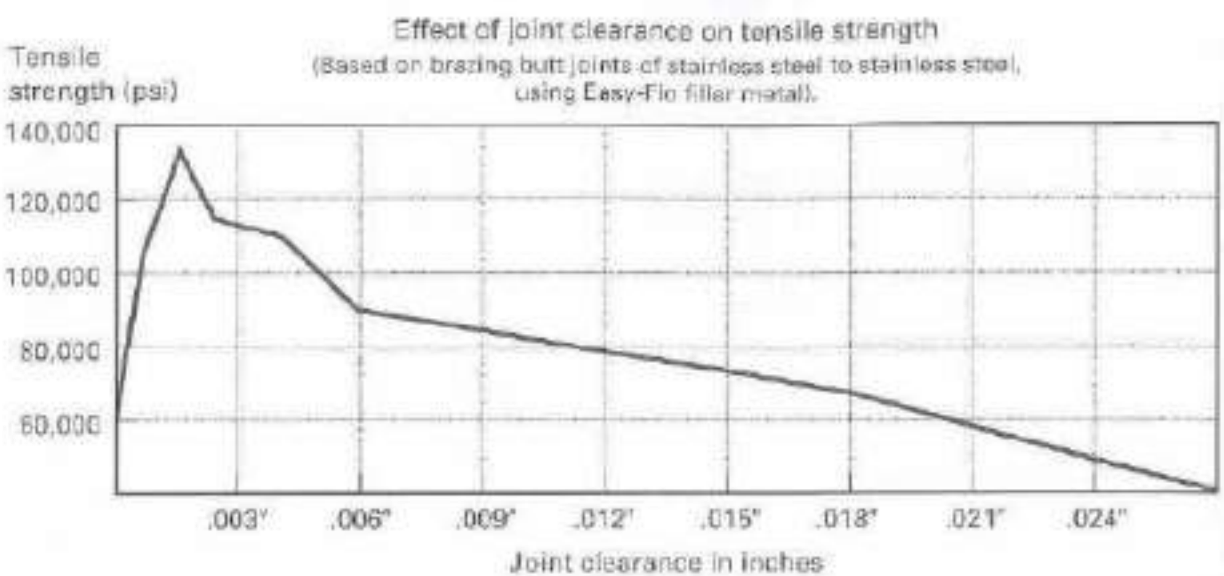
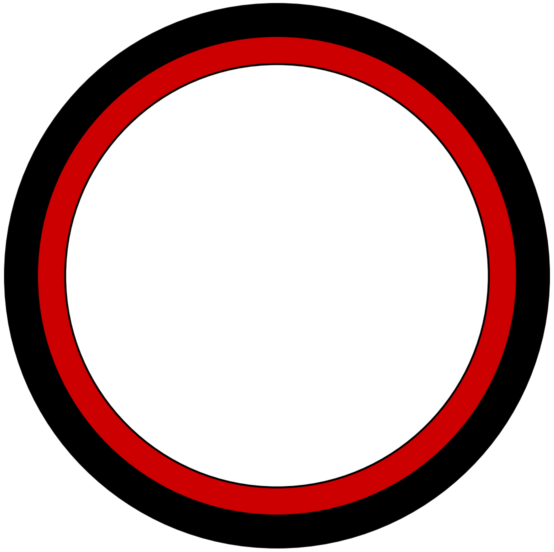


FIGURE 37-1 Typical variation of tensile strength with different joint clearances in a butt joint design. *(Courtesy of Handy & Harman).*

- The clearances are estimated at the brazing temperature.
- Estimate the initial dimensions based on the expansion coefficient→ gap or interference



BRAZE WELDING →a joining process where the capillary attraction is not used to distribute the filler metal. The molten filler is deposited before brazing is done.

→ special fluxes are used (Borax) to: remove the oxide
improve the fluidity of the fillers
wet the joint surfaces

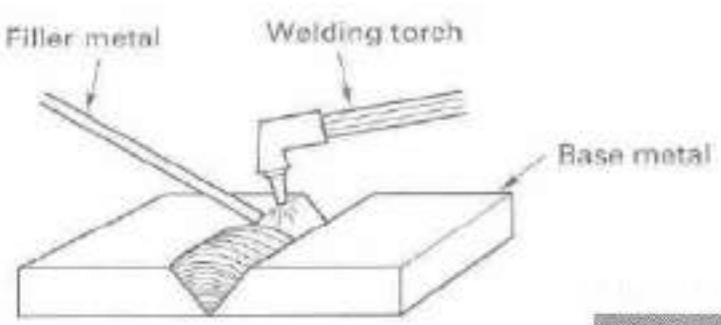


FIGURE 37-7 Schematic of the braze welding process.

TABLE 37-2. Engineering Materials and Their Compatibility with Brazing

Material	Brazing Recommendation
Cast iron	Somewhat difficult
Carbon and low-alloy steels	Recommended for low- and medium-carbon materials; difficult for high-carbon materials; seldom used for heat-treated alloy steels
Stainless steel	Recommended; Silver and nickel brazing alloys are preferred
Aluminum and magnesium	Common for aluminum alloys and some alloys of magnesium
Copper and copper alloys	Recommended for copper and high-copper brasses; somewhat variable with bronzes
Nickel and nickel alloys	Recommended
Titanium	Difficult, not recommended
Lead and zinc	Not recommended
Thermoplastics, thermosets, and elastomers	Not recommended
Ceramics and glass	Not recommended
Dissimilar metals	Recommended, but may be difficult, depending on degree of dissimilarity
Metals to nonmetals	Not recommended
Dissimilar nonmetals	Not recommended

TABLE 39-2. Some Common Braze Metal Families, Metals They Are Used to Join, and Typical Brazing Temperatures

Braze Metal Family	Materials Commonly Joined	Typical Brazing Temperature (°C)
Aluminum-silicon	Aluminum alloys	565–620
Copper and copper alloys	Various ferrous metals as well as copper and nickel alloys and stainless steel	925–1150
Copper-phosphorus	Copper and copper alloys	700–925
Silver alloys	Ferrous and nonferrous metals, except aluminum and magnesium	620–980
Precious metals (gold-based)	Iron, nickel, and cobalt alloys	900–1100
Magnesium	Magnesium alloys	595–620
Nickel alloys	Stainless steel, nickel, and cobalt alloys	925–1200

Brazing Materials:

copper alloys
silver alloys
aluminium alloys

Basic joint types in brazing:

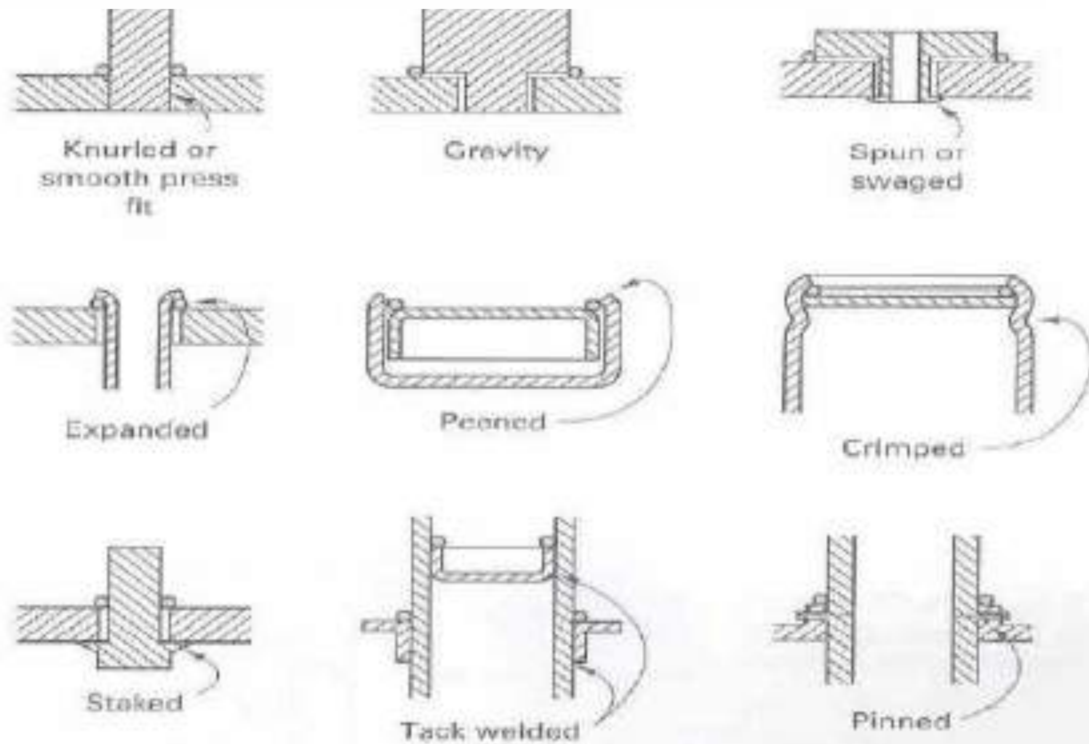


FIGURE 37-2 Methods of applying braze metal and positioning or fixturing various joints.

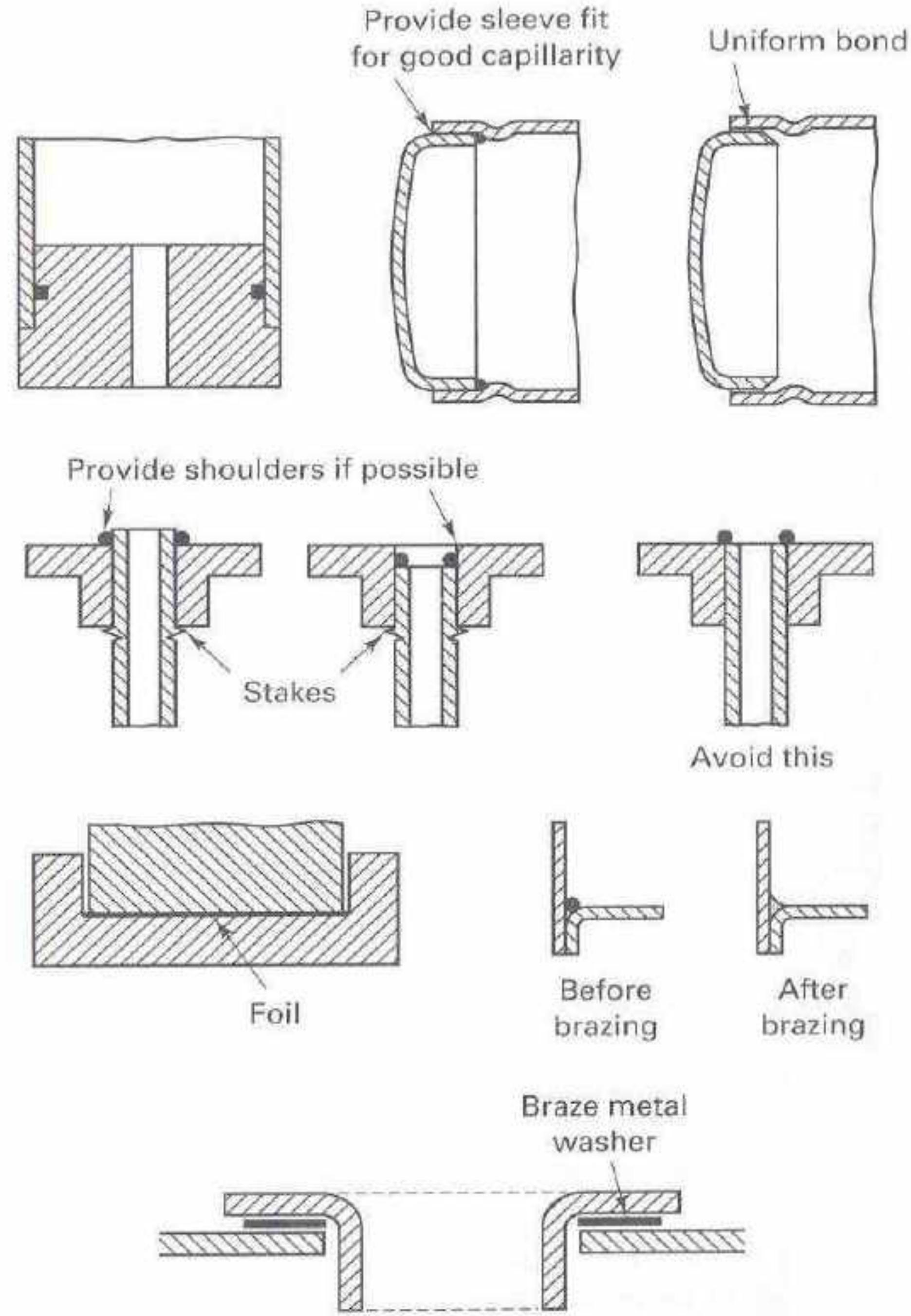


FIGURE 37-3 Techniques to apply brazing wire, foil, or sheet to assure proper flow into the joint.

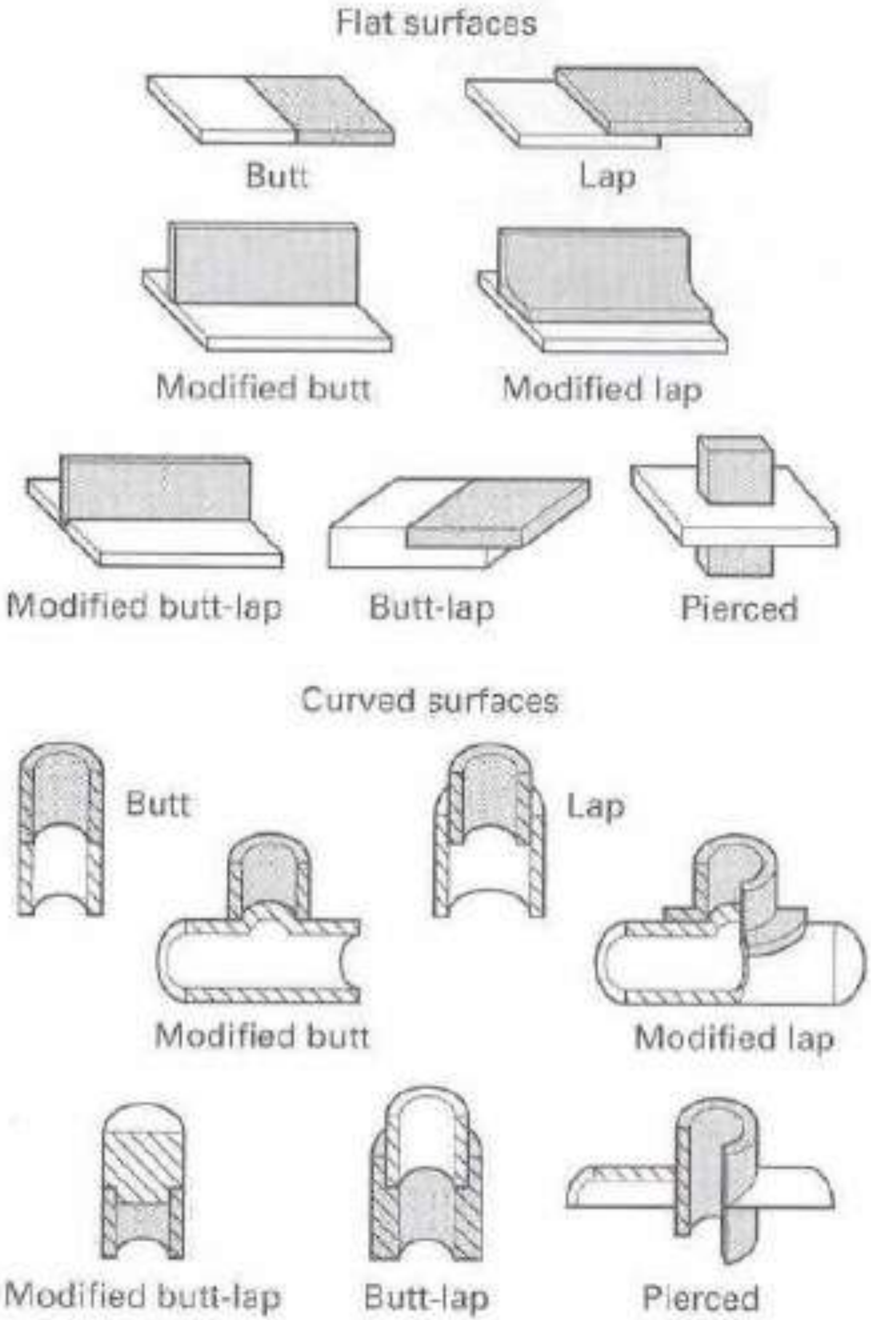


FIGURE 37-5 Some common designs of brazed joints for flat and curved surfaces. *(Adapted from* The Brazing Book, *Handy & Harman).*

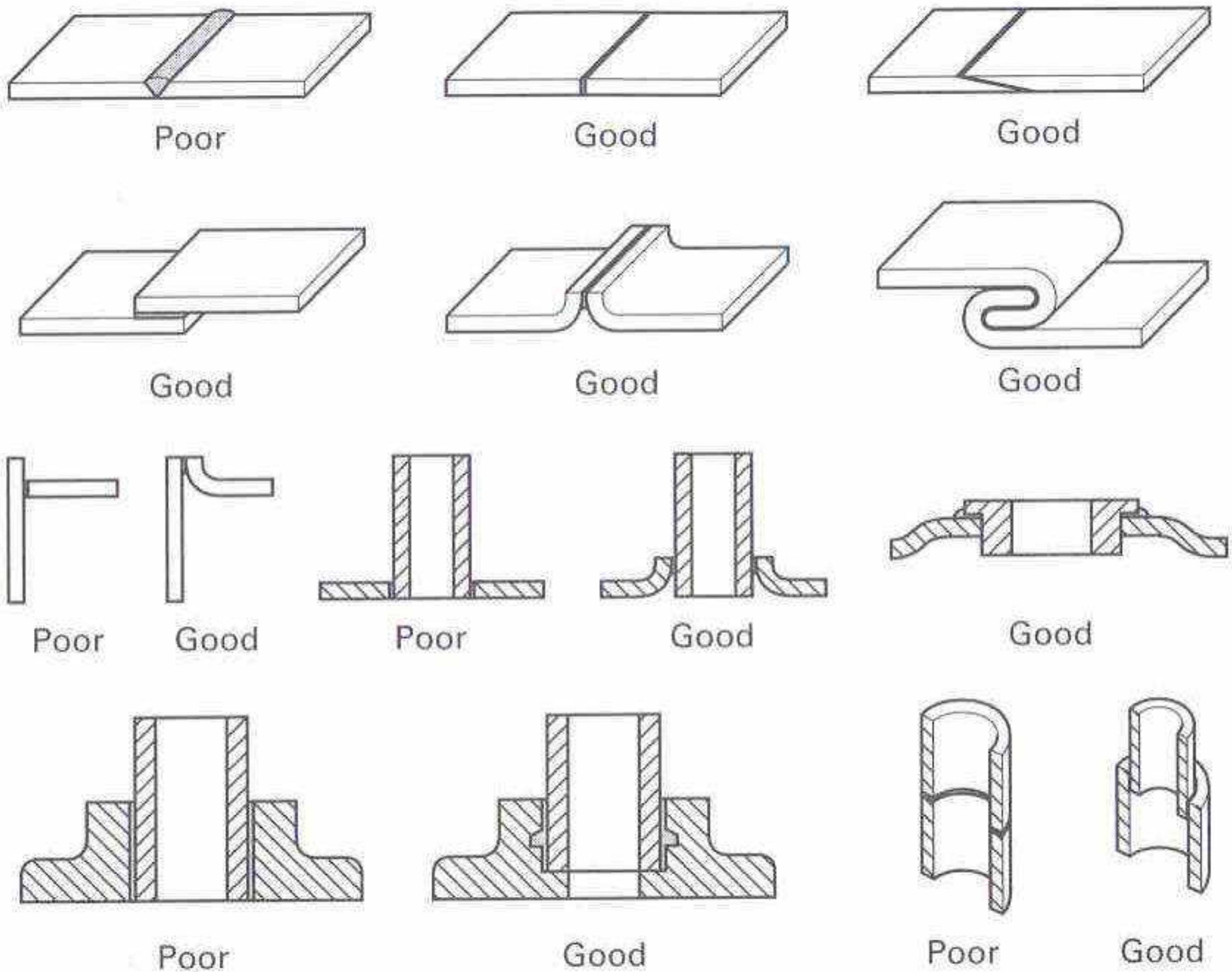


FIGURE 37-6 Examples of good and bad joint design for brazing.

Quality of joints:

Rule of thumb: stronger joints for larger contact area
stronger joints for optimal clearance
stronger joints for appropriate brazing material

Brazing of pipes – in hydraulic works, can be performed in different ways →
Induction brazing (brazing process named by the method that is used to heat assembly), furnace, dipping, torch, electric

The brazing operation must be preceded by cleaning and setting of the proper gap [jigs are used to hold the parts at their position during brazing]

Typical Process Assembly of pipes, carbide tips, radiators, heat exchangers, repair of casting

FIGURE 37-4 Typical furnace-brazed assemblies. *(Courtesy of Pacific Metals Company.)*

Chapter 35

WELDING

Metal joining process – without different metal added between.

Coalescence– can be obtained by heat and/or pressure, metallurgical conditions

BY HEAT → hot welding (melted partly at the joint)

BY PRESSURE →metallurgical process at the level of the intermolecular forces
→ cold welding (attraction forces between atoms at the contact surface)

PROBLEMS:

- **Keeping weld clean – coalescence is improved by cleanliness of surface to be welded**
- **Surface oxides –removed before welding → fluxes are used during the welding, the fluxes burn and produce *slag* → because they float as slag on the molten metal and protect it from atmospheric contamination (made of SiO_2 + additives).**
- **In gas welding, the filler metal rod is often coated with flux**
- **In electrical arc – welding – the electrode is coated with flux or the flux is added as powder over the welding seem**
- **A non – oxidising atmosphere is created and the welding is shielded against oxygen (oxidation)**
- **Inert gasses used to protect the weld created from oxygen**

CLASSIFICATION

FIGURE 33-1 Classification of common welding processes along with their AWS (American Welding Society) designations.

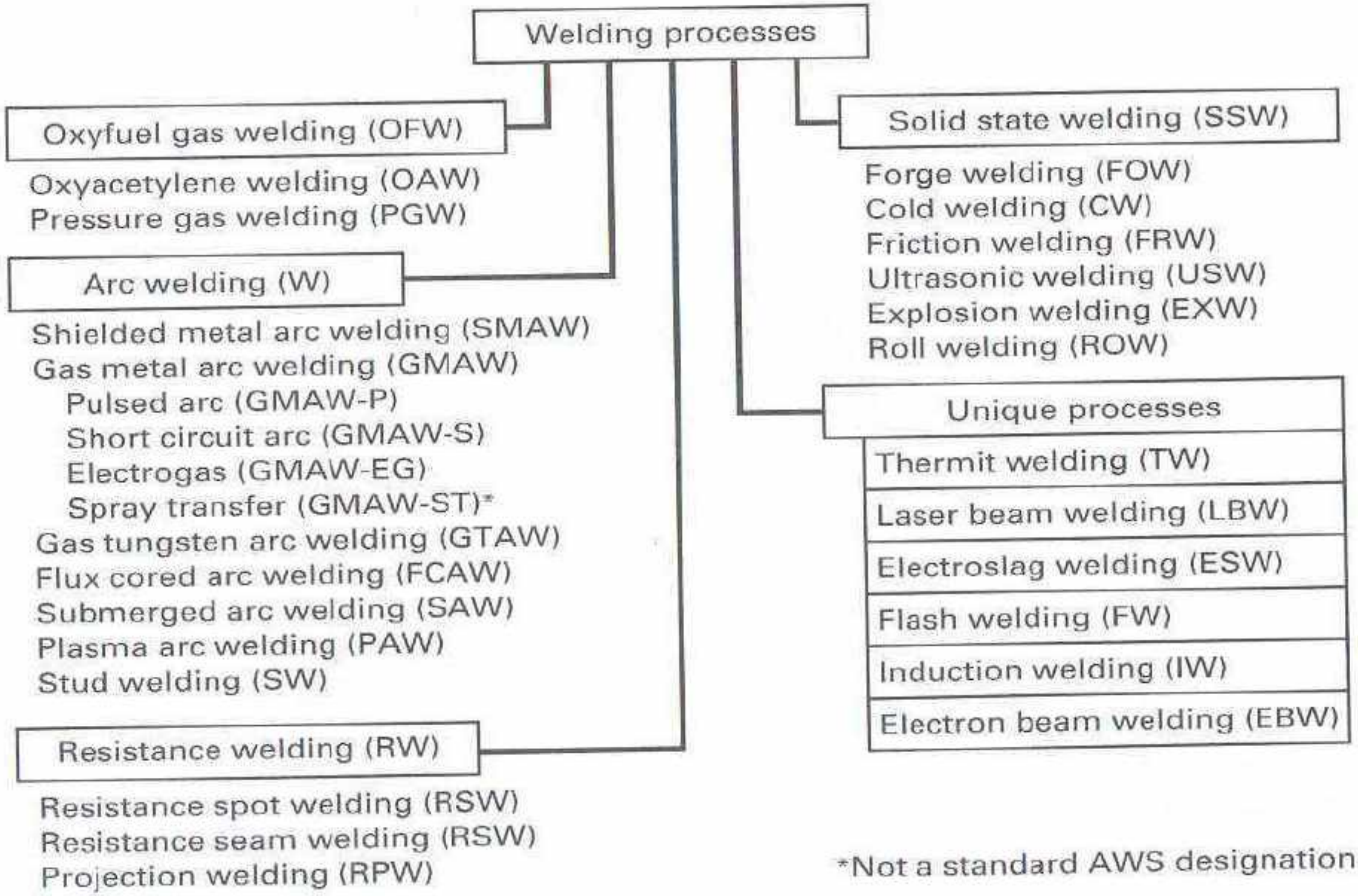
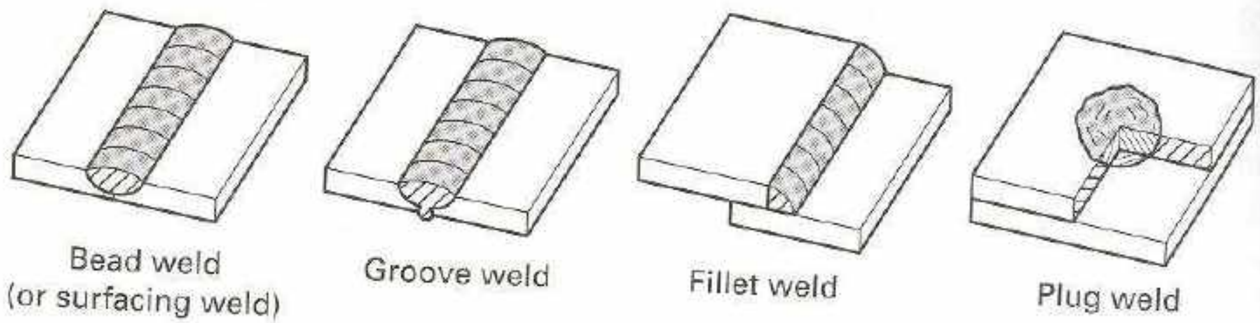


FIGURE 35-3 Four basic types of fusion welds.



... solidified from the molten state.

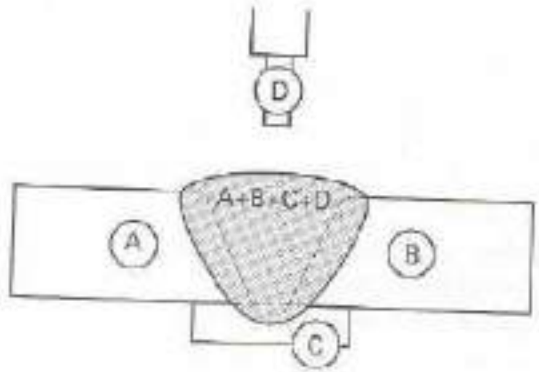
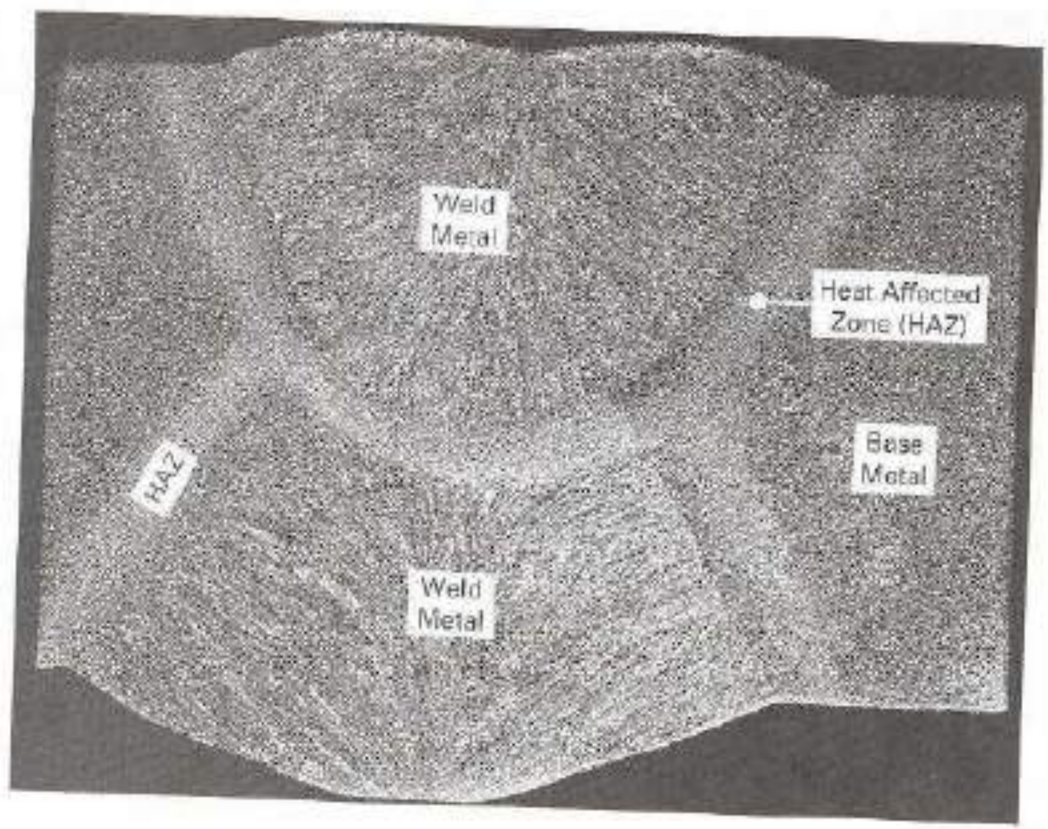
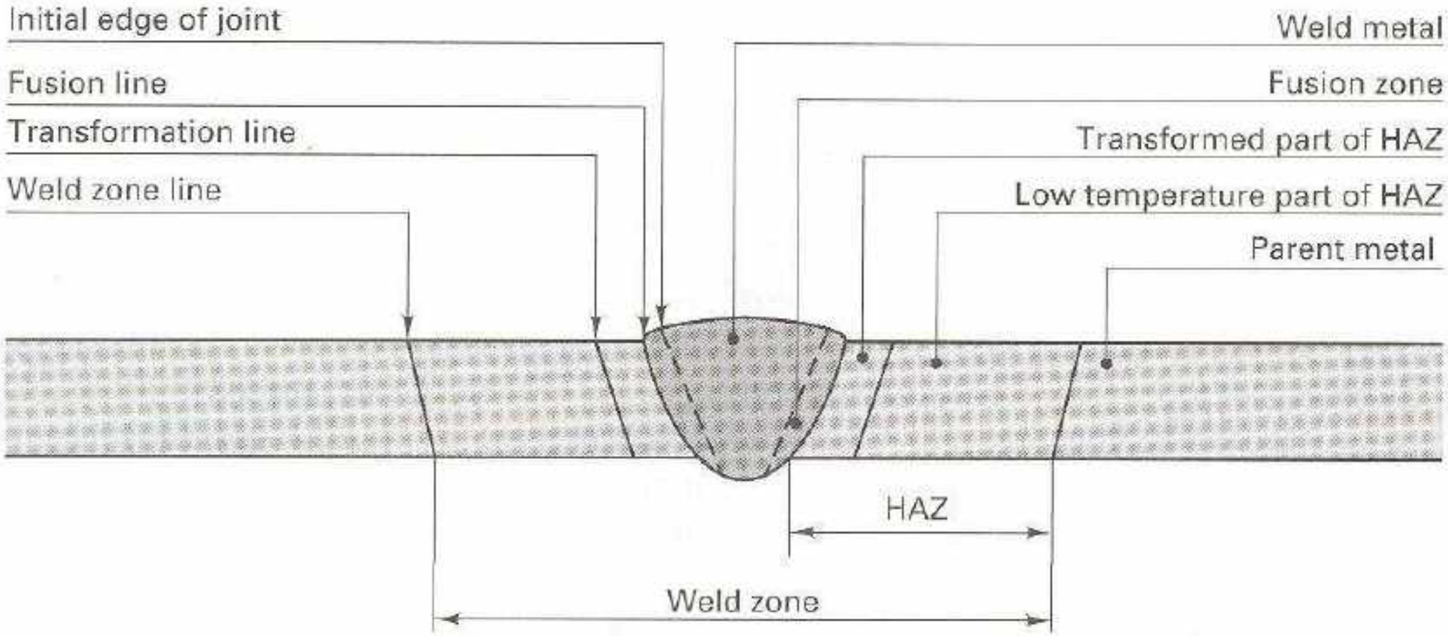


FIGURE 35-9 Schematic of a butt weld between a plate of metal A and a plate of metal B, with a backing plate of metal C and filler of metal D. The resulting weld nugget becomes a complex alloy of all four metals.



GURE 35-10 Grain structure d various zones in a fusion eld.

hematic of a
presenting
or the various
s. Part of the
is been
nsformation
form a new
g. The
f the heat-
nces heat
l structure.



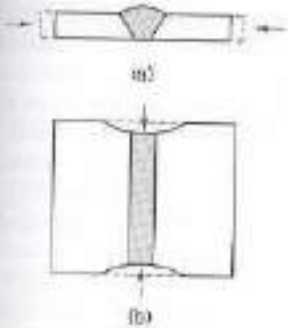


FIGURE 35-14 Shrinkage of a typical butt weld in the transverse (a) and longitudinal (b) directions as the material responds to the induced stresses. Note that restricting transverse motion will place the entire weld in transverse tension.

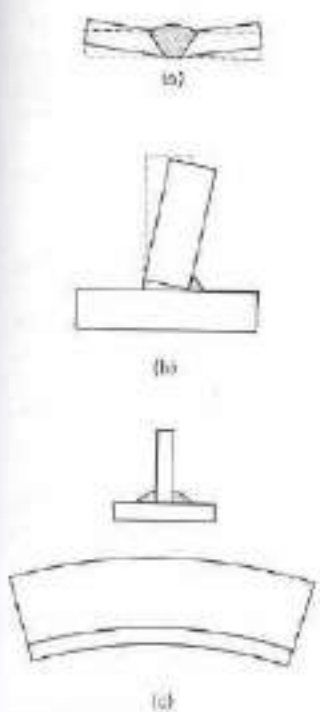


FIGURE 35-15 Distortions or warpage that may occur as a

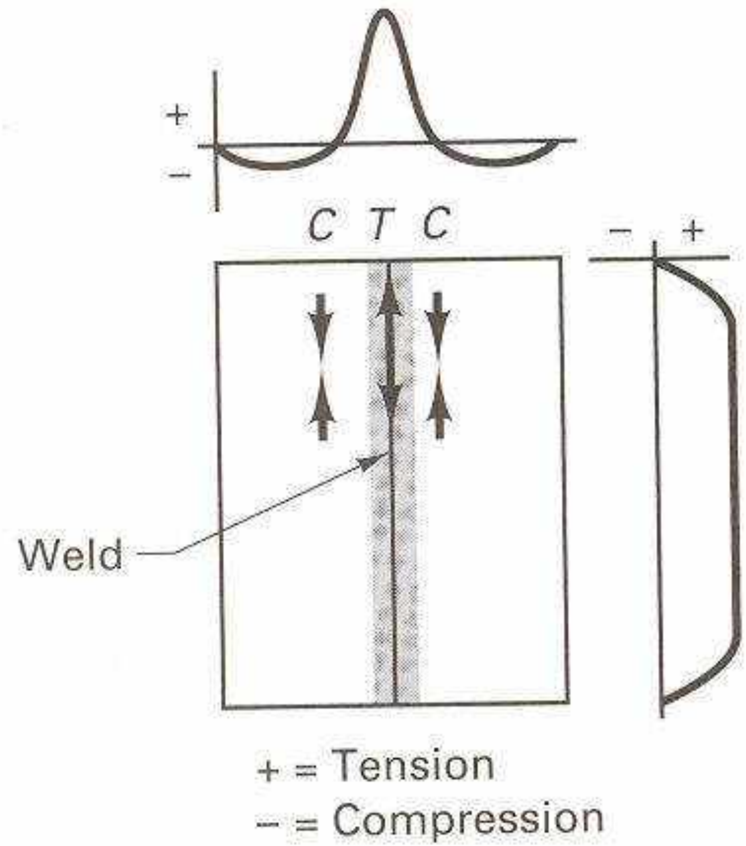


FIGURE 35-13 Schematic of the longitudinal residual stresses in a fusion-welded butt joint.

TABLE 35-2 Weldability or Joinability of Various Engineering Materials[a]

Material	Arc Welding	Oxyacetylene Welding	Electron Beam Welding	Resistance Welding	Brazing	Soldering	Adhesive Bonding
Cast iron	C	R	N	S	D	N	C
Carbon and low-alloy steel	R	R	C	R	R	D	C
Stainless steel	R	C	C	R	R	C	C
Aluminum and magnesium	C	C	C	C	C	S	R
Copper and copper alloys	C	C	C	C	R	R	C
Nickel and nickel alloys	R	C	C	R	R	C	C
Titanium	C	N	C	C	D	S	C
Lead and zinc	C	C	N	D	N	R	R
Thermoplastics	Heated tool R	Hot gas R	N	Induction C	N	N	C
Thermosets	N	N	N	N	N	N	C
Elastomers	N	N	N	N	N	N	R
Ceramics	N	S	C	N	N	N	R
Dissimilar metals	D	D	C	D	D/C	R	R

[a]C, commonly performed; R, recommended (easily performed with excellent results); D, difficult; N, not used; S, seldom used.

Chapters 36, 37 and 38

WELDING PROCESSES

1. FORGE WELDING (FOW)

- **Welding with use of pressure & heat – not much in use today**
- **Hot metal are hammered together until welded (but not melted)**

2 COLD WELDING (CW) – no heat is used → coalescence through rapid application of pressure

- **Surface must be very clean, flat in order to bring the atoms of metal very close**
- **Done by a punch-press or hammer – a kind of cold working process**

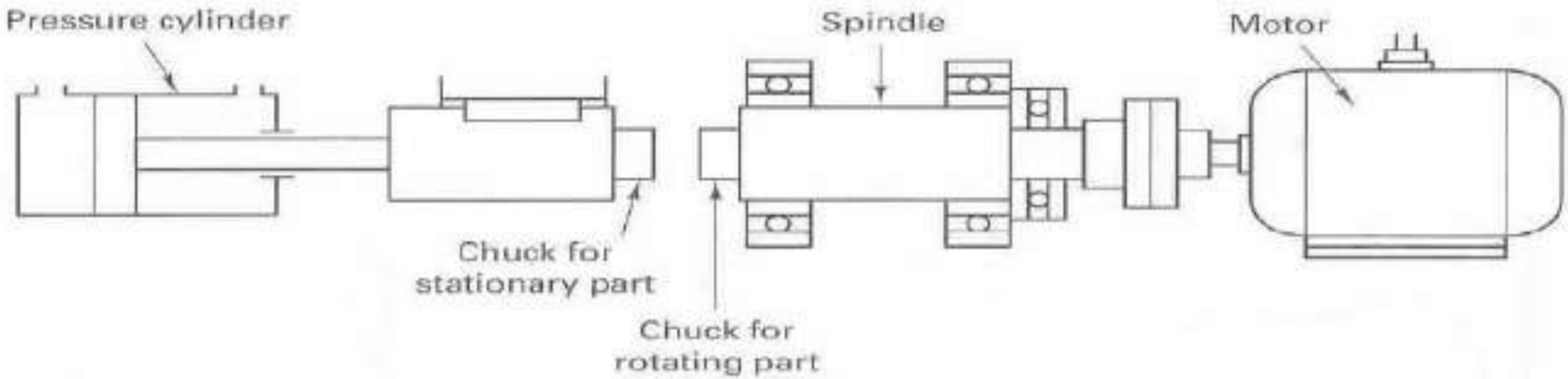


FIGURE 36-3 Schematic diagram of the equipment used for friction welding. *(Courtesy of Materials Engineering.)*

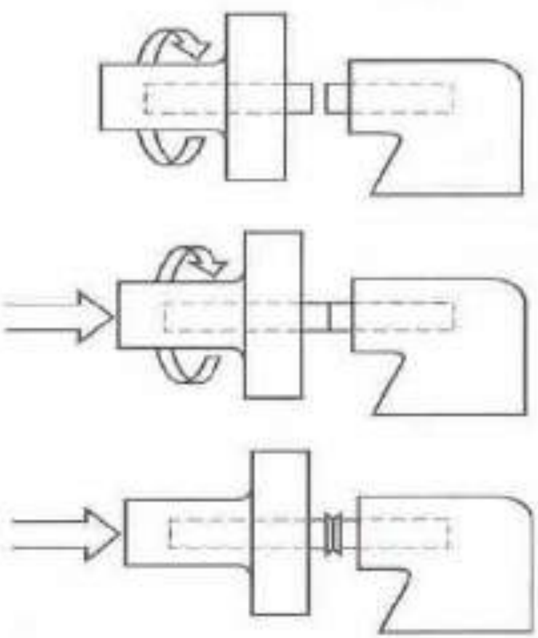
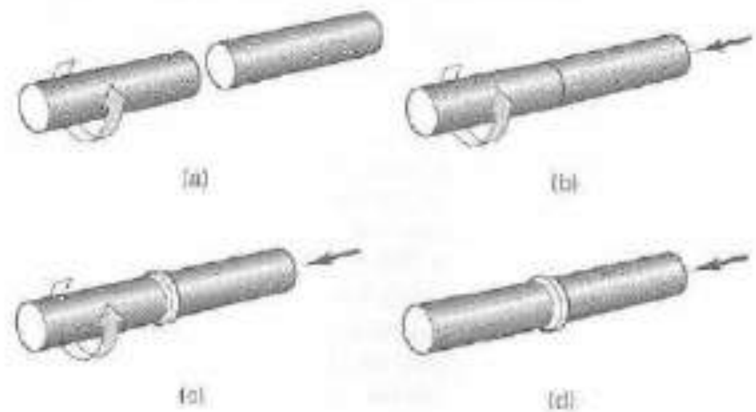


FIGURE 36-4 Schematic representation of the three steps in inertia welding.

FIGURE 36-2 Sequence for making a friction weld. (a) Components with square surfaces are inserted into a machine where one part is rotated and the other is held stationary. (b) The components are pushed together with a low axial pressure to clean and prepare the surfaces. (c) The pressure is increased, causing an increase in temperature, softening, and possibly some melting. (d) Rotation is stopped and the pressure is increased rapidly, creating a forged joint with external flash.



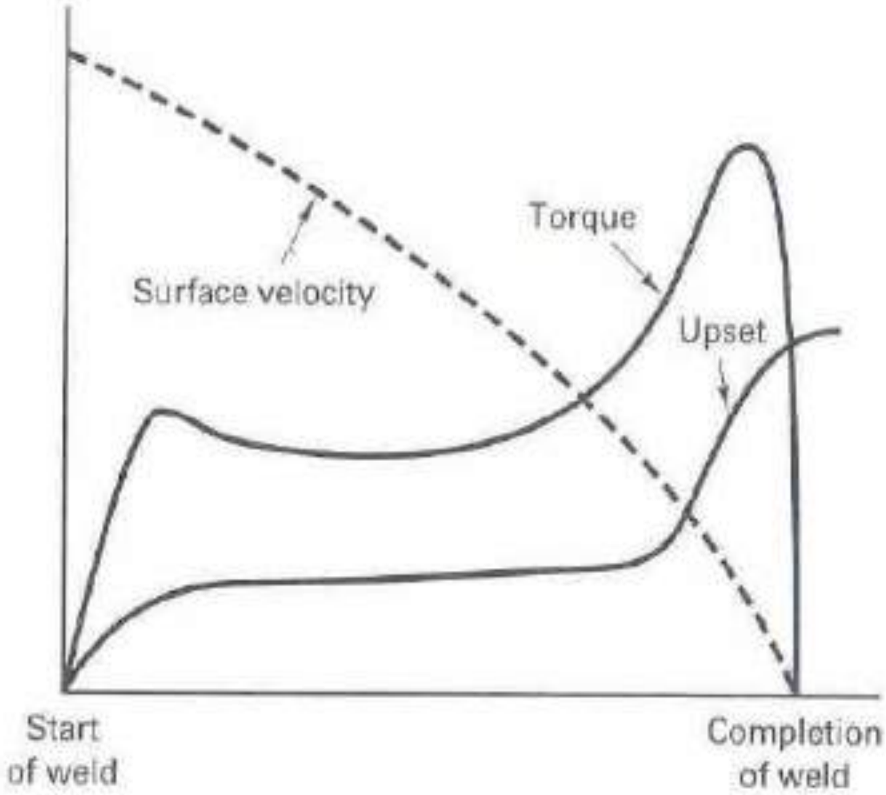


FIGURE 36-5 Relationship between surface velocity (speed), torque, and upset throughout the inertia welding process.

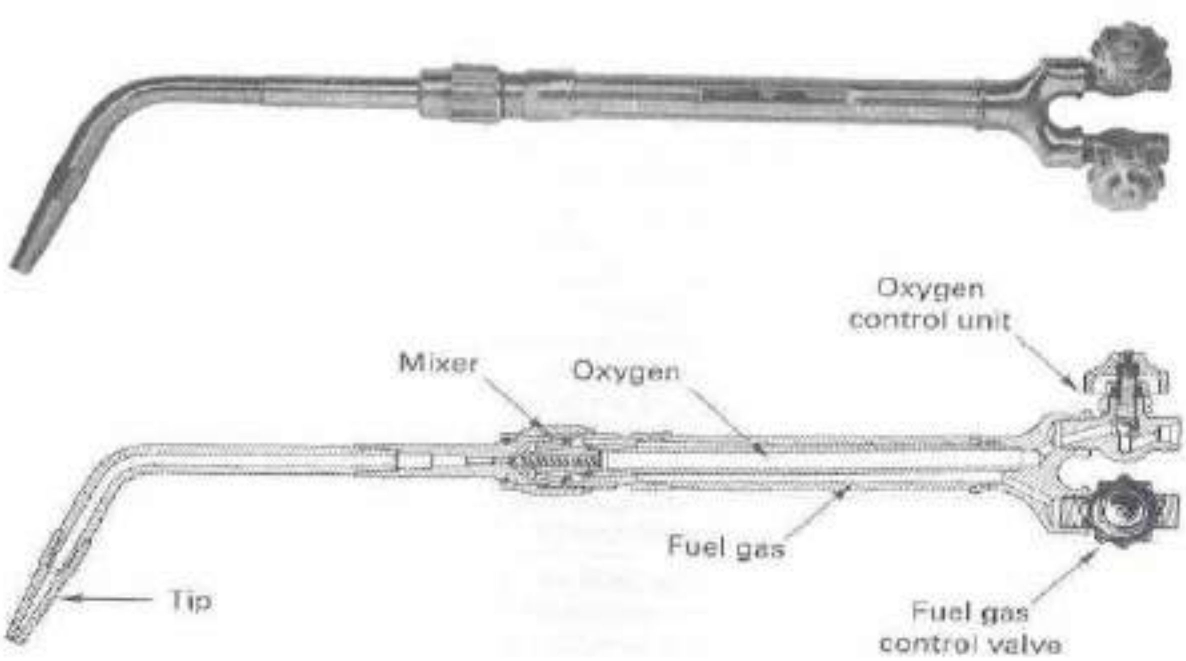
FIGURE 36-6 Some typical friction-welded parts. (*Left*) Impeller made by joining a chrome–moly steel shaft to a nickel–steel casting. (*Center*) Stud plate with two mild steel studs joined to a square plate. (*Right*) Tube component where a turned segment is joined to medium-carbon steel tubing. *(Courtesy of Newcor Bay City, Div. of Newcor, Inc.)*

3. OXYFUEL GAS WELDING (OFW):old method → metals are heated with a flame produced from reaction of oxygen with acetylene

+ use of a filler – metal to fill the gap (the same metal)

- to a state of fusion → no pressure is used
- Oxygen → from air → stored in steel cylinders at a pressure of 2000 psi (140 bar)
- acetylene gas (C_2H_2)- obtained from reaction between calcium carbide + water (or in bottles (cylinders) – 250 psi /17 bar)
- mixing & burning of acetylene + oxygen → torch (the flow controlled by valves)

FIGURE 33-2 Typical oxyacetylene welding torch and cross-sectional schematic. *(Courtesy of Victor Equipment Company.)*



• **pure oxygen provides a flame with temperature much higher than using air (up to 3500^0 C)**

Combustion reactions:

Primary: 3500°C 1. $C_2H_2 + O_2 = 2CO + H_2$ -> very high temp. @ cone of flame

Secondary: 2. $2CO + O_2 = 2CO_2$ -> outside the cone

2'. $H_2 + 1/2\ O_2 = H_2O$ -> from atmosphere

- **Control of the flow rates of oxygen and acetylene – very important.**
  This affects the characteristic of the flame which depends on O_2/C_2H_2 ratio

- **Three types of flame can be obtained:**
  REDUCING, NEUTRAL & OXIDIZING

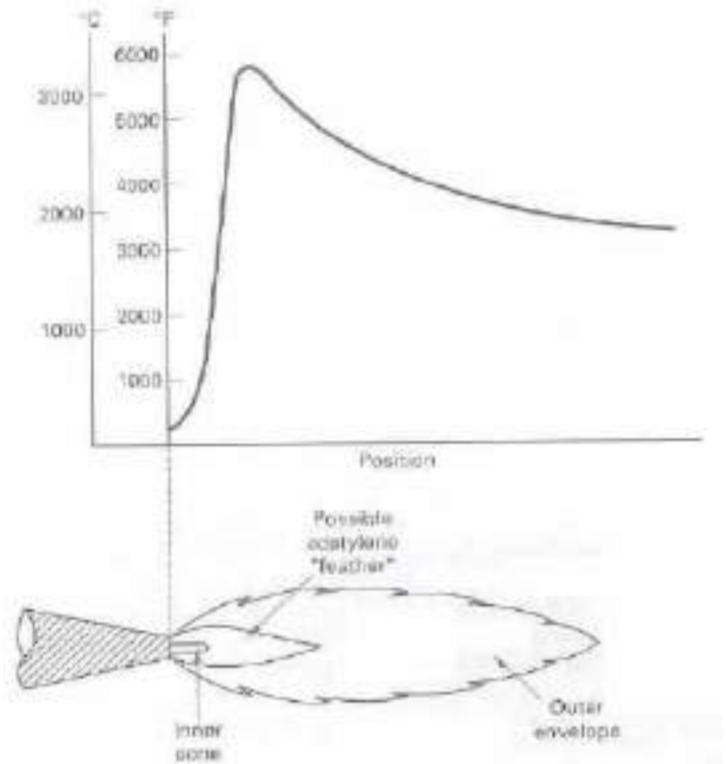


FIGURE 33-3 Typical oxyacetylene flame and the associated temperature distribution.

NEUTRAL flame → the widest application : the inner luminous cone has 1:1 ratio (stochiometric) of O_2 and C_2H_2

- **First part of reaction ($C_2H_2 + O_2 = 2CO + H_2$) occurs near the torch tip**

- **SAFETY – a real problem: eye protection from the radiation + explosion**
  Ex: C_2H_2 fitting has left hand valve and O_2 right hand thread, to avoid mistakes.

- **Utilisation: gas –flame welding largely replaced by arc or resistance welding except for repair work, field welding or some special applications (thin metal sheet welding, artistic welding)**

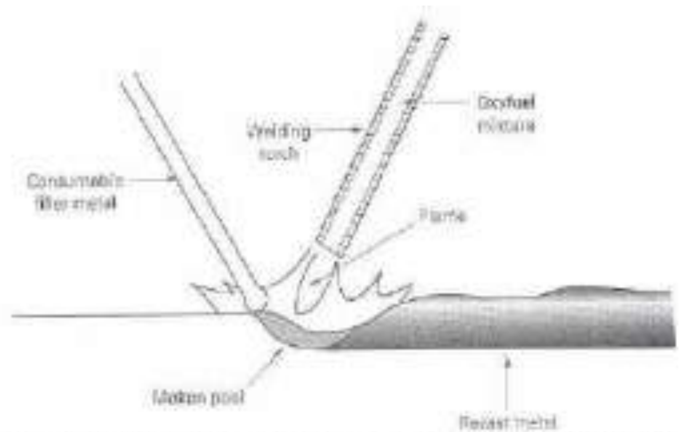


FIGURE 33-6 Schematic of oxyfuel gas welding with a consumable welding rod.

ADVANTAGES:

by gas welding even with thin materials, temperatures can be easily controlled

DISADVANTAGES:

exposure of heated metal to various gases from the atmosphere,
without shielding →contamination;

distortion of thin metal parts (non uniform heating)

more expensive→replaced by shielded metal arc welding & inert gas metal welding

TABLE 33-1 Engineering Materials and Their Compatibility with Oxyfuel Welding

Material	Oxyfuel Welding Recommendation
Cast iron	Recommended with cast iron filler rods; braze welding recommended if there are no corrosion objections
Carbon and low-alloy steels	Recommended for low-carbon and low-alloy steels, using rods of the same material; more difficult for higher carbon
Stainless steel	Common for thinner material; more difficult for thicker
Aluminum and magnesium	Common for aluminum thinner than 1 in.; difficult for magnesium alloys
Copper and copper alloys	Common for most alloys; more difficult for some types of bronzes
Nickel and nickel alloys	Common for nickel, Monels, and Inconels
Titanium	Not recommended
Lead and zinc	Recommended
Thermoplastics, thermosets, and elastomers	Hot-gas welding used for thermoplastics, not used with thermosets and elastomers
Ceramics and glass	Seldom used with ceramics, but common with glass
Dissimilar metals	Difficult; best if melting points are within 50°F; concern for galvanic corrosion
Metals to nonmetals	Not recommended
Dissimilar nonmetals	Difficult

4. Pressure – Gas Welding. (PGW) – To make butt joints between bars or ends heated with gas flame but below the melting point temperature, and then forced to join together under pressure

- **Can be considered as solid phase weld → this method requires special equipment**

5. Arc Welding – in general

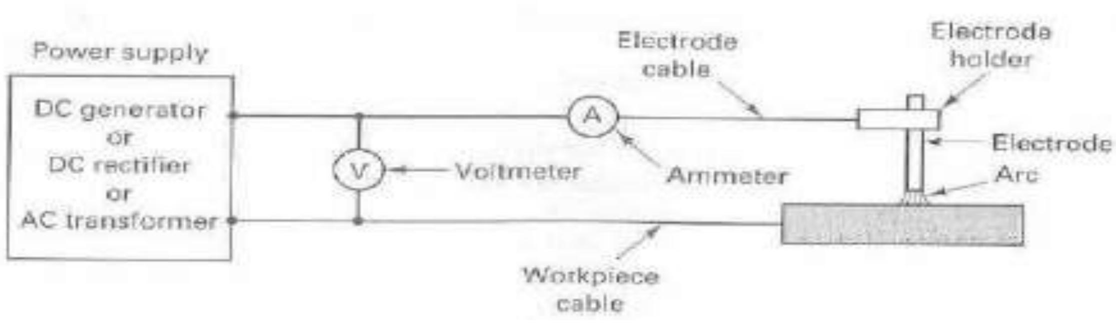
Process in which coalescence is obtained by heat produced from an electric arc created between the work piece and an electrode. – no pressure applied;

The electrode or filler metal is also heated to a liquid state and deposited into the joint to make the weld.

The two electrodes: 1. Workpiece and 2. Electrode → an electric circuit is created

- **By closing the electrodes, the arc is formed at low voltage (28V), high current (few hundreds of A)**
- **the electric energy is converted into an arc with intense heat release which creates high temperature, around 3900^0 C**
- **difficult to control the temperature → by on –off method only**
- **there is no possibility to control the temp. as in gas welding**
- **Traditionally, DC was used with heavy and expensive rectifiers**

FIGURE 34-1 Basic circuit for arc welding.



Two procedures:

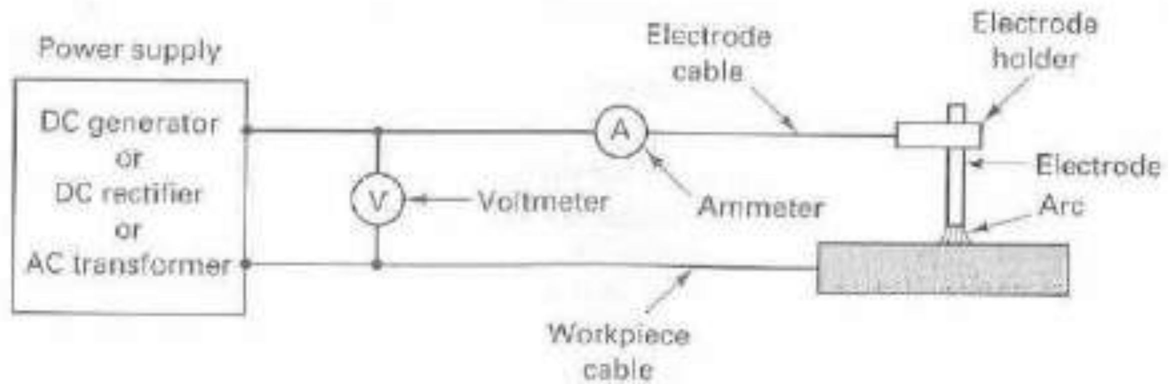
- **1. Straight polarity → electrode –**

  (e$^-$ pulled to job, Heavy ions to electrode, more heat at electrode → more melting and filling of electrode → but shallow weld penetration in job.

- **2. Reversed polarity → electrode +**

  The reverse happens, more heat at the job → more melting of job → heavier ions result in deeper weld penetration.

FIGURE 34-1 Basic circuit for arc welding.



- Now: AC → more spread because of the simplicity of the equipment (no rectifiers but just an inexpensive transformer)
- the electrode used usually melts at temp. below the temp. of the arc
  → electrodes consume in the welding process
  → this electrode is moved towards the workpiece when consumed.
- also, not consumable electrode, made of tungsten are used.
- The method needs to feed the weld filler.

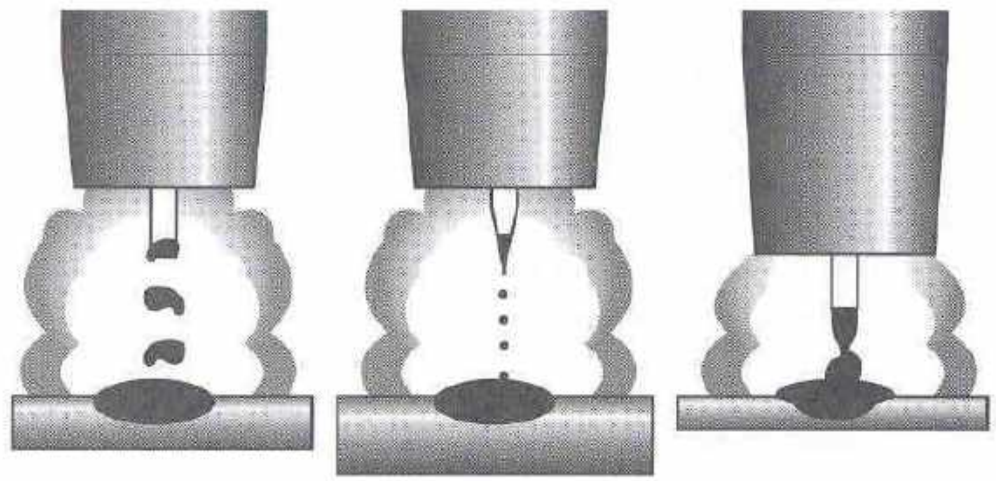


FIGURE 34-2 Three modes of metal transfer during arc welding. *(Courtesy of Republic Steel Corporation.)*

TYPES OF ELECTRODES

1. **Bare electrodes:** **limited use for iron and mild steel → low quality materials**

2. **Fluxed electrodes:** **with light coat of flux →eliminate undesirable oxides and prevent their formation**

3. **Heavy coated electrode:** very used presently for shielded metal arc welding (95%) →a gas shield is provided around the arc to eliminate the undesirable oxides and nitrides to be formed in weld metal. It also provides the weld metal with a protective slag coating, which prevents oxidation of the surface metal during cooling

*** the type of coating of the flux is considered in terms of the type of welding and the materials that must be welded: flux compounds Coating consists of slag forming compounds**

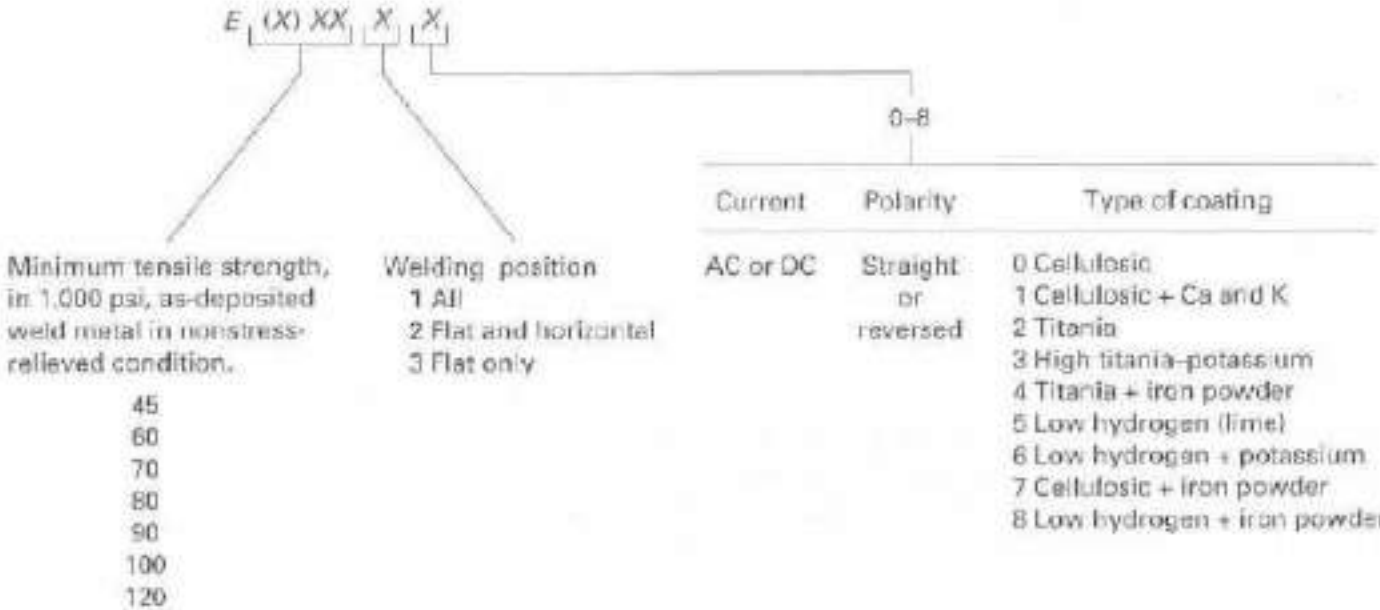


FIGURE 34-3 Designation system for arc-welding electrodes.

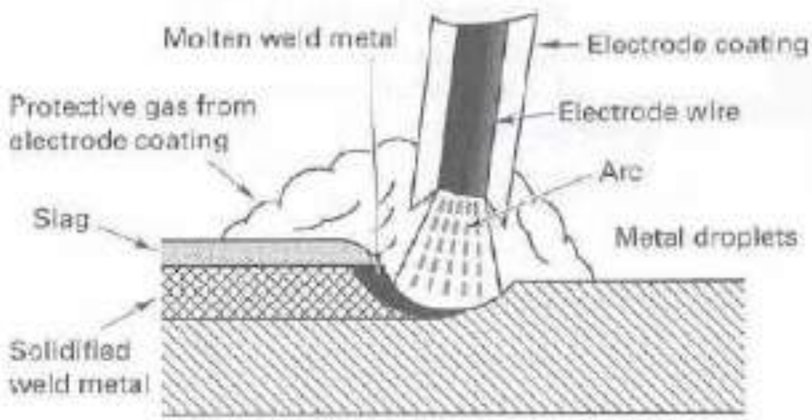


FIGURE 34-4 Schematic diagram of shielded metal arc welding (SMAW). *(Courtesy of American Iron and Steel Institute, Washington, D.C.)*

TYPES OF ARC WELDING PROCESS

5a. Shield Metal Arc Welding – (SMAW) – uses heavy –coated electrodes

5b. Gas Tungsten Arc Welding – (GTAW)

Special purpose such as stainless steel welding → to prevent oxidation

- **The inert gas substitutes for the shielded electrodes (Ar, He)**
- **Electrode – non consumable – by tungsten → NO SLAG**
- **Filler metal must be provided**

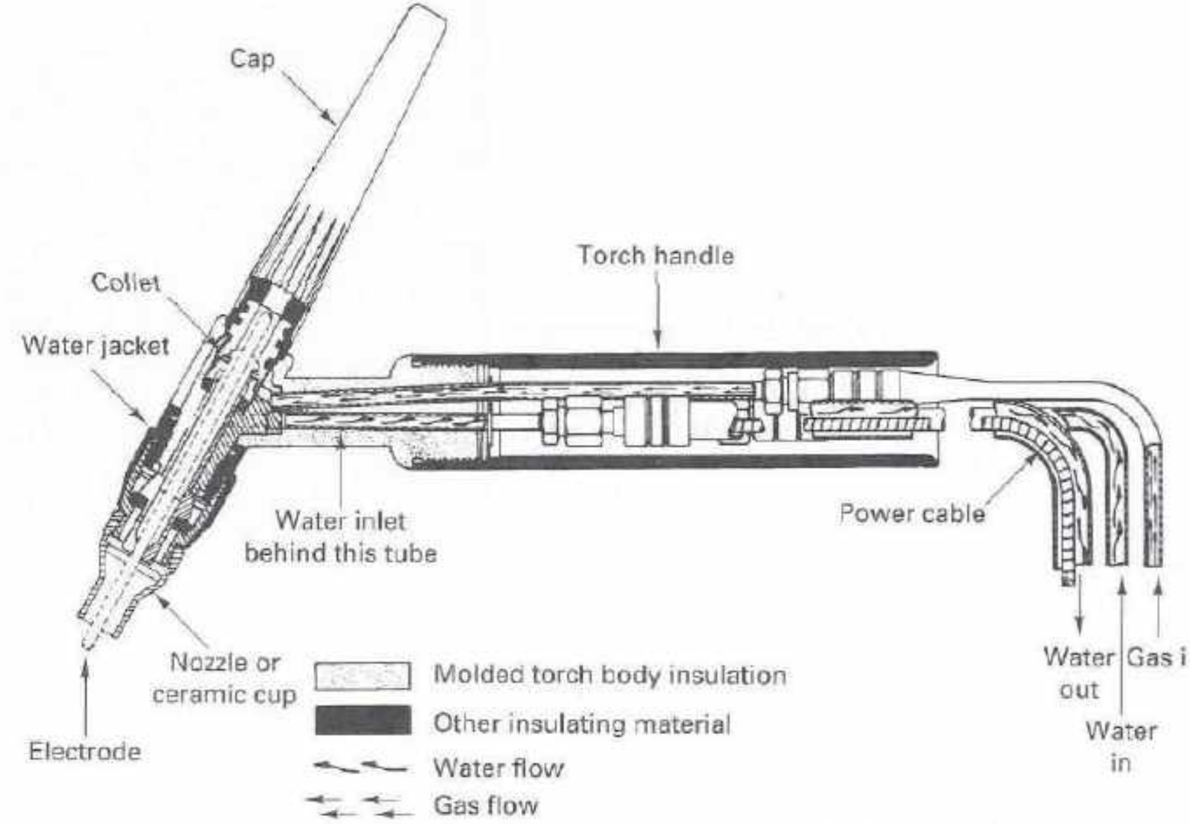


FIGURE 34-5 Welding torch used in nonconsumable-electrode, gas tungsten arc welding (GTAW), showing feed lines for power, cooling water, and inert gas flow. *(Courtesy of Linde Division, Union Carbide Corporation.)*

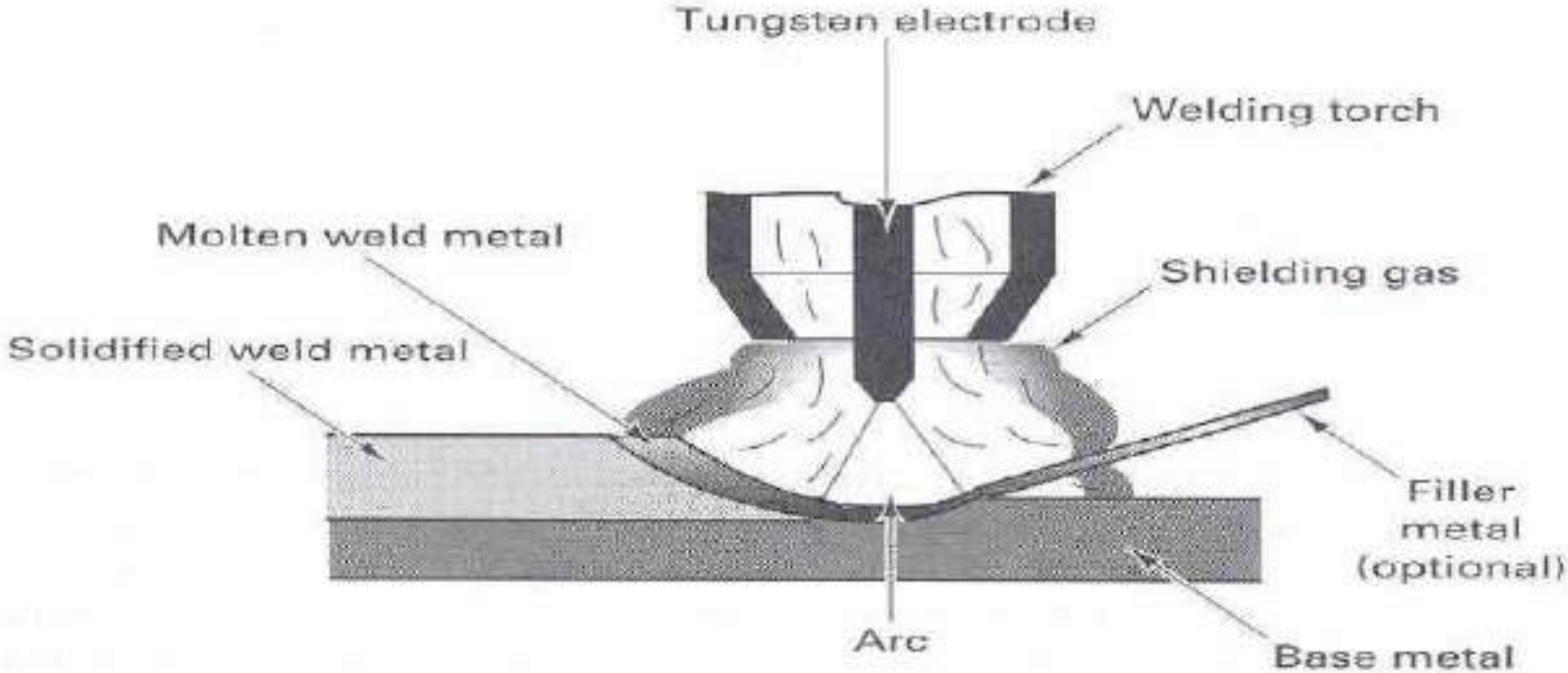


FIGURE 34-6 Schematic diagram of gas tungsten arc welding (GTAW). *(Courtesy of American Iron and Steel Institute, Washington, D.C.)*

5c. Gas Metal Arc Welding →
inert gas used for shielding against atmosphere (CO_2, N_2 - inexpressive)

- **consumable bare electrode are used**
- **for non – ferrous metals –(aluminium)**

→ NO SLAG

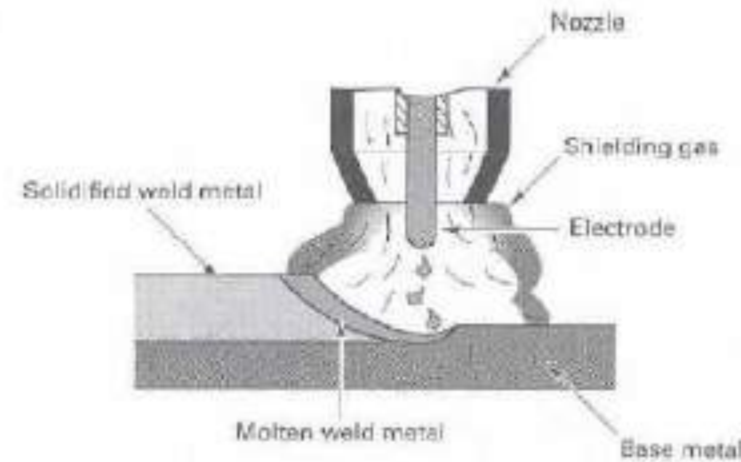


FIGURE 34-10 Schematic diagram of gas metal arc welding (GMAW). *(Courtesy of American Iron and Steel Institute, Washington, D.C.)*

5d. Flux Cored Arc Welding (FCAW)

- **Flux core – inside the electrode**
- **SLAG coats the hot weld**
- **gas produced from flux burning protects the weld**

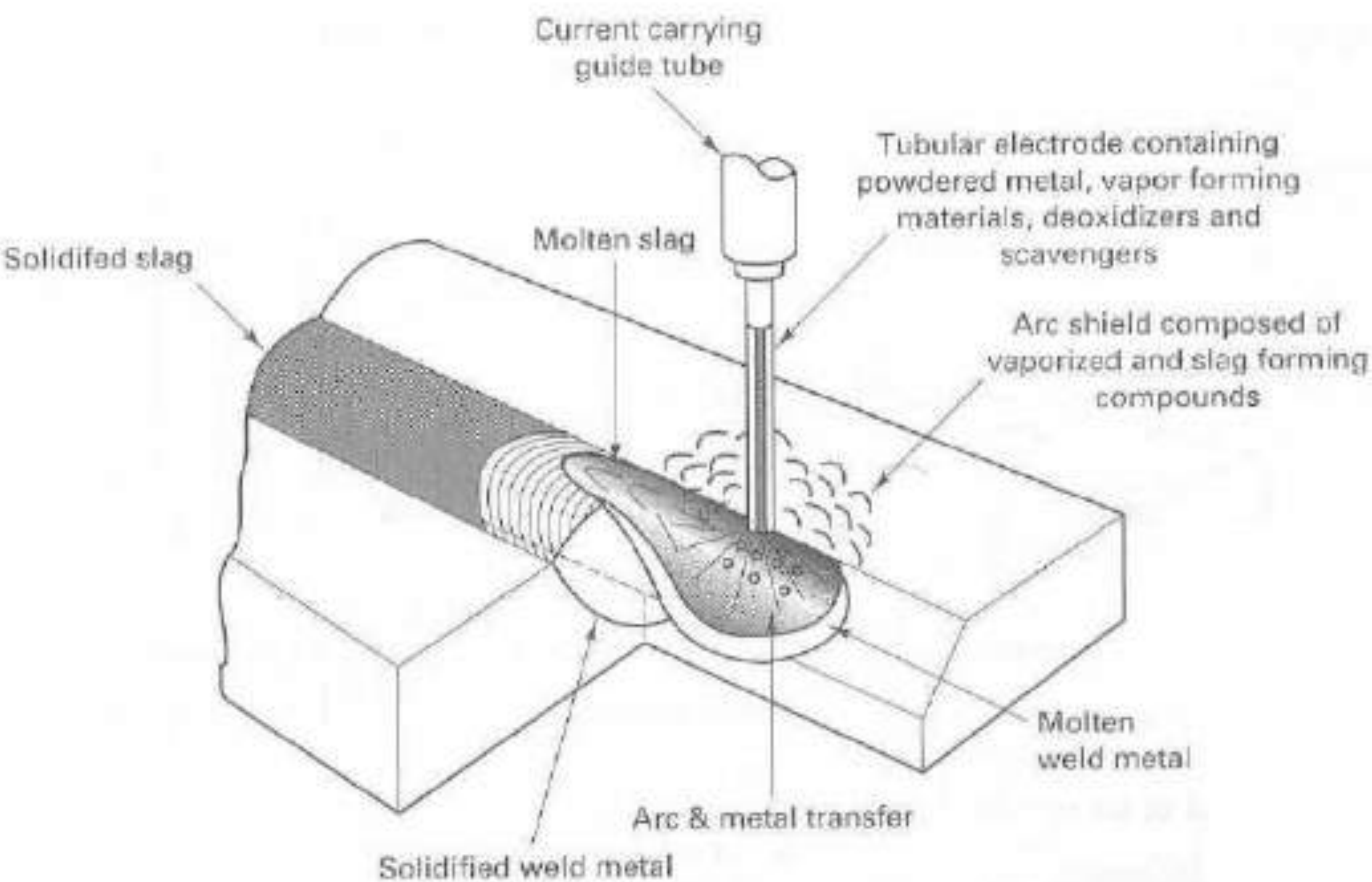


FIGURE 34-11 Schematic representation of the flux-cored arc welding process (FCAW). *(Courtesy of The American Welding Society, New York.)*

5e. Submerged – Arc welding (SAW)

- **Suitable for automation →(automation process)**

- **Arc is shielded by a blanket of granular flux fed from a hopper during welding**

- **Bare electrode is fed into the granular flux which laid down along the seam to be welded**

- **Welding action takes place beneath the flux which laid down along the seam to be welded**

- **Welding action takes place beneath the flux cover**

- **Intense heat of the arc produces a pad of molten metal in the joint →the same time, a portion of the granular flux which will float on top of the molten metal will burn and produce slag → will protect the melted metal from the oxidation**

- **After cooling, the fused slag solidifies → is removed easily**

- **flux can be required**

  Ex: vessel welding →

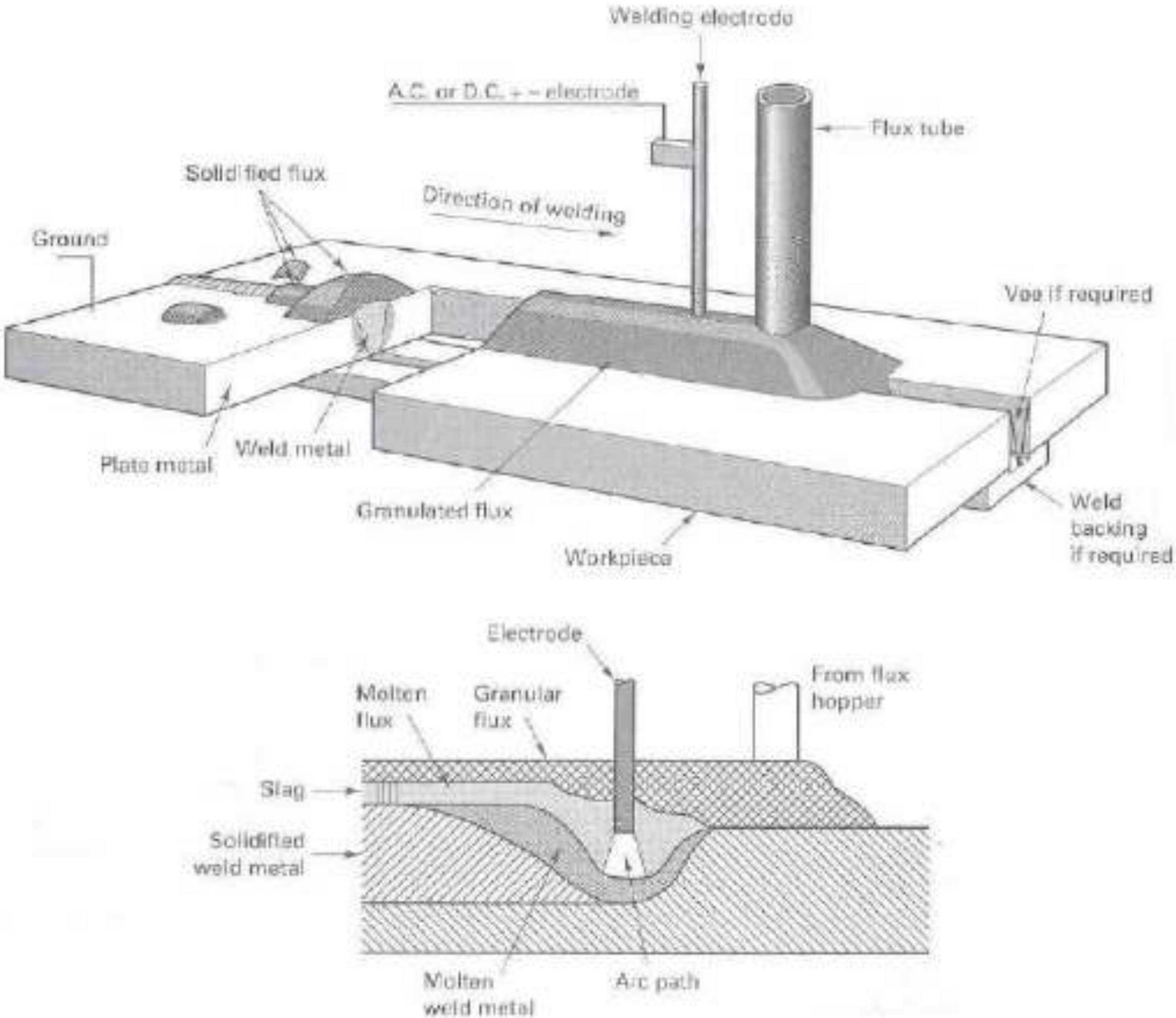


FIGURE 34-12 *(Top)* Basic features of the submerged arc welding process (SAW). *(Courtesy of Linde Division, Union Carbide Corporation.)* (Bottom) Cutaway schematic of submerged arc welding. *(Courtesy of American Iron and Steel Institute, Washington, D.C.)*

- **Only flat surface or surfaces with large aperture can be welded**
- **high welding rate can be obtained with mechanised process**
- **good weld control obtained**
- **thick metal plates can be welded**

5f. Stud Welding –(S.W) – arc welding process to end –weld metal studs to flat surfaces

- **Special welding gun is used to hold the stud**
- **when the trigger is pressed, the stud is lifted to create an arc, and then, forced against molten pool by backing springs**
- **the operation – automatically controlled – no skill required**
- **frequency 60 operations/min**

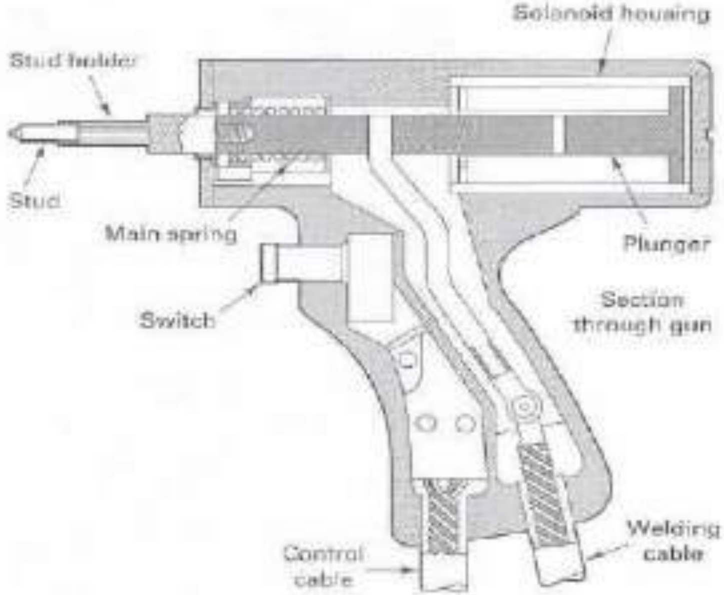


FIGURE 34-14 Schematic diagram of a stud welding gun. *(Courtesy of American Machinist.)*

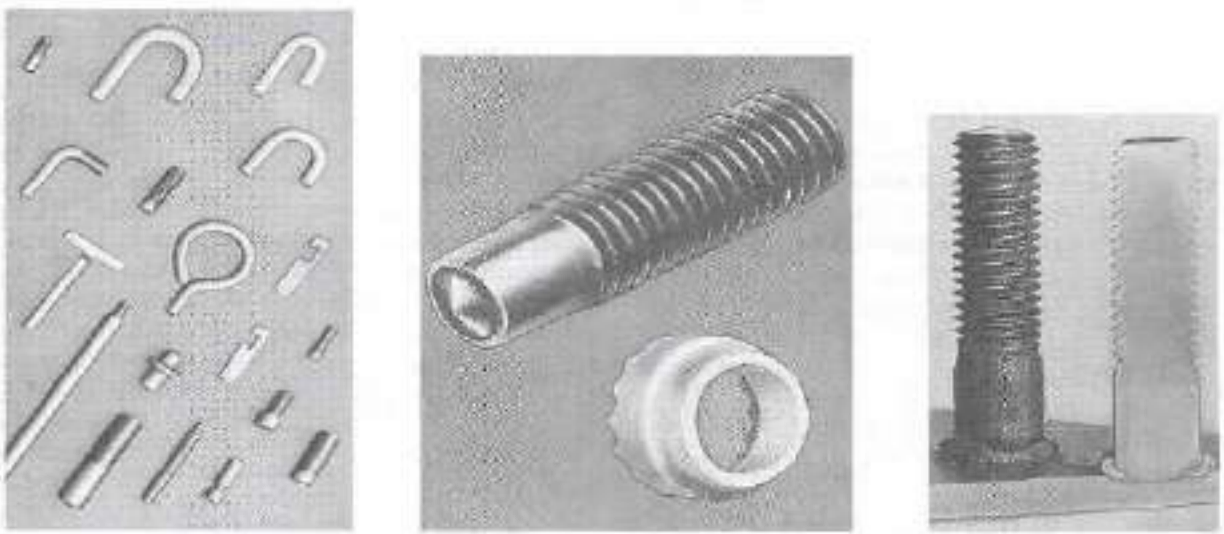


FIGURE 34-15 *(Left)* Types of studs used for stud welding. *(Center)* Stud and ceramic ferrule. *(Right)* Stud after welding and a section through a welded stud. *(Courtesy of Nelson Stud Welding Co.)*

6. Resistance Welding-

Phenomenon when high current is passed through a joint and heat is released

Joule's effect → $E = I^2Rt$

- **Heat and pressure are used to join parts: suitable for automation →robots perform this job.**
- **For plates and sheets => heavy current is passed through both parts causing local heating at the joint (the highest resistance)**
- **Welding is completed by application of pressure**
- **low voltages ~ 4-12 V at high flow (current) from transformers**
- **When the current passes through metal, most heat →at the joint point → greatest resistance (in the electrical path, which is at the interface of the sheets)**

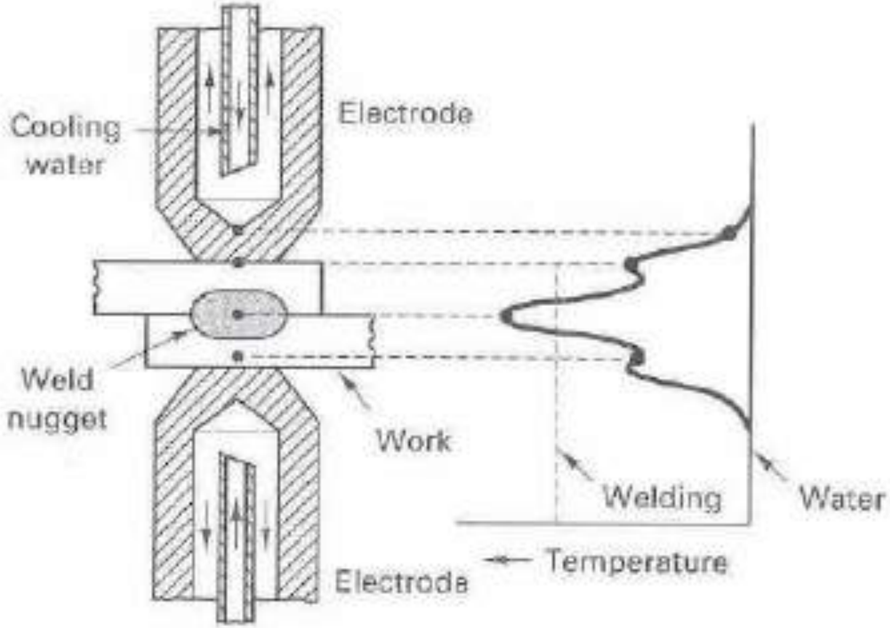


FIGURE 35-2 The des
temperature distributio
the electrodes and the
workpieces in lap resist
welding.

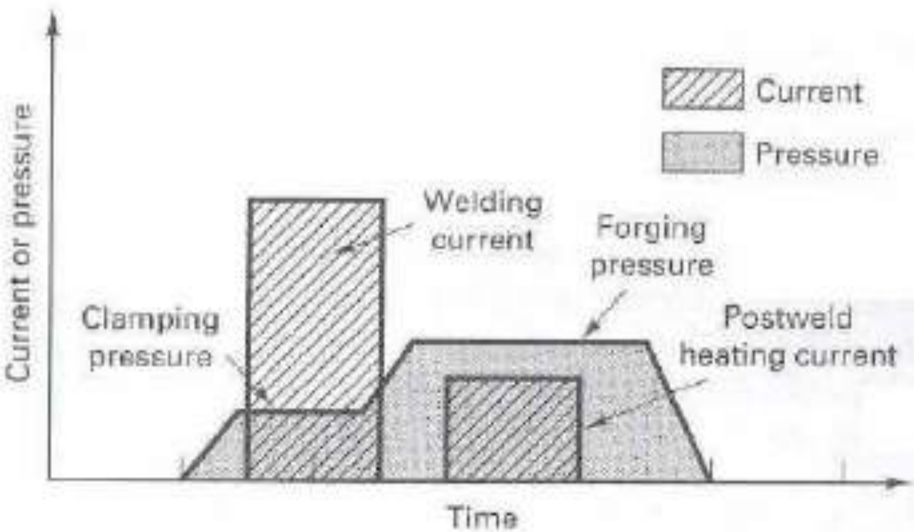


FIGURE 35-3 Typical current and pressure cycle for resistance welding. The cycle includes forging and postheating operations.

- Power flow 30-40 KVA/ in max. 10 sec. Time
- Pressure to complete the weld is 4000-8000 psi (28-55 MPa)
- Resistance of the workpiece is determined by the type of the metal and its thickness →it is usually small
- Electrodes – high conductivity → copper, do not melt, has cooling circuit
- Resistance between the surface depends on:
  - the finish of the surface
  - the contamination of surface
  - the pressure applied
  - the contact area of surface

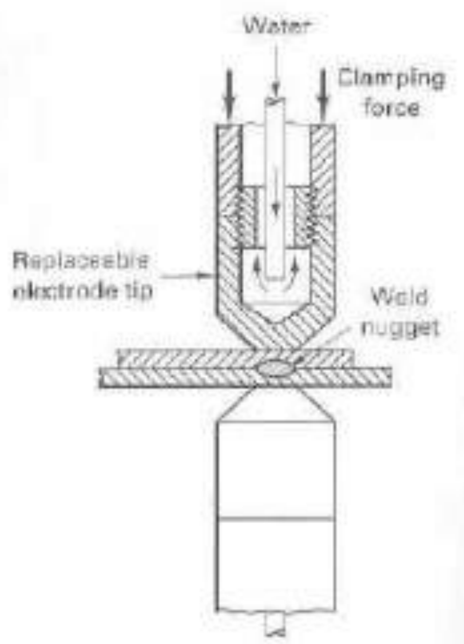


FIGURE 35-4 The arrangement of the electrodes and the work in spot welding, showing design for replaceable electrode tips.

6a. Resistance spot welding (RSW): **two or more sheets of metal are hold between metal electrodes.**

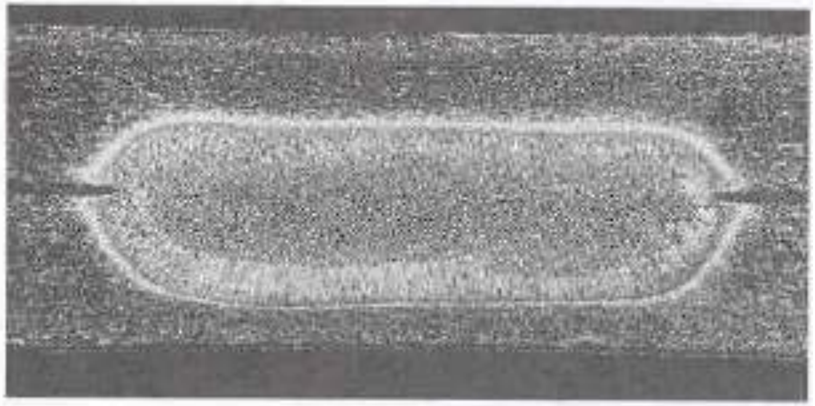


FIGURE 35-5 A spot-weld nugget between two sheets of 0.05-in. (1.3-mm) aluminum alloy. The nugget is not symmetrical because the radius of the upper electrode was greater than that of the lower electrode. *(Courtesy Locheed Aircraft Corporation.)*

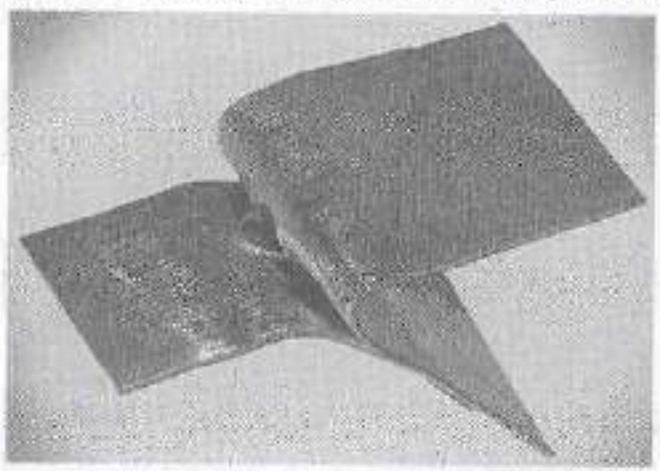


FIGURE 35-6 Tear test of a satisfactory spot weld, showing how failure occurs outside of the weld.

Welding cycle: **electrodes contact the metal (pressure is applied)**

⇒Known as squeeze time

- **Current is passed between electrodes →the temperature increases at the contact point → the metals melt → the electrodes squeeze the material → weld time**

- **Current is shut – down →pressure increased → hold time**

pressure is released →off time
weld nugget is formed

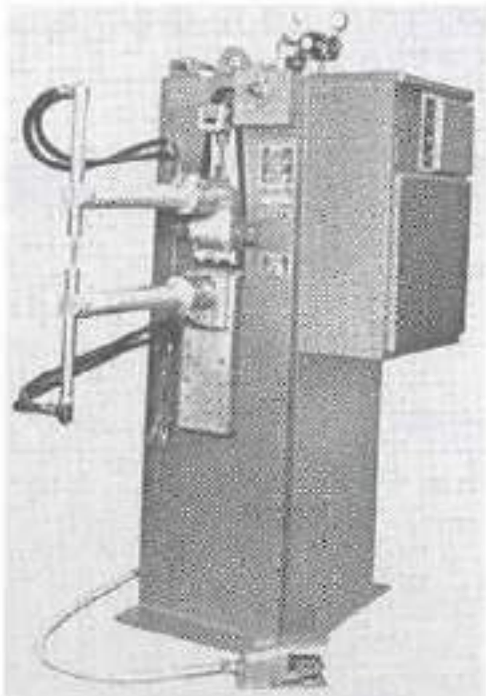


FIGURE 35-7 Foot-operated rocker-arm, spot-welding machine. *(Courtesy Sciaky Bros., Inc.)*

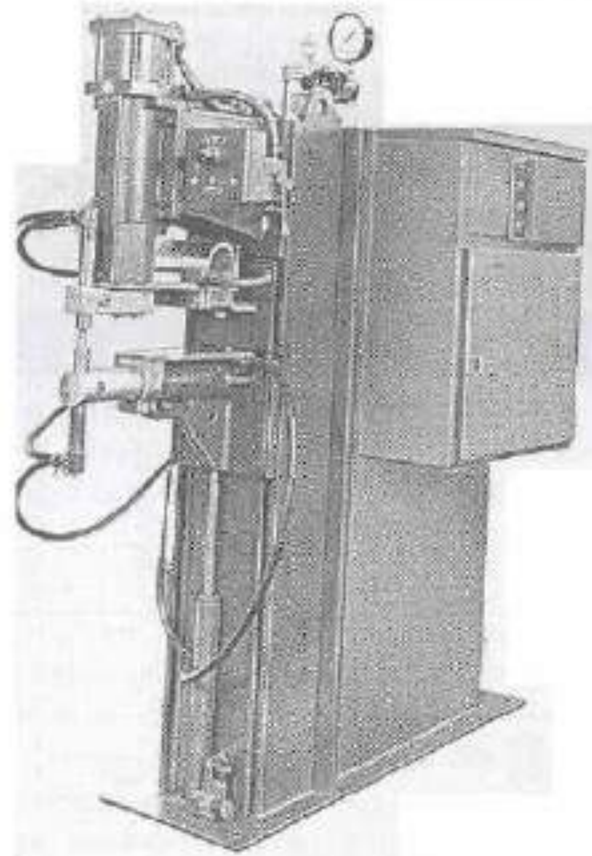


FIGURE 35-8 Single-phase, air-operated, press-type resistance welder with microprocessor control. *(Courtesy Sciaky Bros., Inc.)*

6b. Resistance Seam Welding (RSEW)

- **Continuous weld on two overlapping pieces of sheet metal – can be leak proof (tanks, reservoirs)**
- **It is like frequency spot welding process, with the current applied periodically.**
- **Typical welding speed (~ 60 in/min)**

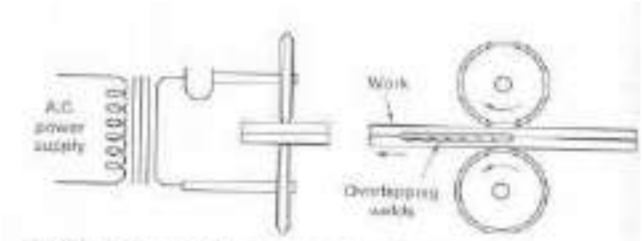


FIGURE 35-10 Schematic representation of seam welding.

Types of seam

- lap seam weld

- finish seam weld – only one side of the joint is visible

Water cooling of electrodes is needed

Seam welding used in manufacturing of metal containers, automobile parts, tanks, pipes.

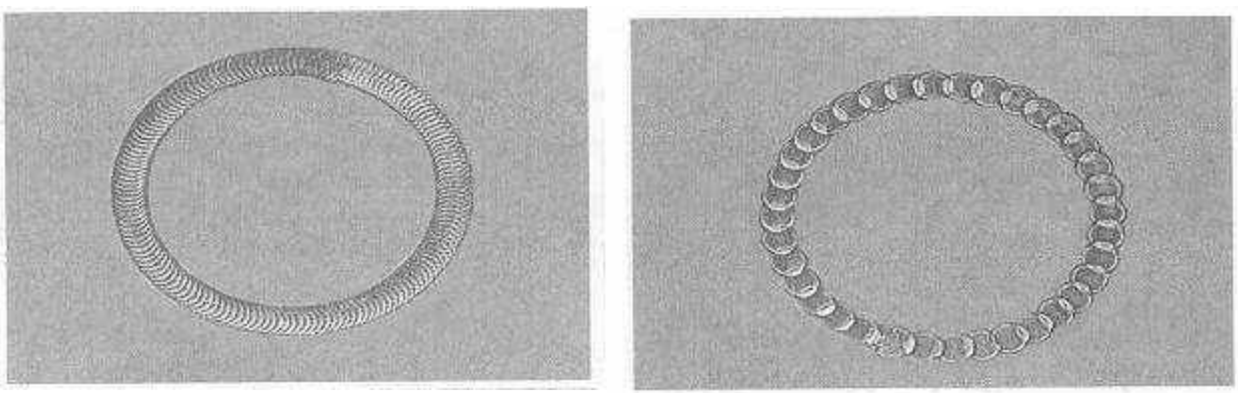


FIGURE 35-9 Seam welds made with overlapping spots of varied spacing.

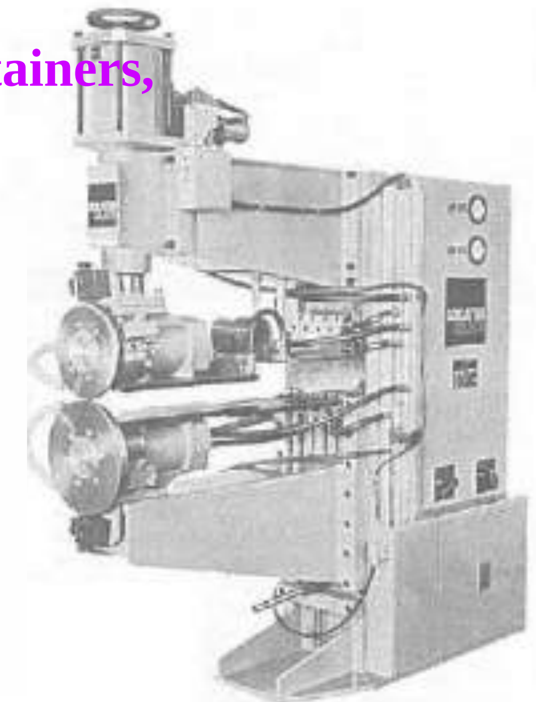


FIGURE 35-11 Typical commercial seam welder. (Courtesy H. A. Schlatter AG.)

6c. Butt welding → a sort of resistance welding → to weld two identical parts by pressure and heat generation just on the surface using high frequency current

6d. Pipe Welding → most of seam welding → welding, in (shaping or forming)
Sides of the strips brought together and current is passed through
→ RESISTANCE BUTT WELDING

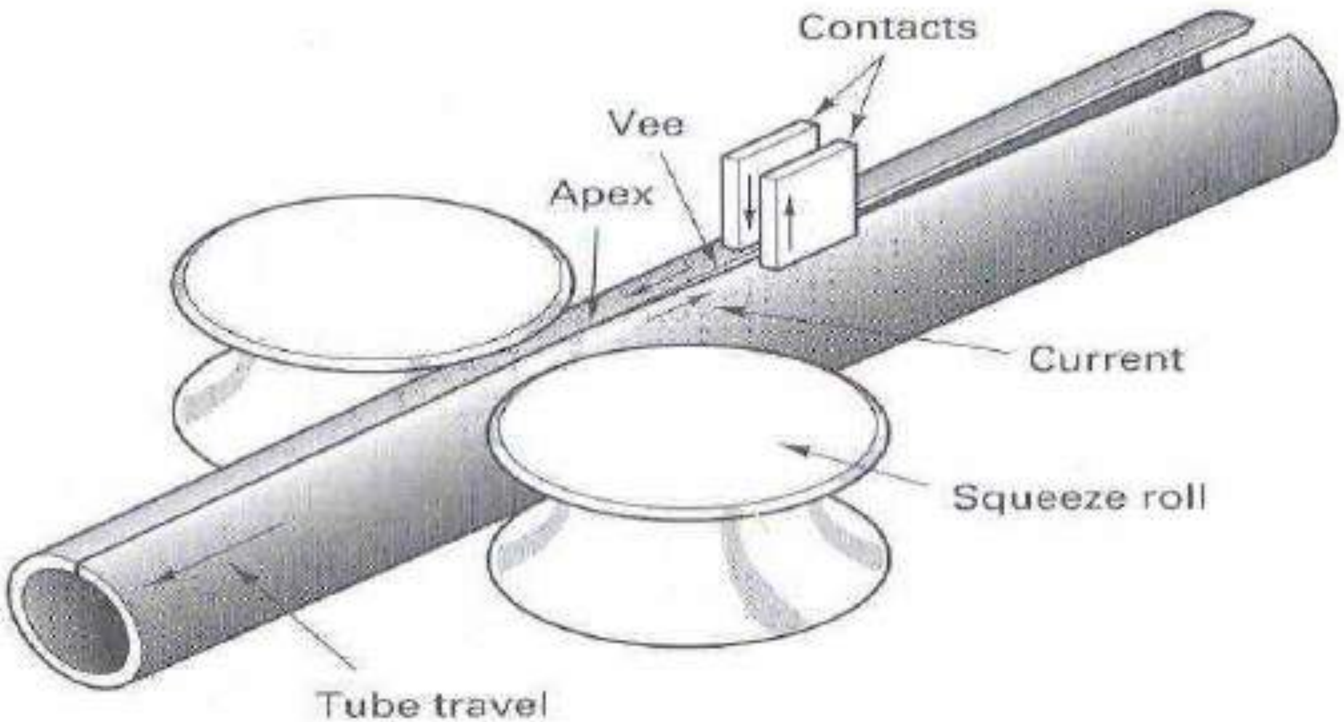


FIGURE 35-12 Using high-frequency ac current to produce a resistance seam weld in butt-welded tubing. Arrows from the contacts indicate the path of the high-frequency current.

Another method : high frequency induction heating of the surface before the material is squeezed together → **HIGH FREQUENCY WELDING OF PIPES**

MACHINES FOR RESISTANCE WELDING

- stationary single spot machine
- portable single spot machine
- multiple spot machine
- robots

PORTABLE SPOT WELDING MACHINES

- Different metals can be spot – welded together
- sheets can be welded to rolled shapes and castings
- practically →size limitation of 1/8 inch (~ 3 mm) for a sheet to be spot welded

6e Resistance Projection Welding (RPW) →similar to spot welding

- One of metal sheets to be welded, has to be put through a punch press which makes small projection or buttons in the metal sheet

- Projection welds are produced at localised points in work pieces help under pressure between suitable electrodes.

- Welds are made simultaneously

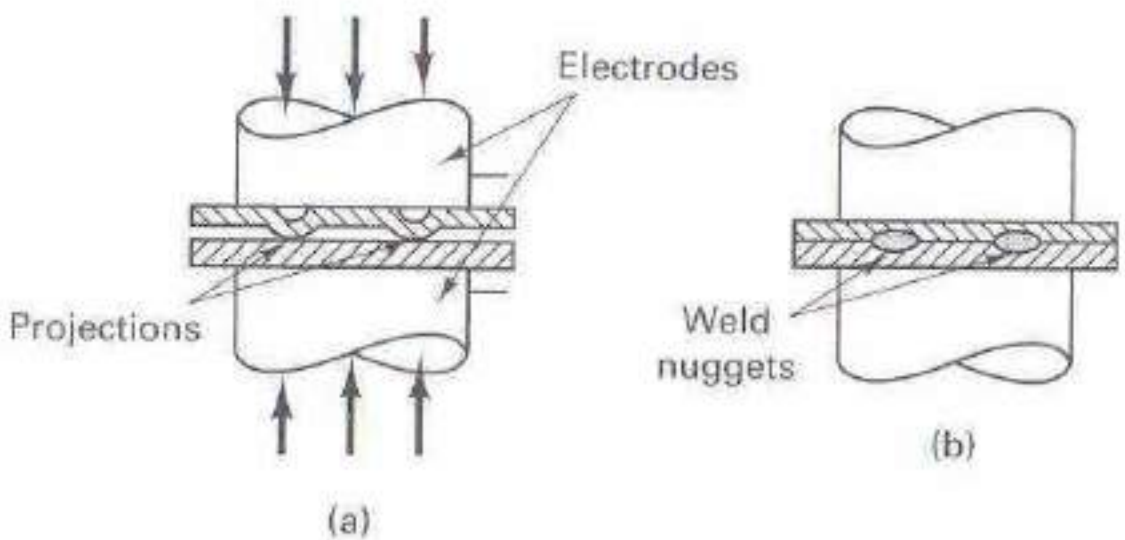


FIGURE 35-13 Principle of projection welding: prior to application of current and pressure (a) and after formation of the welds (b).

COMPARISON: Oxy-fuel, Arc, Resistance

Gas welding:

- **Functionally competitive to arc welding – but not as convenient from the equipment point of view (requires gases in bottles and expensive)**

Arc Welding:

- **Requires high skill operator**
- **Convenient supply of electric power**
- **New techniques of shielding, metal welding and submerged welding**

Resistance Welding:

- **High production process,**
- **Easy to automate**
- **Dependent on the skills of the operator**

QUALITY CONTROL OF WELDS

Cracks occurring in welds

hot cracks → in weld and fusion zone

cold cracks → in the heat affected zone

Due to the heating, the grain size of the weld is changing and so is the hardness → where hardness is the smallest, cracks can occur

WELD INSPECTION:

Visual

FPI

MPI

(cracks or internal defects → distorted magnetic fields. Current is passed through the weld seam →magnetic particles will gather at the crack)

X-ray (for safety reasons)

(not ultrasonic, which needs a flat datum)

NEW WELDING PROCESS

1. Electron Beam welding (EBW)

New technology for "clean welds"

- principles: high velocity e^- are emitted & directed towards the metal from, a tungsten that is heated to 2200^0 C → e^- pass through a magnetic field → centered by the anode and deflecting coils.
- The e^- beam is produced in vacuum. high purity of the weld. (also, fusion temperature is lower for the metal/ for all materials)
- High penetration of e-beam.
- Depth to width ratio of weld is 25:1 and the beam is 0.8 –3.2 mm DIA. (could be made much smaller).
- Low heat input, low distortion, narrow heat affected zone → high purity of weld is assured.

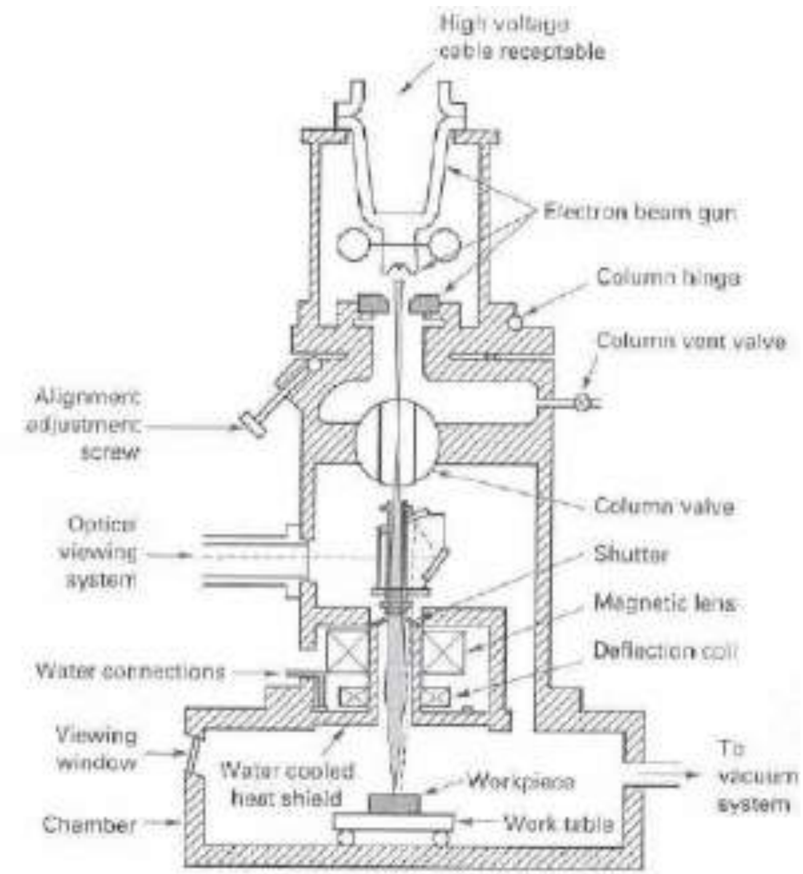


FIGURE 36-10 Schematic diagram of the electron beam welding process. *(Courtesy of American Machinist.)*

2. Laser Beam Welding (LBW)

- Focused laser beam is used for metal vaporisation
- Vaporised metal heats the surrounded metal
- Depth to width ratio > 4:1
- Laser beam welding has some advantages over e beam
    - vacuum is not required
    - can weld inside the transparent containers (eye surgery)

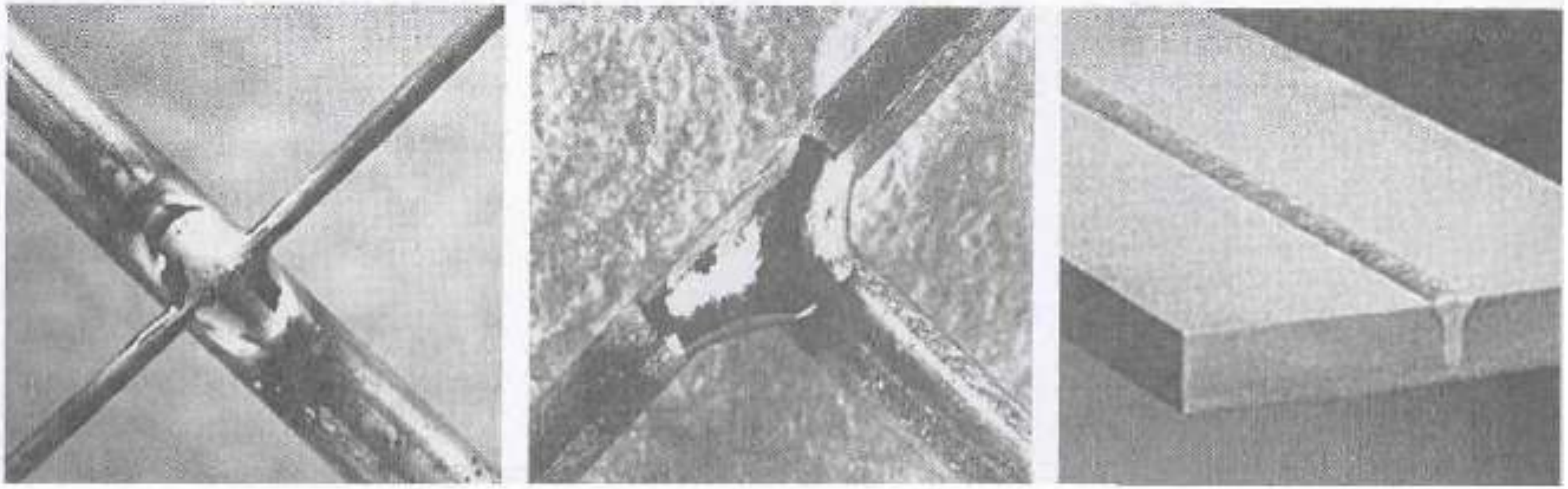


FIGURE 36-12 (*Left*) Small electronic welds made by laser welding. *(Courtesy of Linde Division, Union Carbide Corporation.)*, (*Right*) Laser butt weld of 0.125-in. (3-mm) stainless steel, made at 60 in./min (1.5 m/min) with a 1250-W laser. *(Courtesy of Coherent, Inc.)*

3. Ultrasonic Welding (USW)

- Coalescence is obtained by high shear vibration + pressure localised on the welded pieces
- Used in electronic industry for special precision welding without temperature impact
- Frequency → 10 – 200kHz mechanical vibrations
- Welding depends on right combination of time, pressure and energy output

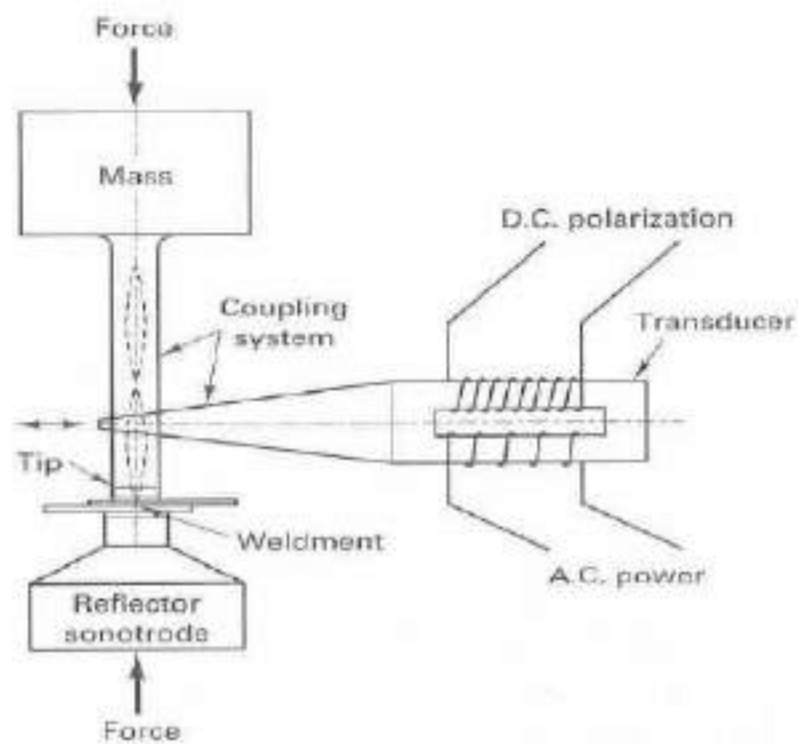


FIGURE 36-7 Schematic diagram of the equipment used in ultrasonic welding.

METALLIZING – metal spraying

- By gas flame, electric arc, plasma
- plasma spray process → highest temperatures (up to 16000^0 C)
- can spray materials with melting point temperature up to 3300^0 C
- For ceramics: conductive or protective surface coating → to protect against built – up surfaces

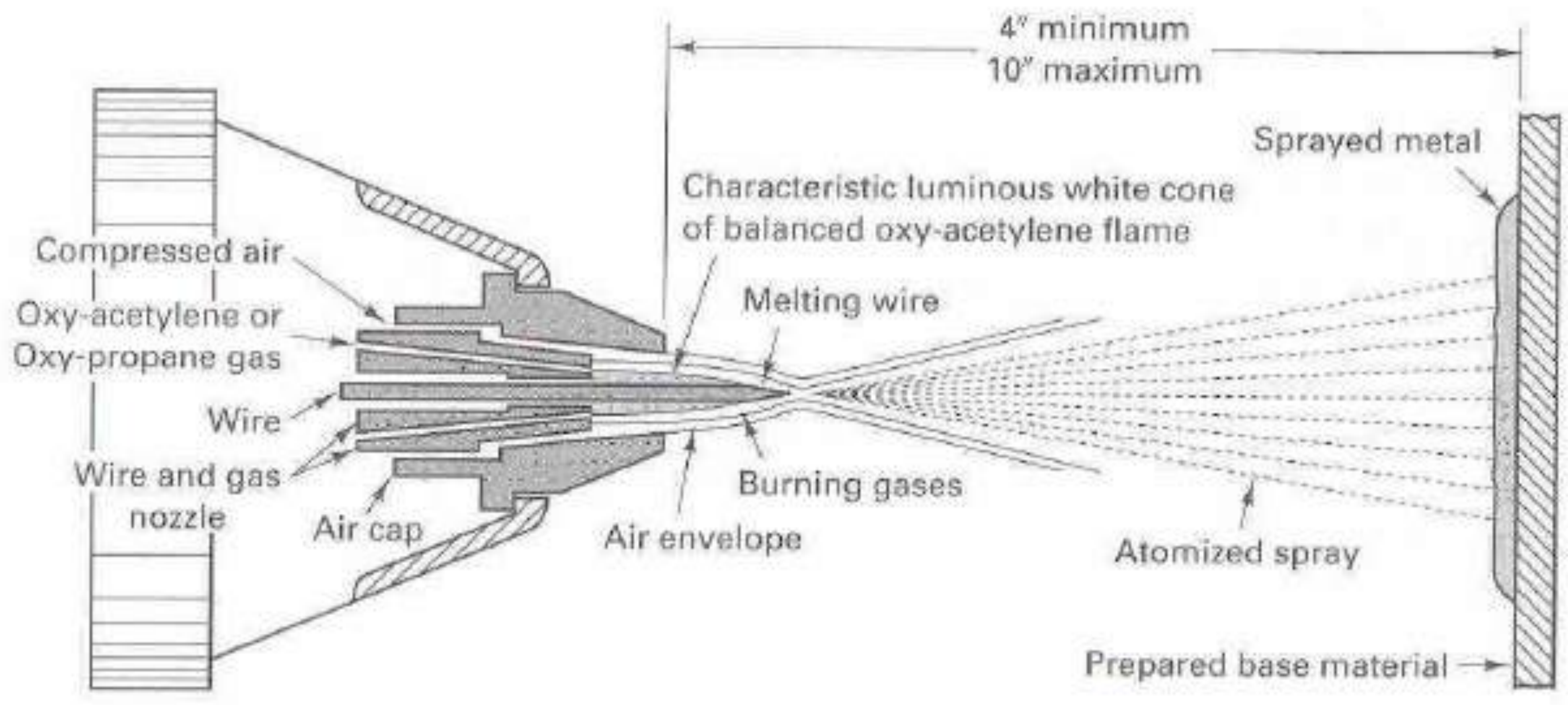


FIGURE 36-17 Schematic diagram of an oxyacetylene metal-spraying gun. (*Courtesy of METCO, Inc.*)

WELDING OF PLASTICS

- Thermoplastic materials only → torch flame temp ~ 300^0 C
- vibration or friction welding (low frequency – 100-240 Hz)

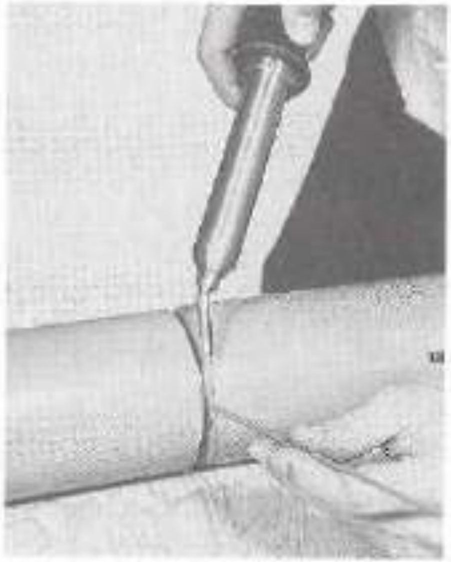


FIGURE 36-16 Using a hot-gas torch to make a weld in plastic pipe.

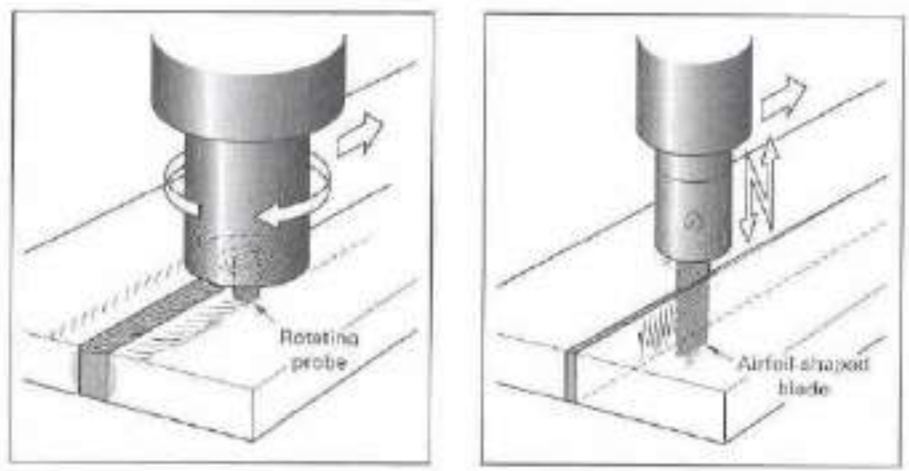


FIGURE 36-15 Friction stir welding using rotary and reciprocal motions to produce welds in plastics. The shoulder on the rotating probe provides additional friction heating to the top surface and prevents expulsion of the softened material from the joint. *(Courtesy of ASM International.)*

GAS & ELECTRIC ARC CUTTING

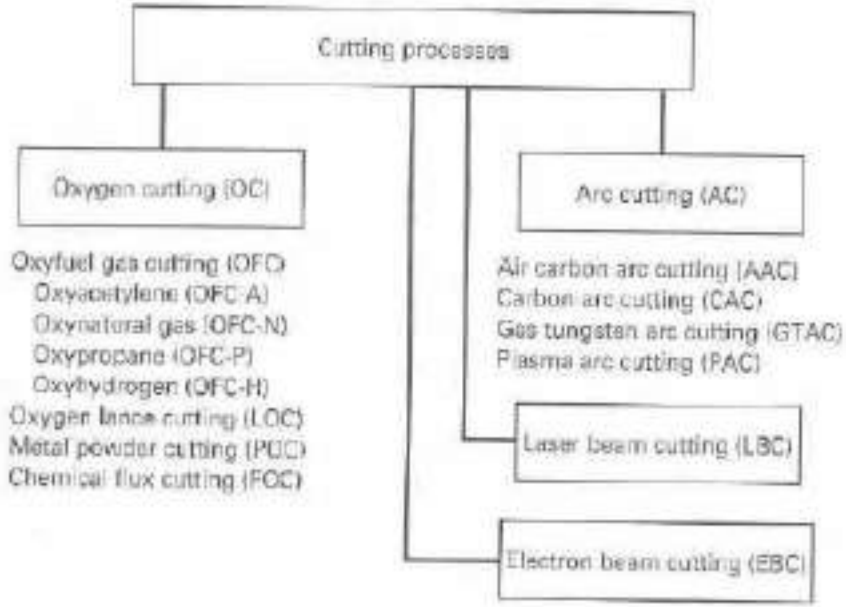


FIGURE 33-5 Classification of common cutting processes with their AWS (American Welding Society) designations.

Oxyacetylene torch cutting: important production processes

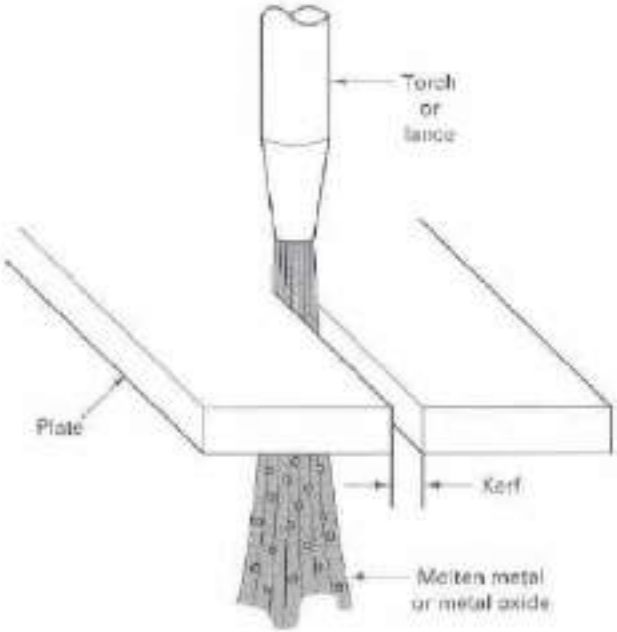


FIGURE 33-6 Flame cutting of a metal plate.

Torch made for cutting is different: It has several small holes surrounding a central hole through which pure oxygen passes → no premixing

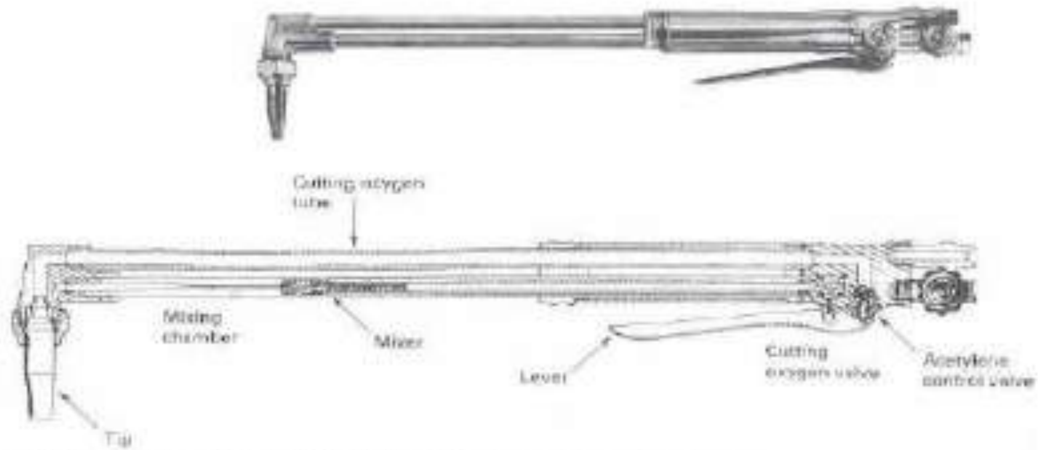


FIGURE 33-7 Typical oxyacetylene cutting torch and cross-sectional schematic. (Courtesy of Victor Equipment Company.)

Principle of cutting → oxygen has affinity for ferrous materials (and for Al)

- If steel is heated to the red temperature and a jet of pure O is blown on the surface, the steel is burned instantaneously → iron oxide

  $3Fe + 2O_2 = Fe_3O_4 + heat$

  Metal plates up to 30 in thick can be cut by this method

UNDERWATER CUTTING: Torches are provided with connections for three gases:

- Preheating gas (H_2)
- Oxygen
- Compressed air: Air bubbles around the tip of the torch to stabilise the flame and to displace the water from the tip area

- H2 – for preheating (C_2H_2 – not safe to operate under high pressure created by the water → it can explode)
- Cutting machine → with automatic control of the torch movement
- Usually → a copying system, numerically controlled torch cutting designed with control of speed, preheating, torch light, path, etc.
- Non ferrous metals, cost iron and high manganese alloys are difficult to cut with this method (except Al)

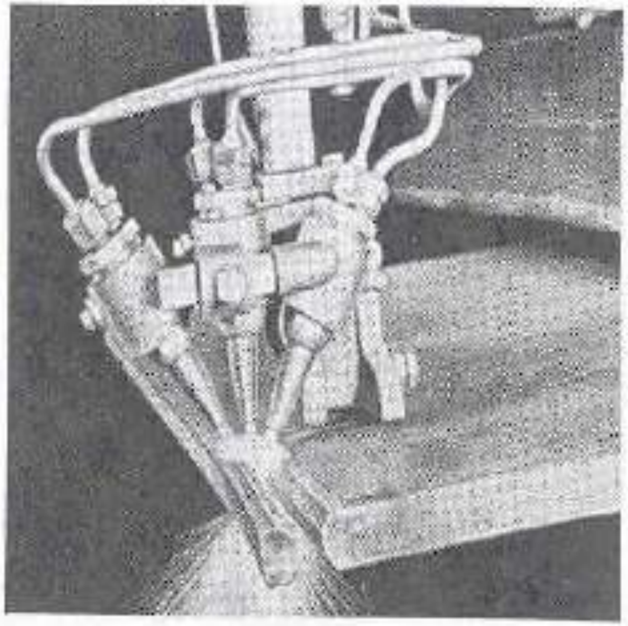


FIGURE 33-9 Plate edge being prepared for welding. The beveled shape is produced by three simultaneous oxyacetylene cuts. *(Courtesy of Linde Division, Union Carbide Corporation.)*

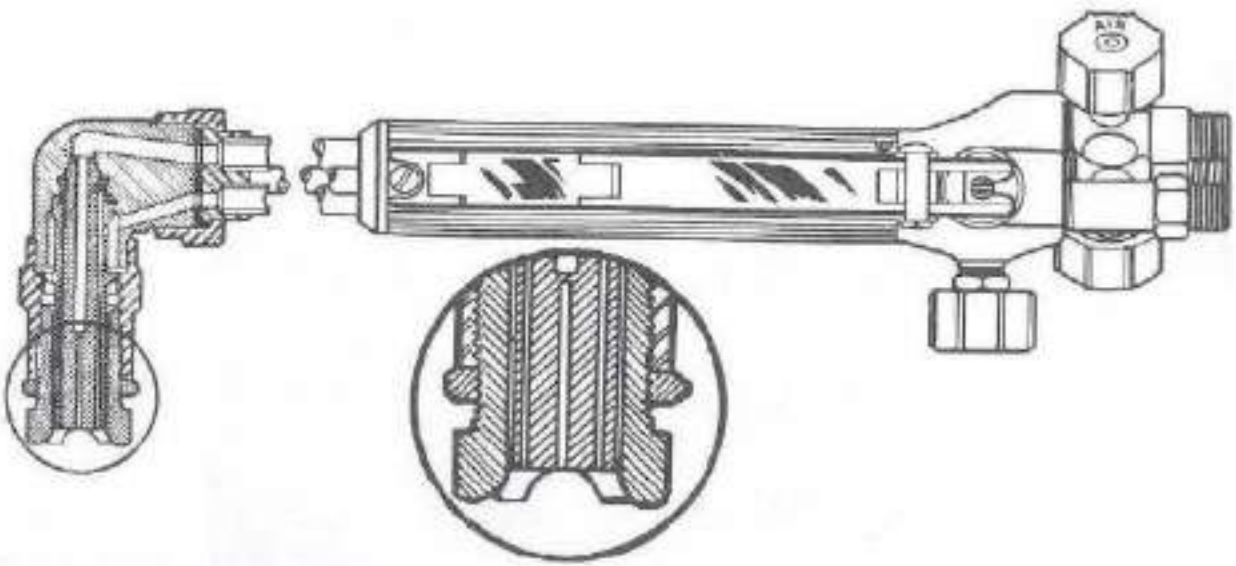


FIGURE 33-10 Underwater cutting torch. Note the extra set of gas openings in the nozzle to permit the flow of compressed air and the extra control valve. *(Courtesy of Bastian-Blessing Company.)*

ARC CUTTING PROCESS

- Melting metal to produce a kerf
- Carbon Arc Cutting (CAC)
- Carbon electrode produces arc
- Air is blowing the metal out from the cut – not oxidising (good for cast iron, which is difficult to cut with oxygen flame)

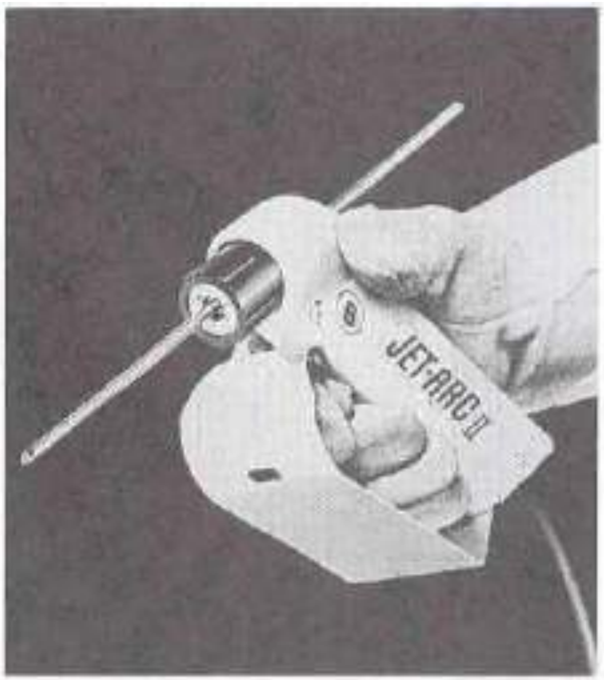


FIGURE 34-18 Gun used in the arc-air cutting process. Note the air holes surrounding the electrode in the holder. *(Courtesy of Jackson Products.)*

PLASMA ARC CUTTING

- Very high temperature – used for Stainless steel and non ferrous materials (carbon electrode cathode)
- inert gas flowing through the arc is forming plasm
- Two types of torch;
  non-transferred arc: ~ $16,000^0$ C
  transferred arc (~ 30000^0 C) for non metals
- cutting speeds:
  2.5 m/min (steel)
  7.5 m/min Al – in thick plates

FIGURE 34-20 Cutting sheet metal with a plasma torch. *(Courtesy of GTE Sylvania.)*

LASER BEAM CUTTING (CO_2 lasers)

- Uses the heat of laser cutting to melt and evaporate metal
- any known material can be cut, $T>11000^0$ C, very accurate, poor surface finishing.

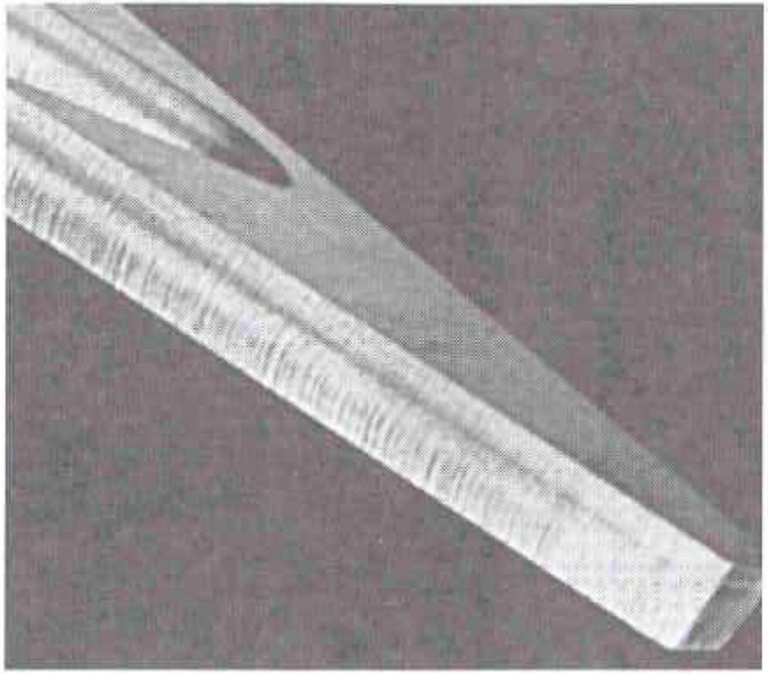


FIGURE 36-13 Surface of $\frac{1}{4}$-in. (6-mm)-thick carbon steel cut with a 1250-W laser at 70 in./min (1.8 m/min). *(Courtesy of Coherent, Inc.)*

Module 5

UNCONVENTIONAL MACHINING PROCESS – UNIT 1 INTRODUCTION

Prepared by
S. SENTHIL KUMAR
AP / MECH
SVCET

INTRODUCTION

- Conventional machining process
  - Metal is removed by means of tool which is harder than work piece and they both are in contact with each other

- Demerits of conventional machining process
  - Disposal and recycling of the chips are difficult and tedious process
  - Large cutting forces are involved in this process

NEED FOR UCM

- Unconventional manufacturing process
  - Unconventional machining process
  - Unconventional forming process

- Need for unconventional machining process
  - Harder and difficult to machine materials, can be machined easily and precisely

CLASSIFICATION OF UCM

- Classification of UCM
  - Based on type of energy required to shape the material
    - Thermal energy methods
    - Electrical energy methods
    - Electro chemical energy methods
    - Chemical energy methods
    - Mechanical energy methods
  - Based on mechanisms involved
    - erosion
    - Ionic dissolution
    - vaporization

- Based on the source of energy required for material removal
  - Hydrostatic pressure
  - High current density
  - High voltage
  - Ionized material
- Based on medium of transfer of energies
  - High voltage particles
  - Electrolyte
  - Electron
  - Hot gases

Process Selection

- Points to be considered for correct selection pf UCM are
  - Physical parameters
  - Shapes to be machined
  - Process capability or machining characteristics
  - Economic consideration

Physical parameters

Parameters	ECM	EDM	EBM	LBM	PAM	USM	AJM
Potential, V	5 – 30	50 – 500	200 x 10^3	4.5 x 10^3	250	220	220
Current, A	40,000	15 – 500	0.001	2	600	12	1.0
Power, KW	100	2.70	0.15	20	220	2.4	0.22
Gap, mm	0.5	0.05	100	150	7.5	0.25	0.75
Medium	Electrolyte	Dielectric Fluid	Vacuum	Air	Argn or hydrogen or nitrogen	Abrasive grains & water	N_2 or CO_2 or Air
Work Material	Difficult to machine materials	Tungsten Carbides and electrically conductive materials	All materials	All materials	All materials which conduct electricity	Tungsten Carbide, Glass, Quartz	Hard and brittle materials

Shapes to be machined

For producing micro holes	LBM is best suited
For producing small holes	EBM is well suited
For deep holes (L/D>20) and contour machining	ECM is best suited
For shallow holes	USM and EDM are well suited
For precision through cavities in work pieces	USM and EDM are best suited
For honing	ECM is well suited
For etching small portions	ECM and EDM are well suited
For grinding	AJM and EDM are best suited
For deburring	USM and AJM are well suited
For threading	EDM is best suited
For clean, rapid cuts and profiles	PAM is well suited
For shallow pocketing	AJM is well suited

Process capability

Process	Process Capability			
	Material Removal Rate (mm^3/s) MRR	Surface Finish (µm, CLA)	Accuracy	Specific Power ($KW/cm^3/min$)
LBM	0.10	0.4 to 6.0	25	2700
EBM	0.15 to 40	0.4 to 6.0	25	450
EDM	15 to 80	0.25	10	1.8
ECM	27	0.2 to 0.8	50	7.5
PAM	2500	Rough	250	0.90
USM	14	0.2 to 0.7	7.5	9.0
AJM	0.014	0.5 to 1.2	50	312.5

Process economy

Process	Capital Cost	Tooling and	Power requirement	Efficiency	Total Consumption
EDM	Medium	High	Low	High	High
CHM	Medium	Low	High	Medium	Very low
ECM	Very High	Medium	Medium	Low	Very Low
AJM	Very Low	Low	Low	High	Low
USM	High	High	Low	High	Medium
EBM	High	Low	Low	Very High	Very Low
LBM	Medium	Low	Very Low	Very High	Very Low
PAM	Very Low	Low	Very Low	Very Low	Very Low
Conventional Machining	Very low	Low	Low	Very Low	Low

- Advantages of UCM
  - Increases productivity
  - Reduces no. of rejected components
  - Close tolerance is possible
  - Toll material need not be harder than work piece
  - Machined surface does not have residual stress

- Limitations of UCM
  - More expensive
  - MRR is slow

UNCONVENTIONAL MACHINING PROCESS – UNIT 2
Mechanical Energy Based process

Prepared by
S. SENTHIL KUMAR
AP / MECH
SVCET

Mechanical Energy Based process

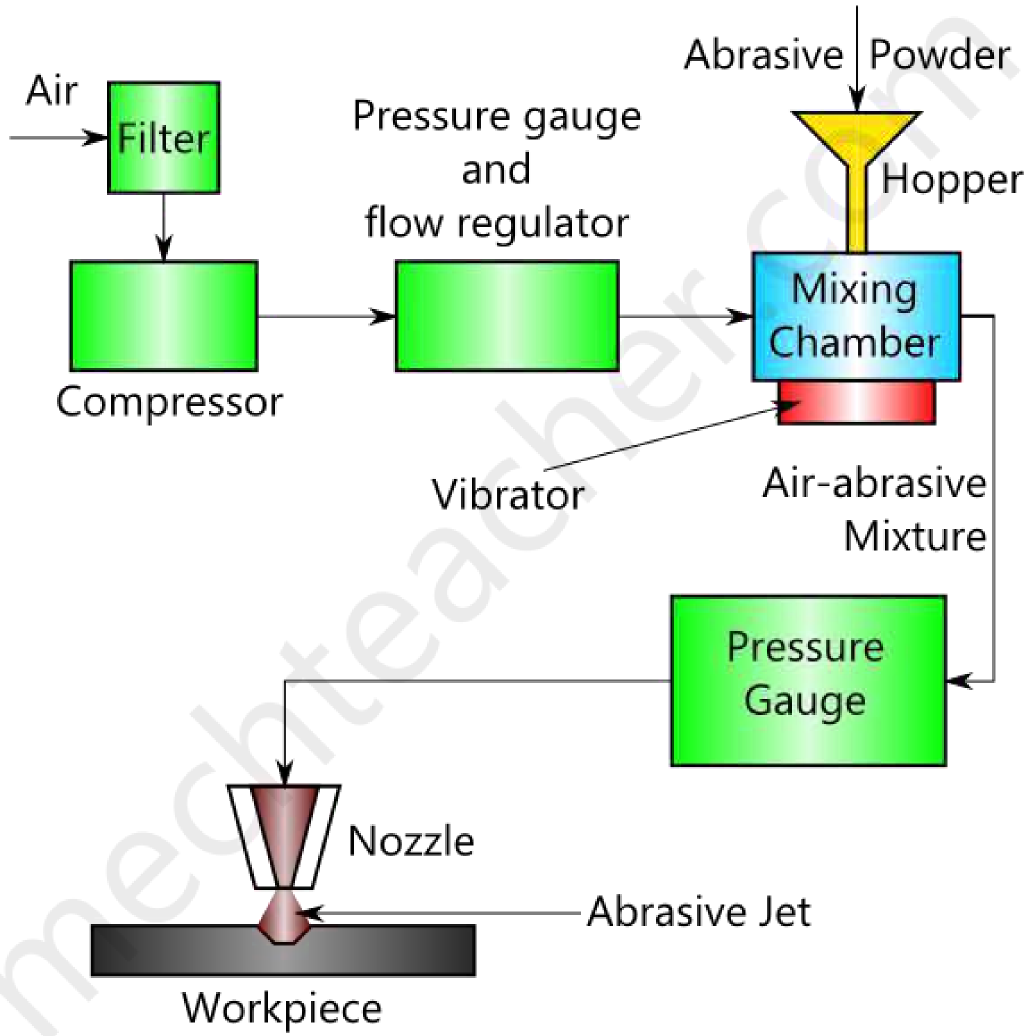
- Material is removed by mechanical erosion of work piece material
  - Abrasive Jet Machining (AJM)
  - Water Jet Machining (WJM)
  - Ultrasonic Machining (USM)

ABRASIVE JET MACHINING (AJM)

- Principle
  - A high speed stream of abrasive particles mixed with high pressure air or gas are injected through a nozzle on the workpiece to be machined

AJM

- Construction and working principle



AJM

- Process parameters
  - Mass Flow rate
  - Abrasive grain size
  - Gas pressure
  - Velocity of abrasive particles
  - Mixing ratio
  - Nozzle tip clearance

AJM

- Characteristics

Work material	Hard and brittle materials
Abrasive	Al_2O_3, SiC, glass powder
Size of abrasive	Around 25 microns
Flow rate	2 to 20 g/min
Medium	N_2 , CO_2 or air
Velocity	125 to 300m/s
Pressure	2 to 8 kg/centimetre square
Nozzle material	Tungsten carbide or synthetic sapphire
Life of nozzle	WC – 12 to 12 hrs Sapphire – 300 hrs
Nozzle tip clearance	0.25mm to 15mm
Tolerance	±0.05 mm
Machining operation	Drilling, deburring, cleaning

AJM

- Applications
  - To machine hard and brittle materials
  - Fine drilling and micro welding
  - Machining of semiconductors
  - Machining of intricate profiles
  - Surface etching
  - Surface preparation
  - Cleaning and polishing of plastics, nylon and teflon

AJM

- Advantages
  - Process is suitable to cut all materials
  - Even diamond can be machined using diamond abrasives
  - No direct contact between tool and workpiece
  - Low initial investment
  - Good surface finish
  - Used to cut intricate hole shapes

AJM

- Disadvantages
  - MRR is slow
  - Soft material cannot be machined
  - Machining accuracy is poor
  - Nozzle wear rate is high
  - Abrasive powder once used can never be used again
  - Requires some kind of dust collection system
  - Cleaning is essential after the operation

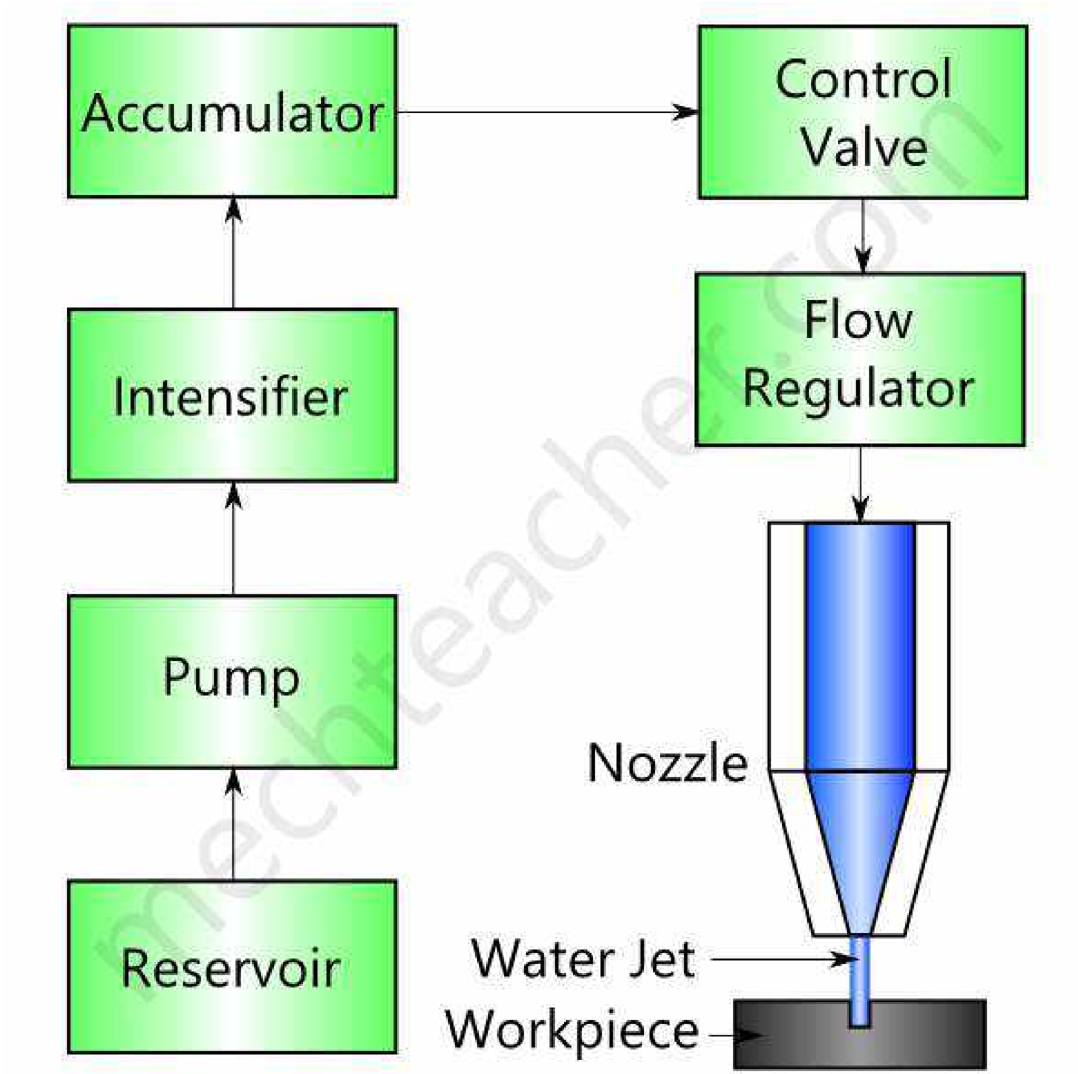
WATER JET MACHINING (WJM)

- Principle
  - When high velocity of water jet comes out of the nozzle and strikes the material, its kinetic energy gets converted into pressure energy inducing a high stress in the work material. When this stress exceeds the ultimate shear stress of the material, small chips of the material got loosened and fresh surface is exposed

  - Used to cut paper boards, plastics, wood, fibre glass, leather

WJM

- Construction and working



WJM

- Process parameters
  - Material removal rate
  - Geometry and surface finish of work material
  - Wear rate of nozzle

- Disadvantages
  - Initial cost is high
  - Noisy operation
  - Difficult to machine hard material

WJM

- Characteristics

Work material	Soft and non-metallic materials
Tool	Water or water with additives
Additives	Glycerin, polyethylene oxide
Pressure of water	100 to 1000 Mpa
Mass flow rate	8 lit/min
Power	45 KW
MRR	0.6 Cu.m/S
Feed rate	1 to 4 mm/s
Nozzle material	Tungsten Carbide, synthetic sapphire
Stand off distance	2 to 50 mm

WJM

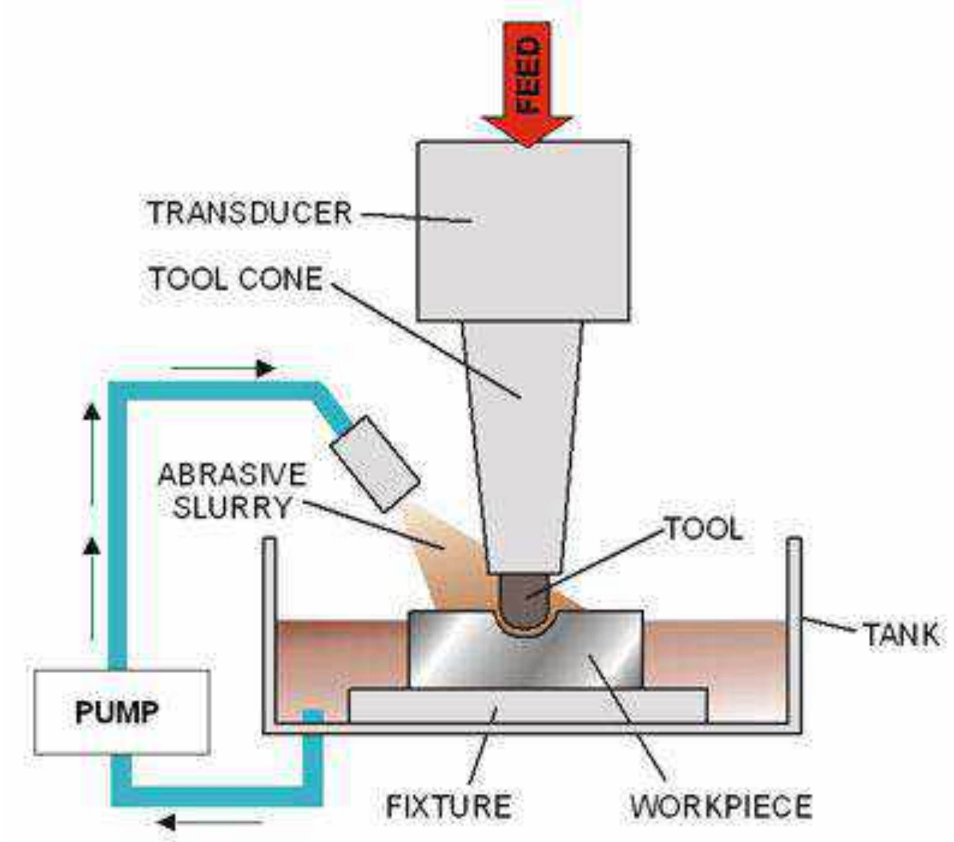
- Advantages
  - Water is used as energy medium and hence it is cheap, non-toxic and easy to dispose
  - Low operating cost
  - Low maintenance cost
  - Work area remains clean and dust free
  - Easily automated
  - No thermal damage to work

ULTRASONIC MACHINING (USM)

- Principle
  - A slurry of small abrasive particles are forced against the work piece by means of a vibrating tool and it causes the removal of metal from the work piece in the form of extremely small chips
  - Also known as ultrasonic grinding or impact grinding
  - Ultrasonic refers to high frequency – above 20khz

USM

- Construction and working



USM

- Process parameters
  - MRR
  - Tool material
  - Work material
  - Surface finish
  - Tool wear rate
  - Abrasive material & abrasive slurry

USM

- Characteristics

Abrasive	Boron carbide, silicon carbide, diamond, aluminum oxide
Abrasive slurry	Abrasive grains + water(20 – 30 %)
Vibration frequency	20 to 30 KHz
Amplitude	25 to 100 microns
Wear ratio	1.5:1 for tungsten carbide 100:1 for glass 50:1 for quartz 75:1 for ceramics 1:1 for steel
Tool material	Low carbon steel, stainless steel
Work material	WC, Germanium, glass, quartz
Surface finish	0.2 to 0.7 micron

USM

- Advantages
  - Extremely hard and brittle materials can be machined easily
  - Noiseless operation
  - Cost of metal removal is low
  - No heat generation on this process
  - Equipments are safe to operate
  - No conductive materials can easily be machined

USM

- Disadvantages
  - MRR is slow
  - Softer materials are difficult to machine
  - Wear rate of tool is high
  - Initial setup cost is high
  - High power consumption
  - Tool cost is high
  - Abrasive should be replaced periodically

USM

- Applications
  - Holes as small as 0.1 mm can be drilled
  - Precise and intricate shaped articles can be machined
  - Efficiently applied to machine glass, ceramics, tungsten
  - Used for making tungsten carbide and diamond wire drawing dies and dies for forging and extrusion process

USM

- Limitations
  - Under ideal conditions
    - Penetration rate – 5cu.m/min
    - Power – 500 to 1000 W
  - MRR on brittle materials – 0.18 cu.m/J
  - Hole Tolerance – 25 microns
  - Surface finish – 0.2 to 0.7 microns
- Recent developments
  - Instead of using slurry, the tool is impregnated with diamond dust
  - In some cases it is impossible to rotate the tool, so the work piece will be rotated in some cases

UNCONVENTIONAL MACHINING PROCESS – UNIT 3
Electrical Energy based processes

Prepared by
S. SENTHIL KUMAR
AP / MECH
SVCET

Electrical Energy based processes

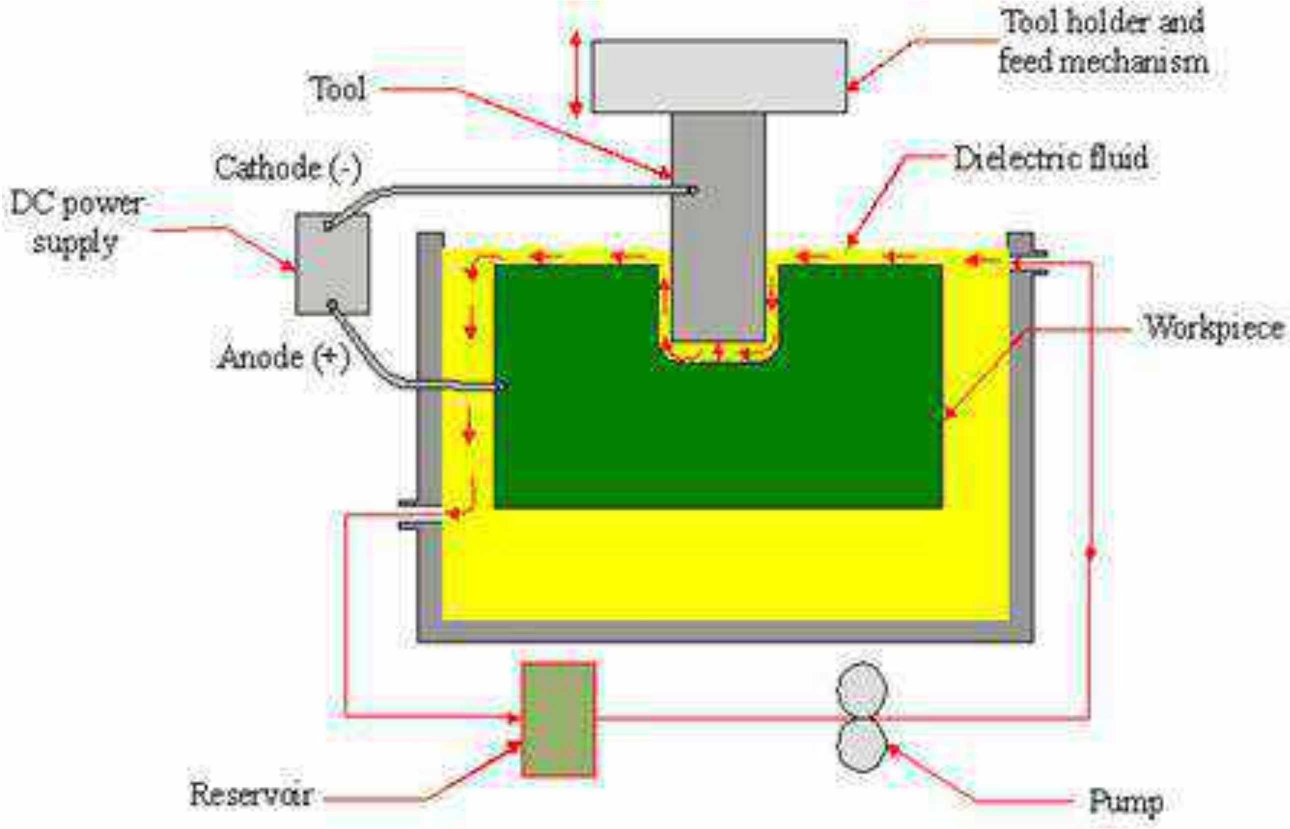
- Electrical energy is directly used to cut the material to get the final shape and size
  - Electrical discharge machining (EDM)
  - Wire cut Electrical Discharge Machining (WC EDM)

Electrical Discharge Machining (EDM)

- Principle
  - Metal is removed by producing powerful electric spark discharge between the tool (cathode) and the work material (anode)
  - Also known as Spark erosion machining or electro erosion machining

EDM

- Construction and Working



EDM

- Dielectric Fluid
  - Fluid medium which doesn’t conduct electricity
  - Dielectric fluids generally used are paraffin, white spirit, kerosene, mineral oil
  - Must freely circulate between the work piece and tool which are submerged in it
  - Eroded particles must be flushed out easily
  - Should be available @ reasonable price
  - Dielectric fluid must be filtered before reuse so that chip contamination of fluid will not affect machining accuracy

EDM

- Functions of dielectric fluid
  - Acts as an insulating medium
  - Cools the spark region & helps in keeping the tool and work piece cool
  - Carries away the eroded material along with it
  - Maintains a constant resistance across the gap
  - Remains electrically non-conductive

EDM

- Tool materials and tool wear
  - Metallic materials
    - Copper, Brass, Copper-tungsten
  - Non metallic materials
    - graphite
  - Combination of metallic and non metallic
    - Copper – graphite
  - Three most commonly used tool materials are
    - Copper, graphite, copper-tungsten

EDM

- Tool materials
  - Graphite
    - Non-metallic
    - Can be produced by molding, milling, grinding
    - Wide range of grades are available for wide applications
    - It is abrasive and gives better MRR and surface finish
    - But costlier than copper
  - Copper
    - Second choice for tool material after graphite
    - Can be produced by casting or machining
    - Cu tools with very complex features are formed by chemical etching or electroforming
  - Copper-tungsten
    - Difficult to machine and also has low MRR
    - Costlier than graphite and copper

EDM

- Selection of cutting tool is influenced by
  - Size of electrode
  - Volume of material to be removed
  - Surface finish required
  - Tolerance allowable
  - Nature of coolant application
- Basic requirement of any tool materials are
  - It should have low erosion rate
  - Should be electrically conductive
  - Should have good machinability
  - Melting point of tool should be high
  - Should have high electron emission

EDM

- Tool wear
  - Tool does not comes in contact with the work
  - So, life of tool is long and less wear takes place

$$\text{Wear ratio} = \frac{\text{vol. of work material removed}}{\text{vol. of electrode consumed}}$$

- Tool wear ratio for
  - Brass electrode is 1:1
  - Copper of 2:1
  - Copper tungsten is 8:1
  - Graphite varies between 5 and 50:1

EDM

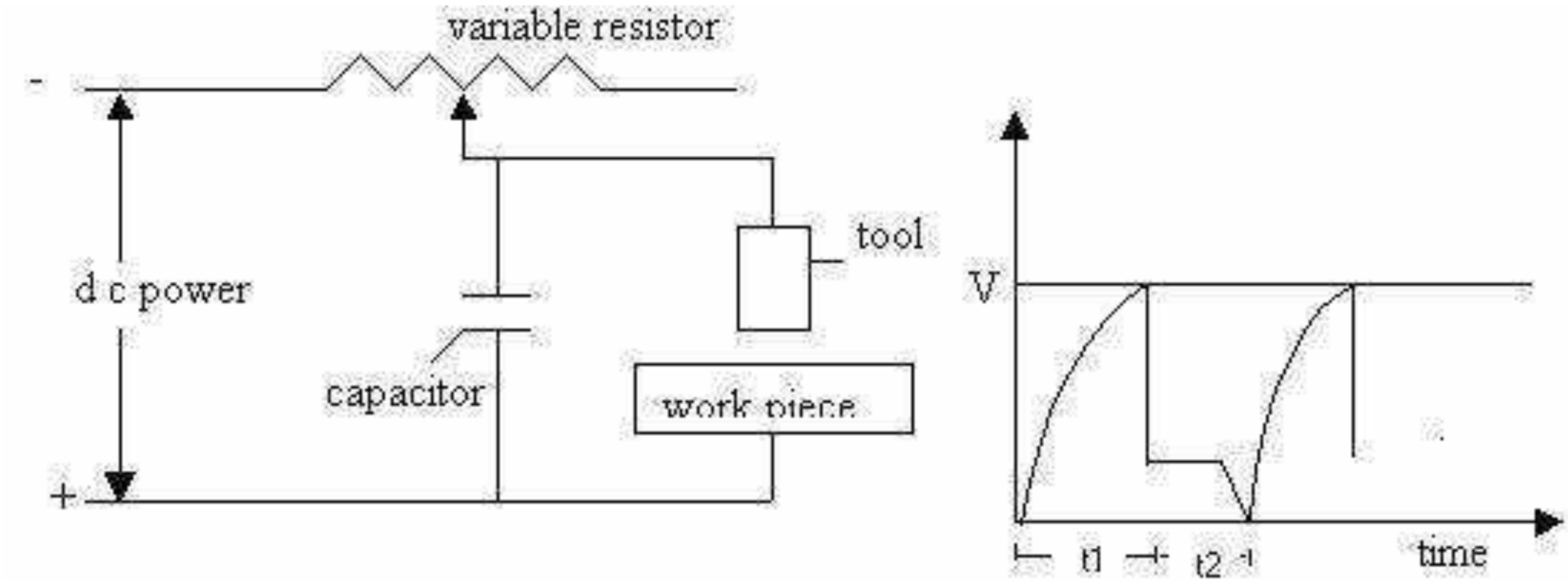
- Metal Removal Rate (MRR)
  - Defined as volume of metal removed per unit time
  - Depends upon current intensity and it increases with current
  - Usually a rough cut with heavy current and finishing cut with a less current is performed
  - MRR up to 80Cu.mm/S, can be obtained
  - Surface finish of 0.25 microns is obtained
  - Tolerances of the order of ±0.05 to 0.13 mm are commonly achieved

EDM

- Factors affecting MRR
  - Increases with forced circulation of dielectric fluid
  - Increases with capacitance
  - Increases up to an optimal value of work-tool gap, after that it drops suddenly
  - Increases up to an optimum value of spark discharge time, after that it decreases
  - MRR is maximum, when the pressure is below atmospheric pressure

EDM

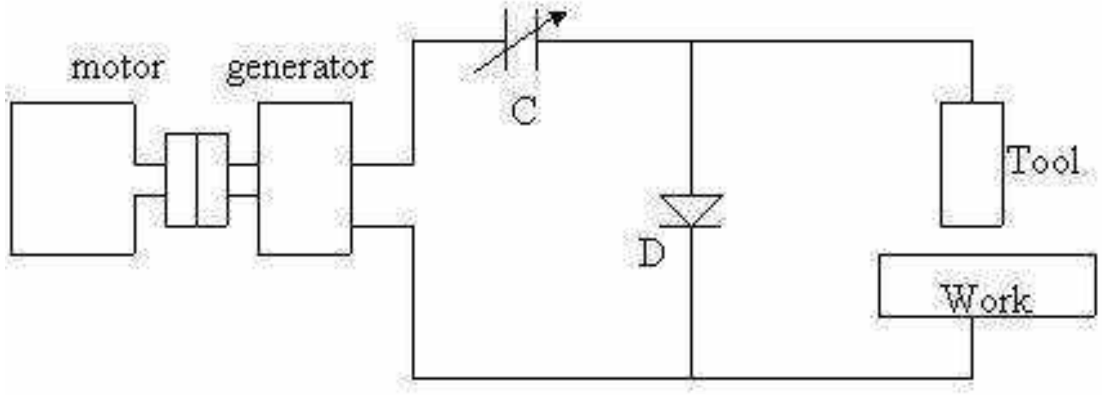
- Power generating circuits
  - Resistance capacitance circuit (RC Circuit)



  - R-C-L Circuit

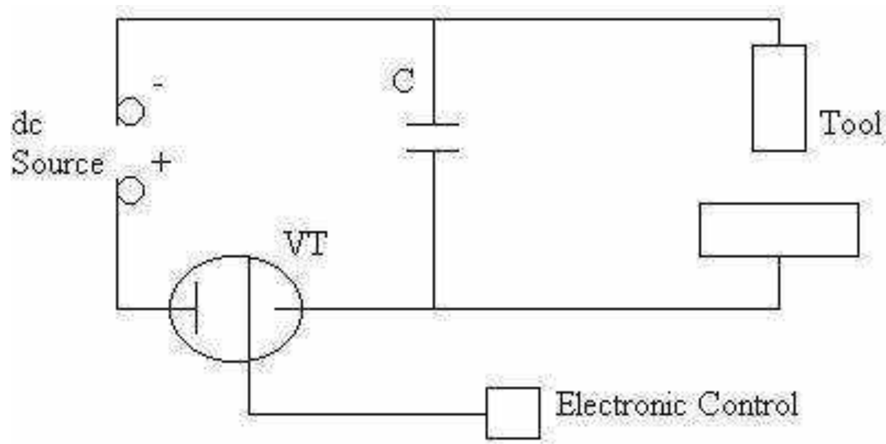
EDM

– Rotary pulse generator circuit



Rotary Impulse Generator for EDM

– Controlled pulse generator circuit



EDM with Control Pulse Circuit

EDM

- Process Parameters
  - Operating parameters
    - Electrical energy
    - Voltage
    - Time interval
    - Instantaneous current
    - Torque
    - Pulse width
  - Taper
  - Surface finish
    - Energy of the pulse
    - Frequency of operation
  - Current density

EDM

- Characteristics of EDM

Metal removal technique	By using powerful electric spark
Work material	Electrically conductive materials
Tool material	Copper, alloy of Zinc, yellow brass, Copper-Tungsten
MRR	15 to 80 Cu.mm/S
Spark gap	0.005 to 0.05 mm
Spark frequency	200 to 500 KHz
Volts	30 to 250 V
Current	5 to 60 A
Temperature	10,000 degree celcius
Dielectric fluid	Petroleum based HC fluids, Paraffin, White Spirit

EDM

- Applications
  - Production of complicated and irregular profiles
  - Thread cutting in jobs
  - Drilling of micro holes
  - Helical profile drilling
  - Curved hole drilling
  - Re-sharpening of cutting tool and broaches
  - Re-machining of die cavities without annealing
- Recent developments
  - EDM change from using relaxation circuit to faster and more efficient impulse circuits
  - Instead of using Cu; WC is used as electrode

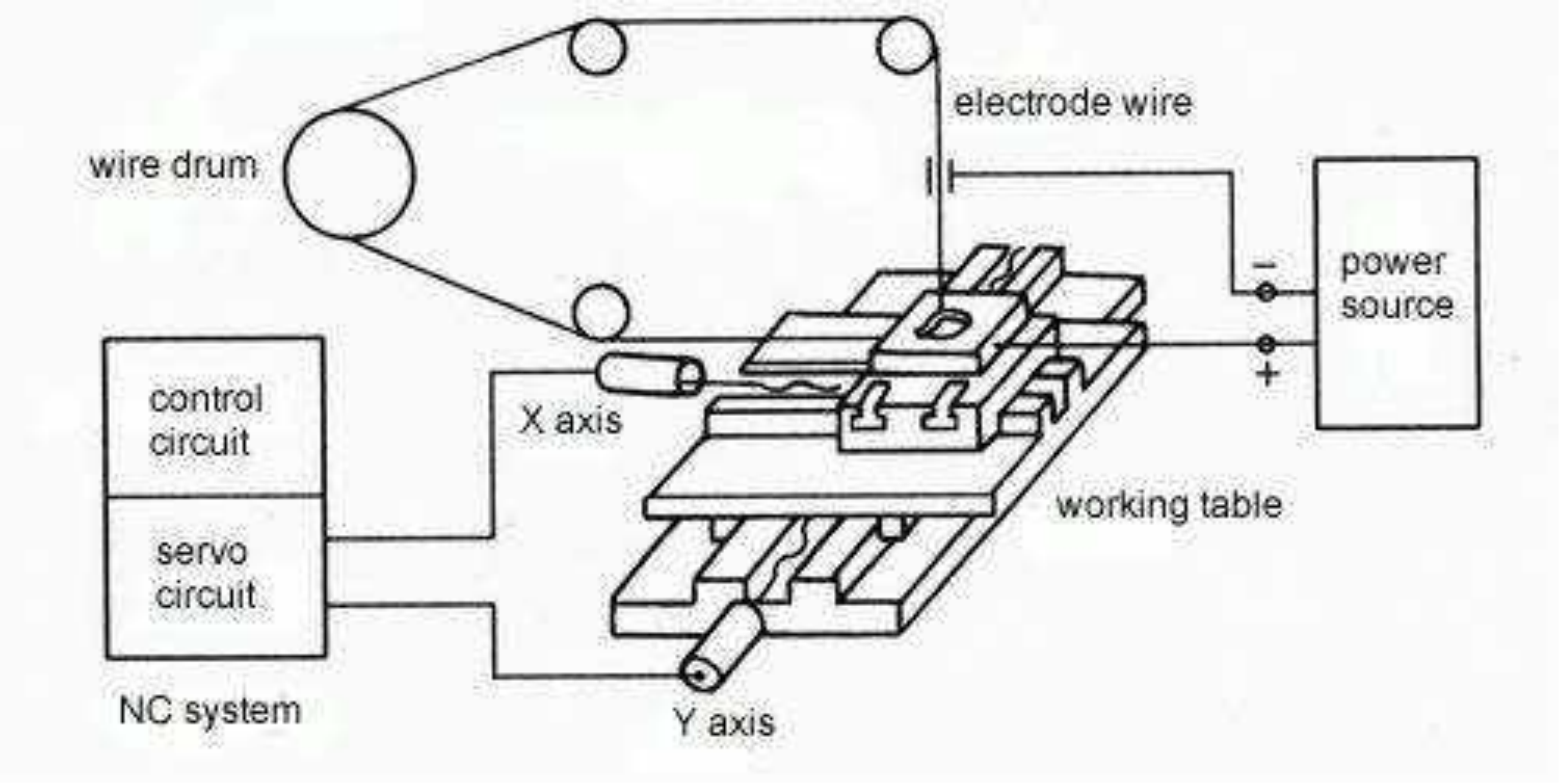
EDM

- Advantages
  - Can be used to machine various conductive materials
  - Gives good surface finish
  - Machining of very thin section is possible
  - Does not leaves any chips or burrs on the work piece
  - High accuracy is obtained
  - Fine holes can be easily drilled
  - Process once started does not need constant operators attention
  - It is a quicker process
  - Well suited to machine complicated components

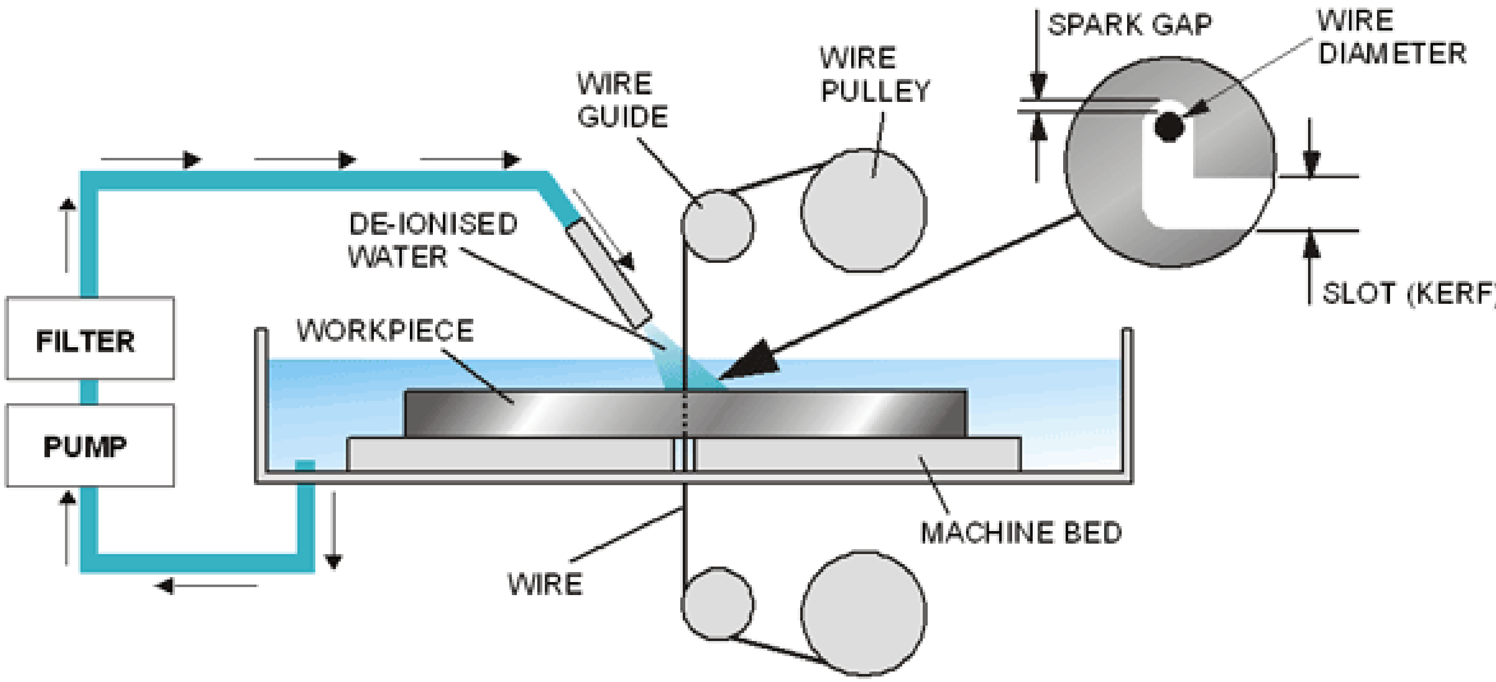
EDM

- Disadvantages
  - Used to machine only electrically conductive materials
  - Non-metallic compounds such as plastics, ceramics or glass can never be machined
  - Suitable for machining small work pieces
  - Electrode wear and overcut are serious problems
  - Perfect square corners can not be machined
  - MRR is slow
  - Power requirement is high
  - The surface machined has been found to have micro holes

Wire Cut Electro-Discharge Machining (WC EDM)



WC EDM


SPARK GAP
WIRE DIAMETER
WIRE PULLEY
WIRE GUIDE
DE-IONISED WATER
SLOT (KERF)
FILTER
WORKPIECE
PUMP
MACHINE BED
WIRE

WC EDM

- Applications
  - Best suited for production of gears, tools, dies, rotors, turbine blades and cams
- Disadvantages
  - Capital cost is high
  - Cutting rate is slow
  - Not suitable for large work pieces

WC EDM

- Features / Advantages of WC EDM
  - Manufacturing electrode
  - Electrode wear
  - Surface finishing
  - Complicated shapes
  - Time utilization
  - Straight holes
  - Rejection
  - Economical
  - Cycle time
  - Inspection time

Difference between EDM & WC EDM

S. No	Wire Cut EDM	EDM
1	Very thin wire made of brass is used as tool	Expensive alloy of silver and tungsten are used as electrode
2	Whole work piece is not submerged in dielectric medium	Whole work piece is submerged in dielectric medium
3	Easy to machine complex two dimensional profiles	Difficult to cut complex two dimensional profiles

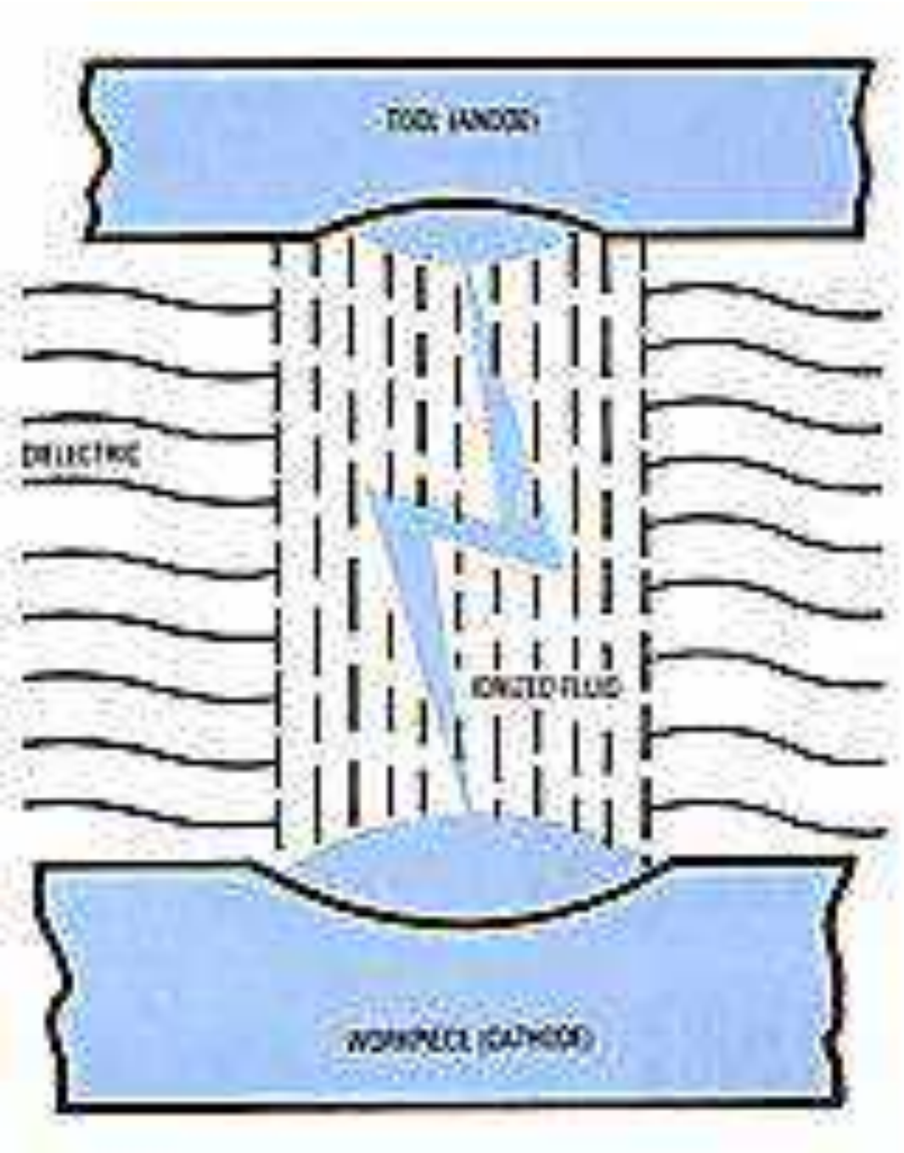
Module 6

MODULE 3

- ELECTRIC DISCHARGE MACHINING
- ULTRASONIC MACHINING
- ELECTRO CHEMICAL MACHINING

ELECTRIC DISCHARGE MACHINING (EDM)

- Its a manufacturing process whereby a desired shape is obtained using electrical discharges (sparks).



EDM spark erosion is the same as having an electrical short that burns a small hole in a piece of metal it contacts.

Electro Discharge Machining (EDM) is an electro-thermal non-traditional machining process, where electrical energy is used to generate electrical spark and material removal mainly occurs due to thermal energy of the spark.

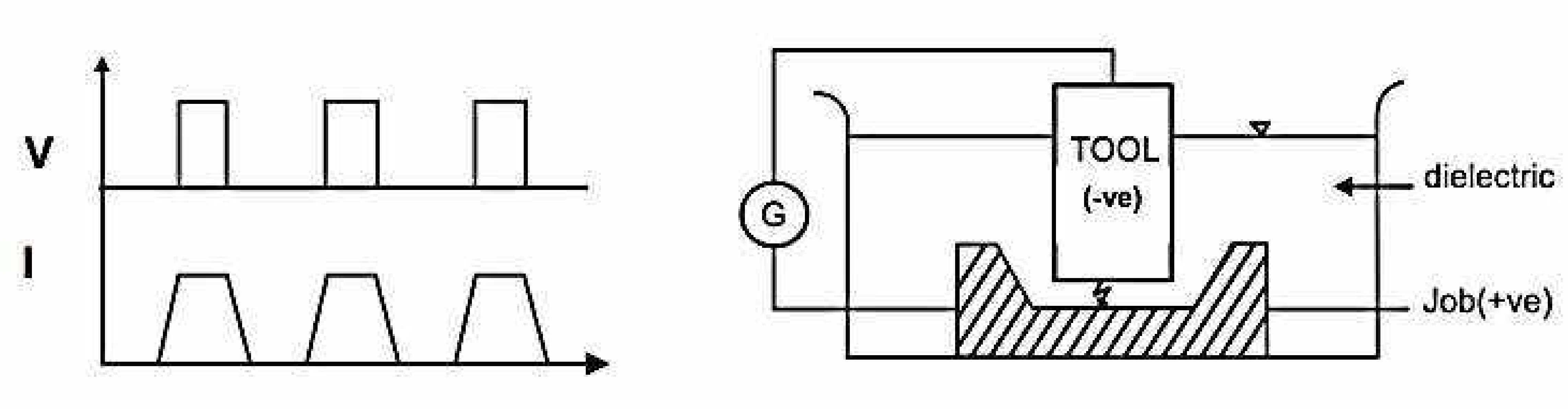
- EDM is mainly used to machine difficult-to-machine materials and high strength temperature resistant alloys.
- EDM can be used to machine difficult geometries in small batches or even on job-shop basis.
- Work material to be machined by EDM has to be electrically conductive.

The EDM process can be used in two different ways:

1. A preshaped or formed electrode (tool),usually made from graphite or copper, is shaped to the form of the cavity it is to reproduce. The formed electrode is fed vertically down and the reverse shape of the electrode is eroded (burned) into the solid workpiece.

2. A continuous-travelling vertical-wire electrode, the diameter of a small needle or less, is controlled by the computer to follow a programmed path to erode or cut a narrow slot through the workpiece to produce the required shape.

EDM - Process



Schematic representation of the basic working principle of EDM process

In EDM,

- ✓ A potential difference is applied between the tool and workpiece.
- ✓ Both the tool and the work material are to be conductors of electricity. The tool and the work material are immersed in a dielectric medium.
- ✓ A gap is maintained between the tool and the workpiece.
- ✓ Depending upon the applied potential difference and the gap between the tool and workpiece, an electric field would be established.

- ✓ Generally the tool is connected to the negative terminal of the generator and the workpiece is connected to positive terminal.
- ✓ As the electric field is established between the tool and the job, the free electrons on the tool are subjected to electrostatic forces.
- ✓ If the work function or the bonding energy of the electrons is less, electrons would be emitted from the tool (assuming it to be connected to the negative terminal).
- ✓ Such emission of electrons are called or termed as cold emission.

- ✓ “Cold emitted” electrons are then accelerated towards the job through the dielectric medium.

- ✓ As they gain velocity and energy, and start moving towards the job, there would be collisions between the electrons and dielectric molecules.

- ✓ Such collision may result in ionisation of the dielectric molecule depending upon the work function or ionisation energy of the dielectric molecule and the energy of the electron.

- ✓ Thus, as the electrons get accelerated, more positive ions and electrons would get generated due to collisions.

- ✓ This cyclic process would increase the concentration of electrons and ions in the dielectric medium between the tool and the job at the spark gap.

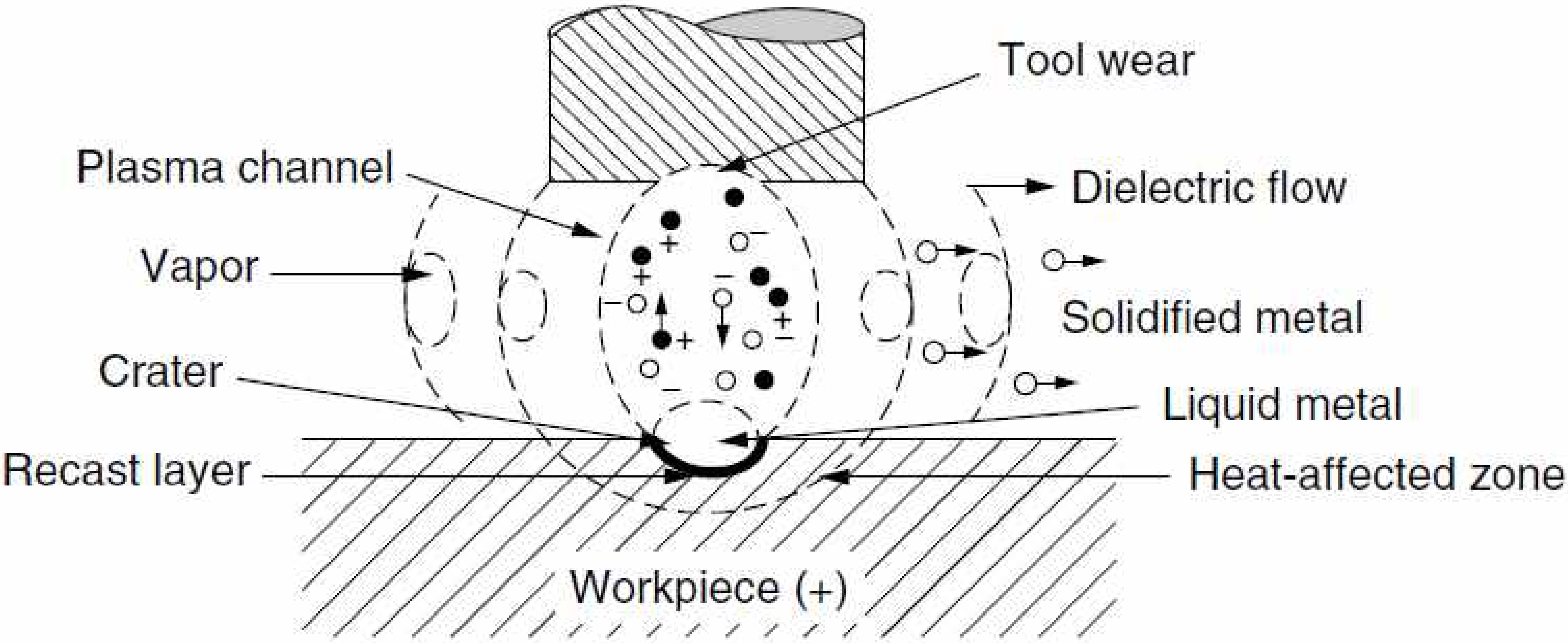
- ✓ Concentration would be so high that the matter existing in that channel could be characterised as "plasma".

- ✓ Electrical resistance of such plasma channel would be very less.

- ✓ Thus all of a sudden, a large number of electrons will flow from the tool to the job and ions from the job to the tool.

- ✓ This is called avalanche motion of electrons.

EDM – Working Principle



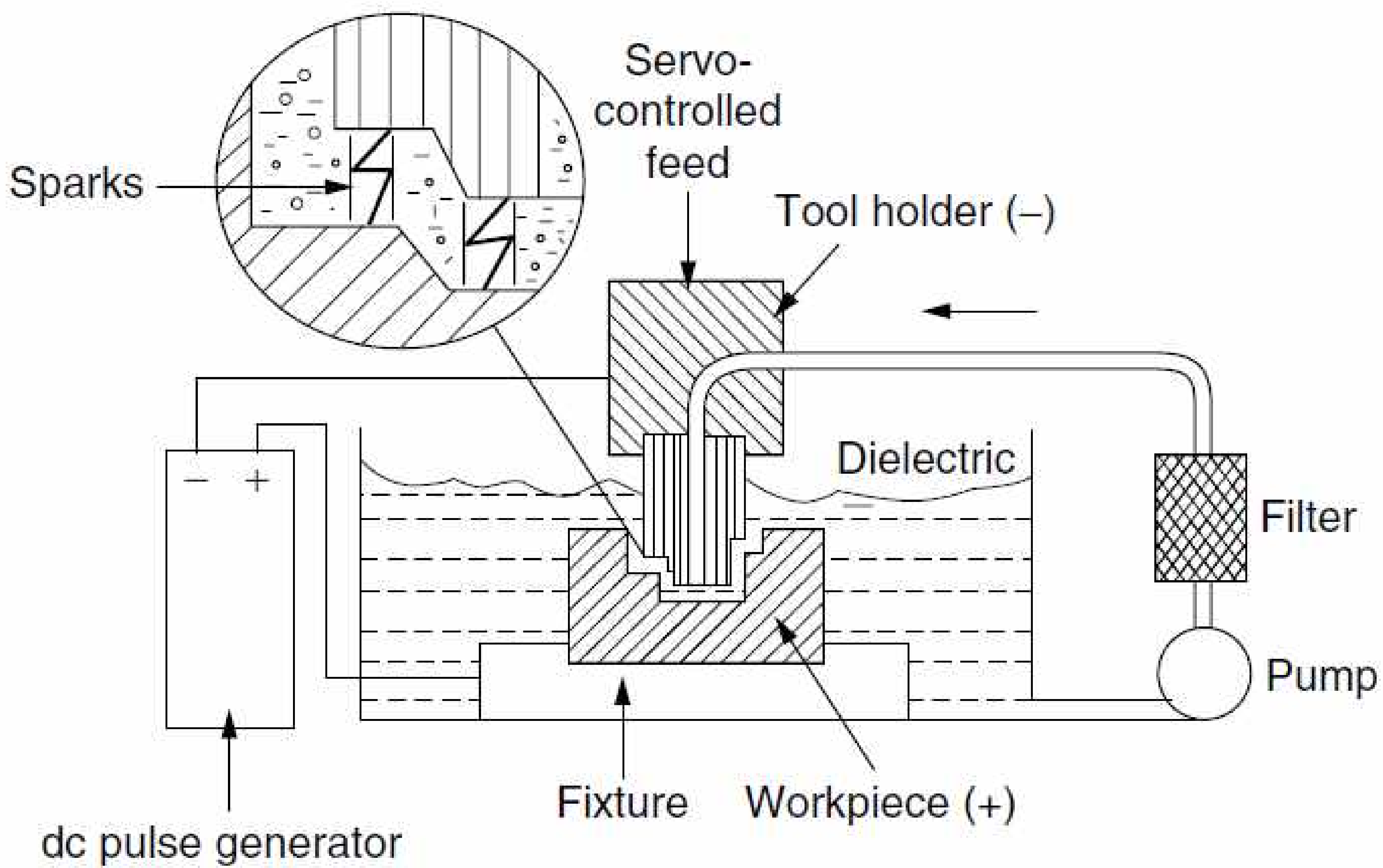
EDM spark description.

- ✓ Such movement of electrons and ions can be visually seen as a spark.
- ✓ Thus the electrical energy is dissipated as the thermal energy of the spark.
- ✓ High speed electrons then impinge on the job and ions on the tool.
- ✓ Kinetic energy of the electrons and ions on impact with the surface of the job and tool respectively would be converted into thermal energy or heat flux.
- ✓ Such intense localised heat flux leads to extreme instantaneous confined rise in temperature which would be in excess of 10,000°C.

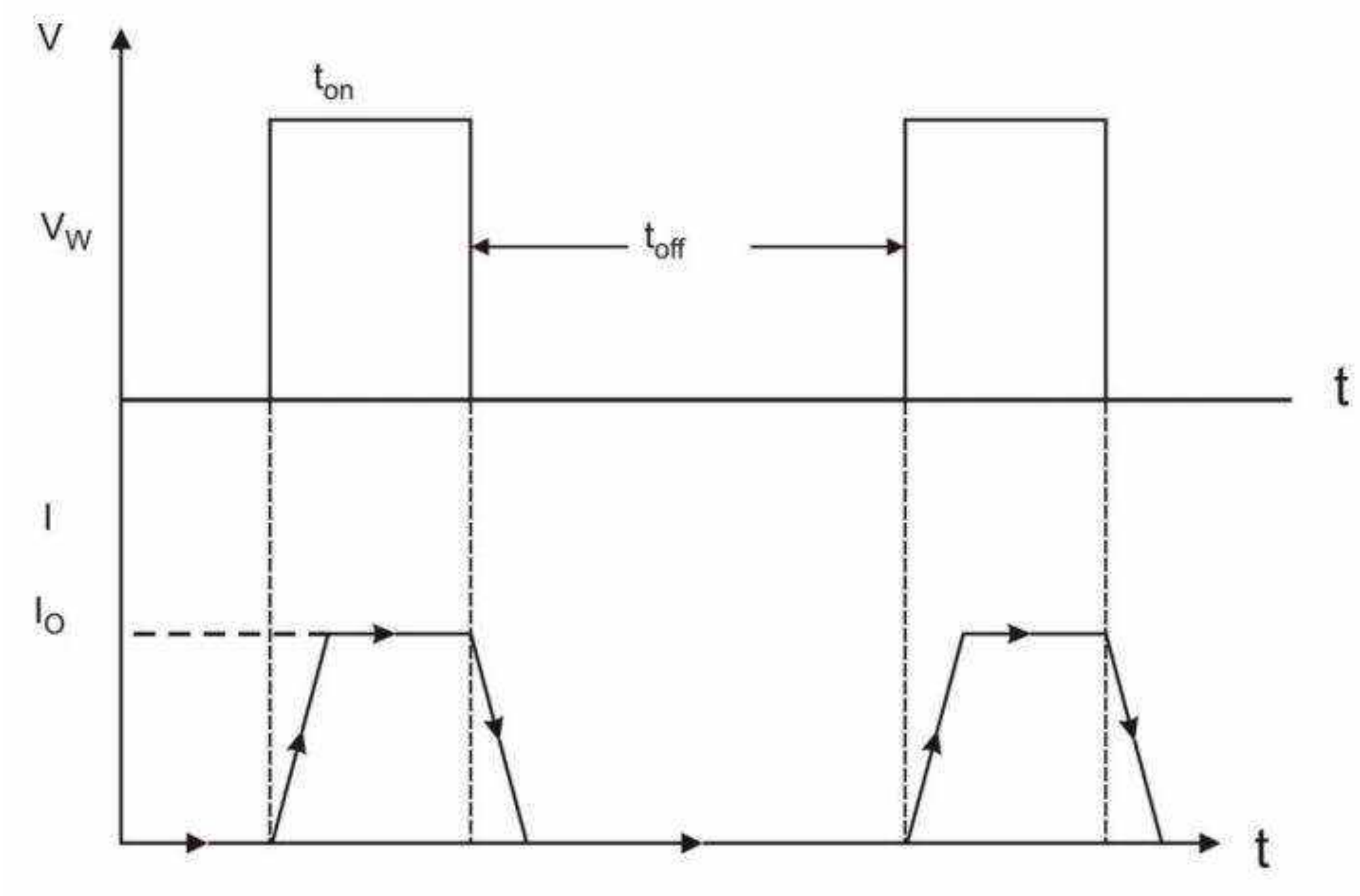
- ✓ Such localised extreme rise in temperature leads to material removal.
- ✓ Material removal occurs due to instant vapourisation of the material as well as due to melting.
- ✓ The molten metal is not removed completely but only partially.
- ✓ As the potential difference is withdrawn, the plasma channel is no longer sustained.
- ✓ As the plasma channel collapse, it generates pressure or shock waves, which evacuates the molten material forming a crater of removed material around the site of the spark.

Material removal in EDM mainly occurs due to formation of shock waves as the plasma channel collapse owing to discontinuation of applied potential difference.

EDM Schematic



Process Parameters



The waveform is characterised by the

- The open circuit voltage - Vo
- The working voltage - Vw
- The maximum current - Io
- The pulse on time – the duration for which the voltage pulse is applied - t_{on}
- The pulse off time - t_{off}
- The gap between the workpiece and the tool – spark gap - δ
- The polarity – straight polarity – tool (-ve)
- The dielectric medium
- External flushing through the spark gap.

Characteristics of EDM

(a) The process can be used to machine any work material if it is electrically conductive

(b) Material removal depends on mainly thermal properties of the work material rather than its strength, hardness etc

(c) In EDM there is a physical tool and geometry of the tool is the positive impression of the hole or geometric feature machined

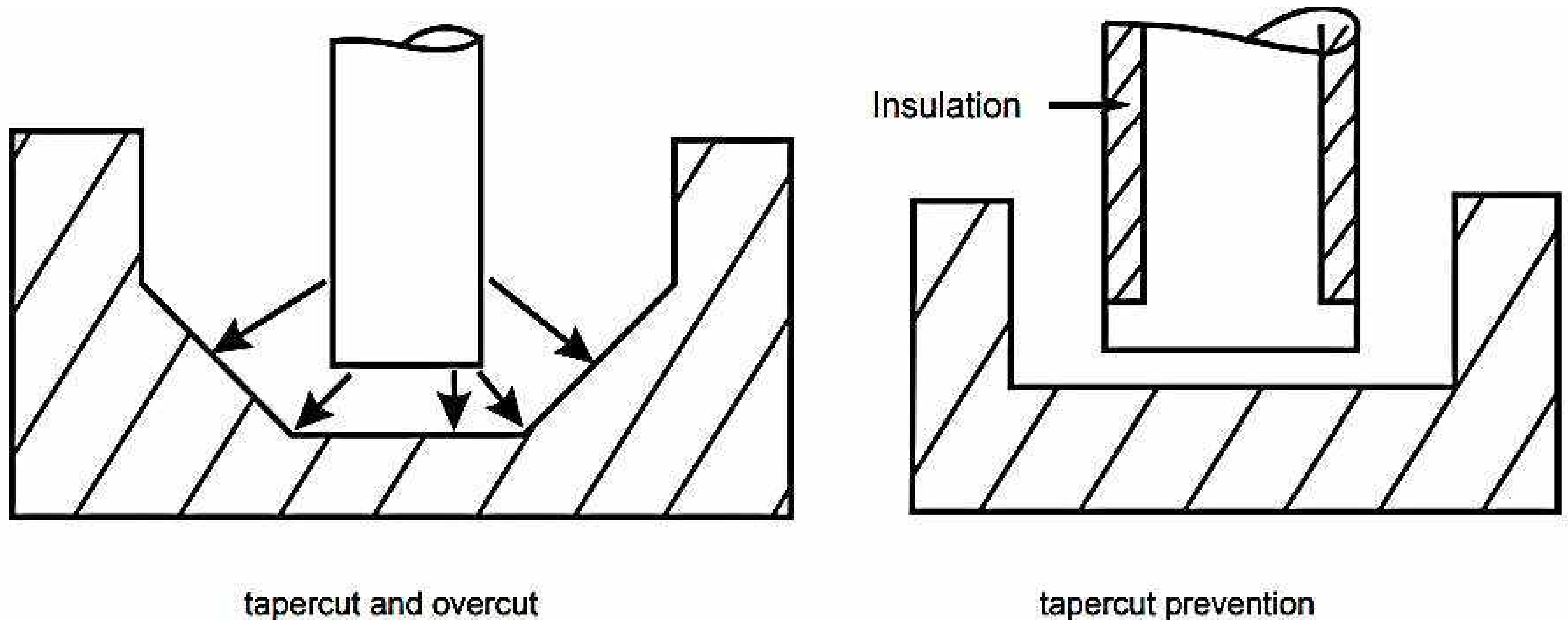
(d) The tool has to be electrically conductive as well. The tool wear once again depends on the thermal properties of the tool material

(e) Though the local temperature rise is rather high, still due to very small pulse on time, there is not enough time for the heat to diffuse and thus almost no increase in bulk temperature takes place.

Thus the heat affected zone is limited to 2 – 4 μm of the spark crater

(f) However rapid heating and cooling and local high temperature leads to surface hardening which may be desirable in some applications

(g) Though there is a possibility of taper cut and overcut in EDM, they can be controlled and compensated.



Schematic depiction of taper cut and over cut and control of taper cut

Dielectric – low viscosity hydrocarbon oil

- Dielectric fluid should provide an oxygen free machining environment.
- It should have enough strong dielectric resistance so that it does not breakdown electrically too easily but at the same time ionise when electrons collide with its molecule.
- During sparking it should be thermally resistant as well.

Dielectric

Generally kerosene and deionised water is used as dielectric fluid in EDM.

Tap water cannot be used as it ionises too early and thus breakdown due to presence of salts as impurities occur.

Dielectric medium is generally flushed around the spark zone. It is also applied through the tool to achieve efficient removal of molten material.

Functions of Dielectric fluid: Essential functions of a dielectric fluid used in EDM process are:

1. Remain electrically non-conductive until the required breakdown voltage is attained, i.e., it should possess high dielectric strength.
2. When once the breakdown voltage is reached it should breakdown electrically instantly.
3. Deionize the spark gap, i.e., quench the spark rapidly after the discharge has occurred.
4. Carry away the metal particles removed from the arc gap.
5. Act as a good cooling medium.

Desirable Properties of dielectric fluid: In order to act as a good dielectric medium and meet the various functions the fluid is required to possess the following properties:

1. High electric strength for proper insulation.
2. High flash and fire point to prevent fire hazards.
3. Low viscosity and good wetting properties
4. Chemically neutral to prevent corrosion.
5. Non-toxic in nature.
6. Low decomposition rate for long life.
7. Low cost
8. Good quenching properties.

Sl. No.	Dielectric fluid	Material removal Rate cm^3/amp min $\times 10^4$	Wear ratio-work material /tool material
1.	Kerosene	40.0	2.8
2.	Distilled water	54.5	2.7
3.	Tetraethylene glycol	103.0	6.8

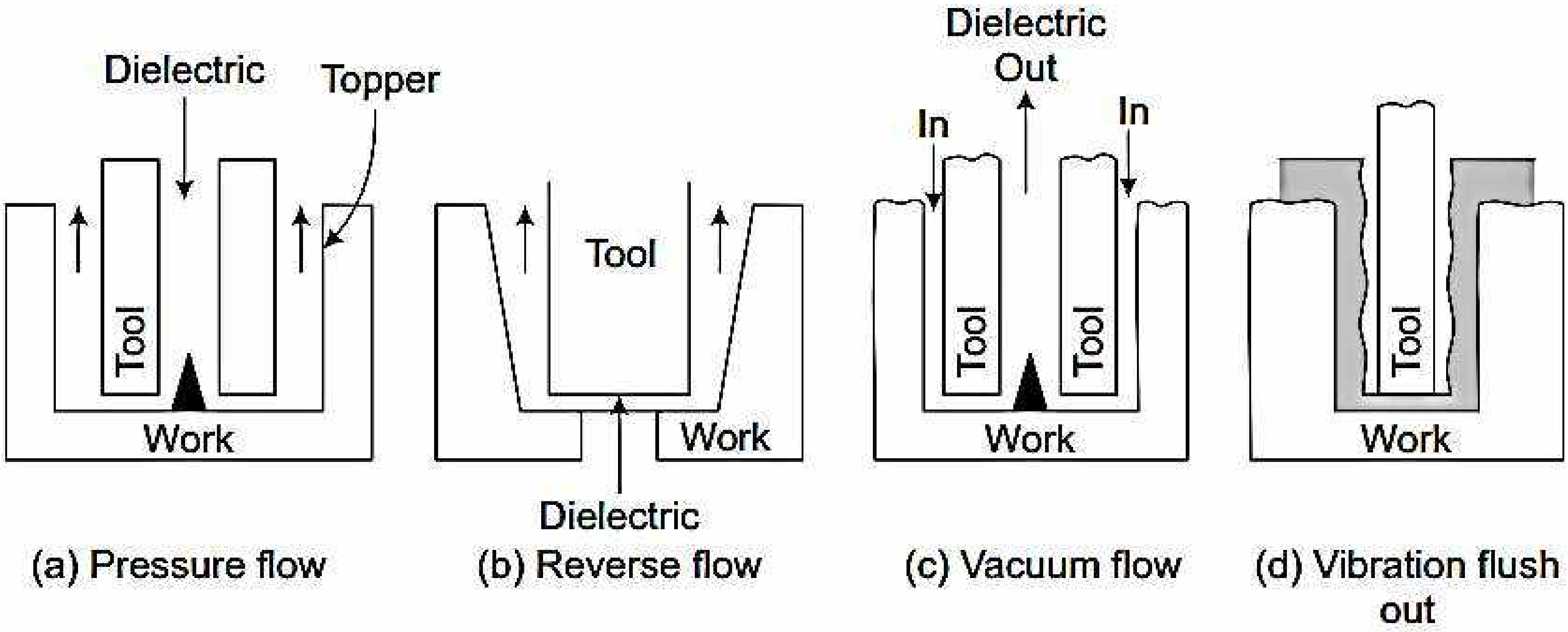
Performance of different dielectric fluids in machining steel using brass tool.

FLUSHING OF DIELECTRIC

Flushing refers to proper circulation of dielectric fluid at the gap between the work and electrode tool in EDM

The different methods of circulation of dielectric fluid for flushing in EDM are:

1. Pressure dielectric flow
2. Reverse dielectric flow
3. Vacuum dielectric flow
4. Vibration flush cut



TYPES OF FLUSHING

EDM Tool Material

The main factors that determine the suitability of a material for application as electrode tool material in EDM are:

1. Higher metal removal rate
2. Lower tool wear
3. Higher degree of electrical efficiency

TOOL MATERIAL USED IN EDM AND THEIR CHARACTERISTICS

Material	*Material Removal Rate*	*Wear ratio*	*Fabrication*	*Cost*	*Application*
Graphite	High	Low	Easy	High	All metals
Copper	High in roughing	Low	Easy	High	All metals
Brass	High in finishing	High	Easy	Low	All metals
Tungsten	Low	Low	Difficult	High	For small holes
Tungsten-Copper alloys	Low	Low	Difficult	High	Accurate work
Cast Iron	Low	Low	Easy	Low	Restricted
Steel	Low	High	Easy	Low	Finishing
Zinc Alloys	High in roughing	High	Easy	Low	All metals

EDM Equipment

EDM machine has the following major modules

- Dielectric reservoir, pump and circulation system
- Power generator and control unit
- Working tank with work holding device
- X-y table accommodating the working table
- Tool holder
- Servo system to feed the tool

EDM - APPLICATIONS

1. Dies, fixtures, gauges
2. Cutting tools
3. Press tools, extrusion dies
4. Die moulds for plastics
5. Diecasting dies, mould inserts
6. Remachining, repairing of worn dies for hot and cold forging
7. Making forging dies like connecting rod forging dies, etc.
8. Sintering dies
9. Calibrating tools
10. Shaping carbide tools, templates.

Wire Cut Electric Discharge Machining (WEDM)

- A thin metallic wire is fed on-to the workpiece, which is submerged in a tank of dielectric fluid such as deionized water.

- This process can also cut plates as thick as 300mm and is used for making punches, tools and dies from hard metals that are difficult to machine with other methods.

- The wire, which is constantly fed from a spool, is held between upper and lower diamond guides.

- Guides are usually CNC-controlled and move in the x–y plane.

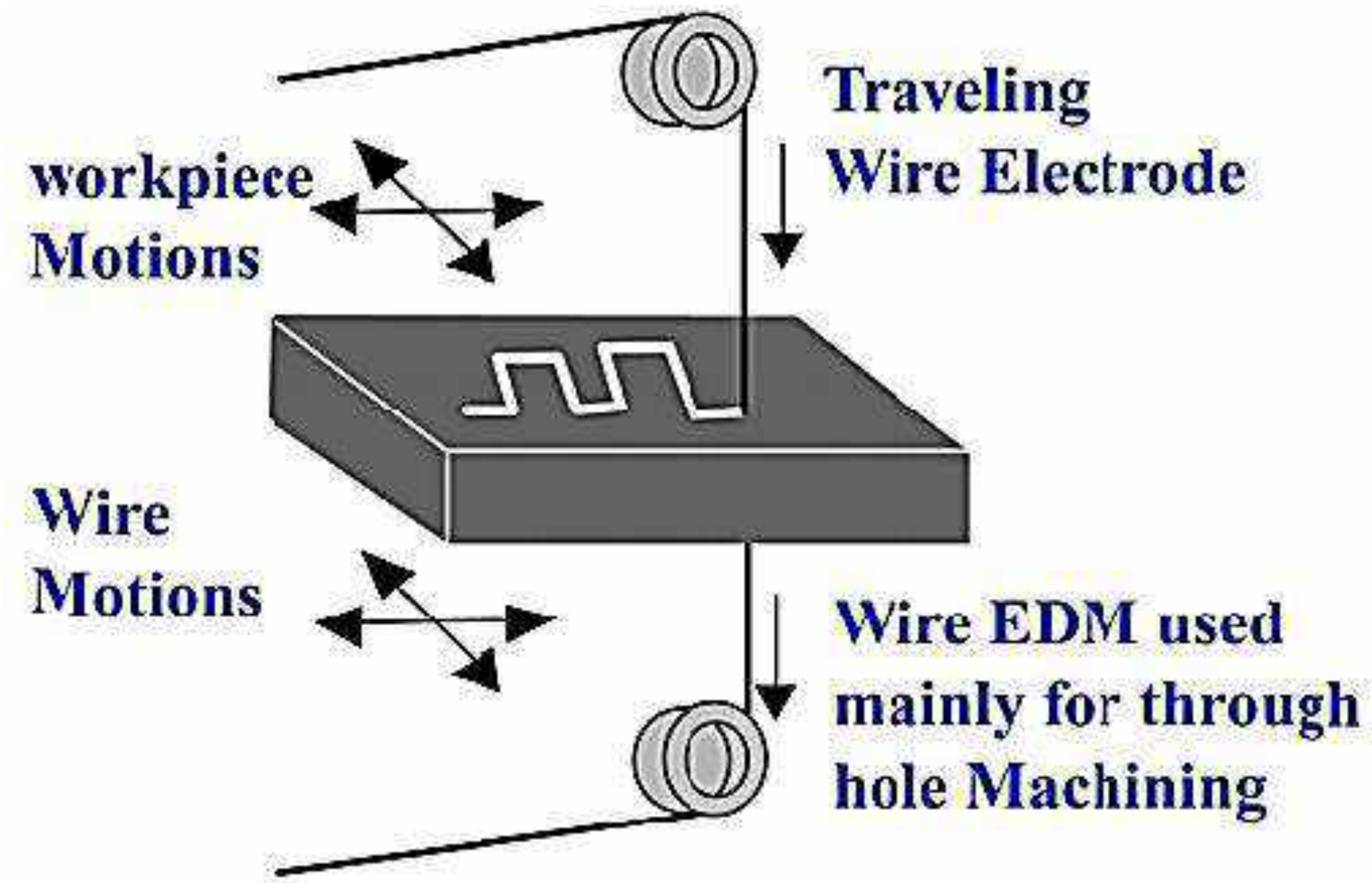
- On most machines, the upper guide can move independently in the z–u–v axis, giving it a flexibility to cut tapered and transitioning shapes

- Wires made of brass are generally preferred, (also uses copper or tungsten or brass coated and multi coated wires).

- Water helps in flushing away the debris from the cutting zone.

- Flushing also helps to determine the feed rates to be given for different thickness of the materials

Wire-cut EDM Process - SCHEMATIC



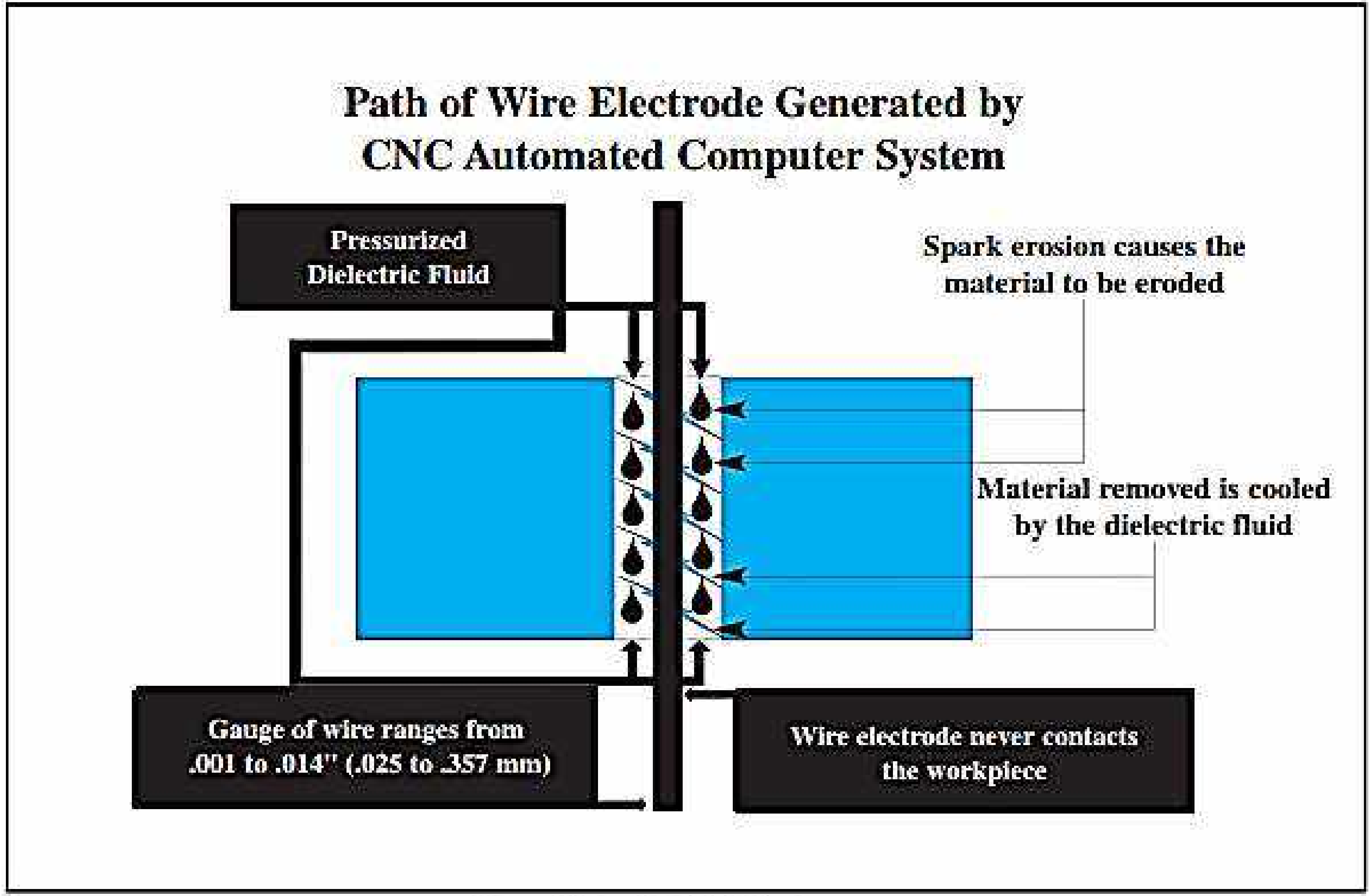
PROCESS OF MATERIAL REMOVAL IN WIRE CUT EDM

- In the WEDM process, the motion of wire is slow.
- Wire is fed in the programmed path and material is cut/ removed from the workpiece accordingly.
- Material removal takes place by a series of discrete discharges between the wire electrode and workpiece in the presence of a di-electric fluid.

- Di-electric fluid gets ionized in between the tool-electrode gap thereby creating a path for each discharge.

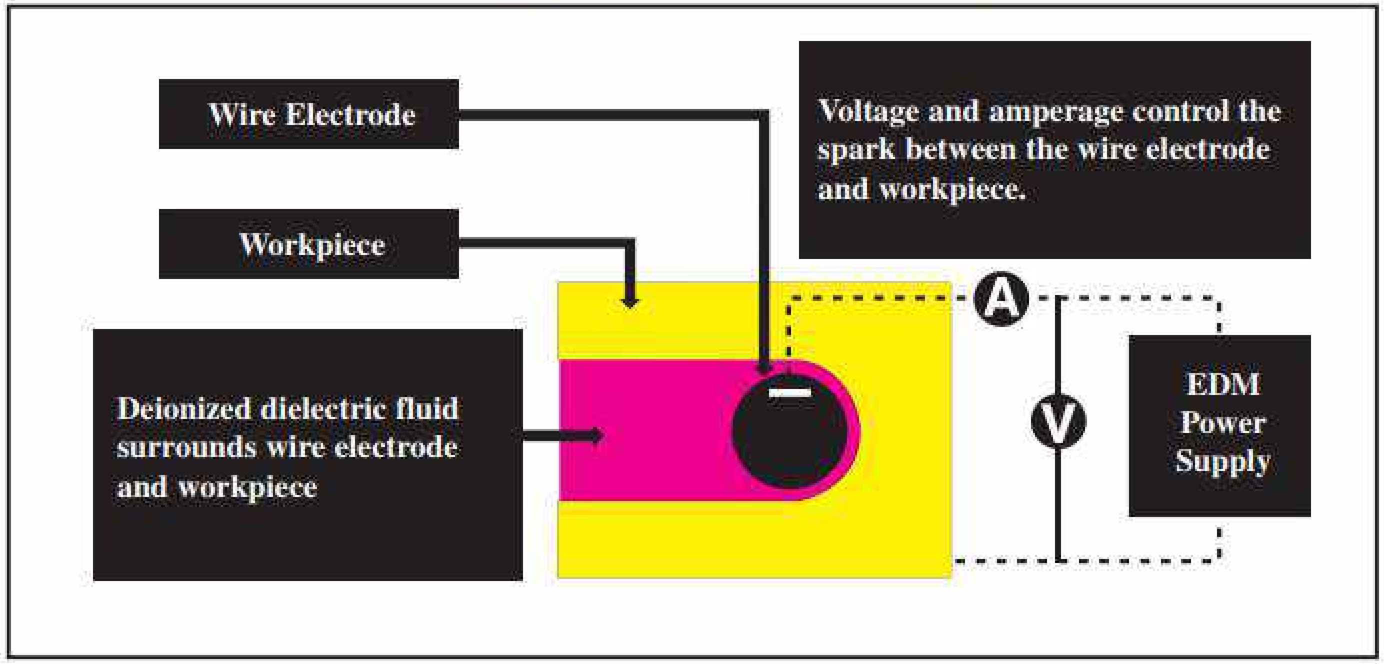
- Area wherein discharge takes place gets heated to very high temperatures such that the surface gets melted and removed.

- Cut particles (debris) get flushed away by the continuously flowing dielectric fluid.



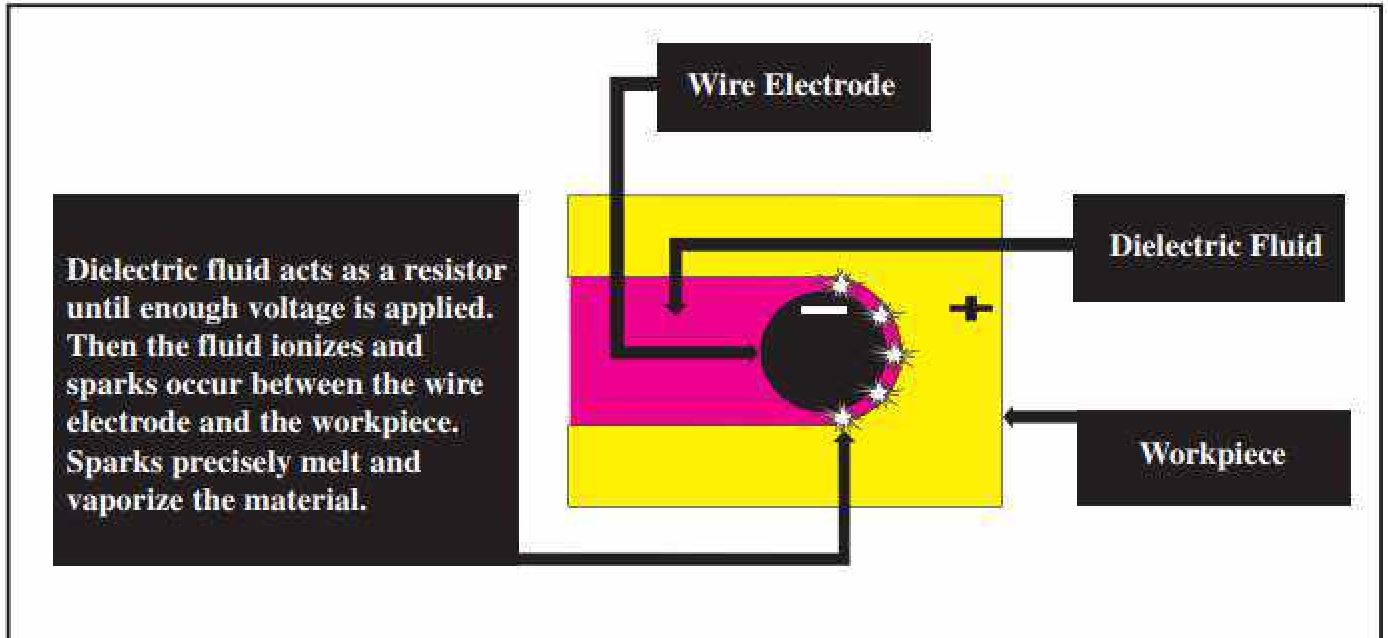
How Wire EDM Works
Precisely controlled sparks erode the metal using deionized water.
Pressurized water removes the eroded material.

A. Power Supply Generates Volts and Amps

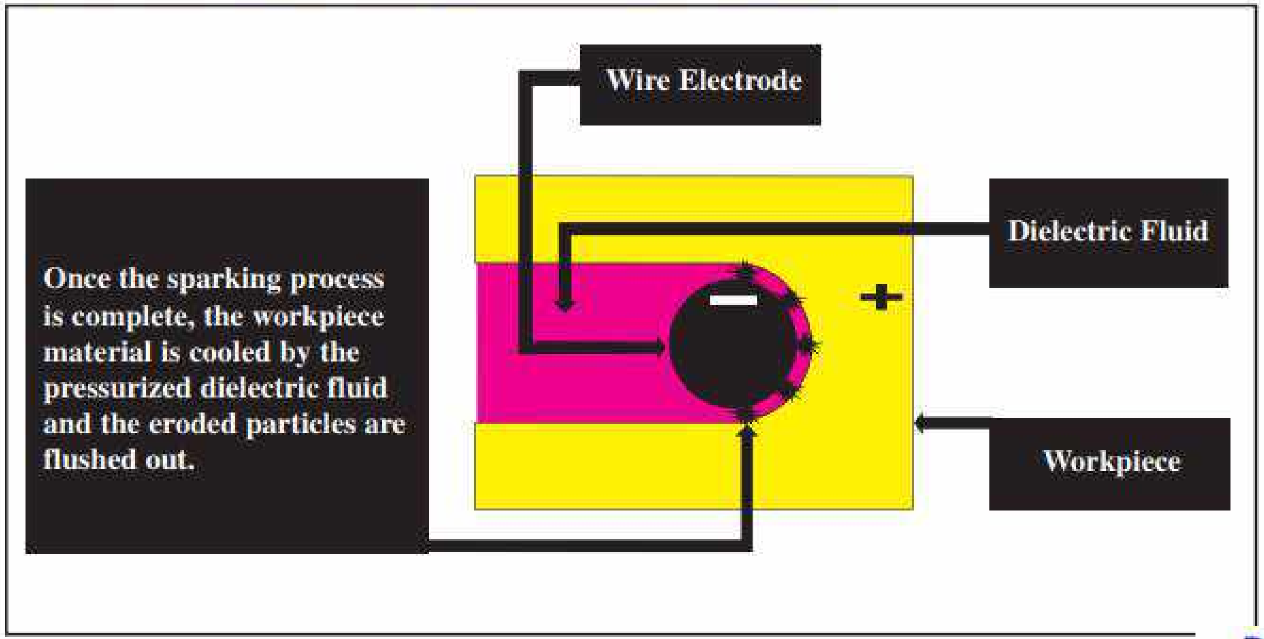


STEP BY STEP PROCEDURE

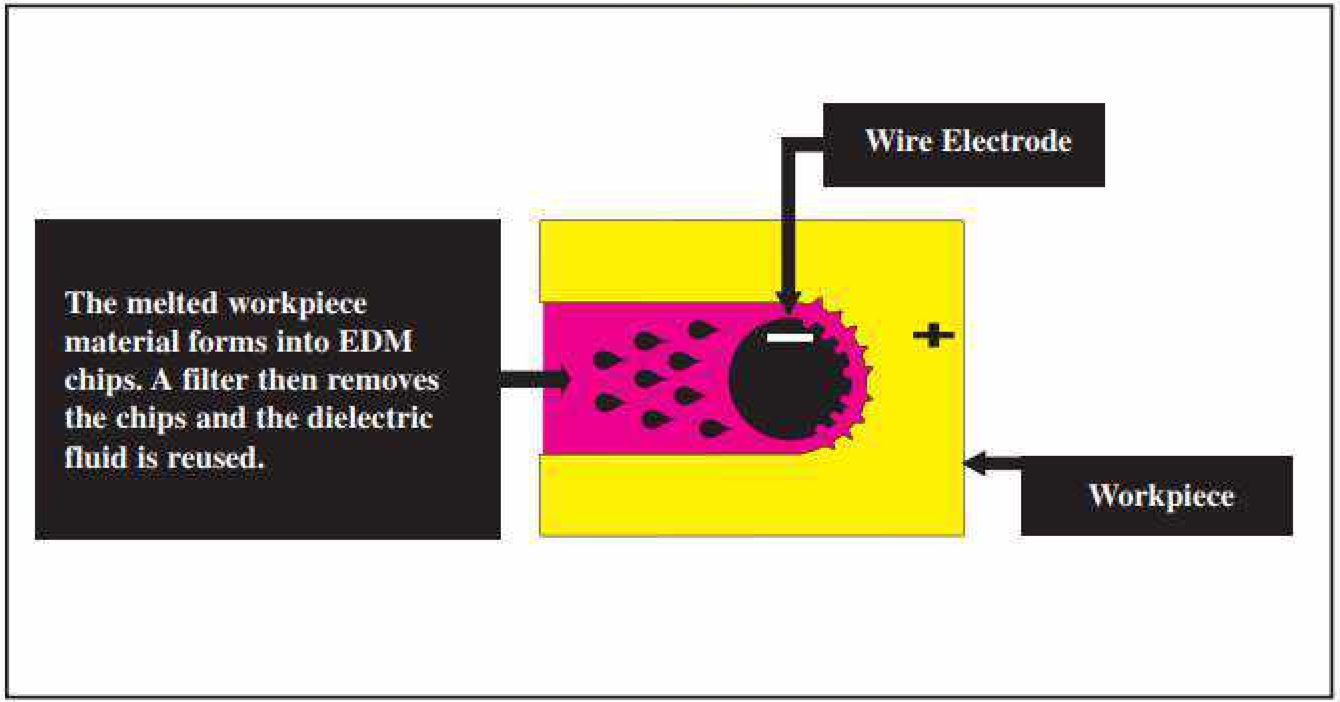
B. During On Time Controlled Spark Erodes Material



C. Off Time Allows Fluid to Remove Eroded Particles



D. Filter Removes Chips While the Cycle is Repeated



WEDM - APPLICATIONS

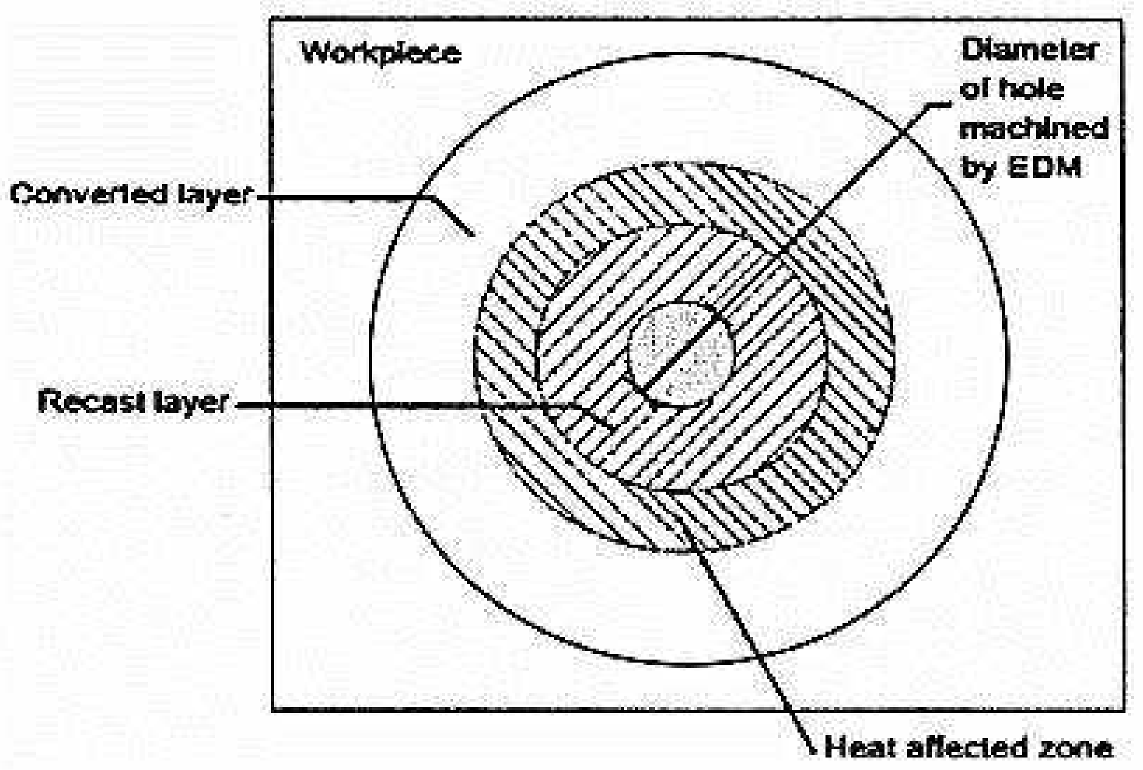
Wire EDM is used for cutting aluminium, brass, copper, carbides, graphite, steels and titanium

- ✓ Aerospace, Medical, Electronics and Semiconductor applications
- ✓ Tool & Die making industries.
- ✓ For cutting the hard Extrusion Dies
- ✓ In making Fixtures, Gauges & Cams
- ✓ Cutting of Gears, Strippers, Punches and Dies
- ✓ Manufacturing hard Electrodes.
- ✓ Manufacturing micro-tooling for Micro-EDM, Micro-USM and such other micromachining applications

Wire EDMing Internal Keyways

MICROSCOPIC STUDY OF EDMed COMPONENTS REVEALS THE PRESENCE OF 3 KINDS OF LAYERS

- ✓ RECAST Layer
- ✓ HEAT AFFECTED ZONE (HAZ)
- ✓ CONVERTED Layer



RECAST LAYER

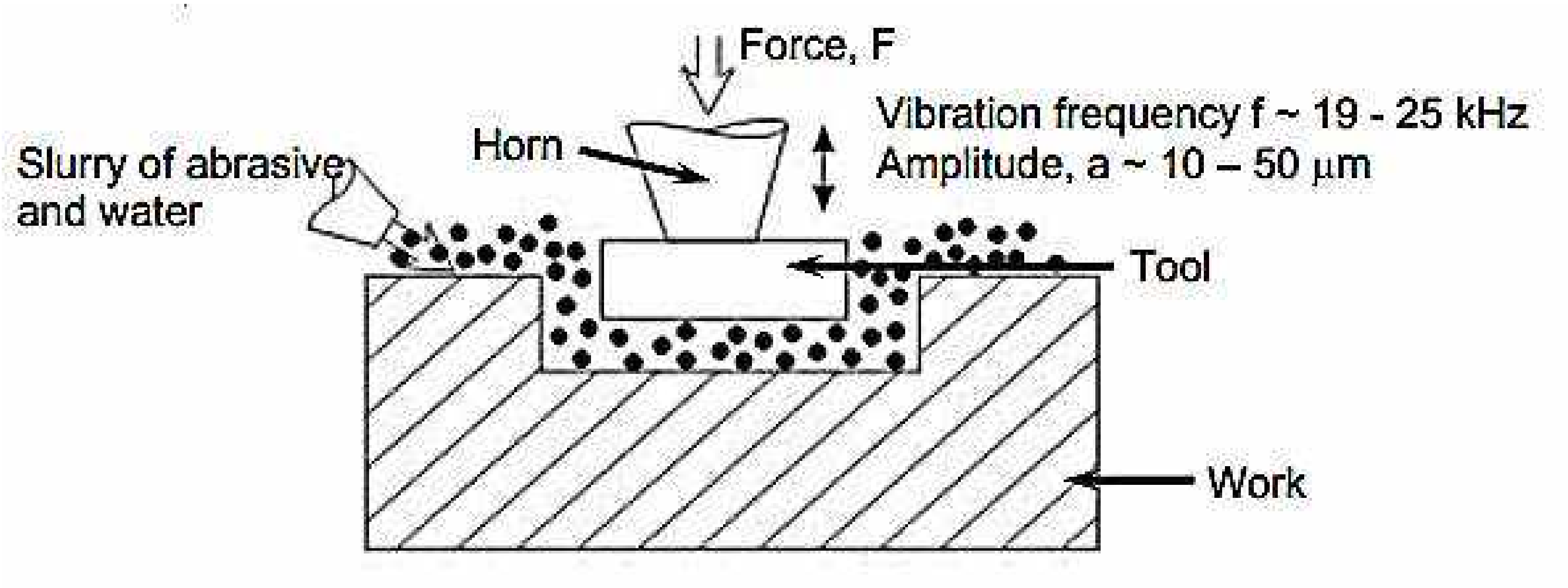
If molten material from the workpiece is not flushed out quickly, it will resolidify and harden due to the cooling effect of the dielectric and gets adhered to the machined surface. This thin layer of about 2.5-50 μm is formed and is called re-cast layer.

HAZ

- Beneath the recast layer, a HAZ is formed due to rapid heating and quenching cycles during EDM.
- Layer is approximately 25 μm thick.
- Heating-cooling cycle and diffused material during machining are the responsible reasons for the presence of this zone.
- Thermal residual stresses, grain boundary weaknesses, and grain boundary cracks are some of the characteristics of this zone.

Conversion zone (or converted layer) is identified below the HAZ and is characterized by a change in grain structure from the original structure

ULTRASONIC MACHINING (USM)


Force, F
Vibration frequency f ~ 19 - 25 kHz
Amplitude, a ~ 10 – 50 μm
Horn
Slurry of abrasive and water
Tool
Work

USM PROCESS

ULTRASONIC MACHINING

- ✓ In ultrasonic machining, a tool of desired shape vibrates at an ultrasonic frequency (19~25 kHz) with an amplitude of around 15 – 50 μm over the workpiece.

- ✓ Generally the tool is pressed downward with a feed force, F.

- ✓ Between the tool and workpiece, the machining zone is flooded with hard abrasive particles generally in the form of a water based slurry.

- ✓ As the tool vibrates over the workpiece, the abrasive particles act as the indenters and indent both the work material and the tool.

Abrasive particles, as they indent, the work material, would remove the same, particularly if the work material is brittle, due to crack initiation, propagation and brittle fracture of the material.

Hence, USM is mainly used for machining brittle materials {which are poor conductors of electricity and thus cannot be processed by Electrochemical and Electro-discharge machining (ECM and ED)}.

Mechanisms of Material Removal in USM

- Material removal primarily occurs due to the indentation of the hard abrasive grits on the brittle work material. As the tool vibrates, it leads to indentation of the abrasive grits.

- During indentation, due to Hertzian contact stresses, cracks would develop just below the contact site, then as indentation progresses the cracks would propagate due to increase in stress and ultimately lead to brittle fracture of the work material under each individual interaction site between the abrasive grits and the workpiece.

- ✓ Tool material should be such that indentation by the abrasive grits does not lead to brittle failure.

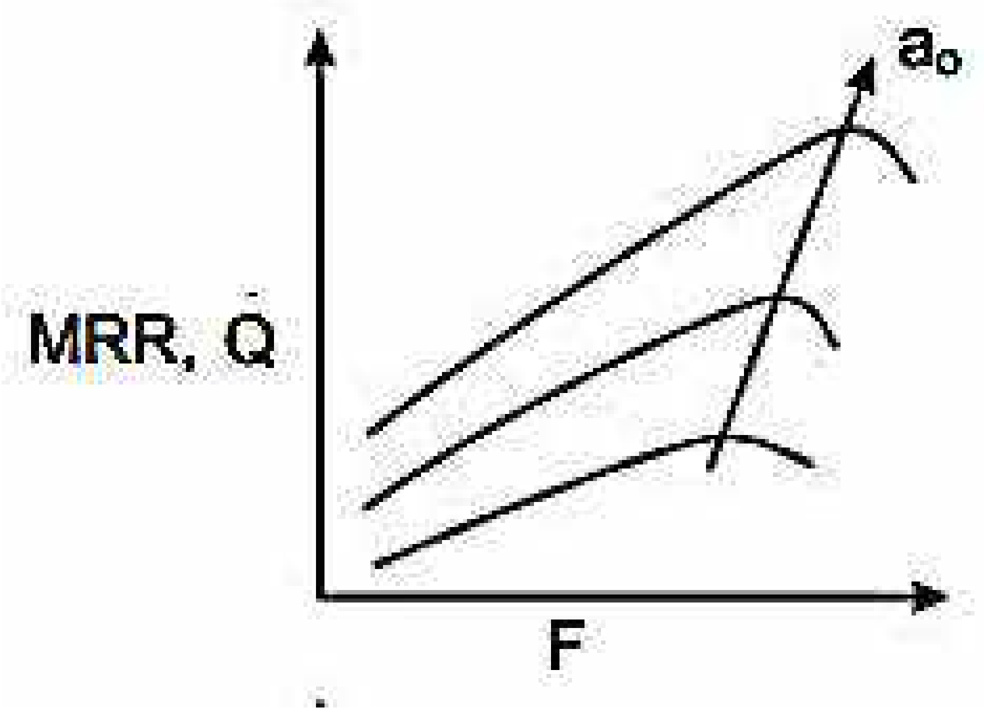
- ✓ Thus the tools are made of tough, strong and ductile materials like steel, stainless steel and other ductile metallic alloys.

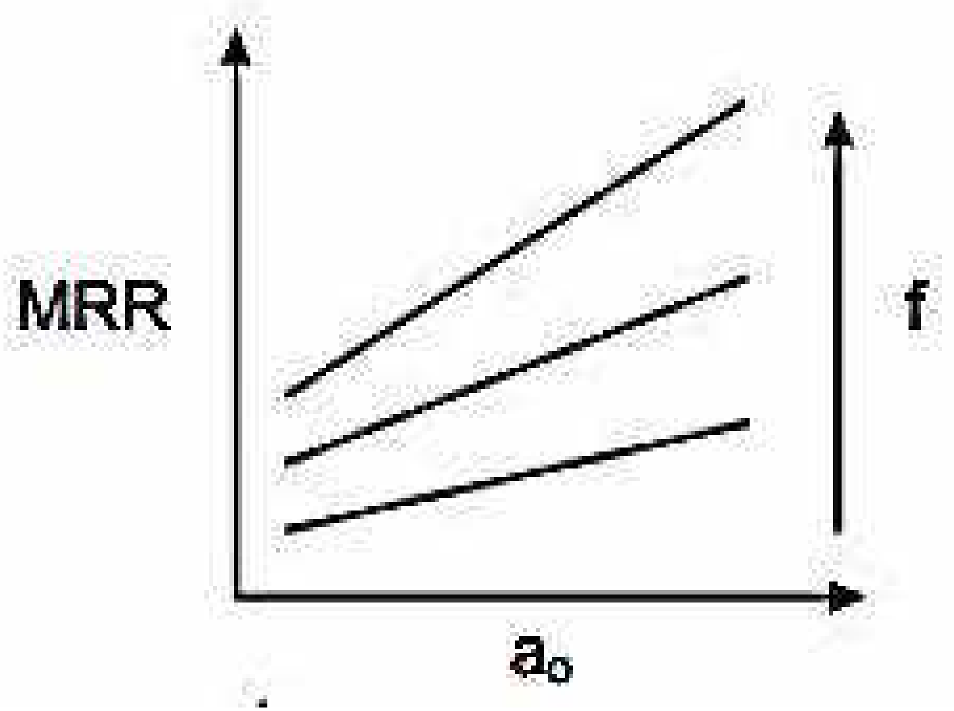
- ✓ Other than this brittle failure of the work material due to indentation some material removal may occur due to free flowing impact of the abrasives against the work material and related solid-solid impact erosion, but it is estimated to be rather insignificant.

Process Parameters and their Effects

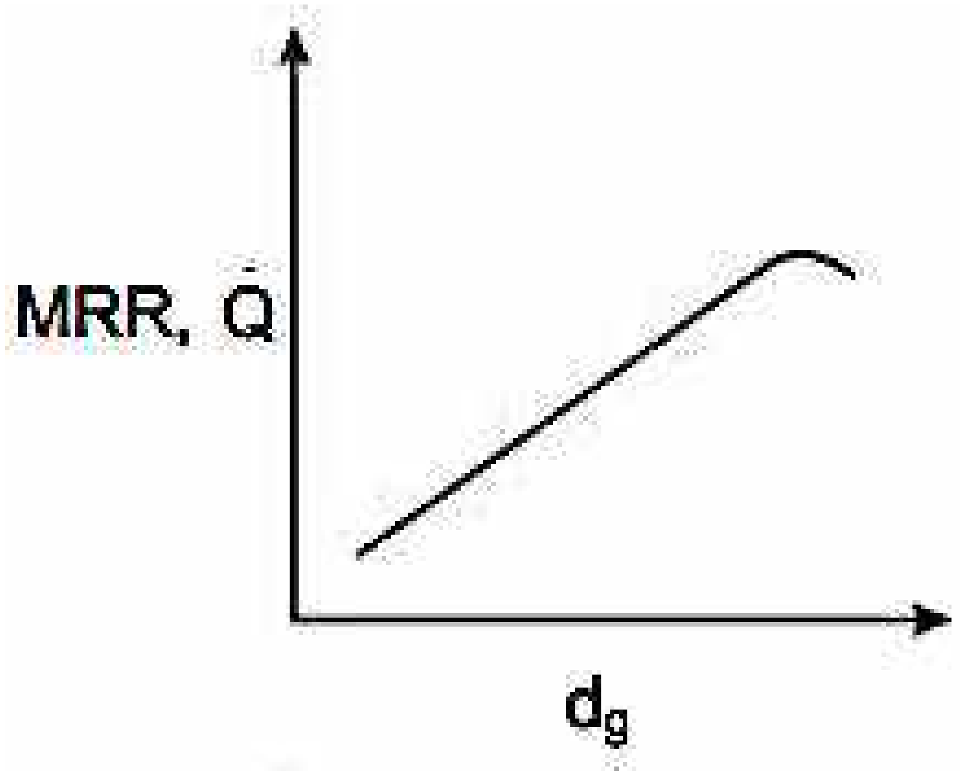
- ✓ Amplitude of vibration (ao) – 15 – 50 μm
- ✓ Frequency of vibration (f) – 19 – 25 kHz
- ✓ Feed force (F) – related to tool dimensions
- ✓ Feed pressure (p)
- ✓ Abrasive size – 15 μm – 150 μm
- ✓ Abrasive material – Al_2O_3 - SiC - B_4C - Boronsilicarbide - Diamond
- ✓ Flow strength of work material
- ✓ Flow strength of the tool material
- ✓ Contact area of the tool – A
- ✓ Volume concentration of abrasive in water slurry – C

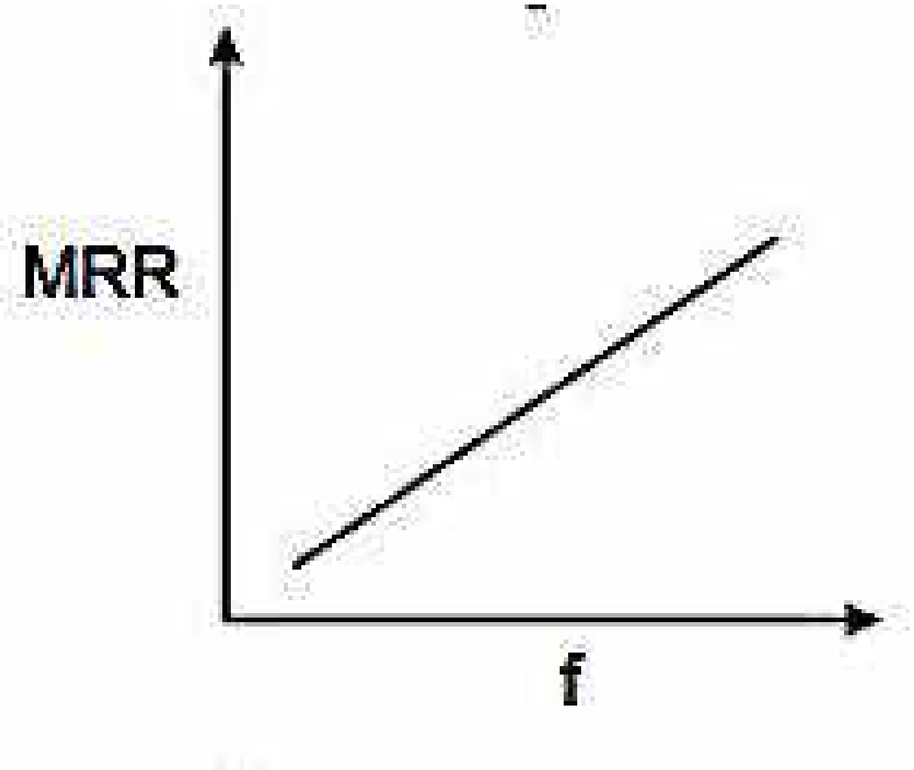
Effect of machining parameters on MRR



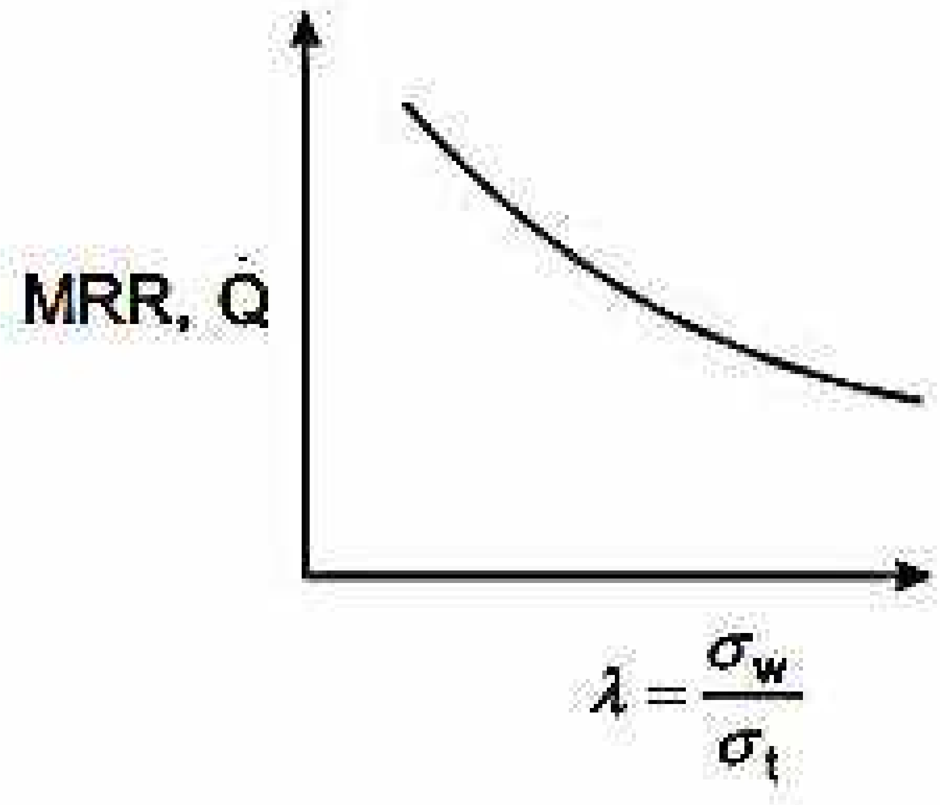


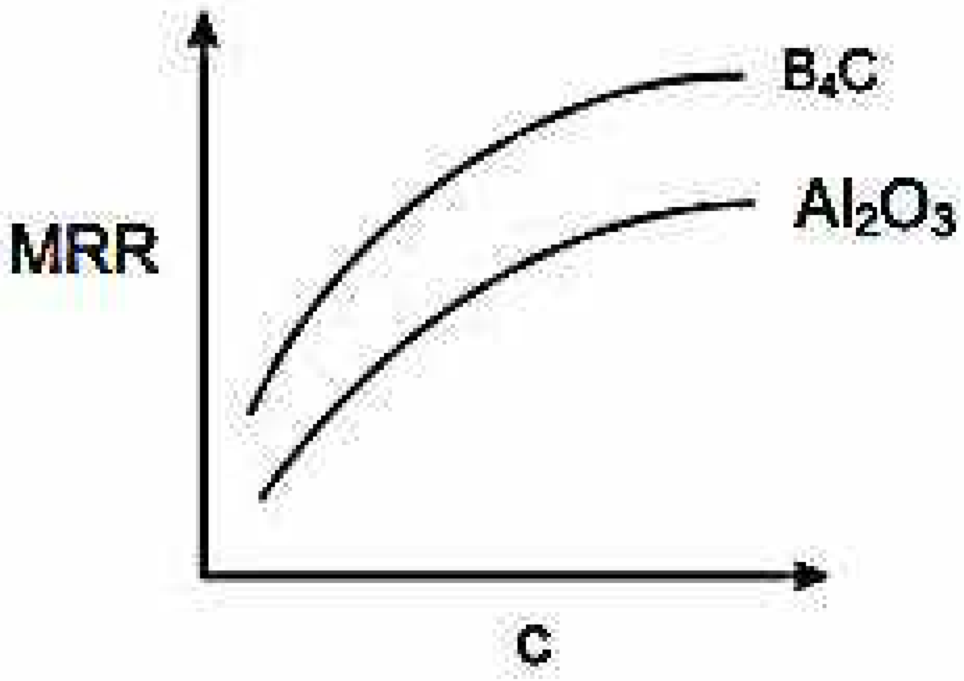
Effect of machining parameters on MRR





Effect of machining parameters on MRR





USM Machine

- The basic mechanical structure of an USM is very similar to a drill press.

- However, it has additional features to carry out USM of brittle work material.

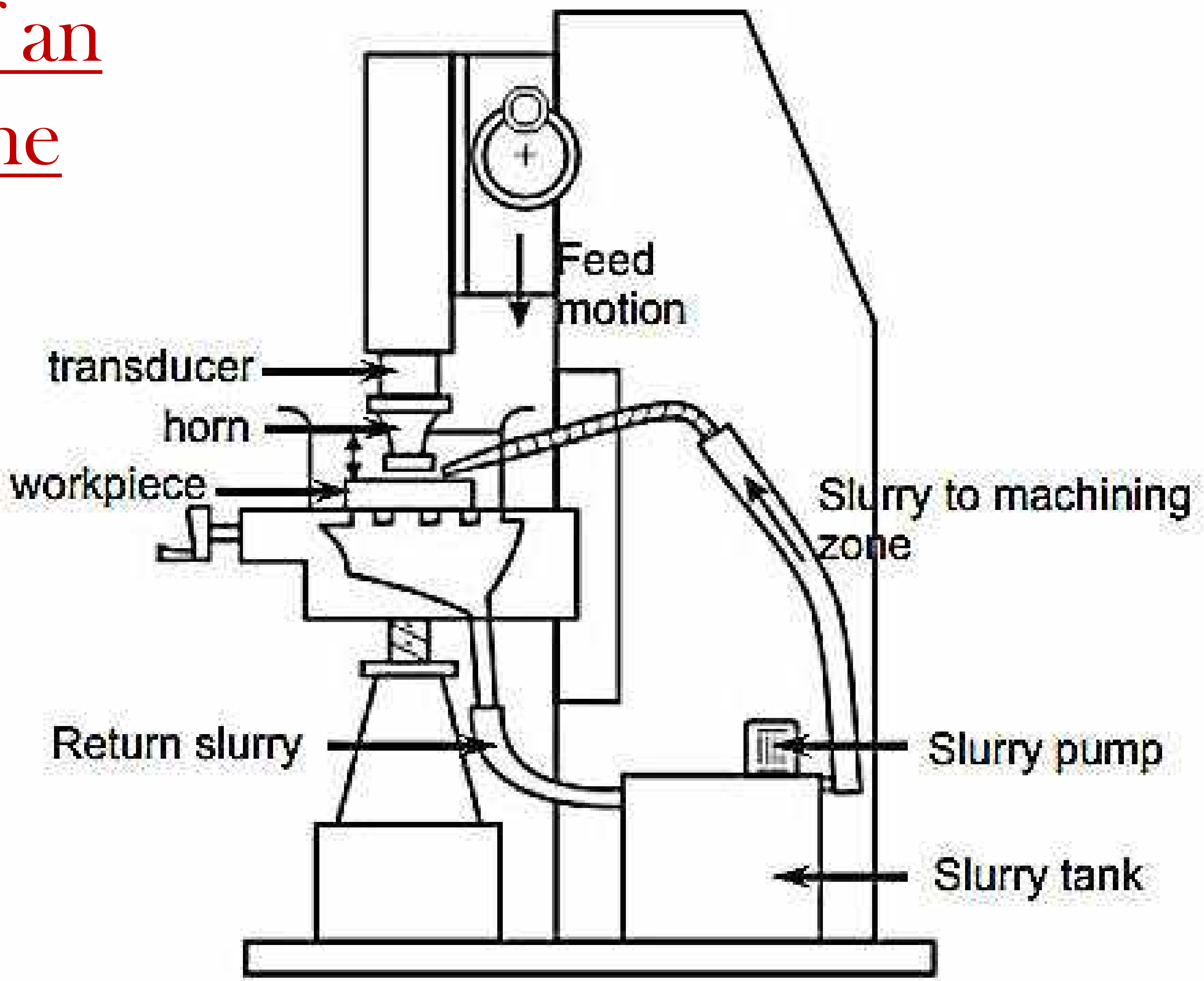
- Workpiece is mounted on a vice, which can be located at the desired position under the tool using a 2 axis table.

- Table can further be lowered or raised to accommodate work of different thickness.

The typical elements of an USM are

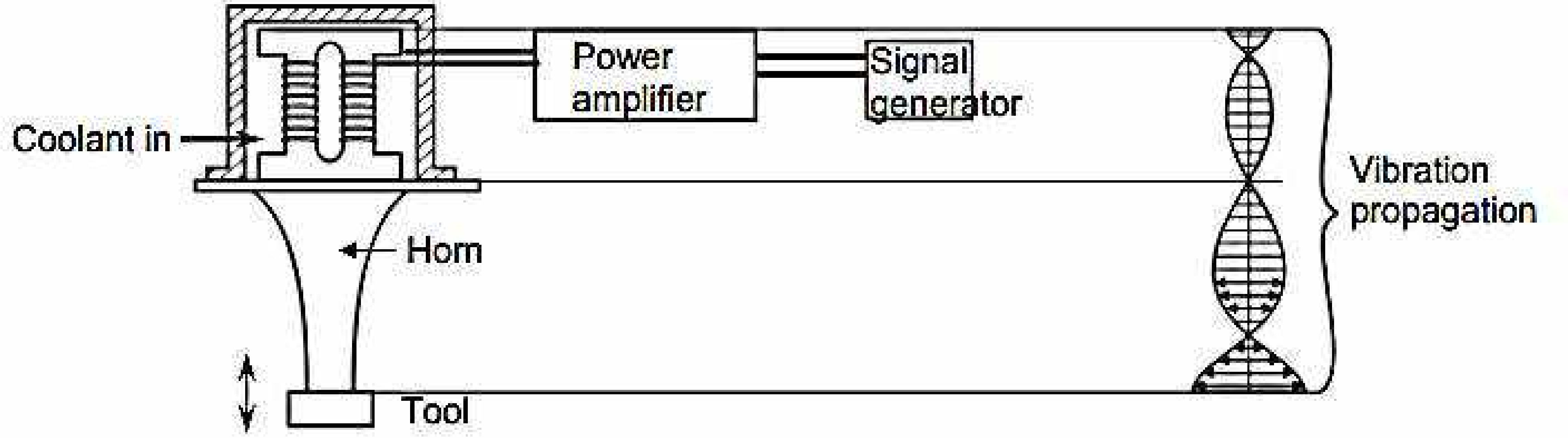
- Slurry delivery and return system
- Feed mechanism to provide a downward feed force on the tool during machining
- Transducer, which generates the ultrasonic vibration
- Horn or concentrator, which mechanically amplifies the vibration to the required amplitude of 15 – 50 μm and accommodates the tool at its tip

Schematic view of an Ultrasonic Machine



- The ultrasonic vibrations are produced by the transducer.
- The transducer is driven by suitable signal generator followed by power amplifier.
- The transducer for **USM** works on the following principle

Piezoelectric effect
Magnetostrictive effect
Electrostrictive effect

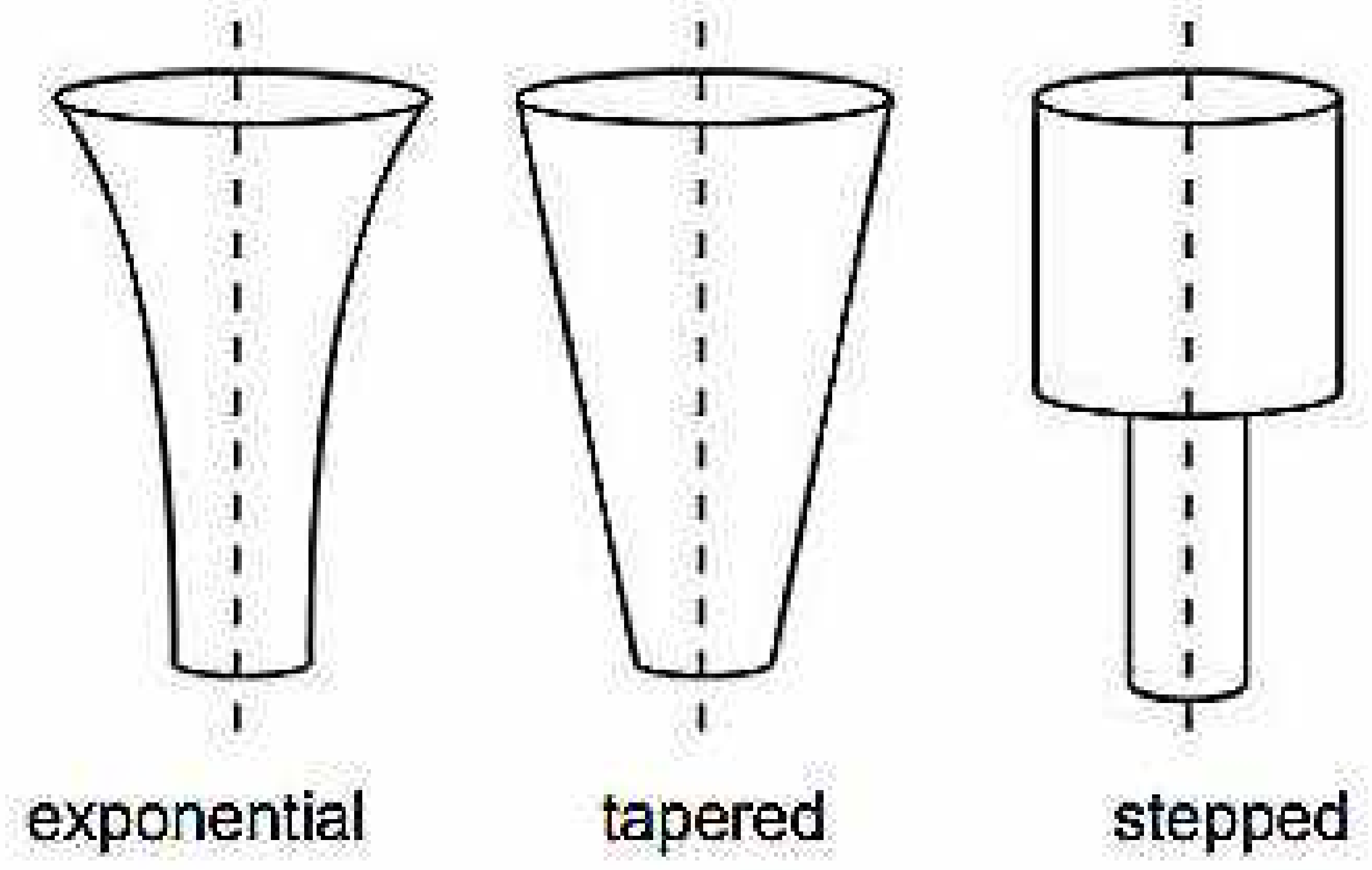


Working of horn as mechanical amplifier of amplitude of vibration

The horn or concentrator is a wave-guide, which amplifies and concentrates the vibration to the tool from the transducer.

The horn or concentrator can be of different shape like

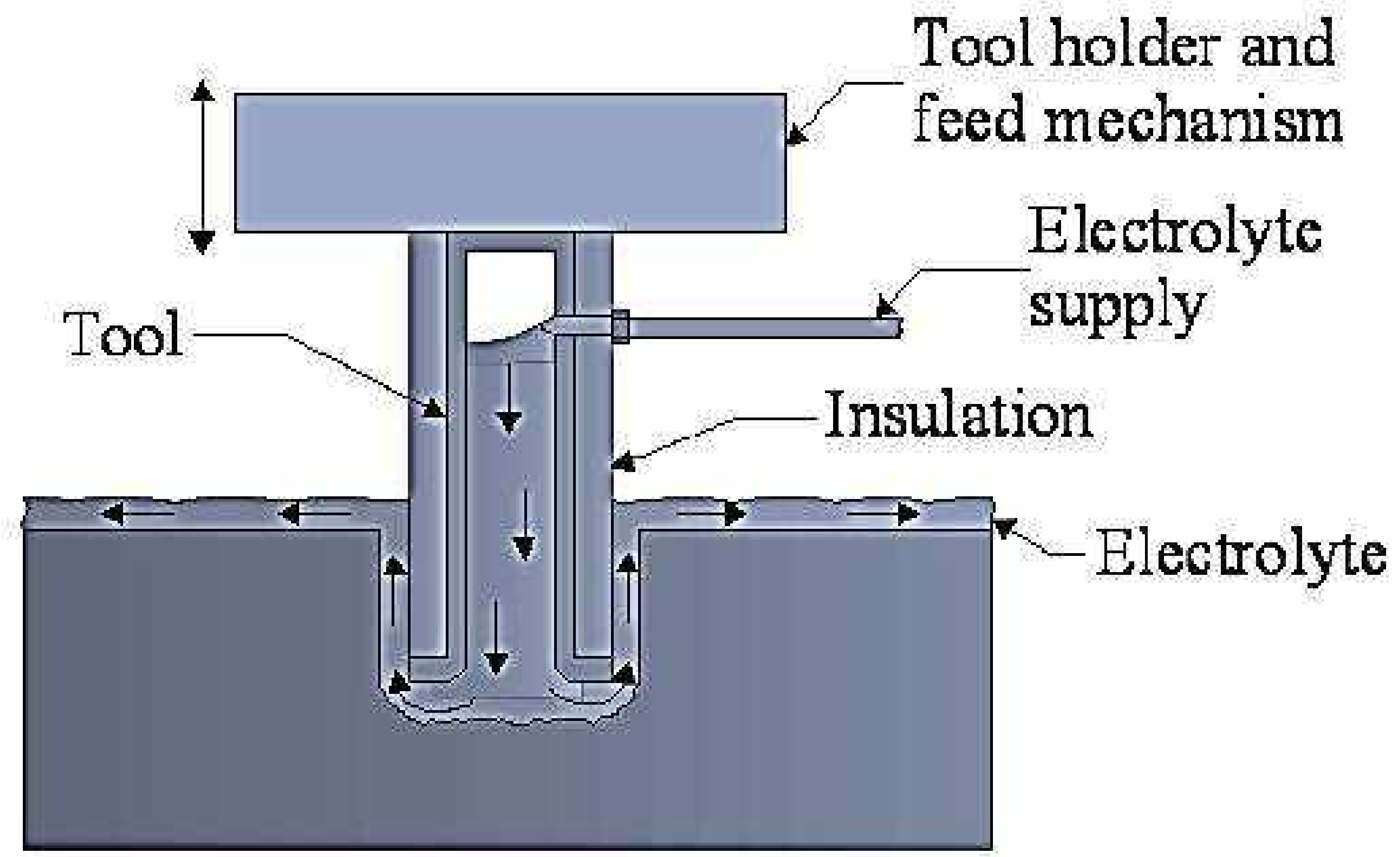
- Tapered or conical
- Exponential
- Stepped



Applications of USM

- Used for machining hard and brittle metallic alloys, semiconductors, glass, ceramics, carbides etc.
- Used for machining round, square, irregular shaped holes and surface impressions.
- Machining, wire drawing, punching or small blanking dies.

ELECTROCHEMICAL MACHINING



- In the actual process of ECM, the cathode is tool shaped(mirror image of work-piece) and anode is the work-piece.
- A gap(0.05 to 0.7 mm) is provided between the tool and work-piece and electrolyte flows through the gap at a velocity of 30 to 60 m/s and it completes the electrical circuit.
- Electrolyte is pumped at high pressure of 20 kgf/cm^2(1.96 MPa) through the gap.
- Electrolyte must be circulated at a rate sufficiently high to conduct current between them and to carry heat.
- Metal is removed from the work-piece by dissolution

- The electric current is of the order of 50 to 40,000 A at 5 to 35 V D.C for current density of 20 to 300 A/cm^2.
- Power of 3 KWh is needed to remove 16 cm^3 of metal which is almost 30 times the energy required in the conventional process(when the material is readily machinable).

Electrochemical machining (ECM) is a metal-removal process based on the principle of reverse electroplating (*means it removes metal instead of adding it*)

- ✓ In this process, particles travel from the anodic material (workpiece) toward the cathodic material (machining tool).
- ✓ A current of electrolyte fluid carries away the deplated material before it has a chance to reach the machining tool.
- ✓ The cavity produced is the female mating image of the tool shape.

- ✓ Similar to EDM, the workpiece hardness is not a factor, making ECM suitable for machining difficult-to –machine materials.

- ✓ Difficult shapes can be made by this process on materials regardless of their hardness.

- ✓ The ECM tool is positioned very close to the workpiece and a low voltage, high amperage DC current is passed between the workpiece and electrode.

Principle

Faraday's law of electrolysis :

Weight of the substance produced during electrolysis process is directly proportional to

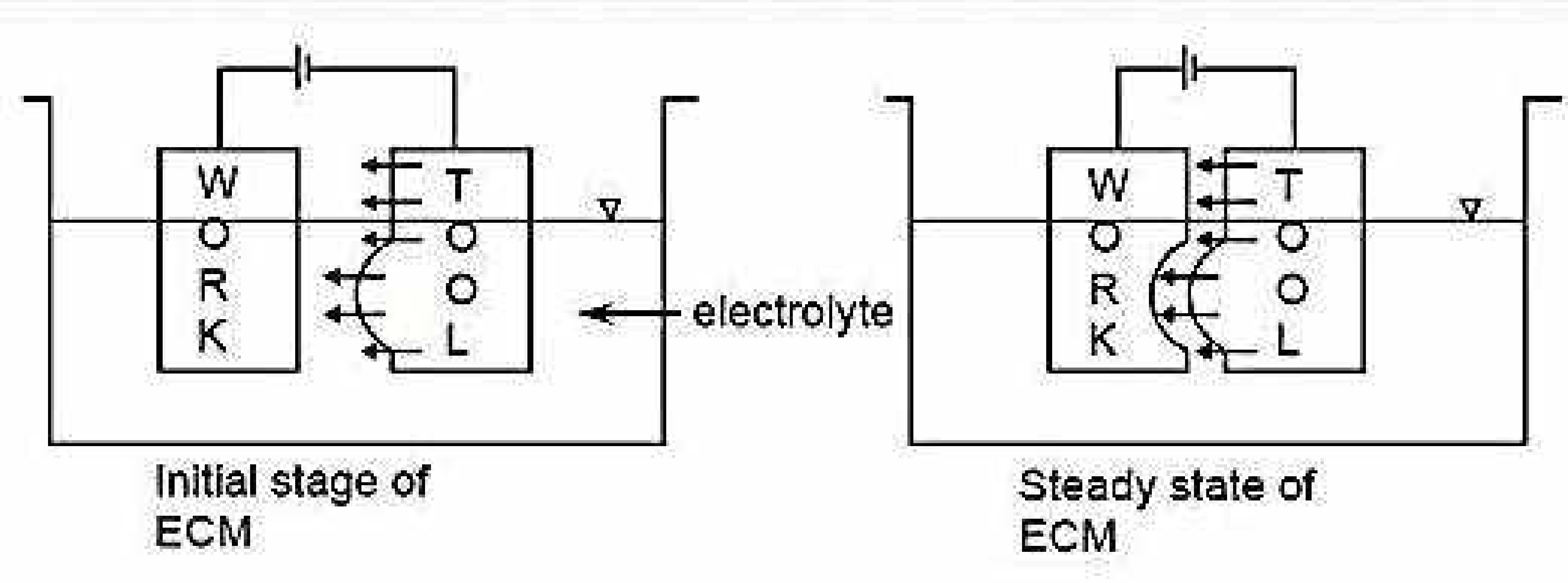
1.the current which passes

2.the length of time of process

3.The equivalent weight of the material

- Two dissimilar metals are in contact with an electrolyte and anode loses metal to cathode

- Anode : Workpiece
- Cathode : Tool
- Electrolyte : An electrically conductive fluid

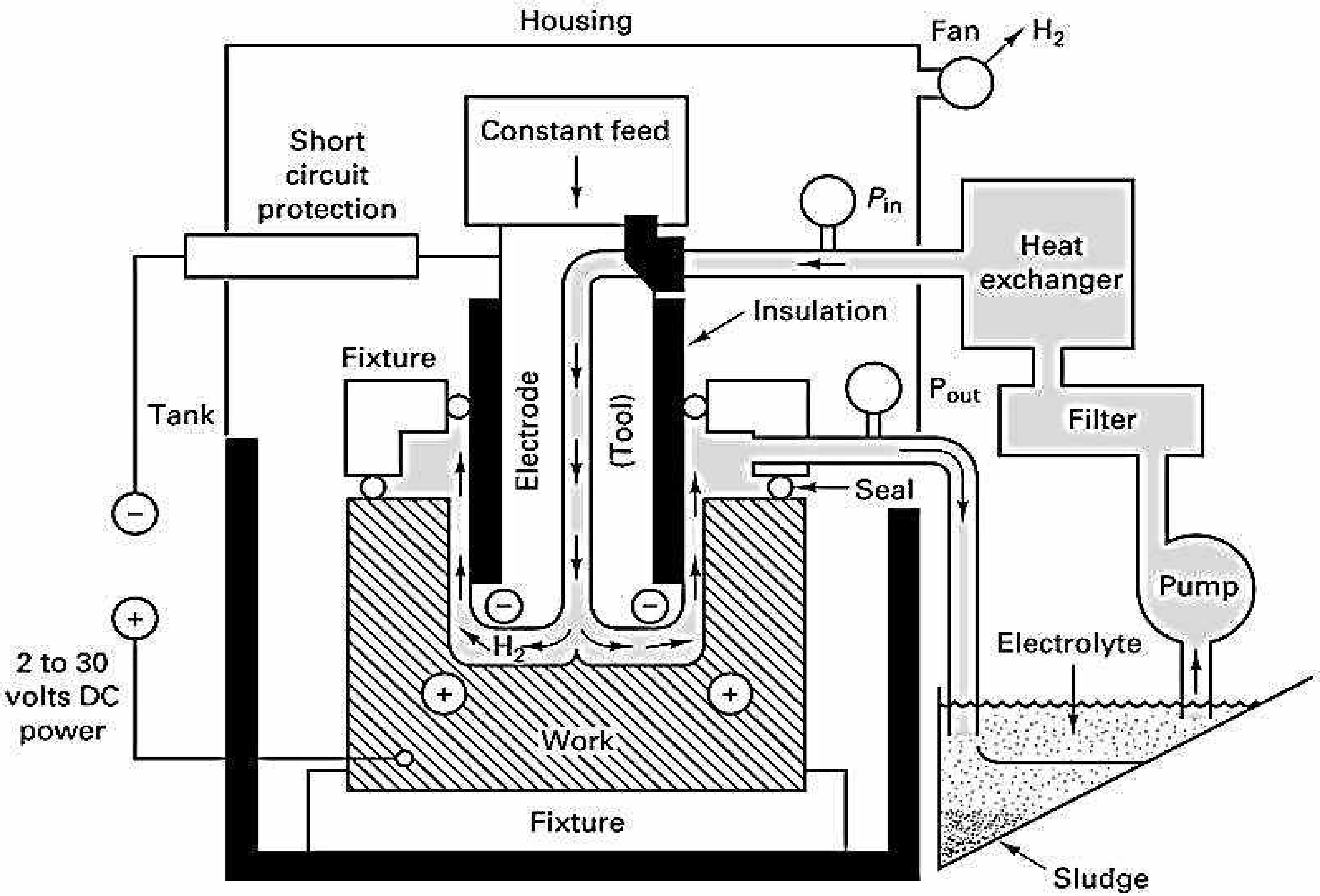


Schematic principle of ECM

PROCESS PARAMETERS

Power Supply	
Type	direct current
Voltage	2 to 35 V
Current	50 to 40,000 A
Current density	0.1 A/mm^2 to 5 A/mm^2
Electrolyte	
Material	NaCl and $NaNO_3$
Temperature	20°C – 50°C
Flow rate	20 lpm per 100 A current
Pressure	0.5 to 20 bar
Dilution	100 g/l to 500 g/l
Working gap	0.1 mm to 2 mm
Overcut	0.2 mm to 3 mm
Feed rate	0.5 mm/min to 15 mm/min
Electrode material	Copper, brass, bronze
Surface roughness, R_a	0.2 to 1.5 μm

ECM PROCESS



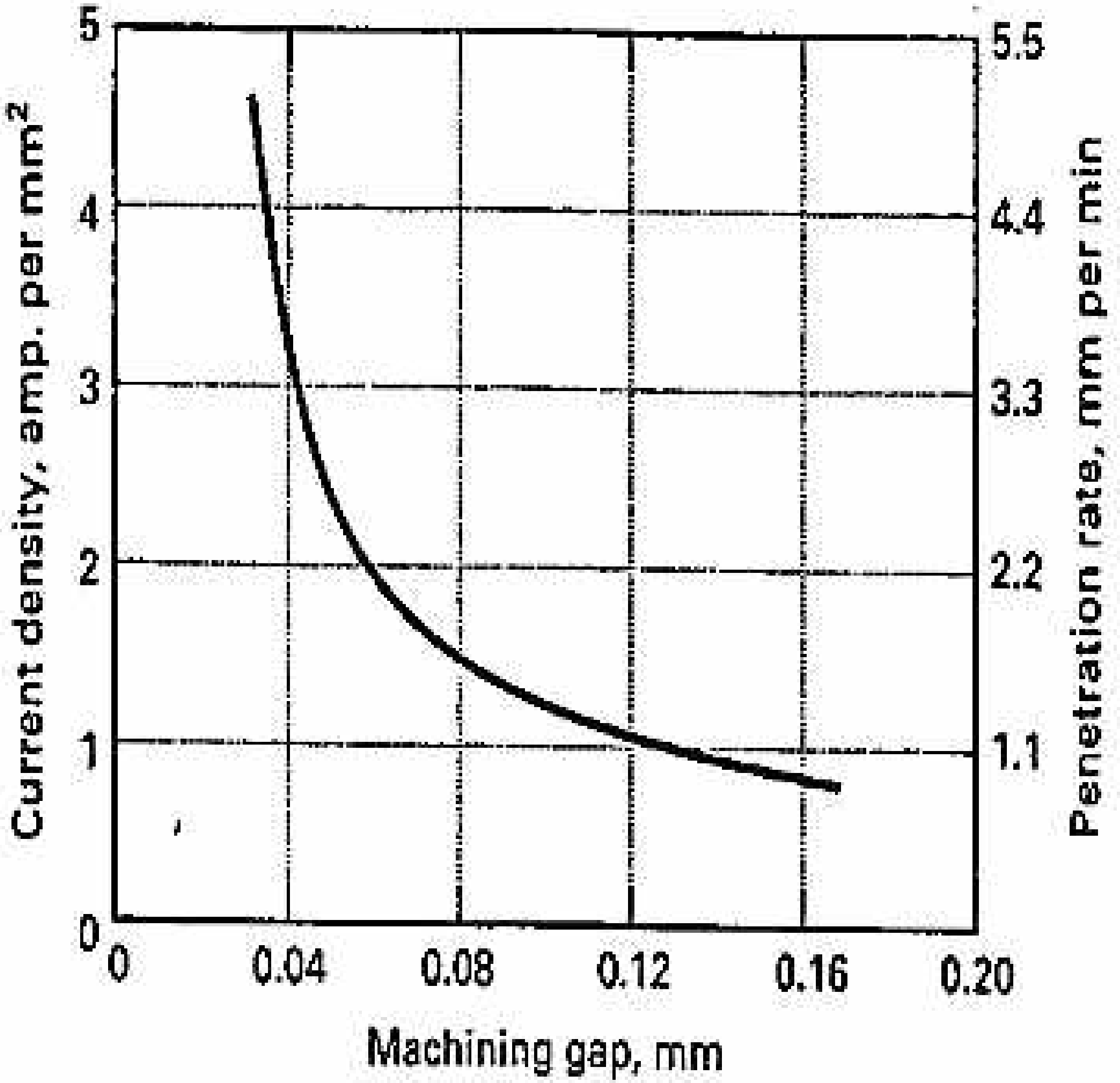
Housing
Fan
H_2
Constant feed
Short circuit protection
P_{in}
Heat exchanger
Insulation
Fixture
Electrode
(Tool)
Tank
P_{out}
Filter
Seal
Pump
Electrolyte
2 to 30 volts DC power
H_2
Work
Fixture
Sludge

Main sub sytem

- Power Supply
- Electrolyte
- Tool
- The Control system
- The machine

Power Supply

- Available in sizes upto 10,000 amp (some circuits are available upto 40,000amp)
- Range of voltage – 2 to 30 volts d.c.
- A constant voltage has to be maintained and high density is required



Relationship of current density, penetration rate, and machining gap in electrochemical machining.

Electrolyte

- Essential for electrolytic process
- It cools the cutting zone which becomes hot due to the flow of high current
- Neutral salts are used as electrolyte in place of highly corrosive acids and alkalies
- Electrolyte solution is pumped between the tool/workpiece gap at about 2.5 N/mm^2 and 30 m/s

Tool

Requirements of Tool For ECM :

- ✓ Good thermal conductivity
- ✓ Strong enough to withstand high pressures
- ✓ It should be easily machined

- ➢ Material for tool : Copper,brass or stainless steel

- ➢ Outer insulation material : Vinyl, Teflon, epoxy, enables or high temperature varnish

The control system

- Control Parameters include
  - Voltage
  - Inlet and outlet pressure of electrolyte
  - Temperature of electrolyte

- The current is dependent on above parameters and feed rate

Parts made by ECM

Advantages of ECM

- The components are not subject to either thermal or mechanical stress.
- No tool wear during ECM process.
- Fragile parts can be machined easily as there is no stress involved.
- ECM deburring can debur difficult to access areas of parts.
- High surface finish (up to 25 µm in) can be achieved by ECM process.
- Complex geometrical shapes in high-strength materials particularly in the aerospace industry for the mass production of turbine blades, jet-engine parts and nozzles can be machined repeatedly and accurately.
- Deep holes can be made by this process.

Limitations of ECM

- ECM is not suitable to produce sharp square corners or flat bottoms because of the tendency for the electrolyte to erode away sharp profiles.

- ECM can be applied to most metals but, due to the high equipment costs, is usually used primarily for highly specialised applications.

Material removal rate, MRR, in electrochemical machining:

$$MRR = C \cdot I \cdot h \ (cm^3/min)$$

C: specific (material) removal rate (e.g., 0.2052 cm^3/amp-min for nickel);

I: current (amp);

h: current efficiency (90–100%).

- ✓ The rates at which metal can electrochemically remove are in proportion to the current passed through the electrolyte and the elapsed time for that operation.

- ✓ Many factors other than current influence the rate of machining.

These involve electrolyte type, rate of electrolyte flow, and some other process conditions.

Module 7

Module 4

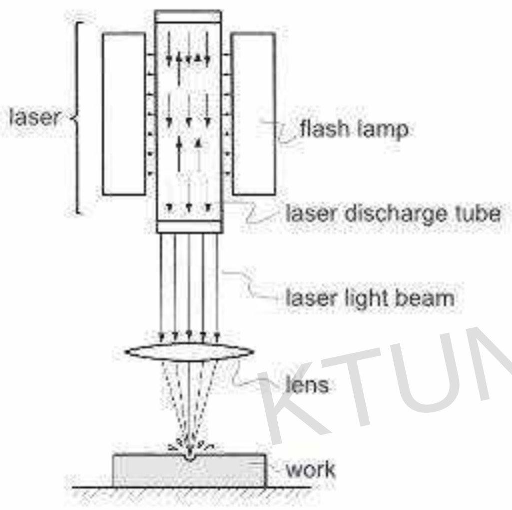
IV	Laser Beam Machining (LBM), Electron Beam Machining (EBM), Plasma arc Machining (PAM), Ion beam Machining(IBM) - Mechanism of metal removal, attributes of process characteristics on MRR, accuracy etc and structure of HAZ compared with conventional process; application, comparative study of advantages and limitations of each process.
	Abrasive Jet Machining (AJM), Abrasive Water Jet Machining **(AWJM)** - Working principle, Mechanism of metal removal, Influence of process parameters, Applications, Advantages & disadvantages.

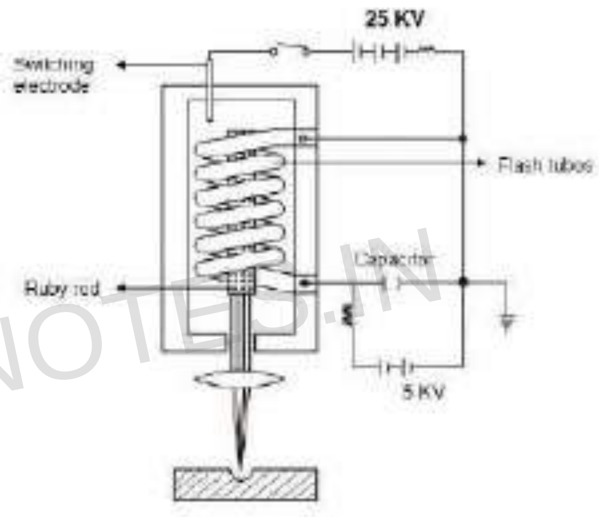
Laser Beam Machining (LBM)

Laser beam machining is a technology that uses a laser beam which is a narrow beam of intense monochromatic light to cut required shapes of profile or pattern in almost all types of materials. The laser beam machining process can be used to process any material irrespective of its hardness, irrespective of its melting point.

Laser beam melts the material by focusing a coherent beam of monochromatic light on the work-piece. The light produced by the laser has significantly less power than a normal white light, but it can be highly focused, thus delivering a significantly higher light intensity and respectively temperature in a very localized area.

Laser cutting is a common manufacturing process employed to cut many types of materials. Materials which may be cut included ferrous metal, non-ferrous metal, stone, plastic, rubber and ceramic. The LBM process does not involve mass material removal, but does provide rapid material removal with an easily controlled, non-contact, non-wearing tool.





Cooling Mechanism: to avoid its overheating in long continuous operation.

Tool Feed Mechanism

Focusing laser beam (cutting tool) at a pre-decided point in the work piece serves as the tool. The movement of the converging lens to shift the focussing is the tool feed mechanism in LBM process. The lens then focuses the beam into the desired geometry

Advantages of LBM

1. In laser machining there is no physical tool. Thus no machining force or wear of the tool takes place.
2. Large aspect ratio holes can be achieved along with acceptable accuracy
3. Micro-holes can be drilled in difficult – to – machine materials
4. Materials which cannot be machined by conventional methods are machined by LBM (ceramics, glass to softer materials like plastics, rubber wood).
5. Heat is very much focused so rest of the work piece is least affected by the heat.
6. The fragile materials are easy to cut on a laser without any support.
7. Laser produces high quality cuts without extra finishing requirements
8. Absence of direct contact between the tool and work piece; thus no forces are induced and as a result simple work holding system to hold the work piece.

Disadvantages of LBM

1. Laser processes involve high capital investments and high operating costs.
2. Recommended for some specific operations only as production rate is very slow.
3. Cannot be used for high heat conductivity materials light reflecting materials.
4. Skilled operators are required.
5. Laser holes are tapered to some extent (approximately 1% of the drill depth)
6. It cannot drill blind holes to precise depths. Hence there is limitation on its thickness.
7. Reflected laser lights can lead to safety hazards.

Applications of LBM

LBM is used to perform different machining operations like drilling, slitting, slotting and scribing operations.

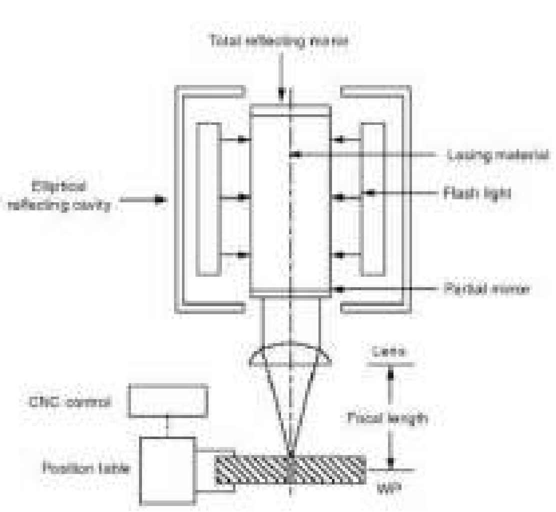
- It is used for drilling holes of small diameter of the order of 0.025 mm.
- Making complex profiles in thin and hard materials like integrated circuits and printed circuit boards (PCBS).
- Machining of mechanical components of watches.
- Machining of very hard material parts.
- Process can be performed on the ceramics, organics, non-metals, metals, plastic etc.

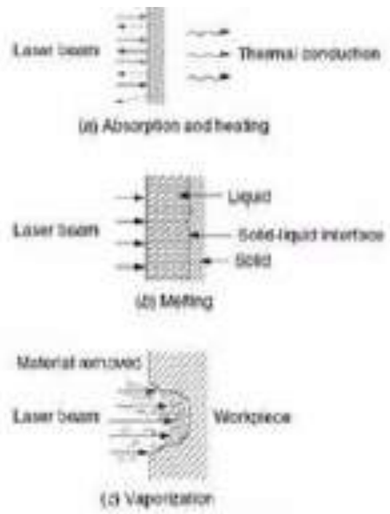
Mechanism of Material Removal

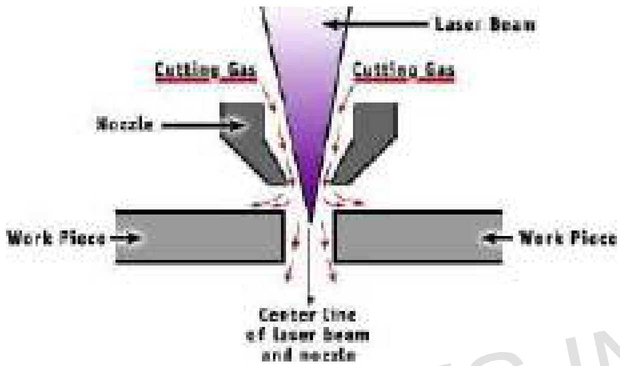
Laser cutting works by directing a high power pulsed laser at a specific location on the material to be cut. The energy beam is absorbed into the surface of the material and the energy of the laser is converted into the heat, which melt or vaporize the material. Additionally, gas is focused or blown into the cutting region to expel or blow away the molten melt and vapor from cutting path.

The mechanism of material removal is primarily by melting and rapid vaporisation due to intense heating by the laser beam.

1. The focal point of the laser is intentionally focused onto the surface of the work piece for providing the heat in a concentric manner.
2. The movement of machine-axis is through the computer control which helps to achieve the required profiles on the work piece.
3. To clear the molten metal that has not vaporized, gas under pressure is passed on-to the work.

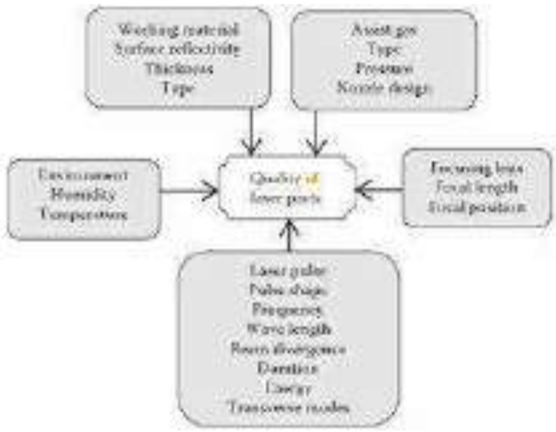






Factors affecting MRR/HAZ and Quality of LBM process

In laser cutting process, cutting performances such as the material removal rate, kerf quality characteristics, surface quality, heat affected zone (HAZ), burr height is of high importance to manufacturers. Laser power, cutting speed, assist gas pressure and focus position were selected as controllable parameters



Material removal rate

In LBM, there are many factors such as beam parameters, material parameters and machining parameters which affects the MRR and various quality characteristics, e.g. surface roughness, Heat Affected Zone (HAZ), recast layer, etc.

Beam related parameters,

1. Beam power intensity
2. Beam geometry,

3. Beam diameter
4. Wave length

Process parameter

1. Spot size
2. Position of focus
3. Gas pressure etc
4. Cutting speed

Work-piece or material related

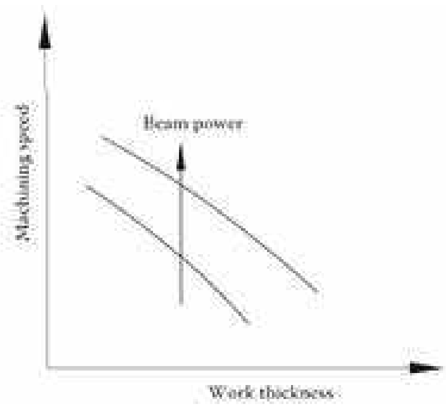
1. Melting point of work
2. composition of the material
3. Reflectivity,
4. Specific heat
5. Thermal conductivity
6. latent heat

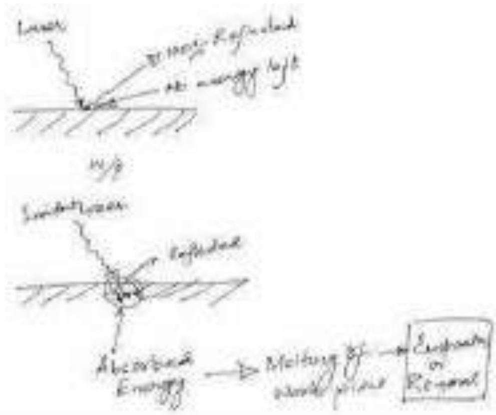
(Items 3–6: physical factors)

- MRR increases with laser power density. The cutting depth of a laser is directly proportional to the power density
- The cutting process requires the spot size is small enough to produce the high intensity power. The small spot size obtained by focusing the laser beam to the surface of the work piece at the focal point
- The four physical parameters preferred to be lower in magnitude for increasing the process efficiency, as the energy required to melt and vaporize the material is lesser
- Lesser the reflectivity of the work-piece material, higher will be the cutting efficiency of laser machining
- The wavelength plays a most decisive role inefficiency, stability and quality of process. It has important effect on material's surface absorptivity.
- High-pressure gas streams are used to enhance the process by aiding the exothermic reaction process, to cool and blow away the vaporized or molten material and slag

Depth of cut $t = \frac{P}{v\,d}$

where t is the depth of cut, P is the laser beam power, v is the cutting velocity, and d is the laser beam spot diameter.





- MRR – Cutting speed can be as high as 4 m/min.
- Typical material removal rate is 5 mm3/min.

- Dimensional Tolerance – Typical ranges from ±0.015 - ±0.125 mm
- Surface Finish – Ra varies between 0.4 – 6.3 µm.

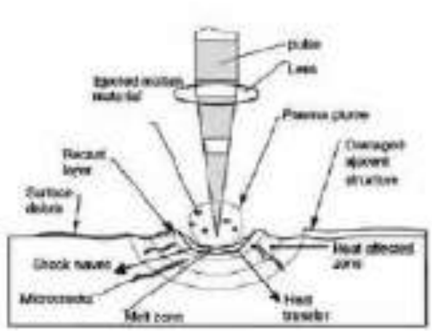
For a specific material type, there is a certain wavelength which can have maximum absorption of laser energy with a lowest reflection Power of beam= Laser energy/ Pulse duration Power density = Power of beam/ area of beam at focal point. The power of laser system is the total energy emitted in the form of laser light per second The beam diameter will define; how fine we will be able to cut on the work-piece. Beam power intensity will dictate, how intensely we can apply the laser power on the work-piece, and how deep we can go with that power intensity, and how fast we can cut.

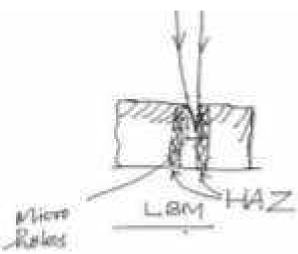
Heat affected zone

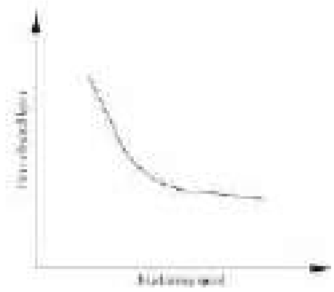
High laser beam intensity, good focusing characteristics resulted into narrow heat affected zone (HAZ) in laser beam machining comparing with other thermal process.

The heat affected zone may lead to undesirable effects such as fatigue resistance, surface cracking, and distortion.

- HAZ width increases with the increase of laser beam power throughout the range;
- Increases with the increase of pulse frequency.
- Laser beam diameter has a negligible effect on HAZ depth
- HAZ depth increases with thickness of work
- As cutting speed increases, the cutting time decreases and less time for the heat to diffuse sideways and the narrower the HAZ.







Low laser power, assist gas pressure and focus position are beneficial for minimization of the width of HAZ, while the cutting speed should be kept at the highest level.

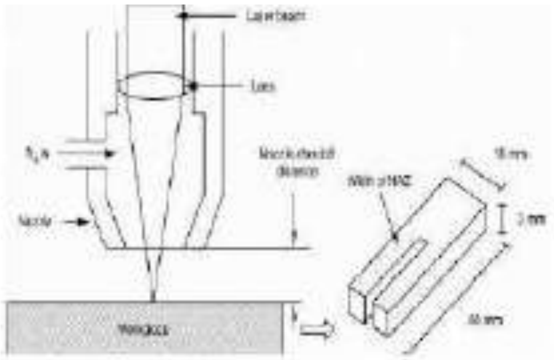
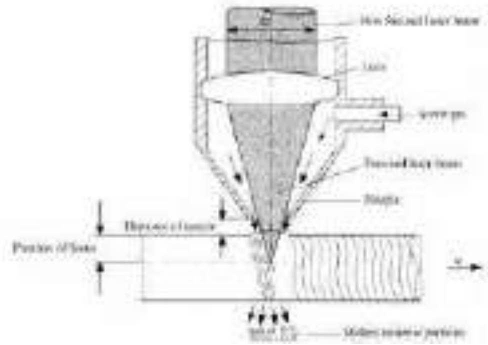
Surface quality/tolerance

Laser cutting, due to the narrow kerf width results in a superior quality, higher accuracy and greater flexibility

Evaluation of laser cut quality is based on: geometry of cut, surface of cut, burr formation and characteristics of material in zone of cut.

1. Focus position is the most significant laser cutting parameter affecting the quality
2. Decreasing power and increasing feed rate generally led to a decrease in kerf width

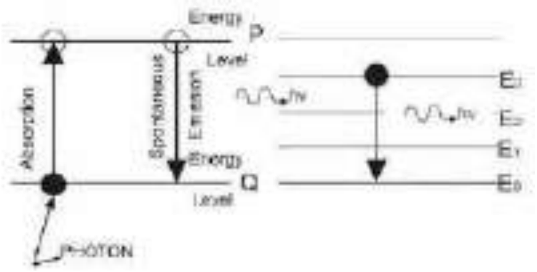
3. Increasing feed rate generally led to increasing surface roughness
4. As the cutting speed increases, the surface roughness decreases and quality improves when the other operating parameters kept constant.
5. Surface roughness values ranging 0.4–6.3 µm Ra
6. Achievable tolerances ranging ±0.015–±0.125 mm.

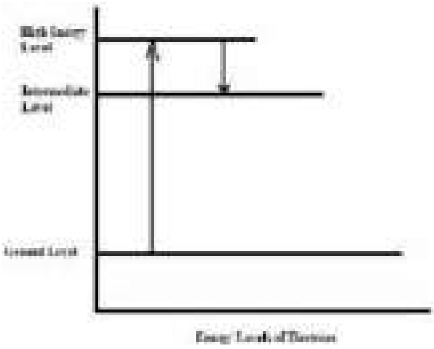



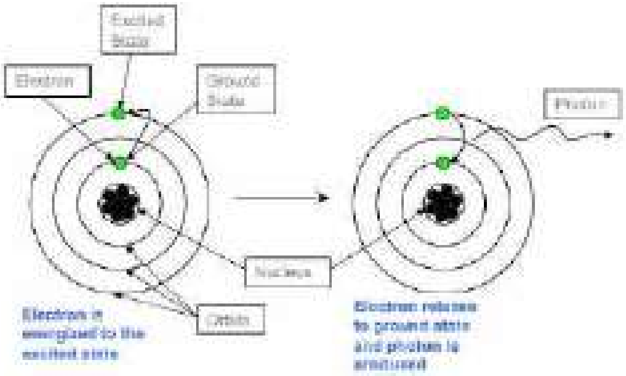
Laser beam

In the model of atom, negatively charged electrons rotate around the positively charged nucleus in some specified orbital paths. The geometry and radii of such orbital paths depend on a variety of parameters like number of electrons, presence of neighbouring atoms and their electron structure, presence of electromagnetic field etc. Each of the orbital electrons is associated with unique energy levels. At absolute zero temperature an atom is considered to be at ground level, when all the electrons occupy their respective lowest potential energy. The electrons at ground state can be excited to higher state of energy by absorbing energy form external sources like increase in electronic vibration at elevated temperature, through chemical reaction as well as via absorbing energy of the photon.

The electron moves from a lower energy level to a higher energy level. On reaching the higher energy level, the electron reaches an unstable energy band. And it comes back to its ground state within a very small time by releasing a photon. This is called spontaneous emission. The spontaneously emitted photon would have the same frequency as that of the “exciting” photon.







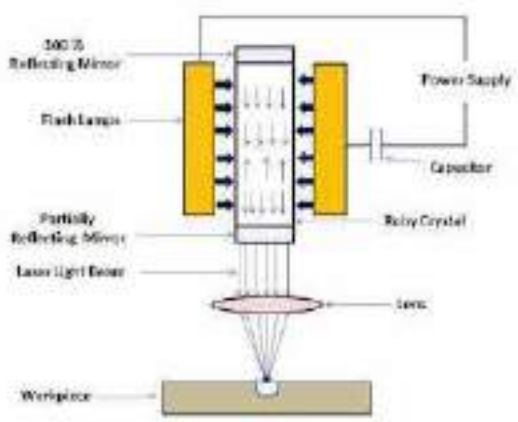
On the basis of the media used for the production of the laser it is classified as

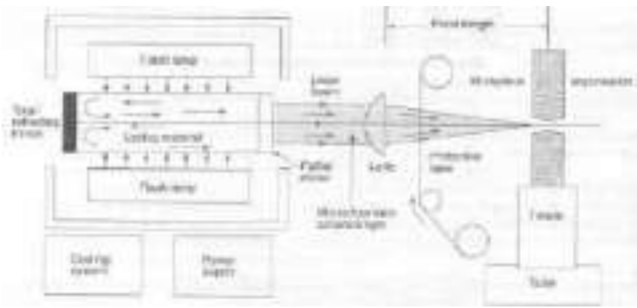
1. **Gas Lasers:** In these types of laser, gases are used as the medium to produce lasers. The commonly used gases are He-Ne, argon and Co2.
2. **Solid State Lasers:** The media of the solid state lasers are produced by doping a rare element into a host material. Ruby laser is an example of solid state laser in which ruby crystal is used as medium for the generation of laser beam.

Gas lasers. Construction of the most common type of carbon dioxide gas laser is very similar to that of the solid state laser. A glass tube containing a flowing mixture of CO2, helium and nitrogen essentially replaces the crystal that acted as the lasing medium for the solid state laser. Instead of a flash lamp, direct electrical energy is used to provide the energy for stimulating the lasing medium

How do the flash tube and the crystal make a laser beam?

1. A high voltage power supply is applied across the flash tube. A capacitor is used to operate the flash tube at pulse mode.
2. As the flash is produced by the flash tube, it emits light photons that contain energy.
3. This light photon emitted by the flash tube is absorbed by the ruby crystal. The photons absorbed by the atoms of the ruby crystals excite the electrons to the high energy level and population inversion (situation when the number of exited electrons is greater than the ground state electrons) is attained.
4. After short duration, this excited electron jumps back to its ground state and emits a light photon. This emission of photon is called spontaneous emission,
5. The emitted photon stimulates the excited electrons and they start to return to the ground state by emitting two photons. In this way two light photons are produced by utilizing a single photon. Here the amplification (increase) of light takes place by stimulated emission of radiation.
6. Concentration of the light photon increases and it forms a laser beam.
7. 100 % reflecting mirror bounces back the photons into the crystal. Partially reflecting mirror reflects some of the photons back to the crystal and some of it escapes out and forms a highly concentrated laser beam. A lens is used to focus the laser beam to a desired location.

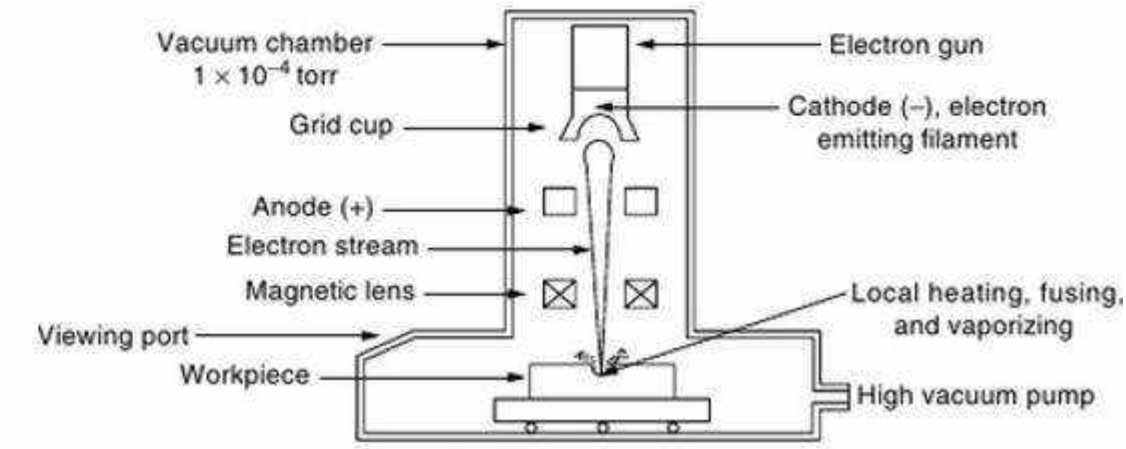




****

Electron Beam Machining (EBM)

EBM is a metal removal process by a high velocity focused stream of electrons. As the electrons strike the work piece with high velocity, their kinetic energy is transformed into thermal energy which melts and vaporizes the material. Due to pattern of electrostatic field produced by grid cup, electrons are focused and made to flow in the form of a converging beam through anode. The electrons are accelerated while passing through the anode by applying high voltage at anode. A magnetic deflection coil is used to make electron beam circular and to focus electron beam at a point (localized heating). The process is carried out in a vacuum chamber to prevent electrons from colliding with molecules of the atmospheric air and to prevent tungsten filament from getting oxidizing with air



Just after the cathode, there is an annular bias grid. A high negative bias is applied to this grid so that the electrons generated by this cathode do not diverge and approach the next element, the annular anode, in the form of a beam. The annular anode now attracts the electron beam and gradually gets accelerated. As they leave the anode section, the electrons may achieve a velocity as high as half the velocity of light. The nature of biasing just after the cathode controls the flow of electrons and the biased grid is used as a switch to operate the electron beam gun in pulsed mode.

After the anode, the electron beam passes through a series of magnetic lenses and apertures. The magnetic lenses shape the beam and try to reduce the divergence. Apertures on the other hand allow only the convergent electrons to pass and capture the divergent low energy electrons from the fringes. This way, the aperture and the magnetic lenses improve the quality of the electron beam. Then the electron beam passes through the final section of the electromagnetic lens and deflection coil. The electromagnetic lens focuses the electron beam to a desired spot. Generally, in between the electron beam gun and the work piece, which is also under vacuum, there would be a series of slotted rotating discs. Such discs allow the electron beam to pass and machine materials but helpfully prevent metal fumes and vapour generated during machining to reach the gun. Work piece is mounted on a CNC table so that holes of any shape can be machined using the CNC control.

One of the major requirements of EBM operation of electron beam gun is maintenance of desired vacuum. Maintenance of suitable vacuum is essential so that electrons do not lose their energy and a significant life of the cathode cartridge is obtained. Such vacuum is achieved and maintained using a combination of rotary pump and diffusion pump.

Advantages of EBM

1. Very small holes can be machined in every type of material with **high accuracy**
2. Drilling holes with high depth/diameter ratios, greater than 100:1
3. Very high drilling rates – up to 4000 holes/sec
4. Drills any material - Hardness, thermal capacity, ductility, electrical conductivity or surface properties etc, are not barriers. (steel, stainless steel, Ti and Ni super-alloys, aluminum, plastics, ceramics can be machined successfully using electron beam).
5. EBM does not apply any cutting force on the work pieces. Thus very simple work holding is required. This enables machining of fragile and brittle materials by EBM.

6. No mechanical distortion.
7. Limited thermal effects because pulse durations are short and Low HAZ effect
8. No tool wear
9. Best obtainable finish, compared to the other unconventional processes used to drill
10. Low operating cost

Disadvantages of EBM

1. Cost of equipment is high.
2. Rate of material removal is low.
3. Limited to 10mm material thickness
4. Vacuum requirements limit the size of work piece.
5. High level of operator skill required

Application of EBM

1. For making fine gas orifices in space nuclear reactors and turbine blades
2. Machining of wire drawing dies having small sectional area (Holes as small as 0.002 mm)
3. Electron beam can be used for welding small pieces of highly reactive and refractory metals.
4. Widely used to perforate many materials like super alloys, plastics, and textiles.
5. Inclined holes are another advantage of Electron beam
6. Non-circular hole drilling
7. Engraving of metals, ceramics

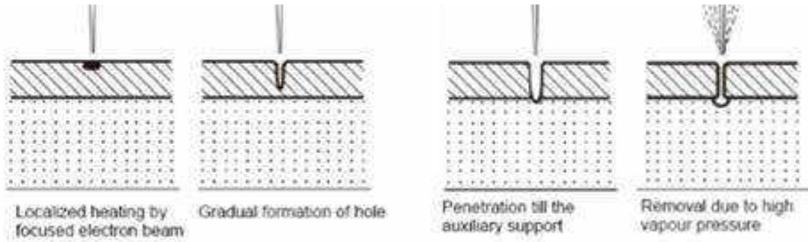
Electron Beam Process Capability

1. EBM can provide holes of diameter in the range of 100 μm to 2 mm. The hole can be tapered along the depth or barrel shaped.
2. Drilling holes with high depth/diameter ratios, greater than 100:1
3. A wide range of materials such as steel, stainless steel, Ti and Ni super alloys, aluminium as well as plastics, ceramics, leathers can be machined successfully
4. EBM does not apply any cutting force on the work pieces. Thus very simple work holding is required. This enables machining of fragile and brittle materials by EBM.
5. No mechanical force and hence fragile, thin components can be easily machined
6. Extraordinary energy (power densities of 106 kW/cm2 have been achieved)
7. Can machine conductive as well as non-conductive materials
8. Residual thermal stresses generated on the work piece due to high temperature
9. However, the heat-affected zone is rather narrow due to shorter pulse duration in EBM. Typically, the heat affected zone is around 20 to 30 μm.

Material removal mechanism in EBM

The high-energy focused electron beam is made to impinge on the work piece with a spot size of 10 – 100 μm. The kinetic energy of the high velocity electrons is converted to heat energy as the electrons strike the work material. Due to high power density instant melting and vaporisation starts and "melt – vaporisation" front gradually progresses, as shown in Fig. Finally, the molten material, if any at the top of the front, is expelled from the cutting zone by the high vapour pressure at the lower part. Electron beam can also be manoeuvred using the electromagnetic deflection coils for drilling holes of any shape.

As has already been mentioned in EBM the gun is operated in pulse mode. Increasing the beam current directly increases the energy per pulse. Similarly increase in pulse duration also enhances energy per pulse. High-energy pulses (in excess of 100 J/pulse) can machine larger holes on thicker plates. Generally, penetration rates up to 0.25 mm/s have been achieved.

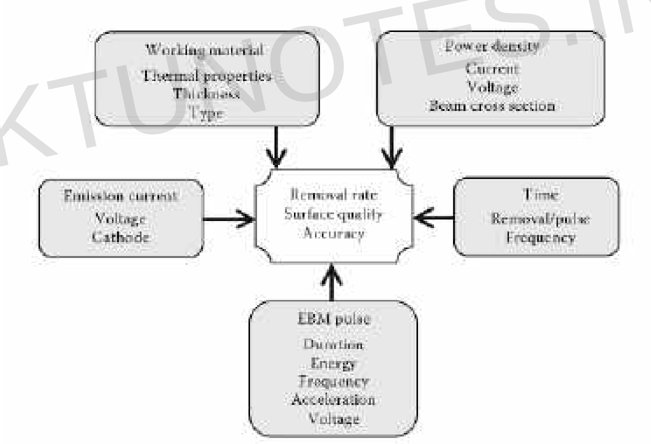


Mechanism of Material Removal in Electron Beam Machining

Electron Beam Process – Parameters

Beam current, pulse duration, lens current and beam deflection are the most important parameters associated with EBM process. The process parameters, which directly affect the machining characteristics in Electron Beam Machining, are:

1. The beam current
2. Pulse duration
3. Energy per pulse
4. Lens current
5. Spot size
6. Power density (energy/pulse*duration of pulse/size of spot)



Material removal rate in EBM

The Material removal rate increase with increase of beam current, Pulse duration, Energy per pulse. Increasing the beam current directly increases the energy per pulse. Similarly, increase in pulse duration also enhances energy per pulse. Material removal rates are a function of the power applied and work piece material.

- **Beam current:** As beam current is increased, the energy per pulse delivered to the work piece is also increased and MRR increases. Beam current once again can be as low as 200 μA to 1A
- **Pulse duration:** Affects both the depth and the diameter of the hole. The longer the pulse duration, the wider the diameter and the deeper the drilling depth capability and MRR
- A higher **energy density,** i.e., for a lower spot size, the material removal would be faster though the size of the hole would be smaller.
- **Lens current:** The diameter of the focused electron beam spot on the work piece will, in turn, determine the diameter of the hole produced. Lens current determines the distance between the focal point and the electron beam gun and determines the size of the focused spot on the work piece.

MRR = area of slot or hole × speed of cutting = A×V

Thermal velocity acquired by an electron of the work material due to electron beam is

$$v = \sqrt{\frac{2K_BT}{M}}$$

Where, K_B = Boltzmann constant

M = mass of one atom of work.

T = rise in temperature

The energy density and power density is governed by energy per pulse duration and spot size. Spot size, on the other hand is controlled by the degree of focusing achieved by the electromagnetic lenses. Maximum MRR = 10 mm3/min

Accuracy/surface quality

EBM can be used for very accurate cutting or boring of a wide variety of metals. Surface finish is better and kerf width is narrower than those for other thermal cutting processes. Electron beam machining is capable of holding tolerances on hole size to about ± 0.013 mm can be possible. The narrowest cut attainable with EBM operations is on the order of 0.03 mm when cutting material of 0.03 mm thickness. The maximum depth of cut is usually about 6 mm.

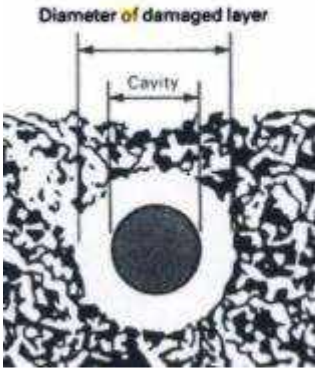
- Surface roughness values ranging 0.4–6.3 μm Ra
- Achievable tolerances ranging ±0.013–±;0.125 mm.

The melting temperature of the material may also have a bearing on quality of surface finish. Produces slightly tapered holes, especially if deep holes are required. Local pitting is a common occurrence. Critical parameters to control surface quality/characteristics are beam current, beam diameter work speed and work material. Thermal properties also have influences on the surface property.

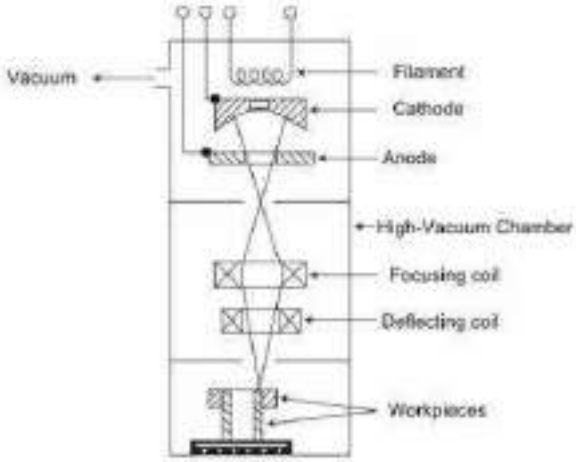
HAZ

The heat-affected zone developed by EBM is generally less than 0.25 mm deep. The heat-affected zone consists of a thin layer of recast material, which may diminish the structural integrity of work pieces, which are highly stressed.

The amount of recast and the depth of HAZ will be governed by the pulse duration, energy per pulse, spot size and thickness of plate etc. Shorter pulse durations will allow less interaction time for thermal effects to reduce the HAZ. Heat-affected zones (HAZ) produced are not desirable



EBM



Mass of an Electron is only 10^{-27} g, but it can Attain Velocity up to 30 – 75% of Speed of Light (= 3 x 108 m/s) by using enough voltage

Equipment is contained in vacuum (10^{-4} mm Hg or more) in order to ensure cutting energy.
Electron source is an 'electron gun' (several times the intensity of a TV gun).
An electron gun is basically a **triode** consisting of:

- **Cathode**, to emit high negative potential electrons
- **Grid cup** (negatively biased with respect to cathode)
- **Anode** (at ground potential).

- Cathode is made from tungsten filament,
- Heated to 2500 – 3000 °C to emit electrons
- Emission current 25 – 100 mA depending on cathode material;
- Current density 5 – 14 A/cm² temperature of accelerating voltage.
- Electrons are **accelerated** using **high potential** between cathode and anode.
- The accelerated electrons are **focused** by the **grid cup**.
- The electrons will flow through the anode.

After exiting the anode, the electrons are **refocused** using **magnetic** and **electrostatic lenses** (controlled beam direction).

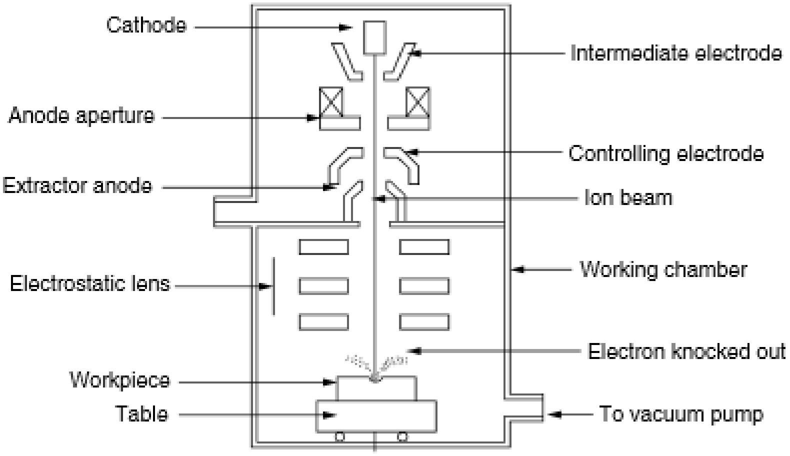
- Electrons maintain speed (in excess of half the speed of light) because they move in **vacuum** (no collision environment) until they hit the workpiece in a small circle of ≈ ϕ 0.025 mm.
- **Cutting path** can be controlled by **diverting the electron** beam or by moving the **worktable**.

Parameter	Details
Accelerating Voltage	50 – 200 kV
Beam Current	100 – 1000 µ A
Power	0.5 to 50 kW
Pulse Duration	4 – 65 ms
Pulse Frequency	0.1 Hz – 16,000 Hz
Vacuum	10^{-2} to 10^{-5} mm Hg
Beam Spot Size (minimum)	12 to 25 µm
Beam Power Density	1.55 x 10^5 to 1.55 x 10^9 W/cm^2
Beam Deflection Angle	6.5 mm square
Tool	Beam of High Velocity Electrons
Work Materials	All Materials
Maximum MRR	10 mm^3/min
Specific Power Consumption	450 W/mm^3/min
Critical Parameters	☐ Accelerating Voltage, ☐ Beam Current, ☐ Pulse Duration, ☐ Spot Diameter (or Beam Diameter), ☐ Beam Deflection Signal ☐ Work Speed i.e. Speed of the Rotation and Translation axes ☐ Melting Temperature

****

Ion beam machining

In IBM, a stream of charged atoms (ions) of an inert gas, such as argon, is accelerated in a vacuum by high energies and directed toward a solid work piece. The beam removes atoms from the work piece by transferring energy and momentum to atoms on the surface of the object. When an atom strikes a cluster of atoms on the work piece, it dislodges between 0.1 and 10 atoms from the work piece material.



IBM system components.

Ion beam machining (IBM) takes place in a vacuum chamber using charged ions fired from an ion source toward the work piece by means of an accelerating voltage. It is the process of knocking out atoms from the work-piece surface by the kinetic energy transfer from incident ion to the target atoms. The process is, therefore, called ion etching, ion milling, or ion polishing. The mechanism of material removal in IBM differs from that of EBM. ION beam machining is the process based on the sputtering off phenomenon.

A heated tungsten filament acts as the cathode, from which electrons are accelerated by means of high voltage (1 kV) toward the anode. During the passage of these electrons from the cathode toward the anode, they interact with argon atoms in the plasma source, to produce argon ions.

$$Ar + e^{-} \rightarrow Ar^{+} + 2e$$

Advantages of IBM

1. Low temperature processing reduces handling an stress problems.
2. No dimensional changes
3. Good adhesion of treated surface
4. Can improve corrosion, oxidation, wear, hardness, friction, fatigue

Disadvantages of IBM

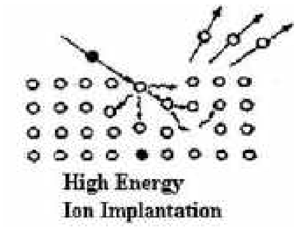
1. Very shallow treatment (< 1 µm)
2. High cost
3. The surface can be weakened by radiation effects

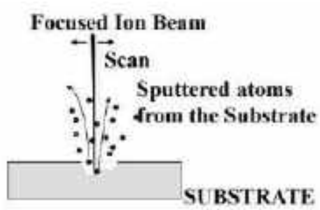
Ion beam machine consists of

- A plasma source generates ions
- Extraction grid for removing the ions from the plasma
- Specimen holding table

Mechanism of material removal

- Sputtering off: knocking out atoms from the work-piece surface by the kinetic energy transfer from incident ion to the target atoms.
- Removal of atoms will occur when the actual energy transferred exceeds the usual binding energy
- Several atoms or molecules will be ejected out and the bombarding ion will become implanted deep within the material
- Energies greater than binding energy of 5 to 10 electron volt are needed to effect the removal of atoms.





The mechanism of material removal in this process differs from those in E B M and P B M that is electron beam machining, and plasma beam machining. In ion beam machining the atoms are ejected from the surface by other ionized atoms, which bomber the work materials. Accordingly, this process is also known as ion itching, ion milling, or iron polishing.

Ion beam machining is generally a surface finishing process in which the material removal takes place by sputtering of ions. It is also called etching process. This is different process from electric discharge, electron beam, laser beam and plasma arc machining

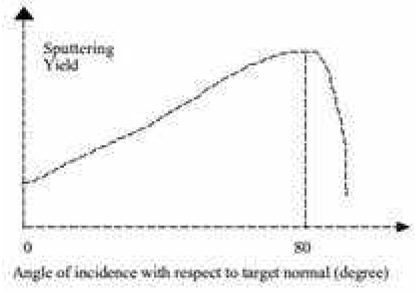
IBM parameters

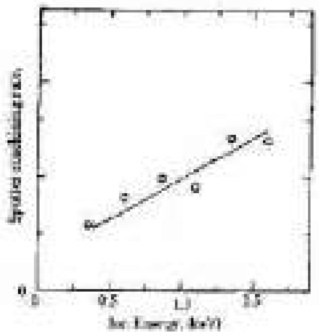
1. Ions energy. The energy of ions is determined by the accelerating potential of ion source electrodes and for ion beams
2. Ion current. The ion current, ion current density determines the sputtering rate.
3. Ion beam power. The ion beam power or power density defines the material sputtering rate and IBF run productivity
4. Working Gas. The working gas determines the optical component material sputtering yield,
5. Angle of incidence
6. Optical Motion pattern

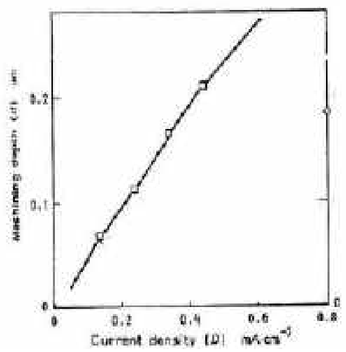
Factor affecting Material removal rate

Sputtering yield (MRR) is a function of atomic number, binding energy, grain size, no. of electrons shell, etc. of the work-piece material.

- The sputtering yield is dependent on the atomic weight of the incident ion. ions. having high atomic number will yield high MRR.
- Angle of incidence: sputtering yield increases gradually reaches a maximum at an ion incidence angle of nearly 50^0 and after that decreases rapidly. As the ion incidence angle increases, more atoms of the work-piece can be knocked out or sputtered away easily from the surface of work-piece
- The specific sputter-machining rates increase linearly with the amount of ion energy
- Machining depth increases with increase in current density



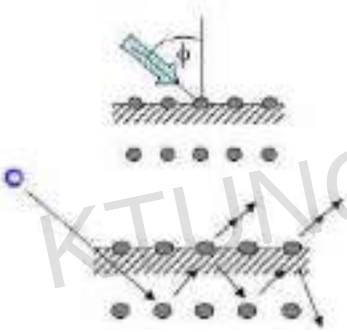


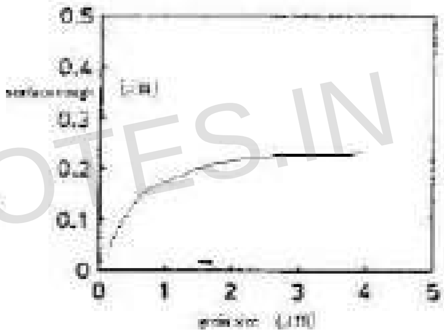


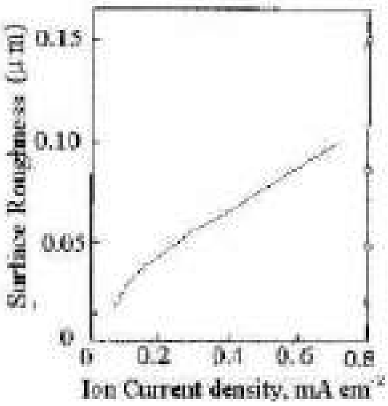
Factors affecting surface finish

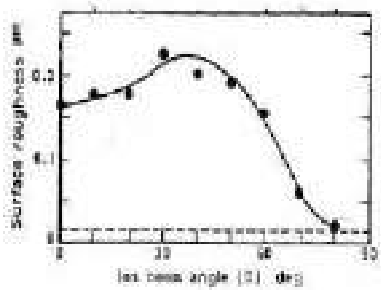
Success of the ion beam polishing depends crucially on the grain size and initial morphology of the surface.

- Surface roughness increases with increase in size of the grain structure, ion energy and current density.
    - o An increase in angle of incidence increases the surface roughness,
    - o For low current density and energy, the smaller value of surface roughness
- Surface morphology has significant effect on the final surface finish.
- Surface roughness increases for incident angle from 0 ^{0} to 50^{0} then decreases rapidly.



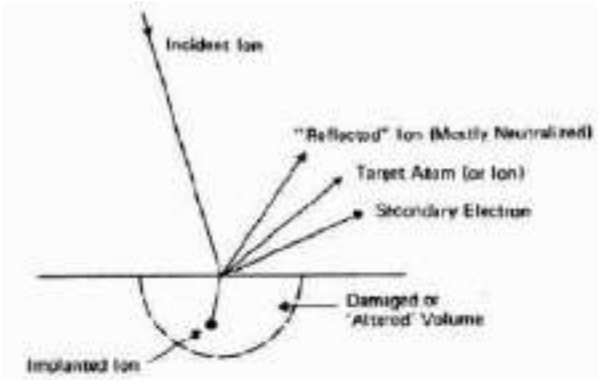






Heat affected zone

Heat affected zone in IBM can be limited to1μm. The mechanism of material removal in IBM is different from EDM or LBM. The material removal is at atomic level. So the heat affected zone is very negligible.



Process capability of IBM

- Machining of small dimensions as 10 to 100 Nano-meter are possible, using ion beam
- Machining accuracy levels ± 1 percent with repeatability is been reported.
- Smoothening to a surface finish of less than 1 micro meter can be obtained.
- Etching rates vary up to 2000 Å per min.
- Tolerances in the vicinity of + 50 Å to - 50 Å are possible. Accuracy of the etching process is considerably high mainly due to the small amount of material removal.
- As there is no load on the work-piece while finishing, it is also suitable for finishing of very thin objects, optics and soft material.
- Possible to achieve surface finish in the order of a fraction of the size of an atoms

Applications of IBM:

1. It is applied mostly in micro-machining of electronic components.
2. Typical materials that can be etched included glass, alumina, quartz, crystal, silica, agates, porcelains, numerous metals, cermets and oxides.
3. It is also being used to deposit materials such as platinum, tungsten and silicon oxide insulators on other material substrate.
4. Ion beam machining is an ideal process for nano-finishing of high melting point hard and brittle materials such as ceramics, semiconductors, diamond etc.
5. The processes can be applied to the manufacturing of ultra-fine precision parts of electronic and mechanical devices.
6. Material removal takes place in the form of removal of atom or molecule from the surface of the work-piece.

****

Plasma arc machining (PAM)

It is also one of the thermal machining processes. Here the method of heat generation is different than EDM. In this process gases are heated and charged to plasma state. Plasma state is the superheated and electrically ionized gases at approximately 5000°C. A high velocity jet flow of hot ionized gas melts the metal and then removes the molten material to form a kerf.

Power Supply and Terminals

Power supply (DC) is used to develop two terminals in the plasma gun. A tungsten electrode is inserted to the gun and made cathode and nozzle of the gun is made anode. Heavy potential difference is applied across the electrodes to develop plasma state of gases.

Cooling Mechanism

As we know that hot gases continuously come out of nozzle so there are chances of its overheating. A water jacket is used to surround the nozzle to avoid its overheating.

The metals usually cut with this process are the aluminium and stainless steels. The process can also be used for cutting carbon steels, copper alloys, and nickel alloys

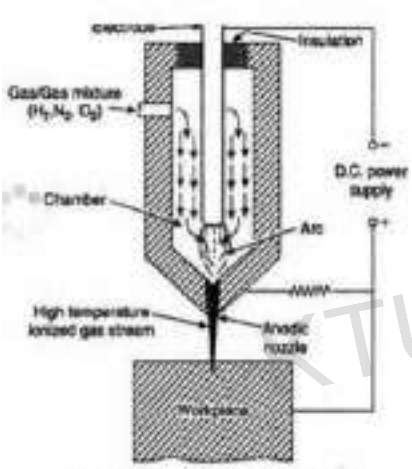
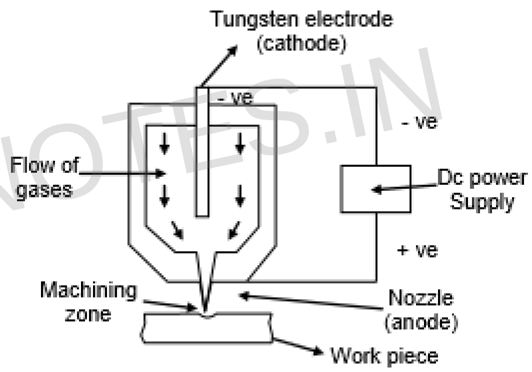


Fig. 12.8 Plasma Arc Machining (PAM)



Advantages of PAM Process /capability

1. It gives faster production rate. Much faster than the EDM and LBM process
2. Very hard and brittle metals can be machined.
3. Small cavities can be machined with good dimensional accuracy.
4. Mild steel of 6mm thick can be cut at 3m/min
5. The plasma arc can be used to cut any metal or even to non-conducting materials like concrete etc., since it is primarily a melting process
6. Due to high speed of cutting the deformation of sheet metals is reduced while the width of the cut is minimum
7. Smooth cuts free from contaminants are obtained in the process
8. Profile cutting of metals especially of stainless steel and aluminum can be very easily done by PAM
9. Operating costs are less when compared to oxy-fuel torch
10. Can be automated

Disadvantages of PAM Process

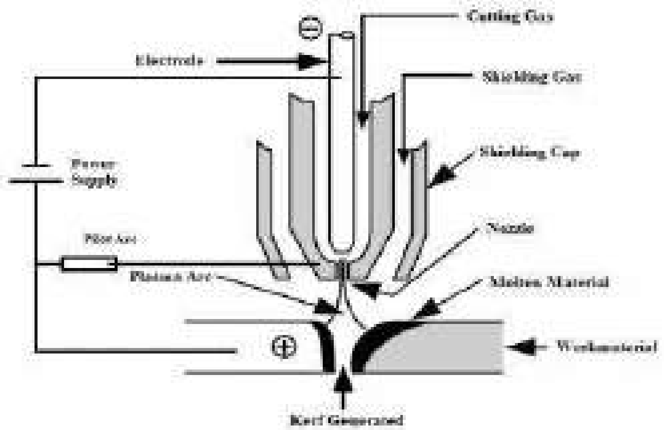
1. Its initial cost is very high.
2. The process requires over safety precautions which further enhance the initial cost
3. Some of the work piece materials are very much prone to metallurgical changes on excessive heating so this fact imposes limitations to this process.
4. It is uneconomical for bigger cavities to be machined.
5. Smoke and noise
6. Sharp corners are difficult to produce because of the wide diameter of the plasma stream
7. Burr is often produced
8. Taper on the work piece may occur

Applications of PAM

1. Chiefly used to cut stainless steel and aluminium alloys. It is preferred to oxy-fuel cutting because it produces comparatively smoother cuts and is free from contamination
2. Other metals which are resistant to oxy-fuel cutting and hence cut by PAC are magnesium, titanium, copper, nickel and alloys of copper and nickel
3. PAC can be used for stack cutting, plate bevelling, shape cutting and piercing.
4. It can also be used for underwater cutting.
5. The plasma jets are used for welding materials like titanium, stainless steel etc.,
6. Plasma arc is used for depositing filler metal on surface to obtain desired properties like corrosion resistance, wear resistance, toughness or anti-friction properties – Plasma arc surfacing
7. The plasma arc can also be used for spraying a prepared surface of the base material with droplets of molten metal to obtain a surface of required thickness

Mechanism of Material removal

The metal removal in PAM is basically due to the high temperature produced. The heating of the work piece is, as a result of anode heating, due to direct electron bombardment plus convection heating from the high temperature plasma that accompanies the arc. The heat produced is sufficient to raise the work piece temperature above its melting point and the high velocity gas stream effectively blows the molten metal away.



Secondary Gases or Water: Surrounds the electric arc to aid in confining it and removing the molten material

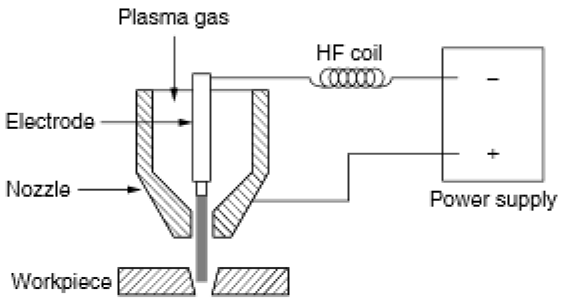
Types of plasma cutting

Plasma generating torches are of two general designs – transferred plasma torch and non-transferred plasma torch.

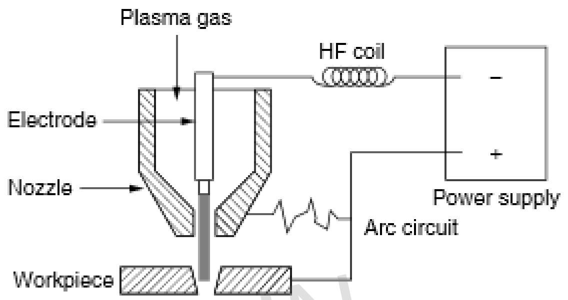
Transferred and non-transferred plasma arc machining

A plasma jet can be operated in the transferred mode, where the electric current flows between the plasma torch electrode (cathode) and the work piece (anode). It can also be operated in the non-transferred mode where the electric current flows between the electrode and the torch nozzle. Both modes of operation are illustrated in Figure. The quality of plasma produced is a function of density (pressure), temperature and torch power (the greater the better).

The Non-trasferred arc torch extends from the electrode or the cathode to the end of the nozzle. The nozzle acts as the anode. This type of plasma jet is completely independent of the work piece.



Nontransferred plasma jet system.



Transferred plasma arc system

- Transferred –Transferred system the arc is completed by making contact with the work piece.
- Non-transferred – In the non-transferred system the arc is completed by making contact with nozzle, it can produce an arc without touching the grounded work piece and can be very dangerous

Process Parameters

Parameters that govern the performance of PAM can be divided into two categories:

1. Those associated with the design and operation of the torch – electrical power delivered, the gases used to form the plasma, the flow rate of the gases through the torch, the orifice diameter through the nozzle duct
2. Those associated with the physical configuration of the set up – torch standoff, angle to the work, depth of cut, feed into the work and speed of the work toward the torch
    1. Current intensity
    2. Plasma arc voltage
    3. Properties of work piece
    4. Thickness work piece
    5. The gases used to form the plasma,
    6. The flow rate of the gases
    7. Working Speed
    8. The nozzle diameter – determines the power density in the flame
    9. Standoff distance

These factors will determine the performance factors as follows

1. MRR/production rate
2. Roughness of surface
3. Cutting width
4. Wear of nozzle
5. HAZ dimension
6. The shape of surface

Metal removal rate

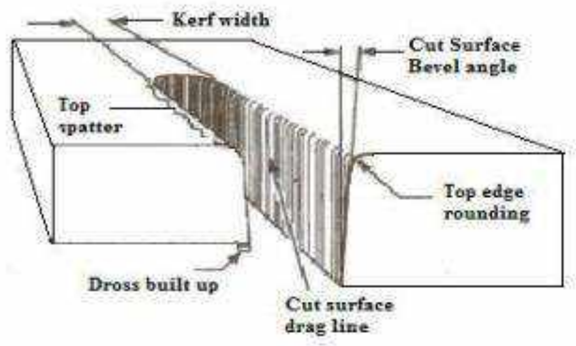
The gas flow rate, orifice size, and power level are intimately related.

- MRR increases with current –but depend on cutting speed, gas flow rate, thickness of work and finish requires (800 to 1000A)
- Higher the value of cutting speed more is the volume of material removed (MRR). Cutting speed, it depends on the thickness of the work piece material you are cutting, work piece material property, and surface speed of the work piece material.
- A proportion of 10% hydrogen and 90% nitrogen or argon usually gives good general-purpose results.
- An increase in plasma gas flow permits an increase in current. This increases the power density of the flame and permits greater speed with less taper on the kerf walls.
- Voltage depends on the ionization voltage and gas flow (300V)

Surface finish:

Quality of cut and dimensional accuracy produced by plasma arc cutting process can be accessed by measuring kerf width, heat affected zone (HAZ), surface finish and, material removal rate etc.

Arc current and arc voltage are found to be most significant parameter which affects cut quality of plasma arc cut. The other factors are Torch standoff, angle to work, depth of cut and feed into the work



- A lower value of arc current and arc voltage was found to produce better surface finish. As the increase in thermal content of the arc was observed to spoil the surface finish and increase the kerf width with increase in HAZ.
- As the thickness of the work material increases lower value of cutting speed tend to produce better cut quality
- Higher standoff distance affects surface roughness and taper angle of the cut surface.

- Tolerance increases with decrease in cutting speed ±0.8mm
- surface finish achieved on the machined surface is 5 to 75 micron
- Proper gas pressure is required to be maintained since lower value will result in formation of spatter at the top surface
- Lower values of gas flow rate may result in double arcing which reduces the life of consumables i.e. electrode and nozzle.
- Taper 5-7^{0}

Metallurgical effects/HAZ

In general, the depth of the heat-affected zone is approximately 0.75 mm. Heat affected zone is a function of thickness of the work material, plasma arc system and material types. Heat affected zone it may be around 0.75 mm to 5 mm

Kerf

Kerf is defined as the width of material that is removed by a cutting process. Kerf is affected by three major variables.

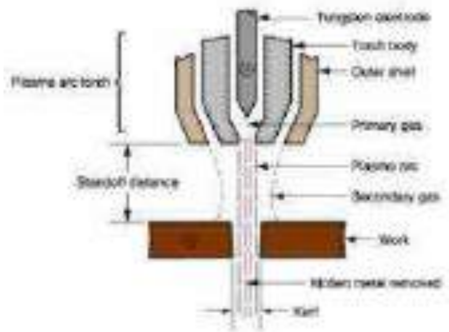
- Increase in the current, top kerf width also increases.
- Cutting Speed. Slower travel speeds will result in a wider kerf
- Lowering standoff will lead to a narrower kerf and eventually loss of cut.
- Thickness of work: the plate gets thicker; the kerf gets wider.

The highest quality plasma cut is usually obtained when maximum thermal intensity is used. To achieve this, the smallest, or next to the smallest, nozzle size that is capable of operating at a power level suitable for the speed and thickness involved is used.

Standoff distance:

Due to the columnar shape of the plasma jet, a wide range of tip-to-work piece spacing is allowable. This permits machine cutting along warped or irregular surfaces. General consideration includes:

1. Better quality cuts usually result from a short standoff distance since arc divergence is less and the thermal intensity of the arc is greater.
2. Excessively close standoff distance can promote arcing due to the accumulation of slag drops on the tip.
3. Increased power input is necessary when the standoff distance is great.
4. Standoff distance can range from 6.5-76.2 mm.

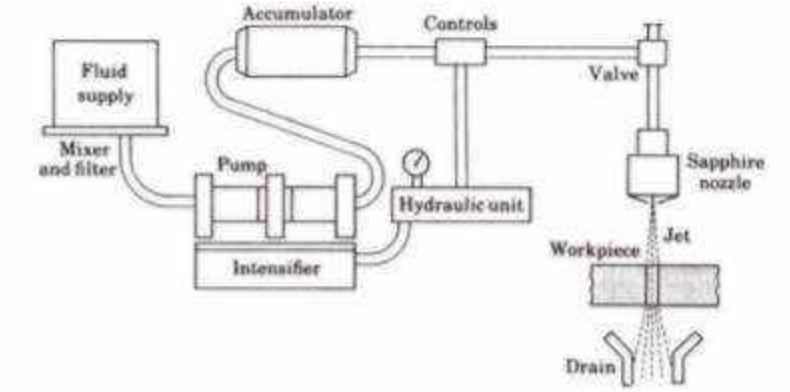


****

Water jet machining and Abrasive Water Jet Machining (WJM/AWJM)

Water jet machining

Water jet cutting uses the beam of water exiting the orifice to cut soft materials. The inlet water is typically pressurized between 1300 – 4000 bars. Water jet cutting is mostly used to cut lower strength materials such as wood, plastics and aluminum. Removes material through the erosion effects of a high velocity, small diameter jet of water. Primarily used to cut and slit porous nonmetals such as wood, paper, leather and foam. It is most suitable process for very thick, highly reflective or highly thermal-conductive materials, as well as hard materials



Normal water is filtered and passed to the intensifier. The intensifier acts as an amplifier as it converts the energy from the low-pressure hydraulic fluid into ultra-high pressure water. The hydraulic system provides fluid power to a reciprocating piston in the intensifier center section to amplify the water pressure. Using a control switch and a valve water is pressurized to the nozzle. Nozzle renders the pressurized water as a water jet at high velocity.

Advantages

1. In most of the cases, no secondary finishing required
2. Machine thick plates
3. Water jet cutting does not produce any dust or particles that are harmful if inhaled.
4. The kerfs width in water jet cutting is very small, and very little material is wasted.
5. Low cutting forces on work pieces
6. Little to no cutting burr
7. Very good surface finish (125-250 microns)
8. No heat affected zone- Almost no heat generated on the part
9. Eliminates thermal distortion and structural change

Limitations of abrasive water jet cutting

- Taper is also a problem with water jet cutting in very thick materials
- Can cause dimensional inaccuracy.
- Cannot cut materials that degrades quickly with moisture
- Surface finish degrades at higher cut
- High capital cost and high noise levels during operation.

In water jet cutting, there is no heat generated. this is especially useful for cutting tool steel and other metals where excessive heat may change the properties of the material. Abrasive water jet cutting is capable of produce parts which do not require further processing with tolerances of ± 0.1 mm.

Application

The cutting ability of water jet machining can be improved drastically by adding hard and sharp abrasive particles into the water jet. WJM is typically used to cut materials like thin sheets and foils, non-ferrous metallic alloys, wood, textiles, honeycomb, polymers, frozen meat, leather etc, but the domain of “harder and “difficult-to machine” materials like thick plates of steels, aluminium and other commercial materials, metal matrix and ceramic matrix composites, etc are reserved for AWJM.

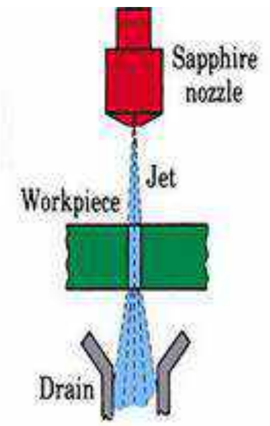
Other than cutting (machining) high pressure water jet also finds application in paint removal, cleaning, surgery, peening to remove residual stress etc. AWJM can as well be used besides cutting for pocket milling, turning, drilling etc. One of the strategic areas where robotic AWJM is finding critical application is dismantling of nuclear plants.

1. Paint removal
2. Cleaning
3. Cutting materials
    a) Steels
    b) Non-ferrous alloys
    c) Ti alloys, Ni- alloys
    d) Polymers
    e) Composite
    f) Concrete
    g) Stone – Granite
4. Textile, Leather industry
5. Surgery
6. Peening
7. Cutting
8. Drilling
9. Turning

Material removal mechanism

In ductile material

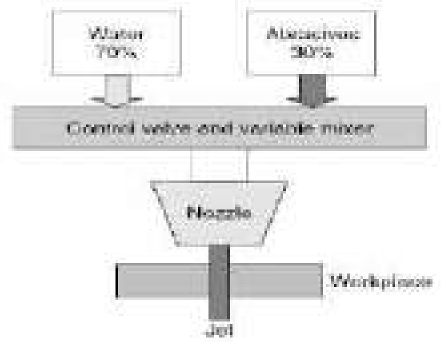
Removes material through the erosion effects of a high velocity, small diameter jet of water and mixed high velocity of abrasive grits on a work piece. Abrasive particles produce micro-cutting. In case of AWJM of brittle materials, material would be removed due to crack initiation and propagations

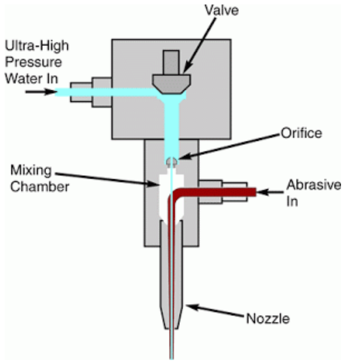


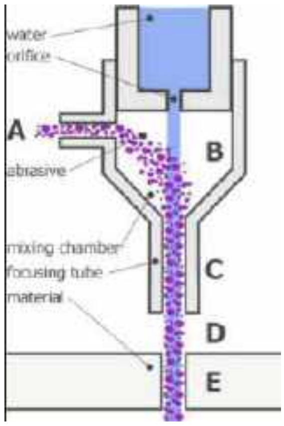
Mechanism of material removal: Erosion

Abrasive water jet machining (AWJM)

Abrasive water jet cutting is an extended version of water jet cutting; in which the water jet contains abrasive particles such as silicon carbide or aluminium oxide to increase the material removal rate above that of water jet machining. Almost any type of material ranging from hard brittle materials such as ceramics, metals and glass to extremely soft materials such as foam and rubbers can be cut by abrasive water jet cutting. Abrasive water jet cutting is highly used in aerospace, automotive and electronics industries. The addition of abrasives to the water jet enhanced MRR and cutting speeds (51 and 460 mm/min). Use of the kinetic energy of the abrasive particles to remove small chips of the work material.

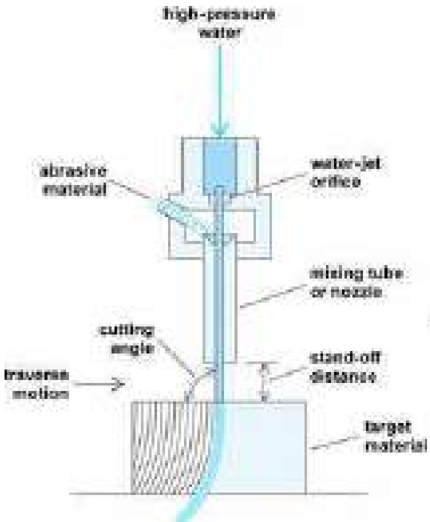


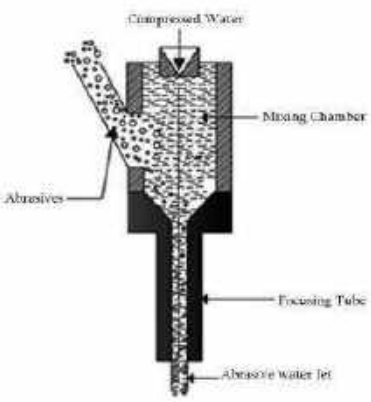




- The potential energy of water under high pressure into kinetic energy of a water jet.
- Transfer of a part of the kinetic energy of the high-speed water jet to abrasive particles by accelerating them and focusing the resulting abrasive water jet.
- Use of the kinetic energy of the abrasive particles to remove small chips of the work

In the process of abrasive water jet cutting the high pressure pump produces the required pressure up to 400 MPa. High-pressure water is fed through the flexible stainless steel pipes to the cutting head. Cutting head consists of orifice, mixing chamber and focussing tube or insert where water jet is formed and mixed with abrasive particles to form abrasive water jet. The potential or pressure head of the water is converted into velocity head (approx. 900 m/s) by allowing the high-pressure water to issue through an orifice of small diameter (0.2 – 0.4 mm). Then, solid abrasive particles are added and mixed with the water jet. Resulting abrasive water jet is focused to the material through abrasive nozzle.

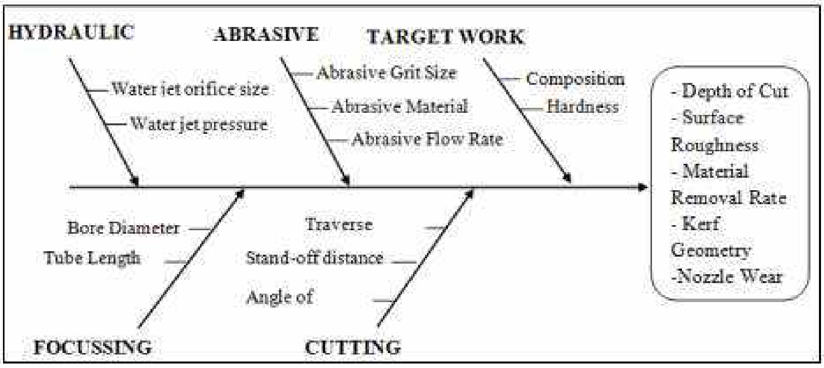




Parameters control the results achieved with WJM

It is found that water pressure, abrasive flow rate, orifice diameter, nozzle diameter and standoff distance and feed rate have significant effect on the MRR and SR.

1. Pressure,
2. Nozzle dimensions
3. Focusing diameter,
4. Traverse rate
5. Standoff distance
6. Abrasive particle size and material



Pressure, nozzle diameter and traverse rate are varied, depending upon the material and the thickness being cut. The ability to cut faster (higher MRR) or to cut thicker materials is also increased by accomplished by increasing the pressure, increasing the nozzle diameter or decreasing the traverse rate

The general domain of parameters in entrained type AWJ machining system is given below:

- Orifice – Sapphires – 0.1 to 0.3 mm
- Focussing Tube – WC – 0.8 to 2.4 mm
- Pressure – 2500 to 4000 bar
- Abrasive –- #125 to #60
- Abrasive flow - 0.1 to 1.0 Kg/min
- Standoff distance – 1 to 2 mm
- Machine Impact Angle – 60^o to 90^0
- Traverse Speed – 100 mm/min to 5 m/min
- Depth of Cut – 1 mm to 250 mm

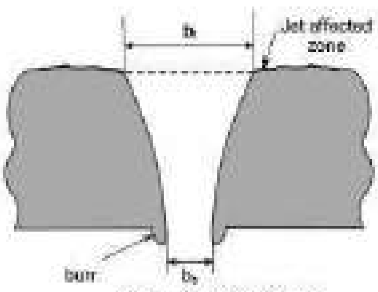
MRR

1. Material removal rate increases with pressure and abrasive flow rate
2. The decreasing orifice diameter increases the velocity of water jet which results in high MRR
3. The material removal rate is increased with increase in grain size and increase in nozzle diameter.
4. Material removal rate increases initially with increase in stand-off-distance and then decreases the material removal on further increases at a particular pressure.

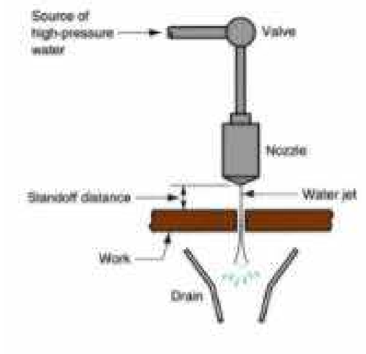
Surface roughness

- The surface finish of a work piece is directly related to the cutting force. The higher the force the rougher will be the surface.

- Higher abrasive flow rate with higher standoff distance produces higher surface roughness owing to larger and random energy distribution.
- The increase in the number of impacting particles improves surface finish.
- With an increase in the abrasive flow rate, the roughness is reduced.
- Higher abrasive flow rate produces greater kerf width,
- A large stand-off-distance results in the flaring up of the jet which leads to poor accuracy.
- The amount of over size of the holes is greater at the entry than at exit resulting in unavoidable conicity



Schematic of AWJM kerf



Process	Process Capability: Metal Removal Rate, (mm^3/s)	Surface Finish (μm, CLA)	Accuracy (μm)	Specific power ($kW/cm^3/min$)	Penetration rate, (mm/min)
ECM	2700	0.1 - 2.5	50	7.5	12.0
EDM	14	0.4 - 12.5	10	1.8	12.0
EBM	0.15	0.4 - 6.0	25	450	160.0
LBM	0.10	0.4 - 6.0	25	2700	100.0
PAM	2700	Rough	250	0.90	250
USM	14	0.2 - 0.5	7.5	9.0	0.50
AJM	0.014	0.5 - 1.2	50	312.5	-
CHM	0.8	0.4 - 2.5	50	-	0.02

Process	MRR (mm^3/min)	Tolerance (μm)	Surface finish (μm)	Depth of surface damage (μm)	Power (watts)
USM	300	7.5	0.2 – 0.5	25	2,400
AJM	0.8	50	0.5 – 1.2	2.5	250
ECM	15,000	50	0.1 – 2.5	5.0	1,00,000
CHM	15	50	0.5 – 2.5	50	-
EDM	800	15	0.2 – 1.2	125	2,700
EBM	1.6	25	0.5 – 2.5	250	150(average) 2,000 (peak)
LBM	0.1	25	0.5 – 1.2	125	2 (average)
PAM	75,000	125	Rough	500	50,000

Process Capabilities of NTMPs

Parameters	USM	AJM	ECM	CHM	EDM	EBM	LBM	PAM
Potential (V)	220	220	10	-	45	1,50,000	4,500	100
Current (Amp)	12 (AC)	1.0	10,000 (D.C)	-	50 (Pulsed D.C)	0.001 (Pulsed D.C)	2 (Average) 200 (Peak)	500 (D.C)
Power (W)	2,400	220	1,00,000	-	2,700	150	-	50,000
Gap (mm)	0.25	0.75	0.20	-	0.025	100	150	7.5
Medium	Abrasive in water	Abrasive in gas	Electrolyte	Liquid chemical	Liquid dielectric	Vacuum	Air	Argon or Hydrogen

Physical parameters of NTMPs

General notes

Process Parameters LBM

These are parameters that characterize the properties of the laser beam which include focusing of laser beams, focal position and dual focus lens, process gas and pressure, nozzle diameter, stand-off distance and alignment, and cutting speed. The cutting process requires the spot size is small enough to produce the high intensity power.

Focusing of Laser Beams

The focal length of lens is about the distance from the position of focal lens to the focal spot. The focal length of the lens has a large impact on size of the focal spot and the beam intensity in the spot. The cutting process requires the spot size is small enough to produce the high intensity power.

Focal Position

In order to get optimum cutting result, the focal point position must be controlled. There are two reasons: the first reason is that the small spot size obtained by focusing the laser beam results in a short depth of focus, so the focal point has to be positioned rather precisely with respect to the surface of the work piece; the other one is differences in material and thickness may require focus point position alterations.

Nozzle Diameter, Stand-Off Distance

Nozzle is used to deliver the assist gas. The nozzle has three main functions in the laser cutting process: to ensure that the gas is coaxial with the beam; to reduce the pressure to minimize lens movements and misalignments; and to stabilize the pressure on the work piece surface to minimize turbulence in the melt pool.

The stand-off distance, which is the distance between the nozzle and the work piece, is also an important parameter. The stand-off distance is usually selected in the same range as the diameter of cutting nozzle-between 0.5 and 1.5 mm-in order to minimize turbulence. A short stand-off distance provides stable cutting conditions, although the risk of damage to the lens from spatter is increased. The stand-off distance is optimized to maximum the cutting speed and quality.

Cutting Speed

It is a travel of a point on the cutting edge relative to the surface of cut in unit time in the process accomplishing the primary cutting motion. The cutting speed must be balanced with the gas flow rate and the power. As cutting speed increases, the cutting time decreases and less time for the heat to diffuse sideways and the narrower the HAZ. The kerf is also reduced due to the need to deposit a certain amount of energy to cause melting. However, striations on the cut edge become more prominent, dross is more likely to remain on the underside and penetration is lost. When the cutting speed is too low, excessive burning of the cut edge occurs, which degrades edge quality and increases the width of the HAZ. In general, cutting speed for a material is inversely proportional to the thickness.

Gas Pressure (P)

Pressure is the expression of force exerted on a surface per unit area.

Module V---Question

1. Briefly explain non-transitional machining process. Give applications
2. Discuss the dimensional tolerance that can be achieved by unconventional machining.
3. What is the importance of non-traditional machining?
4. How is chemical machining different from electrochemical machining?
5. Explain the influence of chemical machining as product tolerance and surface finish.
6. Draw the schematic arrangement of ECM. Explain its working and limitations.
7. Name any two electrolytes used in ECM process.
8. How will you differentiate the ECM with EDM process?
9. With a neat sketch, explain Electro-chemical Machining process. List the major process and applications.

****

10. Explain EDM. What are its applications? (8 marks)
11. Compare the different tool materials used in spark EDM.
12. Explain the principle of Wire EDM. .
13. List out the advantages of EDM
14. Explain EDM. What are its applications? (8 marks)
15. Illustrate arid explain the process of EDM and state the differences in process parameters used in wire cut EDM.
16. List out the advantages of EDM process. .
17. Discuss the EDM process.
18. List out its applications of `WEDM.
19. Explain the role of dielectric' in EDM process. (4 marks)
20. Discuss the various factors of EDM that affect
    a. the metal removal rate and
    b. the accuracy of holes obtained in EDM
21. Why has the wire EDM process become so widely accepted in industry?
22. Sketch and explain an Electro-discharge machining process. List the important process variables and discuss their effects on MRR and surface finish.
23. Discuss the various factors that affect (i) the metal removal rate and (ii) the accuracy of holes obtained in EDM.
24. What are the merits of EDM?
25. Describe the selection of dielectric medium in EDM.
26. What are the capabilities of wire EDM? Could this process be used to make tapered pieces? Explain.

****

27. Explain the working of Electron Beam machining with the help of a neat diagram. Discuss its application areas
28. Distinguish between laser beam machining and electron beam machining. Give their field of application in manufacturing.
29. Draw and explain the construction and working of the Electron Beam   Illustrate the 4 steps leading to material removal by EBM and explain the process. (12 marks)

30. In Plasma Arc Machining, how a transferred is are processes different from a non-transferred arc “process?
31. What are the distances of electron beam over laser beam for machining?
32. List the different types of laser used in Laser beam machining.
33. How is laser produced?
34. Briefly explain the working principle of LBM.
35. Describe the plasma are cutting and machining;

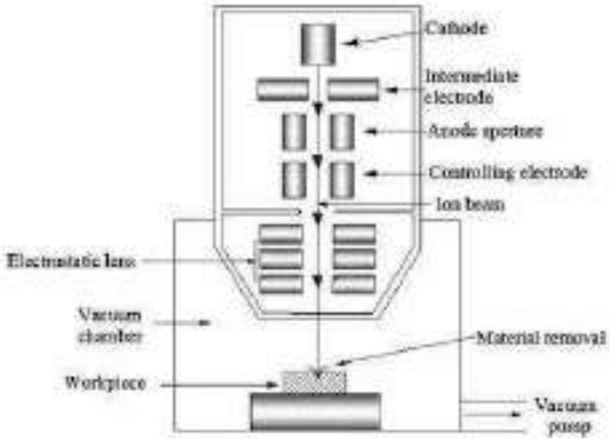
****

36. What is meant by kerfwidth in AJM? How does it relate to the nozzle tip distance?
37. Illustrate and explain the Abrasive Water Jet Machining process and state the advantages, limitations and applications of the process.
38. Draw graphs to relate the following process parameters to the material removal rate in abrasive jet machining
    a. Nozzle tip distance.
    b. Abrasive flow rate.
    c. Abrasive grain size
39. Discuss abrasive water jet machine.
40. List any two advantages of AJ M process.
41. Discuss any four process parameters involved in AJM.
42. List the various elements of AJM process and explain their influence on process parameters.
43. Explain the process parameters which influence Metal Removal rate in Abrasive Jet Machining
44. What are the limitations of abrasive jet machining?
45. Describe, in detail, metal removal by abrasive jet machining.

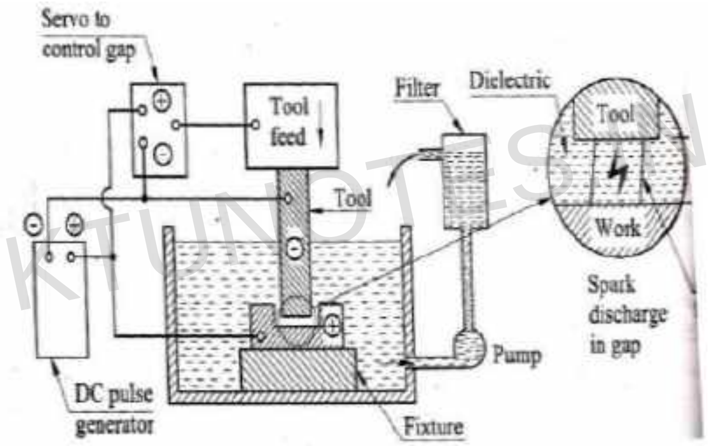
****

46. Why are abrasive slurry is used in ultrasonic machining? _
47. Sketch and explain Ultrasonic Machining.
48. Explain the principle of ultrasonic machining. What are the limitations of USM?
49. Why is frequency tuning a must in Ultrasonic Machining?
50. What is the function of a concentrator in Ultrasonic Machining?

****


Cathode
Intermediate electrode
Anode aperture
Controlling electrode
Ion beam
Electrostatic lens
Vacuum chamber
Material removal
Workpiece
Vacuum pump

IBM


Servo to control gap
Tool feed
Filter
Dielectric
Tool
Tool
Work
Spark discharge in gap
Pump
DC pulse generator
Fixture

EDM