

## Joining of materials

- Joining includes welding, brazing, soldering, adhesive bonding of materials.
- They produce permanent joint between the parts to be assembled.
- They cannot be separated easily by application of forces.
- They are mainly used to assemble many parts to make a system.
- Welding is a metal joining process in which two or more parts are joined or coalesced at their contacting surfaces by suitable application of heat or/and pressure.
- Some times, welding is done just by applying heat alone, with no pressure applied
- In some cases, both heat and pressure are applied; and in other cases only pressure is applied, without any external heat.
- In some welding processes a filler material is added to facilitate coalescence.

## Advantages of welding:

- Welding provides a permanent joint.
- Welded joint can be stronger than the parent materials if a proper filler metal is used that has strength properties better than that of parent base material and if defect less welding is done.
- It is the economical way to join components in terms of material usage and fabrication costs. Other methods of assembly require, for example, drilling of holes and usage of rivets or bolts which will produce a heavier structure.

## Disadvantages of welding:

- Labour costs are more since manual welding is done mostly.
- Dangerous to use because of presence of high heat and pressure.
- Disassembly is not possible as welding produces strong joints.
- Some of the welding defects cannot be identified which will reduce the strength.

**Types of welding:** Welding processes can be broadly classified into (i) fusion welding, and (ii) solid state welding

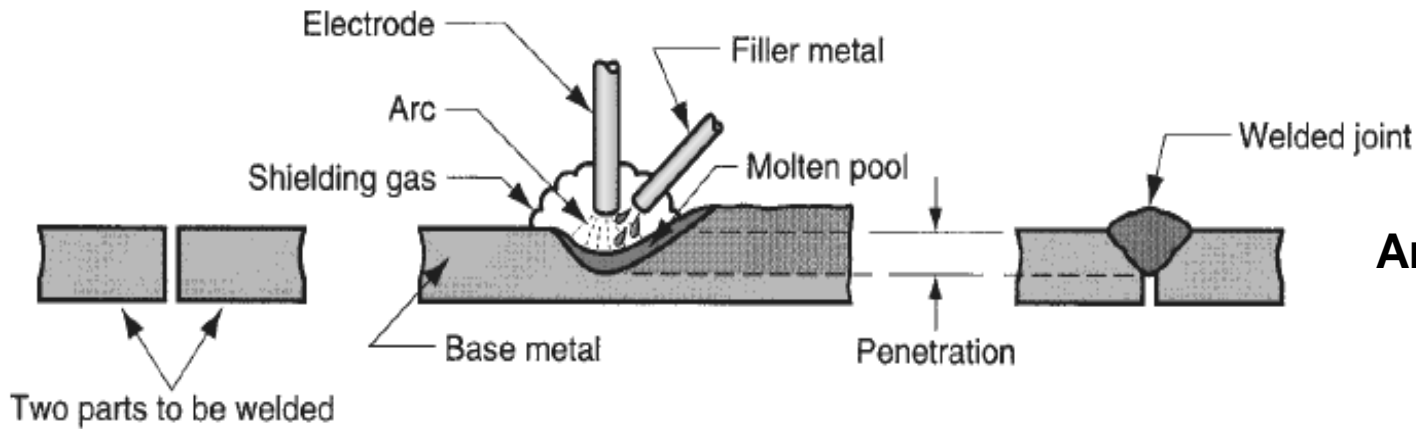
### Fusion welding:

In fusion-welding processes, heat is applied to melt the base metals. In many fusion welding processes, a filler metal is added to the molten pool during welding to facilitate the process and provide strength to the welded joint.

When no filler metal is used, that fusion welding operation is referred to as autogenous weld.

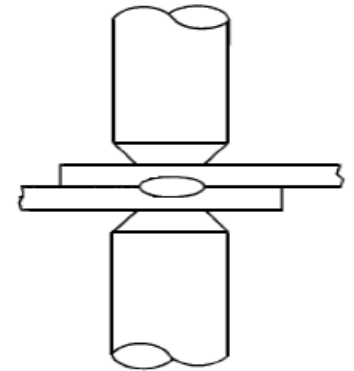
**Types:** Arc welding, Resistance welding, Oxyfuel gas welding, electron beam welding, laser welding

**Arc welding:** In this operation, electric arc is used to produce heat energy and the base metal is heated. Sometimes, both pressure and heat are applied.



**Arc welding steps**

**Resistance welding:** In this operation, electric resistance is generated to the flow of current that generates heat energy between two contacting surfaces that are held in pressure.



**Gas welding:** Oxyfuel gas welding is a welding operation in which heat is generated by a hot flame generated mixture gas of oxygen and acetylene. This heat is used to melt base material and filler material, if used.

## Solid State Welding:

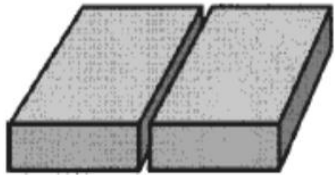
- In this method, joining is done by coalescence resulting from application of pressure only or a combination of heat and pressure.
- Even if heat is used, the temperature in the process is less than the melting point of the metals being welded (**unlike in fusion welding**).
- No filler metal is utilized.

**Diffusion welding:** Two part surfaces are held together under pressure at elevated temperature and the parts join by solid state diffusion.

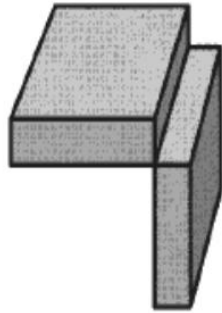
**Friction welding/Stir welding:** Joining occurs by the heat of friction and plastic deformation between two surfaces.

**Ultrasonic welding:** Moderate pressure is applied between the two parts and an oscillating motion at ultrasonic frequencies is used in a direction parallel to the contacting surfaces

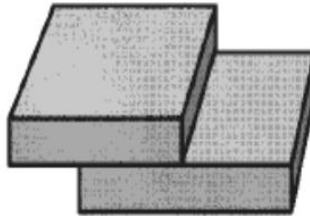
## Weld joint configurations



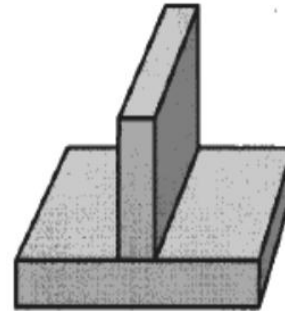
Butt joint



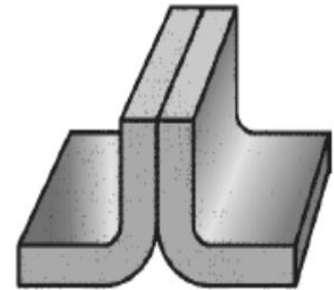
Corner joint



Lap joint

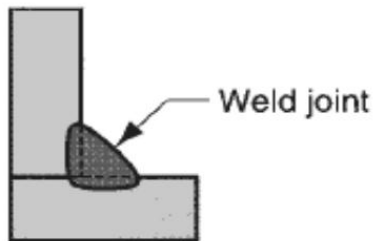


Tee joint

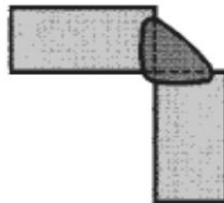


Edge joint

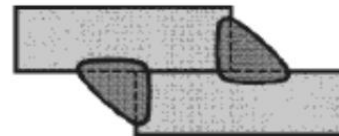
## Weld types



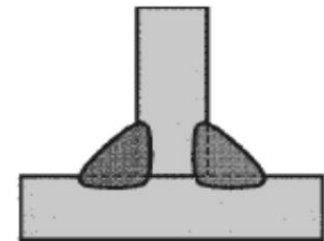
Inside single fillet  
corner joint



Outside single fillet  
corner joint

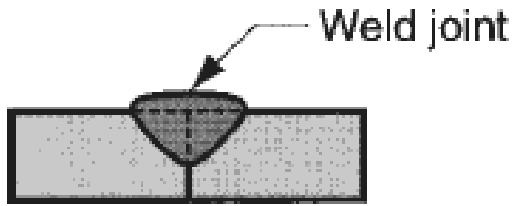


Double fillet lap  
joint

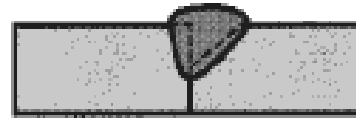


Double fillet  
Tee joint

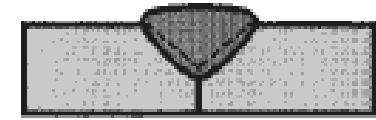
## Fillet welds



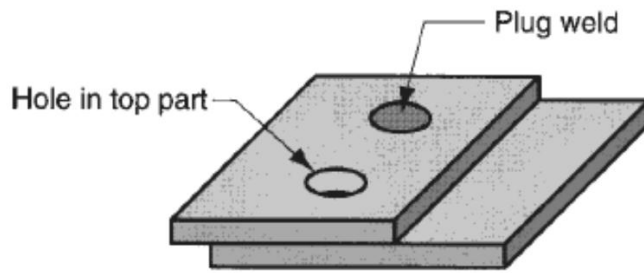
**square groove weld one side**



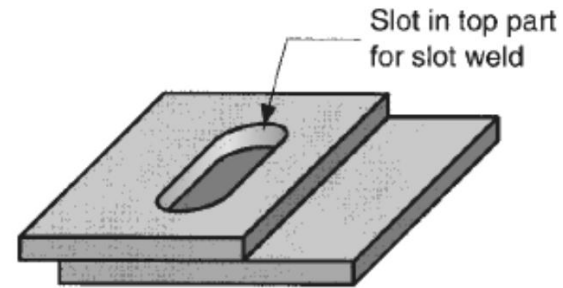
**single bevel groove weld**



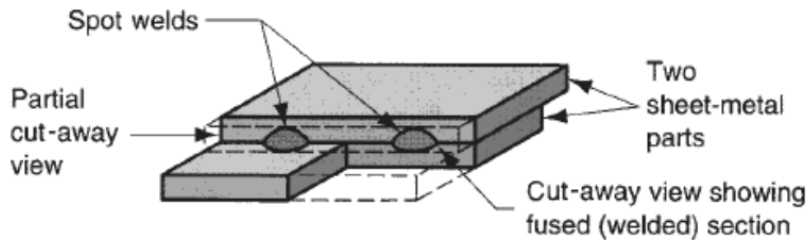
**single V-groove weld**



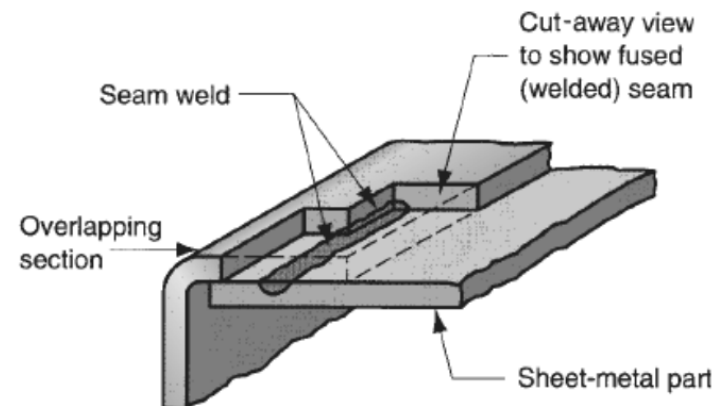
**Plug weld**



**Slot weld**



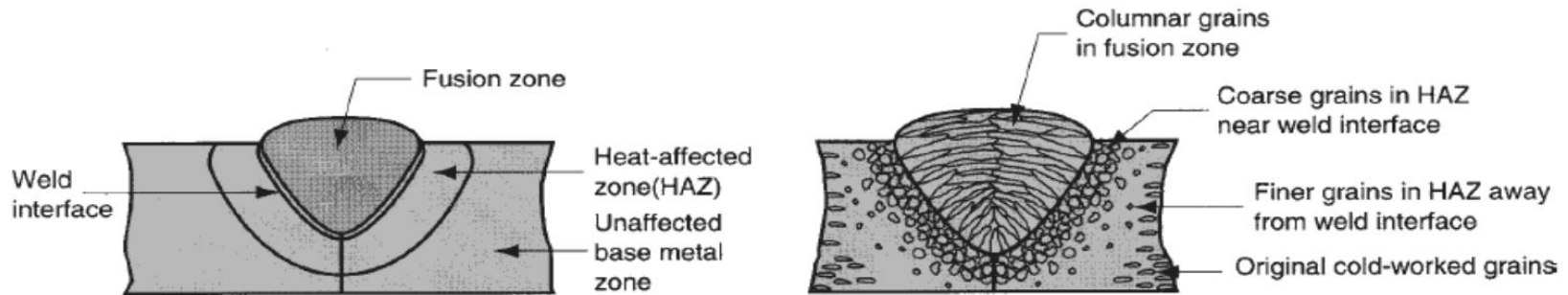
**Spot weld**



**Seam weld**

## Morphology of fusion weld

A typical fusion weld has got few zones like (i) fusion zone, (ii) weld interface, (iii) heat affected zone, (iv) unaffected base material.



**Fusion zone:** It consists of a mixture of filler metal and base metal that have completely melted. A high degree of homogeneity is present among the component metals that have been melted during welding.

In fusion zone, the solidification occurs by **epitaxial grain growth**, in which the atoms in the molten metal solidify at the preexisting lattice sites in the unaffected base material. Moreover the grain structure in the fusion zone has got preferred orientation and they are oriented roughly perpendicular to the weld interface. **This results in coarse columnar grains in fusion zone.**



The grain structure depends on various factors namely welding technique, metals being welded like similar metals and dissimilar metals welded, usage of a filler metal, and the traverse speed at which welding is done.

**Weld interface:** It is a narrow boundary that separates the fusion zone from heat affected zone. This zone consists of a thin band of base metal that was partially melted during the welding process but immediately solidified without mixing with the metal in the fusion zone. Its chemical composition is generally same as that of the base metal.

**Heat affected zone:** This zone is between weld interface and base material. This experience temperatures below melting point, but sufficient enough to change the microstructure and hence the mechanical properties.

The mechanical properties are such that most of the failures occur in this region.

**Base material:** Unaffected because of heat generation and preserve the initial microstructure.

## Heat energy in fusion welding

The amount of heat required to melt a given volume of material depends on,  
(i) heat energy required to change the temperature of solid metal to its melting point that depends on volumetric specific heat,

(ii) melting point of material,

(iii) heat required to change the solid to liquid phase that depends on heat of fusion of the material.

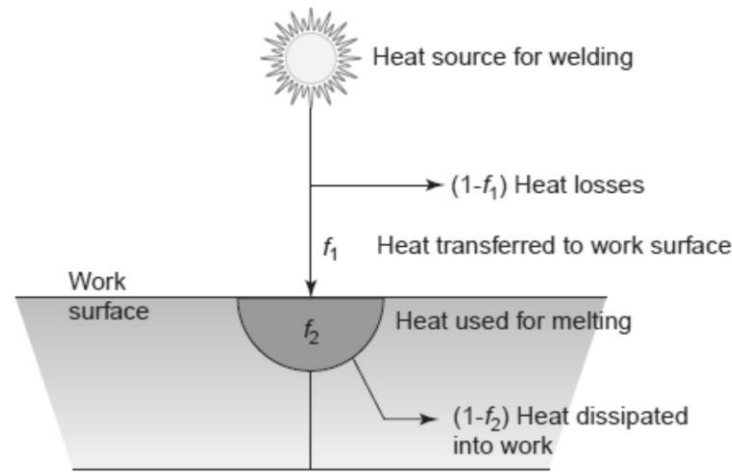
The quantity of heat required to melt a given volume of metal from room temperature ( $U_m$  in J/mm<sup>3</sup>) is given by,

$$U_m = K T_m^2$$

$T_m$  - melting point of the metal in K,  $K$  – constant,  $3.33 \times 10^{-6}$

The heat energy generated by the heat source is not fully used for melting the material.

Two important factors are defined for the losses. They are, heat transfer factor,  $F_1$ , and melting factor,  $F_2$ .



Heat transfer factor,  $F_1$ , is defined as the ratio of heat transferred to work-piece to the heat generated by the heat source.

Melting factor,  $F_2$ , is the proportion of heat that is used for melting. Remaining heat is dissipated through the work in terms of conduction away from the weld.

Now the net heat energy available for welding,  $H_w$  in J, is given by,

$$H_w = F_1 F_2 H; \quad F_1 \text{ and } F_2 \text{ range from 0 to 1}$$

where  $H$  is the total heat generated by the welding process

Heat transfer factor depends on welding process and how efficiently the total heat can be converted into usable heat.

But melting factor depends on welding process, thermal properties of the metal, joint configuration, and work size (like thickness). A high power density combined with a low conductivity work material results in a high melting factor.

Metals with high thermal conductivity like Al, Cu will have quick dissipation of heat from the weld region resulting in lot of welding problems. At the same time, welding techniques like oxyfuel gas welding will provide heat in larger area resulting in low power density.

Now for fusion welding, the heat balance equation can be written as,

$$H_w = U_m V \quad \text{or} \quad R_{Hw} = U_m R_V \text{ (involves rate of process)}$$

Here  $V$  is the volume of metal melted;  $R_{Hw}$  - rate of heat energy delivered to weld region in J/s; and  $R_V$  - volume rate of metal welded,  $\text{mm}^3/\text{s} = A_w v$

So, the above equation is written as,  $R_{Hw} = U_m A_w v$  (for a continuous weld);  $A_w$  - weld cross-sectional area,  $v$  - traverse velocity of the welding

Similarly we can write,  $R_{Hw} = F_1 F_2 R_H$  involving rate of welding.

Now the rate balance equation can be written as,

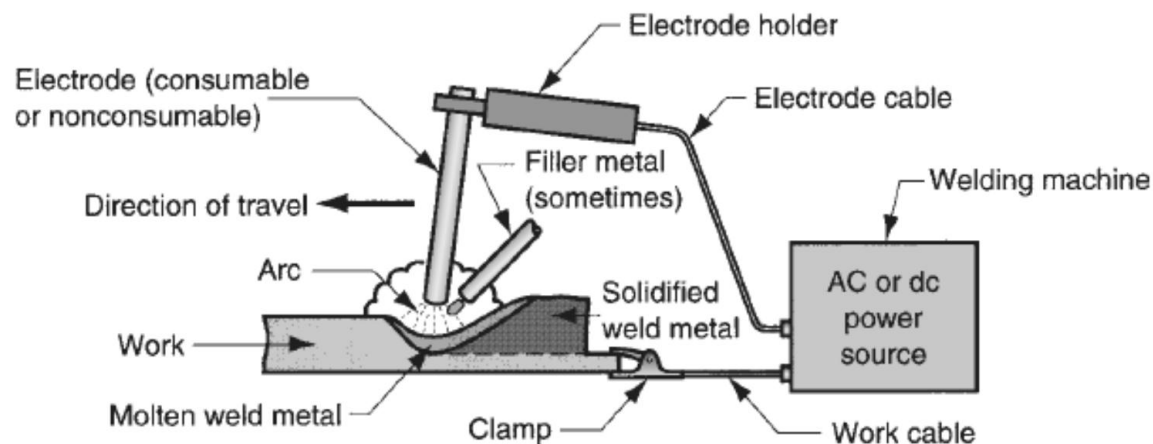
$$R_{Hw} = F_1 F_2 R_H = U_m A_w v$$

# Arc welding

It is a fusion welding process in which the melting and joining of metals is done by the heat energy generated by the arc between the work and electrode.

An electric arc is generated when the electrode contacts the work and then quickly separated to maintain the gap. A temperature of  $5500^{\circ}\text{C}$  is generated by this arc.

This temperature is sufficient to melt most of the metals. The molten metal, consisting of base metal and filler, solidifies in the weld region. In order to have seam weld, the power source moves along the weld line.



# Electrodes

- Two types of electrodes are used: consumable and non-consumable
- Consumable electrodes:

Present in rod or wire form with 200 to 450 mm length and less than 10 mm diameter. This is the source of filler rod in arc welding.

The electrode is consumed by the arc during the welding process and added to the weld joint as filler metal.

The consumable electrodes will be changed periodically as it is consumed for each welding trials. This becomes a disadvantage for welder and reduces the production rate.

- Non-Consumable electrodes:

The electrodes are not consumed during arc welding. Though this is the case, some depletion occurs because of vaporization.

Filler metal must be supplied by means of a separate wire that is fed into the weld pool.

## Arc shielding:

### Shielding gas:

This covers the arc, electrode tip and weld pool from external atmosphere. The metals being joined are chemically reactive to oxygen, nitrogen, and hydrogen in the atmosphere.

So the shielding is done with a blanket of **gas or flux**, or both, which inhibit exposure of the weld metal to air.

**Common shielding gas:** Argon, Helium

### Flux:

Used mainly to protect the weld region from formation of oxides and other unwanted contaminants, or to dissolve them and facilitate removal.

During welding, the flux melts and covers the weld region giving protection and it should be removed by brushing as it is hardened.

**Additional function, other than giving protection:** stabilize the arc, and reduce spattering



## Power source in arc welding:

Both AC and DC can be used; DC is advantageous as better arc control is possible.

## Polarity:

Straight polarity in which workpiece is positive and electrode is negative is suitable for shallow penetration (like in sheets) and joints with wide gaps.

Reverse polarity in which workpiece is negative and electrode is positive is suitable for deeper welds.

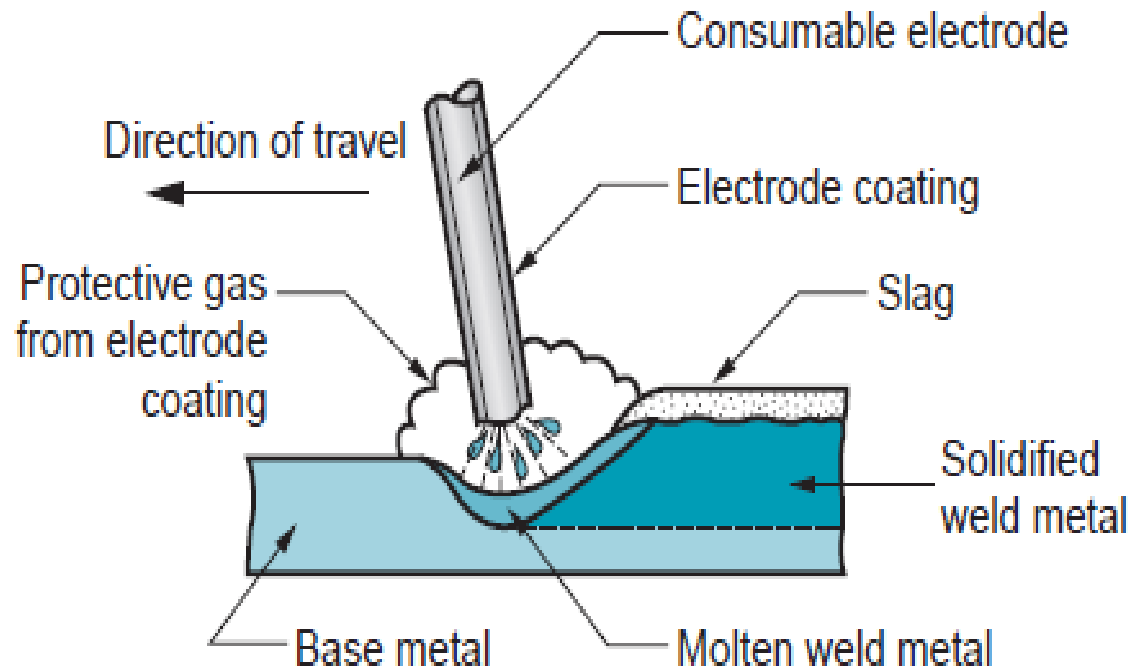
The power balance in arc welding is given by,  $R_{Hw} = F_1 F_2 I E = U_m A_w v$ .

Here E - voltage, I - current .

## Arc welding processes with consumable electrodes

### Shielded metal arc welding (SMAW):

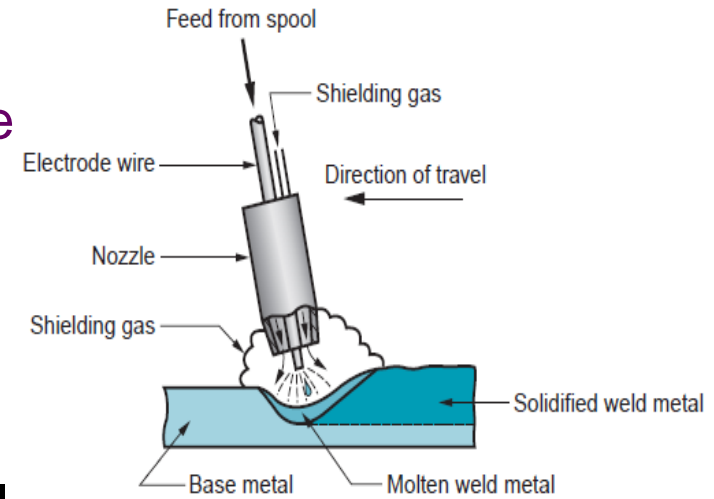
- In this process, a consumable electrode consisting of a filler metal rod which is coated with chemicals that provide flux and shielding, is used.
- Generally the filler metal has chemical composition very close to base metal.
- **Filler rod coating:** Coating consists of powdered cellulose (cotton and wood powders) mixed with oxides, carbonates, combined using a silicate binder.
- This coating provides protective layer to the weld pool and stabilizes the arc.
- current:  $< 300$  A; Voltage: 15 – 45 V.
- **Applications:** ship building, construction, machine structures etc.
- **Materials:** grades of steel, stainless steel etc. are welded. Al, Cu, Ti alloys are not welded using SMAW.
- **Disadvantages:** repeated change of electrodes, current maintained in typical range



SMAW

## Gas metal arc welding (GMAW):

- In this process, electrode is a consumable wire (0.8 to 6.5 mm diameter).
- shielding gas is provided separately over arc by a pipe
- Shielding gas: Helium, Argon, mixture of gases; used mainly for Al alloys.
- active gases like  $\text{CO}_2$  is used for welding steel grade material.
- As compared to SMAW, GMAW can be used for multiple weld passes as there is no deposition of slag and hence no brushing involved. (advantage)
- advantage: automation of welding possible as continuous weld wires are used, and not sticks as in SMAW.
- Also called MIG (metal inert gas) welding,  $\text{CO}_2$  welding (when  $\text{CO}_2$  is used).



GMAW

## Flux cored arc welding (FCAW):

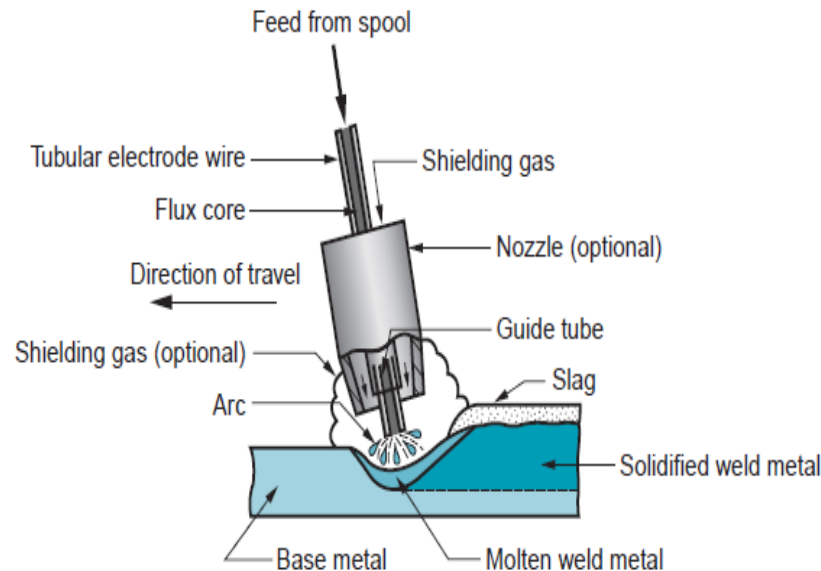
- arc welding process in which the electrode is a continuous consumable tubing that contains flux.

- Self-shielded FCAW:

the arc shielding was provided by the flux core. The core also includes ingredients that generate shielding gases for protecting the arc.

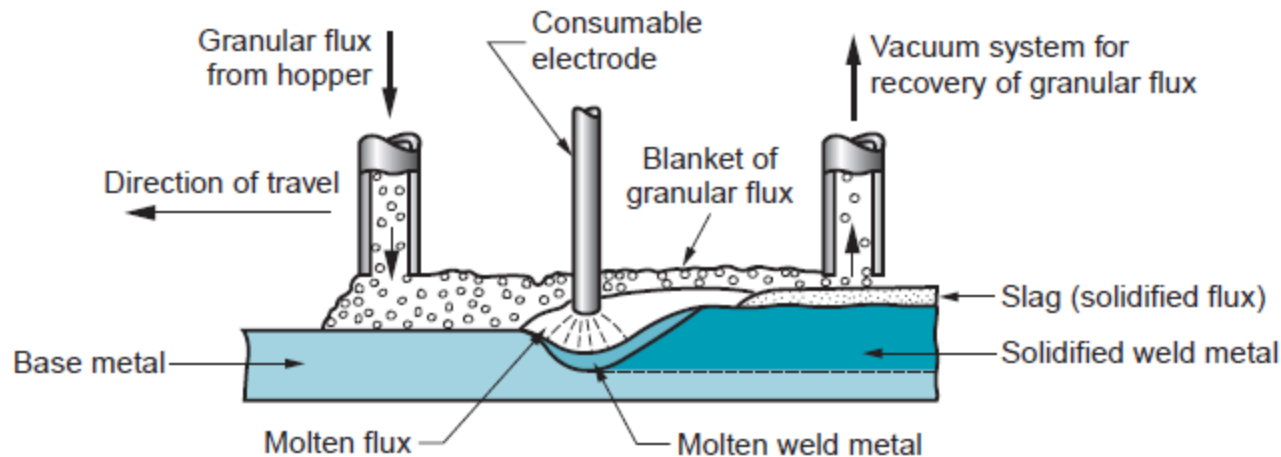
- Gas shielded FCAW:

Shielding is done from externally supplied gases. Since it uses both flux and shielding gas (provided separately), it is considered as a hybrid of SMAW and GMAW.



FCAW

## Submerged arc welding (SAW):



SAW

- In this process, a continuous bare electrode wire is used. The shielding is provided by external granular flux through hopper.
- Granular flux is provided just before the weld arc.
- granular flux completely provides protection from sparks, spatter, and radiation and hence safety glasses, gloves can be avoided.
- some part of flux gets melted and forms a glassy layer.
- This layer and unfused flux results in slow cooling rate and good weld quality.
- The unused flux can be reused.
- application: longitudinal and circumferential welds for large diameter pipes, tanks, and pressure vessels; welded components for heavy machinery. Steel plates of 25 mm thick are welded.

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed

A heat source transfers 3000W to the surface of a metal part. The heat impinges the surface in a circular area, with intensities varying inside the circle. The distribution is as follows: 70% of the power is transferred within a circle of diameter 5 mm, and 90% is transferred within a concentric circle of diameter 12 mm. What are the power densities in (a) the 5-mm diameter inner circle and (b) the 12-mm-diameter ring that lies around the inner circle?

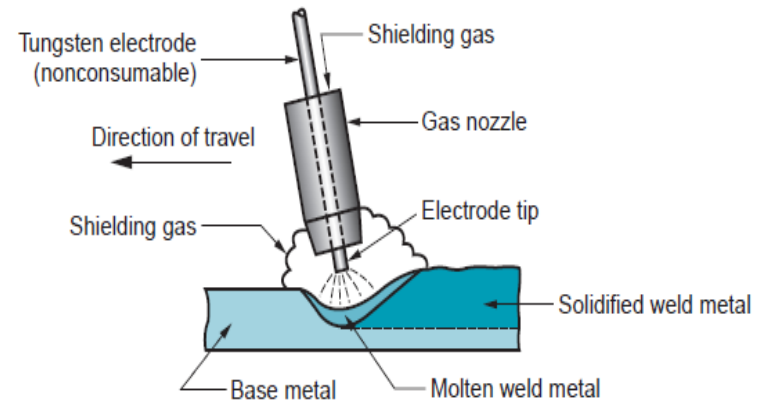
The power source in a particular welding setup generates 3500 W that can be transferred to the work surface with a heat transfer factor 0.7. The metal to be welded is low carbon steel, whose melting temperature is 1760K. The melting factor in the operation is 0.5. A continuous fillet weld is to be made with a cross-sectional area 20 mm<sup>2</sup>. Determine the travel speed at which the welding operation can be accomplished



## Arc welding processes with non-consumable electrodes

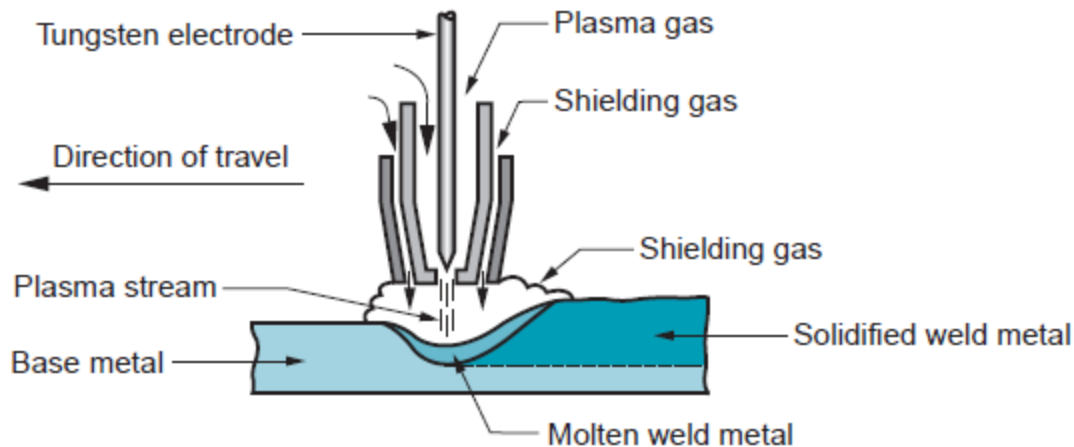
### Gas Tungsten Arc Welding (GTAW):

- It uses a non-consumable tungsten electrode and shielding gas (inert gas) for shielding.
- Also called tungsten inert gas welding (TIG)
- usage of filler wire is optional and is heated by arc and not transferred across the arc.
- Tungsten is a good electrode material due to its high melting point of  $3400^{\circ}\text{C}$ .
- advantages: high quality welds, no weld spatter because no filler metal is transferred across the arc, and little postweld cleaning because no flux is used.



## Plasma arc welding

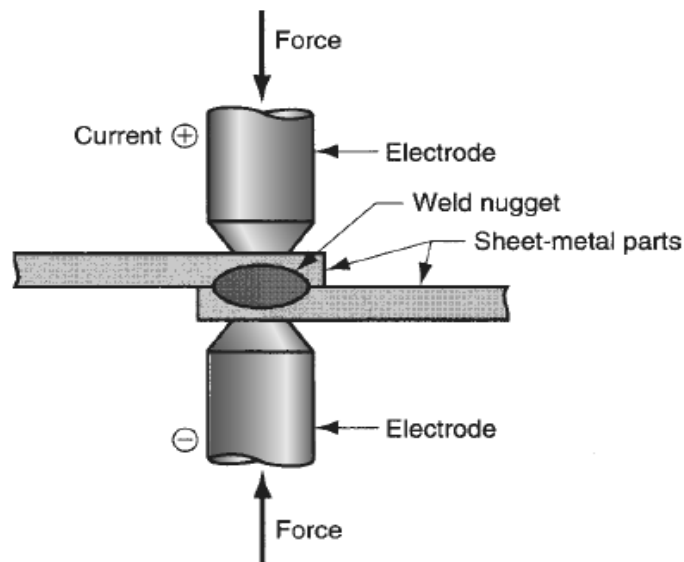
- It is a variety of gas tungsten arc welding in which a constricted plasma arc is used for welding.
- In PAW, a tungsten electrode is kept in a nozzle that focuses a high velocity stream of inert gas into the region of the arc to form a high velocity, intensely hot plasma arc stream.
- Temperatures in plasma arc welding reach  $17,000^{\circ}\text{C}$ . This is mainly due to the constriction of the arc. The input power is highly concentrated to produce a plasma jet of small diameter and very high power density.
- The process can be used to weld almost any material, including tungsten.



PAW

## Resistance welding

- Resistance welding (RW) is a fusion welding processes that uses a combined effect of heat and pressure to accomplish joining. This heat is generated by electrical resistance to current flow at the location to be welded.
- Weld nugget is generated by this process.
- RW uses no shielding gases, flux, or filler metal.
- electrodes that conduct electrical power to the process are non-consumable.



Resistance welding

- The heat energy supplied by RW depends on current flow, resistance of the circuit, and length of time the current is applied. This is expressed as,

$$H = I^2 RT$$

Current : 5000 to 20,000 A

Voltage : < 10V

Duration of current : 0.1 to 0.4 s (in spot-welding operation)

- Resistance in the welding circuit is the sum of (1) resistance of the electrodes, (2) resistances of the sheet parts, (3) contact resistances between electrodes and sheets, and (4) contact resistance of the faying surfaces.
- Resistance at the faying surfaces depends on surface finish, cleanliness, contact area, force. No paint, oil, dirt, and other contaminants should be present to separate the contacting surfaces.
- **Advantages:** no filler rod required, high production rates, automation and mechanization are possible.
- **disadvantages:** restricted to lap joint, costly equipment

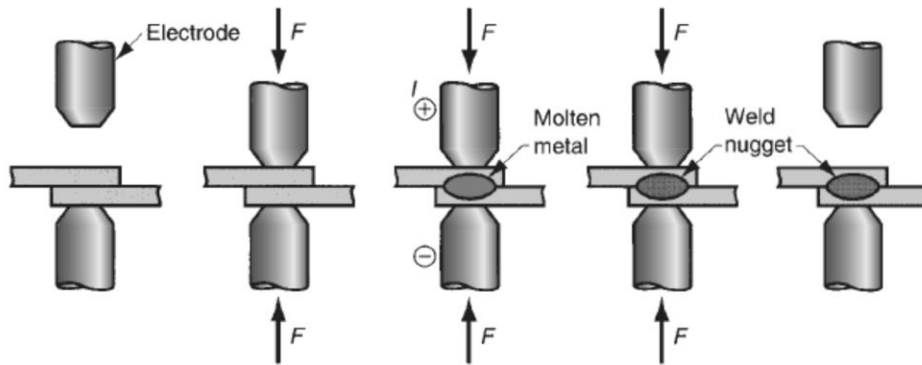
# Resistance spot welding

**Importance:** a typical car body has got app. 15, 000 spot welds.

In this process, the fusion of electrodes is done by electrodes having opposing charges at one location. The sheet thickness has to be less than 3 mm for a good spot weld.

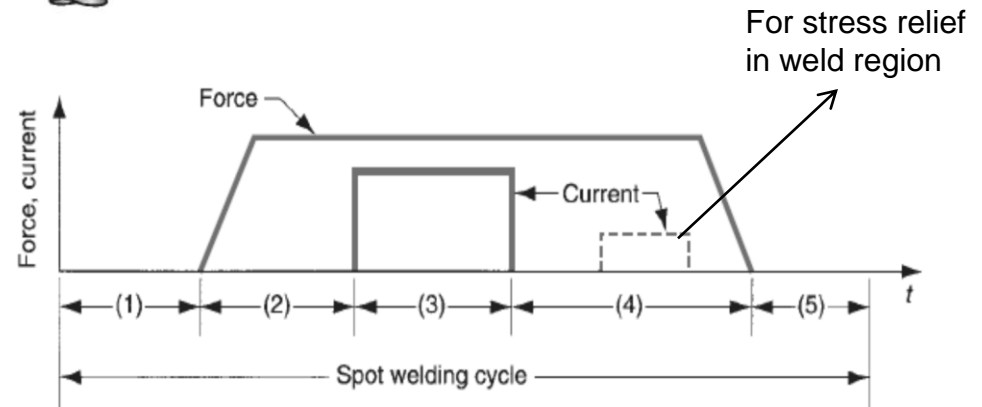
The shape of electrode tip is important like round, hexagonal, square etc. The nugget shape will be app. 5-10 mm in this case.

**Electrodes in RSW:** (i) Copper based, (ii) Refractory metal (Cu, Tungsten combinations)

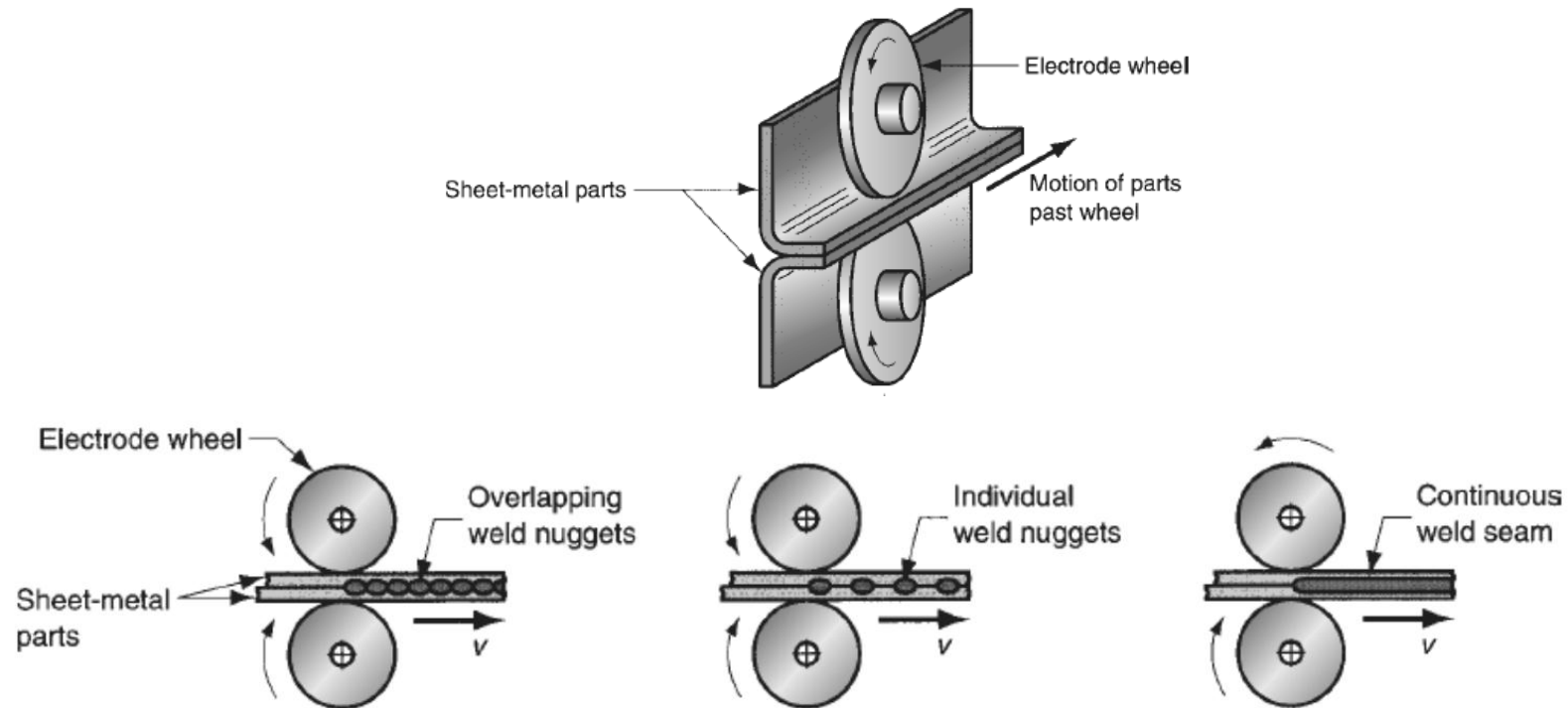


Steps in spot welding

Spot welding cycle



# Resistance seam welding



conventional resistance seam  
welding (overlapping spots)

roll spot welding

continuous resistance seam

In this welding, a roll is used for welding, rather than stick seen earlier. Since the operation is usually carried out continuously, rather than discretely, the seams should be along a straight or curved line. Sharp corners are difficult to weld.

## Gas welding / Oxyfuel gas welding

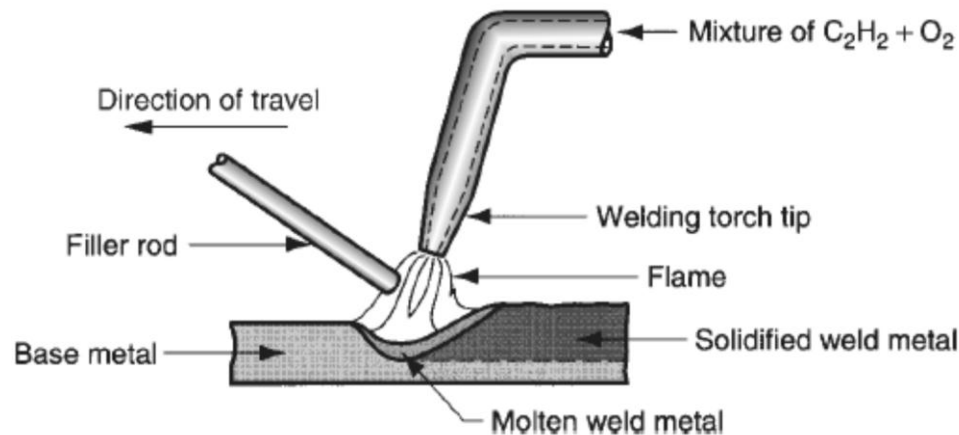
-In this process, various fuels are mixed with oxygen and burnt to perform welding. Eg: Oxyacetylene welding

### - Oxyacetylene welding (OAW):

In this case, welding is performed by a flame formed by the combustion of oxygen and acetylene. The flame comes from a torch.

A filler rod coated with flux is used sometimes which prevents oxidation, creating a better joint.

Acetylene is a famous fuel because it is capable of generating a temperature of  $3500^{\circ}\text{C}$ .



The chemical reaction between oxygen and acetylene happens at two stages as given below.



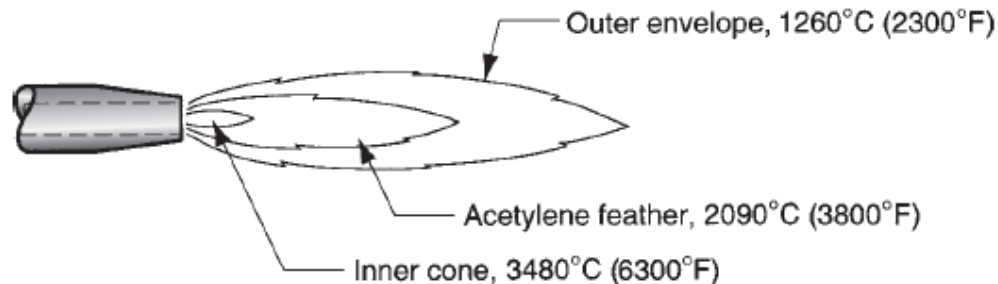
The products of first reaction are combustible and second reaction occurs as,



When both oxygen and acetylene are mixed in ratio of 1:1, then **neutral flame** is seen as shown in figure. The outer envelope delivers a temperature of 1260°C and inner core has app. 3500°C.

The first stage reaction is seen in the inner cone of the flame (bright white colour), while the second stage reaction is seen in the outer envelope (colorless but with tinges ranging from blue to orange). The temperature is very high at the inner core which is app. 3500°C.

Total heat liberated during the two stages of combustion is  $55 \times 10^6 \text{ J/m}^3$  of acetylene. But the heat transfer factor in OAW is 0.1 to 0.3 as the flame spreads over large region.



neutral flame in  
oxyacetylene welding



## Problems and advantages of OAW:

- The combination of acetylene and oxygen is highly flammable and hence hazardous to environment.
- It is unstable at pressures much above 1 atm
- It is mandatory for the welder to wear gloves, goggles etc. as preventive measures.
- The equipment is relatively cheap and portable. So it is used as an economical, versatile process that is well suited for low quantity production and repair jobs.
- It is rarely used to weld plates thicker than 6.5 mm.

## Other gases used in OFW

Fuel	Temperature <sup>a</sup>		Heat of Combustion	
	°C	°F	MJ/m <sup>3</sup>	Btu/ft <sup>3</sup>
Acetylene (C <sub>2</sub> H <sub>2</sub> )	3087	5589	54.8	1470
MAPP <sup>b</sup> (C <sub>3</sub> H <sub>4</sub> )	2927	5301	91.7	2460
Hydrogen (H <sub>2</sub> )	2660	4820	12.1	325
Propylene <sup>c</sup> (C <sub>3</sub> H <sub>6</sub> )	2900	5250	89.4	2400
Propane (C <sub>3</sub> H <sub>8</sub> )	2526	4579	93.1	2498
Natural gas <sup>d</sup>	2538	4600	37.3	1000

b: MAPP-methylacetylene-propadiene; c: used in flame cutting;

d: natural gas- data for methane gas

An oxyacetylene torch supplies 0.3 m<sup>3</sup> of acetylene per hour and an equal volume rate of oxygen for an OAW operation on 4.5-mm-thick steel. Heat generated by combustion is transferred to the work surface with a heat transfer factor  $f_1 = 0.20$ . If 75% of the heat from the flame is concentrated in a circular area on the work surface that is 9 mm in diameter, find (a) rate of heat liberated during combustion, (b) rate of heat transferred to the work surface, and (c) average power density in the circular area.

## Other fusion welding processes

### Electron beam welding:

In this process, welding is carried out by highly focused, high intensity electron beam bombarding against the workpiece.

Generally carried out in vacuum, otherwise there will be disruption of electron beam by air molecules.

Metals that are arc welded can be EB welded. Some of the refractory objects and difficult to arc weld materials can also be EB welded.

EB welding is noted for high quality welds with deep, narrow profiles, limited heat-affected zone, and low thermal distortion.

No filler metal is used. No flux, shielding gases are needed.

**PD during EBW:** Power density =  $f_1 \frac{EI}{A}$  (here  $f_1 = 0.8$  to  $0.95$ )

E = accelerating voltage; I = beam current; and A = work surface area on which the electron beam is focused

**Disadvantages:** high equipment cost, precise joint preparation needed, vacuum requirement, shielding of humans from X-rays.

When first developed, welding had to be carried out in a vacuum chamber to minimize the disruption of the electron beam by air molecules. This requirement is a serious inconvenience in production, due to the time required to evacuate the chamber prior to welding.

**The pump-down time** can take as long as an hour, depending on the size of the chamber and the level of vacuum required. EBW technology IS POSSIBLE without vacuum also.

Three categories:

- (1) high-vacuum welding (EBW-HV)**, in which welding is carried out in the same vacuum as beam generation;
- (2) medium-vacuum welding (EBW-MV)**, in which the operation is performed in a separate chamber where only a partial vacuum is achieved;
- (3) Non-vacuum welding (EBW-NV)**, in which welding is accomplished at or near atmospheric pressure.

The pump-down time during workpart loading and unloading is reduced in medium-vacuum EBW and minimized in non-vacuum EBW.

In the last two cases, the equipment must include one or more vacuum dividers - very small orifices that impede air flow but permit passage of the electron beam, to separate the beam generator (which requires a high vacuum) from the work chamber.

Also, in non-vacuum EBW, the work must be located close to the orifice of the electron beam gun, approximately 13 mm or less. Finally, the lower vacuum processes cannot achieve the high weld qualities and depth-to-width ratios accomplished by EBW-HV.

## Laser beam welding (LBW)

LBW is a fusion welding process in which joining/coalescence is attained by the heat energy of a highly concentrated, coherent light beam focused on the joint to be welded.

LB welds are of high quality, deep penetrated, and exhibit narrow HAZ.

### Advantages of LBW over EBW:

no requirement of vacuum chamber, no X-rays are emitted, laser beams can be focused and directed by optical lenses and mirrors.

### Disadvantages:

**LBW:** < 19 mm thick samples; **EBW:** 50 mm thick samples are welded

Depth to width ratio: 5:1

Only small parts are joined by LBW, because of the highly concentrated energy in the small area of the laser beam.

## Thermit welding

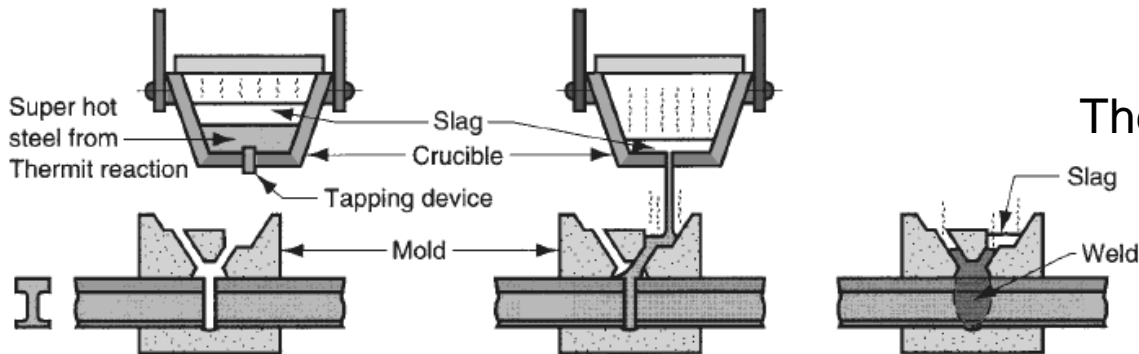
**Thermite (thermit):** a mixture of aluminum powder and iron oxide that produces an exothermic reaction when ignited.

In thermit welding, the heat for coalescence/joining is produced by superheated molten metal formed from the chemical reaction of thermit.

The following chemical reaction is seen when a thermit mixture is ignited at 1300°C. The temperature of the reaction is 2500°C.



At this temperature, superheated molten iron plus aluminum oxide is made that floats on the top as a slag and protects the iron from the atmosphere.



Thermit welding

**Applications of TW:** **Joining of railway lines**, repair of cracks in large steel castings and forgings like ingot molds, large diameter shafts, frames for machinery etc.

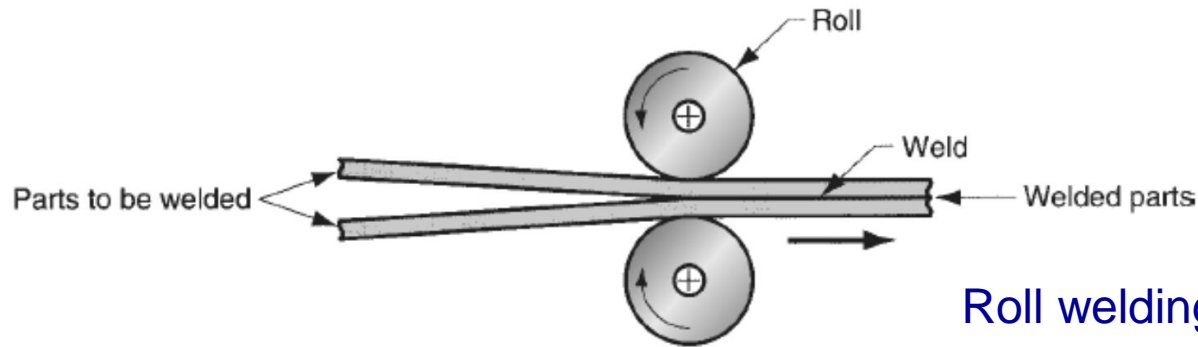
## Solid state welding processes

In solid state welding, joining of materials are performed with the help of heat and pressure or pressure alone.

A metallurgical bond is created with little or no melting of the base metals. To metallurgically bond two similar or dissimilar metals, the two metals must be brought into intimate contact so that their atomic forces attract each other.

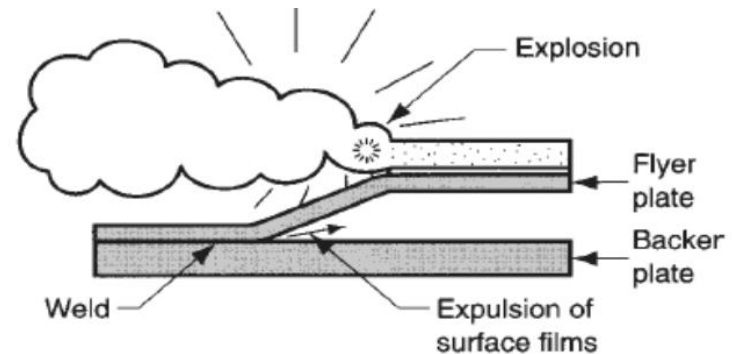
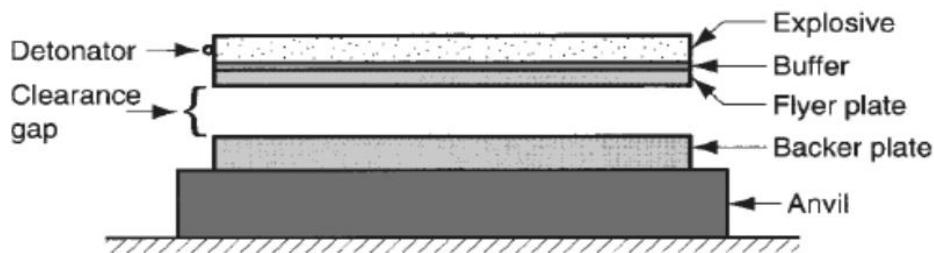
The two surfaces must be cleaned and free of oils, dirt, chemical films, gases etc. to permit atomic bonding.

Some of the solid state welding processes are applicable to join dissimilar metals, without concerns about relative thermal expansions, conductivities, and other problems that usually arise when dissimilar metals are melted and then solidified during fusion welding.



Roll welding or bonding

**Roll welding or bonding:** Two or more sheets are kept one above the other and rolled to generate bonding between them. If done without application of external heat, then it is called cold roll bonding. With the application of external heat, it is called hot roll bonding.

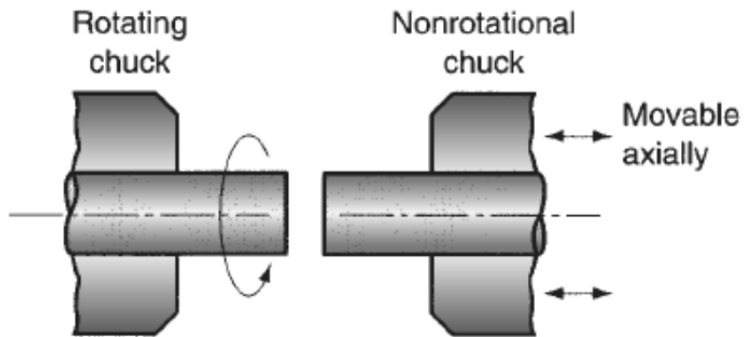


explosive welding

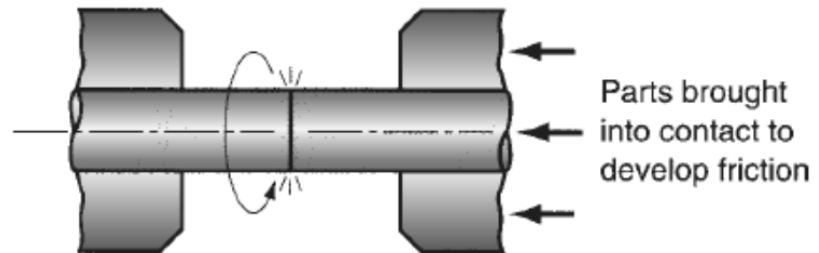
In **explosive welding**, because of progressive explosion, high pressure zone propels the flyer plate to collide with the backer metal progressively at high velocity, so that an angular shape is generated as the explosion advances.



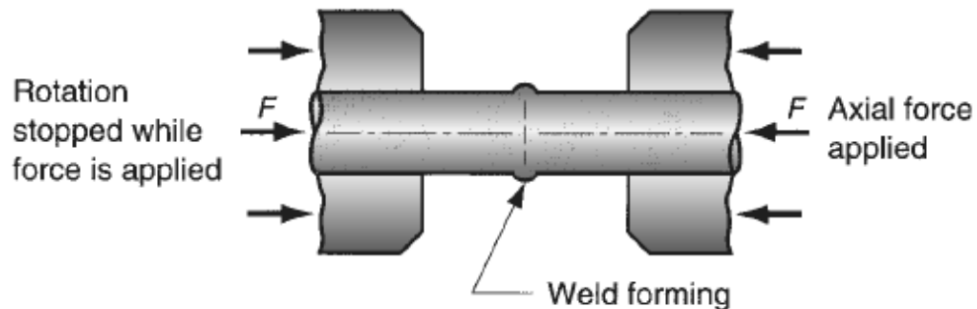
# Friction welding



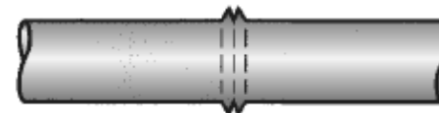
**Two parts are not in contact**



**Parts brought in contact to generate friction and heat**



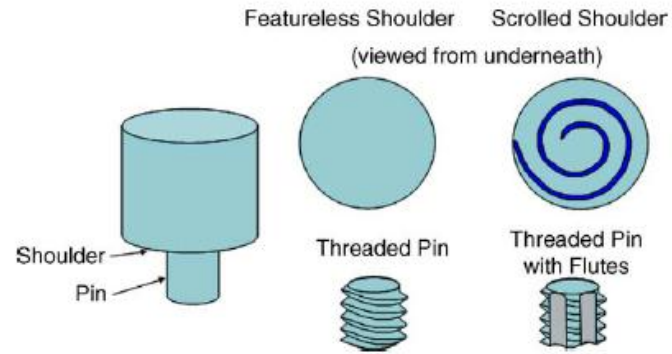
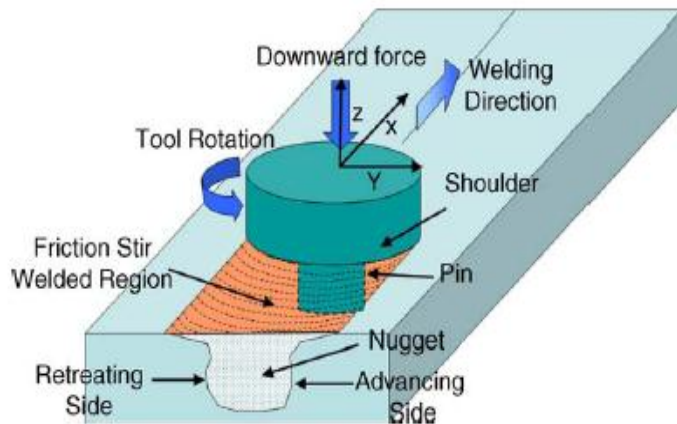
**Rotation is stopped and axial force is applied**



**Creation of weld**

# Friction stir welding (FSW)

Materials Science and Engineering R 50 (2005) 1–78



FSW tools

A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint.

The tool serves two primary functions: (a) heating of workpiece, and (b) movement of material to produce the joint.

The heating is accomplished by friction between the tool and the workpiece and plastic deformation of workpiece. The localized heating softens the material around the pin.

The combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin.

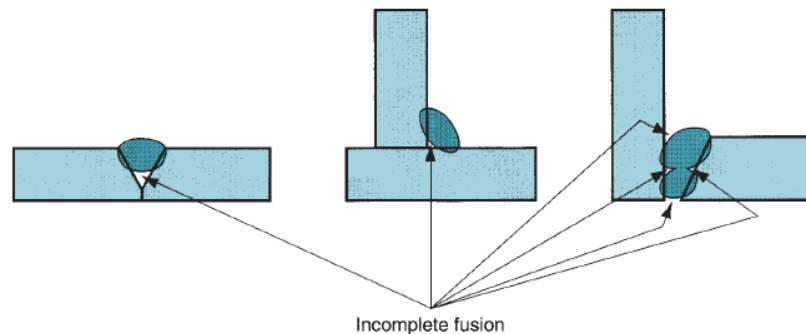
## Welding defects

**Porosity:** Presence of small voids in the weld metal formed by gases entrapped during solidification. It usually results from inclusion of atmospheric gases, sulfur in the weld metal, or contaminants on the surfaces.

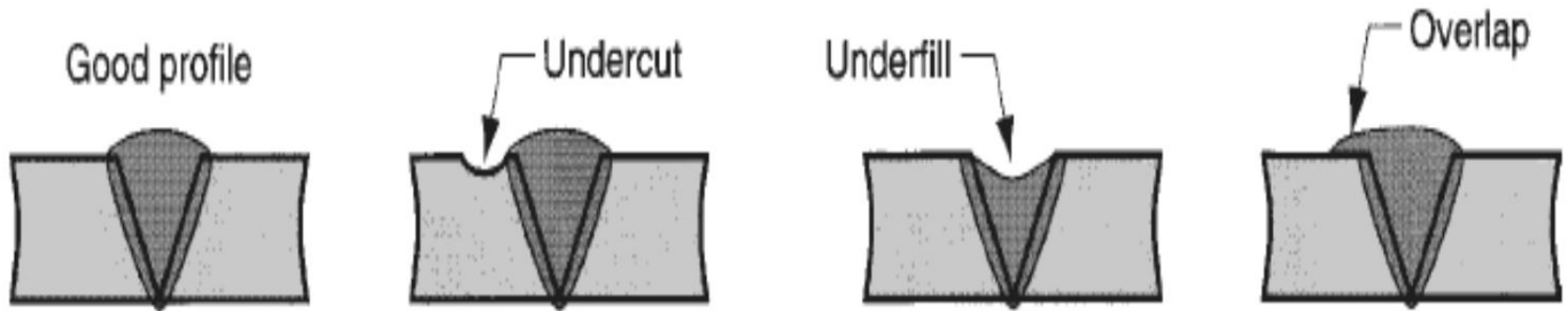
**Shrinkage voids:** Cavities formed by shrinkage during solidification. Both of the cavity type defects are similar to defects found in castings.

**Solid inclusions:** These are nonmetallic solid particles (like flux in arc welding, metallic oxides in welding Al) trapped inside the weld metal.

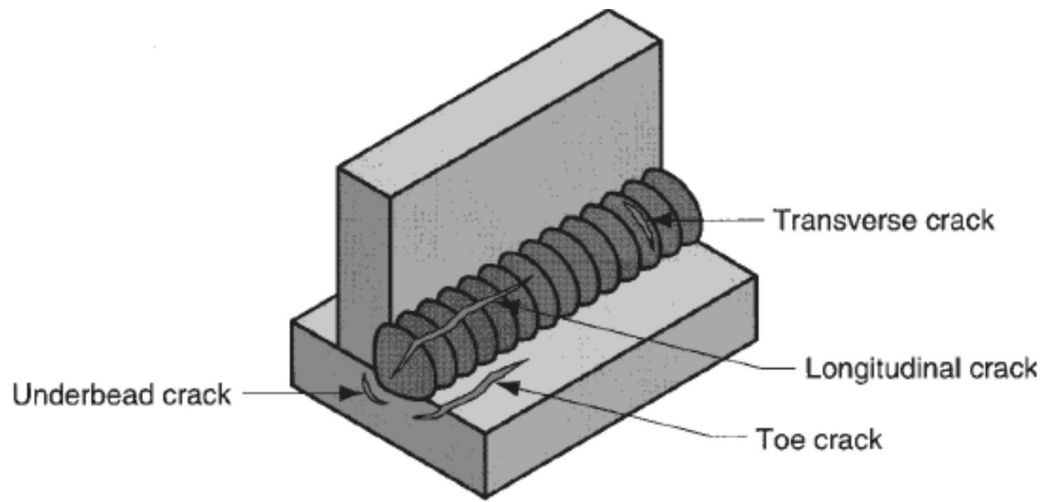
**Incomplete fusion:** It is a weld bead in which fusion has not occurred throughout the entire cross section of the joint.



## Improper weld profile:



## Weld cracks:



# Brazing

- It is a joining process in which a filler metal is melted and distributed by capillary action between the faying (contact) surfaces of the metal parts being joined.
- Base material does not melt in brazing, only the filler melts.
- In brazing, the filler metal has a melting temperature (liquidus) above  $450^{\circ}\text{C}$ , but below the melting point (solidus) of base metals to be joined.

# Advantages of brazing

- Brazing can be used to join a large variety of **dissimilar metals**.
- Pieces of **different thickness** can be easily joined by brazing
- **Thin-walled tubes & light gauge sheet** metal assemblies not joinable by welding can be joined by brazing.
- **Complex & multi-component assemblies** can be economically fabricated with the help of brazing.
- **Inaccessible joint areas** which could not be welded by gas metal or gas tungsten arc spot or seam welding can be formed by brazing.

## Filler materials used for brazing

Filler Metal	Typical Composition	Approximate Brazing Temperature		Base Metals
		°C	°F	
Aluminum and silicon	90 Al, 10 Si	600	1100	Aluminum
Copper	99.9 Cu	1120	2050	Nickel copper
Copper and phosphorous	95 Cu, 5 P	850	1550	Copper
Copper and zinc	60 Cu, 40 Zn	925	1700	Steels, cast irons, nickel
Gold and silver	80 Au, 20 Ag	950	1750	Stainless steel, nickel alloys
Nickel alloys	Ni, Cr, others	1120	2050	Stainless steel, nickel alloys
Silver alloys	Ag, Cu, Zn, Cd	730	1350	Titanium, Monel, Inconel, tool steel, nickel

# Brazing fluxes

Characteristics of a good flux include,

- (1) low melting temperature,
- (2) low viscosity so that it can be displaced by the filler metal,
- (3) facilitates wetting, and
- (4) protects the joint until solidification of the filler metal.

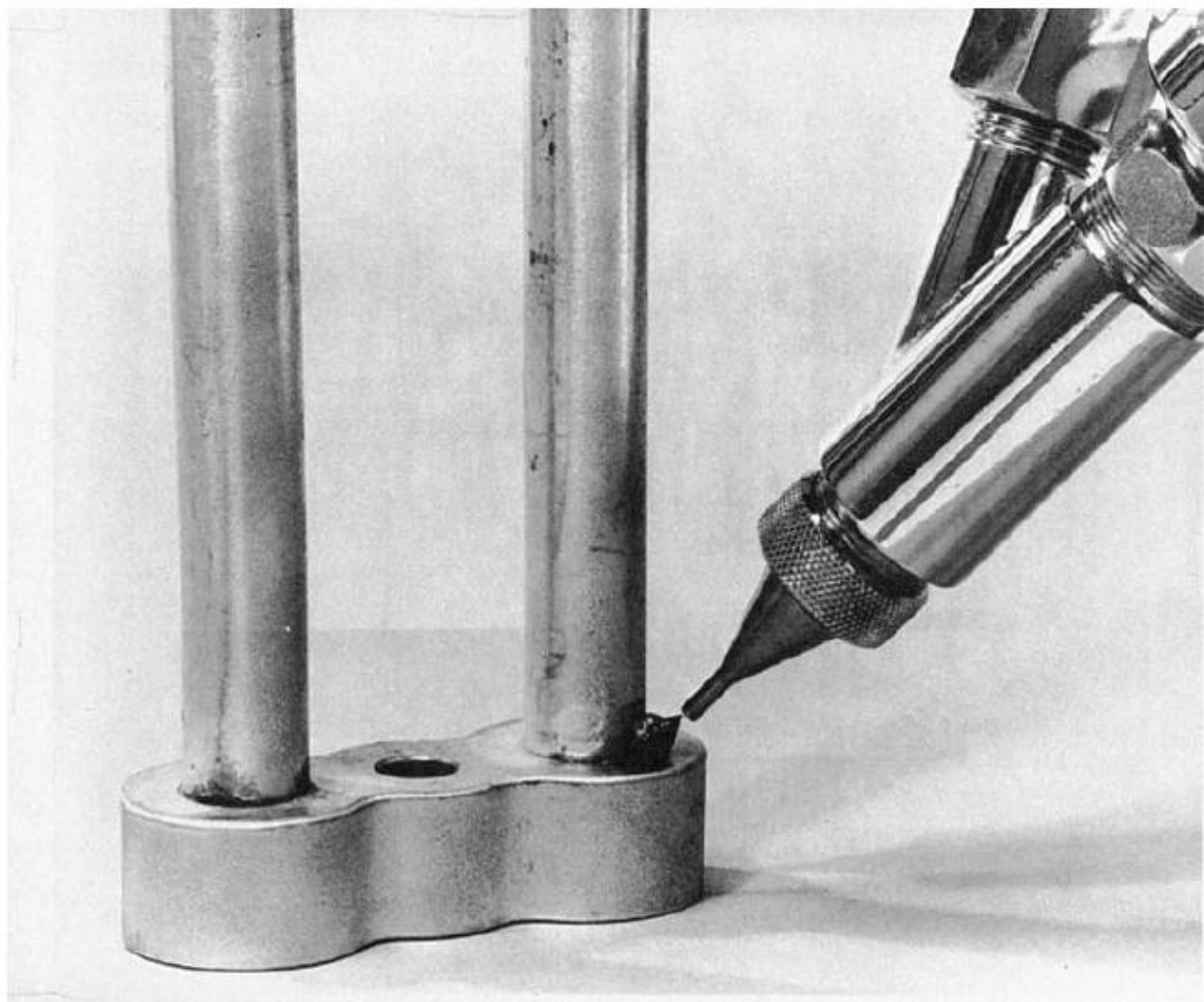


On the basis of method of heating, various brazing process are:

### **Torch brazing**

- Flux is applied to the part surfaces and a torch is used to direct a flame against the work in the vicinity of the joint.
- After the workpart joint areas have been heated to a suitable temperature, filler wire is added to the joint, usually in wire or rod form.
- Fuels used in torch brazing include acetylene, propane, and other gases, with air or oxygen.
- Torch brazing is often performed manually, and skilled workers must be employed.

**Other types:** Furnace brazing, Induction brazing, Resistance brazing, Dip brazing, Infrared brazing



# SOLDERING

Soldering is similar to brazing and can be defined as a joining process in which a filler metal with melting point (liquidus) not exceeding 450°C is melted and distributed by capillary action between the faying surfaces of the metal parts being joined.

As in brazing, no melting of the base metals occurs, but the filler metal wets and combines with the base metal to form a metallurgical bond.

Filler metal, called Solder, is added to the joint, which distributes itself between the closely fitting parts.

**SOLDER:** Alloys of Tin and Lead. Tin is chemically active at soldering temperatures and promotes the wetting action required for successful joining.

Filler Metal	Approximate Composition	Approximate Melting Temperature		Principal Applications
		°C	°F	
Lead-silver	96 Pb, 4 Ag	305	580	Elevated temperature joints
Tin-antimony	95 Sn, 5 Sb	238	460	Plumbing and heating
Tin-lead	63 Sn, 37 Pb	183*	361*	Electrical/electronics
	60 Sn, 40 Pb	188	370	Electrical/electronics
	50 Sn, 50 Pb	199	390	General purpose
	40 Sn, 60 Pb	207	405	Automobile radiators
Tin-silver	96 Sn, 4 Ag	221	430	Food containers
Tin-zinc	91 Sn, 9 Zn	199	390	Aluminum joining
Tin-silver-copper	95.5 Sn, 3.9 Ag, 0.6 Cu	217	423	Electronics: surface mount technology