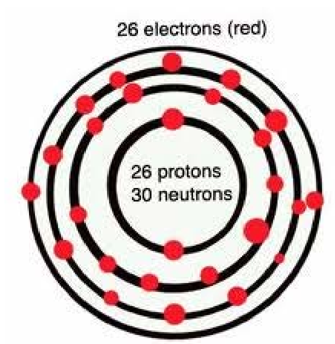
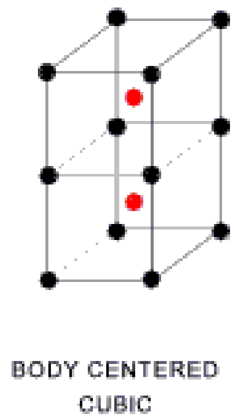
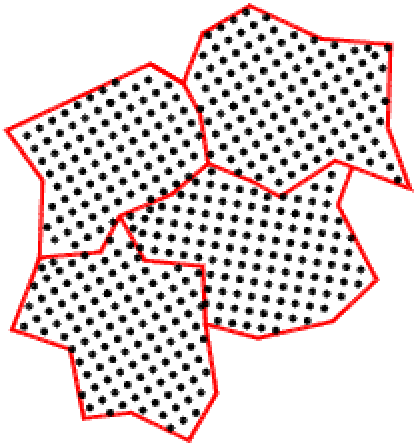
Welding Lectures 3-8

26 July 2016, Tuesday, 10.00-11.50 am
02 Aug 2016, Tuesday, 10.00-11.50 am
09 Aug 2016, Tuesday, 10.00-11.50 am

Some material science basics…







Atoms

Lattice

Grains

- Grain size, Grain boundaries,
- **<u>Recrystalization</u>** ~0.4-0.6 $T_m \rightarrow$ Atoms remain in lattice, but new grains will be formed
- **<u>Melting</u>** $\rightarrow$ Atoms displaced from lattice, free to move

Some material science basics…

- Metals are crystalline in nature and consists of irregularly shaped grains of various sizes
- Each grain is made up of an orderly arrangement of atoms known as lattice
- The orientation of atoms in a grain is uniform but differ in adjacent grains

Basic Classification of welding

(a) Fusion welding (b) solid-state welding

a) Fusion Welding

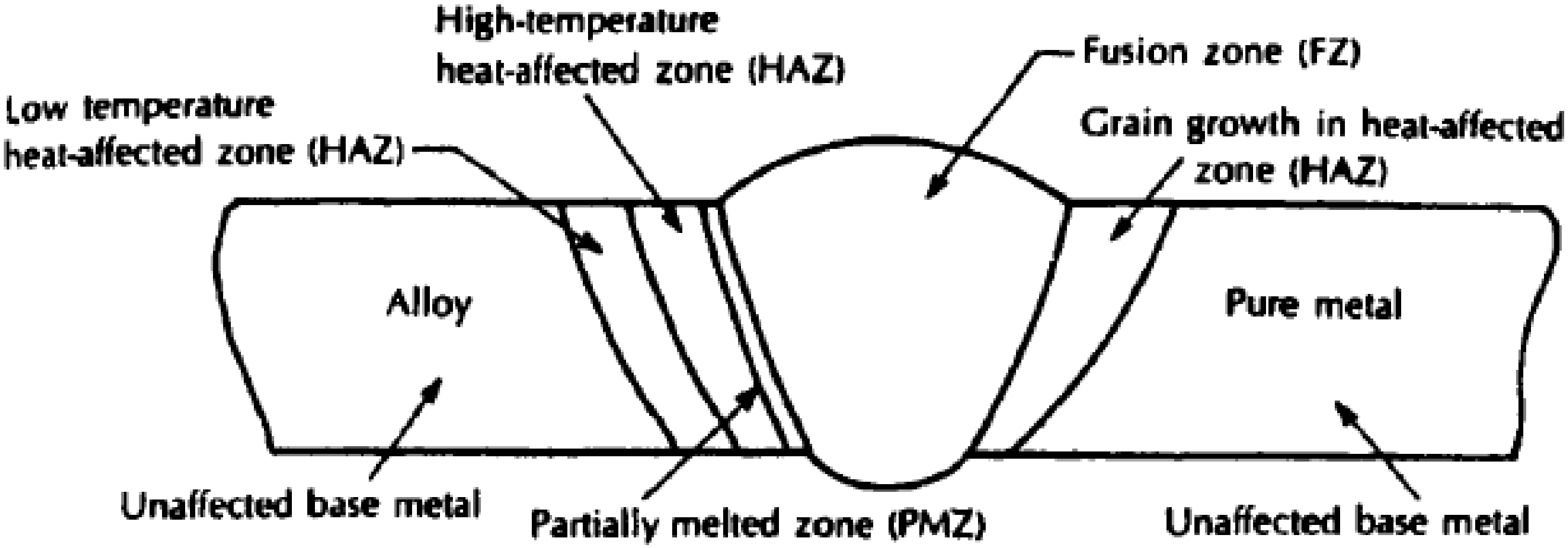
- Uses heat to melt the base metals
- A filler metal is mostly added to the molten pool to facilitate the process and provide bulk and strength to the welded joint.
- e.g., Arc welding, resistance welding, Gas welding, Laser beam welding, Electron beam welding

Basic Classification of welding

b) Solid state Welding

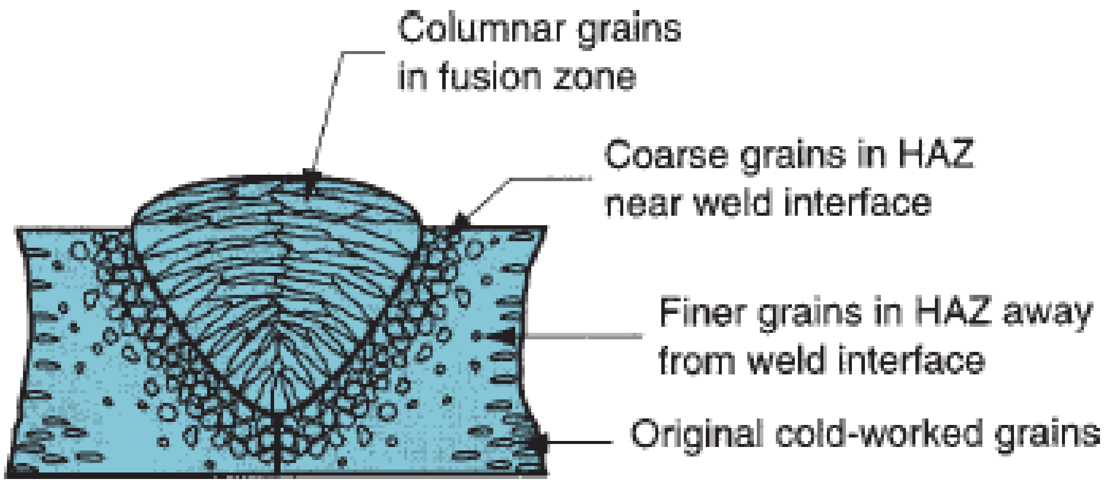
- Coalescence results from application of pressure alone or a combination of heat and pressure
- If heat is used, the temperature in the process is below the melting point of the metals being welded
- No filler metal is used
- e.g., Diffusion welding, friction welding, ultrasonic welding

Micro-structural zones in Fusion welding



1) Fusion zone 2) Weld interface/partially melted zone
3) Heat affected zone 4) Unaffected base metal

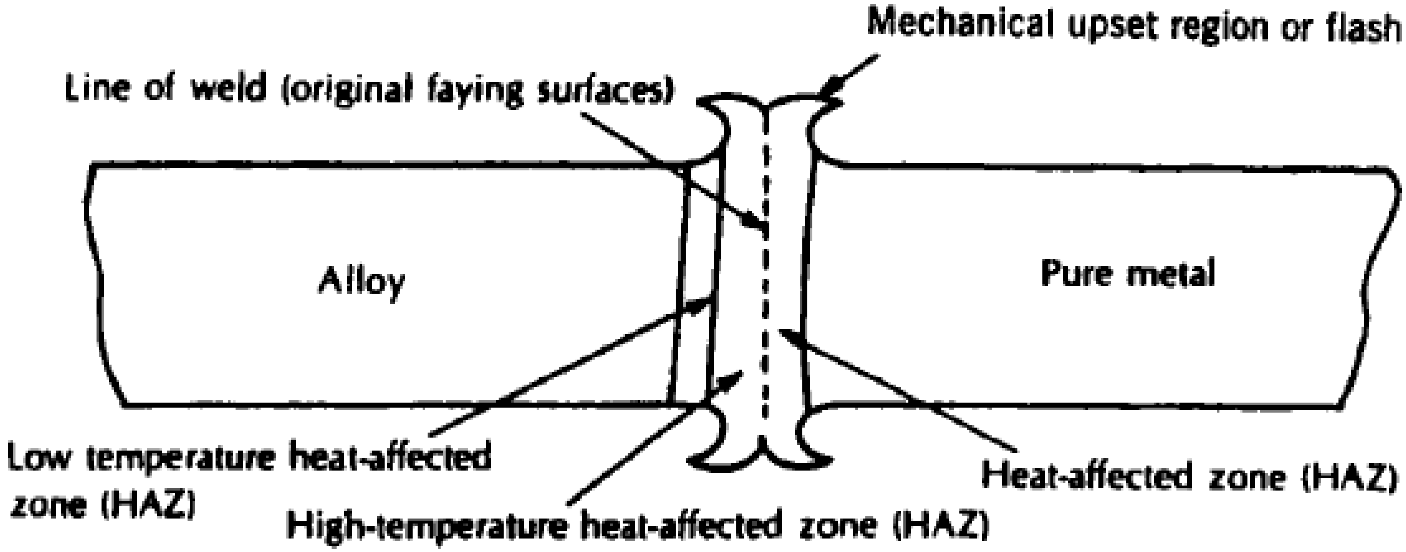
Grain growth in Fusion welding



(b)

- Fusion Zone → Directional solidification → Epitaxial grain growth → Columnar grains
- HAZ → Possible recrystallization/ grain refinement or phase change
- Slow cooling →Coarse grains; Fast cooling → Fine grains
- Shrinkage of fusion zone → Residual stress on the base metal surrounding HAZ

Micro-structural zones in Solid state welding



- No Fusion zone
- Little or no HAZ
- Mechanically upset region (Flash)
- Plastic deformation at the interface

Role of Temperature in Fusion/ solid state welding

- Drives off volatile adsorbed layers of gases, moisture, or organic contaminants
- Breaks down the brittle oxide through differential thermal expansion
- Lowers yield/flow strength of base materials→ helps plastic deformation
- Promotes dynamic recrystallization during plastic deformation (if $T > T_r$)
- Accelerates the rates of diffusion of atoms
- Melts the substrate materials, so that atoms can rearrange by fluid flow (if $T > T_m$)

Role of Pressure in solid state welding

- Disrupts the adsorbed layers of gases/organic compound or moisture by macro- or microscopic deformation
- Fractures brittle oxide or tarnish layers to expose clean base material atoms
- Plastically deform asperities (lattice) to increase the number of atoms that come into intimate contact (at equilibrium spacing)

Mechanisms for obtaining material continuity

(1) Solid-phase plastic deformation, without or with recrystallization $\rightarrow$ Solid state welding

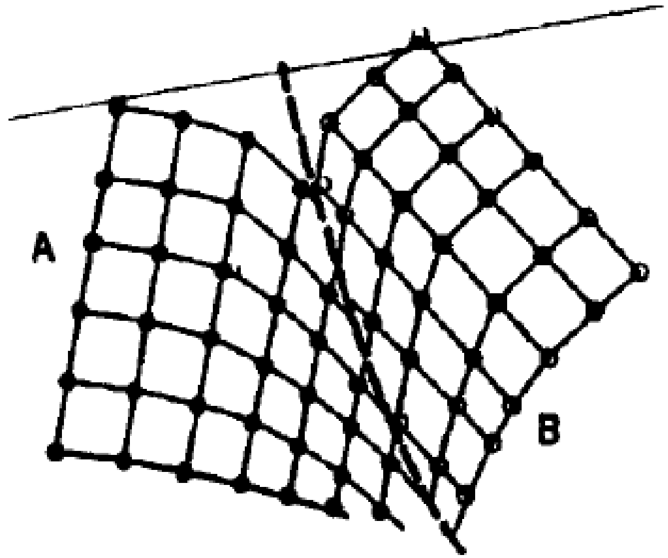
(2) Diffusion, $\rightarrow$ Brazing, Soldering

(3) Melting and solidification $\rightarrow$ Fusion Welding

Obtaining continuity

1a) Solid-phase plastic deformation (**with no heat**)

- Atoms are brought together by plastic deformation
- Sufficiently close to ensure that bonds are established at their equilibrium spacing
- Significant lattice deformation
- Lattices are left in the strained state (distorted) in cold deformation



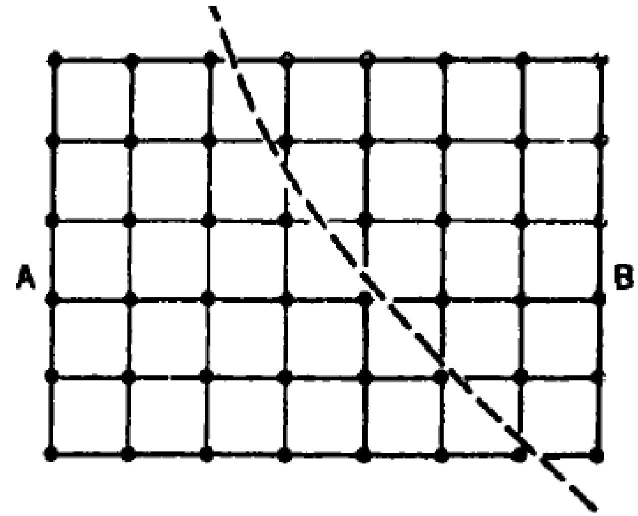
(1a) Cold deformation and lattice strain

Prevailing mechanism in solid state welding with out heat

Obtaining continuity

1b) Solid-phase plastic deformation (**with heat**)

- In hot state (0.4-0.5 T_m), the strained lattice recover from the distorted state
- Atomic rearrangement & Recrystallization
- Grain growth across original interface
- Eliminates the original physical interface



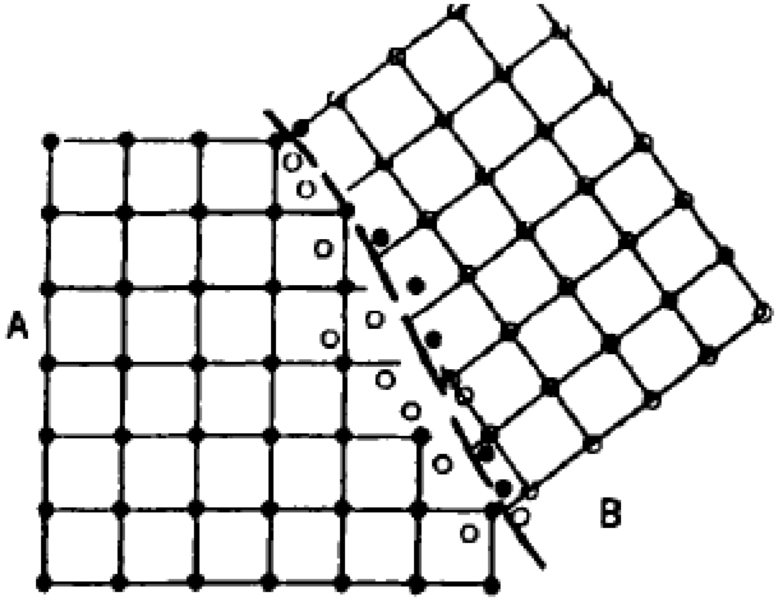
(1b) hot deformation and dynamic recrystallization

Prevailing mechanism in solid state welding with heat

Obtaining continuity

2) Diffusion

- Transport of mass through atom movement
- Can occur entirely in solid phase or with liquid phase
- For dissimilar materials $\rightarrow$ thin layer of alloy at the interface
- Rate of diffusion α Difference in composition (Fick's law), Temperature

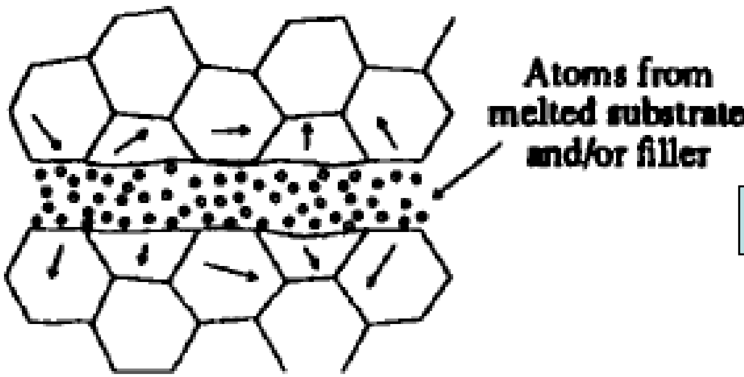


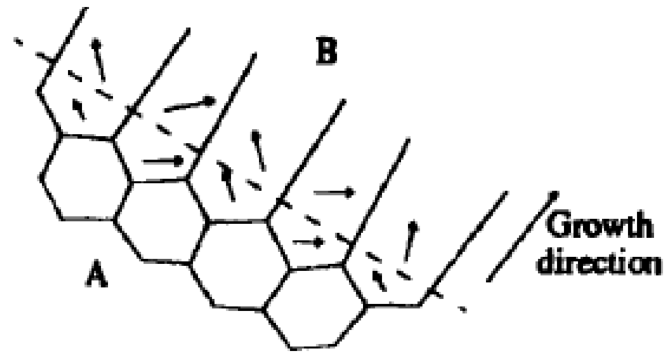
Solid-phase diffusion across the original interface (dotted line)

Prevailing mechanism in brazing/soldering

Obtaining continuity

3) Melting and solidification





Liquid provided by melting the parent materials without or with additional filler

Establishing a bond upon epitaxial solidification of this liquid

- Solidifying crystals take up the grain structure & orientation of substrate/unmelted grains
- Prevailing mechanism in most fusion welding process

Summary: Lectures 1-3

- Overview of welding, applications, advantages, Welded Joint types
- Weld specifications, Symbols
- Fusion & Solid state welding
- Elements of weld setup, Heat Balance, Power density
- **N.B:** Characteristics, micro-structural zones and concept of lattice continuity in fusion & solid state welding

Course details: Welding

	Topic	Hours	Status
1.	Introduction to welding science & technology	2-3	✓
2	Welding Processes	4	
3	Welding Energy sources & characteristics	1-2	
5	Welding fluxes and coatings	1	
4	Physics of Welding Arc	1	
5	Heat flow in welding	1-2	
6	Design of weld joints	2	
7.	Testing and inspection of weld joints	2-3	
8	Metallurgical characteristics of welded joints, Weldability and welding of various metals and alloys	2	
	Total	19	

Welding Processes
1) Oxy-Fuel gas welding

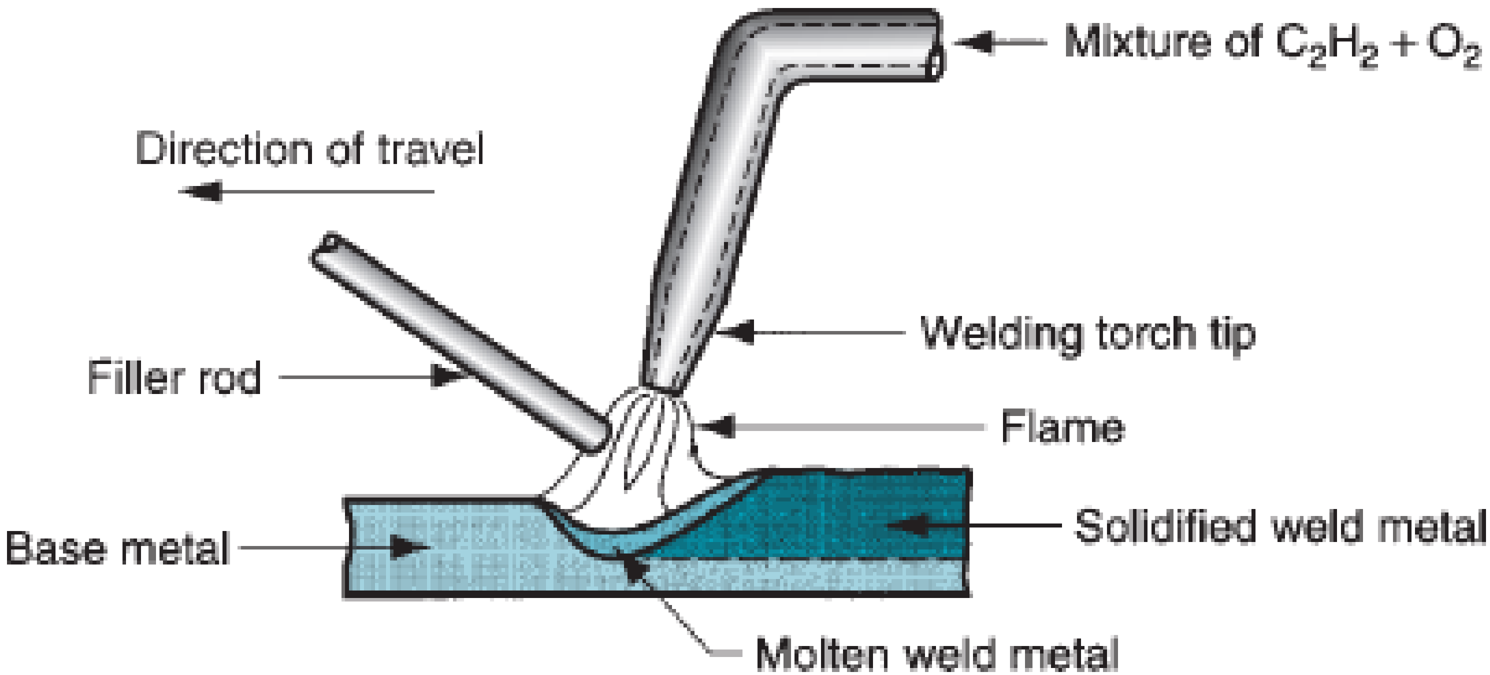
Welding Processes-
1) Oxy-Fuel gas welding

- Uses oxygen as oxidizer
- Acetylene, H_2 or Natural gas, methane, propane, butane or any hydrocarbon as fuel
- Fuel + Oxidizer $\rightarrow$ Energy
- Acetylene is preferred (high flame temperature-3500 °C)

Gases used in Oxy-gas welding

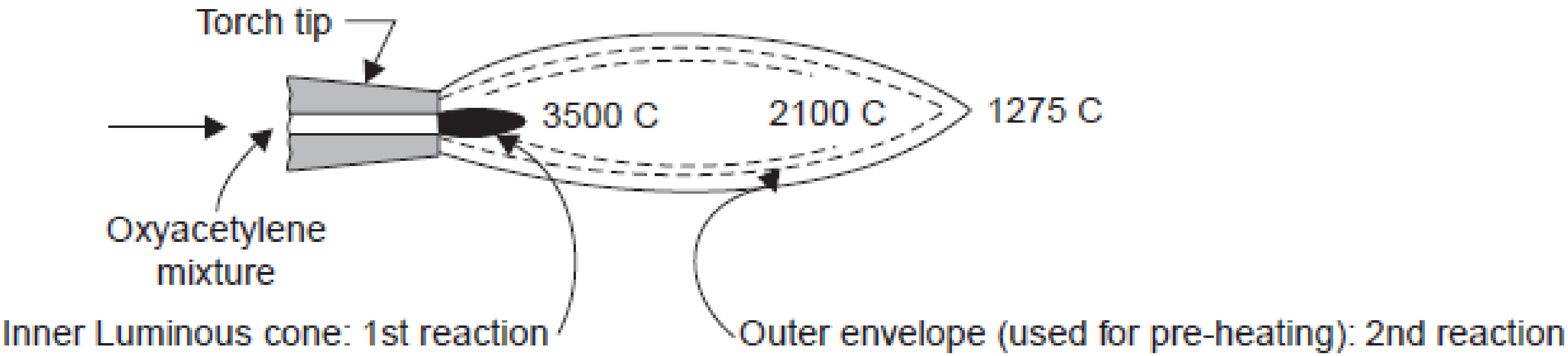
Fuel	Peak reaction Temp (C)	Heat of combustion (MJ/m^3)
Acetylene	**3500**	54.8
Methylacetylene-propadiene (C_3H_4)	2927	91.7
Hydrogen	2660	12.1
Propylene	2900	12.1
Propane	2526	**93.1**
Natural gas	2538	37.3

Oxy-acetylene welding (OAW) operation



Reactions in Oxy-acetylene welding

- Flame in OAW is produced by the chemical reaction of C_2H_2 and O_2 in <u>two stages</u>

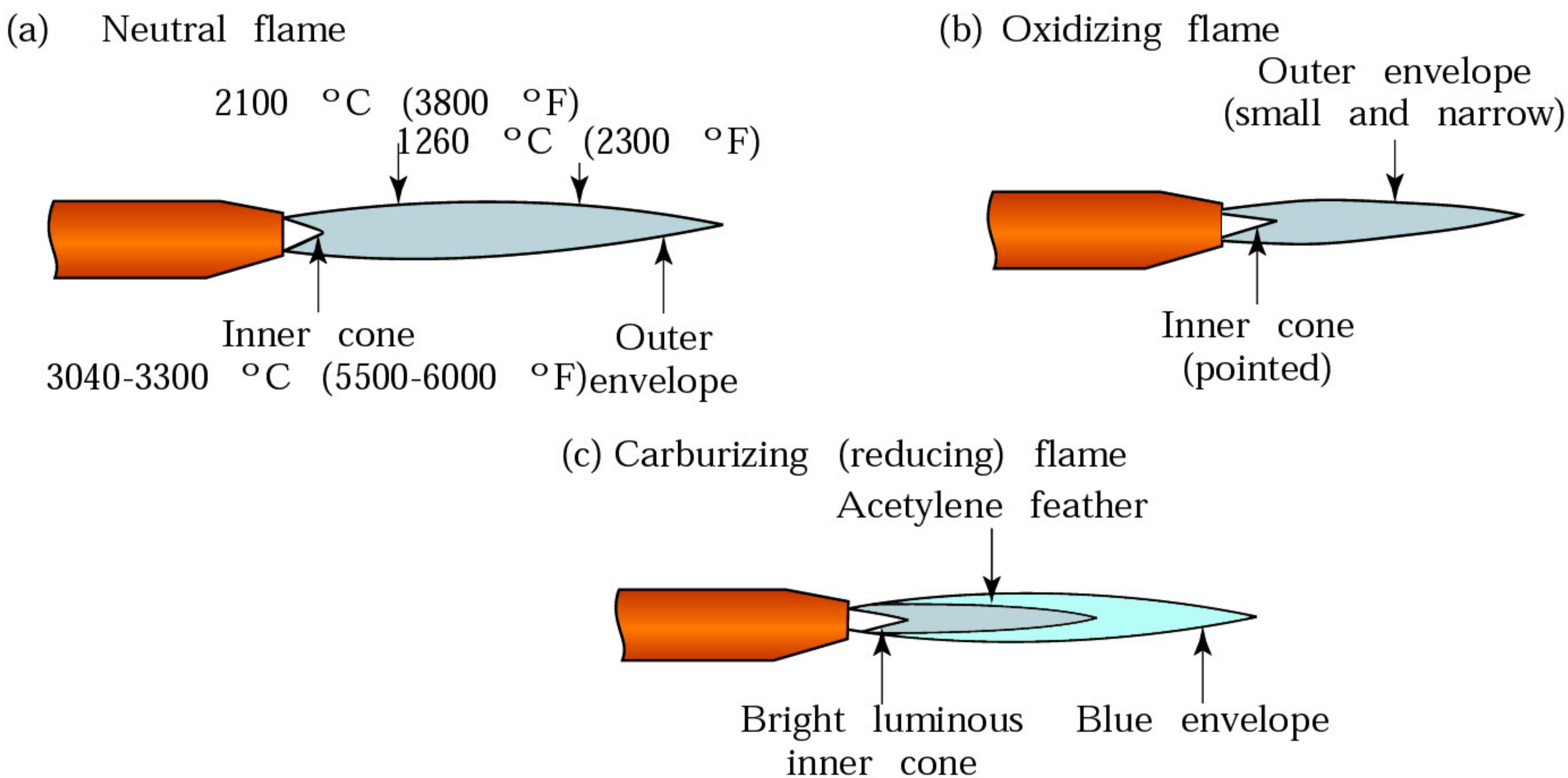


Stage 1 $C_2H_2 + O_2 \rightarrow 2CO + H_2 + \text{Heat (1)}$

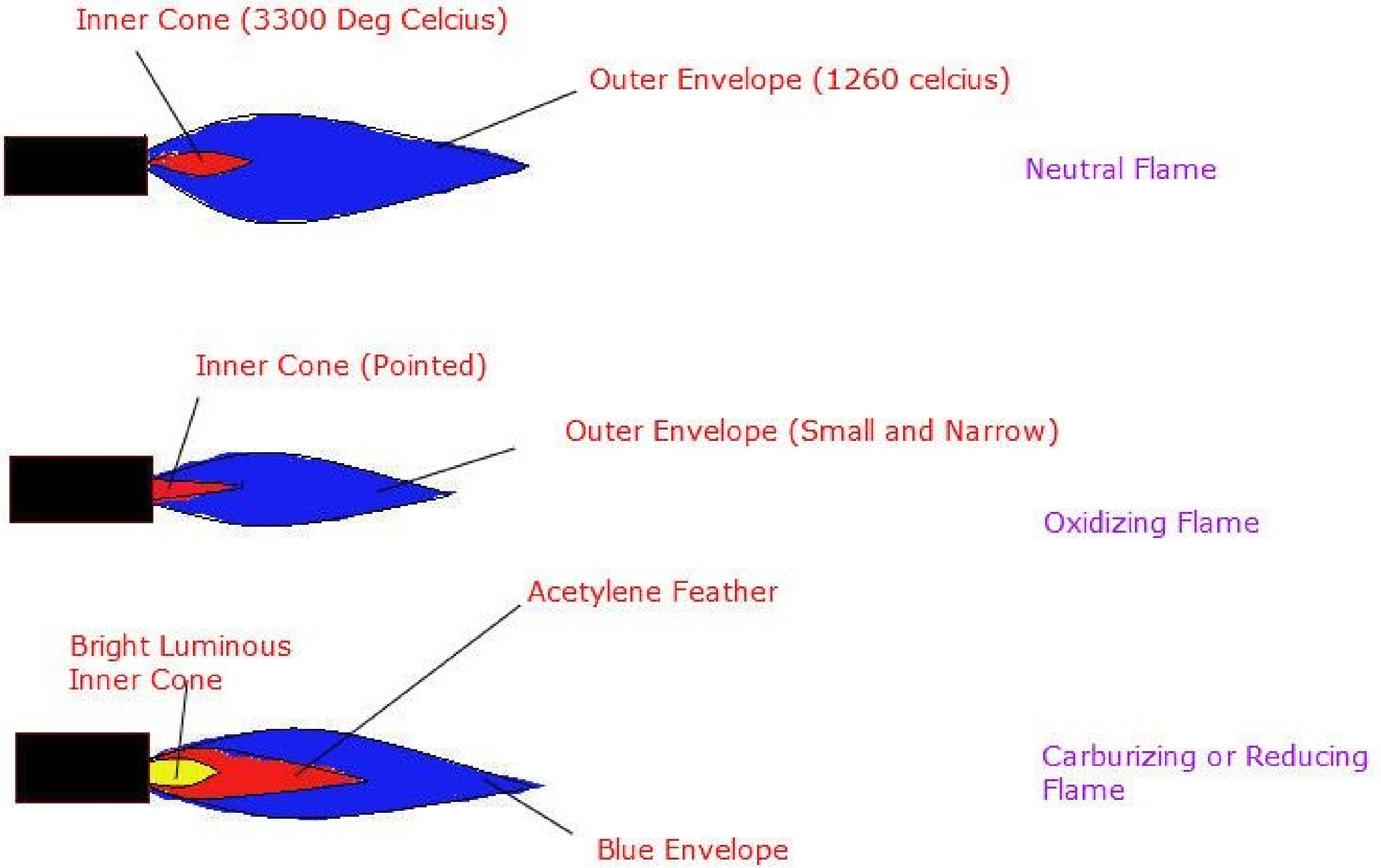
Stage 2 $2CO + H_2 + 1.5O_2 \rightarrow 2CO_2 + H_2O + \text{Heat (2)}$

Heat (1) > Heat (2)

Flames in OAW



Flames in OAW



Neutral flame is used for most applications

Flames in OAW- Reducing flame

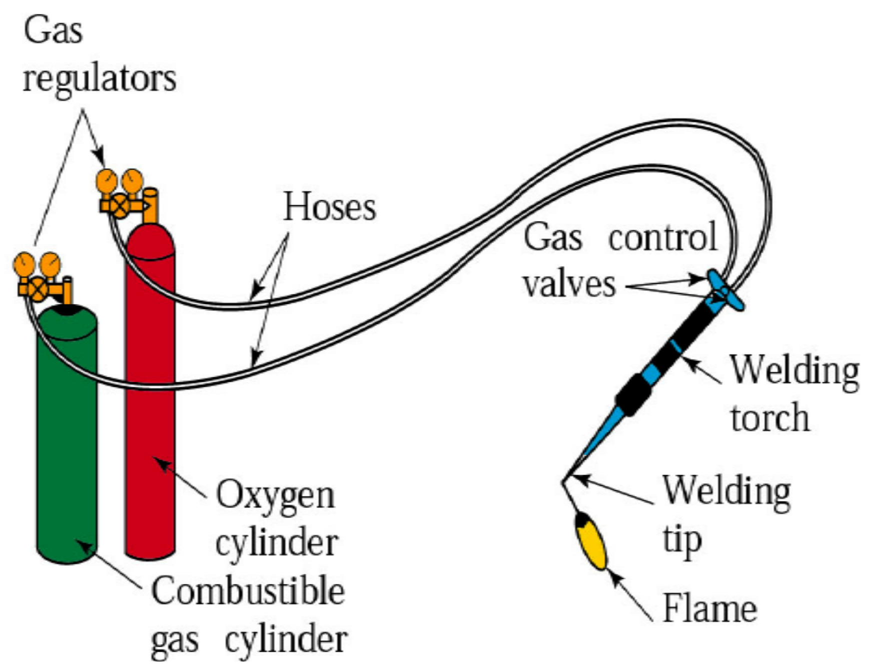
- Reducing flame for removing oxides from metals, such as aluminium or magnesium
- Preventing oxidation reactions during welding
- To prevent decarburization (i.e., C to CO,) in steels.
- Low carbon, alloy steels, monel metal (Ni+Cu+…), hard surfacing

Flames in OAW-Oxy. flame

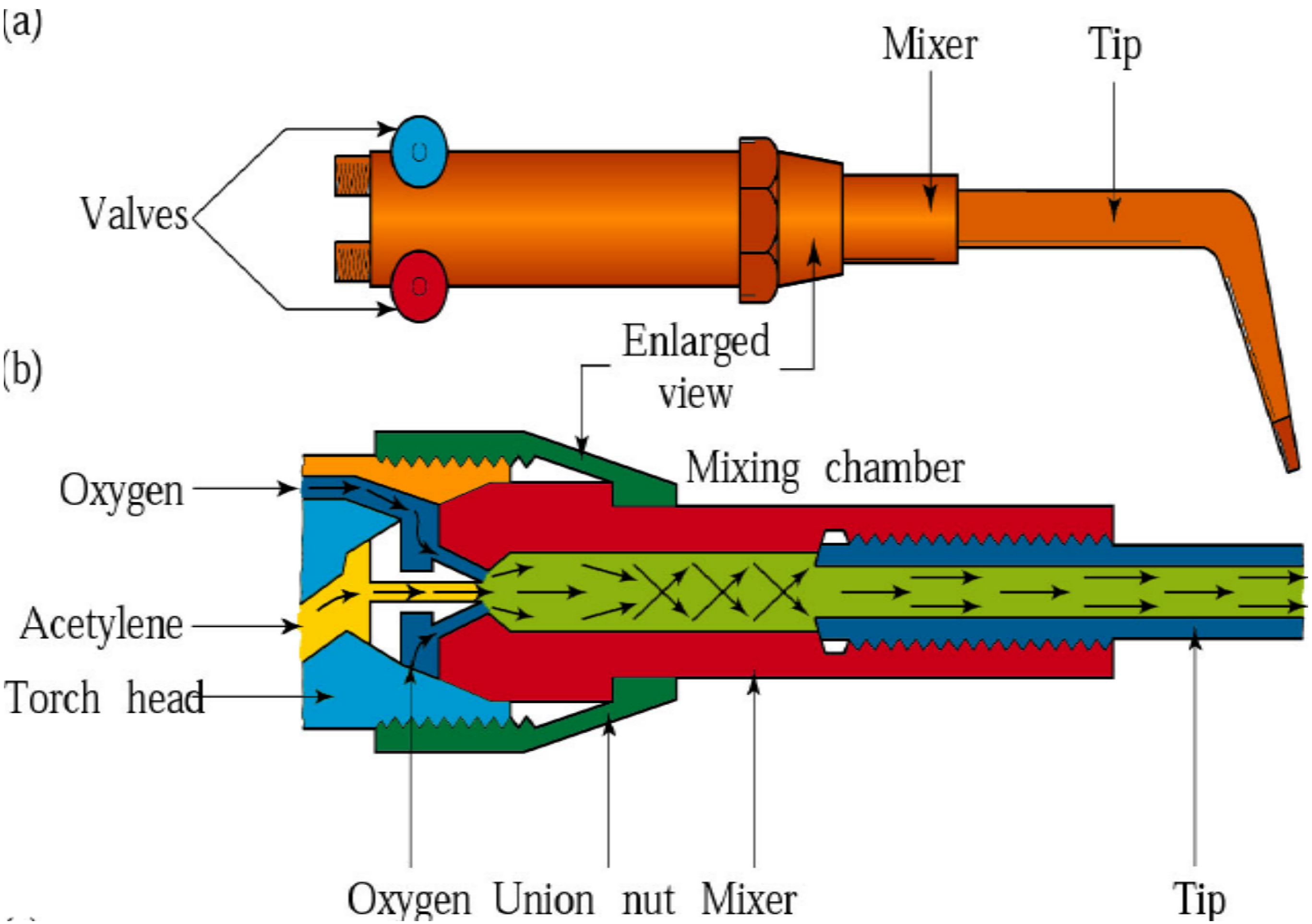
- The oxidizing flame causes the metal being welded to form an oxide.
- Useful for preventing the loss of high vapor-pressure components, such as zinc out of brass, through the formation of an impermeable “oxide skin” (here, copper oxide)
- Brass (Cu + Zn)
- Bronze, Cu, Zn & Sn alloys

OAW set up

- Pressurized cylinders of O_2 and C_2H_2
- Gas regulators for controlling pressure and flow rate
- A torch for mixing the gases
- Hoses for delivering the gases from the cylinders to the torch



OAW Torch



(a)
Mixer
Tip
Valves
Enlarged
view
(b)
Mixing chamber
Oxygen
Acetylene
Torch head
Oxygen
Union nut
Mixer
Tip

Example 1 - OAW

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 f1 = 0.20. If 75% of the heat from the flame is concentrated in a circular area on the work surface that is 9.0 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.

(Heat of combustion of Acetylene in O_2 = 55×10^6 J/m^3)

Example 1 - OAW

(a) The rate of heat generated by the torch is the product of the volume rate of acetylene times the heat of combustion: RH = (0.3 m^3/hr) ($55 \times 10^{6)}$ J/m3 = 16.5×10^6 J/hr or <u>4583 J/s</u>

(b) With a heat transfer factor f1 = 0.20, the rate of heat received at the work surface is
f1 × RH = 0.20×4583 = <u>917 J/s</u>

(c) The area of the circle in which 75% of the heat of the flame is concentrated is A = Pi. $(9)^2/4$ = 63.6 mm^2
The power density in the circle is found by dividing the available heat by the area of the circle:
Power density = 0.75 × 917/63.6 = <u>10.8 W/mm2</u>

OAW-Advantages

- The OAW process is simple and highly portable
- Inexpensive equipment
- Control over temperature
- Can be used for Pre-heating, cutting & welding

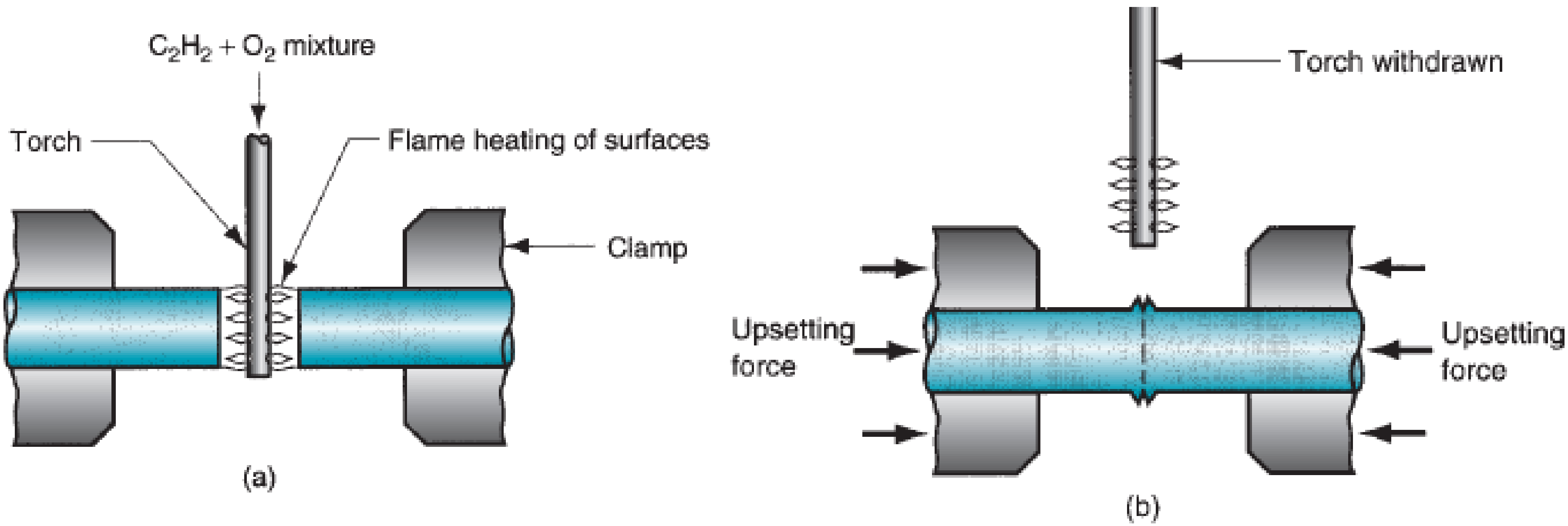
OAW-Disadvantages

- Limited energy $\rightarrow$ welding is slow
- Low protective shielding $\rightarrow$ welding of reactive metals (e.g., titanium) is generally impossible
- Low power density, Energy wastage, total heat input per linear length of weld is high
- Unpleasant welding environment
- Weld lines are much rougher in appearance than other kinds of welds $\rightarrow$ Require more finishing
- Large heat affected zones

OAW-Applications

- Preheating/post heat treatment
- Can be used for cutting, grooving, or piercing (producing holes), as well as for welding
- Oxyfuel gas processes can also be used for flame straightening or shaping
- Oxidizing flame for welding Brass, bronze, Cu-Zn and Tin alloys
- Reducing flame for low carbon & alloy steels

Pressure Gas welding
(Special case of OAW)

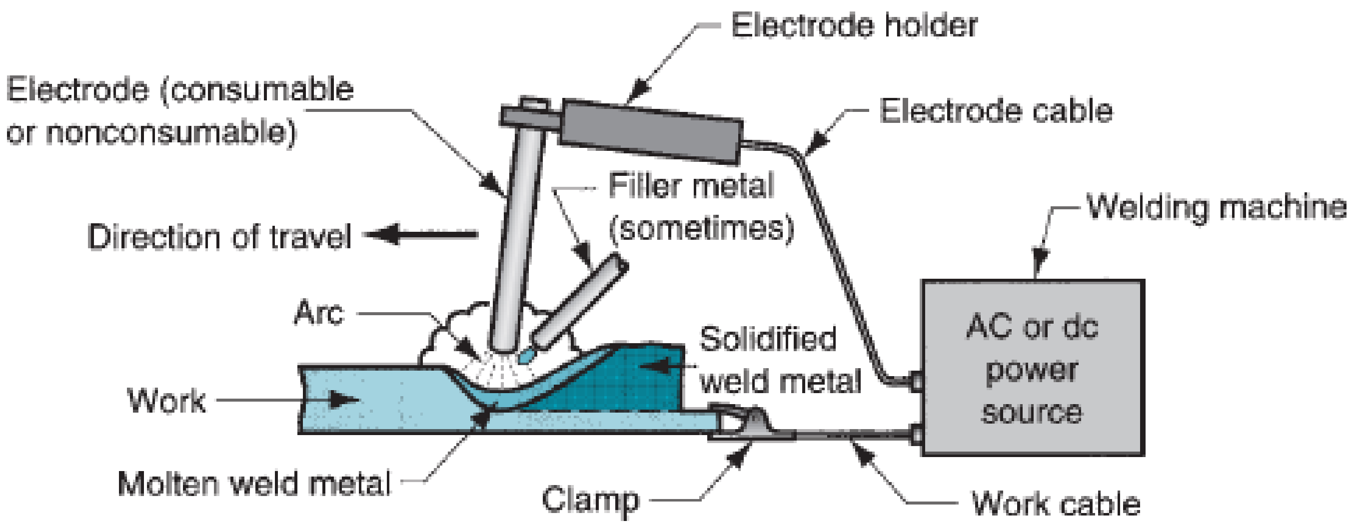


- Oxyfuel gas used for preheating the weld interface

Welding Processes-

2) Arc welding

Arc welding (AW)- Basic configuration



	Arc welding Types
Consumable electrode	SMAW, GMAW (MIG), Submerged arc welding
Non consumable Electrode	GTAW(TIG)

Arc Shielding in AW process

- Accomplished by covering
  - the electrode tip,
  - arc, and
  - molten weld pool with a blanket of gas or flux,

- Common shielding gases $\rightarrow$ argon and helium,

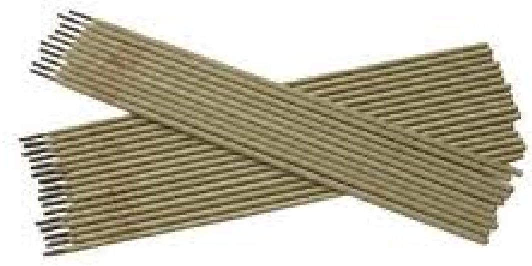
- In the welding of <u>ferrous metals</u> with certain AW processes, oxygen and carbon dioxide are used, usually in combination with Ar and/or He, to produce an oxidizing atmosphere or to control weld shape

Flux in AW process

- Flux is usually formulated to serve several functions:
  - (1) To remove/prevent oxide
  - (2) provide a protective atmosphere
  - (3) stabilize the arc, and
  - (4) reduce spattering
- Flux delivery techniques include
  - (1) pouring granular flux onto the weld
  - (2) using a stick electrode coated with flux material in which the coating melts during welding
  - (3) using tubular electrodes in which flux is contained in the core and released as the electrode is consumed

Arc Welding- Consumable Electrodes

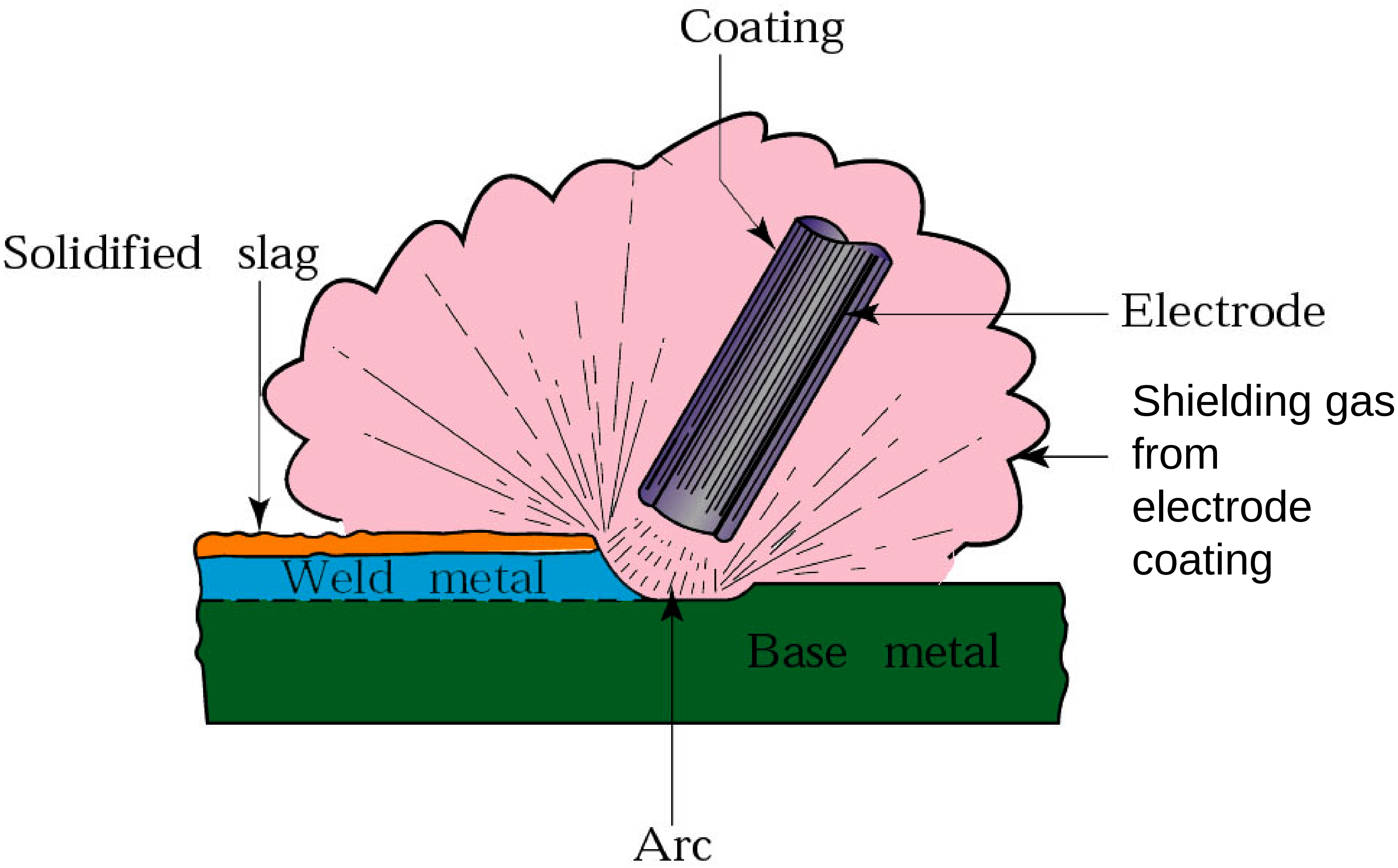
- Consumable electrodes → Rods or wire.
- Welding rods → 225 to 450 mm long, < 10 mm dia.
- Welding rods → to be changed periodically → reducing arc time of welder
- Consumable weld wire → continuously fed into the weld pool from spools → avoiding the frequent interruptions



Arc Welding- Non-consumable Electrodes

- Made of tungsten (or carbon, rarely), which resists melting by the arc
- Slow depletion $\rightarrow$ Analogous to wearing of a cutting tool in machining
- Filler metal must be supplied by means of a separate wire that is fed into the weld pool

AW-Type 1: Shielded metal arc welding (SMAW)



Shielded metal arc welding (SMAW)

- Consumable electrode consisting of a filler metal rod coated with chemicals that provide flux and shielding
- Currents typically used in SMAW range between 30 and 300 A at voltages from 15 to 45 V.
- Usually performed manually
- Most common welding, 50 % of industrial welding uses SMAW

SMAW: Electrode-coating functions

- Produces gases to shield weld from air
- Adds alloying elements
- De-oxidation
- Produces slag to protect & support weld
- Controls cooling rates
- Stabilizes arc

Electrode coating in SMAW-constituents

- Shielding gas is generated by either the decomposition or dissociation of the coating,
  Cellulosic $\rightarrow$generates H_2, CO, H_2O and CO_2
  Limestone ($CaCO_3$)$\rightarrow$ generates CO_2 and CaO slag
  Rutile (TiO_2) up to 40% $\rightarrow$ easy to ignite, gives slag detachability, fine bead appearance, generates O_2 & H_2 by hydrolysis
- Slag formers (flux): SiO, MnO_2, $FeO.Al_2O_3$
- Arc stabilizers: Na_2O, CaO, MgO, TiO_2
- Deoxidizer: Graphite, Al, Wood flour
- Binder: sodium silicate, K silicate
- Alloying elements: V, Co, Mo, Zr, Ni, Mn, W etc.

SMAW-Adv & Applications

- It is preferred over oxyfuel welding for thicker sections—above 5 mm —because of its higher power density.
- The equipment is portable and low cost, making SMAW highly versatile and most widely used AW processes.
- Base metals include steels, stainless steels, cast irons, and certain nonferrous alloys

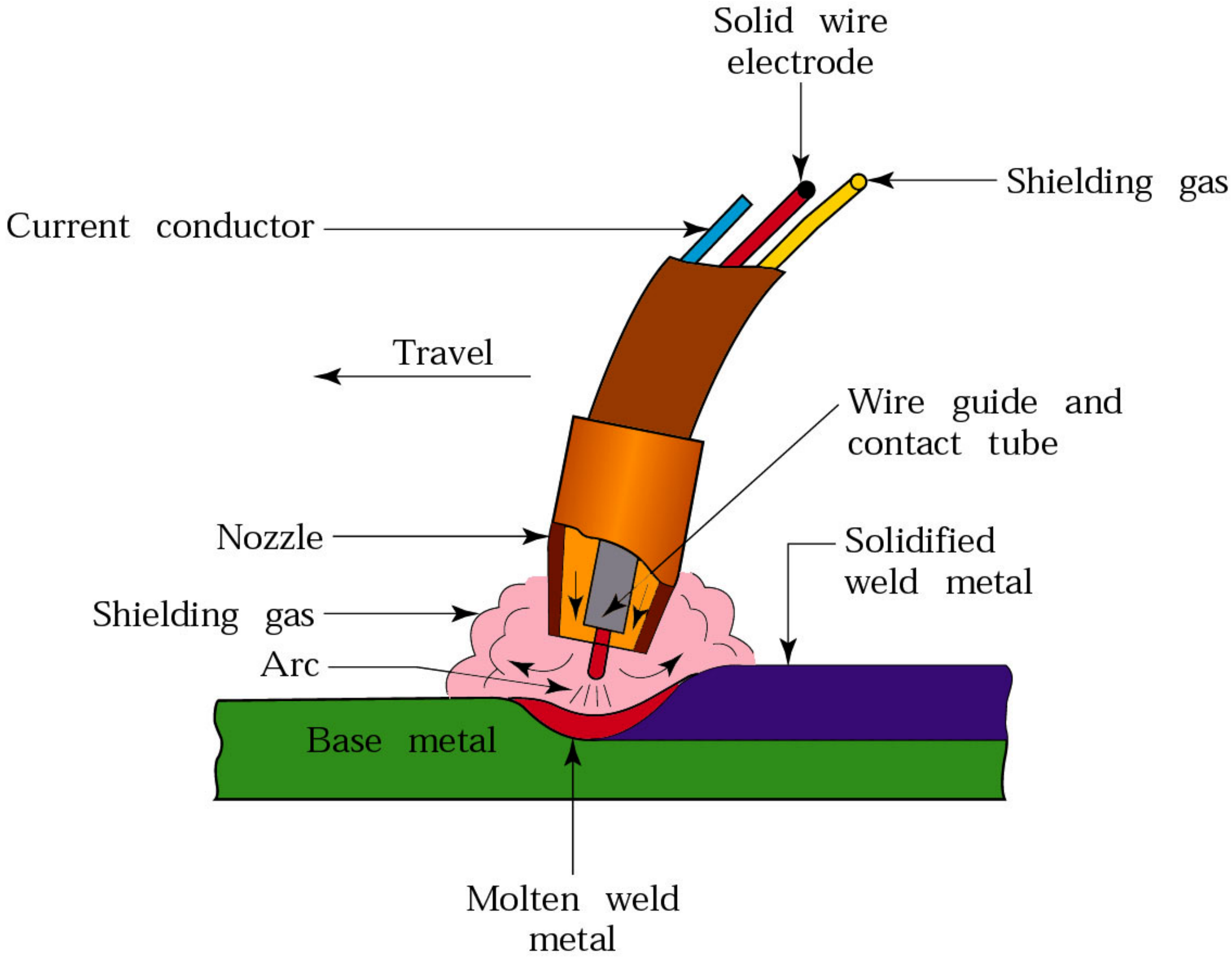
SMAW-Disadvantages

- Electrode length varies during the operation
- Length affects the resistance heating of the electrode,
- Current levels $\rightarrow$ To be maintained within a safe range or the coating will overheat and melt prematurely when starting a new welding stick

SMAW-Disadvantages

- Use of the consumable electrode $\rightarrow$ must periodically be changed $\rightarrow$ reduces the arc time
- Offers limited shielding protection compared to inert gas shielded processes
- Some of the other AW processes overcome the limitations of welding stick length in SMAW by using a continuously fed wire electrode

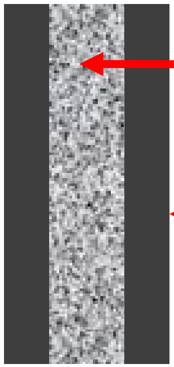
AW-Type 2: Gas metal arc welding (GMAW) -MIG



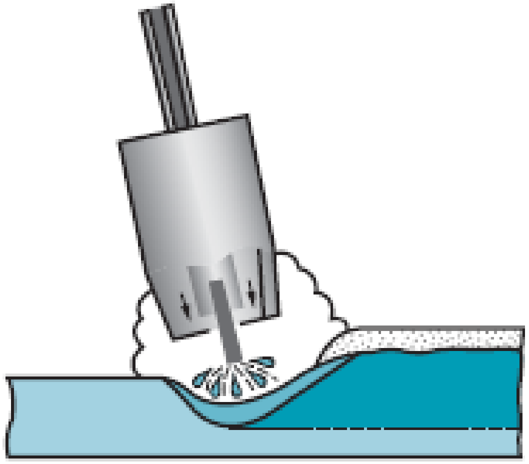
Gas metal arc welding-Features

- Consumable wire electrode is fed continuously and automatically from a spool through the welding gun
- Inert shielding gas : protects the arc and the molten or hot, cooling weld metal from air. Also, provides desired arc characteristics through its effect on ionization
- No electrode coating
- No flux or additional filler
- DCRP used (electrode +ve, work –ve)

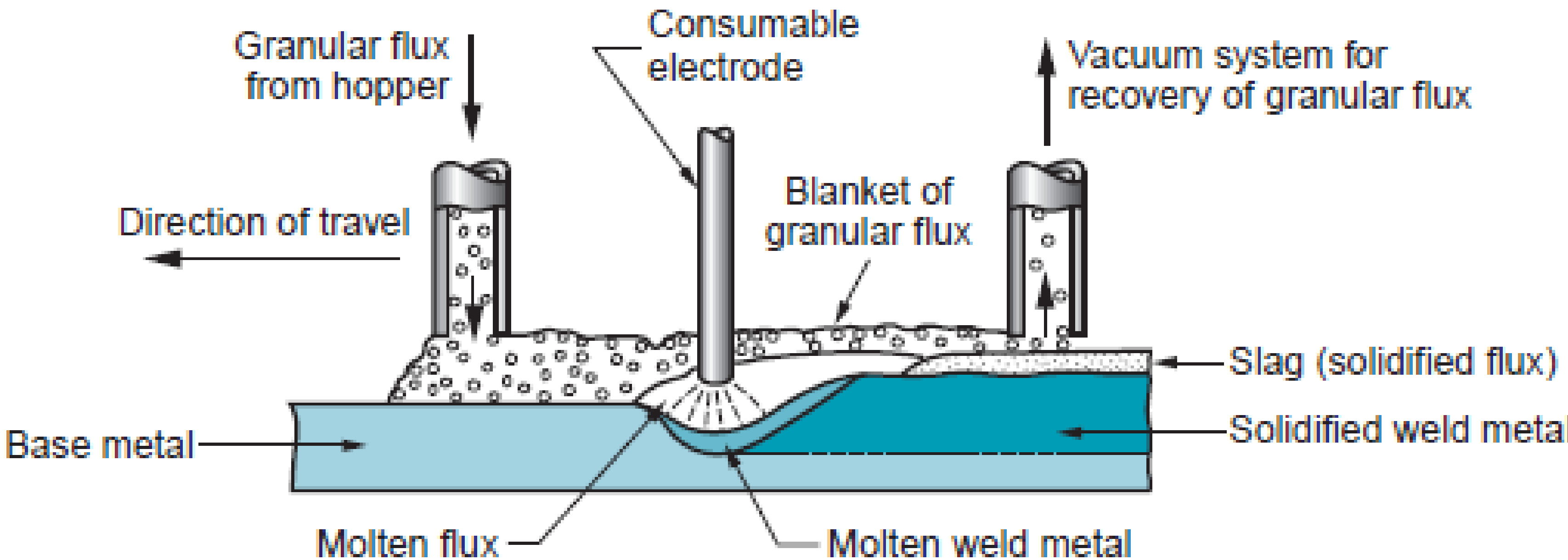
AW-Type 3: Flux-Cored Arc Welding (FCAW)



- Flux cored electrode
- Consumable wire electrode
- With/ Without shielding gas
- Core contents-
  - alloying elements,
  - shielding gas generators
  - flux, etc.



AW-Type 4 Submerged Arc welding (SAW)

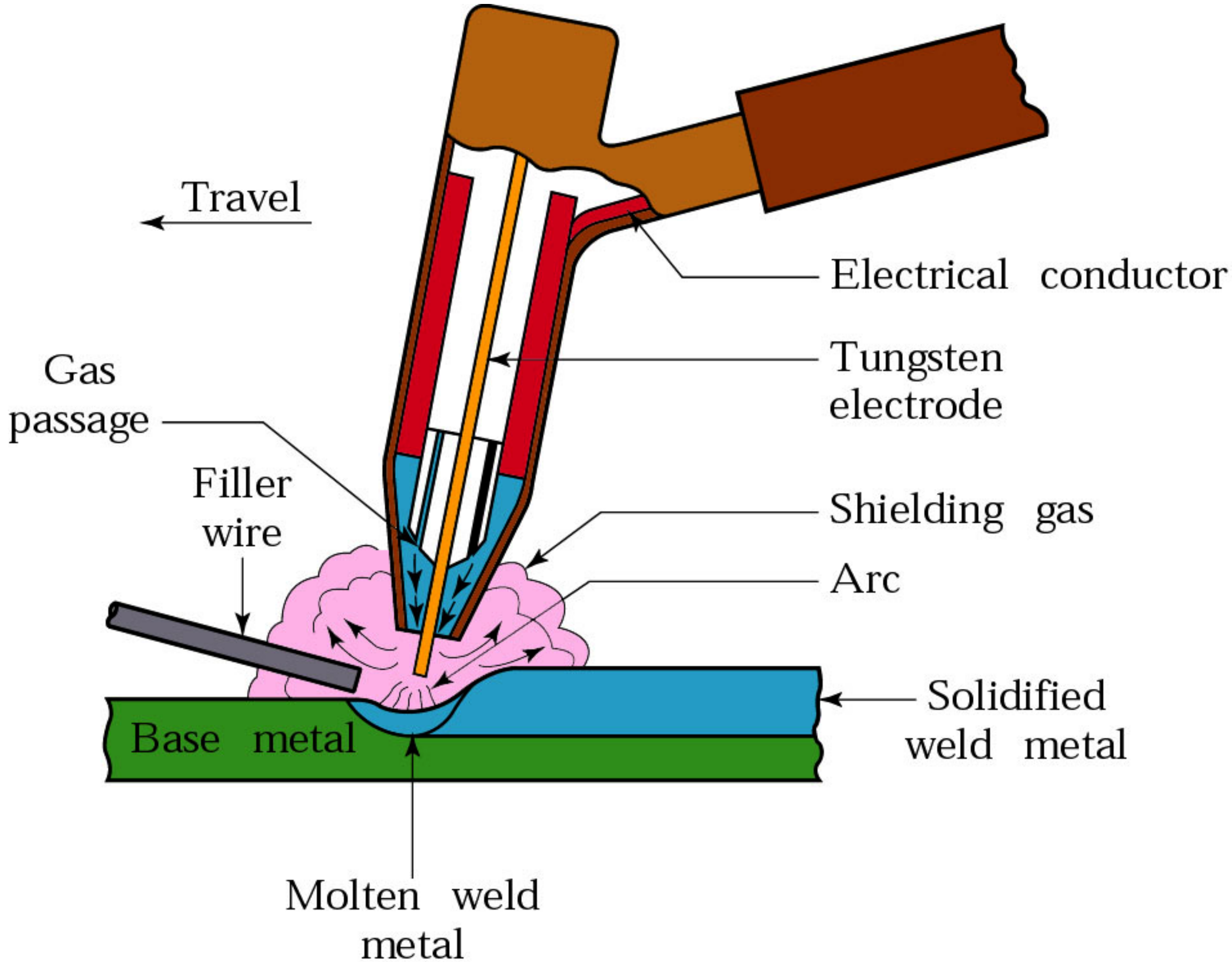


The blanket of granular flux submerges the welding operation, prevents sparks, spatter, and radiation

Submerged Arc welding

- Continuous, consumable bare wire electrode
- Arc shielding provided by a cover of granular flux
- Granular flux is introduced into the joint slightly ahead of the weld arc by gravity from a hopper
- Unfused flux remaining after welding can be recovered and reused
- efficiency of Energy transfer from the electrode to workpiece is very high- Low losses
- Welding is restricted to flat and horizontal positions

AW-Type 5: Gas Tungsten Arc Welding (GTAW or TIG)



GTAW- Features

- Non-consumable tungsten electrode
- Inert gas for arc shielding
- With or without filler rod
- Aluminium and stainless steel
- high-quality welds, no weld spatter because no filler metal
- Little or no post weld cleaning because no flux is used

Arc welding Types-Summary

Name	Electrode type	Electrode coating	Filler rod	Shielding gas	Flux	Remarks
Shielded metal arc welding (SMAW)	Consumable rod	YES	NIL	Provided by electrode coating	Provided by electrode coating	Manual welding
Gas metal arc welding (GMAW)-MIG	Consumable wire	NIL	NIL	YES	NIL	Automated welding
Flux-Cored Arc Welding (FCAW)	Consumable wire electrode	NIL	NIL	With/without	Provided by electrode core	Manual/automated
Submerged Arc welding (SAW)	Consumable wire electrode	NIL	NIL	NIL	Granular flux	Manual/automated
Gas Tungsten Arc Welding (GTAW-TIG)	Non consumable	NIL	With/ without	YES	NIL	Automated welding

Physics of Arc welding

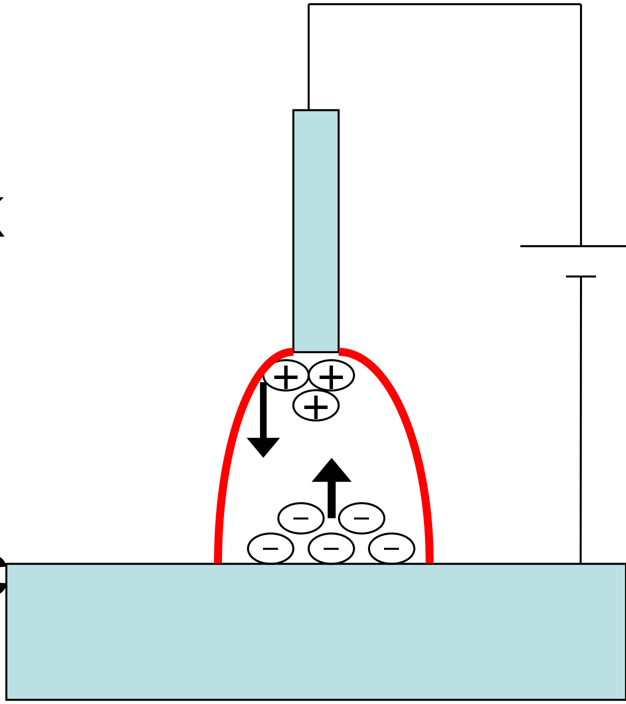
Arc-on-time in Arc welding

- The proportion of hours worked that arc welding is being accomplished
- Arc time = Time arc is ON / Hours worked

	Arc ON time
Manual Welding	~ 20 %
Machine, automatic, & robotic welding	~ 50 %

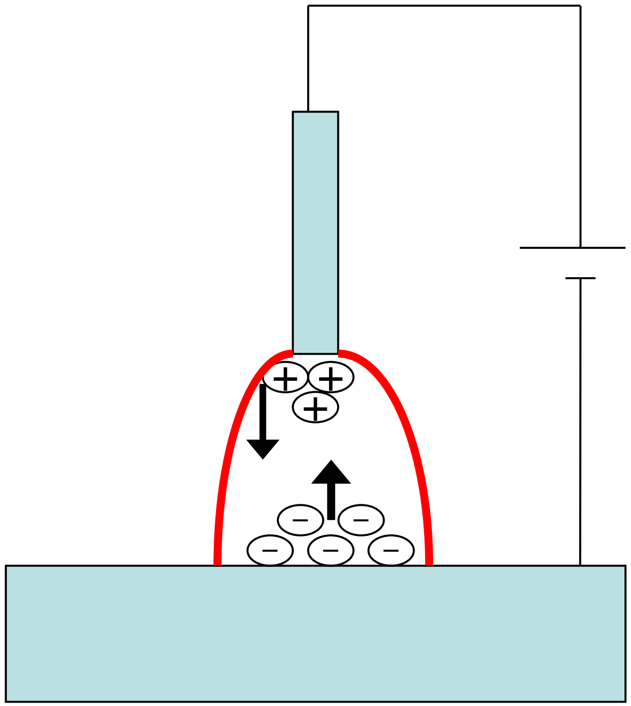
The electric arc

- Thermionic emission: Electrons and positive ions from the electrode and the workpiece.
- Accelerated by the potential field between the electrode and the work
- Produce heat when they convert their kinetic energy by collision with the opposite charged element
- Electrons have much greater kinetic energy because they can be accelerated to much higher velocities under the influence of a given electric field



Polarity in Arc welding

- Consumable electrode → Normally Anode ; work → cathode
- Non consumable electrode → Normally Cathode, Work → anode

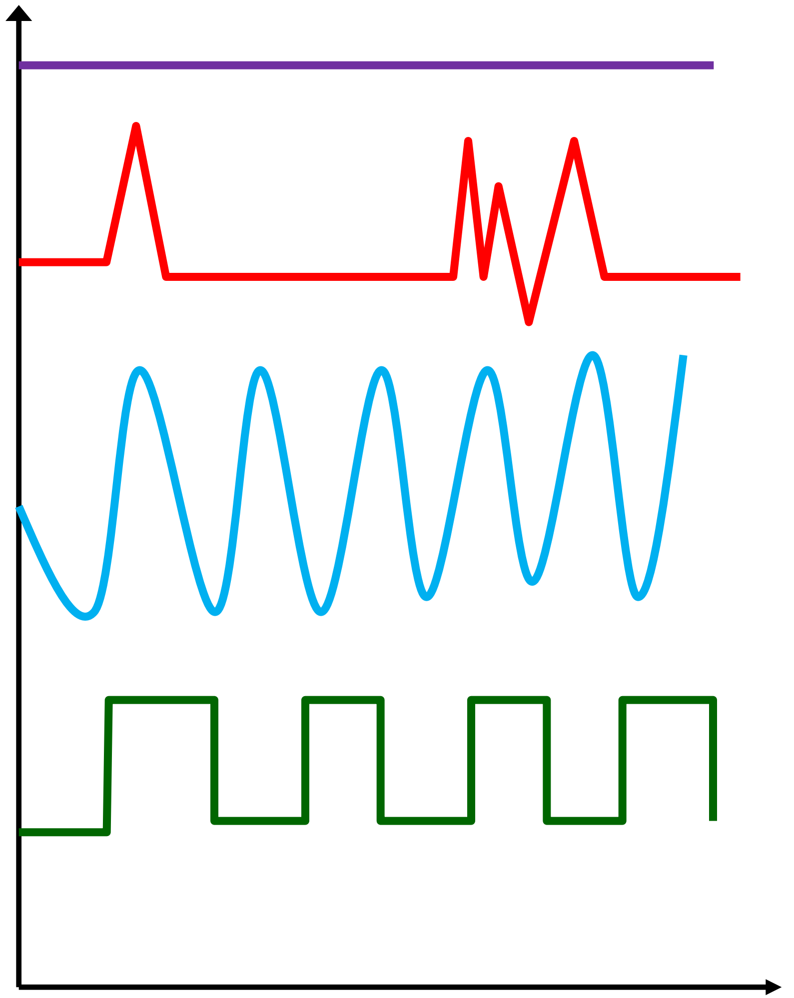


Effect of Magnetic Fields on Arcs

- Arc blow (deflection)
- Arc blow arises from two basic conditions
  - the change in direction of current flow as it leaves the arc and enters the workpiece to seek ground
  - Asymmetrical arrangement of magnetic material around the arc
- The effects of magnetic fields on welding arcs is determined by the Lorentz force, which is proportional to the cross-product of the magnetic field (B) and the current flow density (J), B x J
- Arc blow can be reduced by using AC or pulsed DC

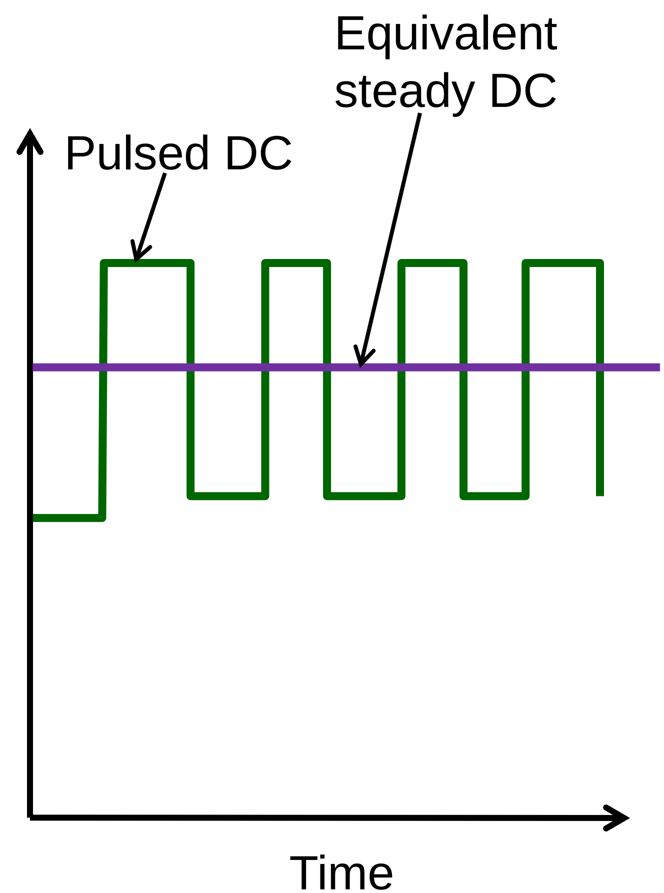
Arc welding - Arc Types

- Steady (from a DC power supply)
- Intermittent (due to occasional, irregular short circuiting)
- Continuously unsteady (as the result of an AC power supply)
- Pulsing (as the result of a pulsing DC power supply)

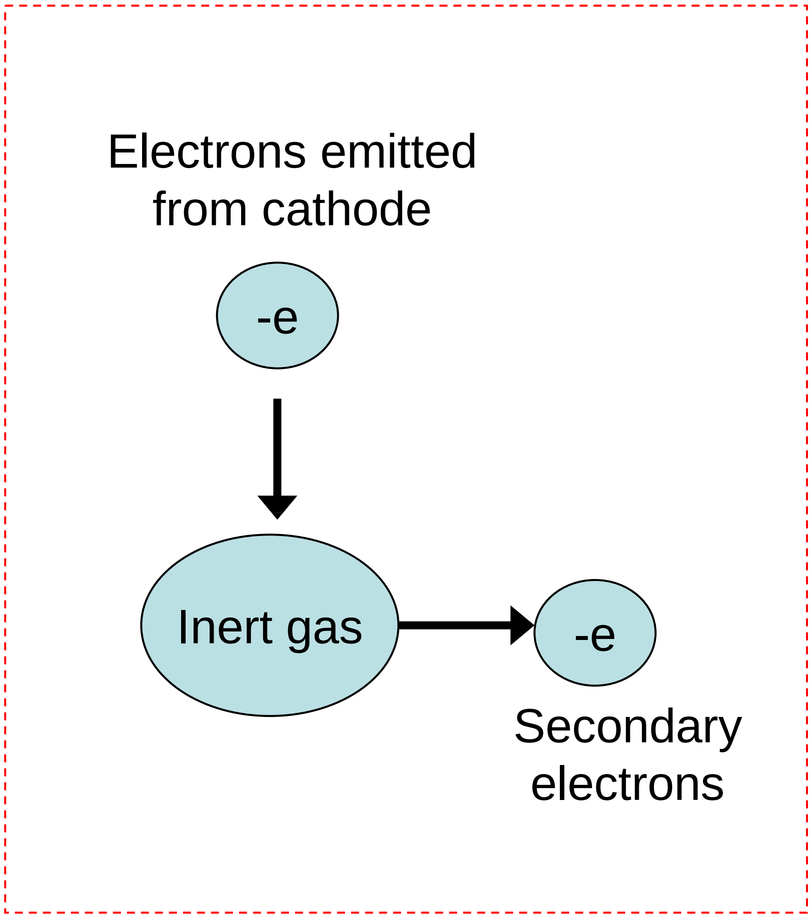


Pulsed DC in Arc welding

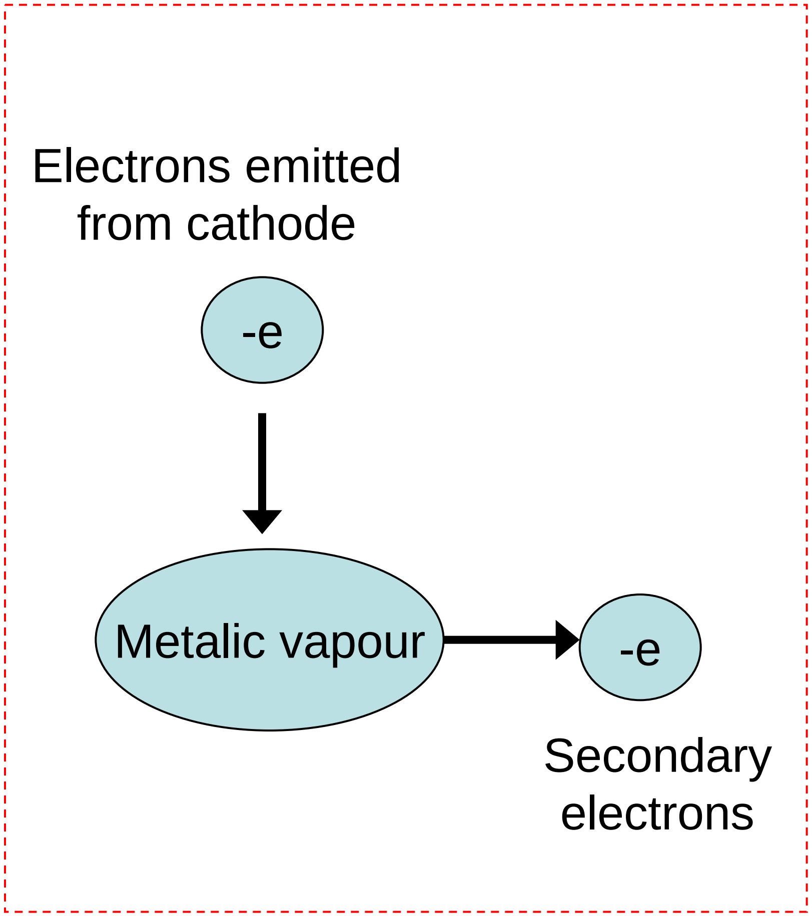
- The higher pulsing rates increase puddle agitation $\rightarrow$ a better grain molecular structure within the weld
- High speed pulsing constricts and focuses the arc; Increases arc stability, penetration and travel speeds
- Reduces arc blow (created by influence of magnetic field)
- A smaller heat-affected zone
- 4 Variables: peak amperage, background amperage, peak time and pulse rate



Creation of arc plasma



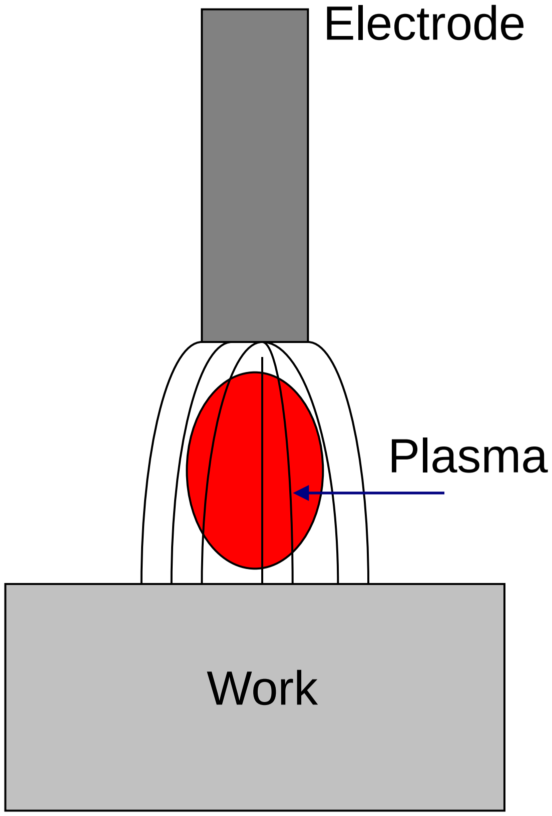
High temperature plasma



Low temperature plasma

The Arc Plasma

- Plasma, the ionized state of a gas
- Comprises of a balance of negative electrons and positive ions (both created by thermionic emission from an electrode) and
- Collisions between these electrons and atoms in the gaseous medium $\rightarrow$ secondary emission from gas $\rightarrow$ ionisation of gaseous medium
- Gaseous medium could be a self-generated (e.g. metal vapour) or externally supplied inert shielding gas



The Arc Plasma

- The establishment of a neutral plasma state $\rightarrow$ attained at equilibrium temperatures $\rightarrow$ magnitude depend on the ionization potential of gas from which the plasma is produced (e.g., air, argon, helium)
- The higher work function of the gaseous medium $\rightarrow$ Higher Arc temperature
- E.g. Helium $\rightarrow$ tighter bonding of outermost electrons compared to Ar $\rightarrow$ Hotter arc

The Plasma Temperature

Formation of a plasma is governed by an extended concept of the ideal gas law and law of mass action

$$\frac{n_e n_i}{n_0} = \frac{2Z_i\left(2\pi m_e kT\right)^{2/3}}{Z_0 h^3 e^{-Vi/kT}}$$

n_e*, *n_i*,** and ***n_o are the number of electrons, ions, and neutral atoms per unit volume (i.e., the particle density),
V_i is the ionization potential of the neutral atom,
T is the absolute temperature (K),
Z_i and ***Z_0*** are partition functions (statistical properties of a system in thermodynamic equilibrium) for ions and neutral particles,
h is Planck's constant (6.63 x 10^{-34} J/s),
m_e is the mass of an electron (9.11 x 10^{-31} kg),
k is Boltzmann's constant (1.38 x 10^{-23}J/K)

Arc/Plasma Temperature

- Factors affect the plasma temperature
  - ✓Constituents of the particular plasma
  - ✓Its density
- Lowered by the presence of fine metallic particles
- Lowered by convection/radiation heat loss

Plasma constituents	Inert gas, Metal particles, vapours, Alkali metal vapours, fine particles of molten flux (or slag)

Arc temperature

Arc Welding type	Arc constituents	~Arc temperature K (Theoretical values)	
Plasma Arc welding (PAW)	Pure plasma, no metal transfer	50,000	Actual values limited by losses (convection, radiation, diffusion)
Gas tungsten arc welding (with inert shielding gas)	Metal vapor from nonconsumable electrode and any molten metal particles from filler	30,000	
GMAW	large concentrations of metal ions and vapor and molten droplets	20,000	
SMAW/ Flux cored arc welding	easily ionized materials such as alkali metals (sodium, potassium)	6000	

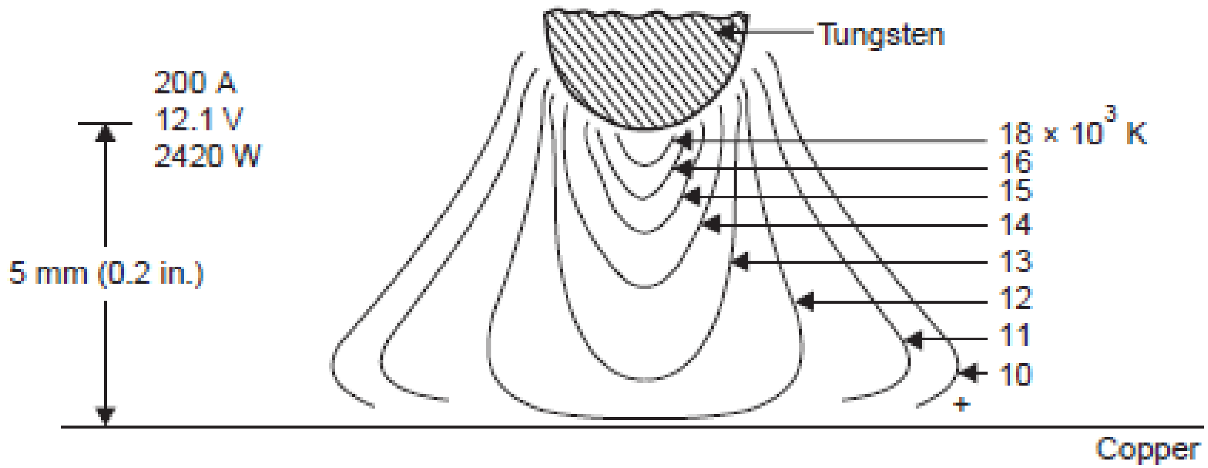
Arc Temperature

Temperature of the arc columns for various gases

Gas	Temperature of arc column close to cathode (K) ~
Alkali-metal vapour (Na, K)	4000
Alkaline earth vapour (Ca, Mg)	5000
Iron vapour	6000
Argon (200 A)	10,000-15,000

Arc Temperature

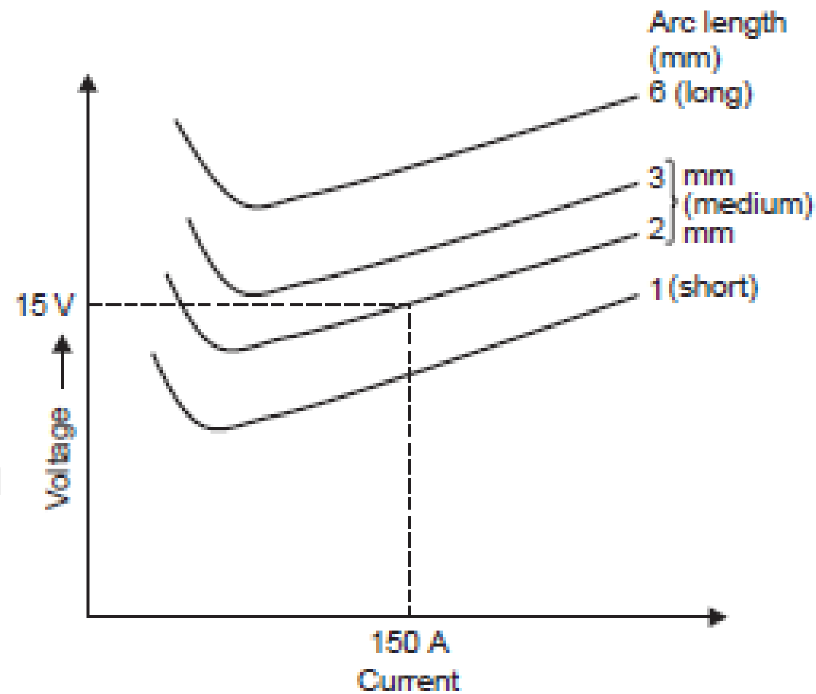
Isothermal Map of an Argon-tungsten arc



- Measured by spectral emission of excited/ionized atoms
- Normally is in the range of 5000 to 30,000 K
- The actual temperature in an arc is limited by heat loss (radiation, convection, conduction, and diffusion), rather than by any theoretical limit

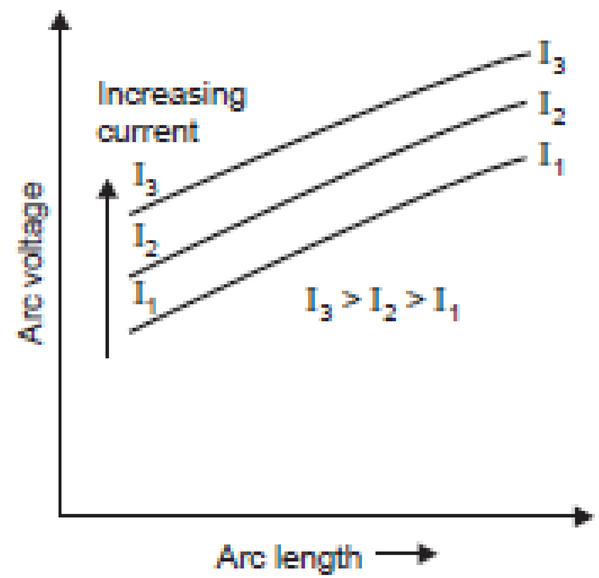
Arc: V-A Characteristics

- The total potential of an arc first falls with increasing current, and then rises with further increases in current
- The initial decrease is attributed to a <u>growth</u> of thermally induced electron emission at the arc cathode and thermal ionization



Influence of Arc length

- Potential barrier increases with the arc length (gap)
- Lengthening the arc → exposes more of the arc column to cool boundary → More losses → Higher demand for voltage



V-A Characteristics of an Arc

- Arc welding $\rightarrow$ <u>low-voltage, high-current</u> arcs between a nonconsumable or consumable electrode and a work piece
- Arc welding power source $\rightarrow$ <u>static and dynamic characteristics</u>
- Static volt-ampere characteristics,
  - (1) <u>constant-current</u> and
  - (2) <u>constant-voltage</u>
- Dynamic characteristics $\rightarrow$ determined by measuring very short-duration (~1 ms) transient variations in output voltage and current that appear in the arc itself

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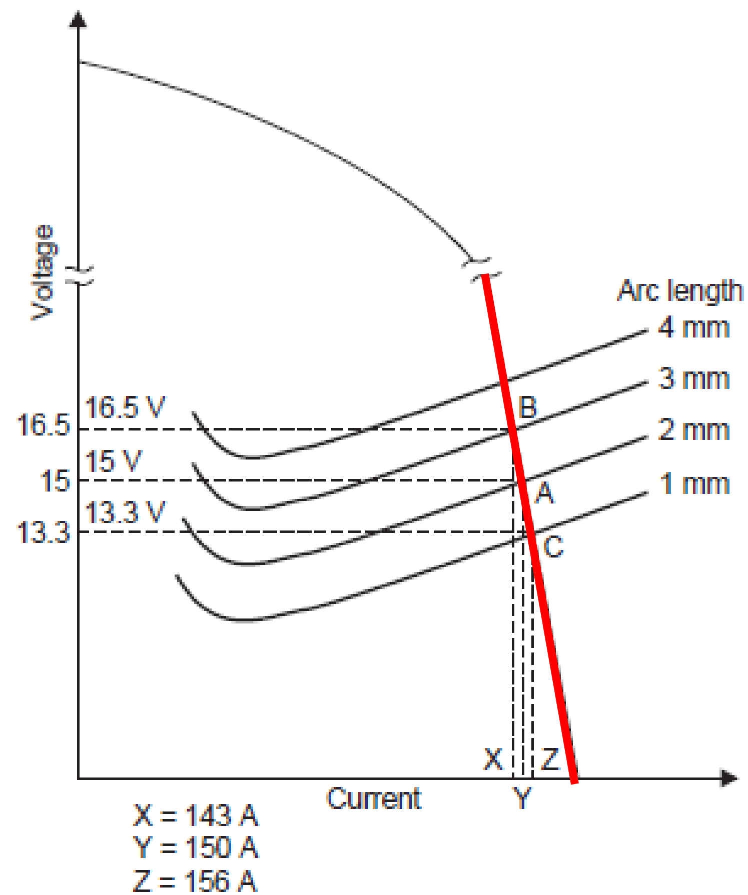
Constant current power sources

- A change in arc length will cause corresponding change in arc voltage and a very small change in current.
- Electrode melting and <u>metal deposition rate remain constant</u> with slight changes in arc length
- Greater tolerance to arc length Variations
- Used for manual SMAW and GTAW



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Constant current power sources

- Used primarily with <u>coated electrodes</u>
- <u>Small change in amperage</u> and arc power for a corresponding relatively large change in arc voltage or arclength
- The curve of a constant current machine drops down-ward sharply $\rightarrow$ often called a *"<u>drooper</u>"*
- In welding with coated electrodes, the amperage is set by the operator while the voltage is designed into the unit
- The operator can vary the arc voltage by increasing or decreasing the arc length

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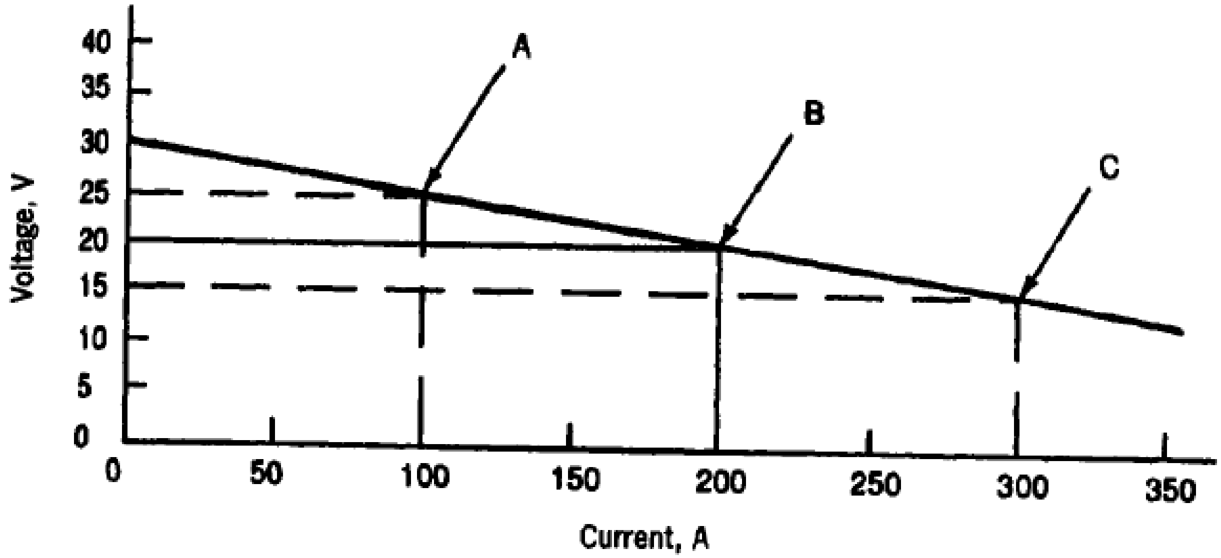
Constant-Voltage Power Sources



- A slight change in arc length causes a large change in current, so melting rate changes rapidly in response.
- This has the effect of self-regulation, increasing the melting rate as arc length is inadvertently shortened, (and vice versa)

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Constant-Voltage Power Sources

- CV power supplies are attractive for constantly fed continuous electrode processes such as GMAW, FCAW, or SMAW, to maintain near-constant arc length.

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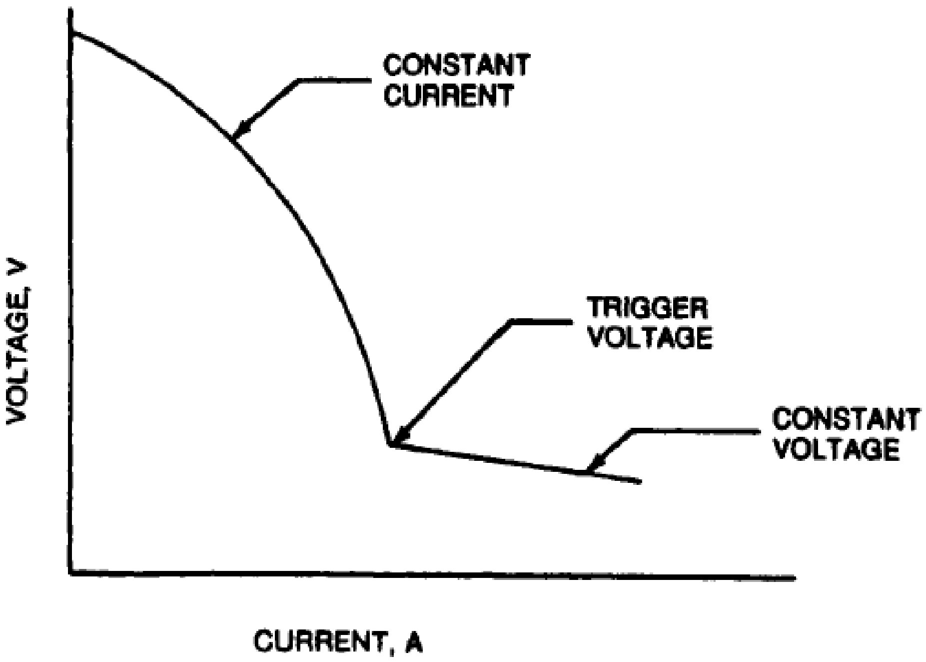
Combined Characteristic Sources

- Single power supply that can provide either constant-voltage or constant-current
- Higher-voltage portion $\rightarrow$ Constant current
- Below a certain threshold voltage, the curve switches to a constant voltage type



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Combined Characteristic Sources

- Utility for a variety of processes, and are actually a combination of the straight CV or CC types
- Useful for SMAW to <u>assist in starting</u>
- <u>Avoid electrode sticking</u> in the weld pool (in those cases where the welder is required to use shorter arc length)

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Arc Electrical Features-impedance

- An electric welding arc is an impedance (related to the resistance of a circuit, but including contributions from capacitance and inductance as well) to the flow of electric current
- Specific impedance at any point in an arc is inversely proportional to the density of the charge carriers and their inherent mobility.
- The total impedance depends on the radial and axial distribution of charge carrier density
- The impedance of the plasma column is a function of temperature (except regions near the arc terminals)

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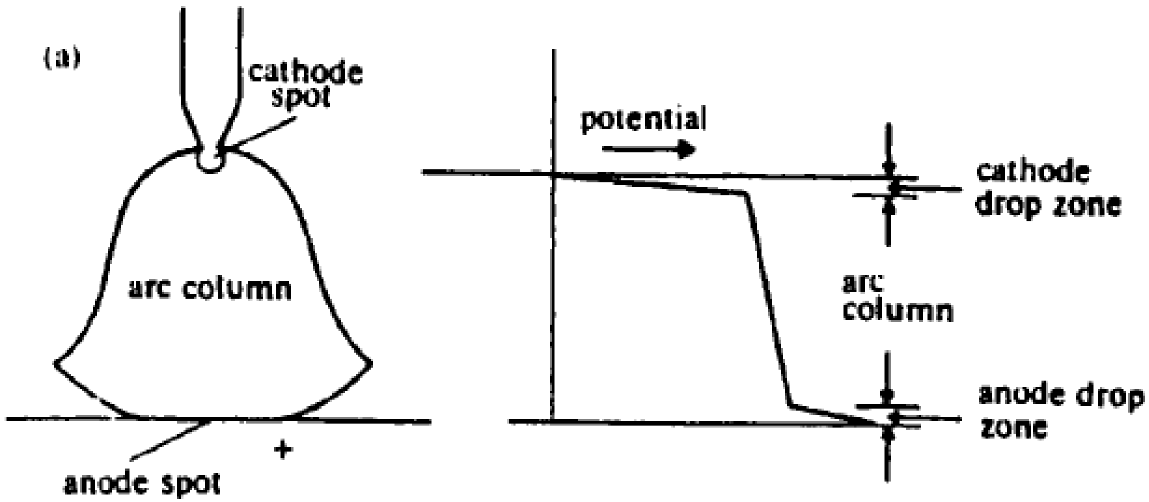
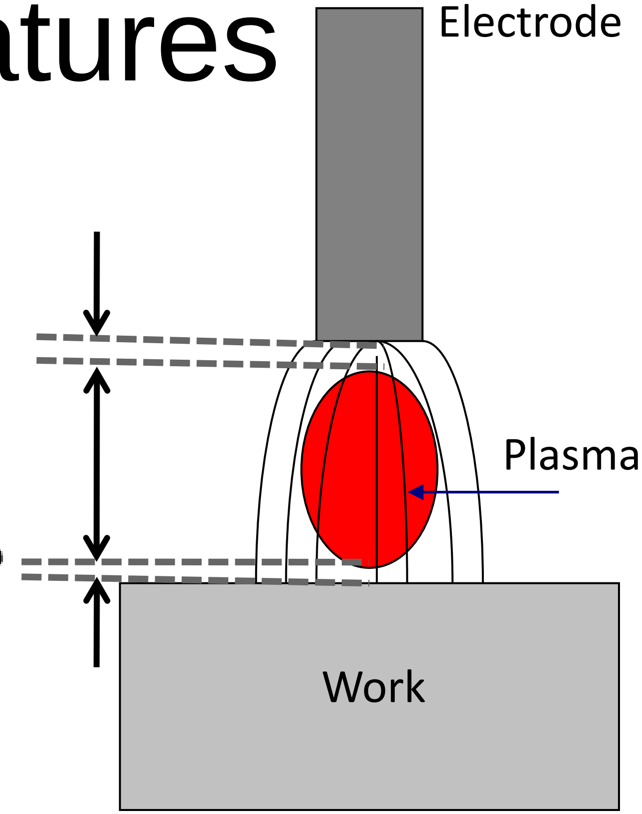
Arc-Electrical features





- All electric arcs consist of three regions
  – the cathode fall space (or drop zone);
  – the plasma column fall space (or drop zone)
  – the anode fall space (or drop zone)

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Arc-Electrical features

- Electrical power dissipated in each regions of the arc given by $P = I(E_a + E_c + \mathrm{E_p})$ where E_a is anode voltage, E_c is cathode voltage, and E_p is plasma column voltage ($E_c > E_a > \mathrm{E_p}$)
- <u>Intermediate regions</u> $\rightarrow$ Involved in expanding or contracting the cross section of the gaseous conductor to accommodate each of these main regions.
- As a consequence, welding arcs assume bell or cone shapes and elliptical or some other noncylindrical contour.

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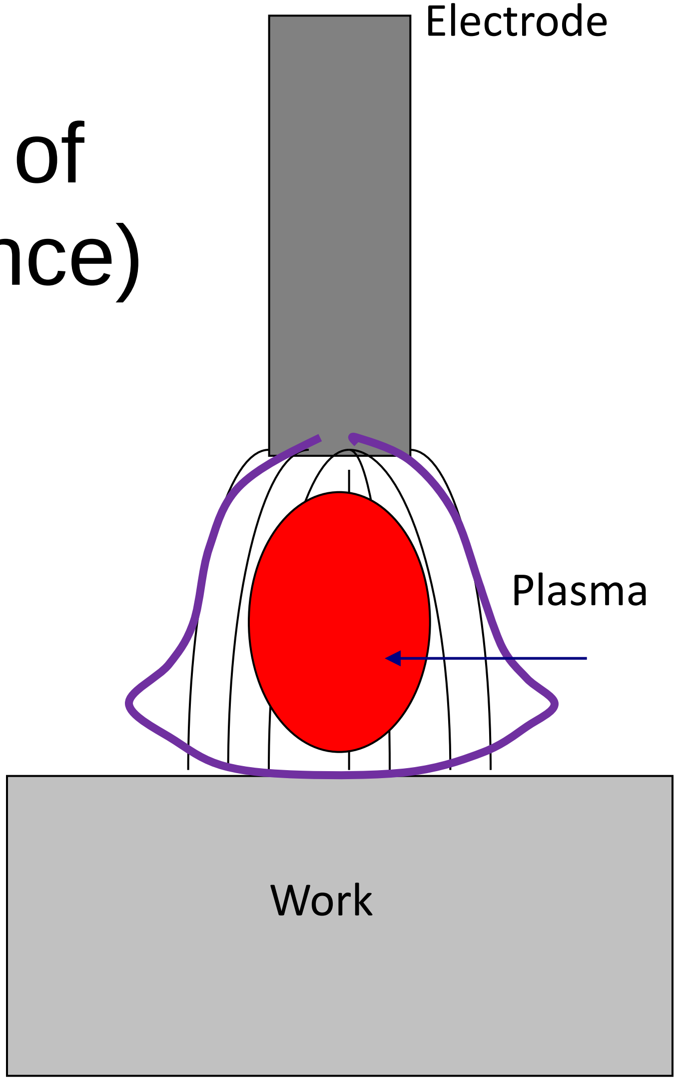
Arc Shape

Arc shape = Interaction of
(Arc + Plasma + Ambience)

- Bell Shape
- Cone
- Elliptical
- Cylindrical



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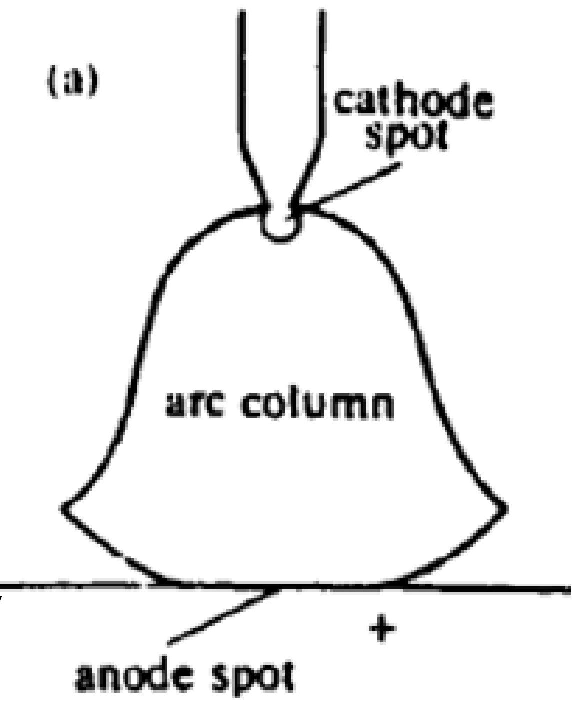
Arc Shape- Influencing factors

1. Shape of the arc terminals (i.e., pointed welding electrode producing a narrow arc focused at the electrode tip and flat work piece electrode, which causes the arc to spread)
2. Gravitational forces
3. Magnetic forces (from both internally generated and externally induced or applied sources)
4. Interactions between the plasma and ambience (shielding gas)



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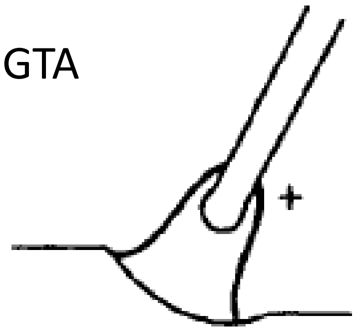
Arc Shape- Influencing factors

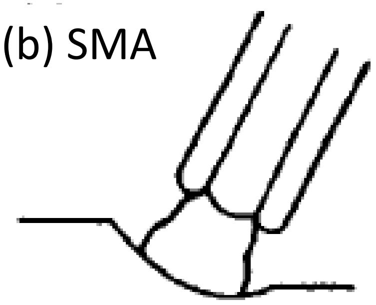
- Nature of electrode- Consumable/non consumable
- Electrode coating/gas generation
- Shielding gas
- Magnitude & polarity of current source

Arc Shape-Examples

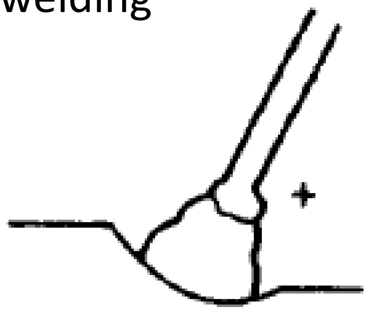
(a) GTA



(b) SMA



(c) CO_2 shielded GMA welding



Non consumable electrode + Inert gas

Consumable coated electrode + Gas generation

Consumable electrode + CO_2 gas

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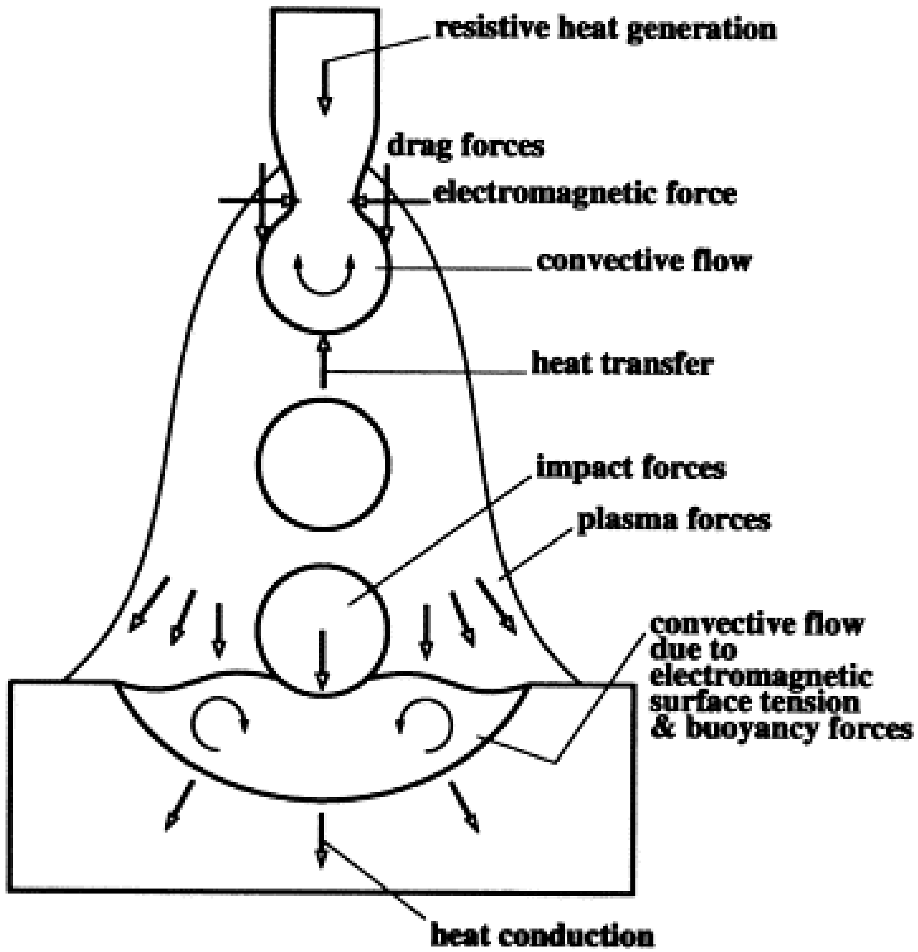
Arc radiation

- Arc radiation → amount and character depends on
  - the atomic mass and chemical composition of the gaseous medium,
  - the temperature, and the pressure.
- Spectral analysis shows line and continuum emissions due to excited and ionized states of atoms and ions
- Radiation → UV, visible, IR
- Energy loss due to radiation → 10-20 %
- Highly hazardous to eyes, skin

Metal transfer in Arc welding
(Consumable electrode)

- The manner in which molten filler metal is transferred to the weld pool $\rightarrow$ profound effects on the performance of a consumable electrode arc welding process
- These effects include
  – Ease of welding in various positions
  – Extent of weld penetration;
  – Rate of filler deposition and
  – Heat input
  – Stability of the weld pool
  – Amount of spatter loss

Metal transfer in Arc welding
(Consumable electrode)



Mode of Metal transfer-Influencing parameters

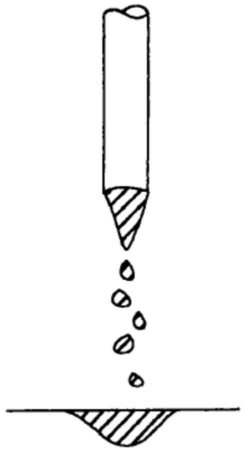
- <u>Pressure generated</u> by the evolution of gas at the electrode tip (for flux-coated or flux-cored electrode processes)
- <u>Electrostatic attraction</u> between the consumable electrode and the workpiece
- Gravity
- <u>"Pinch effect"</u> caused near the tip of the consumable electrode by electromagnetic field forces $\rightarrow$ spray

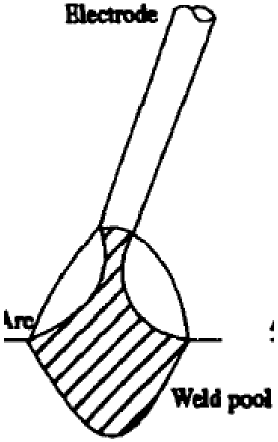
Mode of Metal transfer-Influencing parameters

- <u>Explosive evaporation</u> of a necked region formed between the molten drop and solid portions of the electrode <u>due to very high conducting current density</u>
- Electromagnetic action produced by divergence of current in the arc plasma around a drop.
- Friction effects of the plasma jet (plasma friction)
- Surface tension effects once the molten drop (or electrode tip) contacts the molten weld pool

Metal transfer types

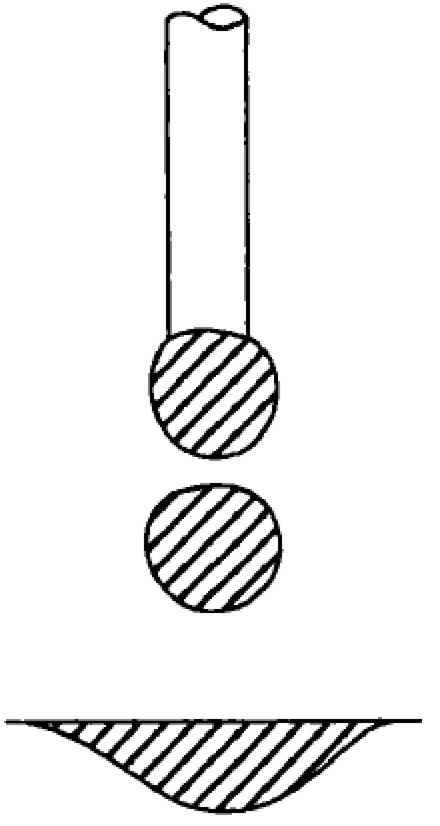
- **Free-flight transfer**: <u>Complete detachment</u> of the molten metal drop from the consumable electrode → flight to the work piece and weld pool, without any direct physical contact
- **Bridging transfer**: molten metal drops are never completely free; rather they are always attached to the consumable electrode and the workpiece, momentarily bridging the two from a material standpoint - and electrically
- **Slag-protected transfer**





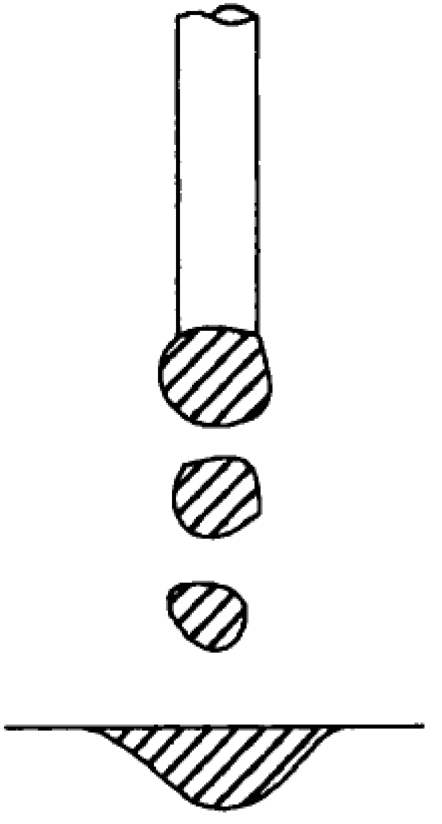
Free-flight-Globular Transfer

- Low welding currents (50-170 A) in pure argon, molten metal from a small diameter solid steel wire electrode is transferred in the form of globules
- Drop's diameter larger than the wire
- <u>Large drops</u> $\rightarrow$ detach by gravity
- Low rate of globule formation, detachment, and transfer (< 1-10 s^{-1})
- Globular transfer $\rightarrow$ down-hand position

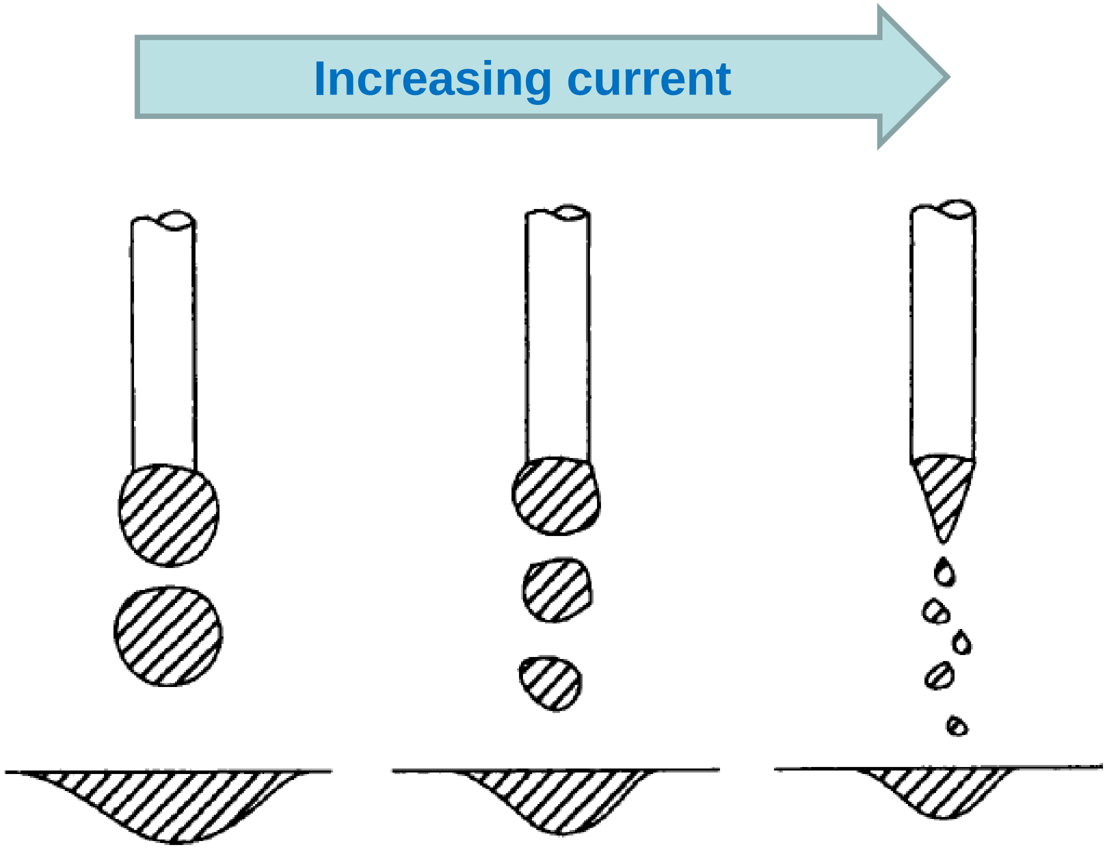


Free flight: Globular-projected Transfer

- As the welding current increases within the range of 50-170A, the drops become progressively smaller, $\rightarrow$ electromagnetic forces are having an increasing effect on detachment
- Drop size inversely proportional to welding current.
- As welding current is increased, the rate of drop transfer also increases



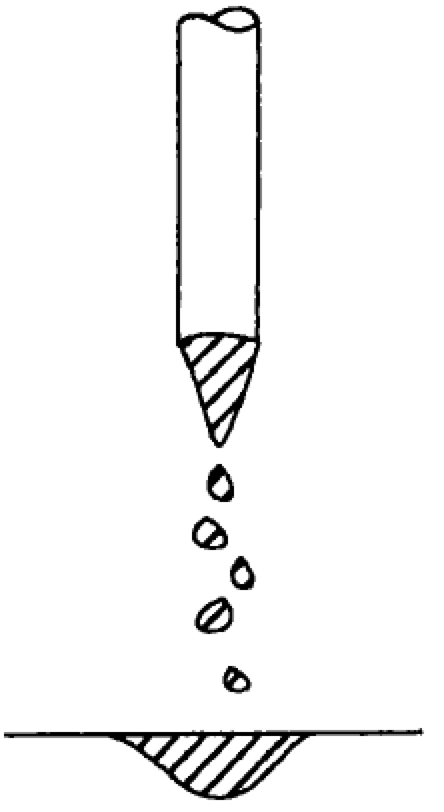
Free-flight transfer modes



Individual drop formation and detachment sequence in (a) globular transfer and (b) projected and (c) streaming axial spray transfer

Free flight -Spray Transfer/streaming transfer

- At current > critical level $\rightarrow$ No individual drops
- Tip of the consumable electrode becomes pointed $\rightarrow$ cylindrical stream of liquid metal flows toward the work piece <u>in line with the electrode.</u>
- Near its tip (nearest the work piece), this cylinder disperses into many very small droplets $\rightarrow$ <u>Electromagnetic pinch effect</u>
- The rate at which droplets are transferred is hundreds per second.

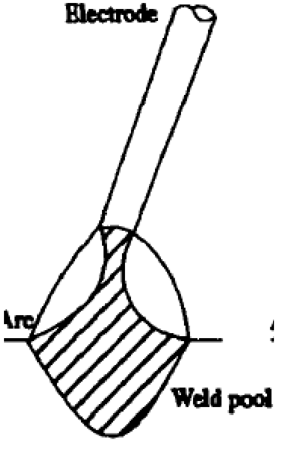


Free flight -Spray Transfer: Features

- Axial spray transfer mode $\rightarrow$ Excellent stability, virtually free of spatter
- Droplets are actively propelled away from the consumable electrode and into the molten weld pool to be captured by surface tension force.
- Droplets are transferred in line with the electrode $\rightarrow$ Filler metal can be directed exactly where it is needed.
- This is a great advantage when making vertical or overhead welds, where the propelling force offsets the disruptive effect of gravity

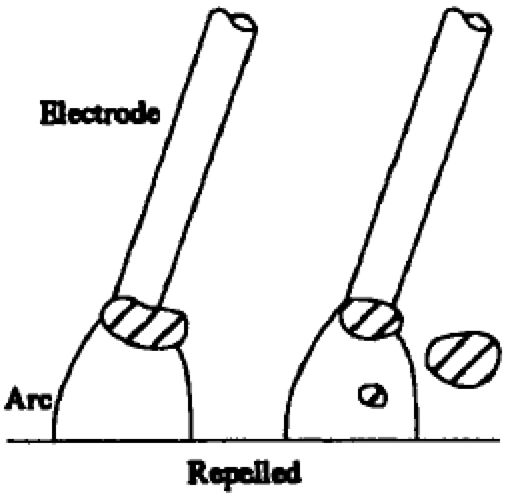
Bridging or short circuiting transfer

- Large dia. Electrodes $\rightarrow$ too high transition current to achieve axial spray transfer (e.g., 200-220A for 1-mm-diameter steel wire) $\rightarrow$ Bridging transfer
- Voltage is kept low (say 17-21 V versus 24-28 V for globular transfer with steel wires)
- The tip of the electrode periodically dipped into the molten weld pool.

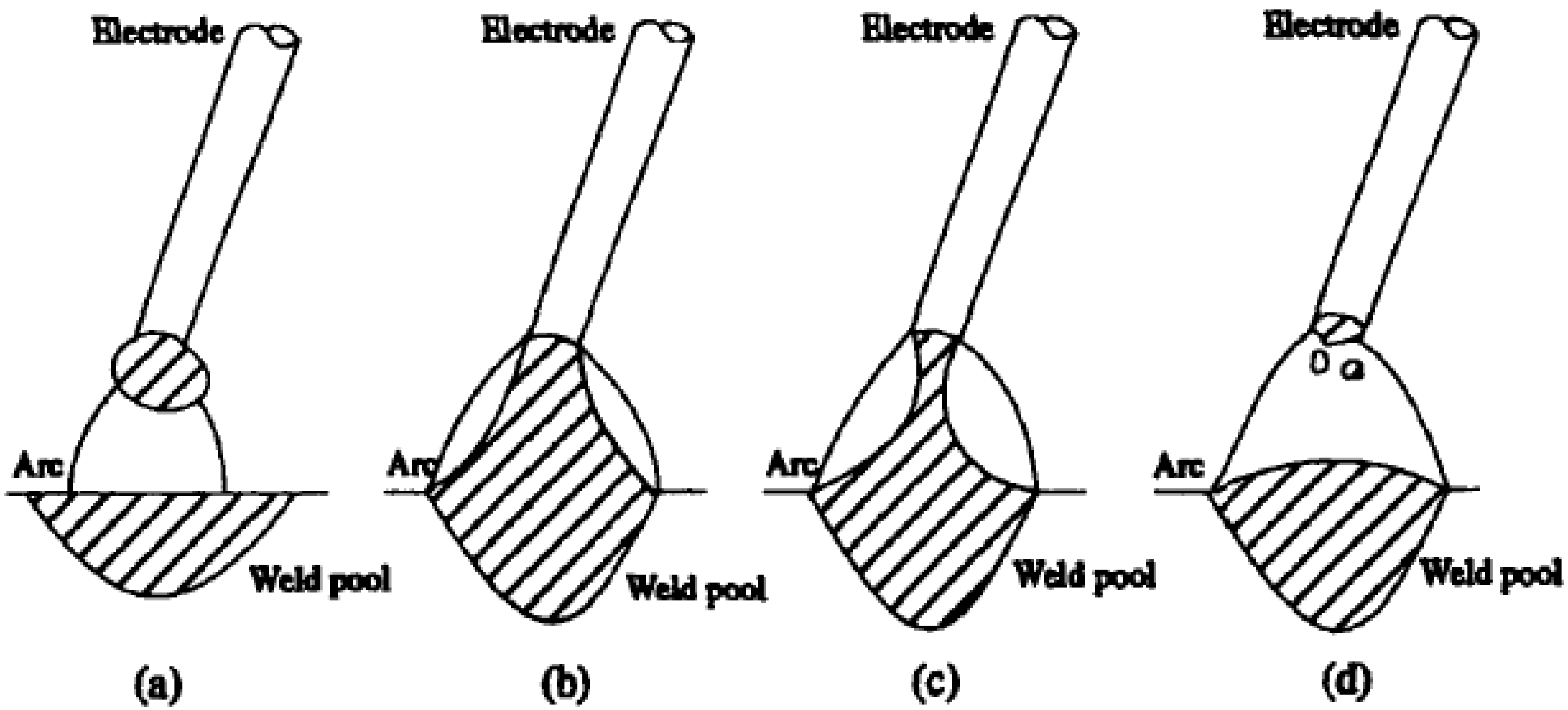


Bridging or short-circuiting transfer

- Bridging → Molten metal transfer by a combination of surface tension and electromagnetic forces
- Repelled transfer → the molten drop at the electrode tip could be pushed upward in some cases [e.g: in the presence of carbon dioxide (CO_2) in shielding gas]. In this case, short-circuiting could be used to capture the drop before it detaches in an unfavorable manner

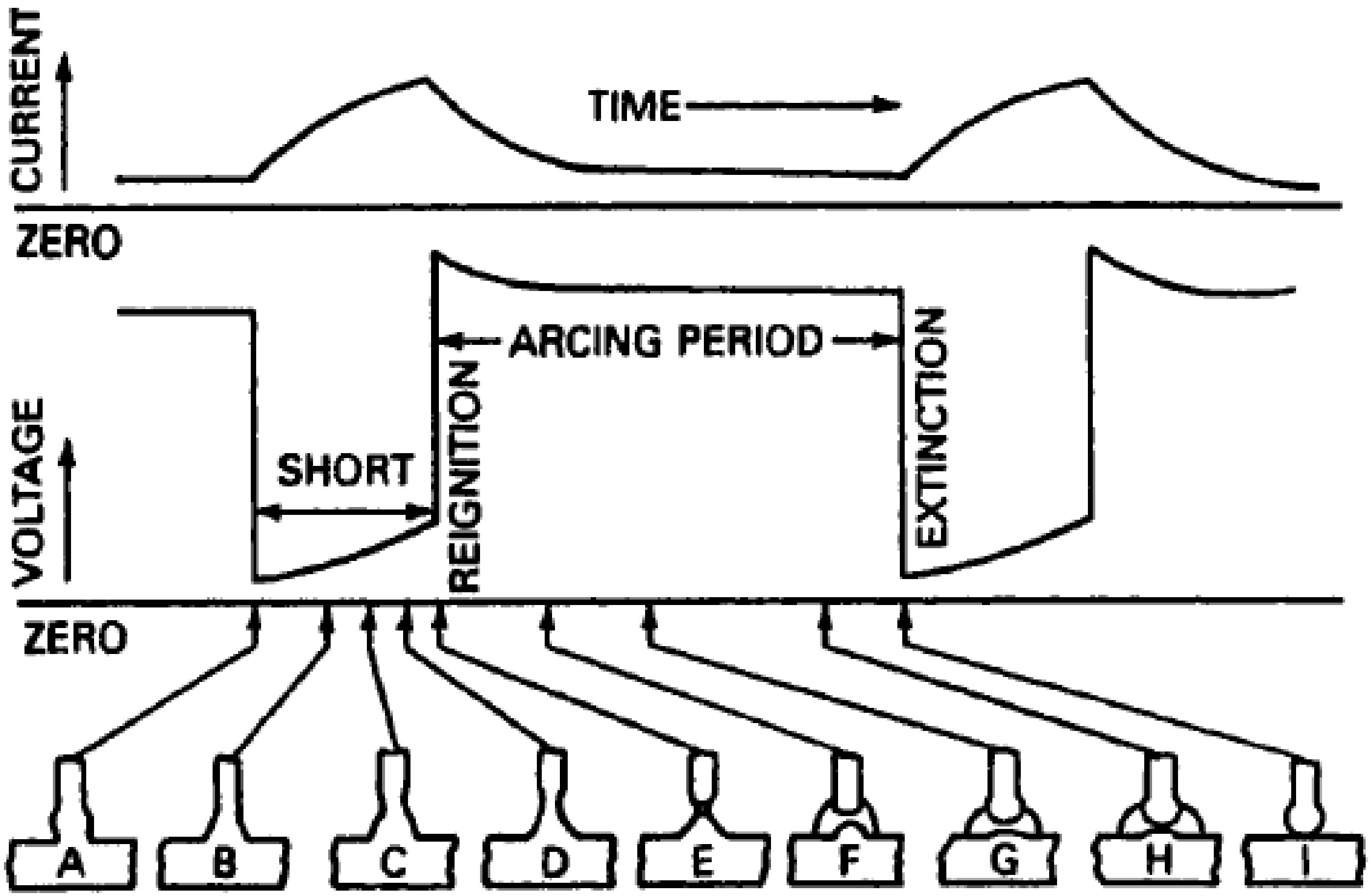


Sequence of short-circuiting transfer



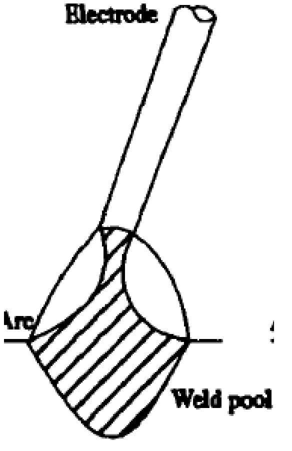
(a) Globule of molten metal builds up on the end of the electrode; **(b)** Globule contacts surface of weld pool; **(c)** Molten column pinches off to detach globule; and **(d)** Immediately after pinch-off, fine spatter may result

Short-circuiting transfer: I-V trace



Short-circuiting transfer-Advantages

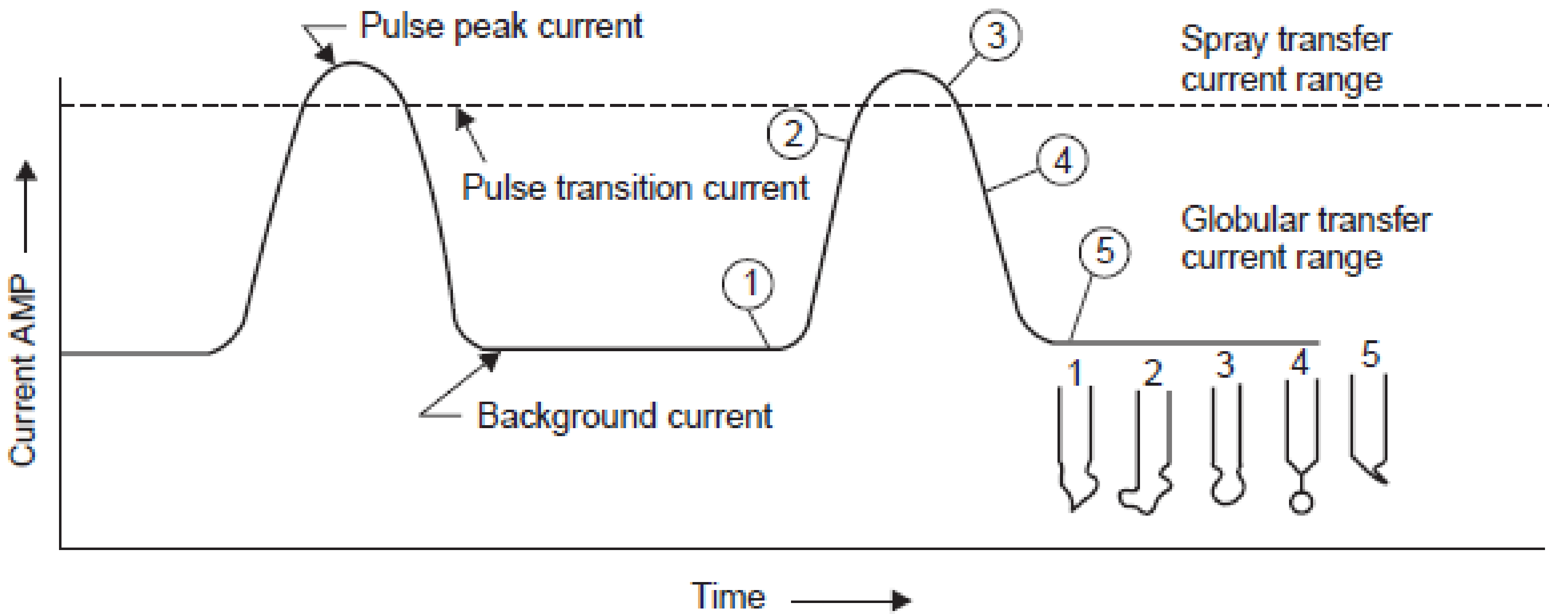
- Less fluid molten metal (due to less superheat)
- Less penetration (due to lower welding voltage and lower net energy input).
- Easy handling in all positions, especially overhead, and for the joining of thin-gauge materials.
- Minimum Spatter



Pulsed arc or pulsed current transfer

- Steady current to maintain the arc and a periodic current pulse to a higher level
- Periodic pulses <u>detaches a drop</u> and propels it into the weld pool,
- Advantage of axial spray transfer at a lower average current, and, thus, lower net heat input.
- The time period of pulses must be short enough to suppress globular transfer, but long enough to ensure that transfer by the spray mode will occur

Pulsed current transfer



Pulsed current transfer

- This pulsed mode differs from the normal spray mode in that
  - The molten metal transfer is interrupted between the current pulses
  - The current to produce spray is below the normal transition current
- Pulse shape (i-e., wave form, especially the rate of the rise and fall of current) and frequency can be varied over a wide range in modern power sources
- Rate of molten metal transfer can be adjusted to be one drop or a few drops per pulse (by adjusting the pulse duration)

Classification of transfer modes

Designation of Transfer Type	Welding Processes (Examples)
1. Free-flight transfer	
1.1. Globular	
1.1.1. Drop	Low-current GMA
1.1.2. Repelled	CO_2 shielded GMA
1.2. Spray	
1.2.1. Projected	Intermediate-current GMA
1.2.2. Streaming	Medium-current GMA
1.2.3. Rotating	High-current GMA
1.3. Explosive	SMA (coated electrodes)
2. Bridging transfer	
2.1. Short-circuiting	Short-arc GMA, SMA
2.2. Bridging without interruption	Welding with filler wire addition
3. Slag-protected transfer	
3.1. Flux-wall guided	SAW
3.2. Other modes	SMA, cored wire, electroslag

Dominant forces in transfer modes

Transfer Type	Dominant Force or Mechanism
1. Free-flight transfer	
1.1. Globular	
1.1.1. Drop	Gravity and electromagnetic pinch
1.1.2. Repelled	Chemical reaction generating vapor
1.2. Spray	
1.2.1. Projected	Electromagnetic pinch instability
1.2.2. Streaming	Electromagnetic
1.2.3. Rotating	Electromagnetic kink instability
1.3. Explosive	Chemical reaction to form a gas bubble
2. Bridging transfer	
2.1. Short-circuiting	Surface tension plus electromagnetic forces
2.2. Bridging without interruption	Surface tension plus (hot wire) electromagnetic forces
3. Slag-protected transfer	
3.1. Flux-wall guided	Chemical and electromagnetic
3.2. Other modes	Chemical and electromagnetic

Effect of welding process parameters on transfer modes-Summary

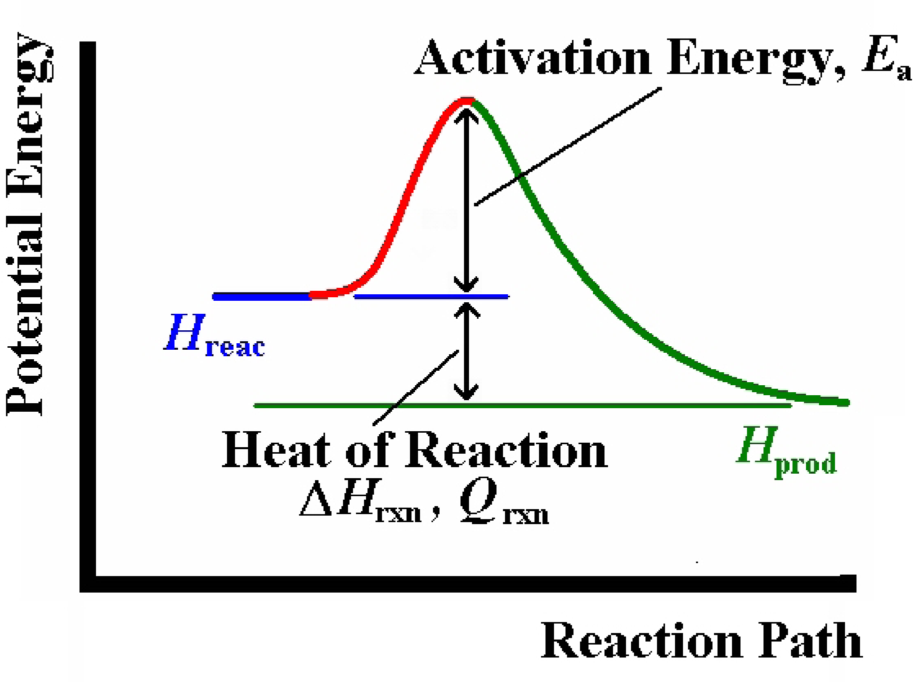
- Current: Current at which transition from globular to spray transfer begins depends on
  - Composition of the consumable electrode,
  - Electrode diameter,
  - Electrode extension,
  - Composition of shielding gas.
- Shielding Gas Effects
- Process Effects
- Operating Mode or Polarity Effects

Welding Processes-
Other fusion welding processes

Thermite mixture

Metallic fuel + Oxidiser $\rightarrow$ Energy

Thermite Reaction



Metal oxide + Aluminum → Metal + Aluminum oxide + Heat

- Bimolecular reactions and reaction rates are controlled by diffusion times between reactants.
- Thermite mixtures of nano-sized reactants reduce the critical diffusion length thus increasing the overall reaction rate

Thermite Reaction stages

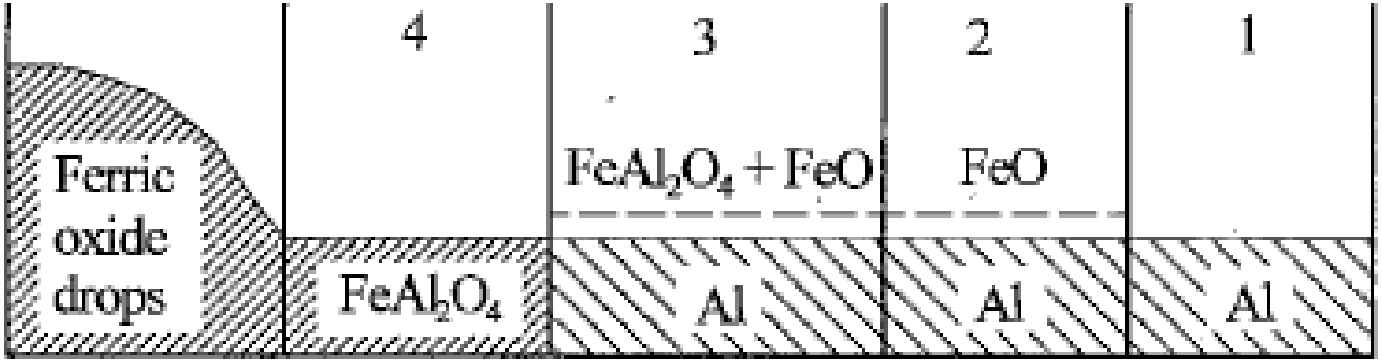


Figure 14 Interaction zones between Fe_2O_3 and aluminium films: (1) pure aluminium film, (2) finely dispersed FeO particles on the aluminium film, (3) fine particles of $FeAl_2O_4$ with traces of FeO on the aluminium film, (4) $FeAl_2O_4$ layer [109].

$(1/2)Fe_3O_4 + Al \rightarrow Fe + (1/2)FeAl_2O_4$

$2FeO + Al \rightarrow (3/2)Fe + (1/2)FeAl_2O_4$

$(1/2)FeAl_2O_4 + (1/3)Al \rightarrow (1/2)Fe + (2/3)Al_2O_3$

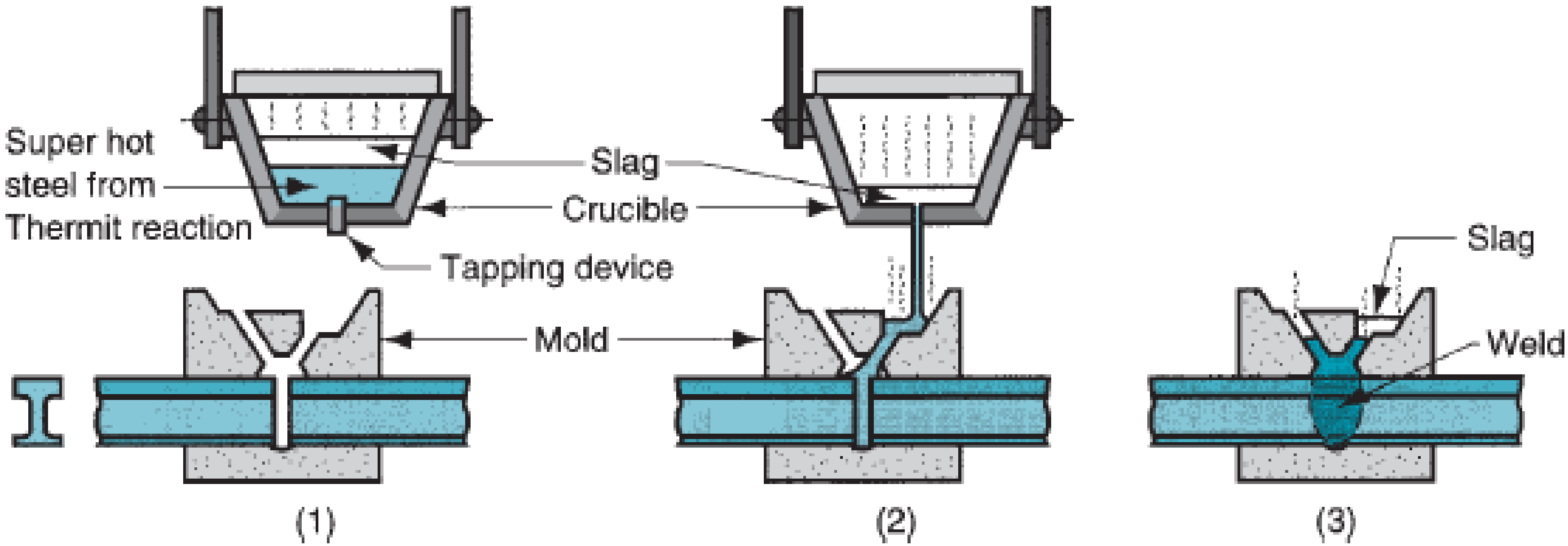
Thermite types

Fuels	Oxidisers
Aluminium, Magnesium, Titanium, Zinc, Silicon, Boron	Boron(III) oxide, Silicon(IV) oxide, Chromium(III) oxide, Manganese(IV) oxide, Iron(III) oxide, Iron(II,III) oxide, Copper(II) oxide, Lead(II,III,IV) oxide,

Thermite welding (TW)

- Heat for coalescence is produced by superheated molten metal from the chemical reaction of Thermite
- Example: $2Al + Fe_2O_3 \rightarrow 2Fe + Al_2O_3$ + heat
- Filler metal is obtained from the liquid metal
- More in common with casting than it does with welding
- Applications in joining of railroad rails and repair of cracks in large steel castings and forgings such as ingot moulds, large diameter shafts, frames for machinery, and ship rudders

Thermit welding (TW)



$$Fe_2O_3 + Al \rightarrow 2Fe + Al_2O_3 + \sim 850kJ$$