Welding Lectures 5-7

Physics of Arc welding

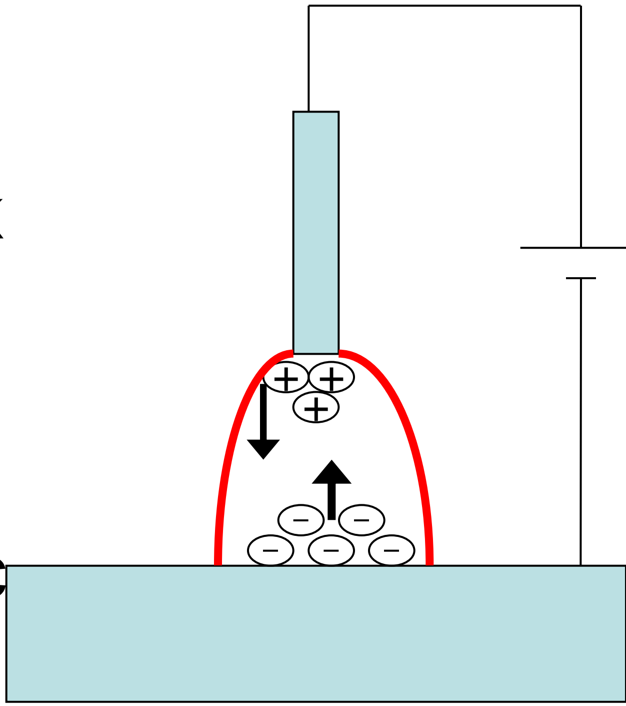
Arc-on-time in Arc welding

- 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 %

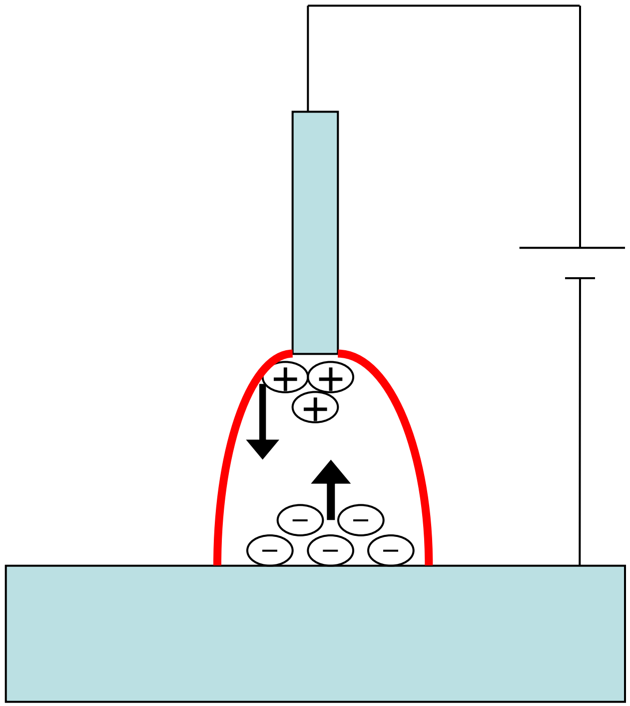
The electric arc

- 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

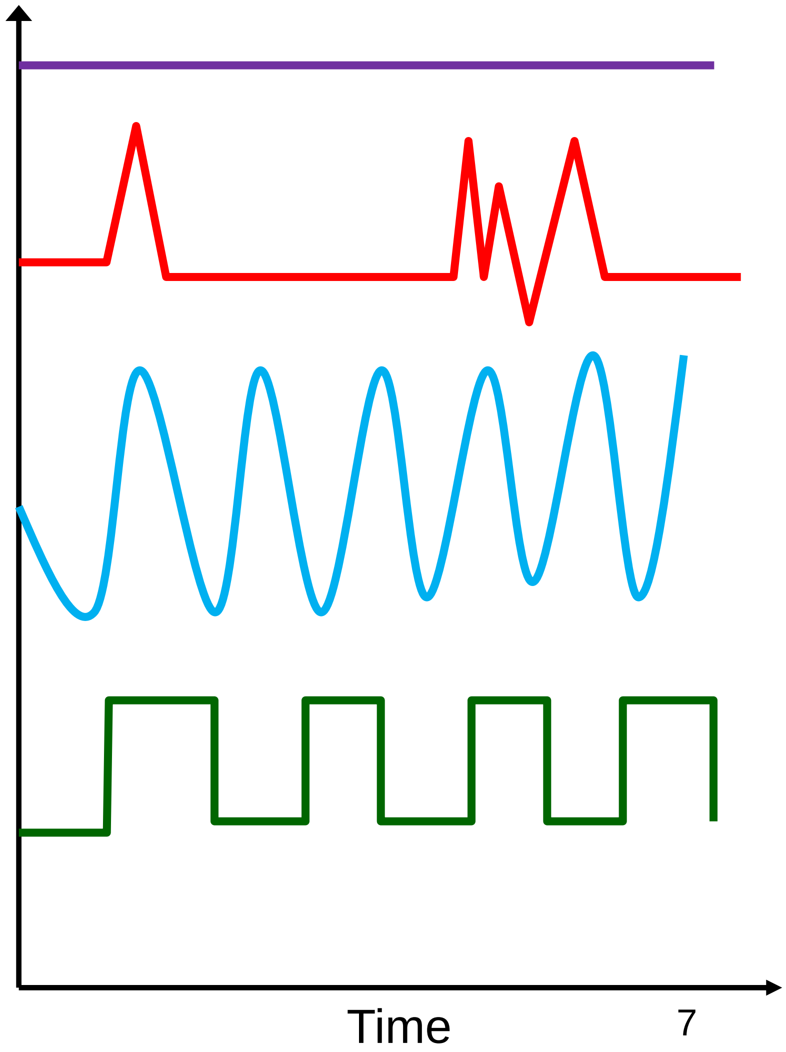


Effect of Magnetic Fields on Arcs

- 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

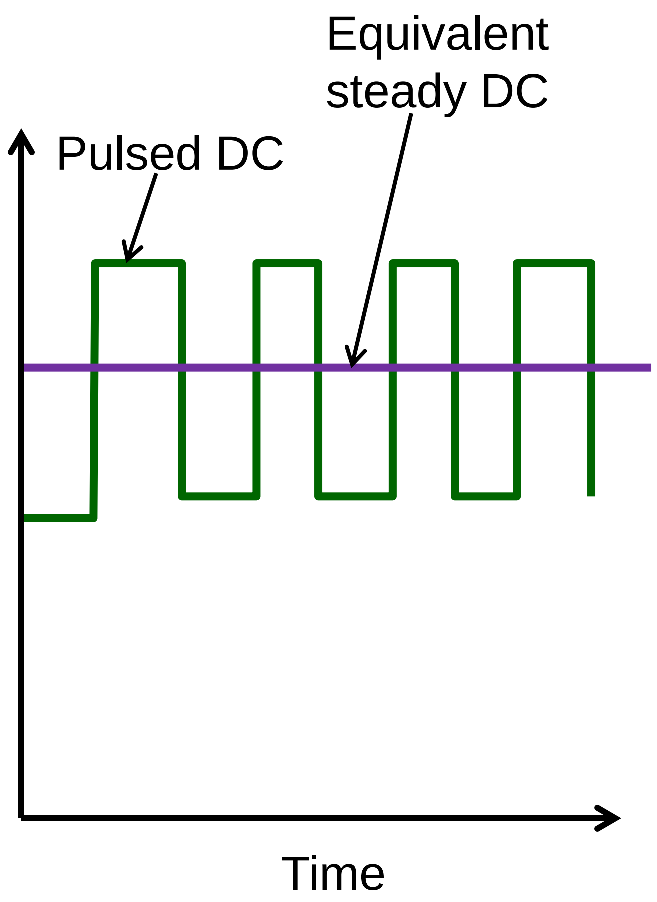
Arc welding - Arc Types

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

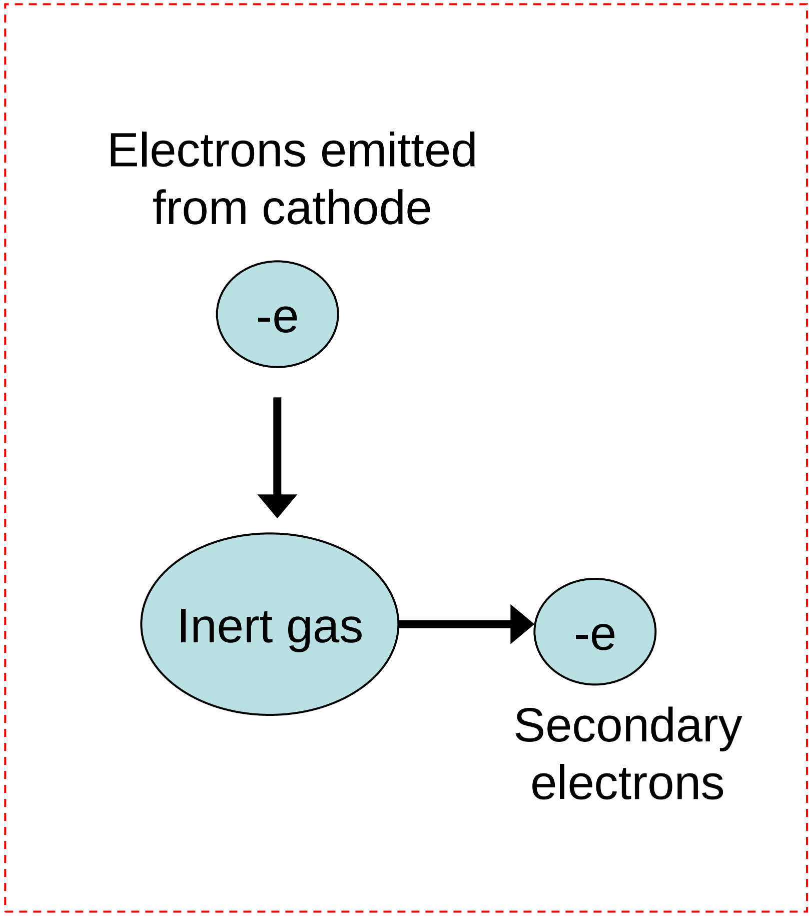


Pulsed DC in Arc welding

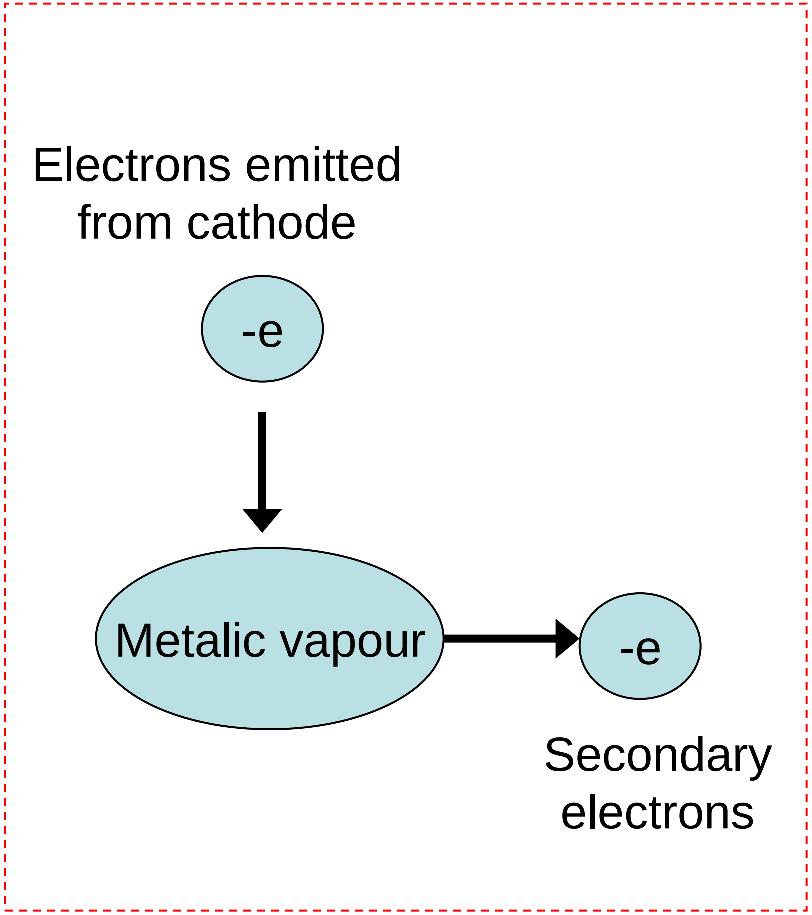
- The higher pulsing rates increase puddle agitation → a better grain molecular structure within the weld
- High speed pulsing constricts and focuses the arc; Increases arc stability, penetration and travel speeds
- Reduces <u>arc blow</u> (created by influence of magnetic field)
- A smaller heat-affected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



Creation of arc plasma



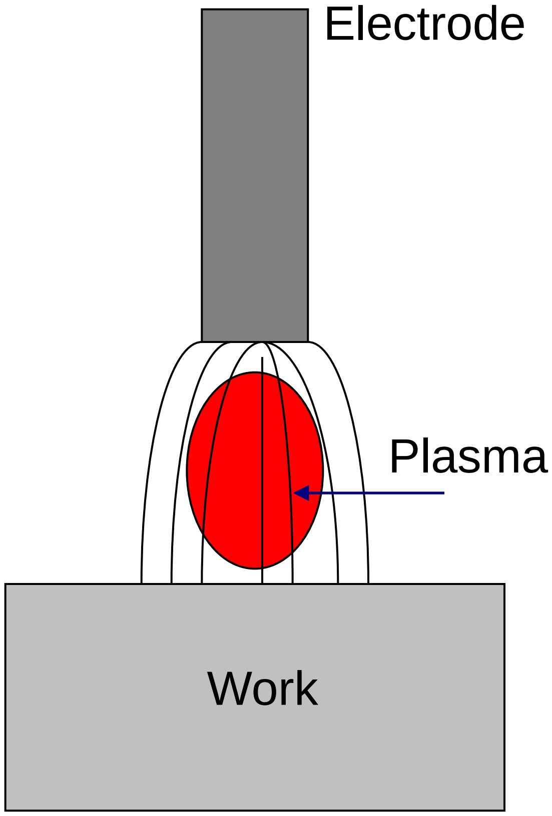
High temperature plasma



Low temperature plasma

The Arc Plasma

- Plasma, the ionized state of a gas
- Comprises of a <u>balance of negative electrons and positive ions</u> (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 <u>neutral plasma state</u> → attained at <u>equilibrium temperatures</u> → 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 → Higher Arc temperature
- E.g. Helium → tighter bonding of outermost electrons compared to Ar → 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

<table>
<tr><th>Arc Welding type</th><th>Arc constituents</th><th colspan="2">~Arc temperature K (Theoretical values)</th></tr>
<tr><td>Plasma Arc welding (PAW)</td><td>Pure plasma, no metal transfer</td><td>50,000</td><td rowspan="4">Actual values limited by losses (convection, radiation, diffusion)</td></tr>
<tr><td>Gas tungsten arc welding (with inert shielding gas)</td><td>Metal vapor from nonconsumable electrode and any molten metal particles from filler</td><td>30,000</td></tr>
<tr><td>GMAW</td><td>large concentrations of metal ions and vapor and molten droplets</td><td>20,000</td></tr>
<tr><td>SMAW/
Flux cored arc welding</td><td>easily ionized materials such as alkali metals (sodium, potassium)</td><td>6000</td></tr>
</table>

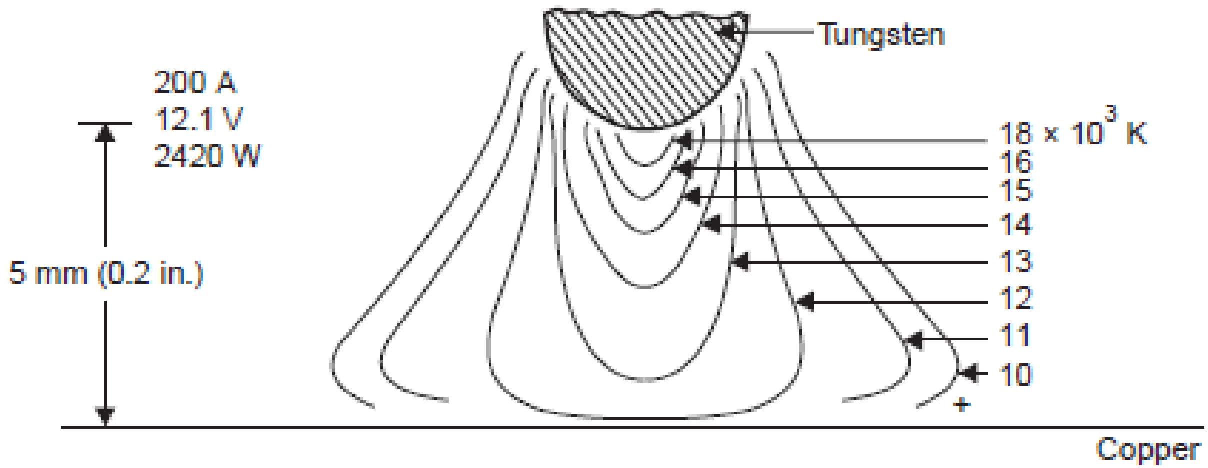
Arc Temperature

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

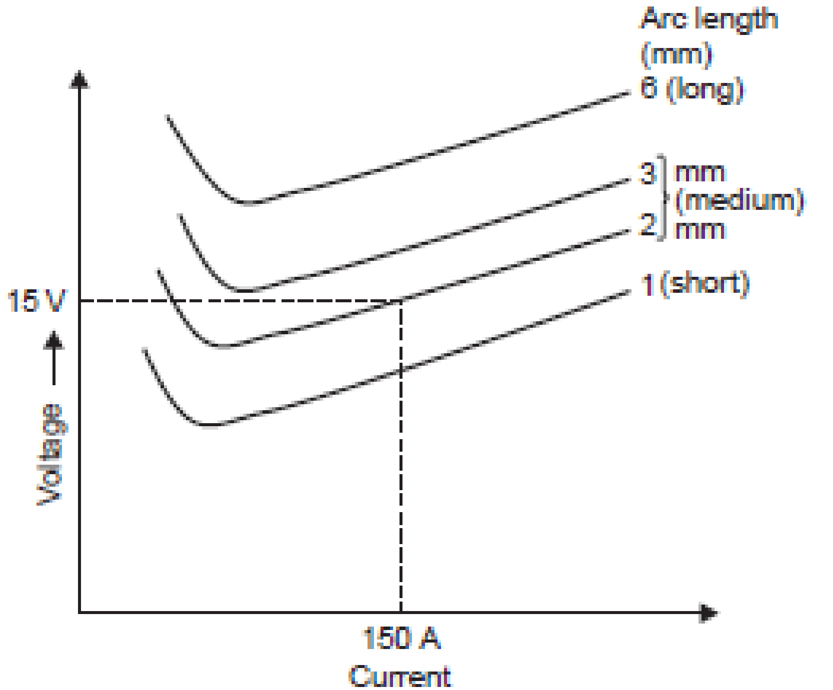
Isothermal Map of an
Argon-tungsten arc



- 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

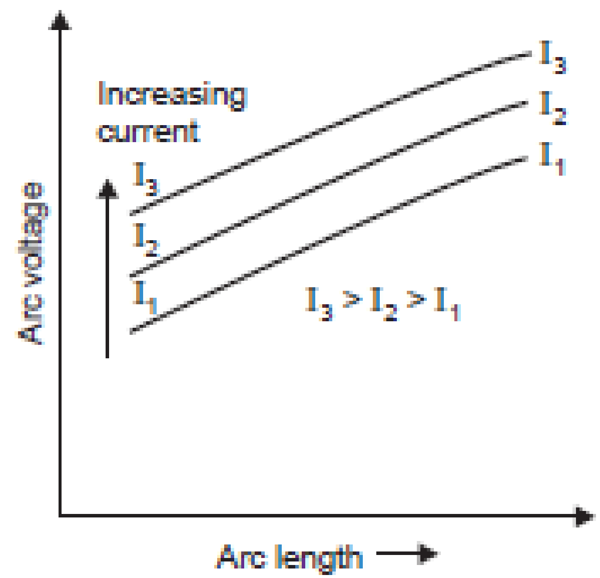
Arc: V-A Characteristics

- 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 growth 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 $\rightarrow$ low-voltage, high-current arcs between a nonconsumable or consumable electrode and a work piece
- Arc welding power source $\rightarrow$ static and dynamic characteristics
- Static volt-ampere characteristics,
  - (1) constant-current and
  - (2) constant-voltage
- 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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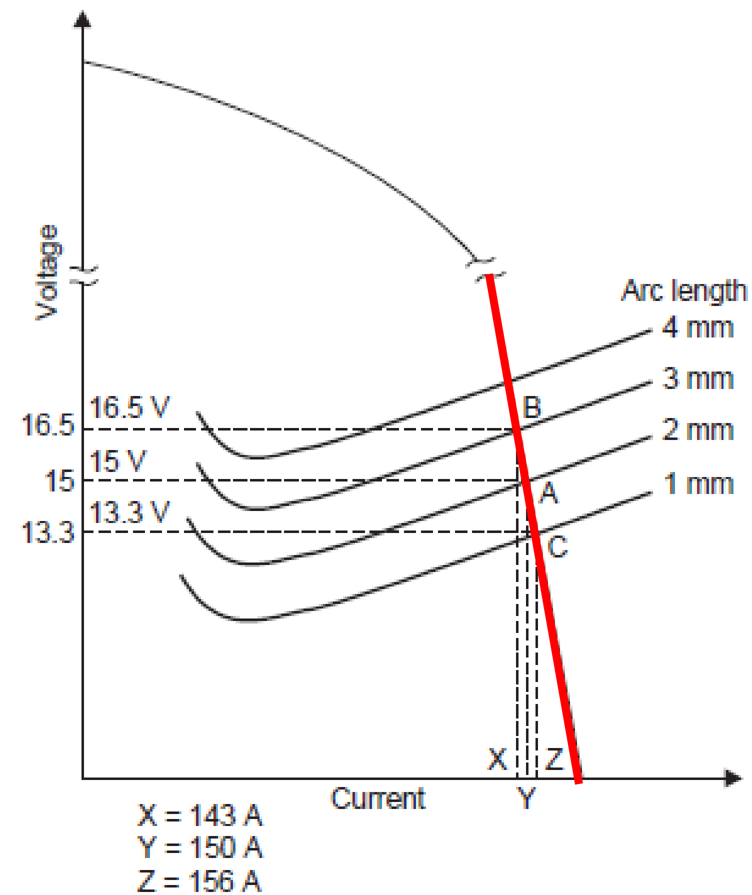
Constant current power sources

- 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 coated electrodes
- Small change in amperage 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 *"drooper"*
- 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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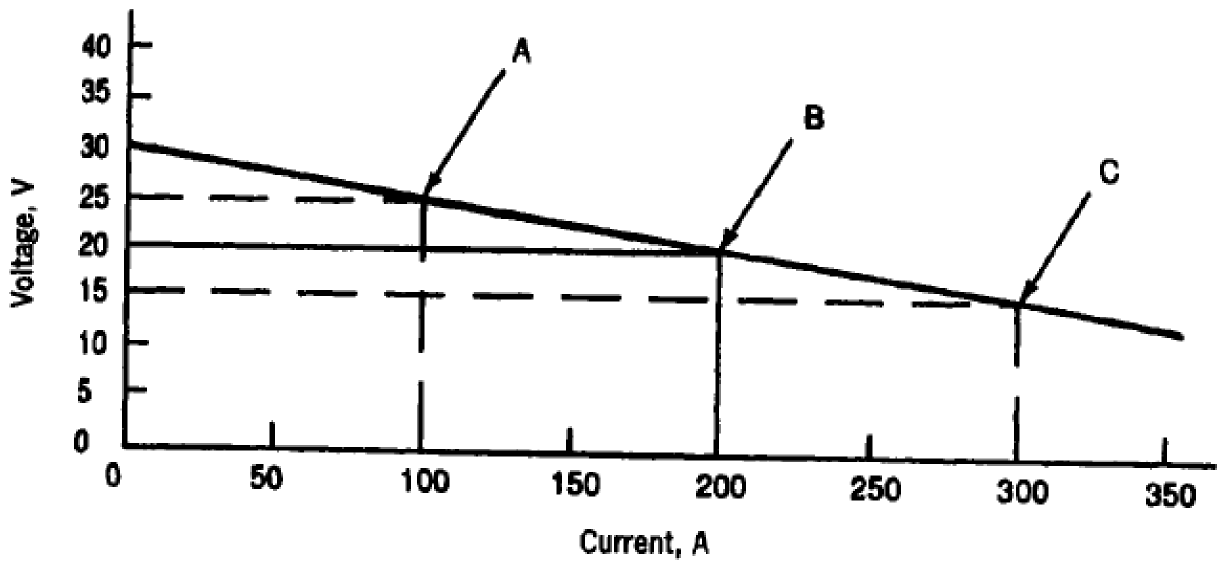
Constant-Voltage Power Sources



- 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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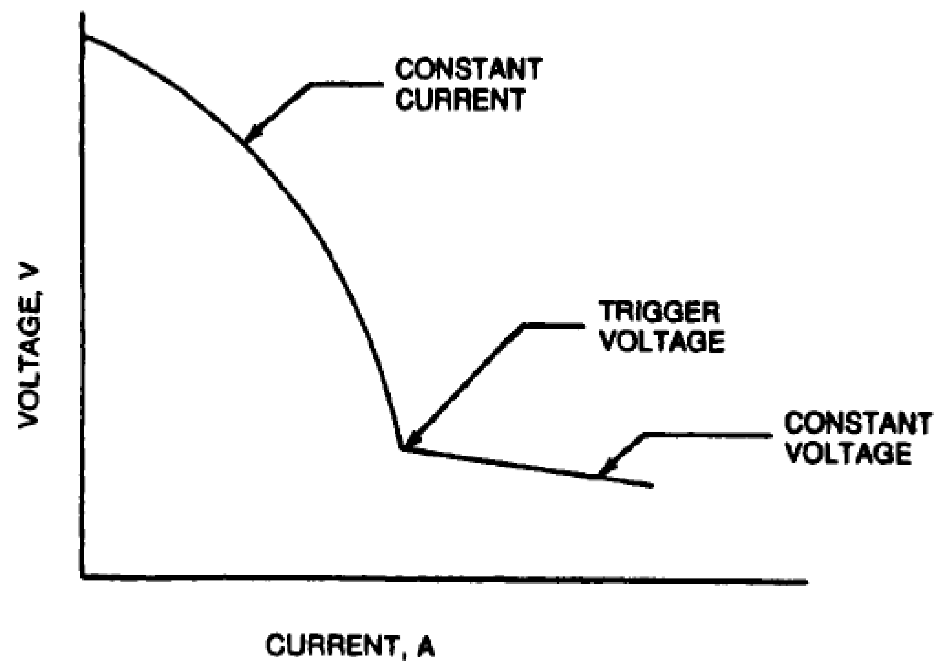
Combined Characteristic Sources

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

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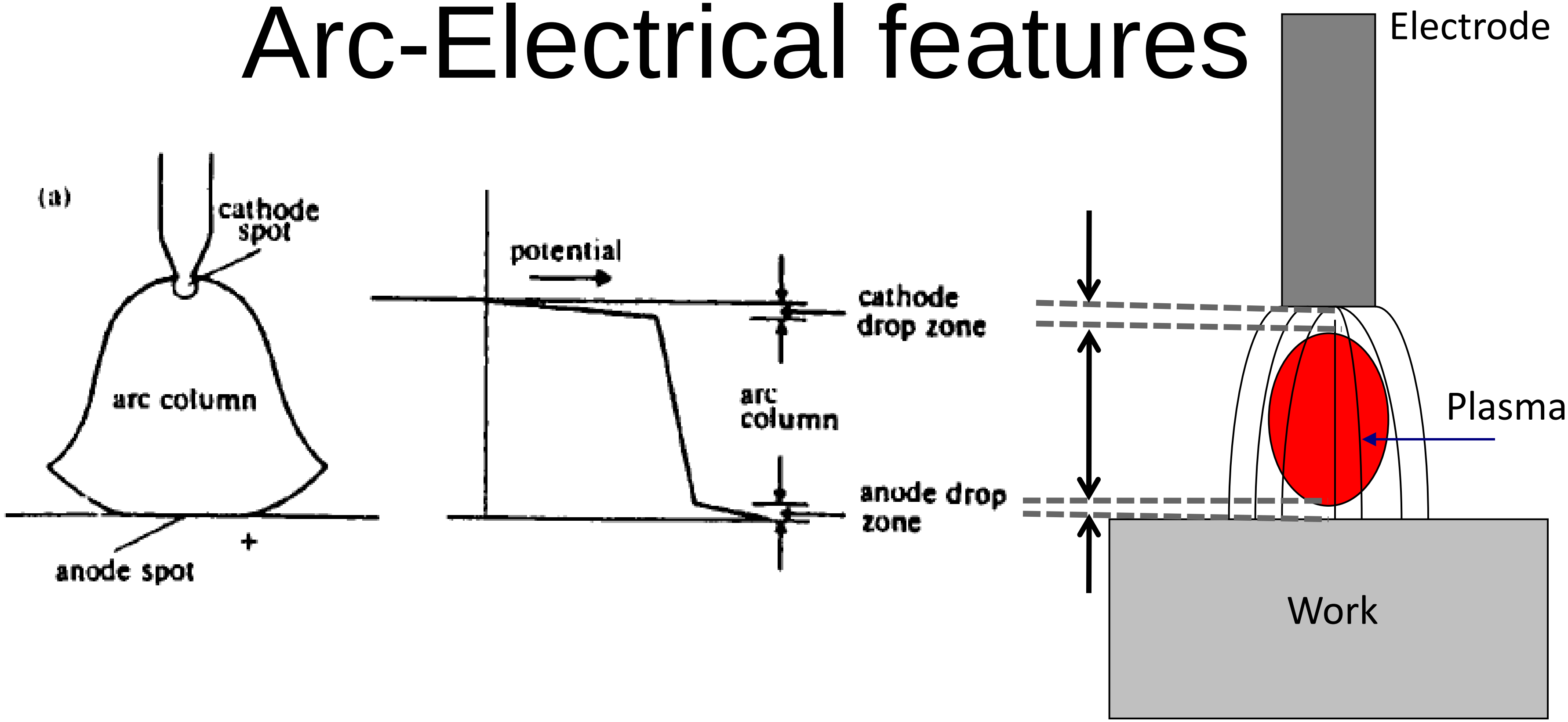
Arc-Electrical features



- 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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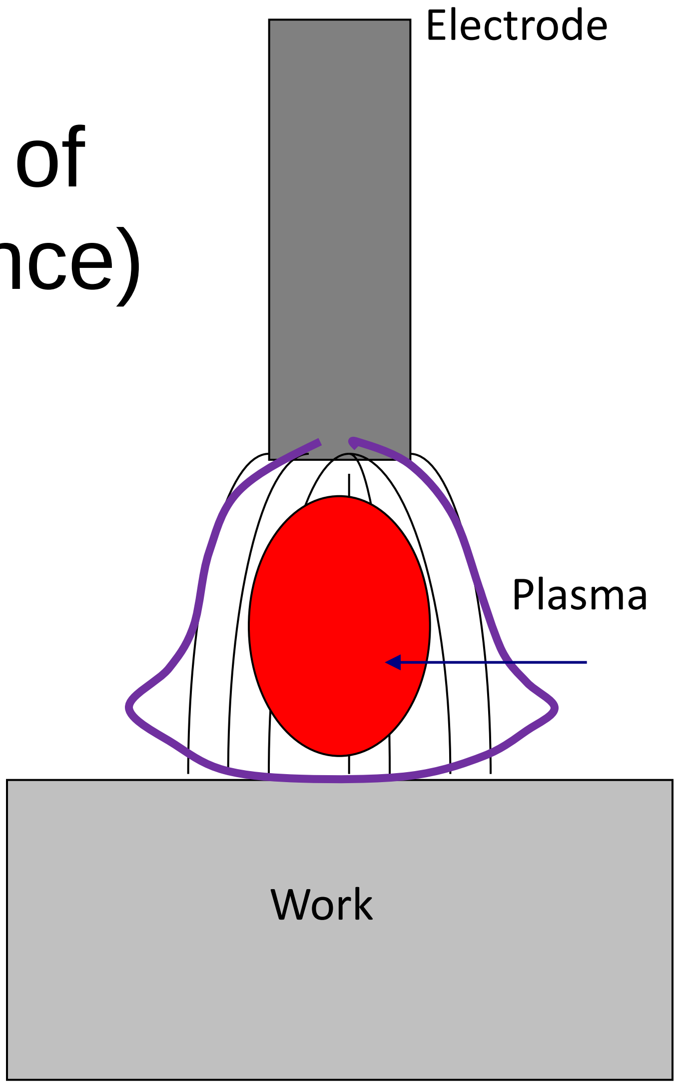
Arc Shape

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

- Bell Shape
- Cone
- Elliptical
- Cylindrical



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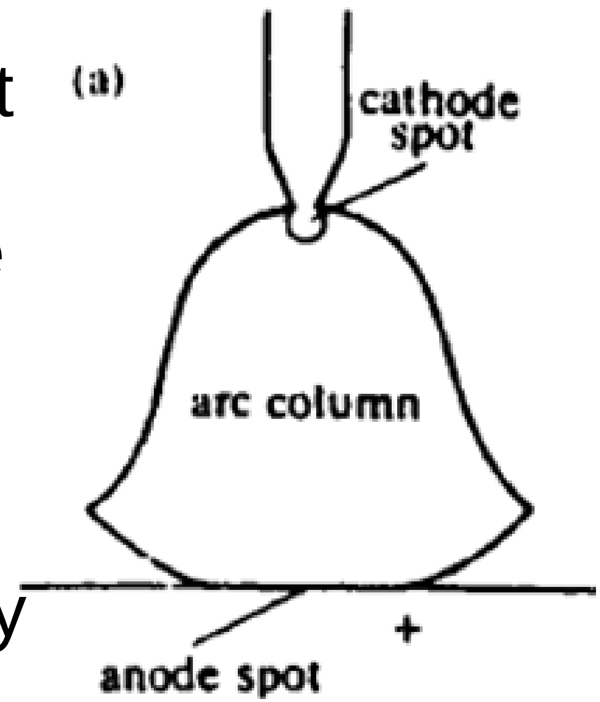
Arc Shape- Influencing factors

1. <u>Shape of the arc terminals</u> (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. <u>Gravitational forces</u>
3. <u>Magnetic forces</u> (from both internally generated and externally induced or applied sources)
4. <u>Interactions</u> between the plasma and ambience (shielding gas)



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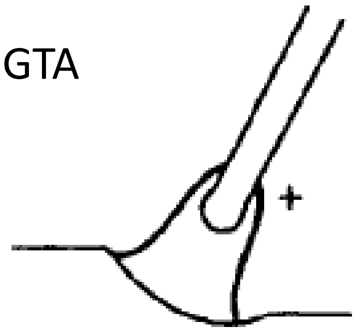
Arc Shape- Influencing factors

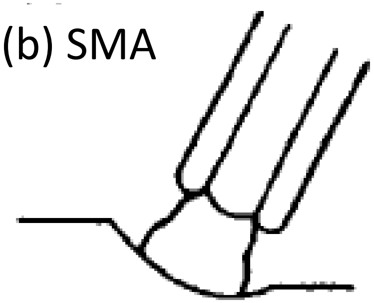
- Nature of electrode- Consumable/non consumable
- Electrode coating/gas generation
- Shielding gas
- Magnitude & polarity of current source

Arc Shape-Examples

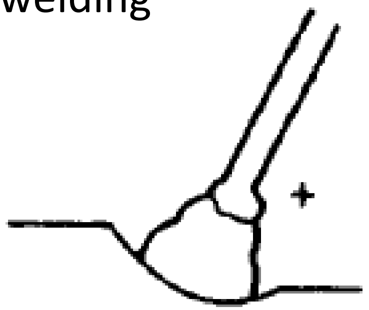
(a) GTA



(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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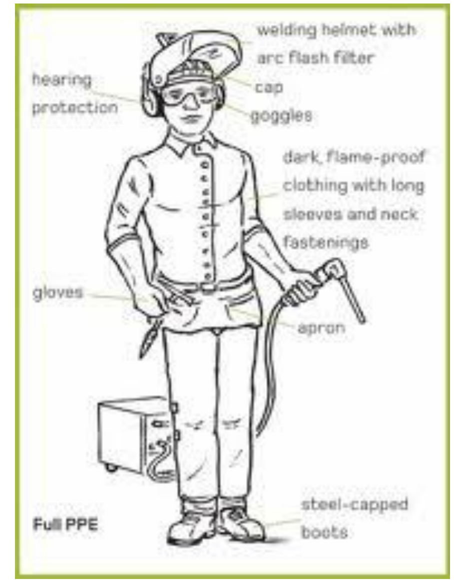
Arc radiation

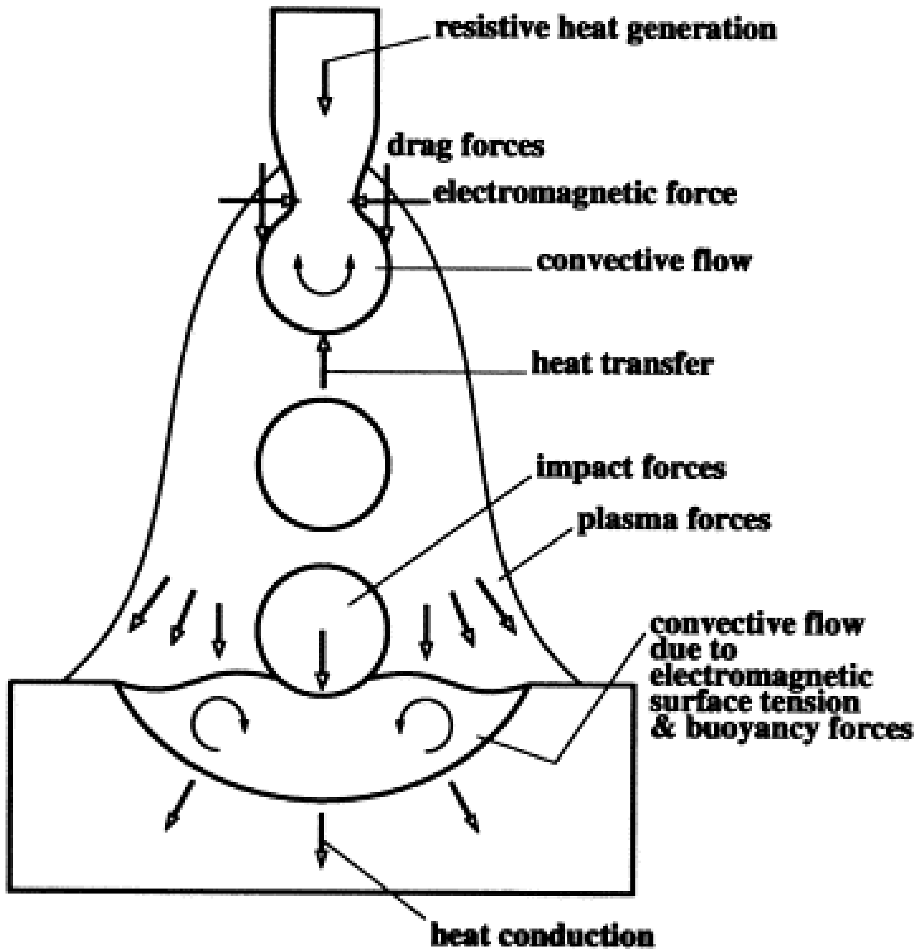
- Arc radiation $\rightarrow$ amount and character depends on
  - the atomic mass and chemical composition of the gaseous medium,
  - the temperature, and the pressure.
- Spectral analysis shows line and continuum emissions due to excited and ionized states of atoms and ions
- Radiation $\rightarrow$ UV, visible, IR
- Energy loss due to radiation $\rightarrow$ 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

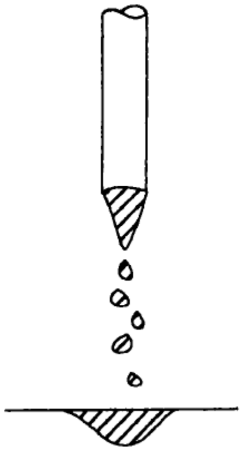
- Pressure generated by the evolution of gas at the electrode tip (for flux-coated or flux-cored electrode processes)
- Electrostatic attraction between the consumable electrode and the workpiece
- Gravity
- "Pinch effect" caused near the tip of the consumable electrode by electromagnetic field forces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

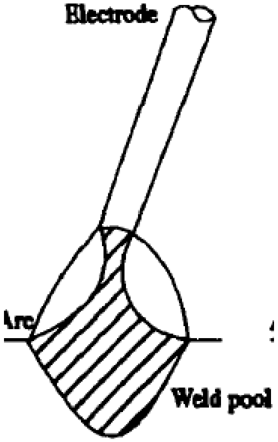
Mode of Metal transfer-Influencing parameters

- Explosive evaporation of a necked region formed between the molten drop and solid portions of the electrode due to very high conducting current density
- 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

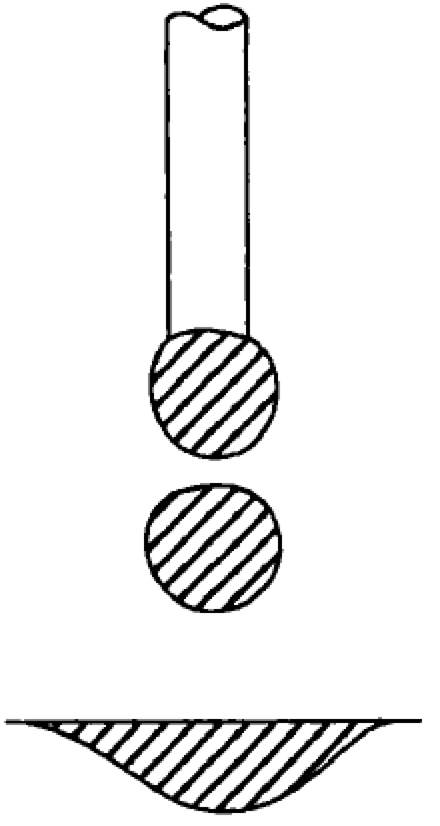
- **Free-flight transfer**: Complete detachment of the molten metal drop from the consumable electrode → flight to the work piece and weld pool, without any direct physical contact
- **Bridging transfer**: molten metal drops are never completely free; rather they are always attached to the consumable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





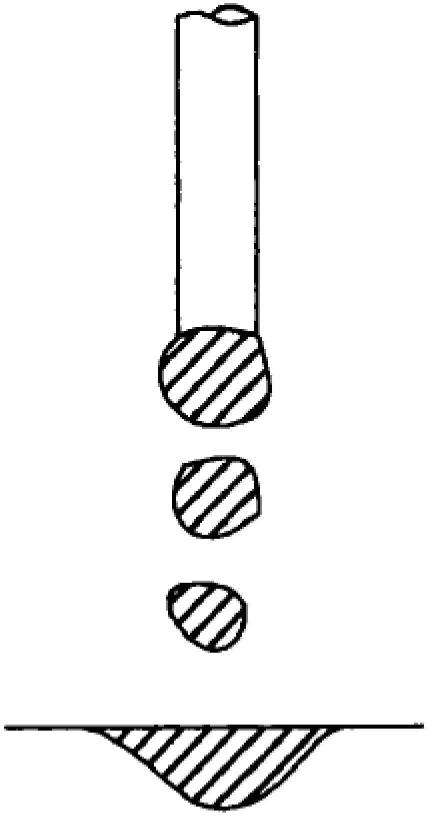
Free-flight-Globular Transfer

- 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
- Large drops $\rightarrow$ detach by gravity
- Low rate of globule formation, detachment, and transfer (< 1-10 s^{-1})
- Globular transfer $\rightarrow$ down-hand position

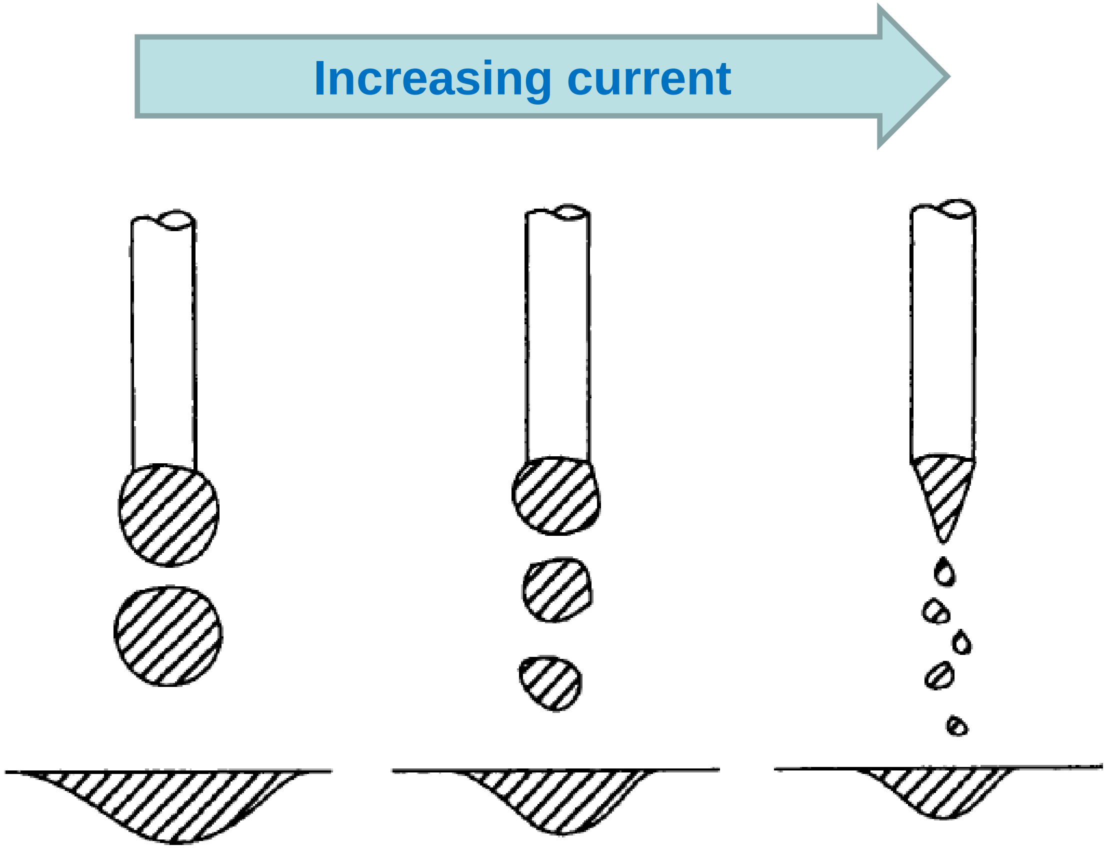


Free flight: Globular-projected Transfer

- 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



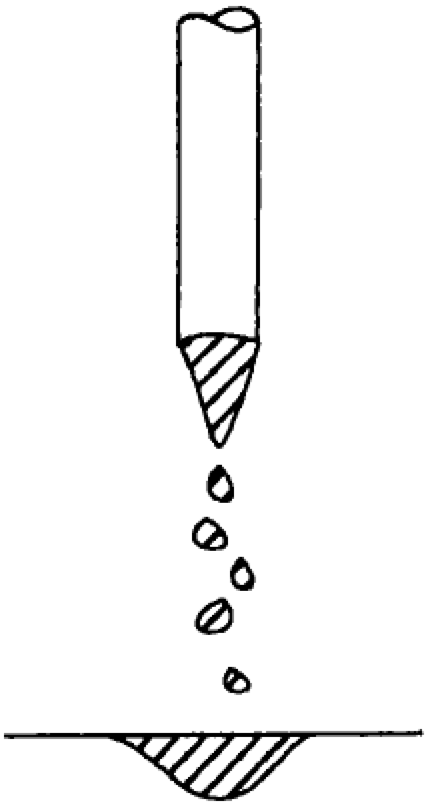
Free-flight transfer modes



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 → No individual drops
- Tip of the consumable electrode becomes pointed → 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 → <u>Electromagnetic pinch effect</u>
- The rate at which droplets are transferred is hundreds per second.

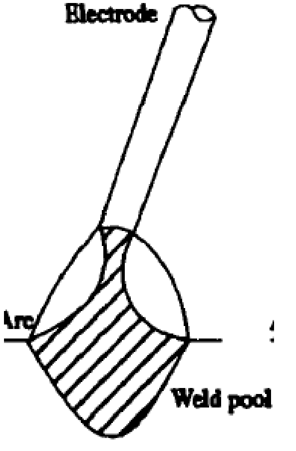


Free flight -Spray Transfer: Features

- 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

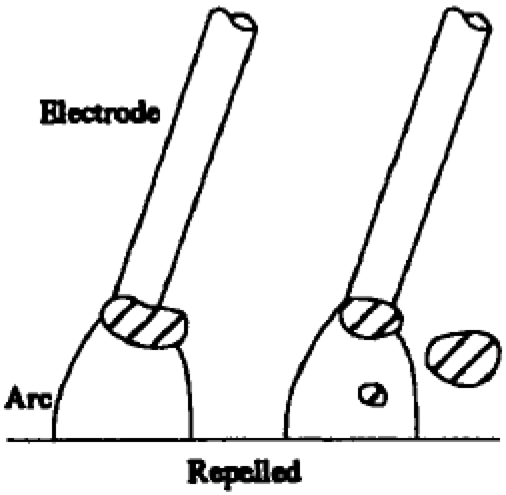
Bridging or short circuiting transfer

- Large dia. Electrodes → too high transition current to achieve axial spray transfer (e.g., 200-220A for 1-mm-diameter steel wire) → 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.

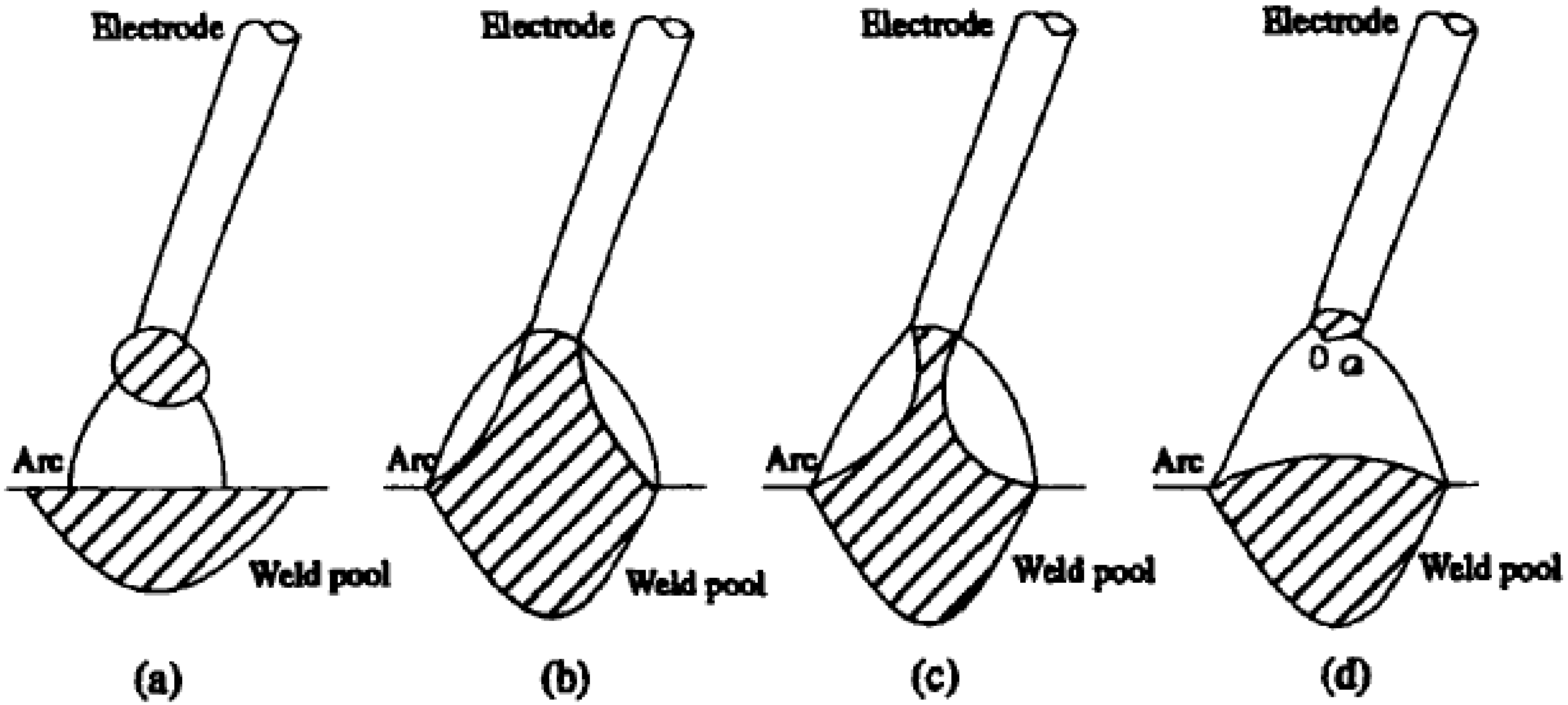


Bridging or short-circuiting transfer

- 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

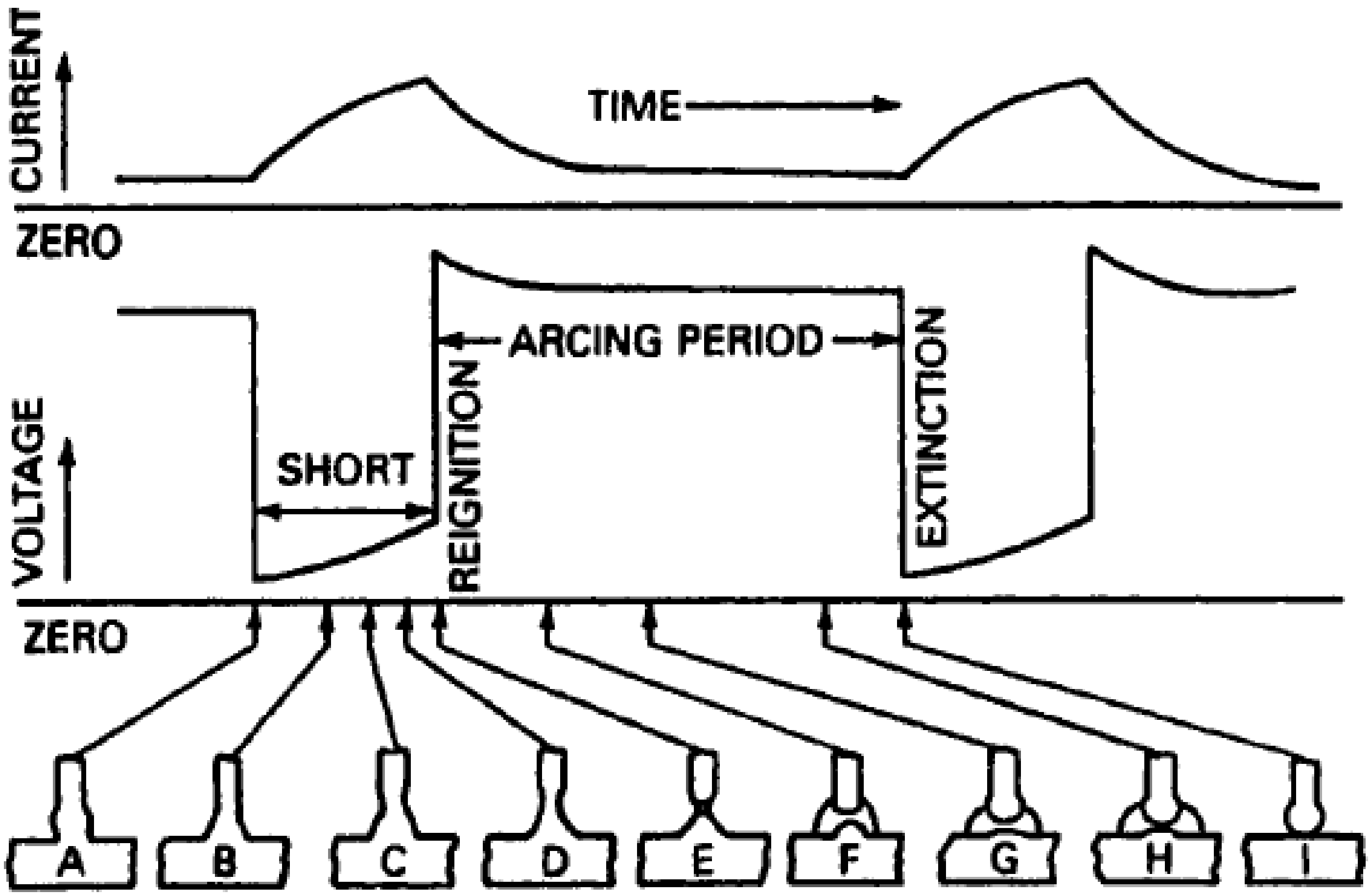


Sequence of short-circuiting transfer



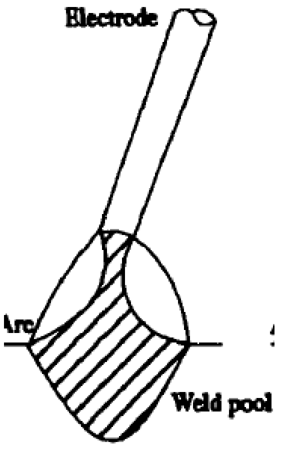
(a) Globule of molten metal builds up on the end of the electrode; **(b)** Globule contacts surface of weld pool; **(c)** Molten column pinches off to detach globule; and **(d)** Immediately after pinch-off, fine spatter may result

Short-circuiting transfer: I-V trace



Short-circuiting transfer-Advantages

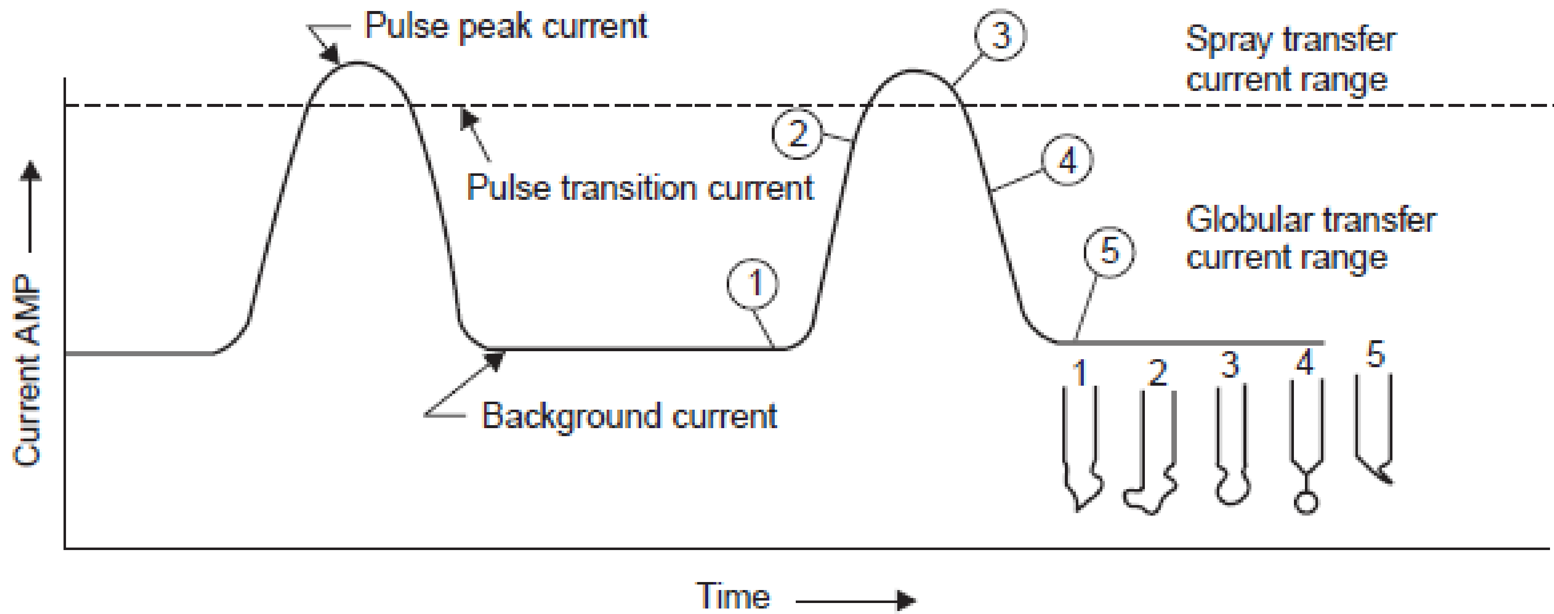
- Less fluid molten metal (due to less superheat)
- Less penetration (due to lower welding voltage and lower net energy input).
- Easy handling in all positions, especially overhead, and for the joining of thin-gauge materials.
- Minimum Spatter



Pulsed arc or pulsed current transfer

- Steady current to maintain the arc and a periodic current pulse to a higher level
- Periodic pulses detaches a drop 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

- <u>Current</u>: 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.
- <u>Shielding Gas Effects</u>
- <u>Process Effects</u>
- <u>Operating Mode or Polarity Effects</u>

Welding Processes-

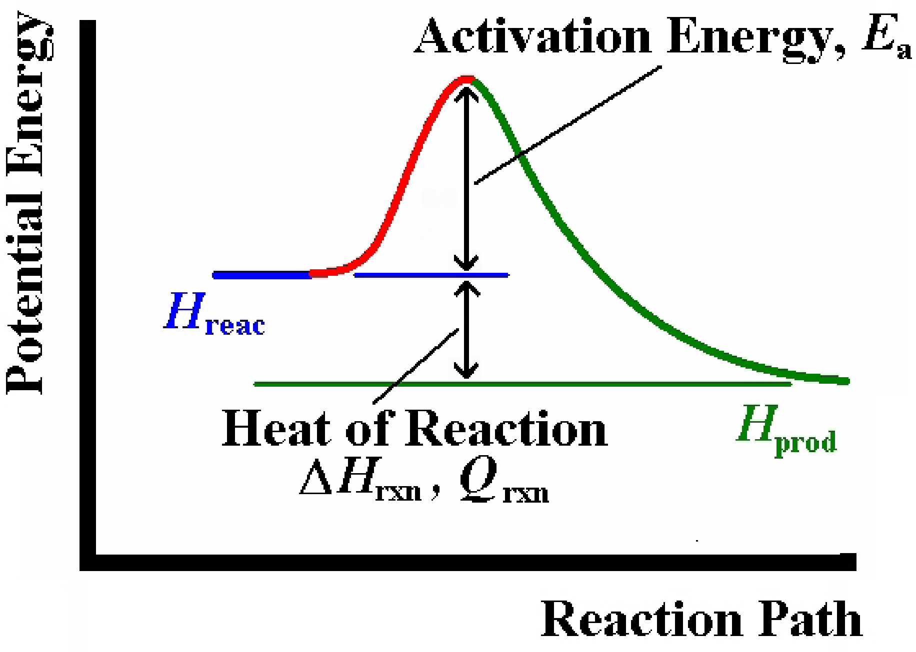
Other fusion welding processes

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

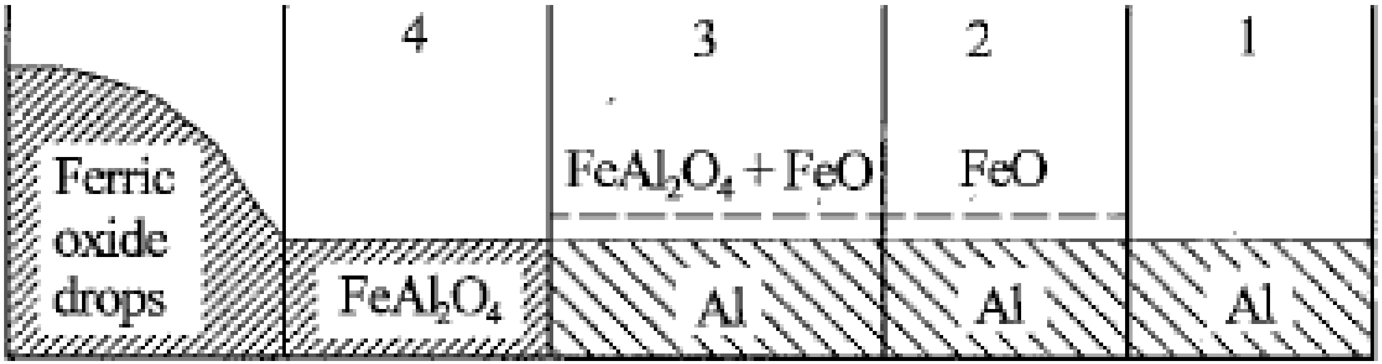


Figure 14 Interaction zones between Fe_2O_3 and aluminium films: (1) pure aluminium film, (2) finely dispersed FeO particles on the aluminium film, (3) fine particles of $FeAl_2O_4$ with traces of FeO on the aluminium film, (4) $FeAl_2O_4$ layer [109].

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

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

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

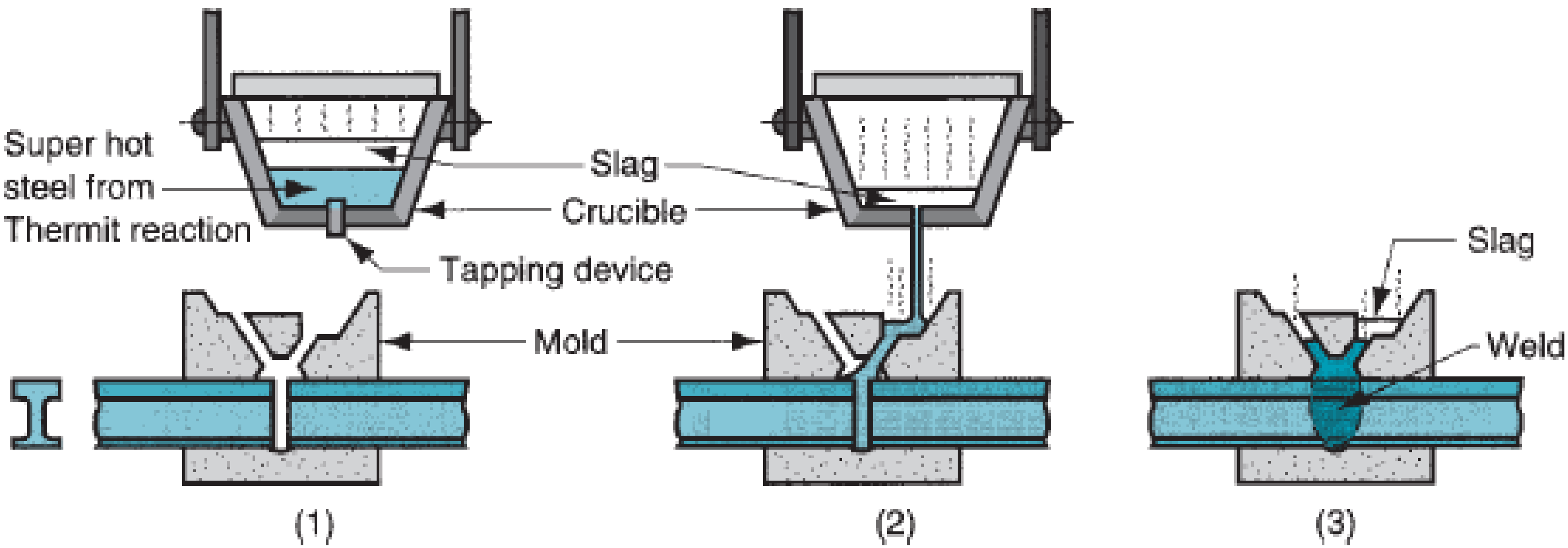
Thermite types

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)



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

Welding Processes-Resistance welding

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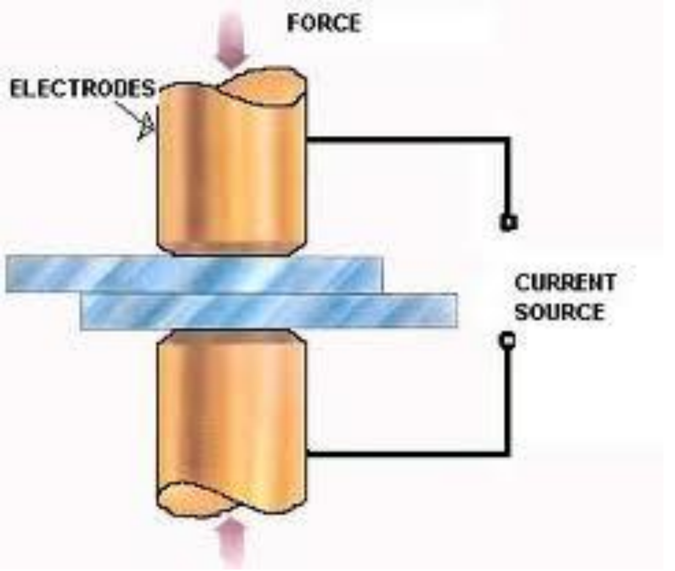
Resistance welding (RW)

- Generate heat through the resistance to the flow of electric current in parts being welded
- The parts are usually an integral part of the electrical circuit
- Contact resistance $\rightarrow$ heats the area locally by I^2R, $\rightarrow$ melting $\rightarrow$ formation of a nugget
- Contact resistance must be higher at the point to be welded than anywhere else.



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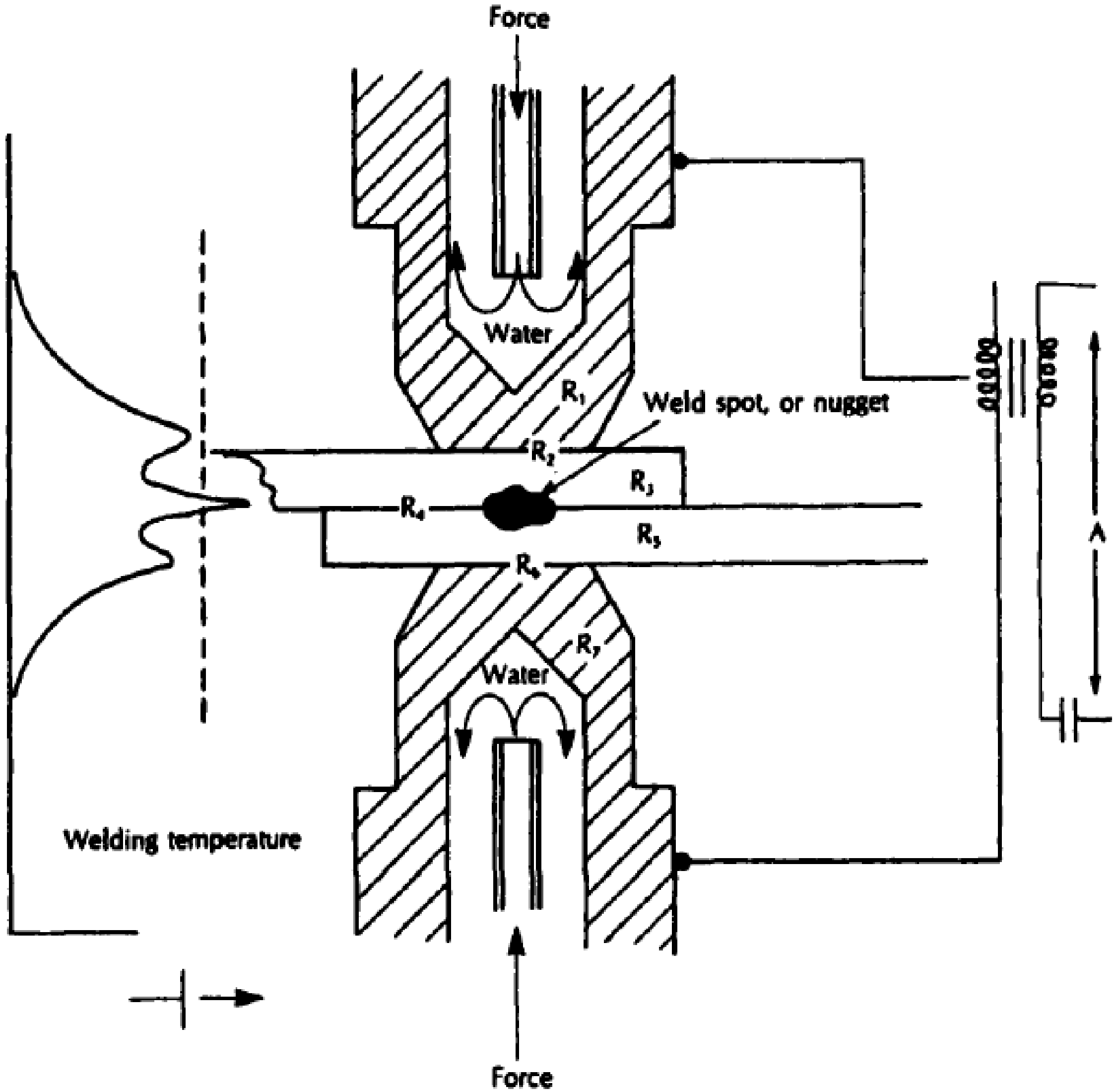
Resistance welding



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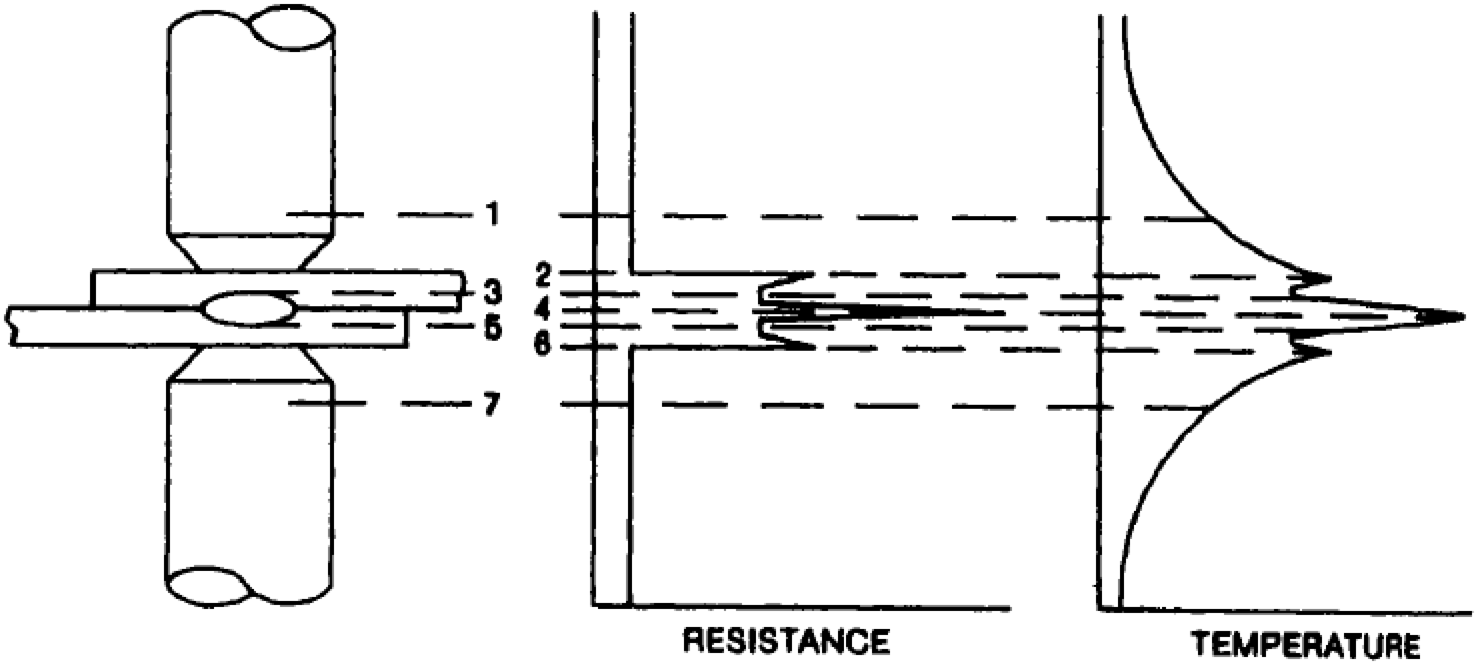
Resistance welding



$$Q = Pt = I^2Rt$$

$$\Delta T = \frac{Q}{mC_p} = \frac{I^2Rt}{mC_p}$$

Resistance welding

- Pairs of water-cooled copper electrodes
- Apply pressure
  - To reduce the contact resistance at the electrode-to-workpiece interface
  - Contain the molten metal in the nugget
  - To literally forge the work surfaces together in the vicinity of the weld
- The principal process variables
  - welding current (several thousands to tens of thousands of amperes)
  - welding time (of the order of s)
  - electrode force and electrode shape
- DC power (provided from either single-phase or three-phase AC line 440-480 V using step-down transformer/rectifiers)
- Usually used to join overlapping sheets or plates as lap joints, which may have different thicknesses

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Resistance welding-types

- Resistance spot welding (RSW)
- Resistance seam welding (RSEW)
- Projection welding (PW)
- Flash welding (FW)
- Upset welding (UW)
- Percussion welding (PEW)

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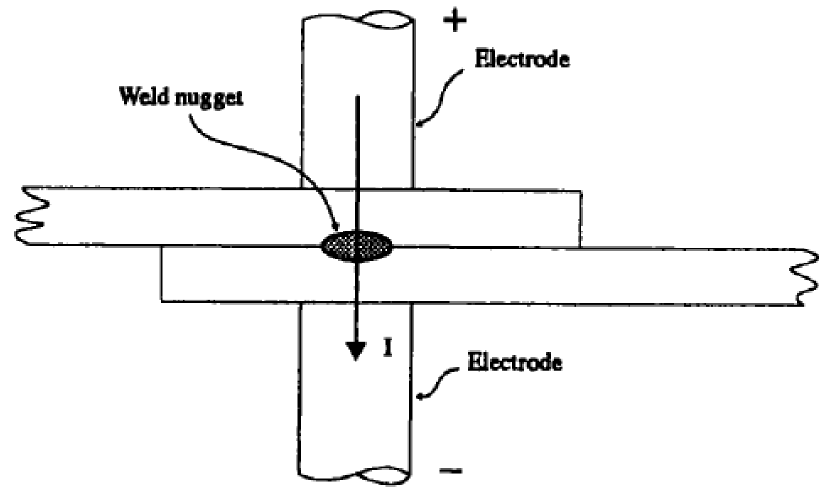
Resistance spot welding **(RSW)**

- Series of discrete nuggets produced by resistance heating
- Nuggets (welds) are usually produced directly under the electrodes, $\rightarrow$ Not necessarily if there is another more favourable path (shunt), for the current



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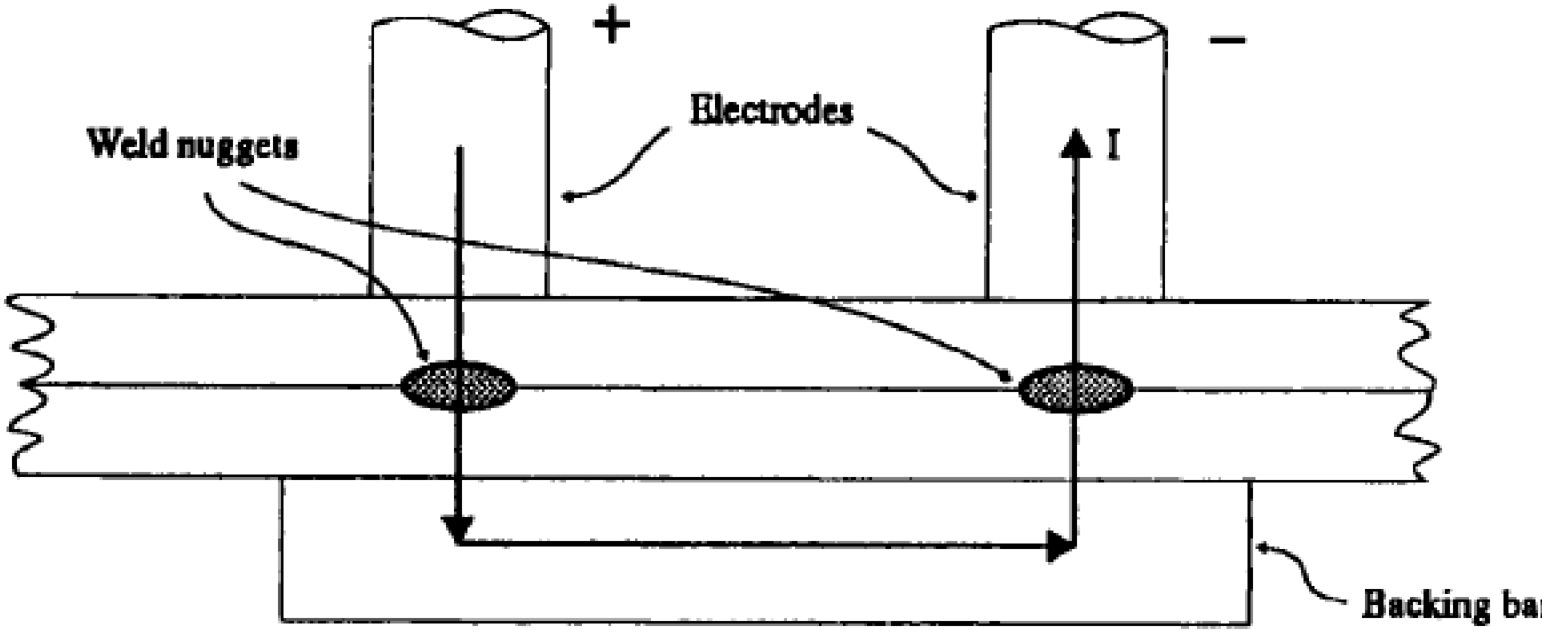
Series resistance spot welding



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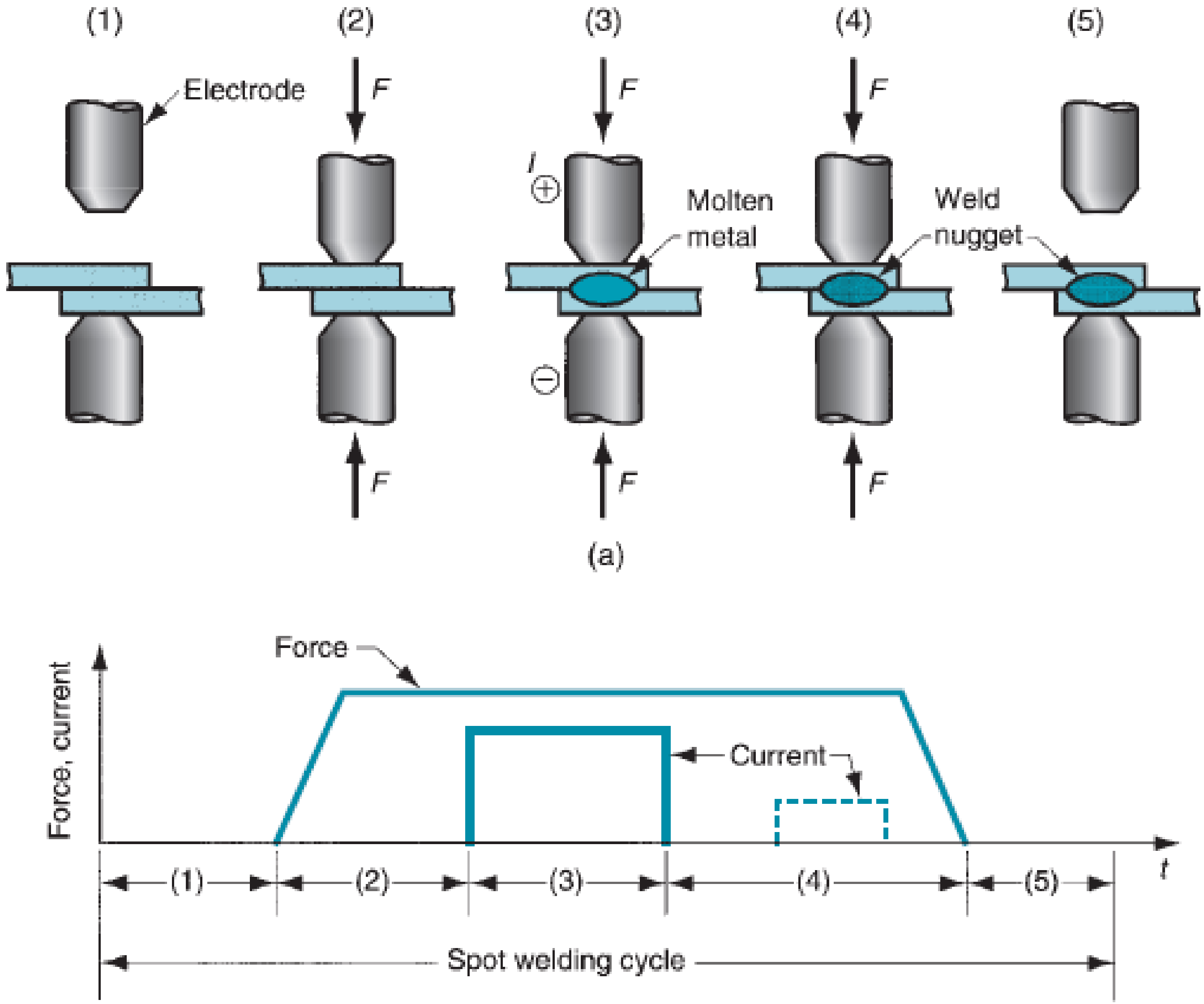
Resistance welding cycle

- Squeeze Time: Time interval between timer initiation and the first application of current needed to assure that electrodes contact the work and establish full force
- Weld time: The time for which welding current is applied (in single impulse welding) to the work
- Hold Time: The time during which force is maintained on the work after the last impulse of welding current ends to allow the weld nugget to solidify and develop strength.
- Off Time: The time during which the electrodes are off the work and the work is moved to the next weld location for repetitive welding.

Pressure-current cycle



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Pressure-current cycle

1. Off time: Parts inserted between open electrodes,
2. Squeeze Time:Electrodes close and force is applied,
3. Weld time— current is switched on,
4. Hold time: Current is turned off but force is maintained or increased (a reduced current is sometimes applied near the end of this step for stress relief in the weld region), and
5. Off time: Electrodes are opened, and the welded assembly is removed.

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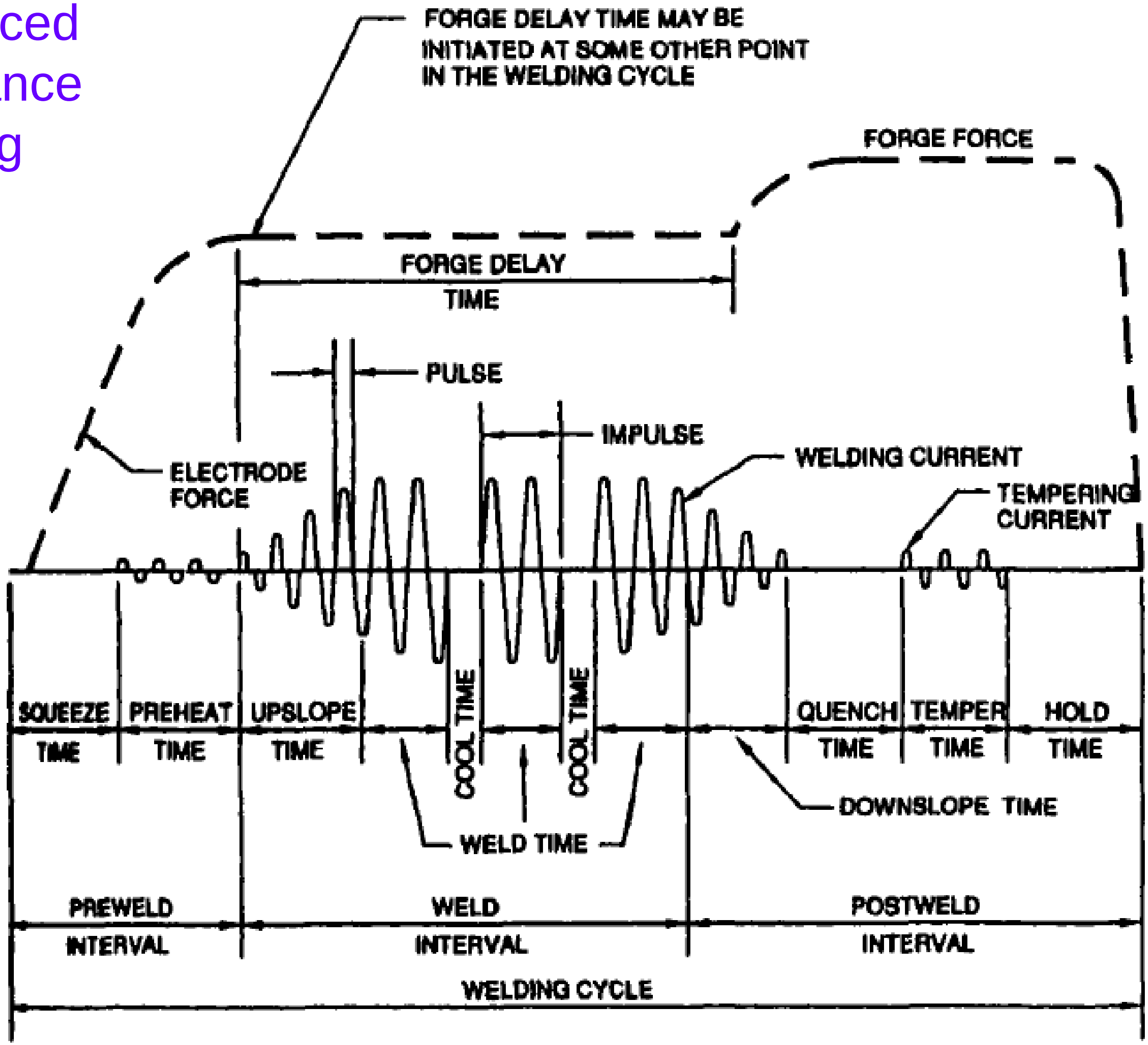
Enhanced welding cycle

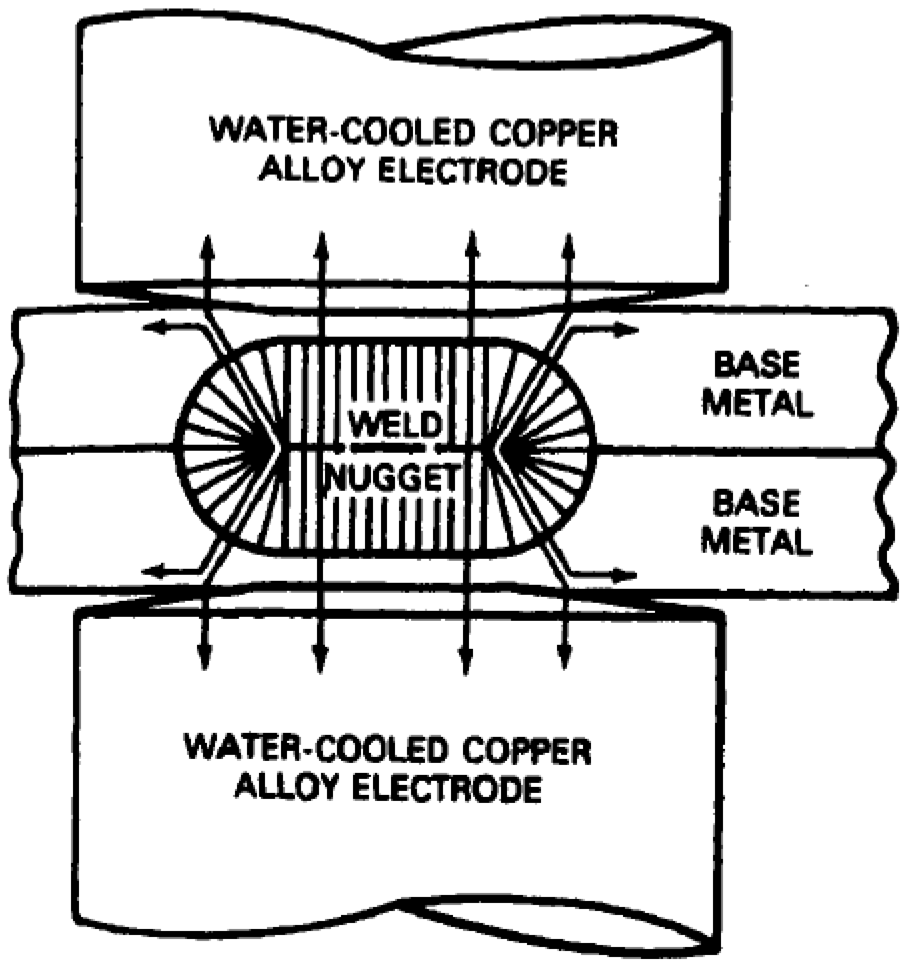
1. Pre-compression force is used to set electrodes and work pieces together
2. Preheat is applied to reduce thermal gradients at the start of weld time or to soften coatings
3. Forging force is used to consolidate weld nugget
4. Quench and temper times are used to produce desired weld properties in hardenable steels;
5. Post heat is used to refine weld nugget grain size and improve strength
6. Current decay is used to retard cooling of aluminum alloys to help prevent cracking

Enhanced resistance welding cycle

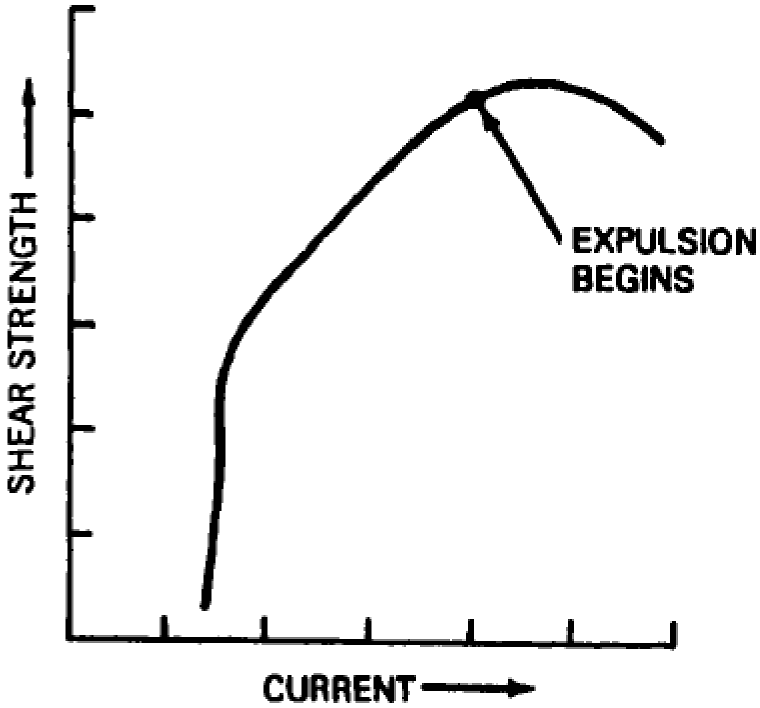


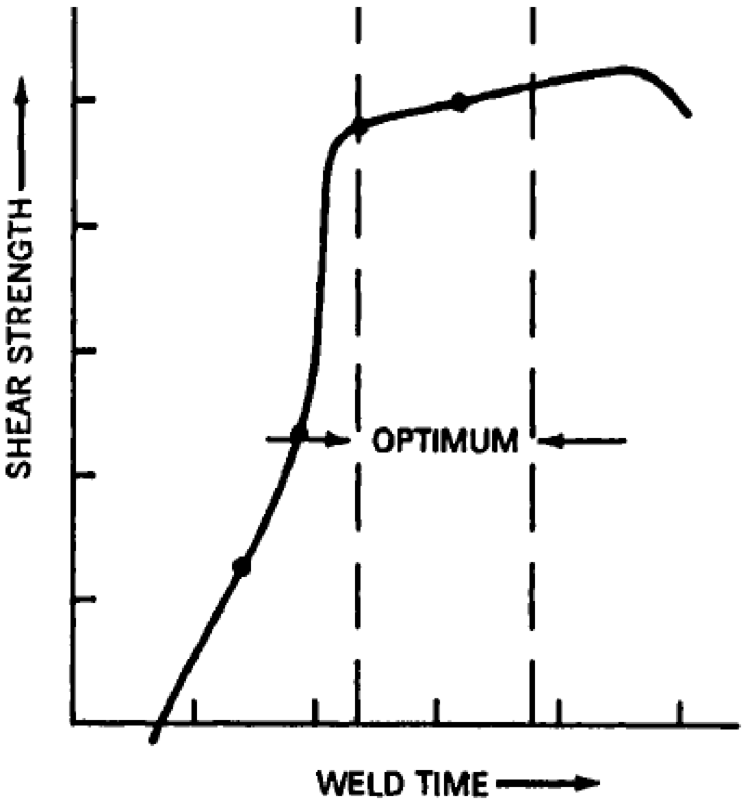
Nugget formation

Nugget formation and heat dissipation into the surrounding base metal and electrodes during resistance spot welding



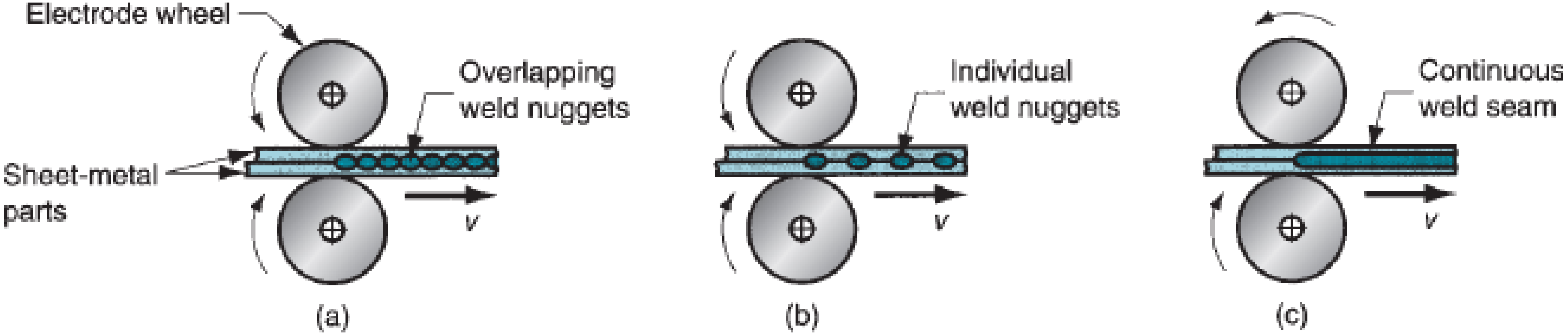
Optimum current, time in RW





- Optimum <u>current</u> and <u>weld time</u> for maximum shear strength of the RW joint

Resistance seam welding



Conventional resistance seam welding, in which overlapping spots are produced

Roll spot welding

Continuous resistance seam

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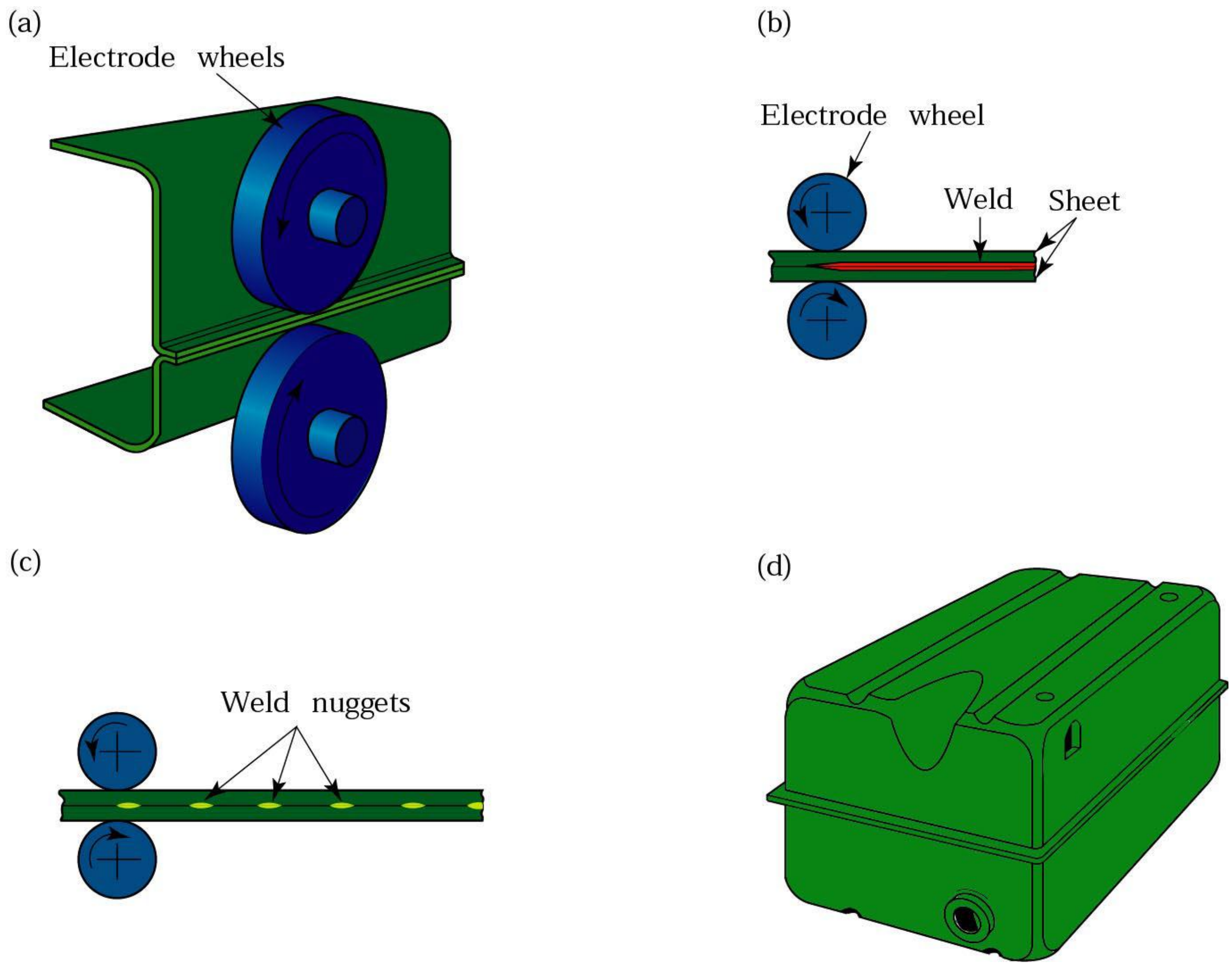
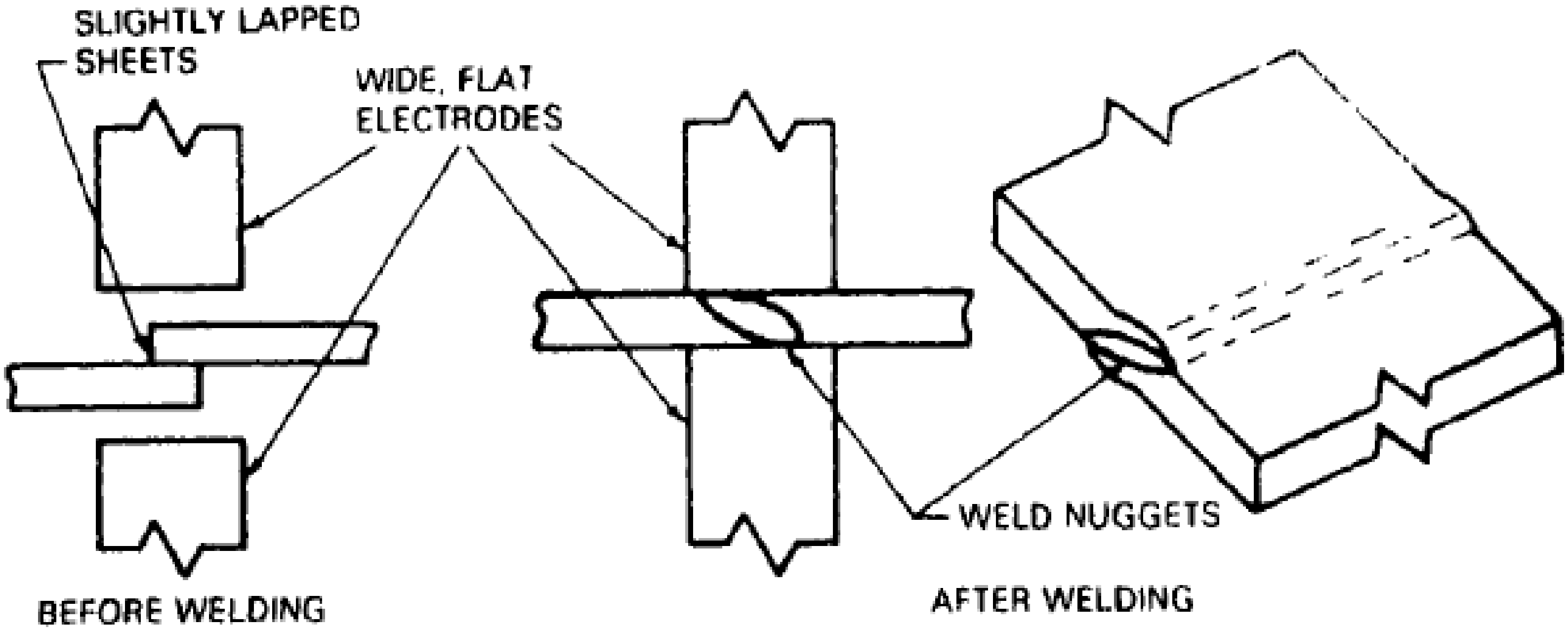
Resistance seam welding



Mash seam weld



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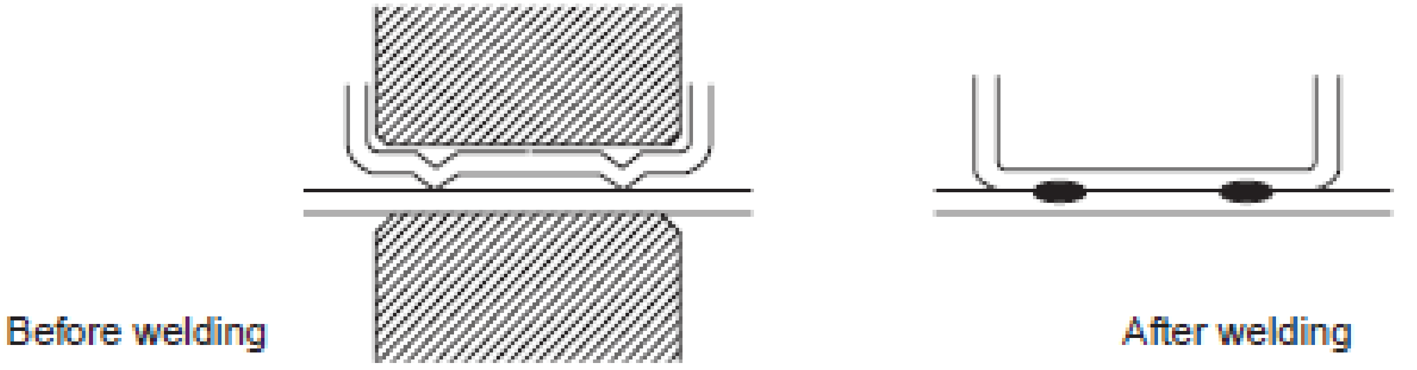
Projection welding (PW),



- Projections or dimples in overlapping joint elements → concentrate the current during welding, focusing the weld energy and helping to locate the weld more precisely
- Contact points determined by the design of the parts to be joined → may consist of projections, embossments, or localized intersections of the parts

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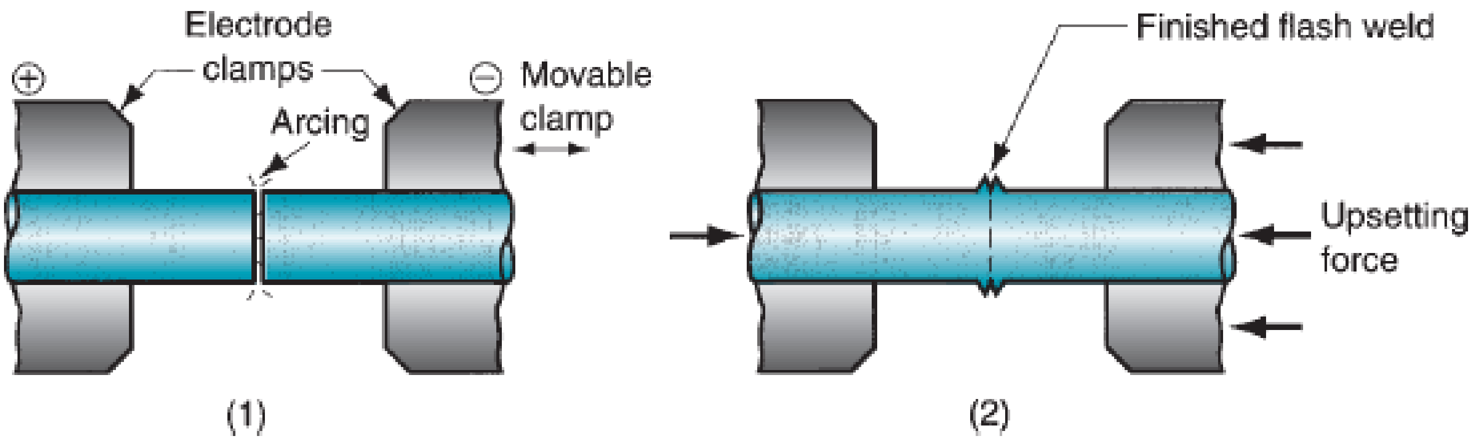
Flash welding(FW)



1. Normally used for butt joints → the two surfaces to be joined are brought into near contact →
2. Electric current is applied →Arcing → Heats the surfaces to the melting point → the surfaces are forced together to form the weld

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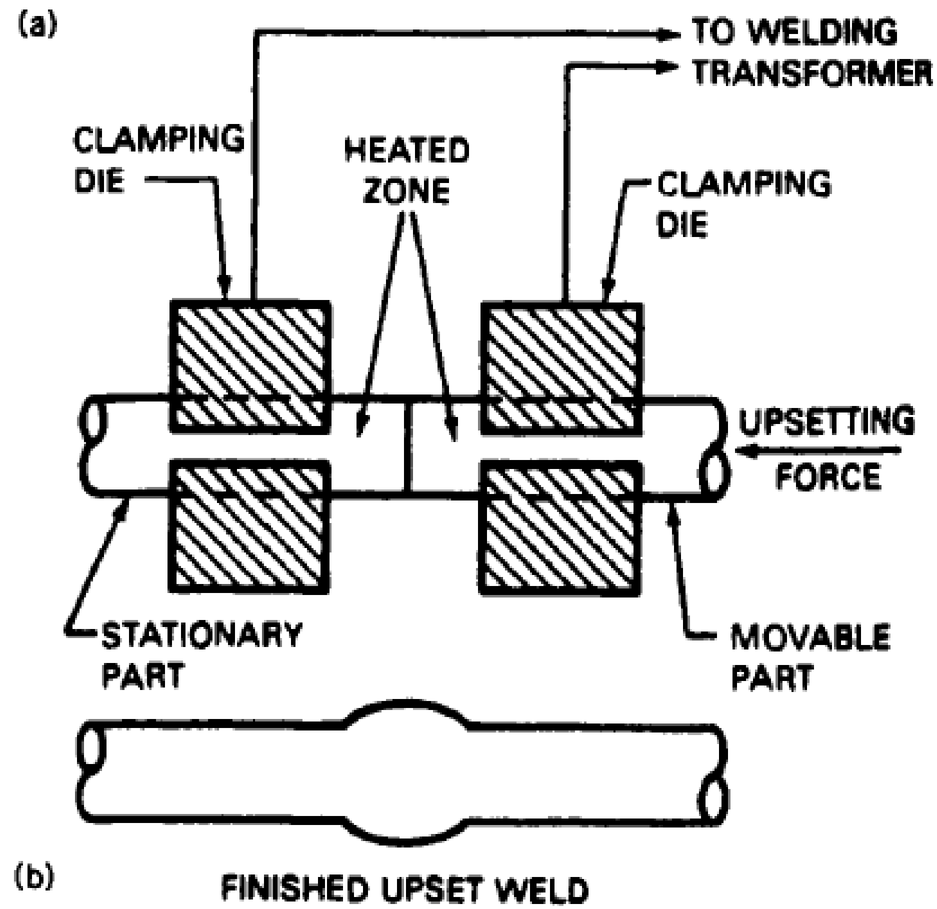
Upset welding (UW)

- Upset welding (UW) is similar to flash welding
- Heating in UW is accomplished entirely by electrical resistance at the contacting surfaces; no arcing occurs.
- Not a fusion-welding process
- Applications of UW & FW- joining ends of wire, pipes, tubes etc.



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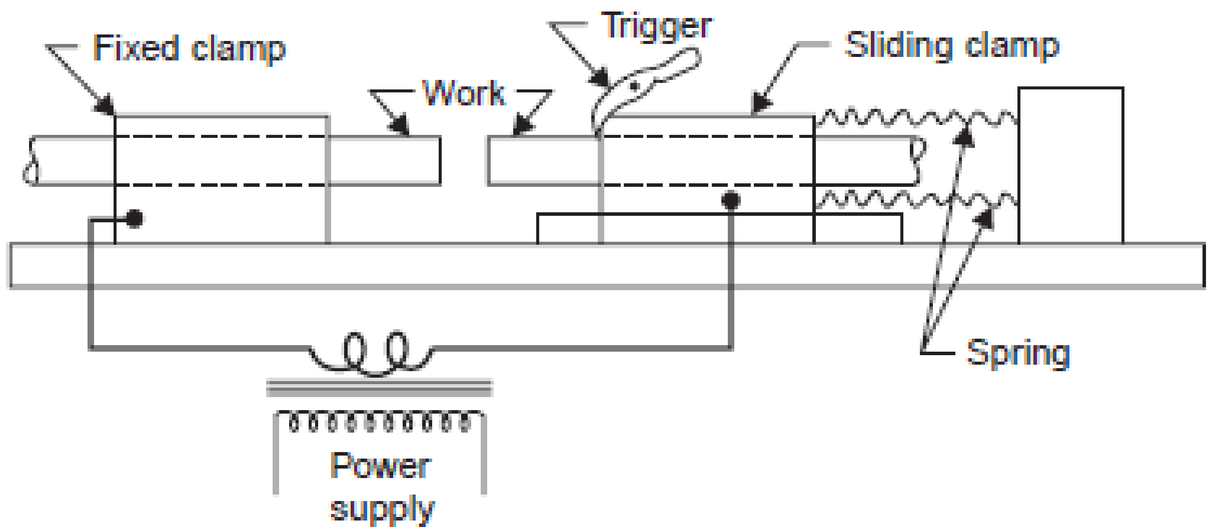
Percussion welding



- Resistance heating by the <u>rapid release of electrical energy</u> from a storage device (e.g., capacitor).
- Similar to flash welding, except that the duration of the weld cycle is extremely short, ~ 1 to 10 ms
- Very localized heating → attractive for electronic applications in which the dimensions are very small

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