Welding Technology ME692

Dr. Virkeshwar Kumar

Department of Mechanical Engineering
IIT Kanpur
Email: virkeshwar@iitk.ac.in

Fluid flow analysis of weldment

Convections

Convections

- ✓Convection: the process of heat transport in a fluid by the combined action of heat conduction (and radiation) and macroscopic fluid motion.
- ✓Forced Convection: If the fluid motion involved in the process is induced by some external means such as a pump, blower, or fan, then the process is referred to as forced convection.

- ✓Natural Convection: If the fluid motion is caused by means of any body forces within the fluid, then it is free (or natural) convection.

Convections

- ✓Weld pools, there are four different driving forces for convection.
- ✓Three of which have an external origin and one of which arises from within the weld pool.

Four forces are

(1) buoyancy or gravity force,

(2) surface tension gradient force or Marangoni force,

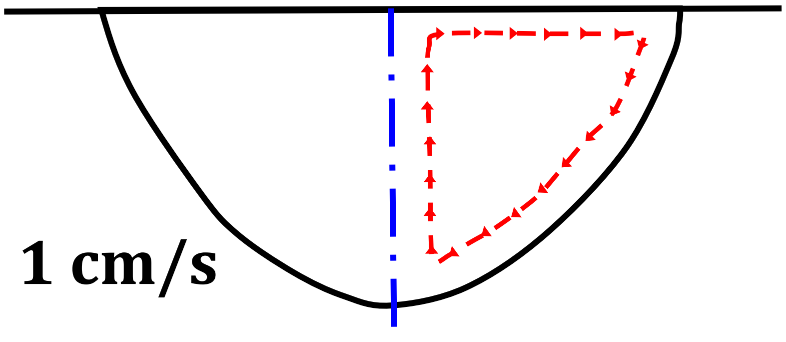
(3) electromagnetic or electromotive force (emf) or Lorentz force

(4) impinging or friction force

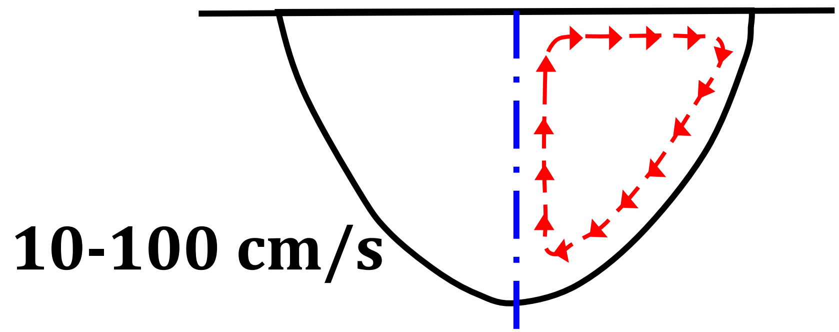
Convections

Divergent type flow: outward across the weld pool surface

only a buoyancy (or gravity) force

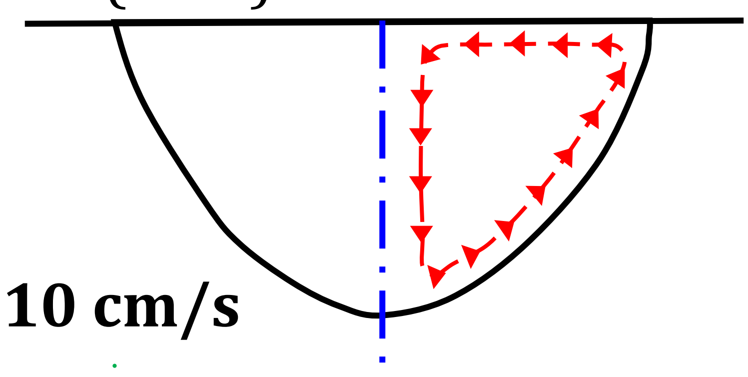


only a surface tension gradient force or Marangoni force

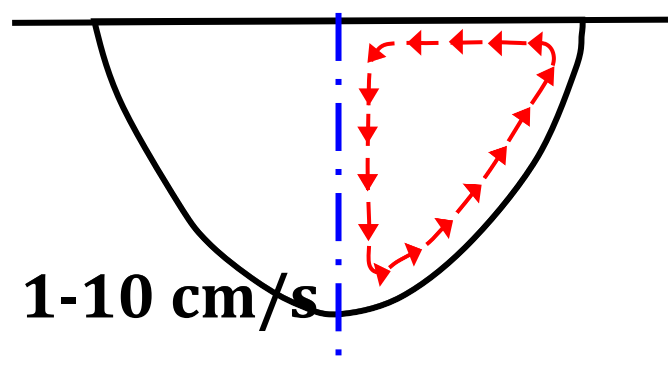


Convergent type flow: inward across the weld pool surface

only an electromagnetic force (EMF) or Lorentz force



only an impinging/frictional force



Buoyancy or Gravity Force

- ✓ **Buoyancy force (F_b)~$\rho g \beta_T \Delta T$**

thermal expansion coeff: β_T

- ✓ Density differences in a molten weld pool can have two origins:

$\rho = \rho_0(1-\beta_T \underset{(T-T_0)}{\Delta T})$

$\beta_T = \frac{1}{\rho}\frac{\partial \rho}{\partial T}\Big|_P$

  - ✓ Local temperature
  - ✓ Local composition

$\rho\uparrow, C\uparrow$

$\boxed{\beta_C = \frac{1}{\rho}\frac{\partial \rho}{\partial C}}$ → solutal expansion coeff.

$\beta_T \Delta T = \frac{\Delta \rho}{\rho}$

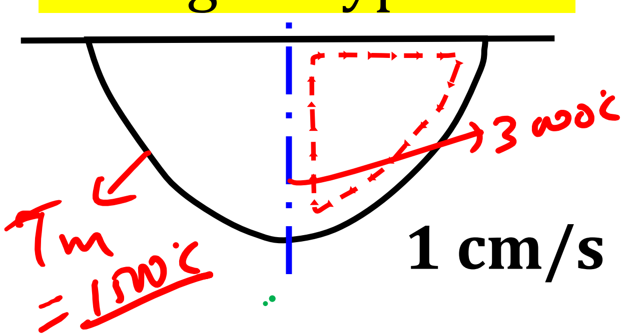
- ✓ As temperature increases above the melting temperature, the density of a liquid decreases.

$\rho = \rho_0(1-\beta_T \Delta T \pm \beta_C \Delta C)$

- ✓ Hot, superheated regions of molten metal in a weld pool are of lower density than cooler regions.

$\beta_T \Delta T > \beta_C \Delta C$

Divergent type flow



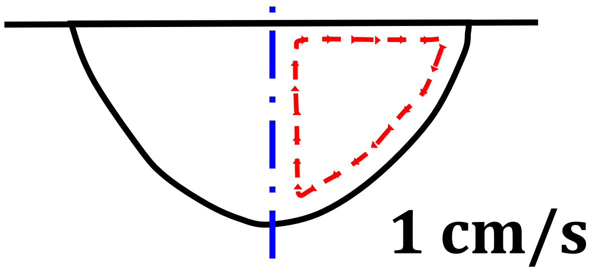
Buoyancy or Gravity Force

- ✓ Cooler, more dense molten metal sinks under the force of gravity, causing hotter, less dense molten metal to be displaced and rise.
- ✓ **$V \sim (g\beta_T \Delta TL)^{0.5}$**

Grashof number= buoyancy force/ viscous force

Rayleigh no= Grashof number × Prandtl number

Divergent type flow



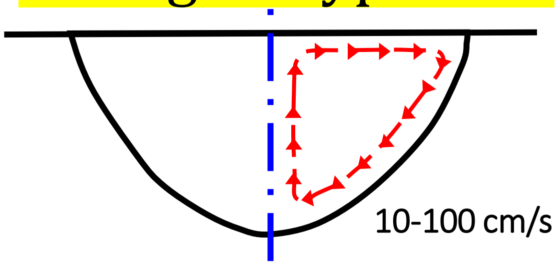
Marangoni Convection

Surface Gradient Force/Marangoni Convection: interfacial Phenomena

✓Surface tension of a liquid increases with decreased temperature to become maximum just above the melting point.

✓Whenever a temperature gradient exists in a liquid, so does a gradient in surface tension, and this gradient exerts a force:

Divergent type flow



$$F_{\gamma} = -\frac{d\gamma}{dT}\nabla T$$

$$V \sim \frac{\Delta\gamma}{\mu}$$

Marangoni number

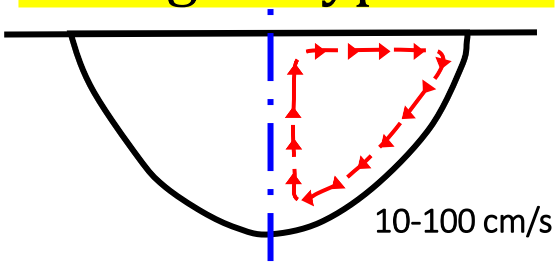
$$Ma = -\frac{\partial\gamma}{\partial T}\frac{L\Delta T}{\alpha\mu}$$

Marangoni Convection

Surface Gradient Force/Marangoni Convection: interfacial Phenomena

✓Surface tension gradients give rise to an extremely strong circulation at rates from 10 to 100 cm/s from the hotter, lower surface tension liquid at the center of the weld pool to the cooler and higher surface tension liquid at the pool edges.

Divergent type flow



$$F_{\gamma} = -\frac{d\gamma}{dT}\nabla T$$

Marangoni number

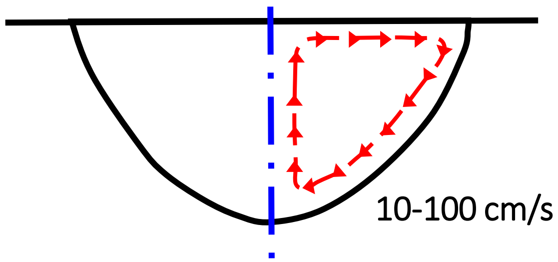
$$V \sim \frac{\Delta\gamma}{\mu}$$

$$Ma = -\frac{\partial\gamma}{\partial T}\frac{L\Delta T}{\alpha\mu}$$

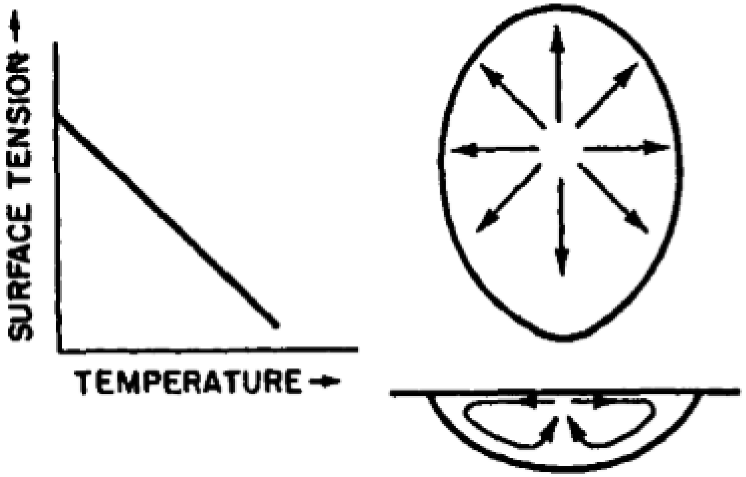
Marangoni Convection

✓Surface tension gradient at the weld pool surface could be changed by the addition of surface-activating agents such as O, S, Se, and Te. Which change flow patterns

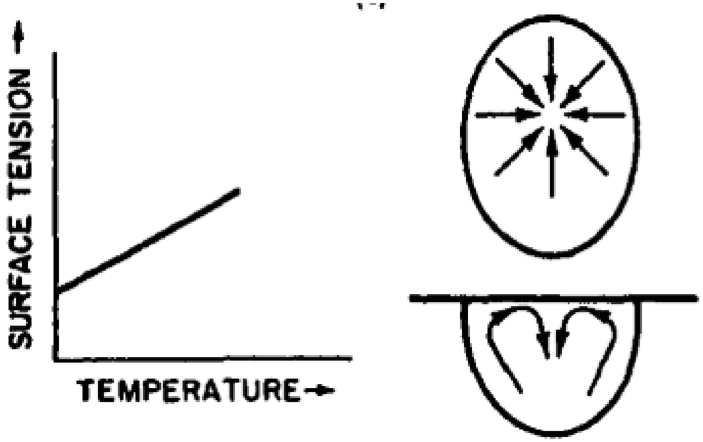
Divergent type flow



Convective flow pattern without a surface-active agent



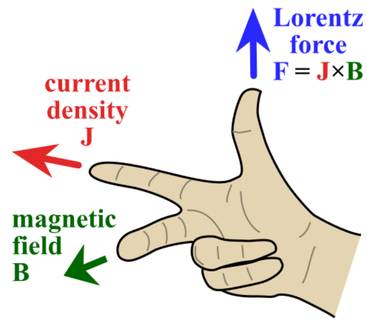
Convective flow pattern with a surface-active agent



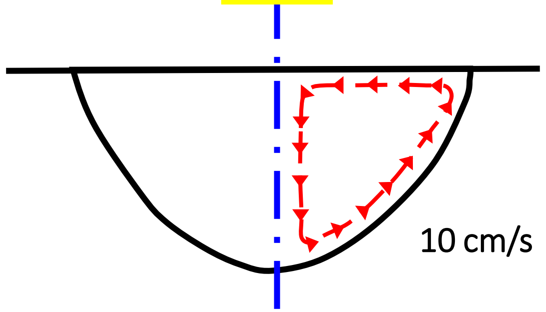
Convection due to Electromotive Force

Convection due to Electromotive Force or Lorentz Force

✓Electric and magnetic fields interact: produce a force in an orthogonal direction.



Convergent type flow



✓The magnitude of this force leads to a circulation velocity of about 10 cm/s.

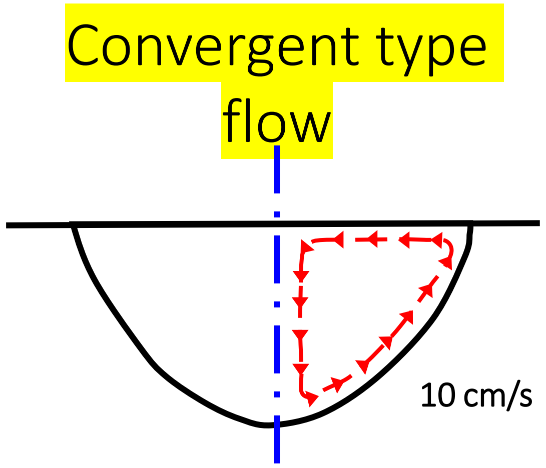
✓Electromagnetic forces: only in electric energy sources, namely arc, resistance, microwave, or electron-beam processes.

J is the vector of current density (with a direction the same as the current, positive to negative).

B is the vector of magnetic flux (with a direction the same as the flux lines)

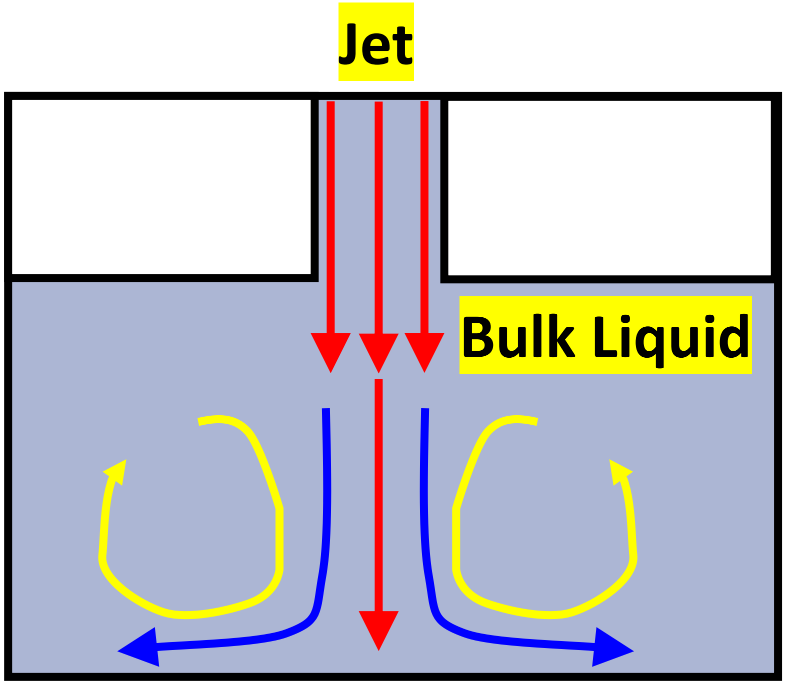
Convection due to Electromotive Force

Convection due to Electromotive Force or Lorentz Force

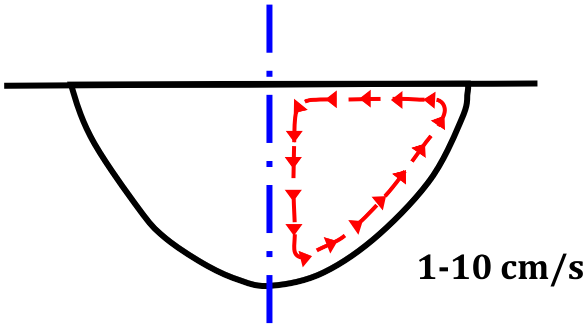


- ✓Totally absent for gas and laser-beam welding.
- ✓The circulation induced is proportional to the strength of the fields involved, so welding current (or voltage in EBW) plays a major role.

Convection due to Impinging or Friction Force



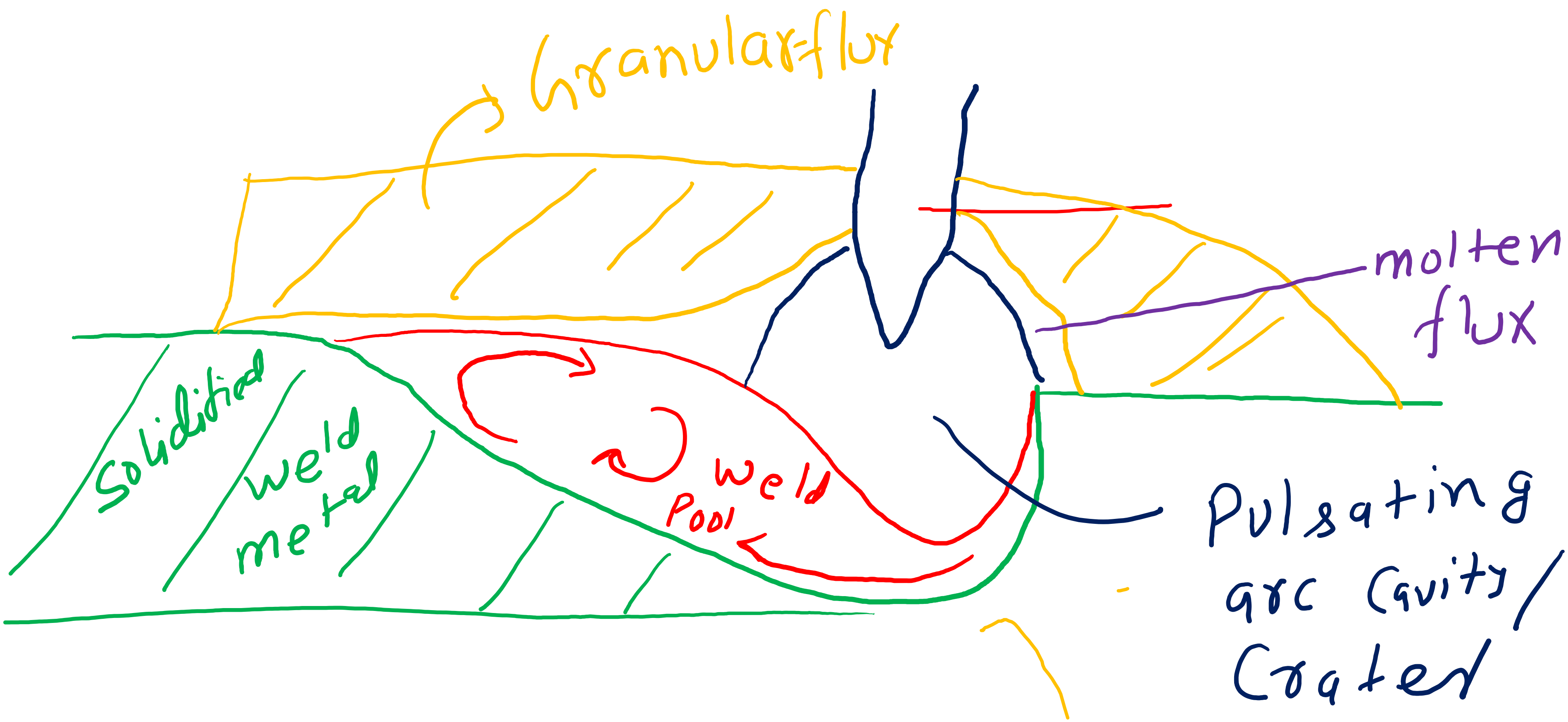
Convergent type flow



- ✓The impinging force is the result of momentum transfer through friction between impinging particles (welding source) and metal atoms in the molten weld pool.

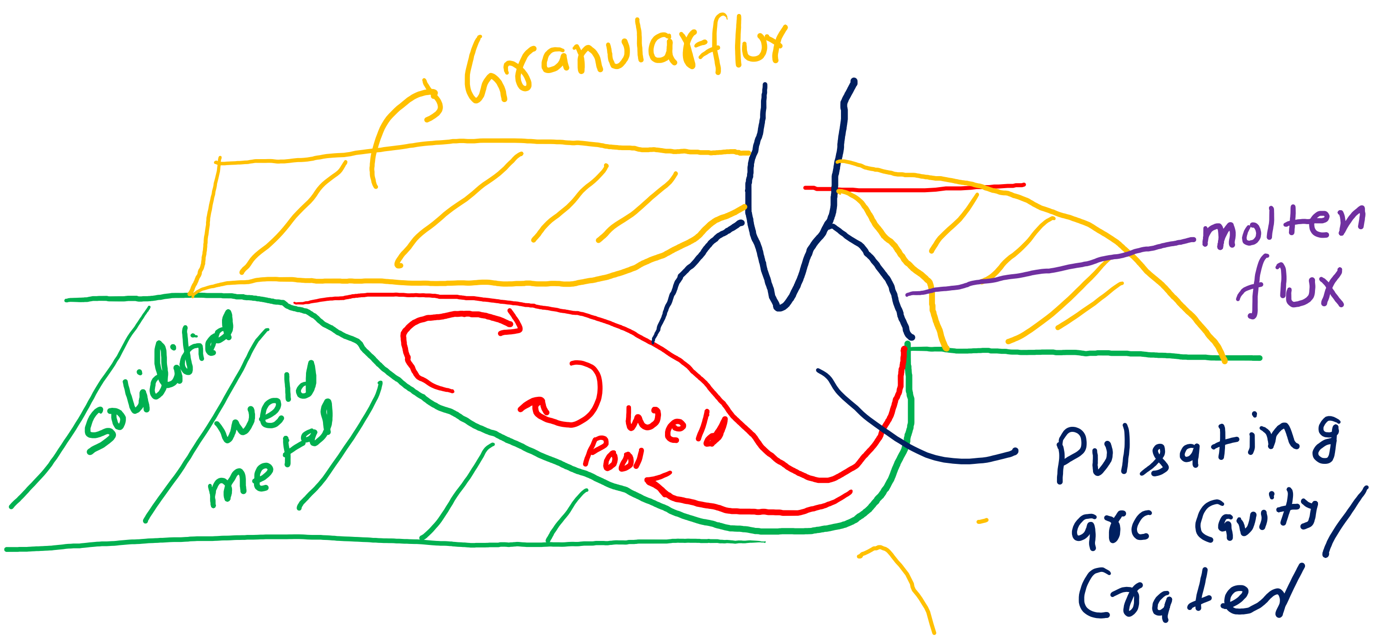
Convections

- ✓ Immediately below an arc/laser beam/gas flame there is a depression, known as a crater or pulsating arc cavity.
- ✓ It is caused by the pressure of the impinging energy (ions, electrons, or photons with high kinetic energy and momentum).



Convections

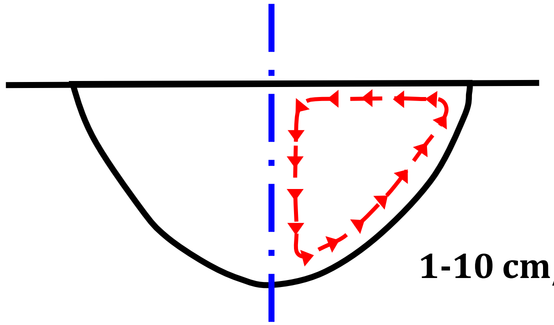
- ✓ For arc welding processes, this depression can be quite deep, due to high current densities: so the momentum of the electrons and positive ions.
- ✓ For electron-beam welding, it is even deeper due to much higher velocities of electrons.
- ✓ Laser beams and gas flames tend to be less deep due to less and slower moving electrons and ions or much less massive photons.



Convection due to Impinging or Friction Force

✓Since **most fusion welding processes use arcs**, this force is often called the arc plasma force.

Convergent type flow



✓Particles are electrons or ions in arc, plasma, or electron-beam welding or photons in laser-beam welding.

✓Thus, the magnitude of the impinging force depends on the process, but the flow pattern is always from edge to center of the weld pool.

Convections

- ✓ **The key conclusion to be drawn from all models of combined forces is that circulation patterns can be complex.**
- ✓ Weld pool convection is seldom the result of a single force (i.e., buoyancy, emf, surface tension gradient, or impinging friction) but is usually the result of combinations of forces that depend on
  - ✓ The welding process (e.g., gas, arc, or laser),
  - ✓ How that process is operated (e.g., polarity, current level, travel speed)
  - ✓ Interactions between the weld and environment (including atmosphere and contaminants).

Effects of Convection on Penetration

- ✓ Moving fluid tends to erode surrounding unmelted base material, particularly since the moving molten weld metal redistributes superheat and can cause melting, known as recalescence.
- ✓ Three effects are worth highlighting.

Effects of Convection on Penetration

- ✓1st: Electromagnetic force
- ✓The electromagnetic force dominates (as it does for most arc welding processes): causes downward circulation at the center of the weld pool, moving hot, superheated molten metal to the bottom of the pool at its center.
- ✓This superheat causes additional melting here, leading to deeper than would-be-expected penetration.
- ✓Increasing current level and localized concentrated current density: A deep spot can arise.

Effects of Convection on Penetration

- ✓ Second: Buoyancy forces and surface tension gradient forces
- ✓ Buoyancy forces and surface tension gradient forces, which cause weld pool circulation in the same direction, resist the effect of any emf.
- ✓ The weld pool is caused to be wider and shallower.

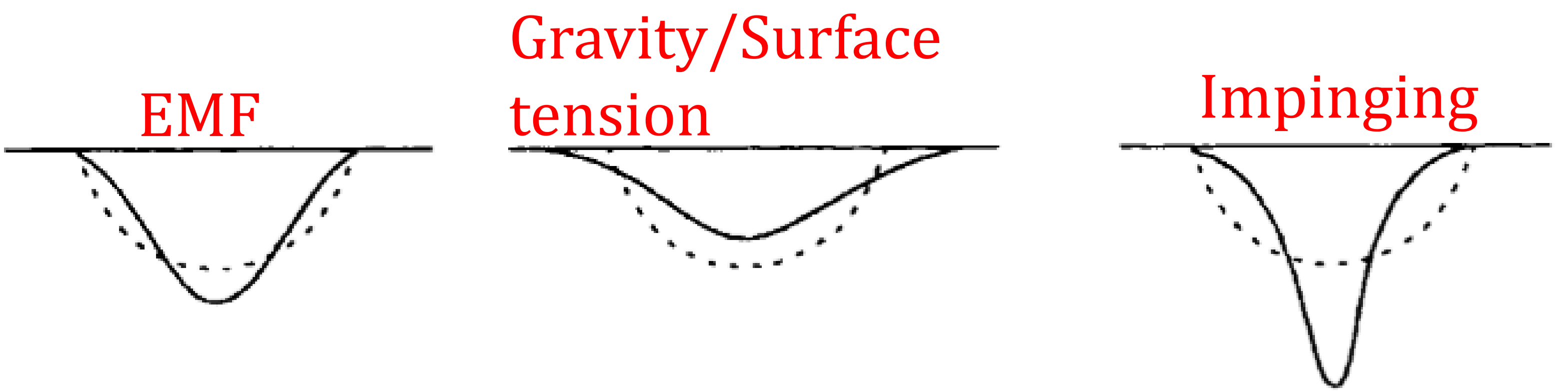
- ✓ Third: impinging force
- ✓ A dominant impinging force, such as is present in processes operating in the keyhole mode, results in exceptional penetration near the center of the weld pool at its bottom.

Effects of Convection on Penetration

Greater penetration at the bottom-center of a weld pool due to convection enhanced by a dominant electromagnetic (Lorentz) force

Shallower but wider penetration due to convection dominated by either a buoyancy or surface tension gradient force (or both together).

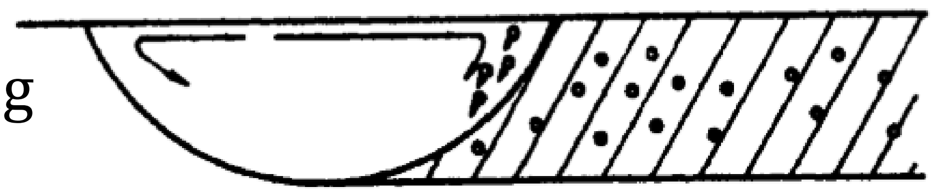
Pronounced deepening at the weld pool bottom due to convection enhanced by a dominant impinging force.



A semi-circular cross-section is shown by a dashed line for comparison.

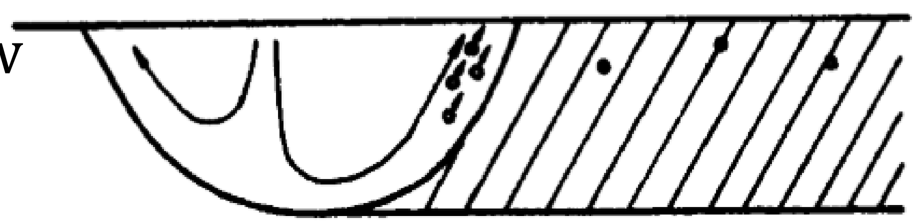
Effect of Convection on Porosity

- ✓Convection promotes stirring and so tends to promote homogeneity.
- ✓On the other hand, it exposes the fresh, reactive molten metal to the surroundings at the weld pool surface, thus helping to promote any gas-metal reactions that might occur.
- ✓Absorbed gases in molten weld metal can lead to porosity, among other things, upon solidification.



(a)

- ✓ Sometimes, it reduces porosity and depends on the specific flow pattern of the convection.



(b)

When EMF plays as key role

Enhancing Convection

- ✓ The electromagnetic or electromotive force can be enhanced in three ways.
  - ✓ Switching from a nonelectric fusion welding process.
  - ✓ Raising the welding current increases J and B.
    - ✓ Increased heat input causes adverse changes in composition, microstructure, and metallurgical transformations.
  - ✓ Without raising the welding current, employ an external magnetic field around the weldment during welding.

Enhancing Convection

- ✓The impinging force can be enhanced by employing higher welding currents, for any arc welding process, by switching from a melt-in to a keyhole mode for processes where that is possible (e.g., PAW, EBW, and LBW), or by increasing the welding voltage, especially for EBW.
- ✓Surface tension gradient force can be altered by adding surface-activating agents such as O, S, Se, or Te.
- ✓The most preferred method is adding oxygen (2-5%) to argon in inert gas-shielded processes (especially GMAW).

Weld Pool Evaporation and their effects

- ✓ At high temperature, significant metal vaporization can occur.
- ✓ Most of this evaporation, due either to exceeding the boiling point of the weld metal or causing the vapor pressure of a component of the weld metal to exceed its partial pressure in the surrounding atmosphere.
- ✓ It takes place in molten metal drops or droplets during their transfer through an arc to the weld pool.
- ✓ Evaporation can also occur from the surface of weld pools, especially as exacerbated by convection.

Weld Pool Evaporation and their effects

- ✓Preferential evaporation of some solute elements is quite high, including Mn (from steels and stainless steels), Mg (from aluminum alloys), and Zn (from brasses).
- ✓Evaporation of alloying elements is a potential problem not only because it changes the composition of a weld filler or weld pool, which could degrade properties (especially corrosion resistance), but also because evaporation removes heat, which can have adverse effects on solidification.
- ✓A way to offset the effects of evaporation is to use a filler that is richer in the volatile component than needed to match the base metal or meet service needs.

Forces and Mode of droplet transfer in welding

Molten Metal Transfer in Arc Welding

- ✓ **Objective**: Molten metal transfer should occur with minimal loss (minimum spattering).
- ✓ Spatter is molten metal from the consumable electrode that does not randomly reach the weld pool but goes elsewhere.
- ✓ The good molten metal transferred depends on
  - ✓ The ease of (if not the ability for) welding in various positions (in a vertical plane or horizontally overhead as opposed to horizontally down-hand)
  - ✓ The extent of weld penetration
  - ✓ The rate of filler deposition
  - ✓ Heat input
  - ✓ The stability of the weld pool
  - ✓ The amount of spatter loss

Metal Transfer Driving Forces

Pressure generated by the evolution of gas at the electrode tip

- ✓ Limited to shielding case: Gas produced in shielding gas: Flux, or provided gas or fluxed core electrode
- ✓ Gas produces a pressure that helps both detach and propel a molten drop from the electrode's tip.

Gravity

- ✓ Gravity tends to detach a liquid drop from an electrode when that electrode points down to the source of the gravity and is a retaining force when the electrode points upward.

Metal Transfer Driving Forces

Electrostatic attraction

- ✓ Oppositely charged entities attract one another electrostatically through Coulombic forces.
- ✓ With consumable electrodes, the molten drop is always attracted to the weld pool in the oppositely charged workpiece, regardless of operating mode.
- ✓ Drop is smaller (less massive) and better able to move (especially once it is detached from the electrode); it does move (usually, but not necessarily, to the workpiece).

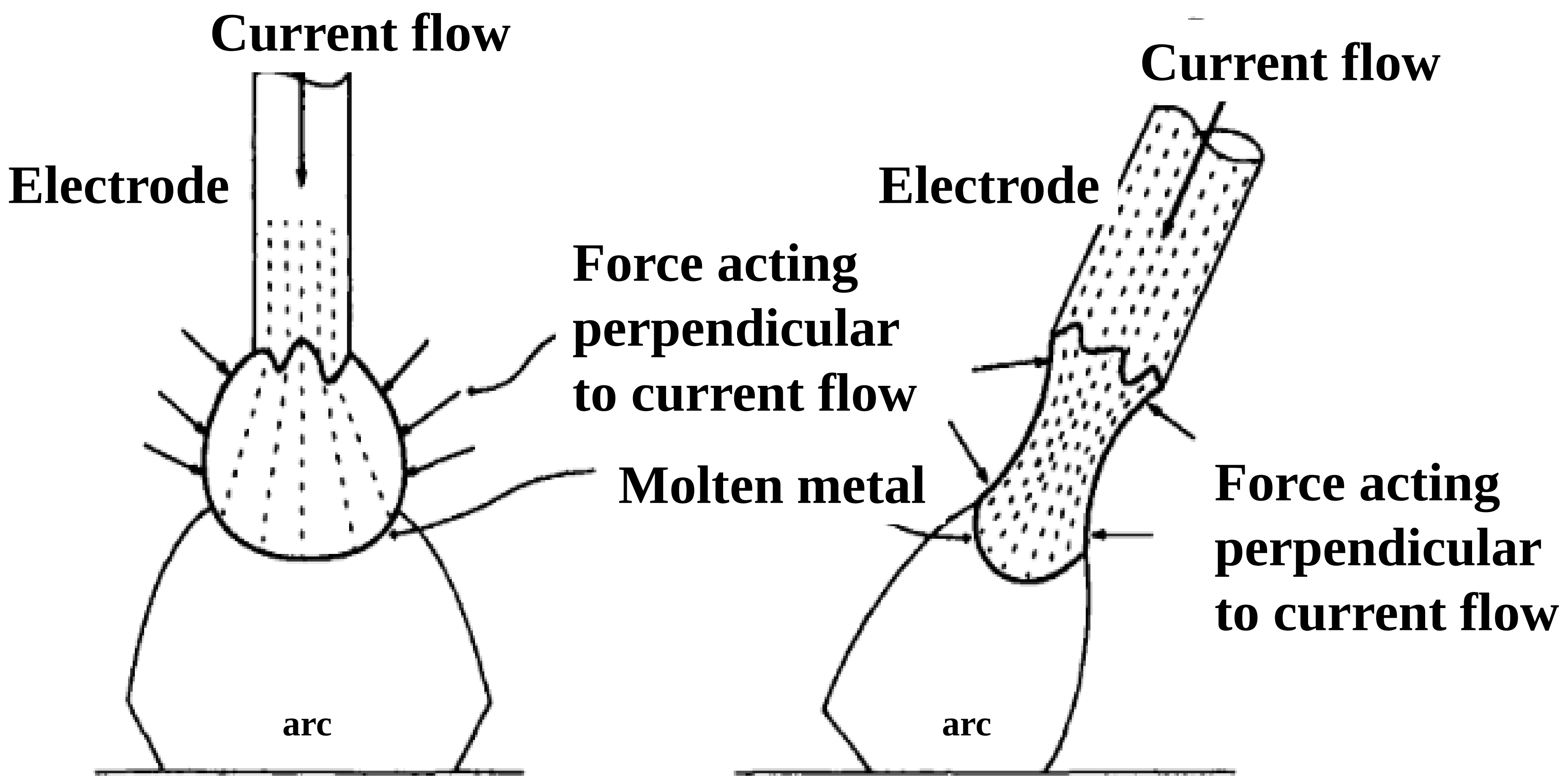
Metal Transfer Driving Forces

Electromagnetic Pinch Effect

- ✓ When an electric current flows through a conductor, a magnetic field is set up around that conductor.
- ✓ EMF acts on the molten droplet.
- ✓ Force acting perpendicular to the current flow.
- ✓ There are two ways in which the Lorentz force may act to detach a drop at the tip of a consumable electrode.

Metal Transfer Driving Forces

Electromagnetic (Lorentz force): Pinch Effect



Electromagnetic Pinch Effect

- ✓ First, when the drop is larger in diameter than the electrode, and the electrode is positive (DCEP or DCRP), the magnetic force tends to detach the drop.
- ✓ Second, when there is a constriction or necking down, such as when the drop is about to detach, the magnetic force acts away from the point of the constriction in both directions.
- ✓ Thus, a drop that has started to detach will be given an acceleration, increasing the separation rate. These two phenomena constitute the "pinch effect."
- ✓ The "pinch effect" caused near the tip of the consumable electrode by electromagnetic field forces.

Metal Transfer Driving Forces

- ✓ **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 pressure**
- ✓ The magnetic force associated with current flow in the welding electrode also sets up pressure within the molten metal drop.
- ✓ The maximum pressure is radial to the axis of the electrode and, at high currents, elongates the drop in the direction parallel to the electrode axis.
- ✓ So, drop propel in line with the electrode, regardless of the direction in which the electrode is pointing, upward or downward.

Metal Transfer Driving Forces

✓ Plasma Friction

- ✓ Drops of molten metal, once detached from a consumable electrode, can be given an acceleration toward the plate electrode or workpiece by the plasma jet or plasma stream.
- ✓ This acceleration is the result of momentum transfer largely by friction between high-velocity particles in the plasma jet (ions and electrons) and the drop, so the force is often called the plasma friction force.

Metal Transfer Driving Forces

- ✓ **Surface tension**
  - ✓ Surface tension is the property of the surface of a liquid that allows it to resist an external force due to the cohesive nature of its molecules.
  - ✓ Surface tension always tends to retain the molten metal drop that forms at the end of a consumable electrode in position, regardless of the welding position.
  - ✓ Thus, surface tension naturally resists detachment.

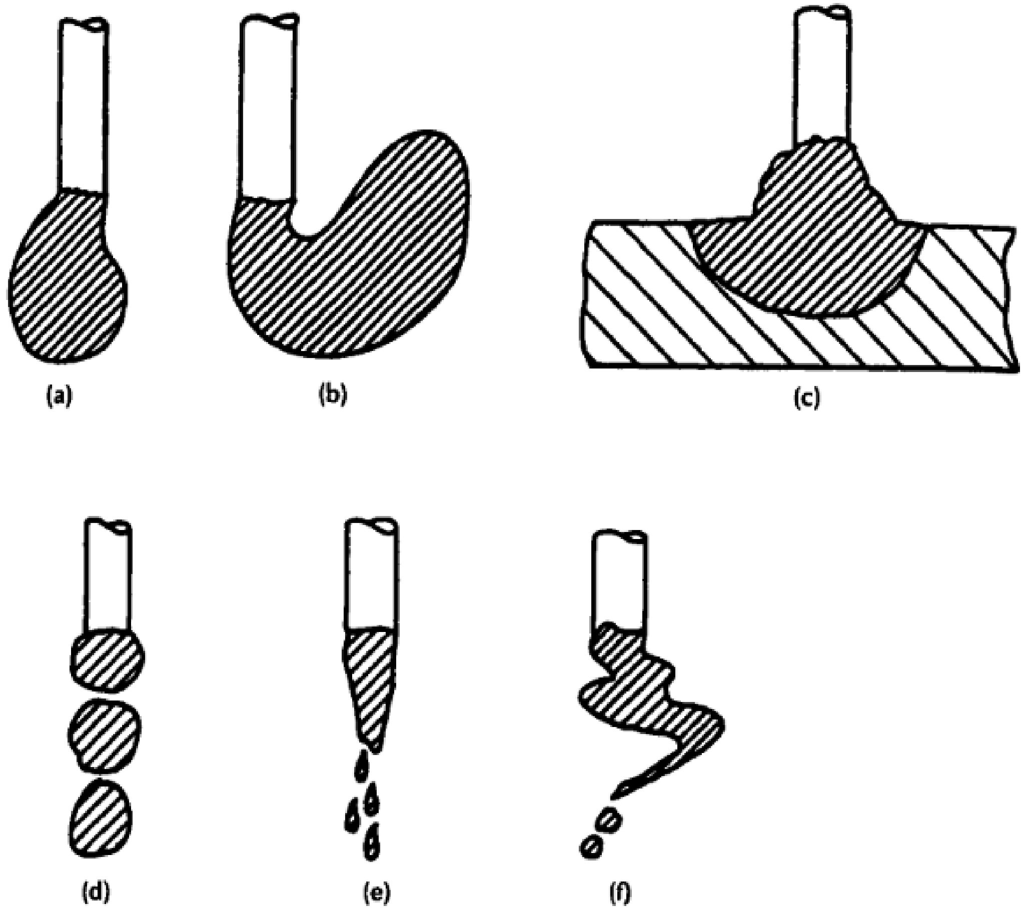
Metal Transfer Driving Forces

- ✓ **Surface tension**
  - ✓ Thus, surface tension naturally resists detachment.
  - ✓ On the other hand, if the molten metal drop formed and being held at the tip of the electrode is caused by contact with the molten metal in the weld pool, surface tension forces tend to pull the small drop into the large weld pool, just as it would a completely detached drop.

Molten Metal Transfer Modes

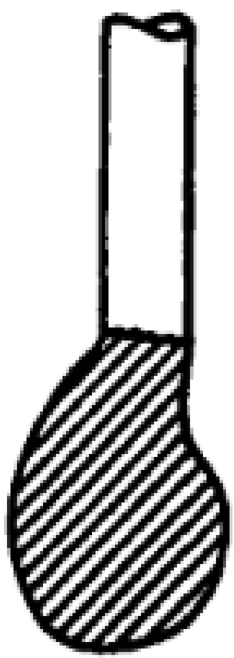
Modes of molten metal transfer in arc welding process:

- ✓Free-flight transfer mode
  - ✓Globular (a)
  - ✓Spray (d, e)
- ✓Bridging Transfer (c)
  - ✓Short circuit (b)
- ✓Pulse arc or pulsed current
- ✓Slag Protected
- ✓Rotation type (f)



Free-flight transfer mode

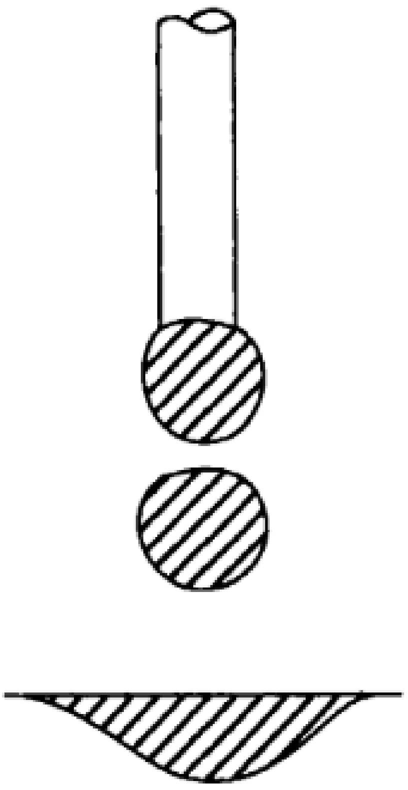
- ✓ **Free-flight transfer mode**
  - ✓ Globular
  - ✓ Spray
- ✓ **Bridging Transfer**
  - ✓ Short circuit
- ✓ Pulse arc or pulsed current
- ✓ Slag Protected
- ✓ Rotation type



- ✓ **Free-flight transfer mode**
- ✓ Without any direct physical contact, molten metal drop flight from the consumable electrode to the workpiece and weld pool.
- ✓ During this flight, the drops are free of both the consumable electrode and the workpiece.

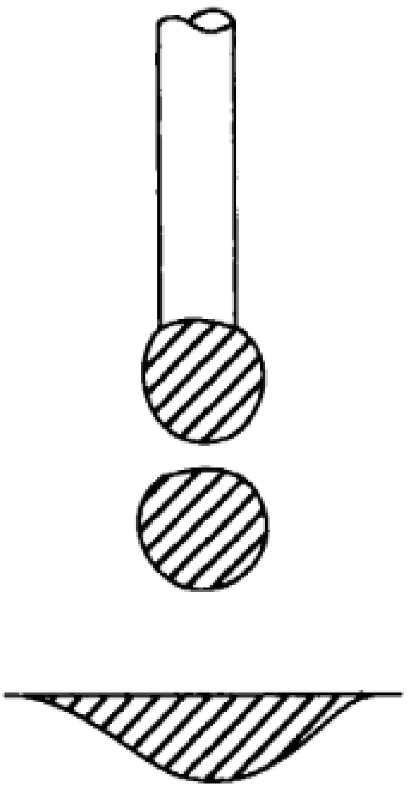
Free-flight transfer mode: Globular

- ✓At low welding currents (50-170 A), molten metal from a small diameter solid steel wire electrode is transferred in the form of drops having a diameter larger than the wire.
- ✓These large drops form at the electrode tip and detach, largely due to the force of gravity.
- ✓The drop or globule formation, detachment, and transfer rate are relatively slow.



Free-flight transfer mode: Globular

- ✓Occurs best in the down-hand position and is not very useful for out of position welding.
- ✓As the welding current increases, the drops become progressively smaller, suggesting that electromagnetic forces are increasingly affecting detachment.

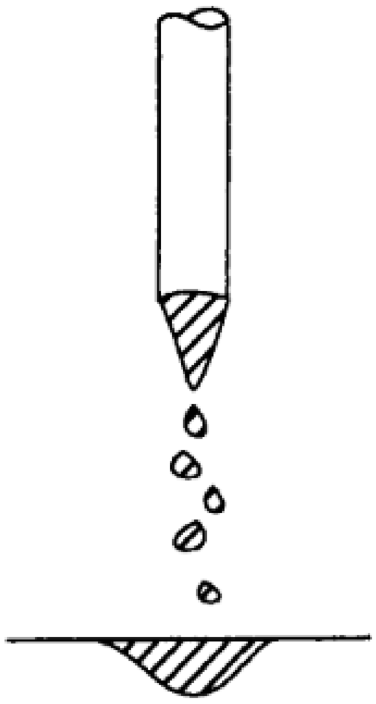


Free-flight transfer mode: Spray

Spray/streaming transfer/ axial spray transfer

✓When the welding current reaches a critical level (transition current), the tip of the consumable electrode becomes pointed, and a cylindrical stream of liquid metal flows toward the workpiece in line with the electrode.

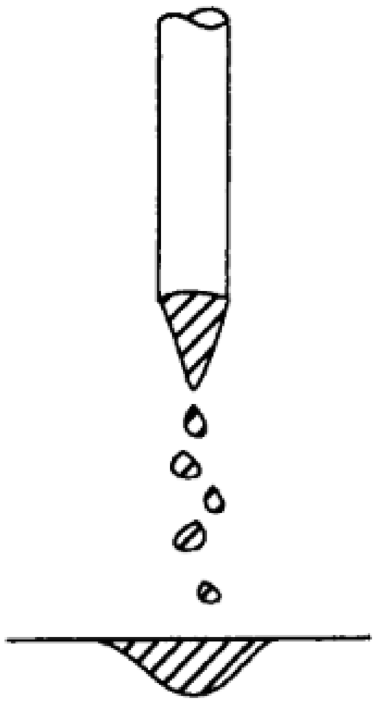
✓Pinching Lorentz force, along with the explosive evaporation force, projects the droplets toward the workpiece.



Free-flight transfer mode: Spray

Spray/streaming transfer/ axial spray transfer

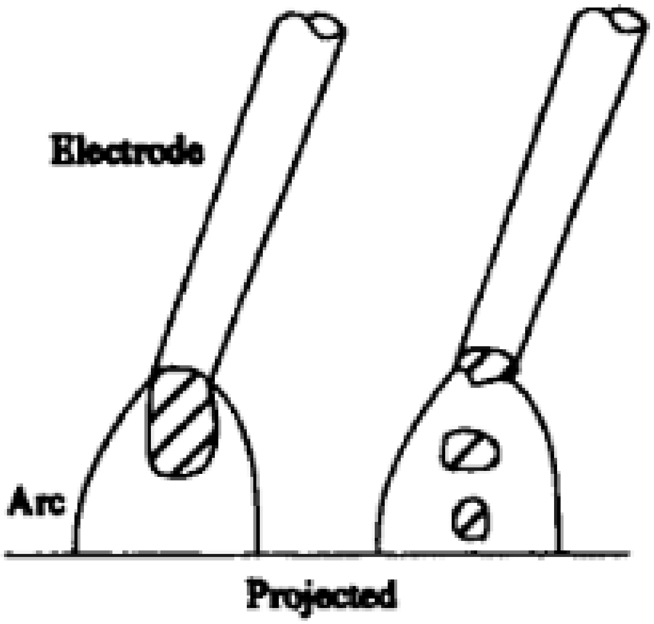
- ✓Excellent stability and virtually free of spatter.
- ✓Droplets are actively propelled away from the electrode. This is a great advantage when making vertical or overhead welds.
- ✓Leads to a high net heat input to the workpiece: deposition rate and/or deep penetration.



Free-flight transfer mode: Projected transfer

- ✓Spray/streaming transfer/ axial spray transfer
  - ✓**Projected transfer**

✓The key to spray transfer is the pinch effect. This pinching Lorentz force, along with the explosive evaporation force, projects the droplets toward the workpiece, so this mode has also been called projected transfer.



✓Often, projected transfer refers to the mode that occurs just after the transition from globular and before full streaming transfer.

Bridging Transfer

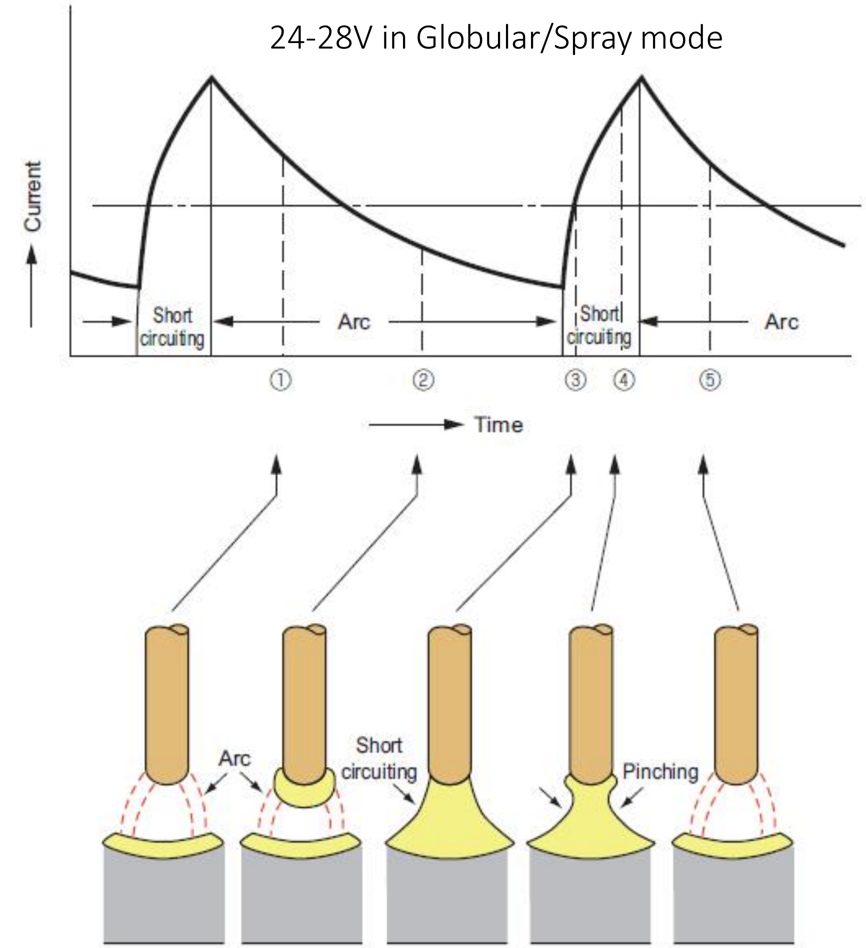
- ✓ **Free-flight transfer mode**
  - ✓ Globular
  - ✓ Spray
- ✓ **Bridging Transfer**
  - ✓ Short circuit
- ✓ Pulse arc or pulsed current
- ✓ Slag Protected
- ✓ Rotation type

- ✓ **Bridging Transfer**
- ✓ In bridging transfer, molten metal drops are never completely free; they are always attached to the consumable electrode and the workpiece.

Bridging Transfer: Short Circuit Transfer

Bridging transfer: Short Circuit Transfer

- ✓If the transition current for spray mode is very high.
- ✓High Current = high heat input overheats the workpiece and may cause severe distortion. Therefore, short-circuit mode is used to operate over a wider current range.



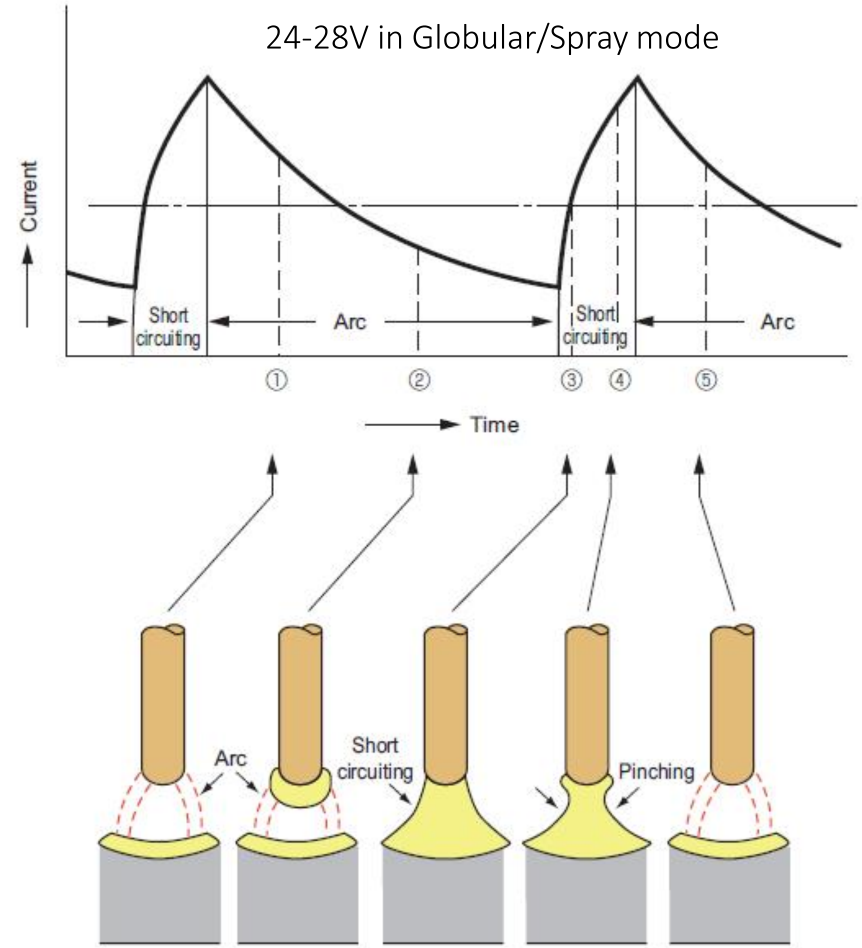
https://www.kobelco-welding.jp/education-center/Fundamentals/Fundamentals02.html

Bridging Transfer: Short Circuit Transfer

Bridging transfer: Short Circuit Transfer

✓In low (17-21 V), the tip of the electrode periodically dipped into the molten weld pool. When this occurs, molten metal being formed at the electrode tip is transferred to the pool by a combination of surface tension and electromagnetic forces.

24-28V in Globular/Spray mode



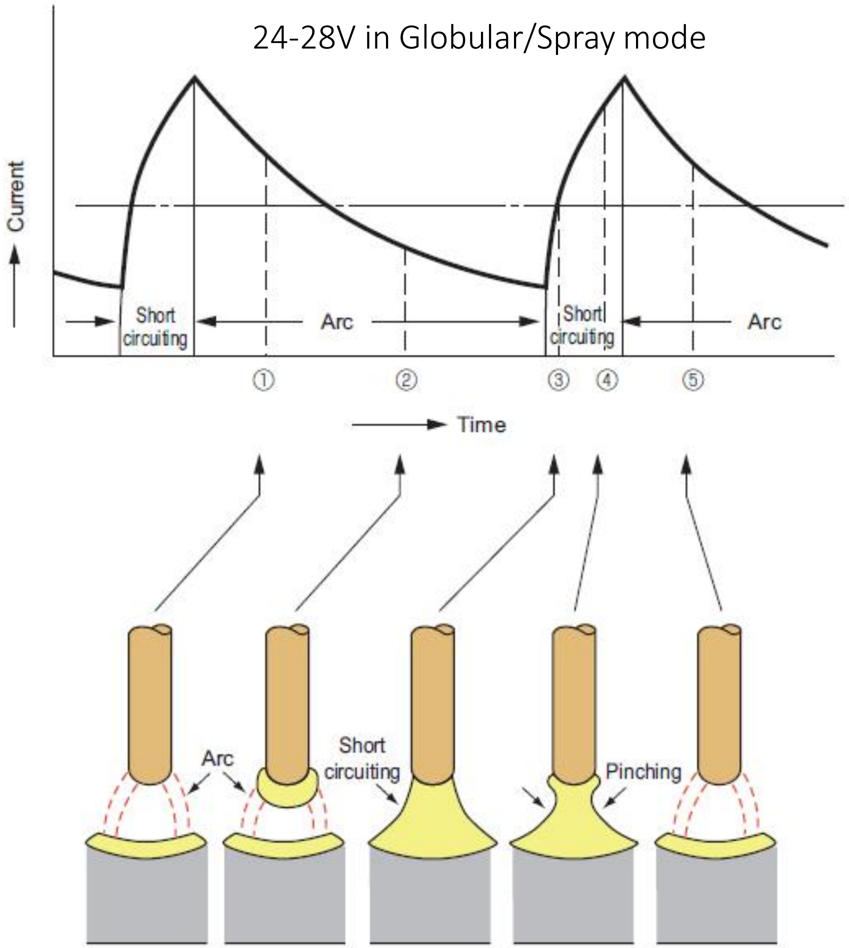
https://www.kobelco-welding.jp/education-center/Fundamentals/Fundamentals02.html

Bridging Transfer: Short Circuit Transfer

Bridging transfer: Short Circuit Transfer

✓At a low voltage, it reduces the rate at which the electrode is melted (the burn-off rate) compared to the rate at which it is being fed from a wire feeder or wire pull-gun.

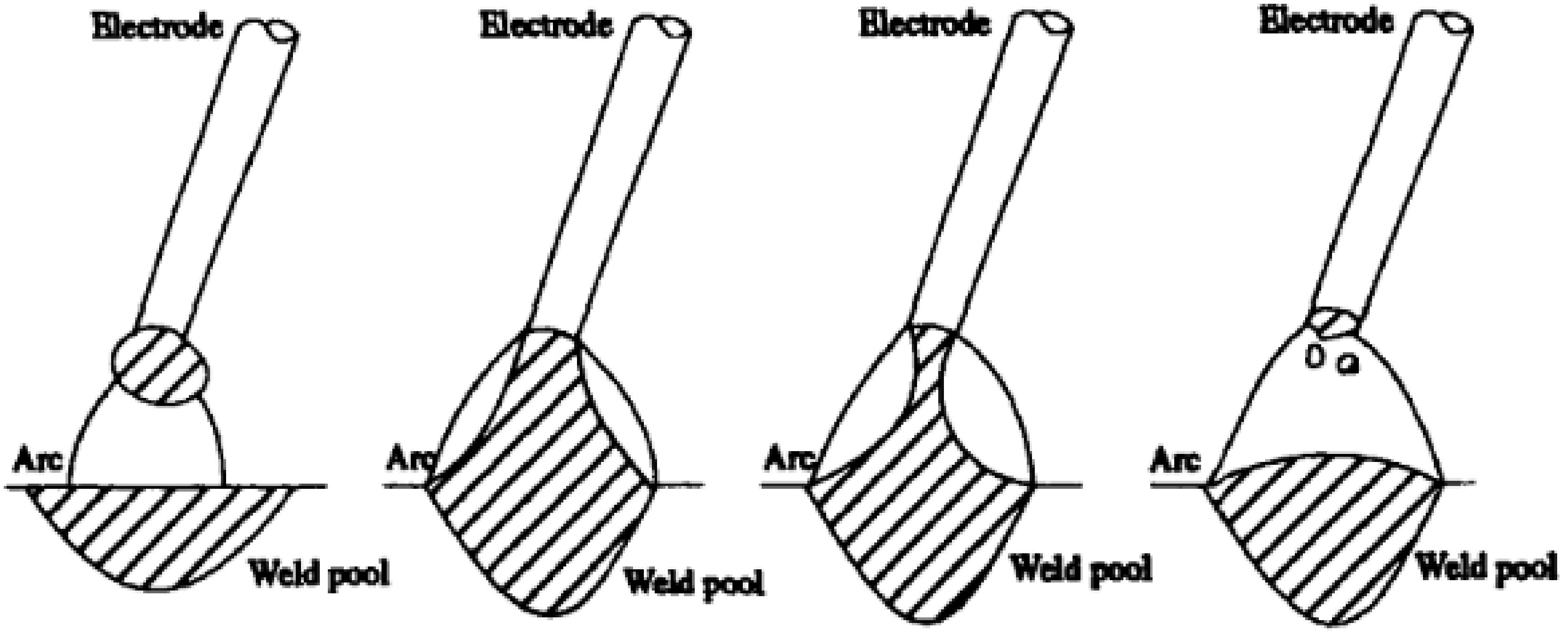
✓With a balance between the wire feed rate and electrode burn-off rate, the wire dips into the weld pool to continually melt and draw in by surface tension.



https://www.kobelco-welding.jp/education-center/Fundamentals/Fundamentals02.html

Bridging Transfer: Short Circuit Transfer

✓Suited for welding thin plates, vertical or overhead welding.



(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

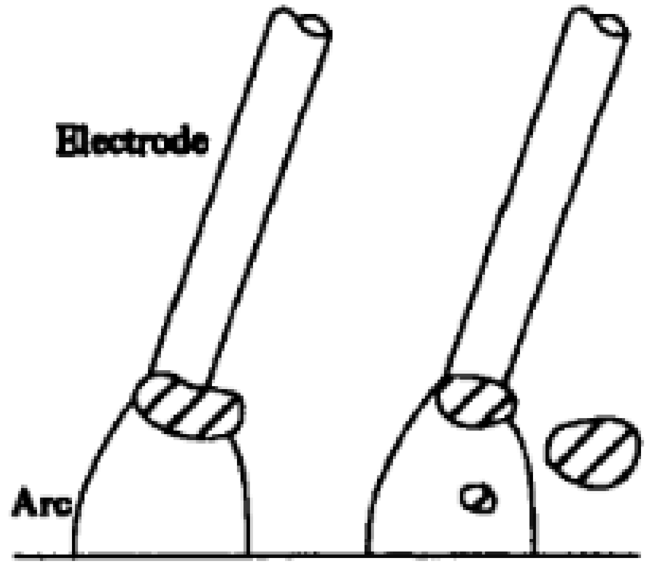
(d) immediately after pinch-off, fine spatter may result.

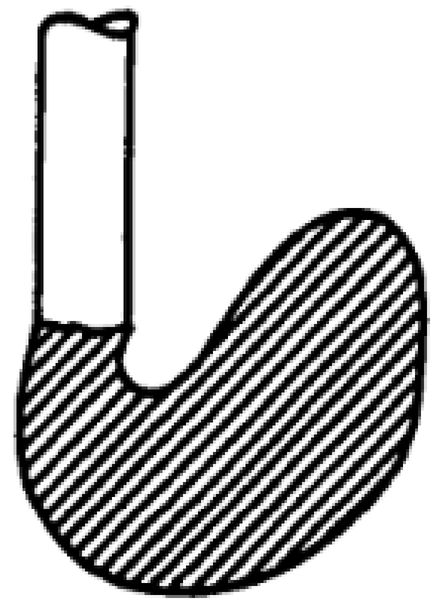
https://www.kobelco-welding.jp/education-center/Fundamentals/Fundamentals02.html

Bridging Transfer: Repelled transfer

- ✓In the presence of carbon dioxide (CO_2) in shielding gas, the molten drop at the electrode tip is pushed upward, giving rise.

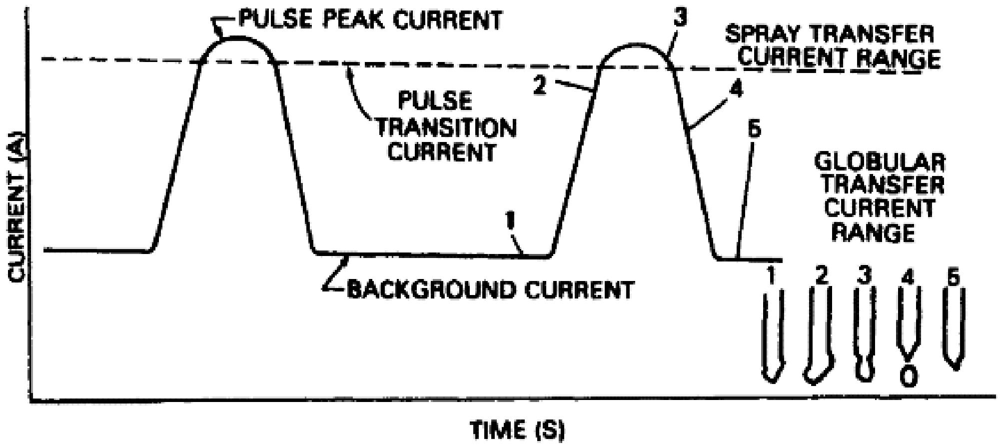
- ✓In this mode, short-circuiting captures the drop before it detaches in an unfavorable manner.





Pulse arc or pulsed current

✓Pulsed current transfer is achieved by employing a low, steady current to maintain the arc and a periodic current pulse to a higher level.



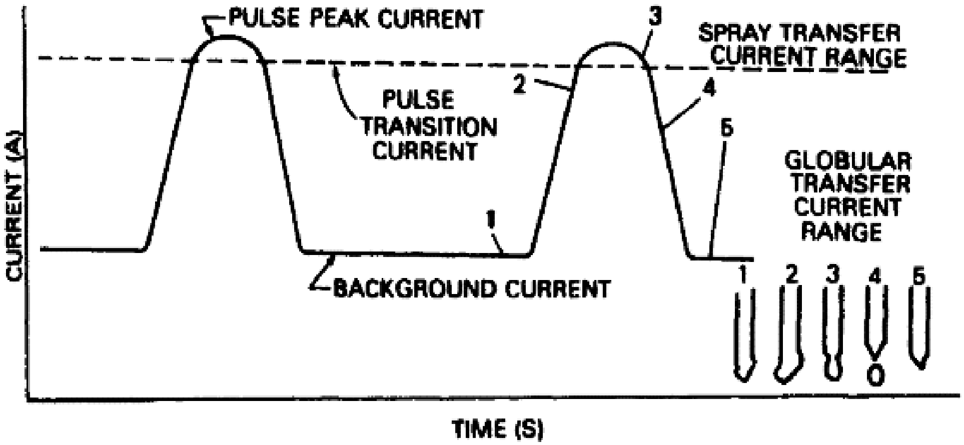
This pulsed mode differs from the normal spray mode in that

(1)The molten metal transfer is interrupted between the current pulses

(2)The current used to produce spray is below the normal transition current.

Pulse arc or pulsed current

✓When correctly timed, such a pulse detaches a drop. It propels it into the weld pool, thereby giving the advantage of axial spray transfer at a lower average current and lower net heat input.



This pulsed mode differs from the normal spray mode in that

(1)The molten metal transfer is interrupted between the current pulses

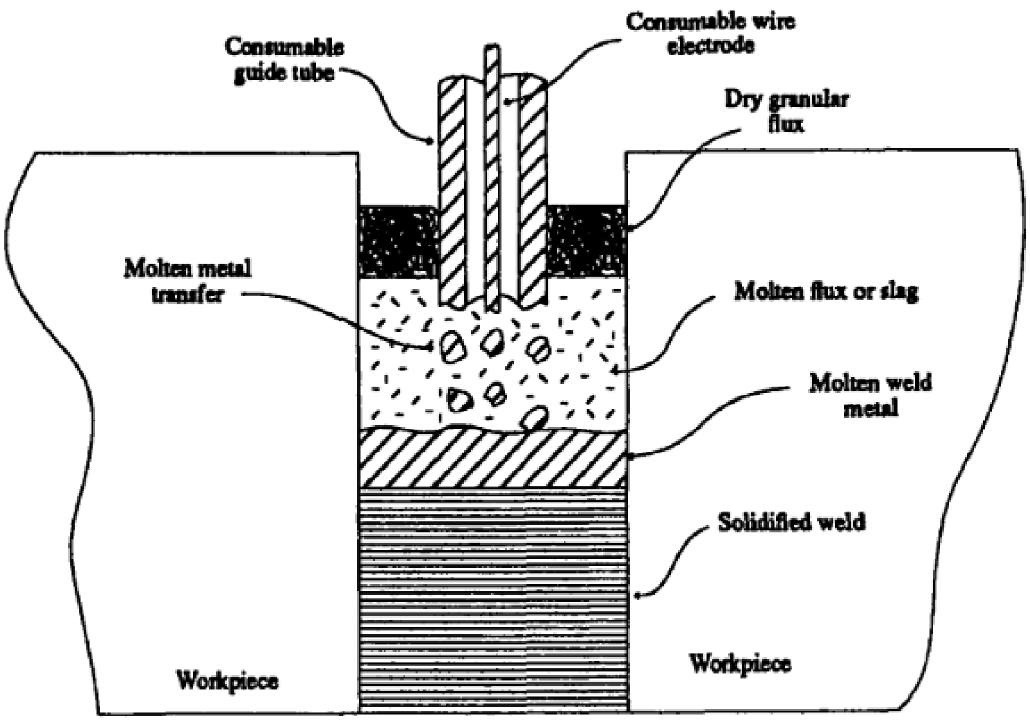
(2)The current used to produce spray is below the normal transition current.

Metal Transfer Modes: Slag Protected

✓Electroslag welding (ESW) and submerged arc welding (SAW).

✓Molten slag covers the weld pool, and molten drops formed at the tip of the consumable electrode must transfer through this liquid to reach the pool.

✓Primary forces acting to cause drop detachment: pinching force, electrostatic attraction, and gravity and transfer are never truly free-flight.

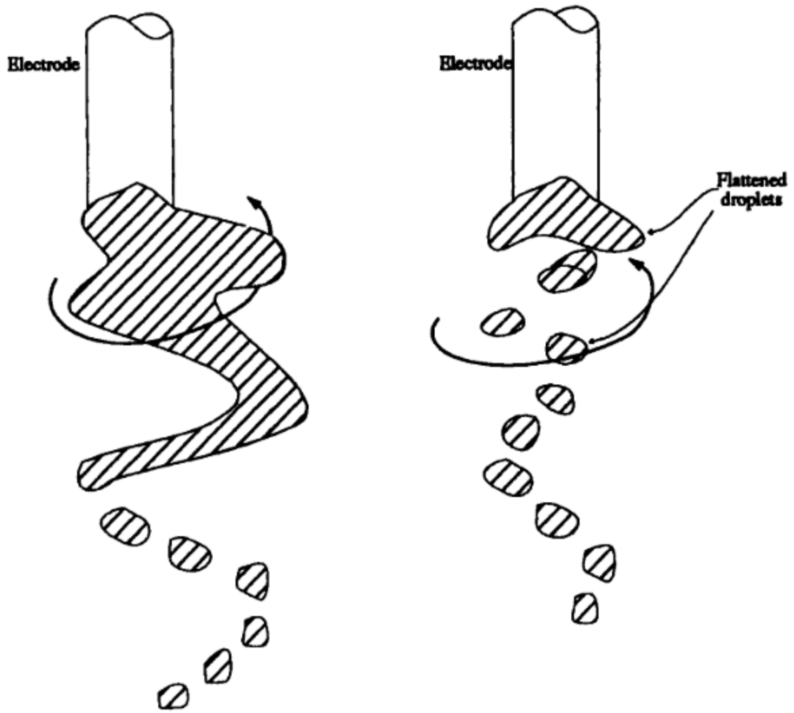


Metal Transfer Modes: Rotating transfer

✓As the welding current rises above the transition current, the liquid cylinder associated with axial spray transfer first collapses into a rotating spiral. This variation of streaming transfer is called rotating transfer.

✓A high deposition rate.

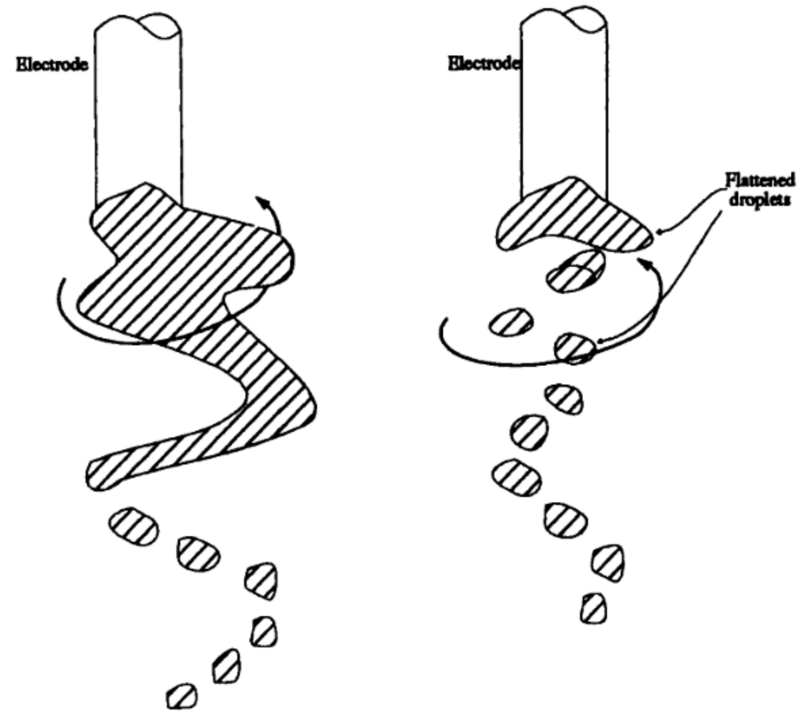
Very welding high currents



Metal Transfer Modes: Rotating transfer

- ✓At very high welding currents, in the region of 400-500 A, or in the presence of a strong longitudinal magnetic field, streaming transfer is suppressed, and a pair of mutually opposed, flattened drops appear at the tip of the consumable electrode.
- ✓These detach and transfer at very high frequencies.

Very welding high currents



Dominant Forces in Metal Transfer

Transfer Type	Dominant Force or Mechanism
Free-flight transfer	
Globular	
Drop	Gravity and electromagnetic pinch
Repelled	Chemical reaction generating vapor
Spray	
Projected	Electromagnetic pinch instability
Streaming	Electromagnetic
Rotating	Electromagnetic kink instability
Explosive	Chemical reaction to form a gas bubble
Bridging transfer	
Short-circuiting	Surface tension plus electromagnetic forces
Bridging without interruption	Surface tension plus (hot wire) electromagnetic forces
Slag-protected transfer	
Flux-wall guided	Chemical and electromagnetic
Other modes	Chemical and electromagnetic

Classification of Molten Transfer Modes

Designation of Transfer Type	Welding Processes (Examples)
Free-flight transfer	
Globular	
Drop	Low-current GMA
Repelled	CO_2 shielded GMA
Spray	
Projected	Intermediate-current GMA
Streaming	Medium-current GMA
Rotating	High-current GMA
Explosive	SMA (coated electrodes)
Bridging transfer	
Short-circuiting	Short-arc GMA, SMA
Bridging without interruption	Welding with filler wire addition
Slag-protected transfer	
Flux-wall guided	SAW
Other modes	SMA, cored wire, electroslag