Welding Metallurgy

Arc Physics and Weld Pool Behaviour

Lecture Topics

- Heat sources for welding
- Welding arcs as heat sources
  - The cathode, arc column and anode
  - Heat transfer from arcs, arc efficiency
- Weld pool behaviour
  - Heat input for melting, melting efficiency
  - Forces motion and temperatures in the weld pool

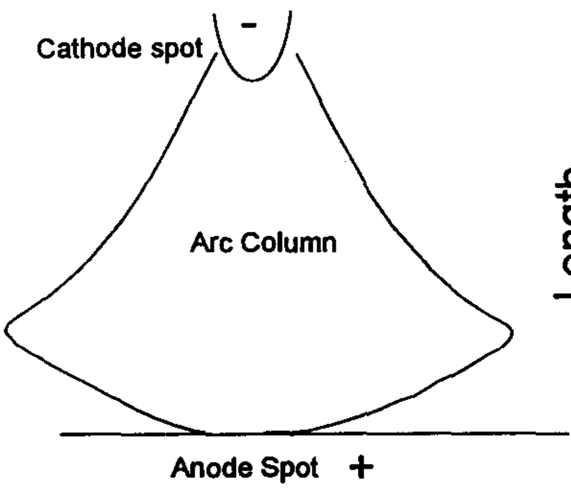
Heat Sources for Welding

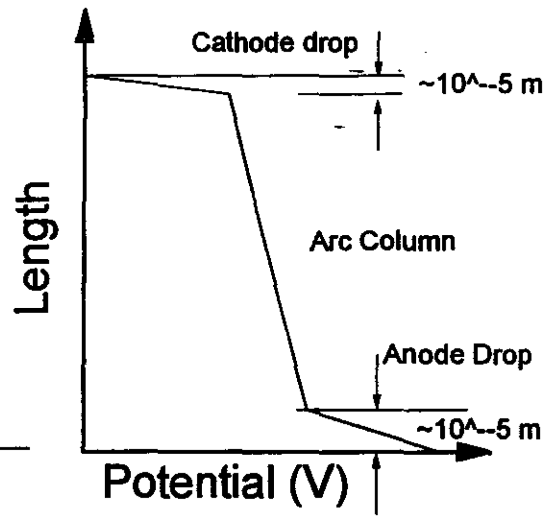
- Heat sources for welding include:
  - exothermic reactions (flames and thermit)
  - arcs
  - electrical resistance heating
  - radiant energy (electron beam, laser)
- Transferred power is the rate at which energy is delivered per unit time
- Energy density is the transferred power per unit area of contact between the heat source and work
- Energy density is a measure of the "hotness" of the source
- The development of welding processes has largely depended on availability of high energy density heat sources

Welding Arcs as Heat Sources

- The welding arc is a high current, low-voltage discharge
- In the arc:
  - electrons are evaporated from the cathode
  - transferred through a region of hot, ionized gas
  - and condensed at the anode.
- The arc may be divided into five parts
  - the cathode spot
  - the cathode drop zone
  - the arc column
  - the anode drop zone
  - the anode spot

The Welding Arc





Electron Interactions

- The energy required to evaporate one electron from a metal surface is known as the work function
- Conversely when an electron condenses in the surface it releases this energy

Metal	Work Function (eV)	First ionization potential (V)
Aluminum	4.0	5.96
Barium	2.1	5.19
Calcium	2.2	6.09
Copper	4.3	7.68
Iron	4.5	7.83
Nickel	5	7.61
Potassium	2.2	4.3
Tungsten	4.5	8.1

The Cathode

- Thermionic cathodes operate at high temperatures such that (e.g. GTAW) electrons are evaporated from the cathode.
- The energy required is derived from incoming positive ions that are accelerated through the cathode drop region.
- The cathode loses heat through the electron work function, electron thermal energy, and by conduction through the electrode and
- The energy balance is:

$$V_C I = (\phi_e + \frac{3}{2}\frac{kT}{e}) I + q_e$$

V_c	=	Cathode drop potential
I	=	Arc current
ϕ_e	=	Cathode work function
k	=	Bolztmann's constant
T	=	Temperature (K)
e	=	Electron charge
q_e	=	Heat loss to electrode

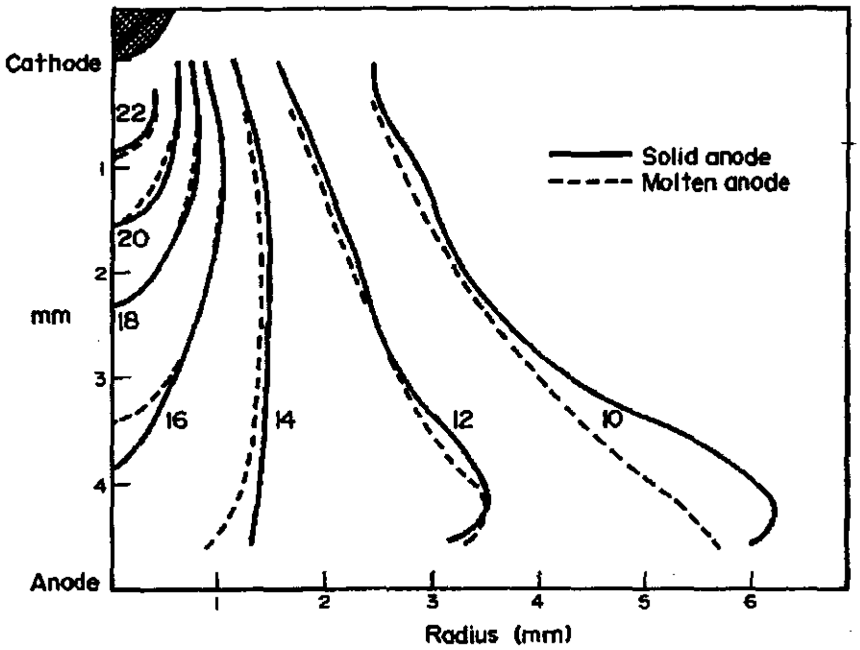
Non-Thermionic Cathodes

- Non-thermionic cathodes are those in which the temperature is too low for thermionic emission of electrons, i.e. on non-refractory metals.
- Where oxide films exist, the cathode appears to operate by positive ions collecting on the surface, setting up a strong electric field through the oxide, and causing electron emission through the oxide
- The general effect is to strip oxides from the surface (exploited in AC welding of Aluminum)
- Little is known about slag-covered cathodes that exist in flux-shielded processes

The Arc Column

- The gas in the space between the cathode and anode is at high temperature (10^4 K), sufficient for it to be highly ionized and electrically conductive
- The arc column is electrically neutral, i.e. the number of positive and negative charges in a given volume balance
- Most of the current is carried by electrons, since they are smaller and more mobile
- The axial potential gradient in the arc column is relatively low, 10^2 to 10^3 V/m.
- The energy generated in the arc column is $q_p = V_p I$
- Heat losses in the column are mostly due to convection in the "plasma jet"

GTAW Arc Plasma Temperatures



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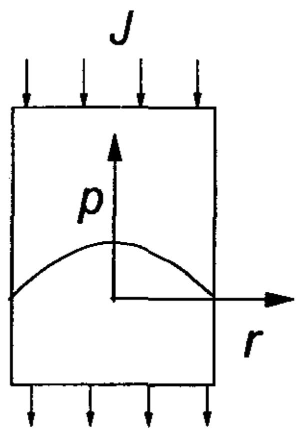
Arc Column Plasma Jet

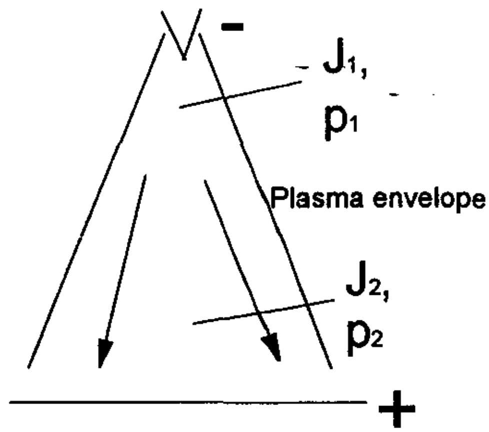
- In a static conducting cylinder, the interaction between the current and its self-induced magnetic field produces a radial pressure.

$$p = \frac{\mu_0 J^2}{4}(R^2 - r^2)$$



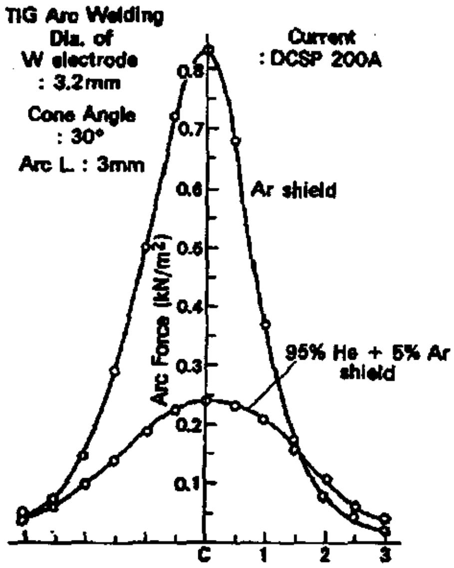
Arc Column Plasma Jet

- The radius of the arc column usually varies along the length
- The greater current density J in the constricted region produces an axial pressure gradient
- The pressure gradient causes net flow through the arc.
- Maecker suggested that the jet stagnation pressure is approximately equal to the pressure in the constricted region
- The strength of the jet depends on current and electrode vertex angle
- Flow velocities and stagnation pressures can reach 10^2 m/s and 1 kPa, respectively



$$\frac{1}{2}\rho v^2 = \frac{\mu_0 J_1^2}{4}$$

GTAW Plasma Jet Pressure



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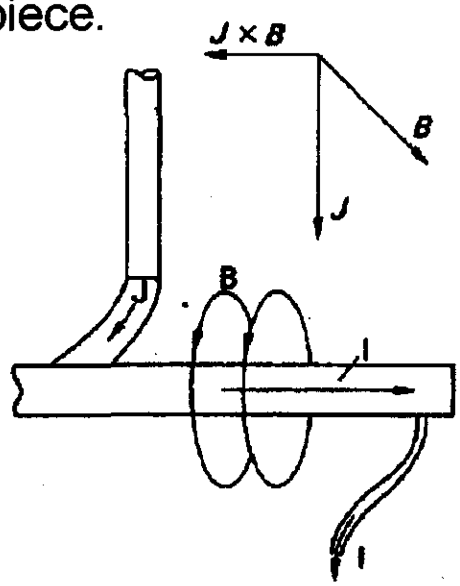
Arc "Blow"

Arc blow results from interaction with magnetic fields in the workpiece.



The Anode

- At the anode, electrons are accelerated across the anode fall potential and condense in the metal surface, thereby releasing energy
- The anode loses energy by radiation but also gains energy by radiation and convection from the plasma
- The energy balance at the anode is:

$$(1-m)q_A = (\phi_A - \frac{3}{2}\frac{kT}{e} + V_A)I + nq_p$$

q_a	=	heat input to workpiece (anode)
m	=	fractional heat loss by radiation
ϕ_a	=	anode work function
k	=	Boltzmann's constant
T	=	electron temperature
e	=	electron charge
V_A	=	anode fall potential
I	=	arc current
nq_p	=	heat transfer from arc column

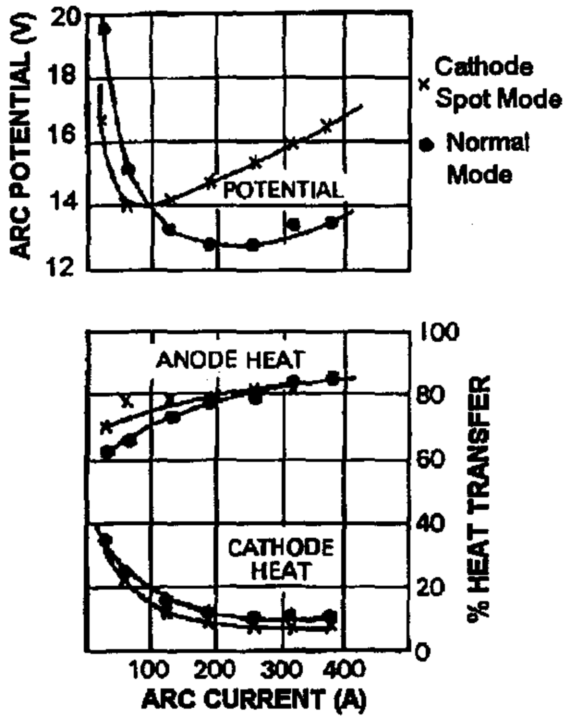
Arc Heat Generation

- The heat generated by the arc may be divided into three parts:
  - the heat generated at the cathode $q_c = V_c I$ (~20%)
  - the heat generated in the arc column $q_p = V_p I$ (~20%)
  - the heat generated at the anode $q_a = V_a I$ (~60%)
- The total arc energy is $VI = (V_c + V_p + V_a)I$
- Arc efficiency, assuming the work is the anode, is:

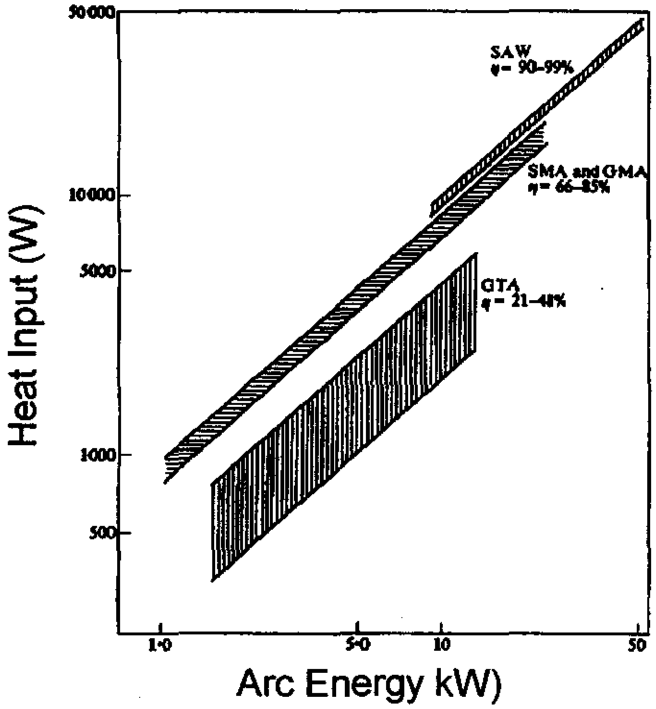
$$\eta = 1 - \frac{q_e + (1-n)q_p + mq_a}{IV}$$

With consumable electrodes, q_c is transferred to the workpiece, increasing arc efficiency

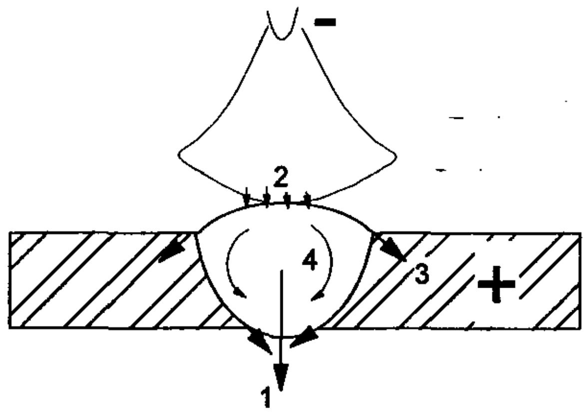
GTAW V-I & Heat Transfer Characteristics



Arc Efficiency of Various Processes



Forces Acting on the Weld Pool

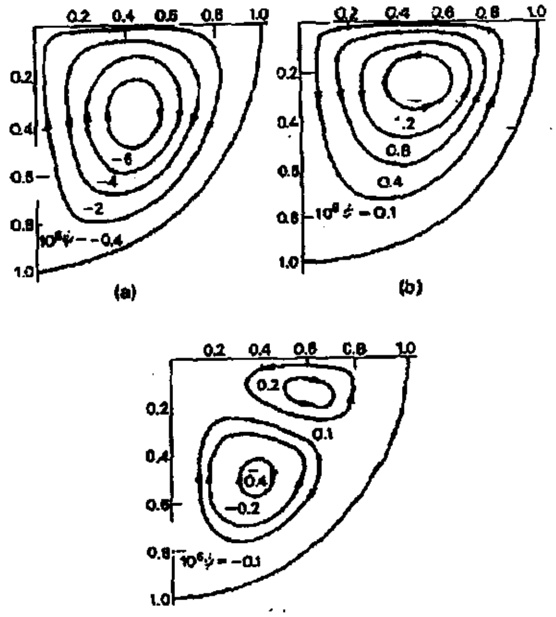


1. Gravity
2. Arc Pressure
3. Surface Tension
4. Lorenz (electromagnetic) forces

Motion in the weld pool

Theoretical MHD flow streamlines for various current source and sink distributions

The Lorenz (JxB) magnetohydrodynamic forces vary as the square of current.



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Surface Tension Flows

- Certain elements in the weld pool such as sulphur and oxygen are "surface active" and affect surface tension (like soap)
- Surface tension gradients can drive flows in the liquid metal (Marangoni convection)
- Thus weld penetration can depend on base metal composition. This has been a particular problem in GTAW welding of stainless steels, e.g. tubing, where a precise weld bead shape is desired.

Effects of Weld Pool Motion

- Weld pool composition tend to be homogenized by fluid motion
- The weld pool is relatively transparent to heat flow
- However, the exact cross-section of the weld bead is difficult to predict and may vary even if welding conditions are nominally constant.