# 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

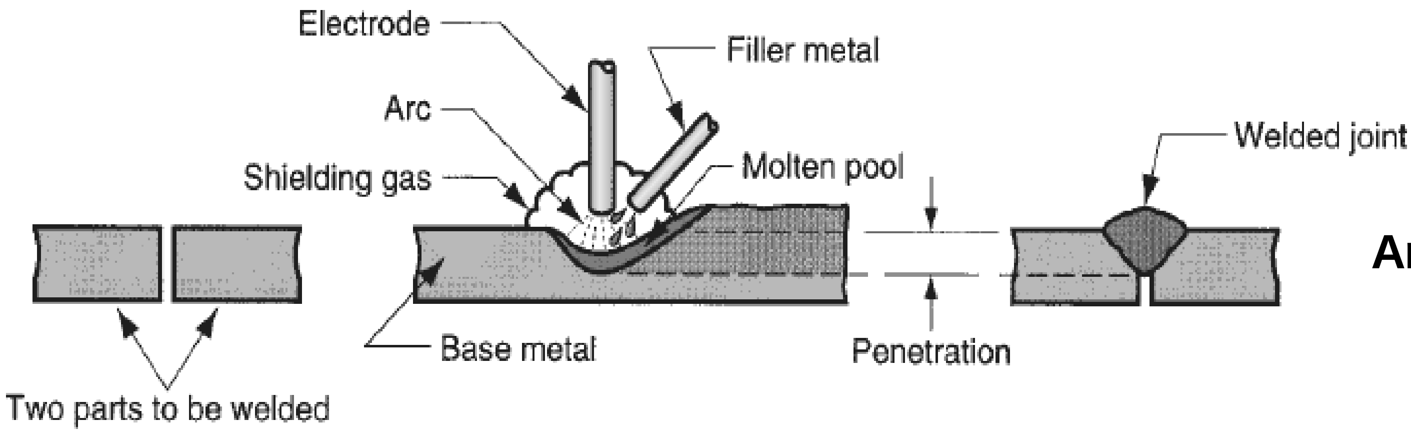
## Fusion welding:

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.

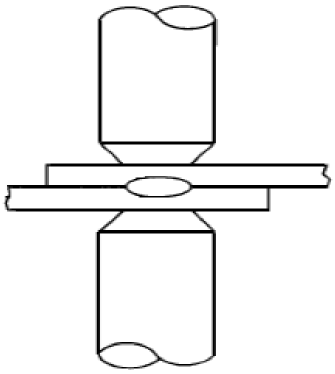
Types: Arc welding, Resistance welding, Oxyfuel gas welding, electron beam welding, laser welding

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

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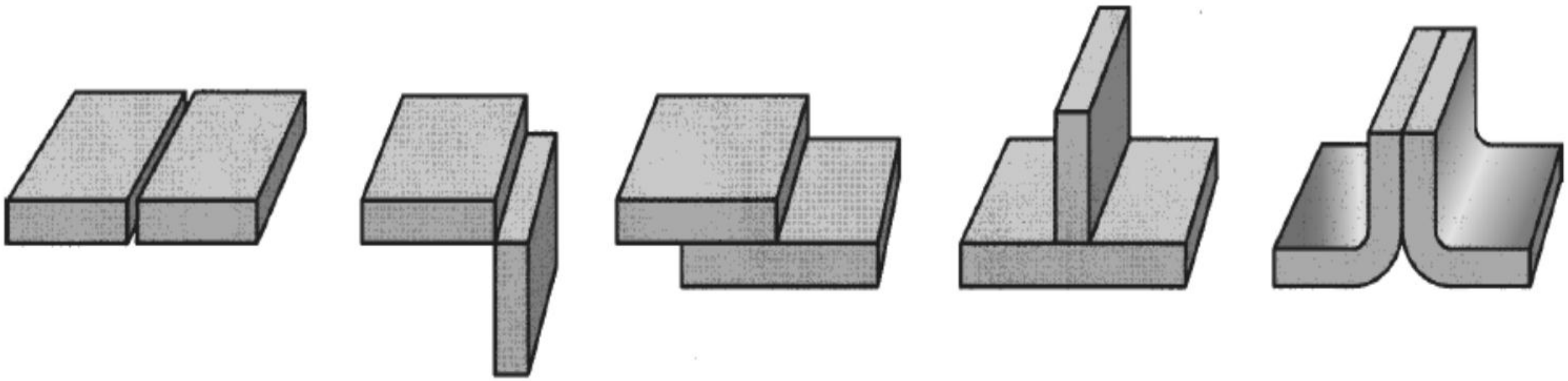
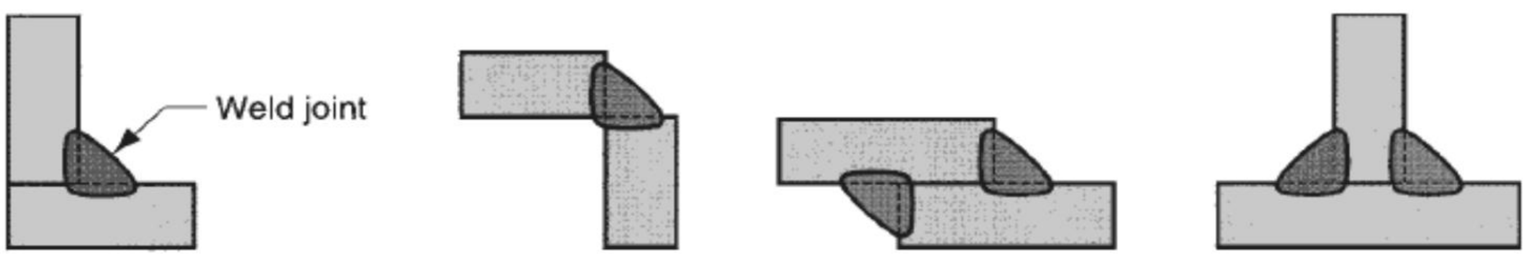
## Weld joint configurations



Butt joint Corner joint Lap joint Tee joint Edge joint

## Weld types



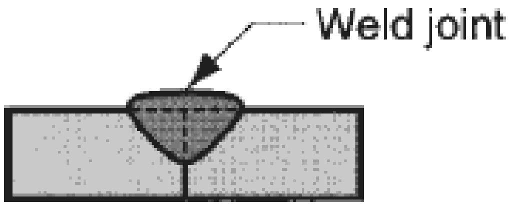

Inside single fillet corner joint

Outside single fillet corner joint

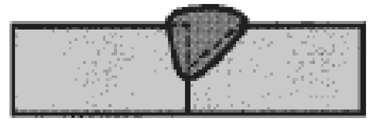
Double fillet lap joint

Double fillet Tee joint

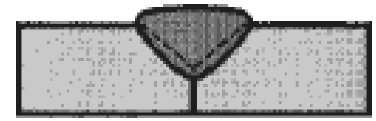
**Fillet welds**



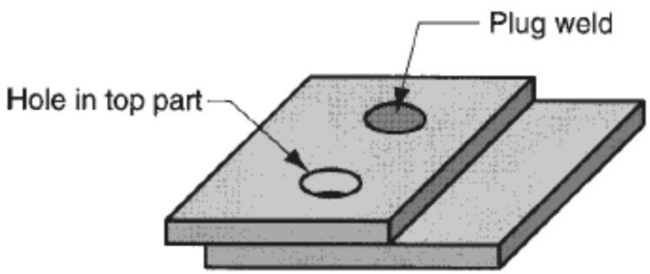

**square groove weld one side**



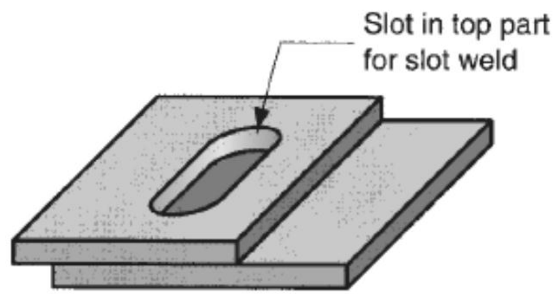
**single bevel groove weld**



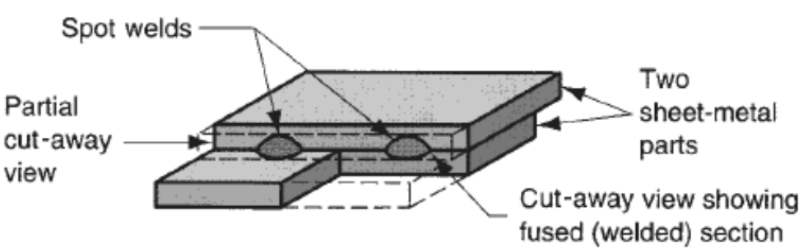
**single V-groove weld**



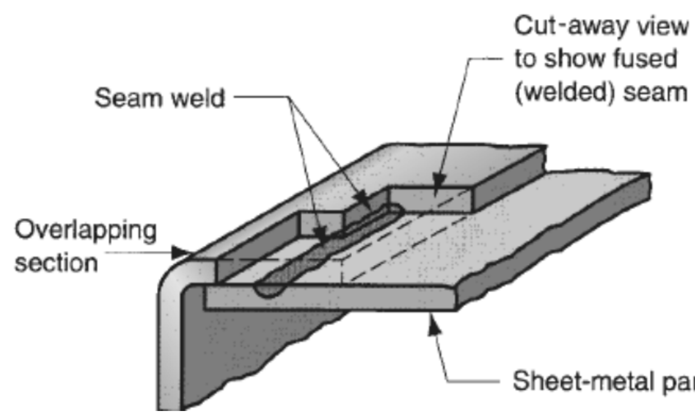

**Plug weld**




**Slot weld**




**Spot weld**




**Seam weld**

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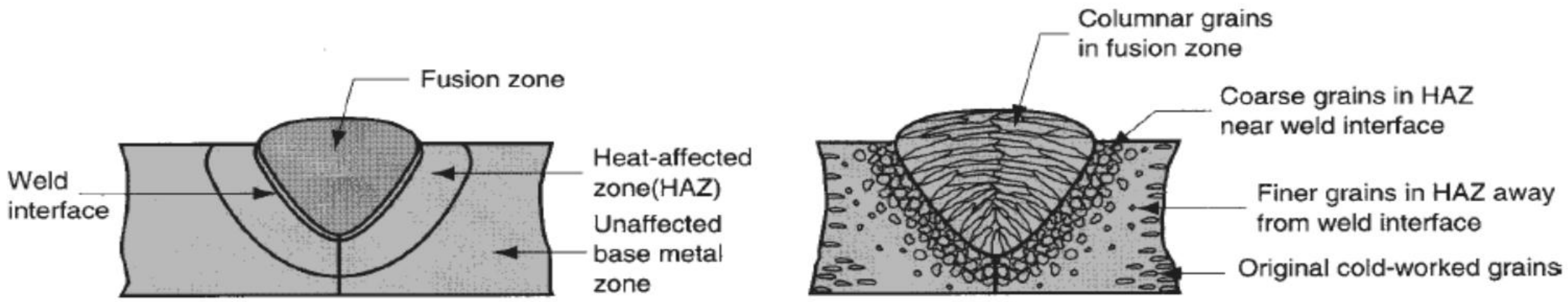
# Morphology of fusion weld

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.

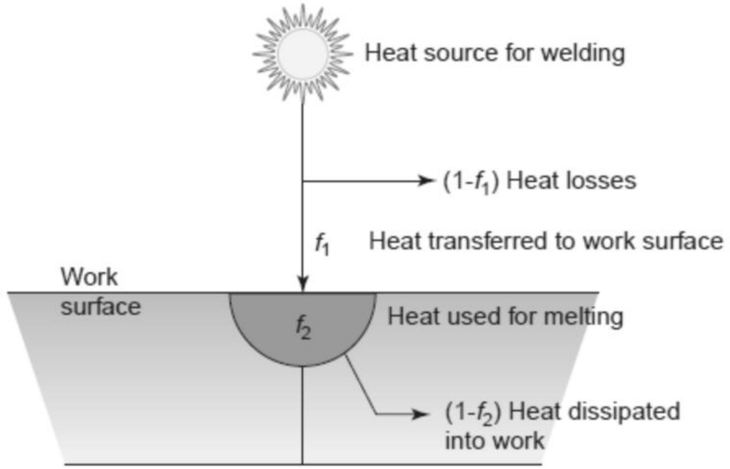
The quantity of heat required to melt a given volume of metal from room temperature ($U_m$ in J/mm$^3$ ) is given by,

$$U_m = K\, T_m^2$$

$T_m$ - melting point of the metal in K, $K$ – constant, $3.33\times10^{-6}$

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, $mm^3/s = A_w v$

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, $R_{Hw} = F_1F_2\ R_H$ involving rate of welding.

Now the rate balance equation can be written as,

$$R_{Hw} = F_1F_2\ R_H = U_m\ A_w\ v$$



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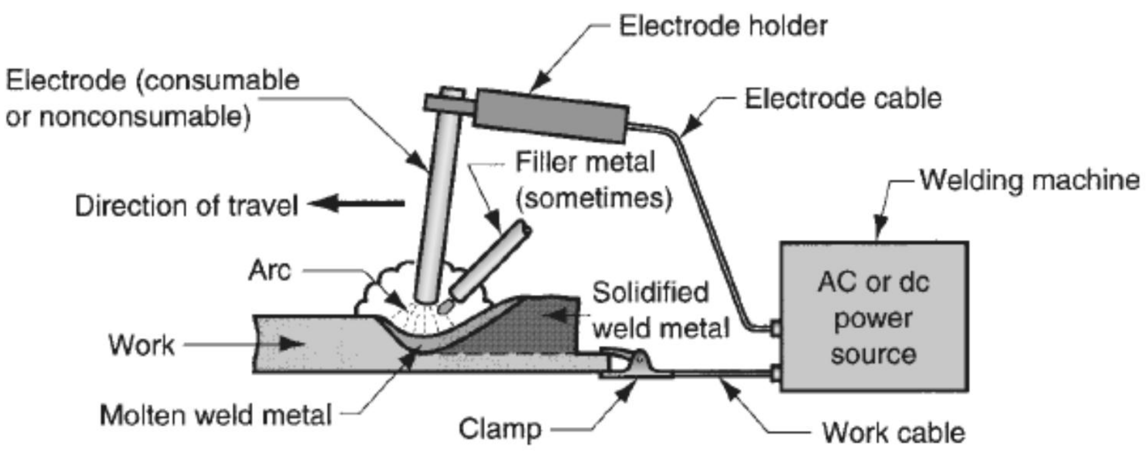
# Arc welding

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°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:

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

<u>Reverse polarity</u> in which workpiece is negative and electrode is positive is suitable for deeper welds.

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

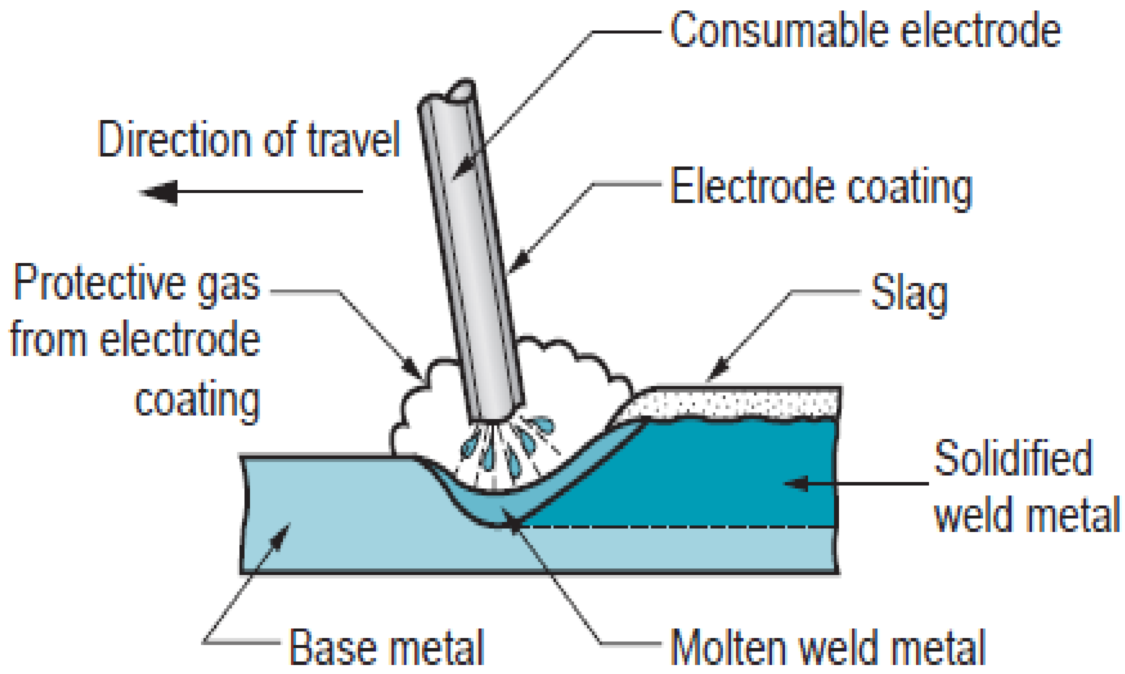
Here E - voltage, I - current .

## 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 welding using SMAW.
- Disadvantages: repeated change of electrodes, current maintained in typical range

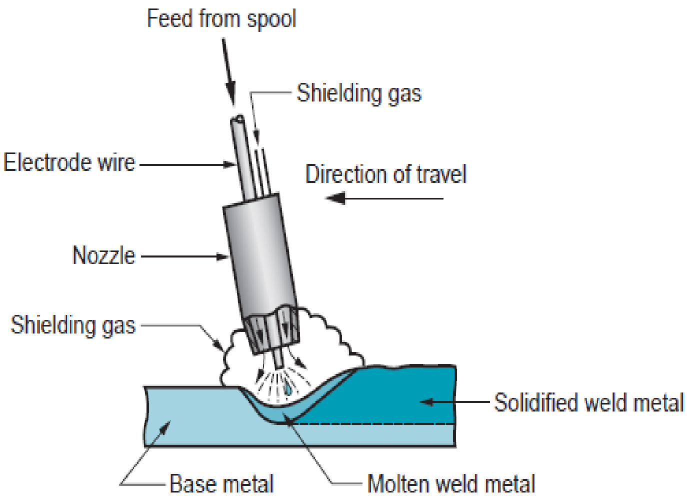


Consumable electrode
Direction of travel
Electrode coating
Protective gas from electrode coating
Slag
Solidified weld metal
Base metal
Molten weld metal


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 $CO_2$ 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, $CO_2$ welding (when $CO_2$ is used).



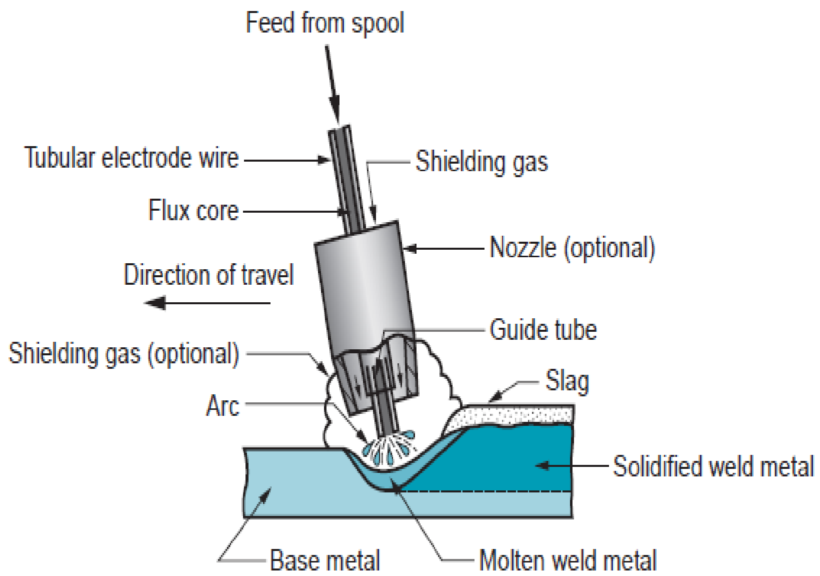

GMAW

Flux cored arc welding (FCAW):

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

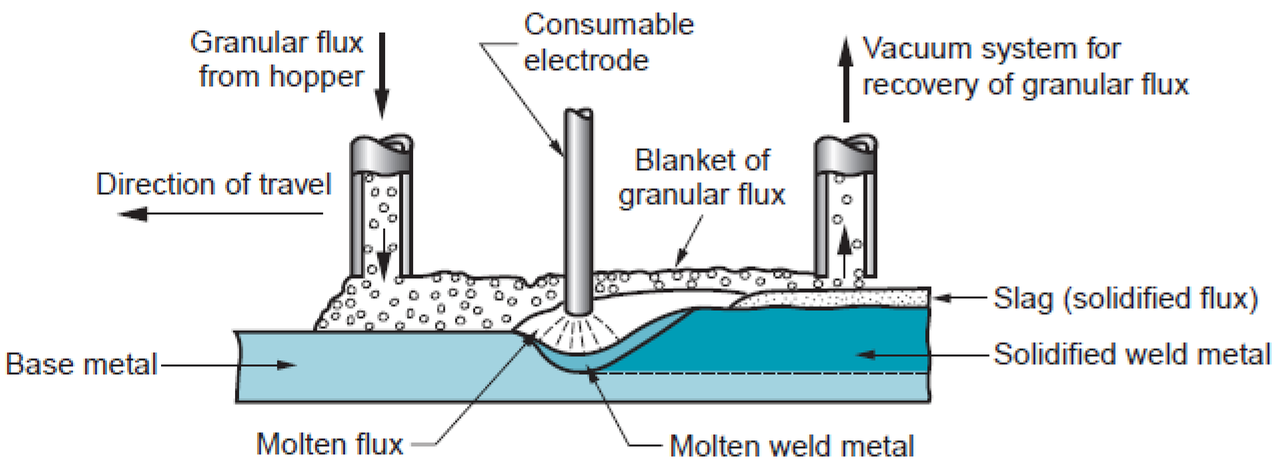
- Self-shielded FCAW:
the arc shielding was provided by the flux core. The core also includes ingredients that generate shielding gases for protecting the arc.

- 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.

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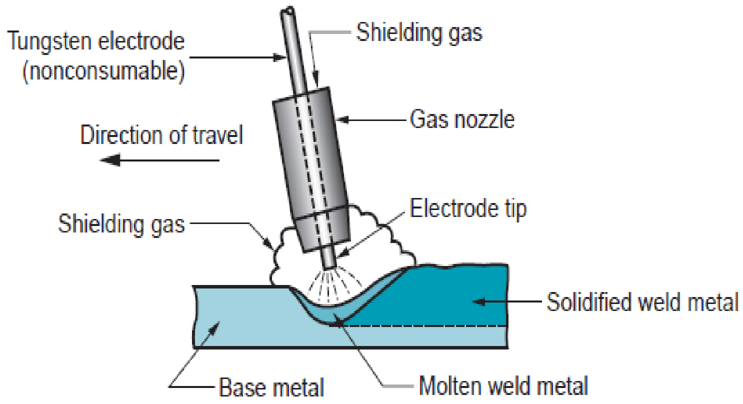
A heat source transfers 3000W to the surface of a metal part. The heat impinges the surface in a circular area, with intensities varying inside the circle. The distribution is as follows: 70% of the power is transferred within a circle of diameter 5 mm, and 90% is transferred within a concentric circle 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 $mm^2$. 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)



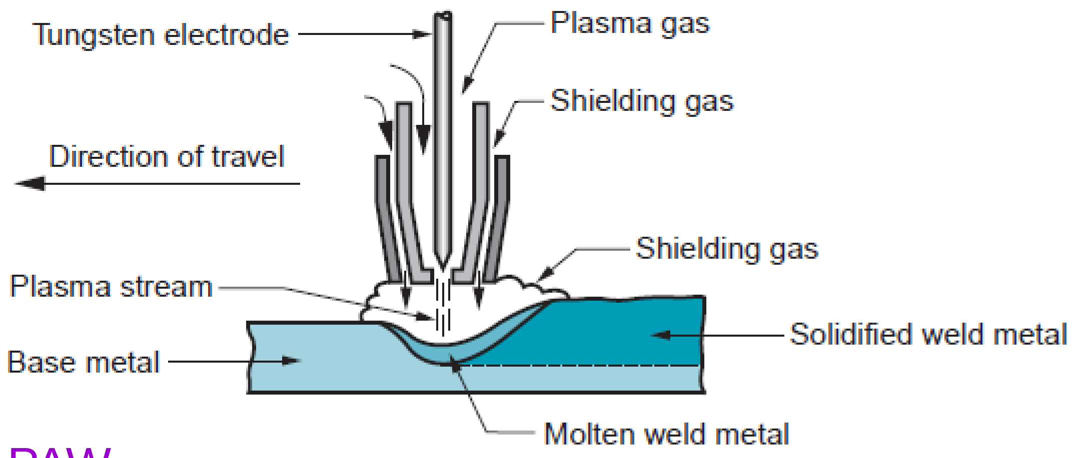

- usage of filler wire is optional and is heated by arc and not transferred across the arc.

- Tungsten is a good electrode material due to its high melting point of 3400°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

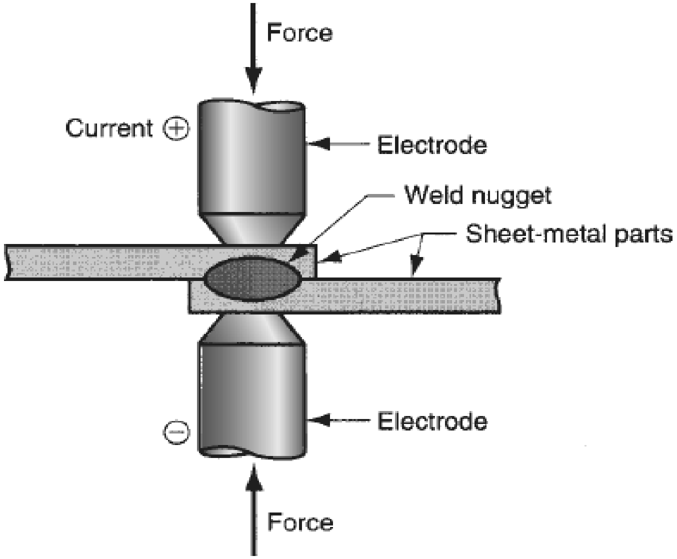
- It is a variety of gas tungsten arc welding in which a constricted plasma arc is used for welding.
- In PAW, a tungsten electrode is kept in a nozzle that focuses a high velocity stream of inert gas into the region of the arc to form a high velocity, intensely hot plasma arc stream.
- Temperatures in plasma arc welding reach 17,000°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,

$$H = I^2RT$$

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

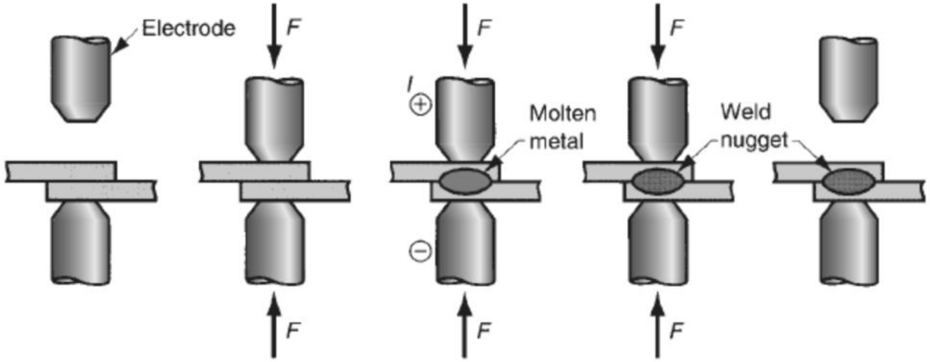
# Resistance spot welding

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.

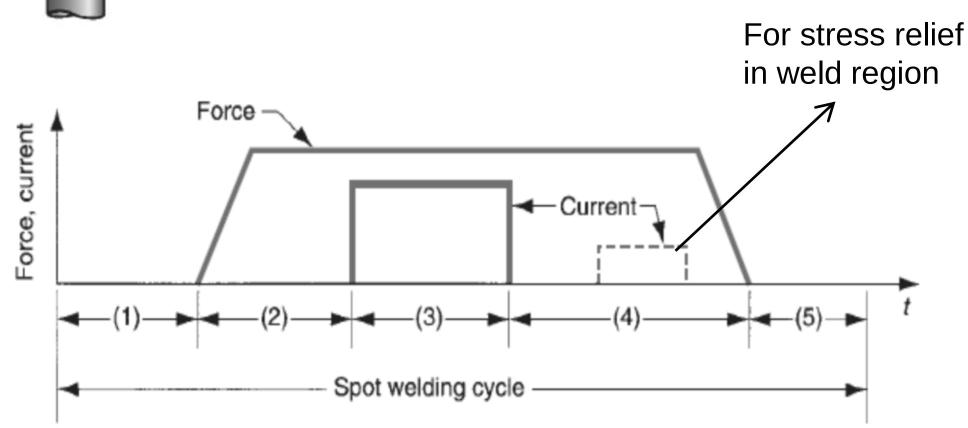
The shape of electrode tip is important like round, hexagonal, square etc. The nugget shape will be app. 5-10 mm in this case.

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

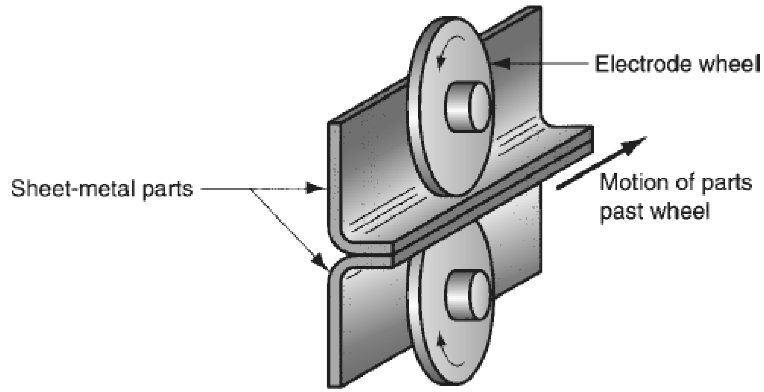


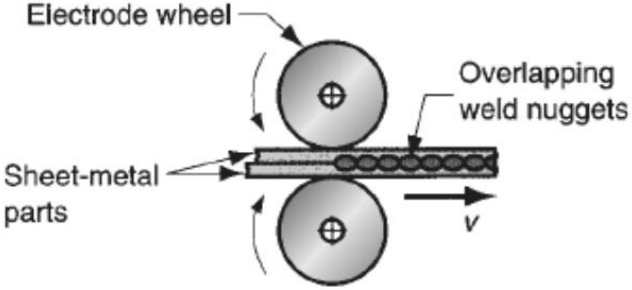

Steps in spot welding

Spot welding cycle

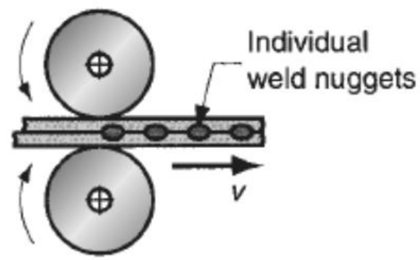


# Resistance seam welding

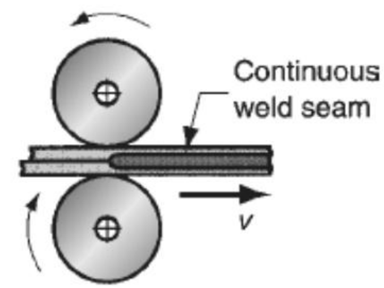



conventional resistance seam welding (overlapping spots)




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.

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# Gas welding / Oxyfuel gas welding

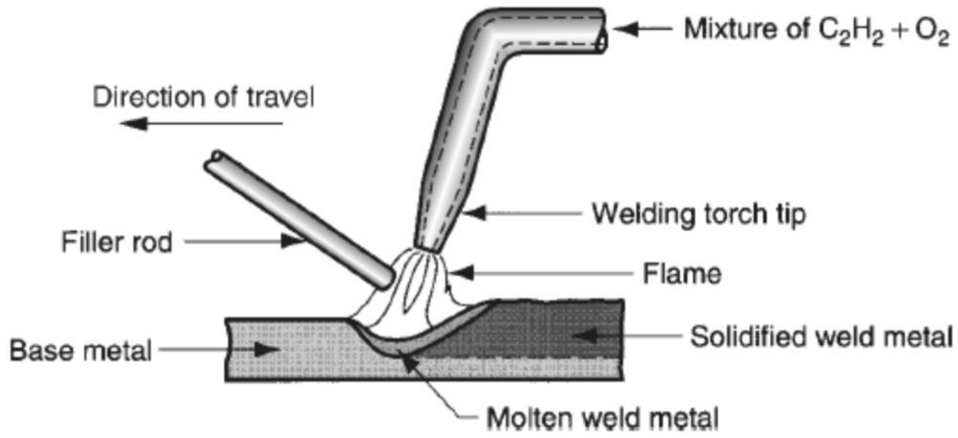
-In this process, various fuels are mixed with oxygen and burnt to perform welding. Eg: Oxyacetylene welding

- 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°C.



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

$$C_2H_2 + O_2 = 2CO + H_2 + \text{HEAT} \text{ (First stage; inner core)}$$

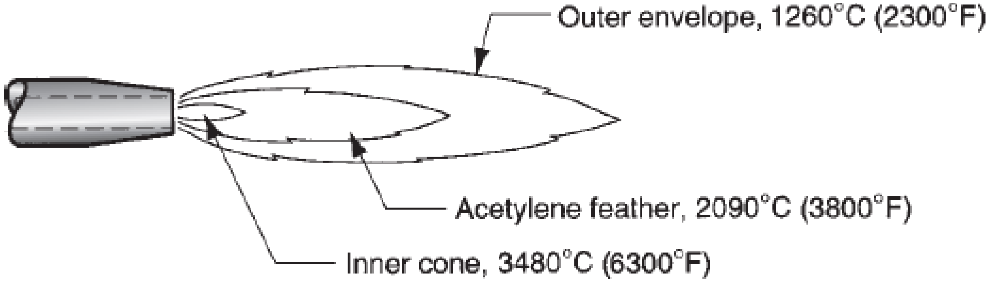
The products of first reaction are combustible and second reaction occurs as,

$$2CO + H_2 + 1.5O_2 = 2CO_2 + H_2O + \text{Heat} \text{ (second stage; outer envelope)}$$

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 $55\times10^6$ 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[a] °C | Temperature[a] °F | Heat of Combustion MJ/m$^3$ | Heat of Combustion Btu/ft$^3$ |
|---|---|---|---|---|
| Acetylene ($C_2H_2$) | 3087 | 5589 | 54.8 | 1470 |
| MAPP[b] ($C_3H_4$) | 2927 | 5301 | 91.7 | 2460 |
| Hydrogen ($H_2$) | 2660 | 4820 | 12.1 | 325 |
| Propylene[c] ($C_3H_6$) | 2900 | 5250 | 89.4 | 2400 |
| Propane ($C_3H_8$) | 2526 | 4579 | 93.1 | 2498 |
| Natural gas[d] | 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$^3$ 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:** $\text{Power density} = f_1 \dfrac{EI}{A} \text{ (here } f_1 = 0.8 \text{ to } 0.95\text{)}$

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

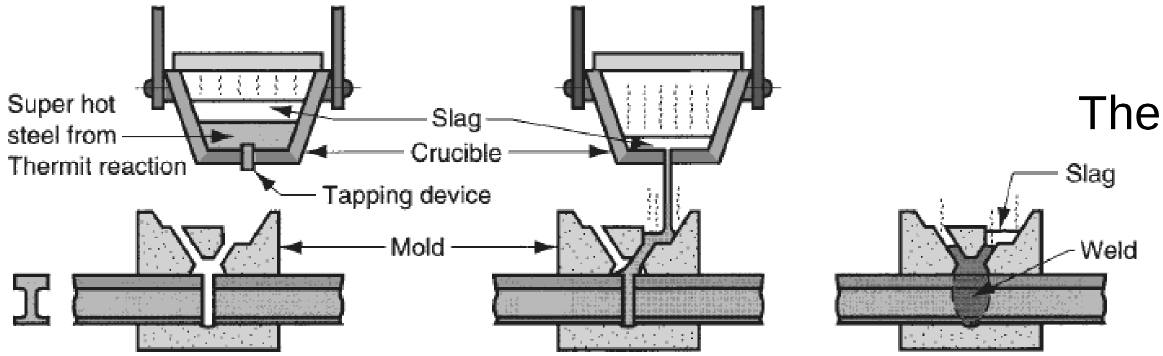
Thermite (thermit): a mixture of aluminum powder and iron oxide that produces an exothermic reaction when ignited.

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.

$$8Al + 3Fe_3O_4 = 9Fe + 4Al_2O_3 + heat$$

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.

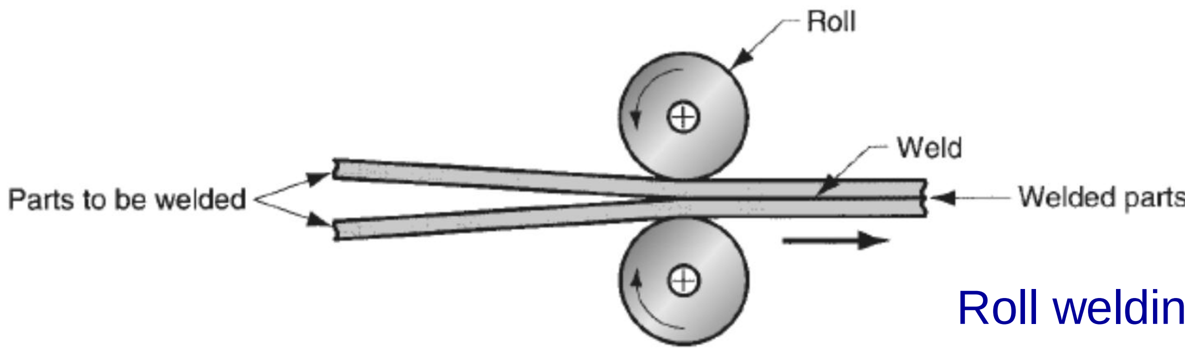
# Solid state welding processes

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.

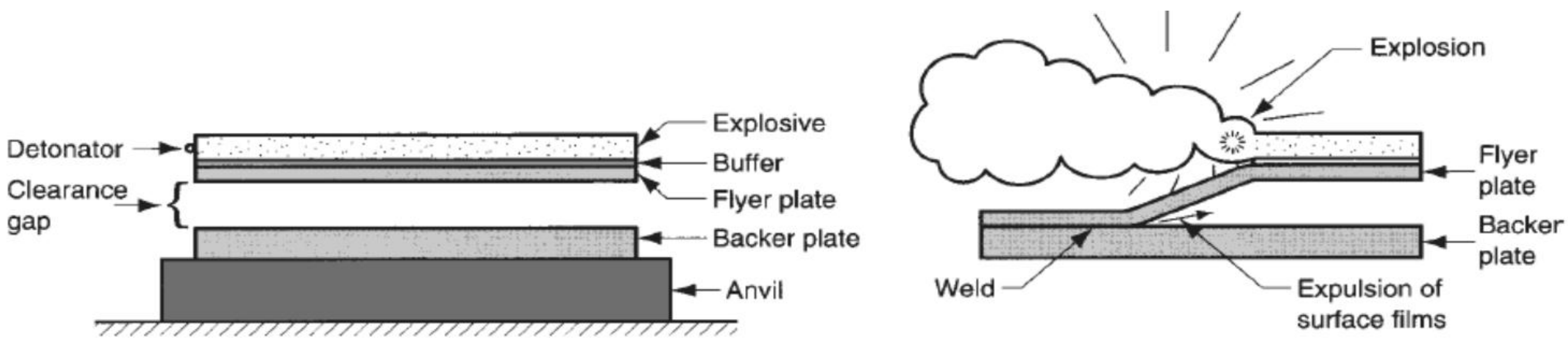
The two surfaces must be cleaned and free of oils, dirt, chemical films, gases etc. to permit atomic bonding.

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

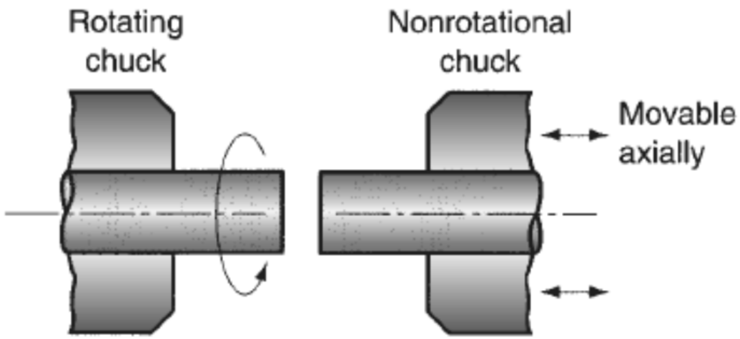
Roll welding or bonding: Two or more sheets are kept one above the other and rolled to generate bonding between them. If done without application of external heat, then it is called cold roll bonding. With the application of external heat, it is called hot roll bonding.



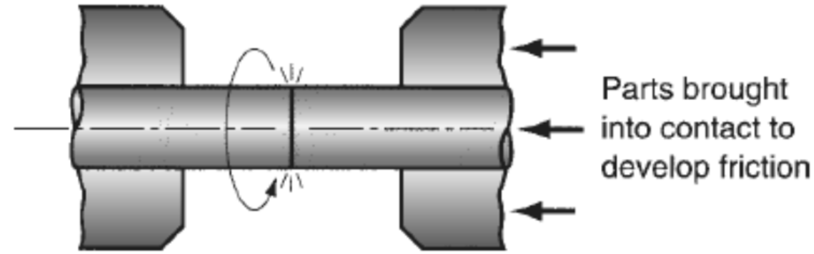

explosive welding

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.

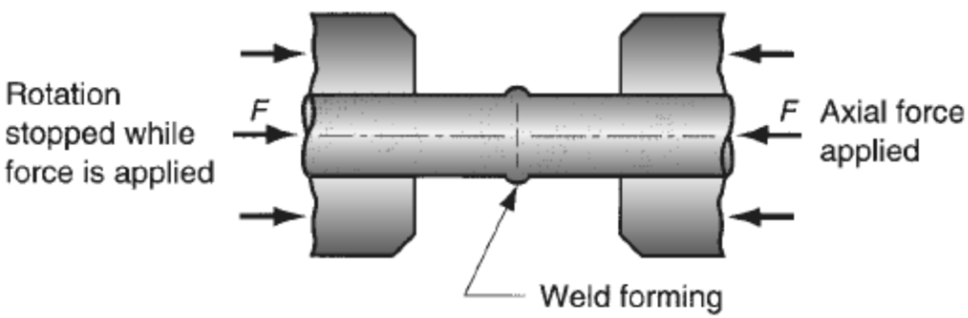
# Friction welding



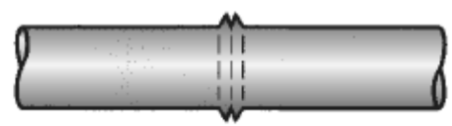

**Two parts are not in contact**




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




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

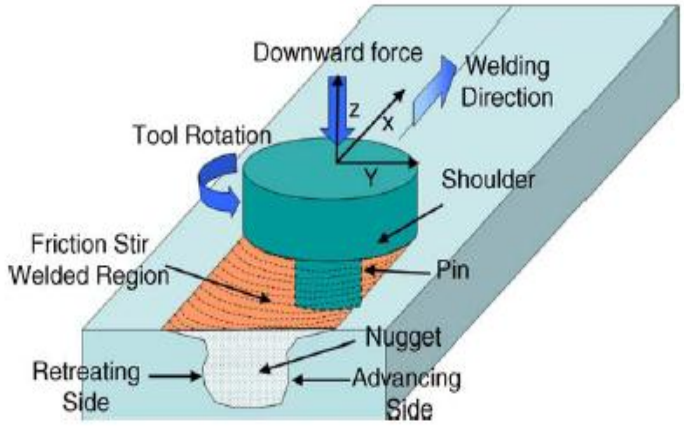


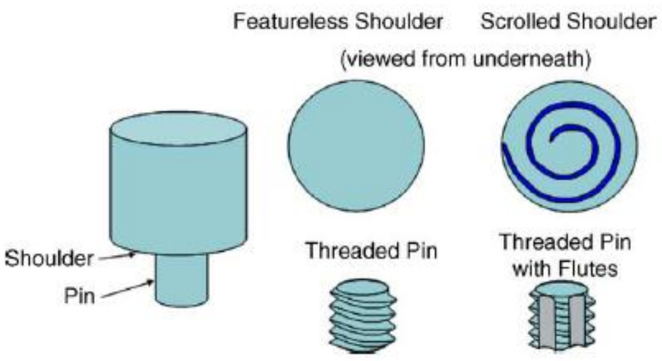
**Creation of weld**

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

# 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.

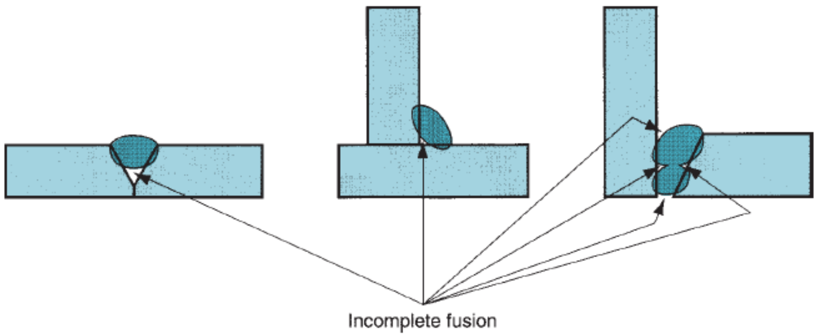
# Welding defects

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.

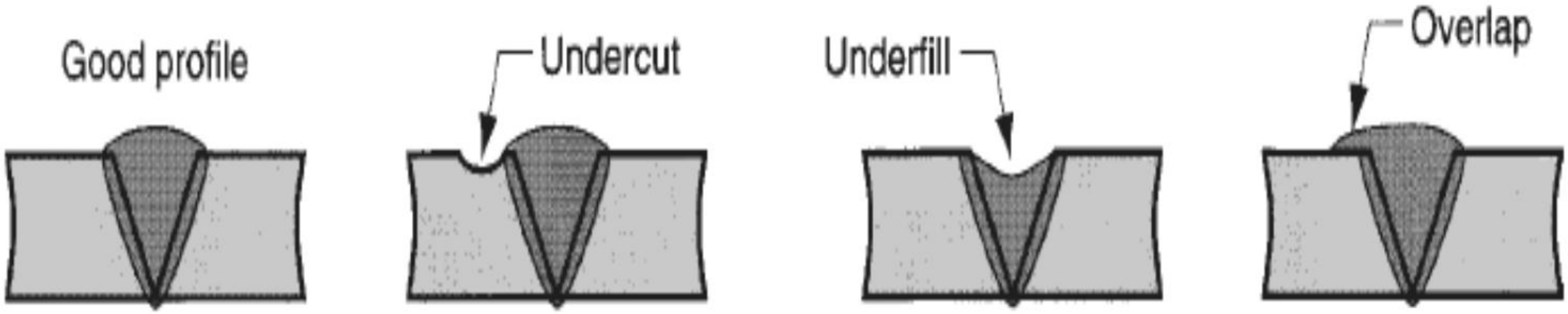
Shrinkage voids: Cavities formed by shrinkage during solidification. Both of the cavity type defects are similar to defects found in castings.

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

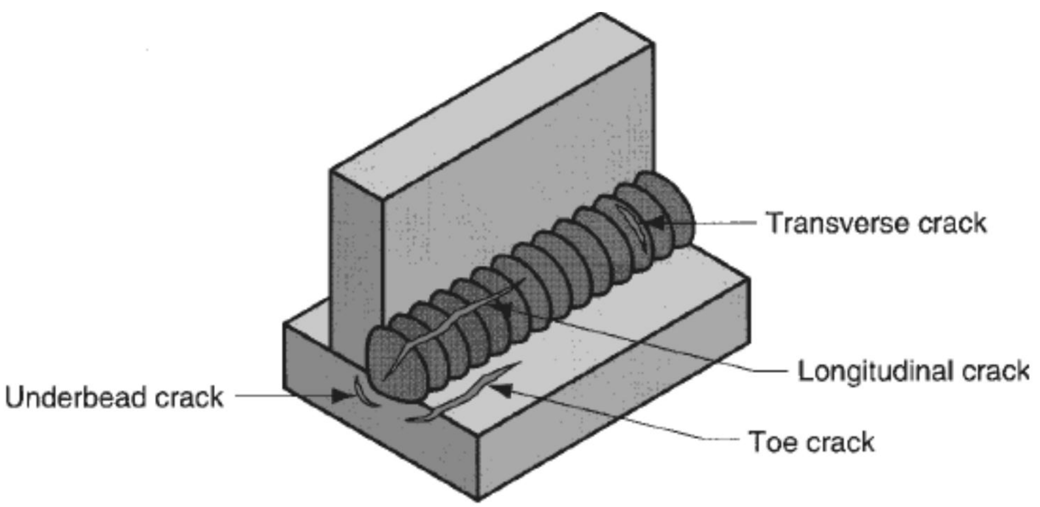
Incomplete fusion: It is a weld bead in which fusion has not occurred throughout the entire cross section of the joint.



## Improper weld profile:



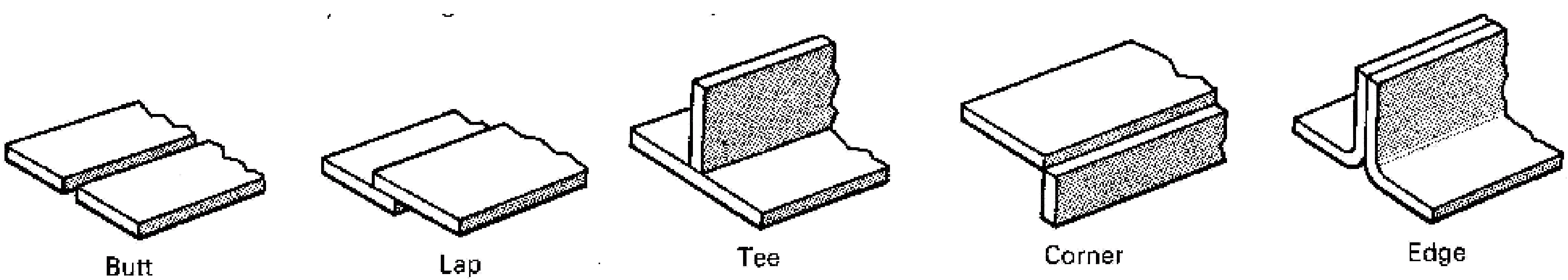

## Weld cracks:




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

# Welding Processes

- <u>Welding</u>: permanent joining of two materials, usually metals, by *coalescence*
- *Coalescence* results in atoms of the materials being joined to form common crystal structures
- *Coalescence* induced by a combination of temperature, pressure and metallurgical conditions




Source: DeGarmo et al, 9th Ed.

# Welding Processes

- High quality weld requires:
  - Source of heat and/or pressure
  - Means to protect/clean metals to be joined
  - Methods to avoid detrimental metallurgical changes

http://www.youtube.com/watch?v=ROcbeamGhJ0

# Classification of Welding Processes

## Oxyfuel gas welding (OFW)

**Oxyacetylene welding (OAW)**
**Pressure gas welding (PGW)**

## Arc welding (AW)

**Shielded metal arc welding (SMAW)**
**Gas metal arc welding (GMAW)**
- **Pulsed arc (GMAW-P)**
- **Short circuit arc (GMAW-S)**
- **Spray transfer (GMAW-ST)**

**Gas tungsten arc welding (GTAW)**
**Submerged arc welding (SAW)**
**Plasma arc welding (PAW)**

## Resistance welding (RW)

**Resistance spot welding (RSW)**
**Resistance seam welding (RSW)**
**Projection welding (RPW)**

## Solid state welding (SSW)

**Forge welding (FOW)**
**Cold welding (CW)**
**Friction welding (FRW)**
**Ultrasonic welding (USW)**
**Explosion welding (EXW)**
**Roll welding (ROW)**

## Unique Processes

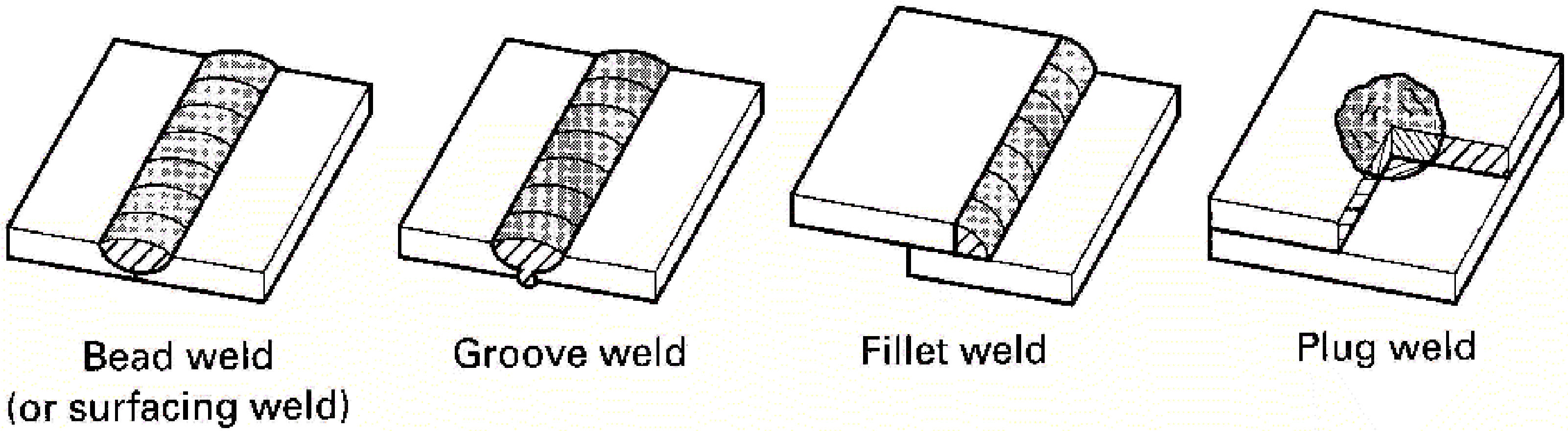
**Thermit welding (TW)**
**Laser beam welding (LBW)**
**Induction welding (IW)**
**Electron beam welding (EBW)**



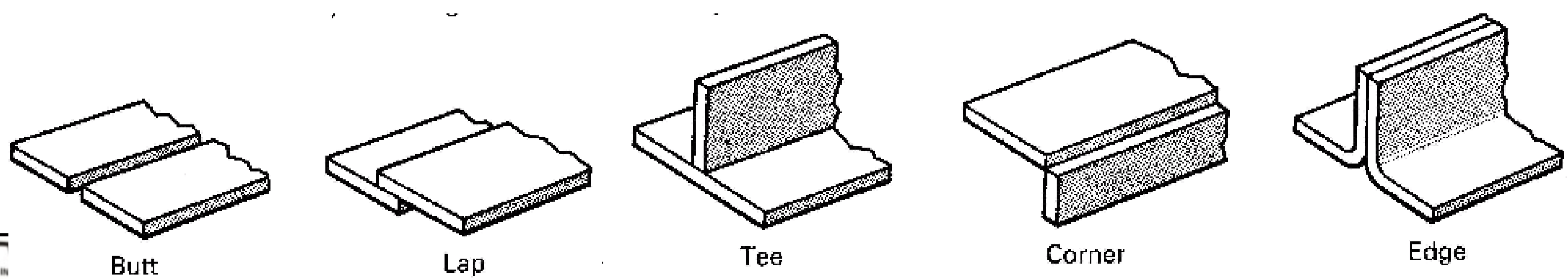
*Source: DeGarmo et al, 9th Ed.*

# Types of Welds and Joints

## Types of Fusion welds



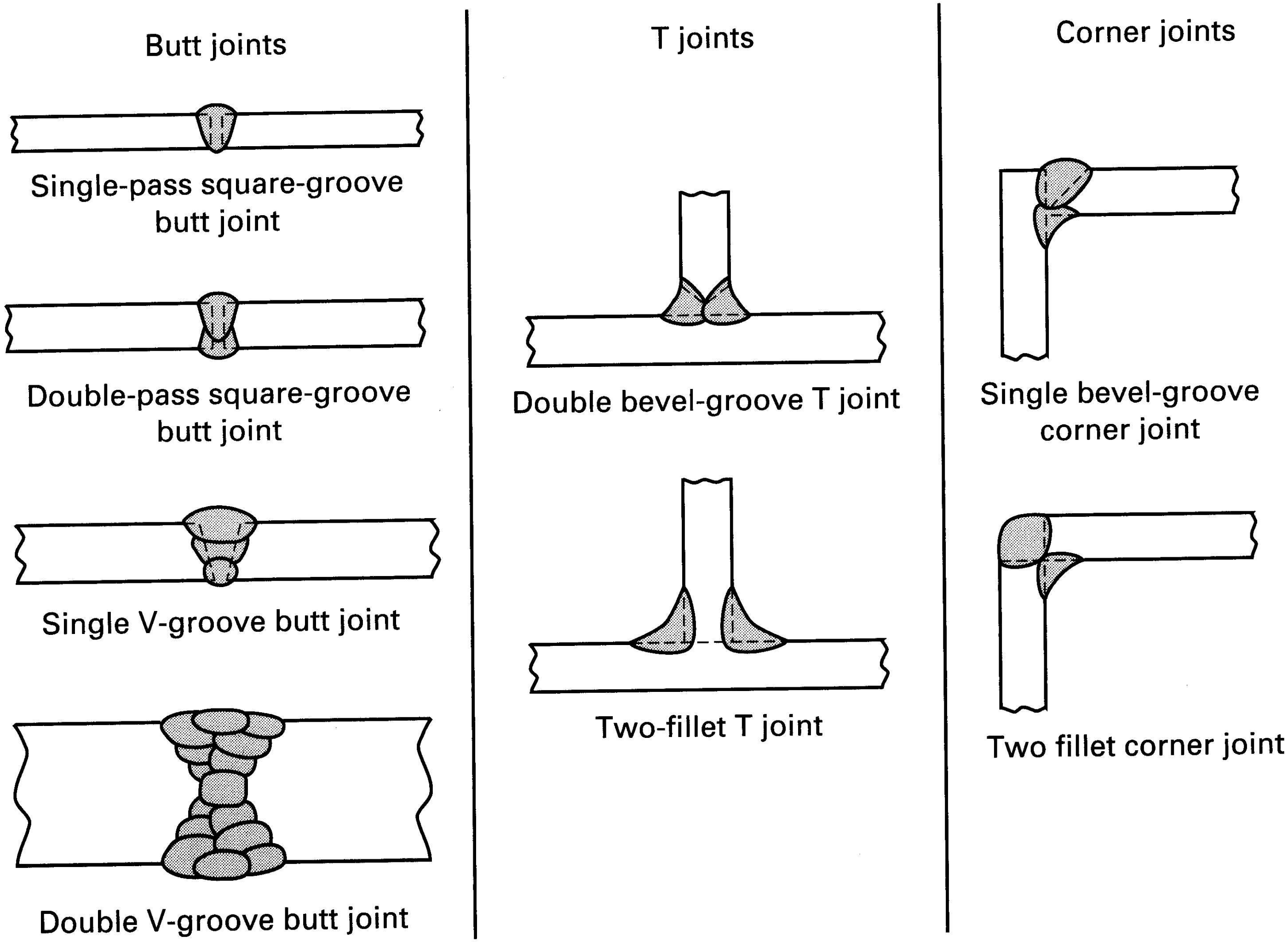

## Types of joints






*Source: DeGarmo et al, 9th Ed.*

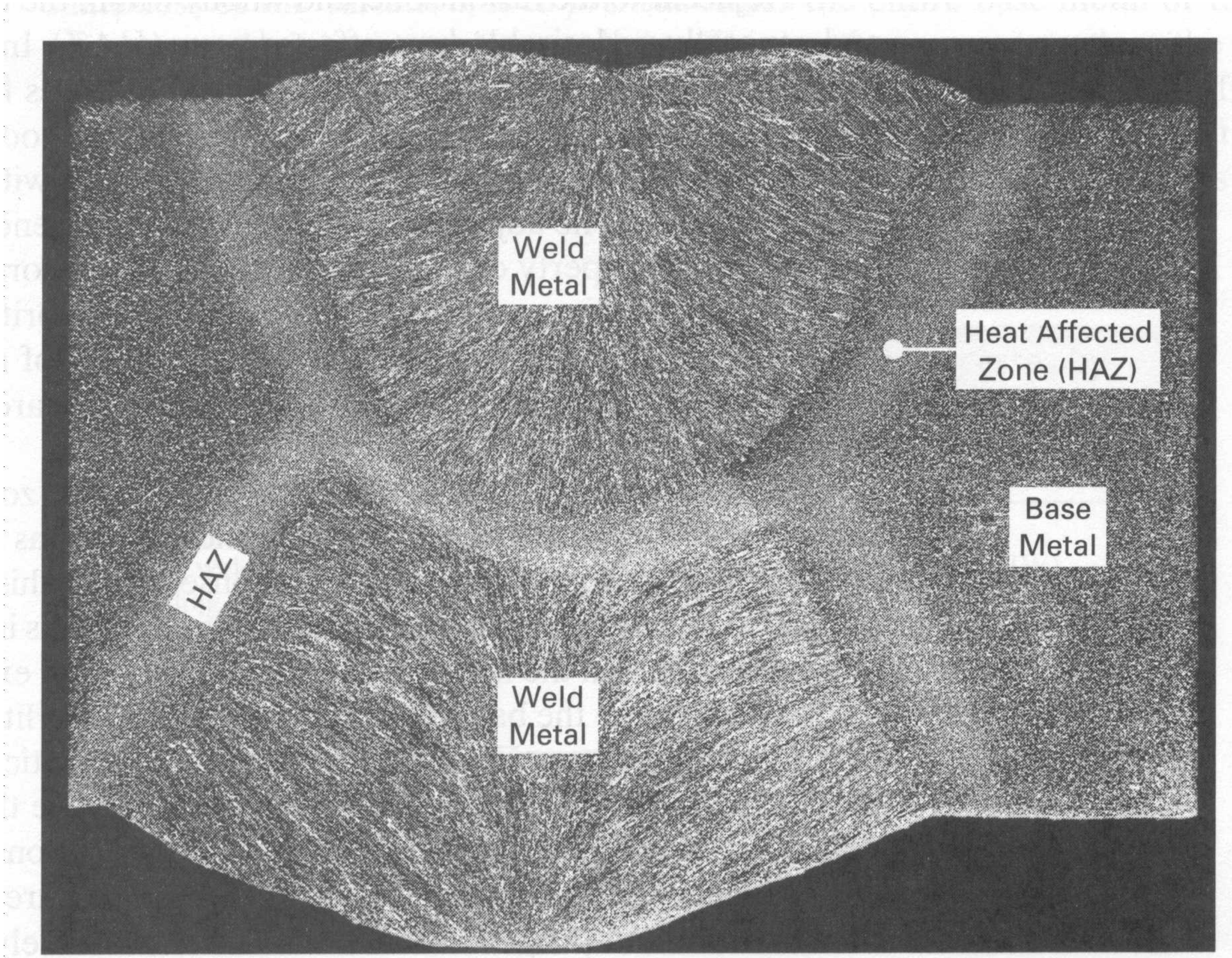
# Examples of Welded Joints






*Source: DeGarmo et al, 9th Ed.*

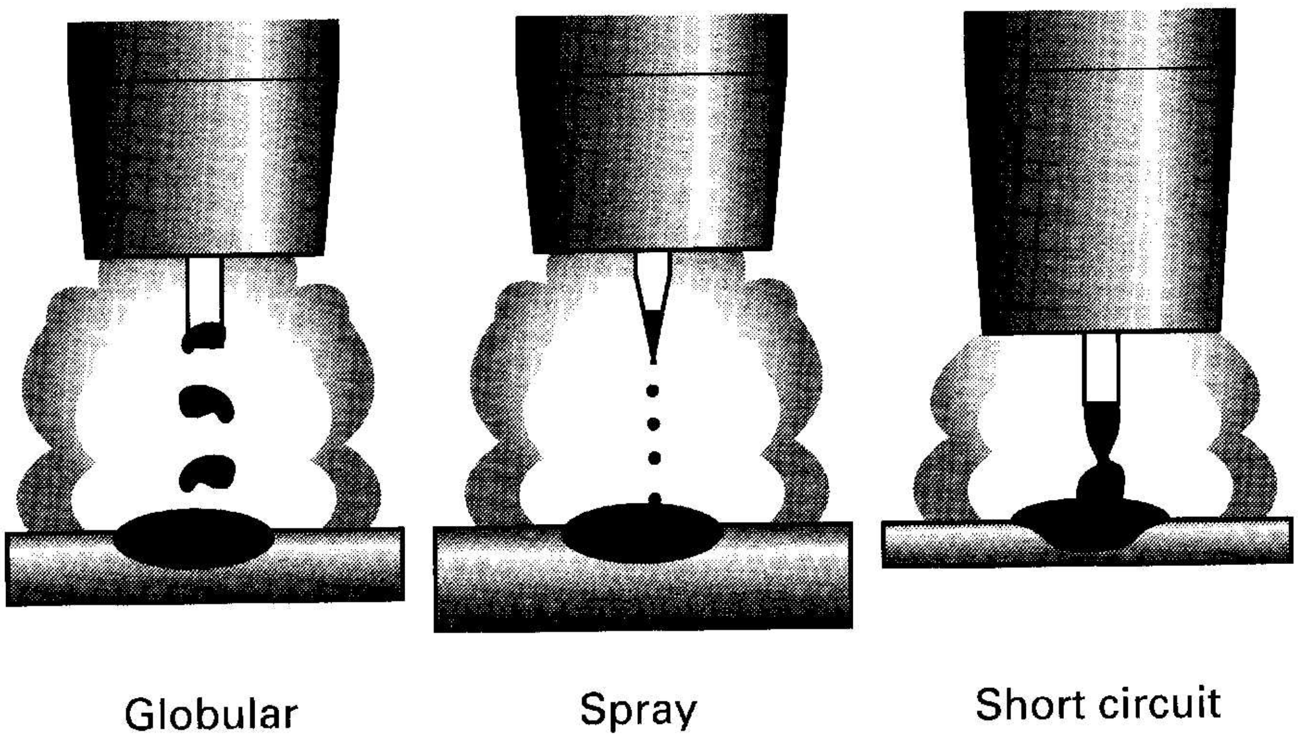
# Typical Weld Microstructure






*Source: DeGarmo et al, 9th Ed.*

# Mode of Metal Transfer

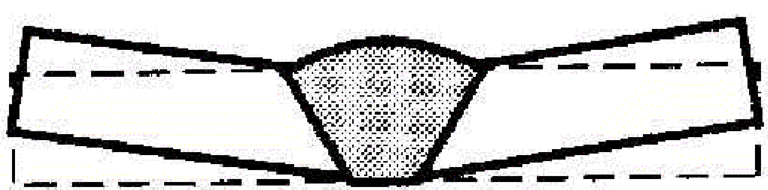




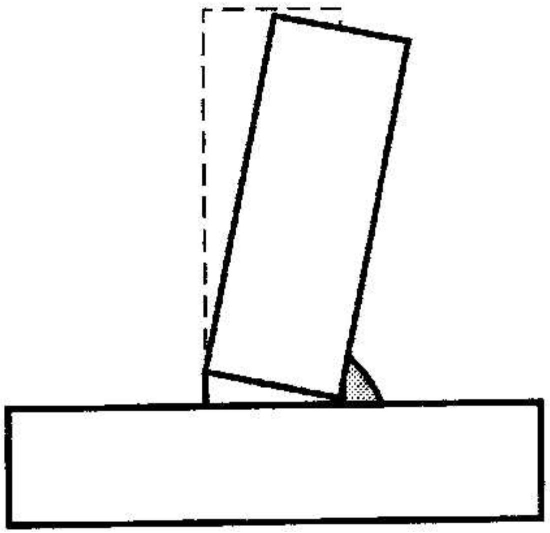

*Source: DeGarmo et al, 9th Ed.*

# Welding Defects

- Heat affected zone (HAZ)
- Residual stresses: thermally-induced
- Welding distortion



**Distorted V-groove butt weld**



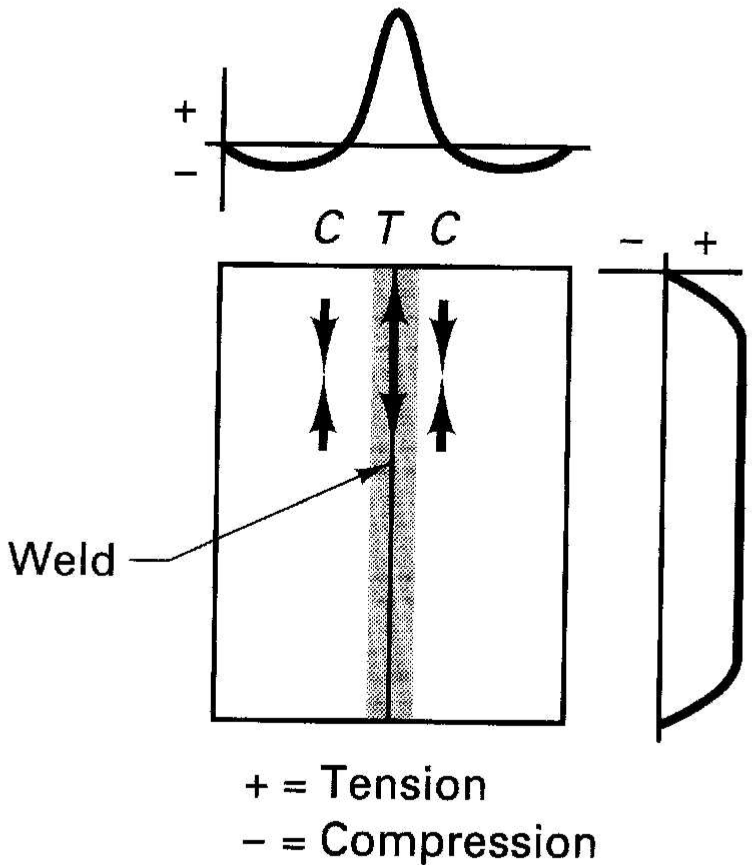
**Distorted fillet welded T-joint**



*Source: DeGarmo et al, 9th Ed.*

# Welding Defects

- Residual stresses: thermally-induced






*Source: DeGarmo et al, 9th Ed.*

# Joining Variations

- **Fastening**: materials are joined together using fasteners (e.g., screws, nails, nuts, bolts)
  - Advantages: any shape or material; can be disassembled; often the least expensive method for volume production
  - Disadvantages: do not develop the full strength of the base material; do not produce hermetic seals; fasteners are extra parts; need to drill holes.
- **True bonding:** formation of a bond
  - The perfect joint is indistinguishable from the material surrounding it (diffusion bonding).
  - Any two solids will bond if surfaces are brought into intimate contact. Two inhibiting factors: 1) surface contamination (in nanoseconds); 2) do not mate perfectly (true contact area <10%).

# Joining Variations (Cont')

- **True bonding**
  - Welding using interfacial shear (cold welding): ultrasonic welding; friction welding
  - Adhesive bonding: viscous fluid fills hills & valleys; bond created by surface tension forces or mechanical interlocking; weaker than interatomic bonds; best for joining sheets, fibers
  - Diffusion bonding: materials held together under high pressure at elevated temperature to increase contact area (surface contaminants must be soluble)
  - Fusion welding: materials are melted and bonded together by means of heat (chemical or electrical).

# Fusion Welding

- Heat + filler material = weld
- Types (different heat sources)
  - Flame: oxygen + fuel (oxy-acetylene)
  - Electric arc
  - Resistance
  - Laser beam
  - Electron beam

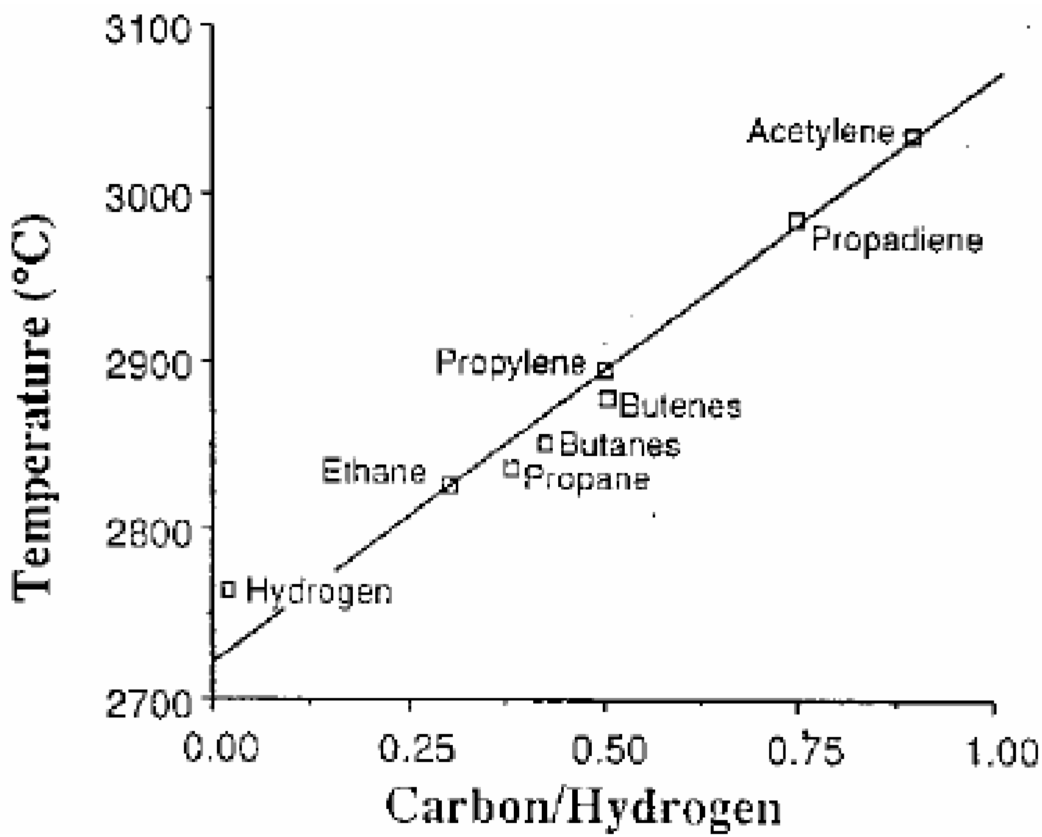
# Oxy-Acetylene Welding


Flames are categorized in terms of their combustion intensity:

$$CI = C_h \cdot C_v$$

CI: W/cm$^2$; $C_h$: heat content of the gas per unit vol, J/m$^3$; $C_v$: gas velocity, cm/s

# Flame temperatures




$$CI \propto T^2$$

1000 W/cm$^2$

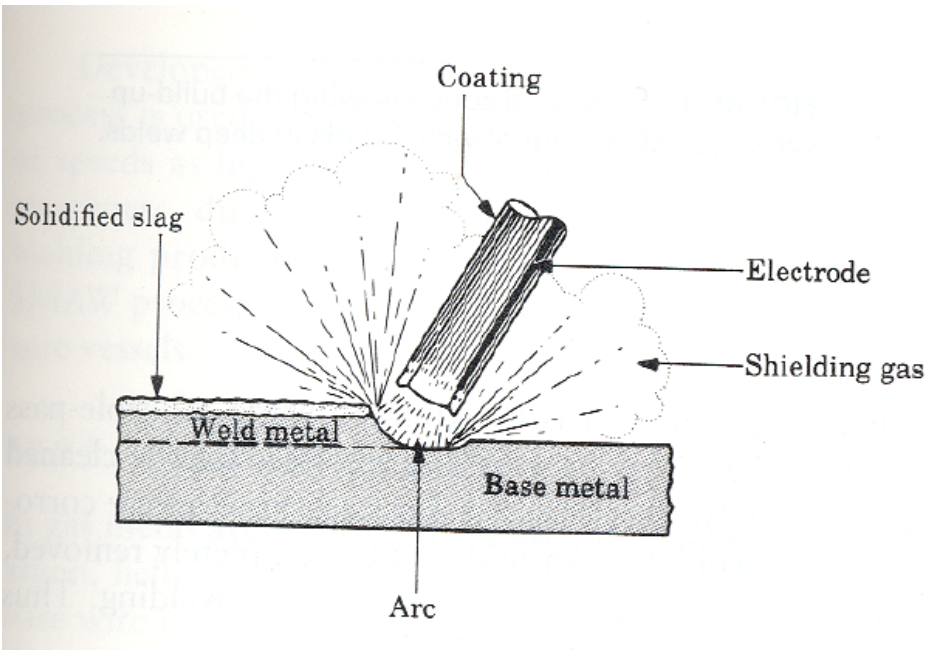
Classification of temperature of combustion of fuels as a function of the C/H ratio

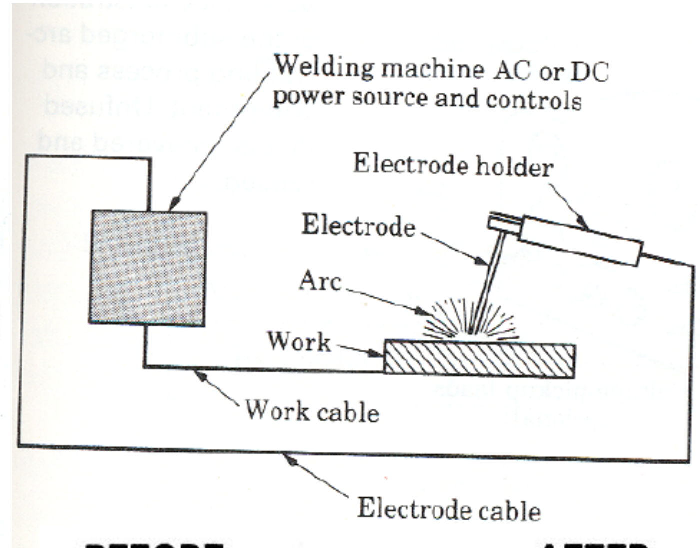
# Arc Welding

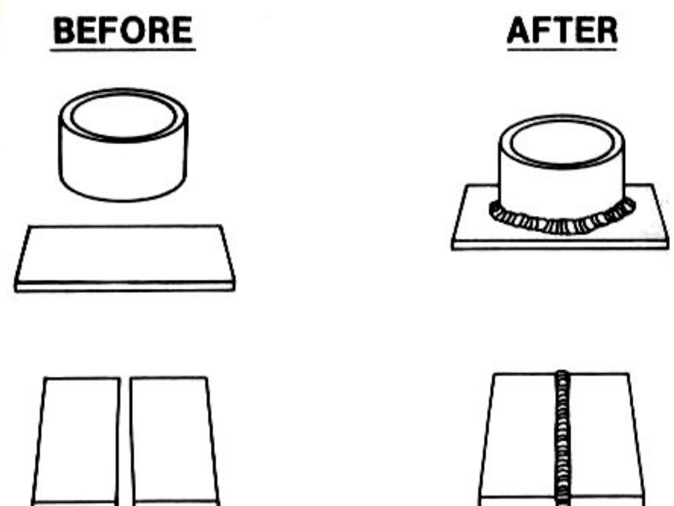
- Consumable Electrode
  - Shielded Metal Arc welding (SMAW)
  - Submerged Arc welding (SAW)
  - Gas Metal Arc welding (GMAW)

- Non-consumable Electrode
  - Gas Tungsten Arc welding (GTAW)
  - Plasma Arc Welding (PAW)

# Shielded Metal Arc Welding (SMAW)






*Source: S. Kalpakjian, 3rd Edition*

# Process Description

- Electrode coating (e.g. cellulose + titania) vaporizes and provides a protective gas shield around arc and weld pool to prevent oxidization
- Electric arc generated by touching the electrode tip against workpiece
- Sufficient distance between workpiece and electrode is required to maintain arc
- Parent material, electrode metal and some material from coating solidify in the weld
- Globular or short circuit mode of metal transfer
- Current ranges from 50 – 300 A
- Power requirement is less than 10 kW

# Electrode Coating Functions

- Protective gas shield around arc and pool of molten metal
- Provide ionizing elements to stabilize arc, reduce weld metal spatter, and increase efficiency of deposition
- Act as flux to deoxidize and remove impurities from molten metal
- Provide protective slag coating to collect impurities, prevent oxidation, and slow the cooling of weld metal
- Add additional filler metal
- Add alloying elements
- Influence arc penetration (depth of melting in workpiece)

# Process Capabilities

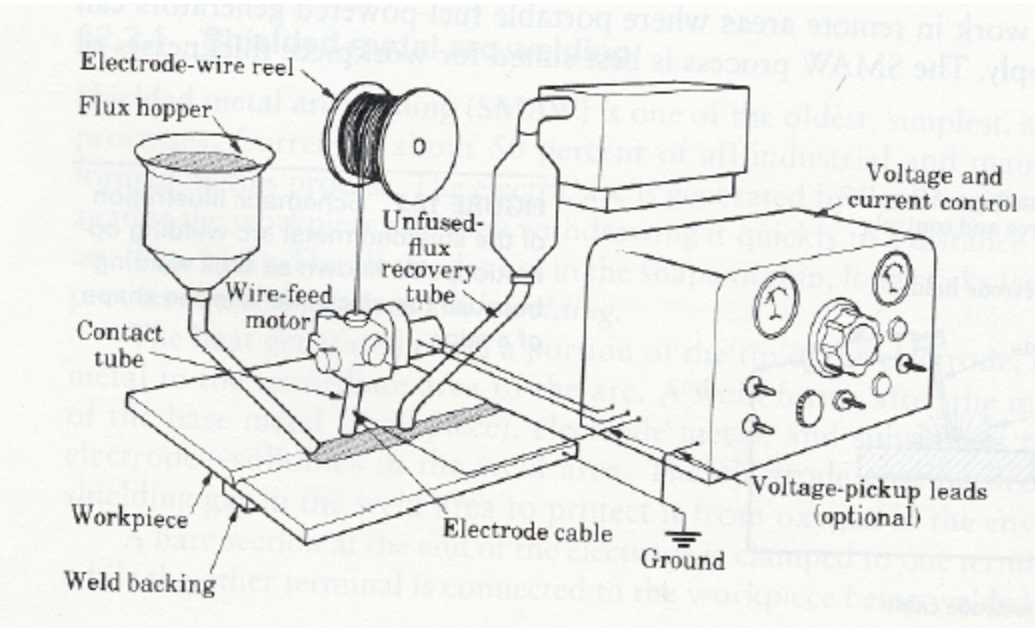
- Weld rates up to 0.2 m/min
- Arc penetration generally < 5 mm
- Minimum sheet thickness = 1.5 mm
- Maximum sheet thickness = 200 mm
- Multiple passes required on sheet thickness ≥ 5 mm (requires slag removal after each pass)
- Commonly welded materials are carbon steels, low alloy steels, stainless steels, Ni alloys and cast iron
- Tolerances $\pm$ 1mm (typical)
- Surface finish is fair to good

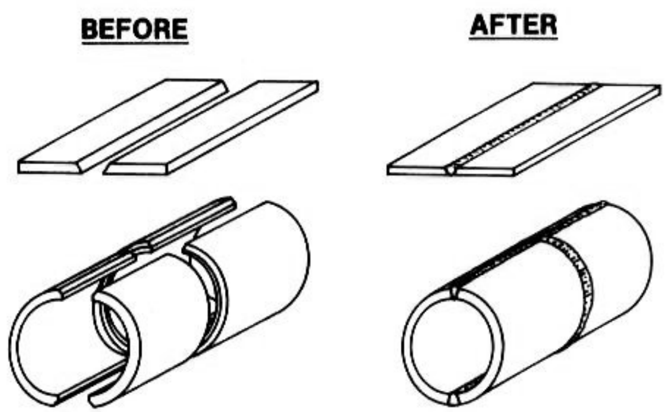
# SMAW

- Advantages
  - Most versatile of all welding processes (50%)
  - Suitable for site work
  - Tooling costs are low
  - All levels of complexity are possible
  - Economical for low production runs

- Limitations
  - Direct labor costs are high
  - Slag produced at the weld area needs grinding
  - Discontinuous process, frequent electrode changes
  - Heat affected zone is present

# Submerged Arc Welding (SAW)






*Source: S. Kalpakjian, 3rd Edition*

# Process Description

- Shielded by gravity fed granular flux, which covers molten material, preventing sparks, spatter and UV radiation
- Electrode is in the shape of wire fed through a tube
- Unused slag is recycled
- Parent metal and wire form the weld pool
- Current ranges from 300 – 2000 A
- Voltage used is 3 phase 440 V
- Can be highly automated
- Heat penetration is deep (up to 25 mm)

# Process Capabilities

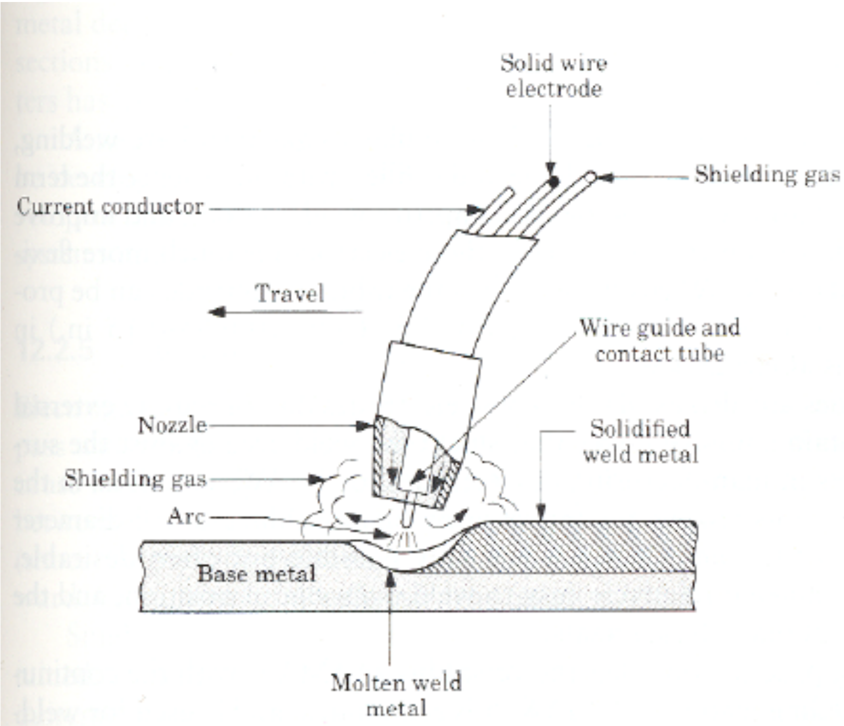
- Weld rates up to 5 m/min
- Minimum sheet thickness = 5 mm
- Maximum sheet thickness = 300 mm for carbon, stainless and low alloy steels
- Maximum sheet thickness = 20 mm for Ni alloys
- Multiple passes required on sheet thickness ≥ 40 mm
- Well-suited for butt and fillet welds in low carbon steels (< 0.3% carbon)
- Typical tolerance: $\pm$ 2 mm
- Surface finish is good

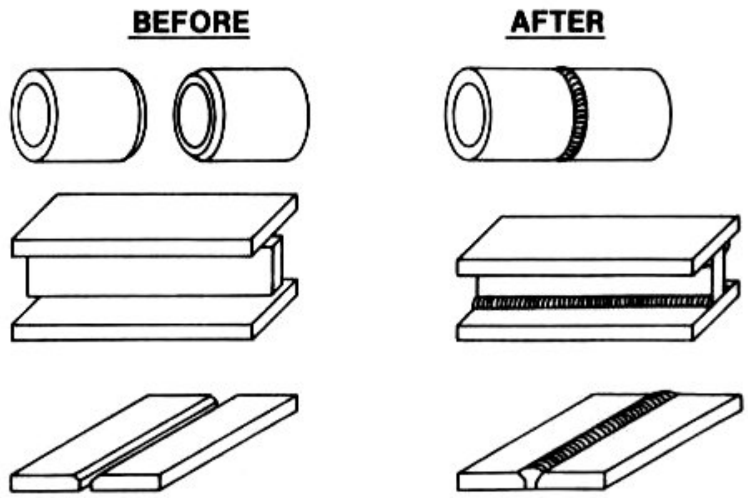
# SAW

- Advantages
  - Self-contained, highly automated with up to 3 welding heads
  - Economic for straight, continuous welding on very thick plates
  - Tooling cost are low to moderate
  - High quality weld with low distortion and high toughness

- Limitations
  - Design complexity is limited
  - Finishing costs are high because of slag removal
  - Flux handling and recycling can be expensive
  - Can alter composition of weld by alloying elements from the electrode
  - Heat affected zone is present

# Gas Metal Arc Welding (GMAW)






*Source: S. Kalpakjian, 3rd Edition*

# Process Description

- Shielded by external source such as argon, helium, $CO_2$ and other inert gas
- Wire electrode fed through a nozzle into the weld arc
- Parent metal is melted and wire acts as filler material
- Power required: 2 kW
- Max. arc penetration 6-10 mm
- Can be automated

# Process Capabilities

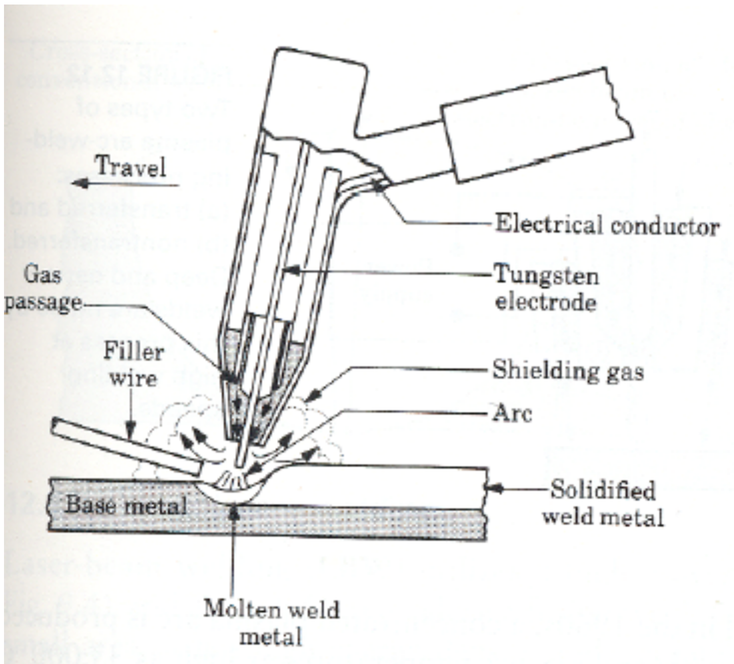
- Weld rates up to 0.5 m/min
- Minimum sheet thickness = 0.5 mm (6 mm for cast iron)
- Maximum sheet thickness = 80 mm for carbon, stainless and low alloy steels, Al, Mg, Ni, Ti alloys and Cu
- Maximum sheet thickness = 6 mm for refractory alloys
- Multiple passes required on sheet thickness ≥ 6 mm
- Typical tolerance: $\pm$ 0.5 mm
- Surface finish is good

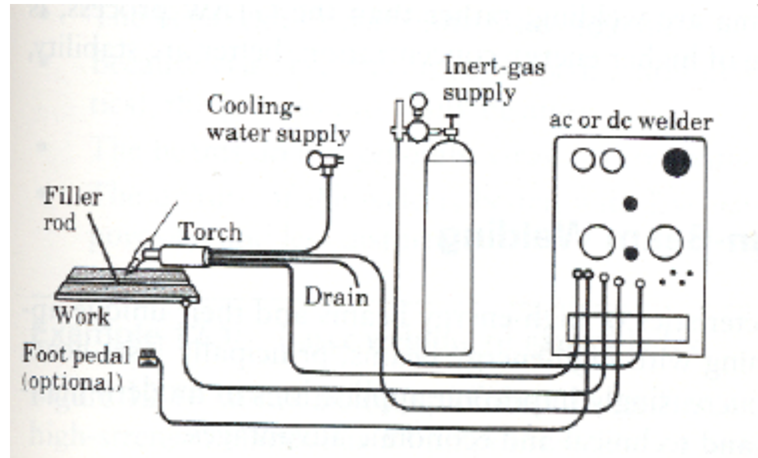
# GMAW

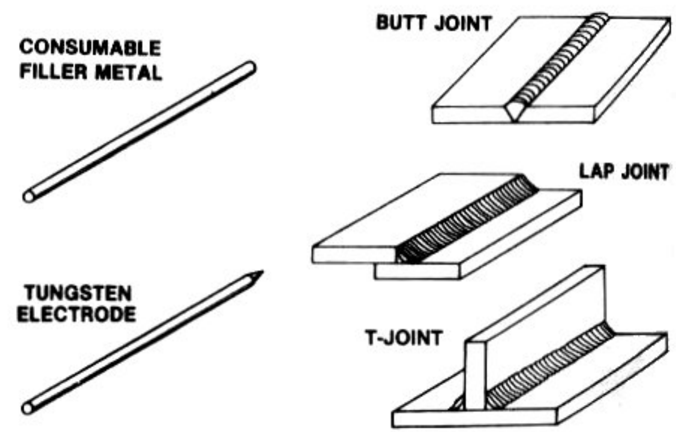
- Advantages
  - All levels of complexity possible
  - High weld deposition rates with continuous operation
  - Well suited to traversing automated and robotic systems
  - Tooling cost are low to moderate

- Limitations
  - Direct labor costs can be high
  - Wire electrode must closely match the composition of the metals being welded
  - Cracking may be experienced when welding high alloy steel
  - Heat affected zone is present

# Gas Tungsten Arc Welding (GTAW)






*Source: S. Kalpakjian, 3rd Edition*

# Process Description

- Shielded by external source, such as argon, helium and their mixture
- Tungsten is used as non-consumable electrode
- Filler metal is supplied from filler wire
- Typical current: <200A DC or <500A AC
- Parent metal is melted and wire acts as filler material
- Power required varies from 8 kW to 20 kW
- Max. arc penetration 3 mm
- Can be automated

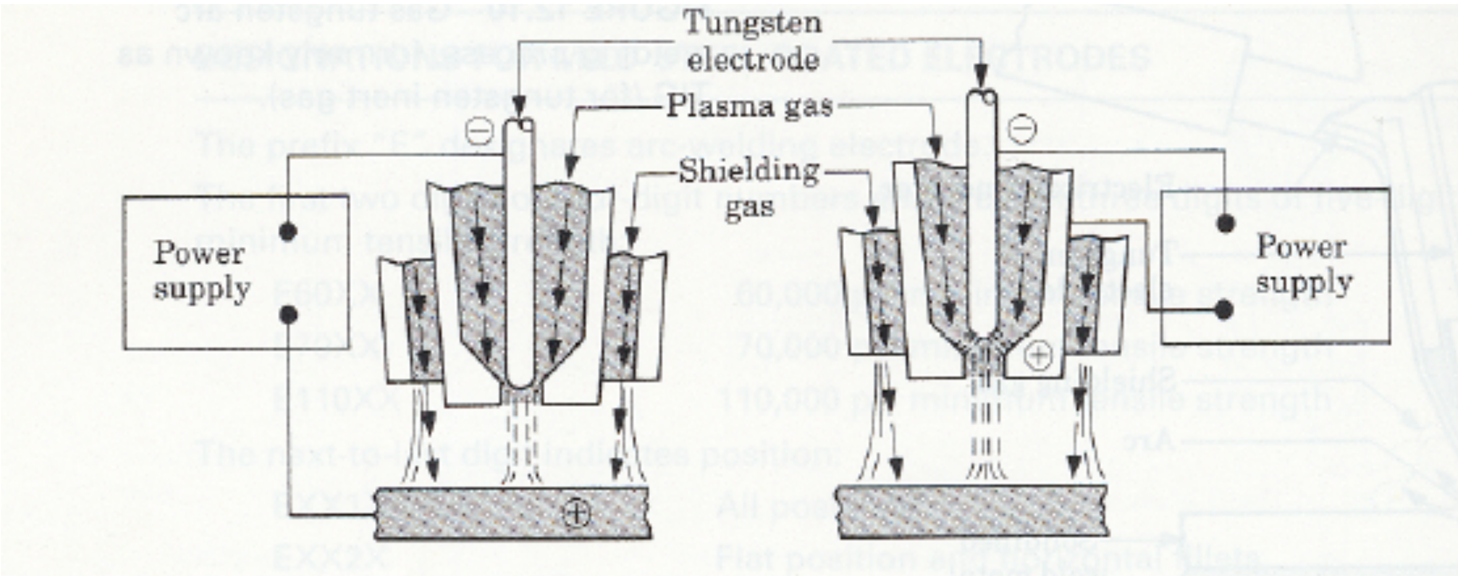
# Process Capabilities

- Weld rates up to 1.5 m/min
- Minimum sheet thickness = 0.1 mm
- Maximum sheet thickness = 6 mm for carbon, stainless and low alloy steels, Mg and Ni alloys
- Maximum sheet thickness = 15 mm Al and Ti alloys
- Maximum sheet thickness = 3 mm for Cu and refractory alloys
- Multiple passes required on sheet thickness ≥ 4 mm
- Typical tolerance: $\pm$ 0.5 mm
- Surface finish of weld is excellent

# GTAW

- Advantages
  - All levels of complexity possible
  - Low distortion can be achieved
  - Automation suited for continuous weld in same plane and relatively inexpensive if no filler is required
  - Economical for low production runs
- Limitations
  - Direct labor costs can be high
  - Filler wire must closely match the composition of the metals being welded
  - Not recommended for site work in wind
  - Heat affected zone is present stress relieving may be required

# Plasma Arc Welding (PAW)




a. Transferred b. Non-transferred



*Source: S. Kalpakjian, 3rd Edition*

# Process Description

- Shielded by external source, such as argon, helium and their mixture
- Tungsten is used as non-consumable electrode
- Concentrated plasma is produced and aimed at the weld area
- Filler metal wire may be used
- Current can be as high as 100 A
- Temperature can be as high as $33{,}000^0$C

# Process Capabilities

- Weld rates vary from 0.12 to 1 m/min
- Maximum sheet thickness = 6 mm and 20 mm for Al and Ti alloys
- Wide variety of materials can be welded
- Typical tolerance: $\pm$ 0.5 mm
- Surface finish is good

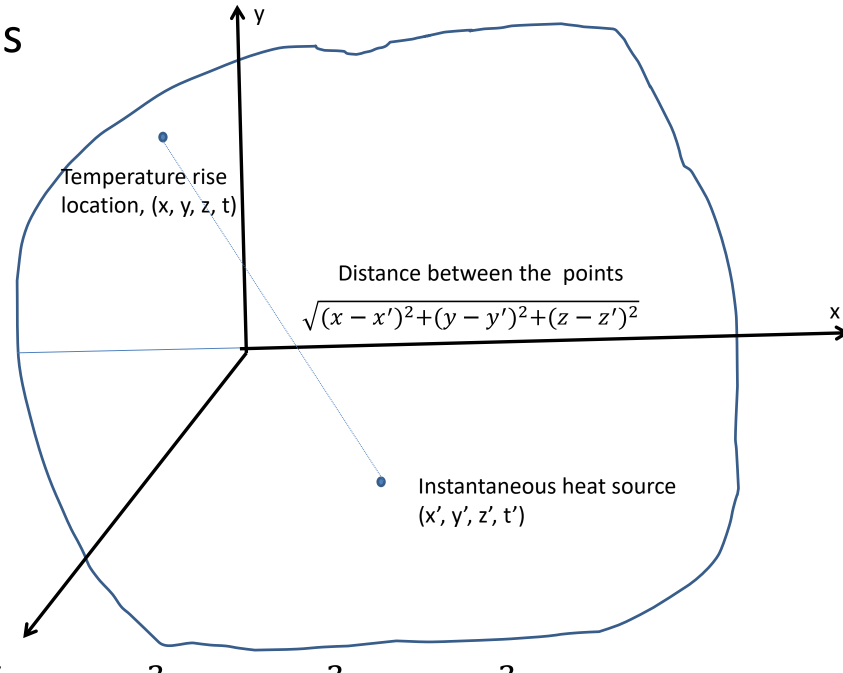
# PAW

- Advantages
  - Low distortion can be achieved
  - Higher energy concentration and better arc stability
  - Automation suited for continuous weld in same plane and relatively inexpensive if no filler is required
  - Economical for low production runs
- Limitations
  - Very High temperatures are encountered
  - Filler wire must closely match the composition of the metals being welded
  - Not recommended for site work in wind
  - heat affected zone is present

# Thermal Modeling: Instantaneous point heat source

The differential equation for the conduction of heat in a stationary medium assuming no convection or radiation, is

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+q=\frac{1}{\alpha}\frac{\partial T}{\partial t}$$



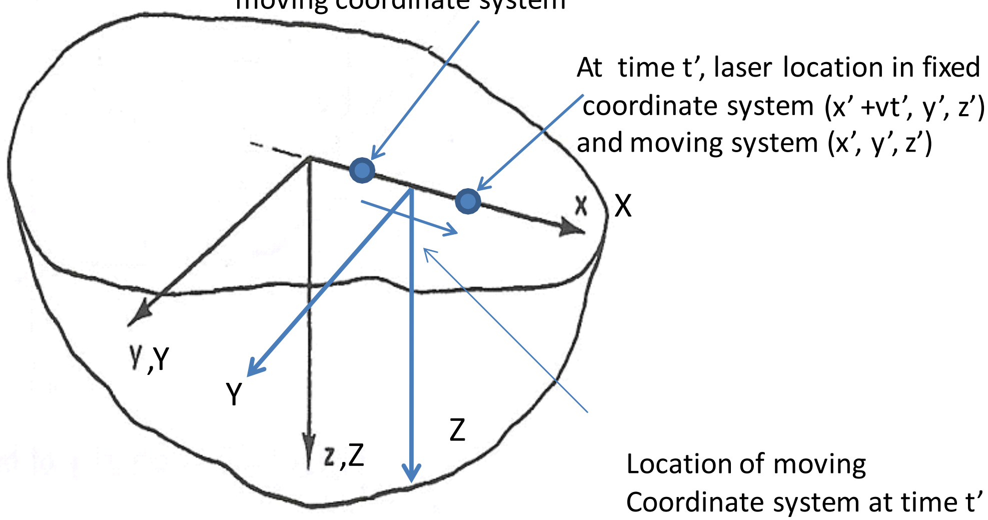

This is satisfied by the

solution for infinite body,

$$\mathrm{d}T(x,y,z,t)=\frac{\delta q}{\rho C\left(4\pi a(t-t')\right)^{3/2}}exp\left[-\frac{(x-x')^2+(y-y')^2+(z-z')^2}{4a(t-t')}\right]$$

gives the temperature rise at position (x, y, z) and time t due to an instantaneous heat source δq applied at position (x', y', z') and time t'; where δq = instantaneous heat generated, C = sp. heat capacity, α = diffusivity, ρ = Density, t = time, K = thermal conductivity.

# Moving point heat source in semi-infinite body




Moving laser source along X -axis in a semi -infinite body

In moving coordinate system:

$$dT(X,Y,Z,t)=\frac{2\delta q}{\rho C(4\pi a(t-t'))^{\frac{3}{2}}}\exp[-\frac{(X-x')^2+(Y-y')^2+(Z)^2}{4a(t-t')}]$$

In fixed coordinate system:

$$dT(x,y,z,t)=\frac{2\delta q}{\rho C(4\pi a(t-t'))^{\frac{3}{2}}}\exp[-\frac{(x-vt'-x')^2+(y-y')^2+(z)^2}{4a(t-t')}]$$

Note that $\delta q = Pdt'$

# Line heat source in infinite body:

Temperature for the line heat source can be obtained directly by integrating the solution of the point source in the moving coordinate system.

- line source in moving coordinate:

Line source parallel to z-axis and passing through point (x' , y') in moving system. The temperature obtained by integrating , where C = sp. heat capacity, ρ = Density, K = thermal conductivity. Here Ql = heat per unit length

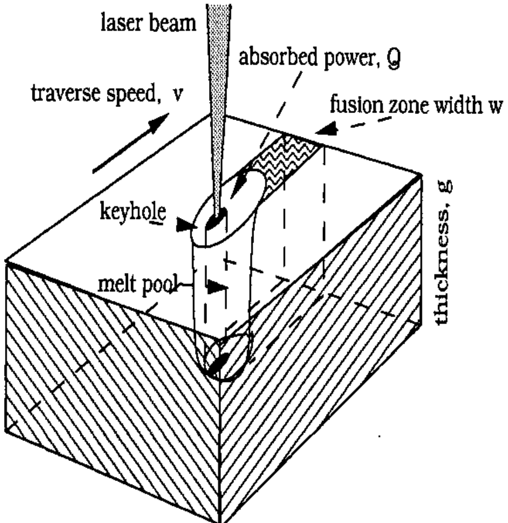



Fig. keyhole model (W. Steen)

For infinite body

$$dT'(X,Y,Z,t)=\frac{\delta q}{\rho C(4\pi a(t-t'))^{\frac{3}{2}}}\exp[-\frac{(X-x')^2+(Y-y')^2+(Z-z')^2}{4a(t-t')}]$$

This point source in moving coordinates can be superposed for infinite line along z,

$$dT'(X,Y,t)=\frac{q_l dt'}{\rho C(4\pi a(t-t'))^{\frac{3}{2}}}\int_{-\infty}^{\infty}\exp[-\frac{(X-x')^2+(Y-y')^2+(Z-z')^2}{4a(t-t')}]dz$$

# Infinite line source

- Integrating in moving coordinate system with respect to spatial variables,

$$dT(\mathrm{X},\mathrm{Y},t) = \frac{q_l dt'}{4\pi k(t-t')} \exp\left[-\frac{(X-x')^2+(Y-y')^2}{4a(t-t')}\right]$$

- Convert to stationary frame and integrate to time

X= x-vt’, Y=y and Z=z

$$T - T_0(x,y,t) = \int_{t'=0}^{t} \frac{q_l\, dt'}{4\pi k(t-t')} \exp\left[-\frac{(\mathrm{x}-\mathrm{vt}'-x')^2+(\mathrm{y}-y')^2}{4a(t-t')}\right]$$

This can be integrated numerically

# Moving line heat source

- Using the same concept used in stationary continuous point where the laser (heat source) started at t' =-$\tau$, and at time $\tau=0$ the laser source is at origin (x'=0 and y'=0). One can get solution at (X, Y) from laser source:

$$T(\mathrm{X},\mathrm{Y},t) = \int_0^t \frac{q_l\, d\tau}{4\pi k(\tau)} \exp\left[-\frac{(\mathrm{X}+\mathrm{v}\tau)^2 + Y^2}{4a(\tau)}\right]$$

The steady state solution at t$\rightarrow \infty$ ,

$$T(X,Y) = \frac{q_l}{2\pi k} e^{-\frac{v\,X}{2\alpha}} BesselK\left(0, \frac{v\sqrt{X^2+Y^2}}{2\alpha}\right)$$

Bessel function of second kind 0 order

It may be noted that it is a steady-state solution and X, Y are from the laser center

# Analysis of Welding

- Motivation
  - Martensite formation, especially in HAZ (Heat Affected Zone) surrounding the fusion area, can result in cracks and failure initiation sites
  - To calculate the time required to avoid fully martensitic regions in HAZ which is estimated by time required for the weld to cool from 800$^{o}$C to 500$^{o}$C, $\tau_{8/5}$

# Instantaneous Infinite Line Heat Source

Time dependent equation for heat transfer from a instantaneous line heat source:

$$dT(\mathrm{X},\mathrm{Y},t) = \frac{Q}{4\pi k(t-t')}\exp\left[-\frac{(X-x')^2+(Y-y')^2}{4a(t-t')}\right]$$

Temperature rise at current time for infinite instantaneous line heat source released at time -t

$$T - T_0 = \frac{Q}{4\pi kt}\exp\left[-\frac{r^2}{4at}\right]$$

where:

T = Metal temperature
k = Thermal conductivity
a = diffusivity
Q = heat/unit length in J/m

# Cooling Times

- Time required to avoid fully martensitic regions in HAZ in case of thick welding (more than six passes). The heat transfer equation yields:

$$\tau_{8/5} = \frac{Q}{4\pi\, k}\left[\frac{1}{(500 - T_0)} - \frac{1}{(800 - T_0)}\right]$$

where:

$\tau_{8/5}$ = Centerline cooling time

$T_0$ = Base metal ambient temperature ($^0$C)

Q = Net heat input per unit length to the weld

# Cooling Times

- Time required to avoid fully martensitic regions in HAZ in case of thin plate. The 2-D dimensional heat transfer equation yields:

$$\tau_{8/5} = \frac{(Q/h)^2}{4\pi k\rho C}\left[\left(\frac{1}{500-T_0}\right)^2 - \left(\frac{1}{(800-T_0)}\right)^2\right]$$

where:

h = Base metal thickness

ρ = Base metal density

C = Specific heat of the base metal

# Cooling Times

- Relative thickness parameter, λ, decides whether to use thick or thin plate parameter

$$\lambda = h\sqrt{\frac{\rho C(550 - T_0)}{Q}}$$

λ > 0.75 implies thick plate and λ< 0.75 implies thin plate

# Power

- Power input per unit length is given by:

$$Q = \eta \frac{VI}{v}$$

where:

v = Welding speed

V= Welding voltage

I = Welding current

η = Weld heat transfer efficiency

# Example

Two 12 mm thick alloy steel plates are submerged arc welded together with the following conditions: 25 V , 300 A and an efficiency of 0.9. test weld beads are deposited at speeds of 6, 7, 8, 9 and 10 mm/s and hardness is measured. The hardness is fully martensitic next to fusion zone at 8 mm/s and faster. The ambient temperature is $25^0$C. Estimate the cooling time that results in a fully martensitic zone.

$\rho = 7.8*10^3$ Kg/m$^3$

$C = 0.5*10^3$ J/Kg K

$k = 0.04*10^3$ W/m K

# Solution

Heat input per unit length of the weld:

$$Q = \eta \frac{VI}{v} = 0.9 \frac{25 \times 300}{8 \times 10^{-3}} 844 \times 10^3 \, J/m$$

Relative plate thickness:

$$\lambda = h\sqrt{\frac{\rho C(550 - T_0)}{Q}} = 12 \times 10^{-3} m \sqrt{\frac{7.8 \times 10^3 \, Kg/m^3 \times 0.50 \times 10^3 \, J/Kg^0C(550-25)^0C}{844 \times 10^3 \, J/m}}$$

= 0.59

Implies use of thin sheet formula

# Solution

- Applying thin plate formula

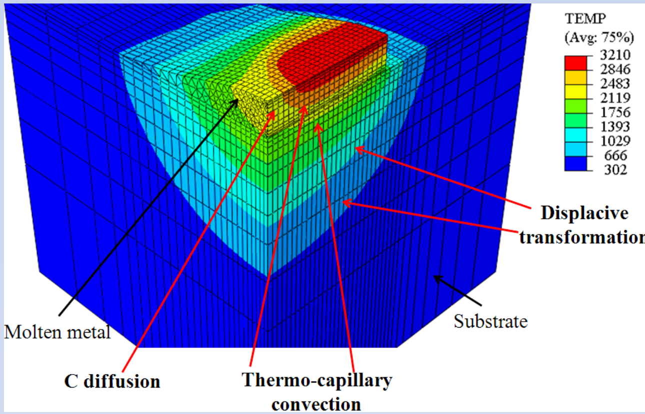
$$\tau_{8/5} = \frac{(Q/h)^2}{4\pi k\rho C}\left[\left(\frac{1}{500-T_0}\right)^2 - \left(\frac{1}{(800-T_0)}\right)^2\right]$$

$$= \frac{\left(\dfrac{844\times10^3\, J/m}{12\times10^{-3}\, m}\right)^2}{4\pi(0.04\times10^3\, J/s.m.^0C)(7.8\times10^3\, Kg/m^3 \times 0.50\times10^3\, J/Kg.^0C}\left[\left(\frac{1}{480}\right)^2 - \left(\frac{1}{780}\right)^2\right] = 6.7s$$

# Algorithm for Moving Heat Source Modeling & Metallo-thermomechanical Analysis in Abaqus

Ashby & Esterling, *1984*
Ramesh & Melkote, *2008*

**AC1:** Austenization start temperature of substrate
**AC3:** Austenization end temperature of substrate
**NT:** Nodal temperature




Start of increment

Define the co-ordinates of the starting point and the moving heat source using DFLUX

Read nodal temperature (NT) at material point

NT > Vaporization temperature (powder) ??

Yes/vaporized

No

Melting temperature (substrate) ≤ NT ≤ Vaporization temperature (powder) ??

Yes/molten

Initial melt pool

Tanner's Law

Clad geometry
Contact angle

No

AC3 < NT < Melting temperature (substrate) ??

No

AC1 ≤ NT ≤ AC3 ??

HAZ

Yes

Transformed

End increment

Strain due to differential thermal expansion & contraction (Clad)

$$\varepsilon_{ij}^{th\_\alpha}(T) = \alpha_T(T)(T - T_{ref}) - \alpha_T(T_0)(T_0 - T_{ref})$$

Volume dilation strain (Transformed)

$$\varepsilon_{ij}^{TF} = \frac{1}{3}(0.044\,F_m)\delta_{ij}$$

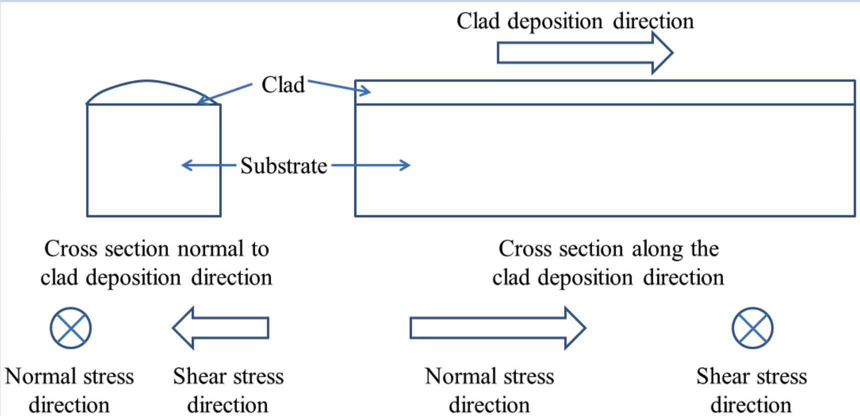
Transformation plasticity strain (Clad)

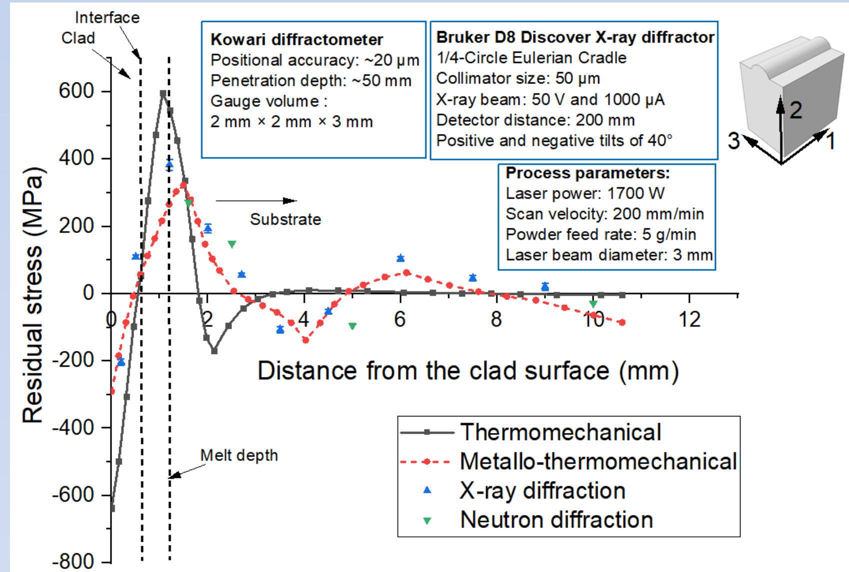
$$\varepsilon_{ij}^{TP} = 3K_{TP}F_m\left(1 - \frac{F_m}{2}\right)S_{ij}$$

Total strain, $\varepsilon_{ij} = f\left(\varepsilon_{ij}^{el}, \varepsilon_{ij}^{p}, \varepsilon_{ij}^{th\_\alpha}, \varepsilon_{ij}^{TP}, \varepsilon_{ij}^{TF}\right)$

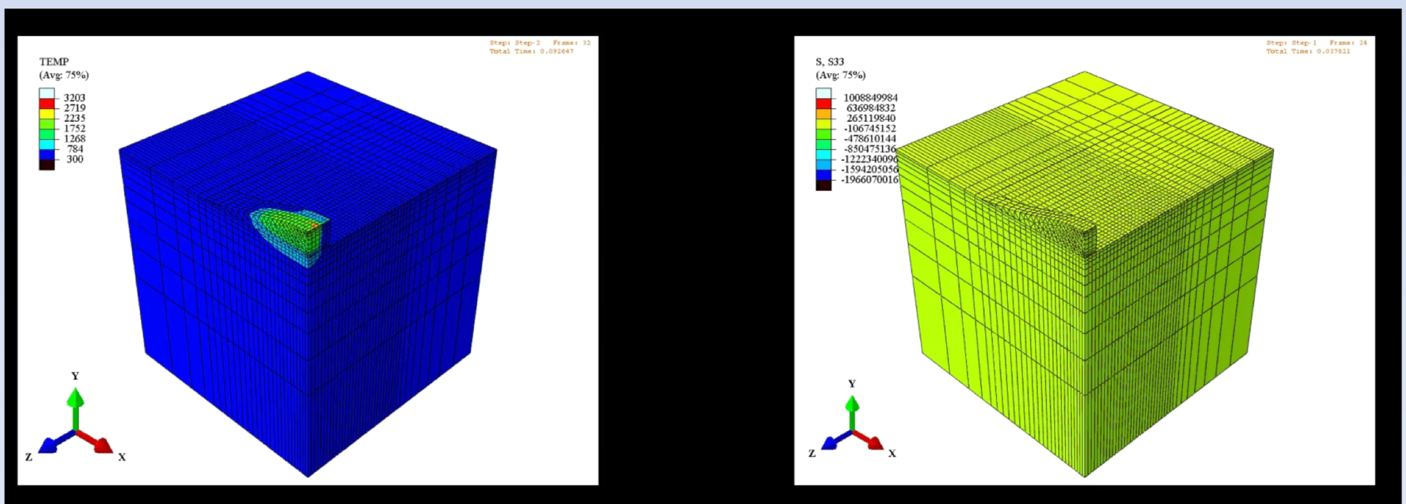
Stress-strain relationship, $\sigma_{ij} = C_{ijkl}\left(\varepsilon_{ij} - \varepsilon_{ij}^{p} - \varepsilon_{ij}^{th}\right)$

# Residual Stress Evolution




Direction of residual stress measurement



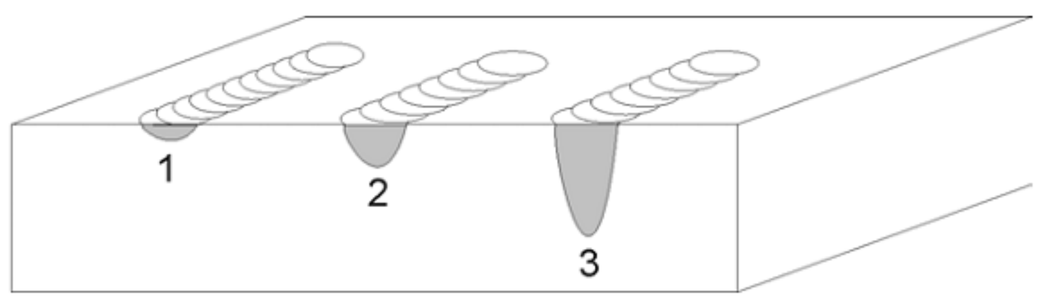

Contour of residual stress along normal direction

# Other Joining Processes

- Laser Welding
- Electron Beam Welding
- Solid State Welding
  - Electrical Resistance Welding
  - Friction Welding
  - Diffusion Bonding
- Brazing
- Soldering

# Laser Welding-Basics

- Laser welding is a non-contact process that requires access to the weld zone from one side of the parts being welded
- The weld is formed as the intense laser light rapidly heats the material-typically calculated in milli-seconds.
- There are typically three types of welds:
  - Conduction mode
  - Conduction/penetration mode
  - Penetration or keyhole mode.



# Laser Welding-Basics

- Conduction mode welding is performed at low energy density forming a weld nugget that is shallow and wide.
- Conduction/penetration mode occurs at medium energy density, and shows more penetration than conduction mode.
- The penetration or keyhole mode welding is characterized by deep narrow welds.
  - In this mode the laser light forms a filament of vaporized material know as a “keyhole” that extends into the material and provides conduit for the laser light to be efficiently delivered into the material.
  - This direct delivery of energy into the material does not rely on conduction to achieve penetration, and so minimizes the heat into the material and reduces the heat affected zone.

# Process Capabilities of Laser Welding

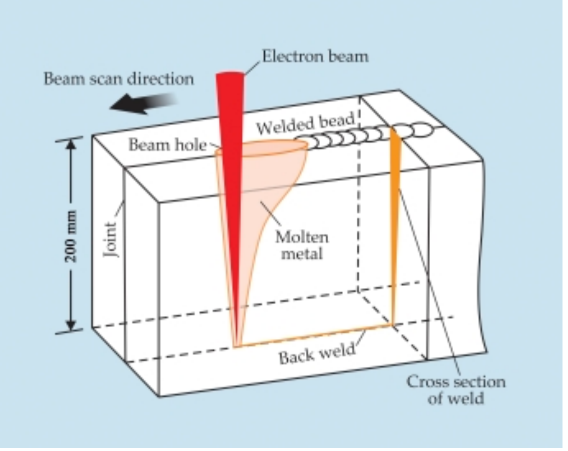
- Sheets up to 12 mm can be joined using high power lasers (~15 kW fiber lasers)
- The speeds can be as high as 80 inches/min for high power lasers
- Very high thicknesses up to 40 mm can be joined by a 65 kW $CO_2$ laser
- The cost of high power lasers are very expensive and thick section welding is typically not recommended by laser welding processes
- Best suited for sheet metal welding but it is difficult for reflective materials, such as aluminum and copper
- It can be easily automated and the weld quality is exceptional

# Electron Beam Welding

- The electron beam welding process is used in automotive in-line part production to single part batch processes in the high-cost aerospace components
- The electrons are generated if the current passes through a filament in vacuum
- An electrostatic field accelerates the electrons to 0.5 to 0.8xspeed of light and shapes them into a beam for welding
- Electron beam welders use this characteristic to electromagnetically focus and very precisely deflect the beam at speeds up to 200 kHz via a pattern generator to reduce porosity
- The kinetic energy of each electron in the beam is converted into thermal energy. This transformation is stable in the high 90% range for all metals regardless of whether the electrons hit the surface at a perpendicular or shallow angle which makes the process robust

# E-Beam Welding

- All grades of steel can be welded
- Low melting alloys such as aluminum and magnesium
- High melting materials such as Nickel- and Cobalt-based alloys.
- The pattern generator, unique to the EB welding process, has proven to be very powerful in stabilizing the key hole to improve the process' robustness and produce defect-free welds.



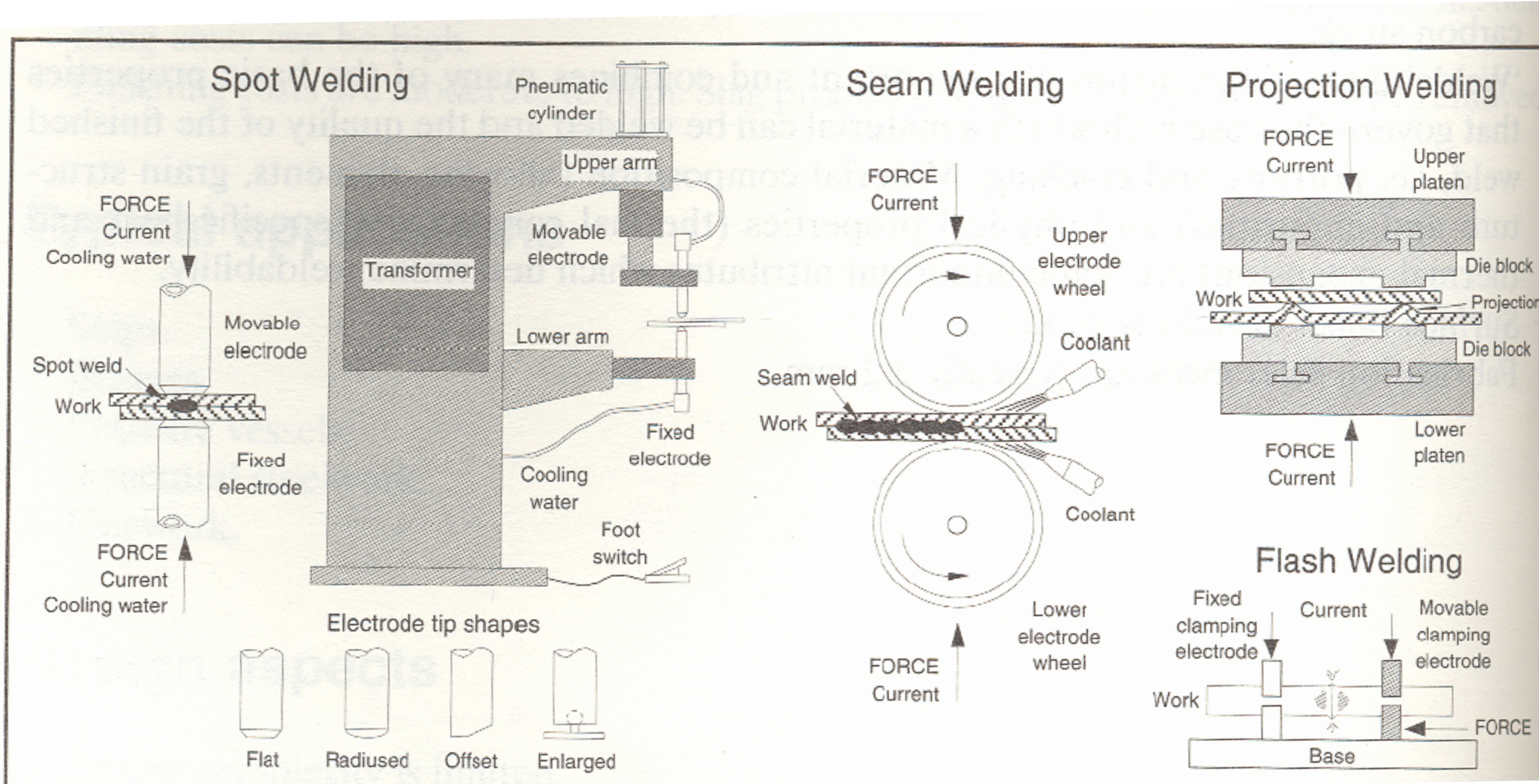

https://ptreb.com/electron-beam-welding-information/technical-papers/electron-beam-welding-process-applications-and-equipment#Page6

# Solid State Welding

- Fusion welding
- brazing
- Solid phase bonding

| Solid phase bonding | |
|---|---|
| Diffusion bonding | Use atoms diffusion by load and temperature |
| Cold pressure welding | Join parts with active treated surface materials (like a Si wafer) |
| Explosive welding | use high speed explosion impact to join 2 different material |
| Forge welding | Join under pressurized bare metal and steel in half welding condition |
| Friction welding | Use bonding generate heat through moving parts by flection. |
| Ultrasonic bonding | Use ultrasonic bonding |
| Friction stir welding | Friction stir welding (FSW) use special tool to rotate tool and mixing up each materials |

# Electrical Resistance Welding




Courtesy: Process Selection, Swift & Booker

# Process Variations

- Spot welding
- Seam welding
- Projection welding
- Flash welding

# Process Description

- Requires no filler metal or fluxes
- Can achieve high speed production
- Is easily automated
- Does not require skilled operators
- Is used primarily on sheet metal
- Uses nonconsumable, low resistance, copper alloy electrodes

# Process Capabilities

- High production rate due to short welding time
- Minimum sheet thickness = 0.3 mm
- Maximum sheet thickness = 6 mm
- Mild steel sheets up to 20 mm with expensive equipment and high current
- Materials handled are low carbon steels
- Cast iron and high carbon steel is not recommended
- Alignment tolerances for flash welding are typically 0.1-0.25 mm total
- Repeatability of $\pm$0.5 mm - 1mm in robot spot welding
- Surface finish is fair to good

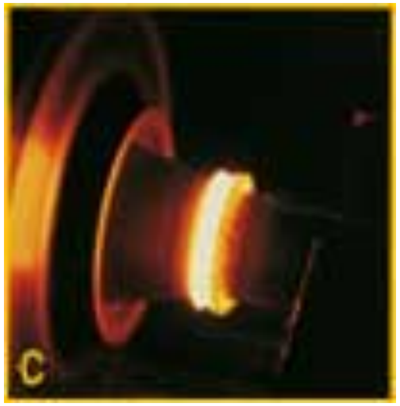
# Electrical Resistance Welding

- Advantages
  - Full automation and integration with component assembly is relatively easy
  - Little or no post-welding heat treatment is required
  - Labor and finishing costs are low
  - No filler material or fluxes required
  - Economical for low production runs
- Limitations
  - Equipment costs are high
  - Access to weld area is important
  - Spot, seam and projection could be difficult to inspect
  - Possibility of galvanic corrosion in case of dissimilar metal welding

# Friction Welding


Two unique materials are rubbed together at a controlled rotational speed


Rotational rubbing motion causes materials to heat up and become plasticized




Axial force is applied for a specific amount of time and upset to create a bond


Rotators are used to control the rotational speed and force for each material

Courtsey: http://www.teamafw.com/wjournal.htm
American Friction Welding Inc.

# Process Description

- Parts are loaded into welder, one in rotating spindle and the other in a stationary clamp
- Component in spindle is brought up to pre-determined rotational speed and then a pre-determined axial force is applied
- Rotation is stopped and increased axial force is applied until desired upset is obtained.
- Environmentally friendly process, no fumes, gases or smoke generated
- Being a solid state process the possibility of porosity and slag inclusions are eliminated

# Process Variations

- Friction Welding
- Linear Friction Welding (Linear vibrations)
- Friction Stir Welding (A rotating tools stirs the material)

Refer to the process videos

# Process Capabilities

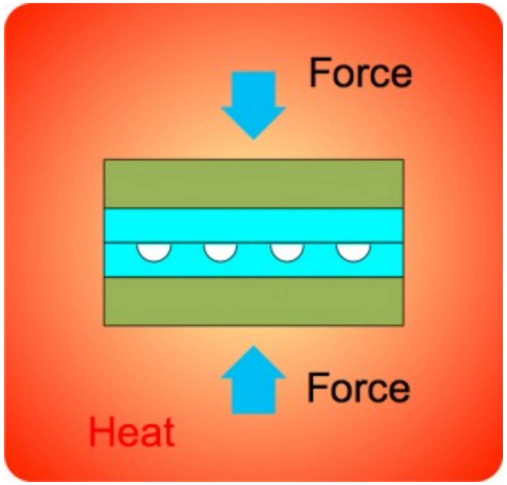
- Rotation speed as high as 900m/min
- Maximum diameter of solid steel bars = 100 mm
- Maximum diameter of hollow steel pipes = 250 mm
- Materials handled are low carbon steels, stainless steels, Al alloys, Non ferrous materials, Titanium and Tungsten carbide
- Dissimilar metals can be welded
- An airtight weld is made across entire cross section, eliminating the risk of porosity, voids, leaks or cracks
- Surface finish is good

# Friction Welding

- Advantages
  - Dissimilar materials normally not compatible for welding can be friction welded
  - No fluxes, filler metal or gases required
  - Joint preparation is minimal, saw cut surface most commonly used
  - Consistent and repetitive process
  - Reduces machining labor, which in turn increases capacity and reduces perishable tooling costs
  - Suitable for quantities ranging from prototype to high production
- Limitations
  - Equipment costs are high
  - One of the components should have rotational symmetry
  - Possibility of galvanic corrosion in case of dissimilar metal welding

# Diffusion Bonding

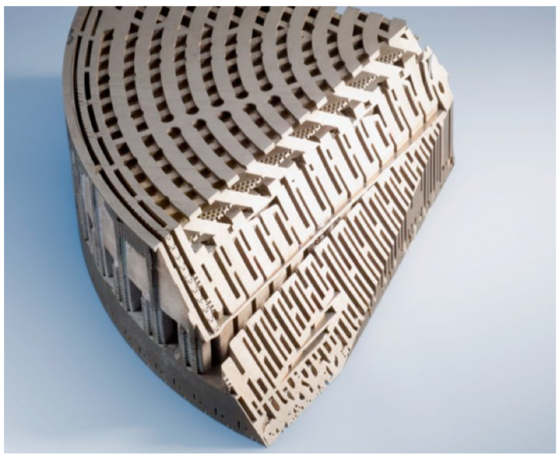
- Diffusion bonding is a technology to bond materials together by applying heat and force to the materials, using diffusion of atoms.
- The materials are joined  together without melting
- Diffusion binding is technology to bond plane surface by layer by layer. Also it could bond different metal and ceramics each other with no interlayer metals. (Metal-to-metal bonding)
- Able to produce fluid device which has tiny fluid channels, or precise 3D hollow structures.




http://www.welcon.co.jp/tech/diffusionbonding/

# Diffusion Bonding

- It needs vacuum furnace so a bit cost intensive
- Can create complex hollow structures which is difficult by other methods



http://www.vpei.com/diffusion-bonding/vpe35-0051-1/

# Summary

- Welding basics
- Arc welding processes
  - SMAW
  - SAW
  - GMAW
  - GTAW
  - PAW
  - Analysis
- Other joining processes