Joining Dissimilar Materials

- Important to distinguish joints made between similar materials (metals, ceramics, composites or plastics) and joints between dissimilar materials (steel bonded to copper, metal bonded to rubber or ceramic, or a metallic contact to a semiconductor).

- In the case of dissimilar (unlike) materials, the engineering compatibility of the two components must be considered.

- Mismatch of the elastic modulus is a common form of mechanical incompatibility which leads to stress concentrations and stress discontinuities at the bonded interface between the two materials.
Joining Dissimilar Materials

- E.g. When a normal load is transferred across the interface between two materials with different elastic moduli, the stiffer (higher modulus) component restricts the lateral contraction of the more compliant (lower modulus) component, generating shear stresses at the interface which may lead to debonding.

- Thermal expansion mismatch is a common problem in metal/ceramic joints. Leads to the development of thermal stresses which tend to be localized at the joint and reduce its load-carrying capacity, ultimately leading to failure of the component. (On cooling from elevated temperature, metal shrinks more than ceramic causing stresses).
Joining Dissimilar Materials

- Poor chemical compatibility is commonly associated with undesirable chemical reactions in the neighborhood of the joint.
- These reactions may occur between the components, for example the formation of brittle, intermetallic compounds during the joining process, or they may involve a reaction with the environment, as in the formation of an electro-chemical corrosion couple due to a change in the electrochemical potential across the joint interface.
Surfaces and contamination

- For some joining processes (especially soldering and adhesive bonding) surface contamination can be a serious problem and surface preparation is then very important.

- Surface films can easily form on surfaces (grease - fingerprints!) and can prevent good joining.

- In some cases heating to the joining temperature can remove some surface contaminants, but can also cause more oxidation. Hence need for protective gases/atmospheres.

- **Surface Roughness**

- This can also cause problems as surfaces are never completely smooth. Also more contamination is trapped on a rough surface and the surfaces to be joined are not in good contact.
What is Welding?

- A process in which materials of the same fundamental type or class are brought together and caused to join (and become one) through the formation of primary (and, occasionally, secondary) chemical bonds under the combined action of heat and pressure.

- The American Heritage Dictionary: "To join (metals) by applying heat, sometimes with pressure and sometimes with an intermediate or filler metal having a high melting point."

- ISO standard R 857 (1958) "Welding is an operation in which continuity is obtained between parts for assembly, by various means,"

- Coat of arms of The Welding Institute (commonly known as TWI): "e duobus unum," which means "from two they become one."
Welding

1. Central point is that multiple entities are made one by establishing continuity. (continuity implies the absence of any physical disruption on an atomic scale, unlike the situation with mechanical fastening where a physical gap, no matter how tight the joint, always remains.

- Continuity does not imply homogeneity of chemical composition across the joint, but does imply continuation of like atomic structure.

- Homogenous weld:
  1. Two parts of the same austenitic SS joined with same alloy as filler
  2. Two pieces of Thermoplastic PVC are thermally bonded or welded

- Heterogeneous weld:
  1. Two parts of gray CI joined with a bronze filler metal (brazing).
  2. 2 unlike but compatible thermoplastics are joined by thermal bonding.
Welding

- When material across the joint is not identical in composition (i.e., Homogeneous), it must be essentially the same in atomic structure, (allowing the formation of chemical bonds):
  1. Primary metallic bonds between similar or dissimilar metals,
  2. Primary ionic or covalent or mixed ionic-covalent bonds between similar or dissimilar ceramics
  3. Secondary hydrogen, van der waals, or other dipolar bonds between similar or dissimilar polymers.
- If materials are from different systems, welding (by the strictest definition) cannot occur. E.G. Joining of metals to ceramics or even thermoplastic to thermosetting polymers.
- There is a disruption of bonding type across the interface of these fundamentally different materials and a dissimilar adhesive alloy is required to bridge this fundamental incompatibility.
2. The second common and essential point among definitions is that welding applies not just to metals.

- It can apply equally well to certain polymers (e.g., thermoplastics), crystalline ceramics, inter-metallic compounds, and glasses.
- May not always be called welding –
  - thermal bonding for thermoplastics
  - fusion bonding or fusing for glasses
- but it is welding!
3. The third essential point is that welding is the result of the combined action of heat and pressure.

- Welds (as defined above) can be produced over a wide spectrum of combinations of heat and pressure:
  - From: no pressure when heat is sufficient to cause melting,
  - To: pressure is great enough to cause gross plastic deformation when no heat is added and welds are made cold.

4. The fourth essential point is that an intermediate or filler material of the same type, even if not same composition, as the base material(s) may or may not be required.
5. The fifth and final essential point is that welding is used to join parts, although it does so by joining materials.

- Creating a weld between two materials requires producing chemical bonds by using some combination of heat and pressure.
- How much heat and how much pressure affect joint quality but also depends on the nature of the actual parts or physical entities being joined: part shape, dimensions, joint properties. One must prevent intolerable levels of distortion, residual stresses, or disruption of chemical composition and microstructure.
- Welding is a secondary manufacturing process used to produce an assembly or structure from parts or structural elements.
Nature of Ideal Weld

- **Achieving Continuity**

Understanding exactly what happens when two pieces of metal are brought into contact is crucial to understanding how welds are formed.

When two or more atoms are separated by an infinite distance there is no force of attraction or repulsion between them.

As they are brought together from this infinite separation a force of electrostatic or Coulombic attraction arises between the positively charged nuclei and negatively charged electron shells or clouds.

This force of attraction increases with decreasing separation. The potential energy of the separated atoms also decreases as the atoms come together.
Forces and potential energies involved in bond formation between atoms.

Nature of Ideal Weld

- As the distance of separation decreases to the order of a few atom diameters, the outermost electron shells of the approaching atoms begin to feel one another's presence, and a repulsion force between the negatively charged electron shells increases more rapidly than the attractive force.

Forces and potential energies involved in bond formation between atoms.
Nature of Ideal Weld

- Attractive and repulsive forces combine and at some separation distance net force becomes zero.
- This separation is known as the equilibrium interatomic distance or equilibrium interatomic spacing.
- At this spacing, net energy is a minimum and the atoms are bonded.
- When all of the atoms in an aggregate are at their equilibrium spacing, each and everyone achieves a stable outer electron configuration by sharing or transferring electrons.
- The tendency for atoms to bond is the fundamental basis for welding.
- To produce a weld - bring atoms together to their equilibrium spacing in large numbers to produce aggregates. The result is creation of continuity between aggregates or crystals, - formation of ideal weld.
- In ideal weld there is no gap and the strength of the joint would be the same as the strength of the weakest material comprising the joint.
Impediments To Make Ideal Weld

- If two perfectly flat surfaces of aggregates of atoms are brought together to the equilibrium spacing for the atomic species involved, bond pairs form and the two pieces are welded together perfectly.

- In this case, there is no remnant of a physical interface and there is no disruption of the structure of either material involved in the joint. The resulting weld has the strength expected from the atom-to-atom binding energy so the joint efficiency is 100%. “Joint efficiency" is the ratio of the joint strength to the strength of the base materials comprising the joint.

Nature of continuity in a metal in part A and B.

- a) two separate aggregates (crystals, grains, parts)
- b) forming a single part after welding.
Impediments To Make Ideal Weld

- In reality, two materials never perfectly smooth, so perfect matching up of all atoms across an interface at equilibrium spacing never occurs.
- Thus, a perfect joint or ideal weld can never be formed simply by bringing the two material aggregates together.
- Real materials have highly irregular surfaces on a microscopic scale.
- Peaks and valleys of 10-1000’s of atoms high or deep lead to few points of intimate contact at which the equilibrium spacing can be achieved.
- Typically, only one out of approximately every billion ($10^9$) atoms on a well-machined (e.g., 4 rms finish) surface come into contact to be able to create a bond, so the strength of the joint is only about one-billionth ($10^{-9}$) of the theoretical cohesive strength that can be achieved.
- This situation is made even worse by the presence of oxide, tarnish and adsorbed moisture layers usually found on real materials.
- Bonding (welding) can be achieved only by removing or disrupting these layers and bringing the clean base material atoms to the equilibrium spacing for the materials involved. Any other form of surface contamination, such as paint or grease or oil, also causes problems.
Impediments To Make Ideal Weld

Two perfectly smooth and clean surfaces brought together to form a weld.

Two real materials (c) and (d) progressively forced together by pressure (e and f) to form a near-perfect weld (g). Melting to provide a supply of atoms (h) to form a near-perfect weld.

Lecture 7
What It Takes To Make A Real Weld

- To make a real weld (obtain continuity) requires overcoming the impediments of surface roughness and few points of intimate contact and intervening contaminant layers.

- There are two ways of improving the situation:
  1. cleaning the surface of real materials,
  2. bringing most, if not all, of the atoms of those material surfaces into intimate contact over large areas.

- There are two ways of cleaning the surface:
  1. chemically, using solvents to dissolve away contaminants or reducing agents to convert oxide or tarnish compounds to the base metals,
  2. mechanically, using abrasion or other means to physically disrupt the integrity of oxides or tarnish layers.

- Once the surfaces are cleaned, they must be kept clean until the weld is produced. (requires shielding). Every viable welding process must somehow provide and/or maintain cleanliness in the joint area.
What It Takes To Make A Real Weld

- Two ways of bringing atoms together in large numbers to overcome asperities. Apply heat and/or pressure.

1. Apply heat. In the solid state, heating helps by
   
   a. Driving off volatile adsorbed layers of gases or moisture (usually hydrogen-bonded waters of hydration) or organic contaminants;
   
   b. Either breaking down the brittle oxide or tarnish layers through differential thermal expansion or, occasionally, by thermal decomposition (e.g. Copper oxide and titanium oxide);
   
   c. Lowering the yield strength of the base materials and allowing plastic deformation under pressure to bring more atoms into intimate contact across the interface.
   
   d. Melting of the substrate materials, allowing atoms to rearrange by fluid flow and come together to equilibrium spacing, or by melting a filler material to provide an extra supply of atoms of the same or different but compatible types as the base material.
What It Takes To Make A Real Weld

2. Apply pressure.
   a. disrupting the adsorbed layers of gases or moisture by macro- or microscopic deformation,
   b. fracturing brittle oxide or tarnish layers to expose clean base material atoms,
   c. plastically deforming asperities to increase the number of atoms, and thus the area, in intimate contact.

- Very high heat and little or no pressure can produce welds by relying on the high rate of diffusion in the solid state at elevated temperatures or in the liquid state produced by melting or fusion.
- Little or no heat with very high pressures can produce welds by forcing atoms together by plastic deformation on a macroscopic scale (as in forge welding) or on a microscopic scale (as in friction welding), and/or by relying on atom transport by solid-phase diffusion to cause intermixing and bonding.
What It Takes To Make A Real Weld

TABLE 1.1 Advantages and Disadvantages of Welding as a Joining Process

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Joints of exceptional structural integrity and efficiency, will not</td>
<td>1. Impossible to disassemble joints without</td>
</tr>
<tr>
<td>accidently loosen or disassemble</td>
<td>destroying detail parts</td>
</tr>
<tr>
<td>2. Wide variety of process embodiments</td>
<td>2. Heat of welding degrades base properties</td>
</tr>
<tr>
<td>3. Applicable to many materials within a class</td>
<td>3. Unbalanced heat input leads to distortion or</td>
</tr>
<tr>
<td></td>
<td>residual stresses</td>
</tr>
<tr>
<td>4. Manual or automated operation</td>
<td>4. Requires considerable operator skill</td>
</tr>
<tr>
<td>5. Can be portable for indoor or outdoor use</td>
<td>5. Can be expensive (e.g., thick sections)</td>
</tr>
<tr>
<td>6. Leak-tight joints with continuous welds</td>
<td>6. Capital equipment can be expensive (e.g.,</td>
</tr>
<tr>
<td></td>
<td>electron-beam guns and vacuum chambers)</td>
</tr>
<tr>
<td>7. Cost is usually reasonable</td>
<td></td>
</tr>
</tbody>
</table>

1836 Acetylene gas discovered
1856 The principle of resistance welding discovered by Joule
1881 First arc welding machine invented
1905 First patent on resistance welding machine
1889-1890 First arc welding with bare wire
1895 LeChâtelier credited with discovering the oxygen-acetylene flame
1900 Aluminum oxide reactions discovered
1900 First oxyacetylene torches made
1907-1910 Coated electrodes developed
1949 Plasma arc welding process introduced
1949 "Hot wire" welding processes introduced
1961 First public disclosure of EBW
1964 "One knob" (Synergic Control) introduced for GMAW
1962 Electrogas welding introduced
1966 First laser beam welding process introduced
1957 First use of CO₂ with GMAW
1956 Friction welding invented
1955 Constricted arc (plasma arc) invented
1954 Self-shielded PCMA introduced
1953 Constricted plasma arc invented
1950 First spray transfer process for welding
1950 Electroslag welding introduced
1950 Electrosheet welding introduced

Lecture 7
MECH 423 Casting, Welding, Heat Treating and NDT

Time: ___ W _ F 14:45 - 16:00

Credits: 3.5      Session: Fall

Welding - Fundamentals

Lecture 8
Permanent joining of 2 materials by coalescence through

- Temperature - Pressure - Metallurgical/material conditions

3 distinctive mechanisms for obtaining continuity (joining by welding):

- Solid phase plastic deformation (with/without recrystallization). E.g. cold welding processes, hot deformation welding processes.

- Diffusion E.g. diffusion welding processes, brazing etc.

- Melting and solidification. E.g. welding processes where melting occurs.

Require:

1) source of heat and/or pressure
2) means of cleaning/protection
3) caution regarding microstructure.
Oxyfuel Gas Welding - OFW

- Processes that use flame (from combustion of gas & oxygen) to heat parts. Now used for portability & versatility.
- Acetylene \((C_2H_2)\) principle fuel. Heat is generated in 2 stages of combustion while acetelyne combusts with Oxygen
  - \[C_2H_2 + O_2 \rightarrow 2CO + H_2 \text{ + Heat}\] Primary combustion
  - \[2CO + O_2 \rightarrow 2CO_2 \text{ + Heat}\] Secondary “
  - \[H_2 + \frac{1}{2}O_2 \rightarrow H_2O \text{ + Heat}\] Secondary “
- First stage near the tip of the torch, second stage beyond the first combustion zone
- Can generate heat of ~ 3250°C
- (Other fuels possible: natural gas/methane, propane, butane, hydrogen)
Oxyfuel Gas Welding - OFW

- **Start:** Open acetylene (fuel) valve, light with spark; open oxygen to desired flame.
- **Stop:** Shut acetylene (fuel) valve, flame goes out; shut oxygen valve.

*Lecture 8*
Oxyfuel Gas Welding - OFW

- Two regions of flame:
- Inner core (hottest - near weld)
- Outer envelope - preheat, shield from oxidation
- Oxygen/fuel gas ratio:
  - 1:1 to 1.15:1 neutral flame (welding)
  - > 1.15:1 oxidising flame, hotter, used in copper and copper alloys (but not steel – oxygen reduces carbon content)
  - < 1:1 reducing/carburizing flame, cooler - no carburization but good protection from oxidation or for removing surface oxides prior to welding.

Lecture 8
Oxyfuel Gas Welding - OFW

Cylinders:

\( \text{O}_2 \) is stored in pure form at 1.7 MPa.
\( \text{C}_2\text{H}_2/\text{acetone/filler} \) (Acetelyne is not safe at higher pressure, so dissolved in Acetone and the cylinders are filled with porous filler which absorbs acetone and helps in dissolving acetelyne)
Also MAPP gas (methyl acetylene propadiene)

Regulators:

1-15 psi (7-105 kPa) is the pressure used in this welding - controlled by regulators. Precautions to prevent mixing by accident. (RH & LH)

Torch:

Orifice size varied to change shape of flame & flow rate
Large tips: high flow & high heat without high velocity or blowing metal.
OEW – Advantages and Disadvantages

- Generally Fusion Welding – no pressure
- Due to gaps in surfaces filler-metal rods:
  - 1.5 - 9.5 mm dia & 0.6 - 0.9 m in length
- For better bonding, fluxes - to clean surfaces; prevent oxidation
- Can be powders, pastes, or precoated rod.

- Advantages – Disadvantages
- Easy heat control, but slow (low energy density).
- But gases etc can cause contamination.
- Large area of metal heated (distortion).
- Not used a lot in mass production, mainly in field, repair, mixed workshops.
- Portable equipment
### TABLE 33-1. Engineering Materials and Their Compatibility with Oxyfuel Welding

<table>
<thead>
<tr>
<th>Material</th>
<th>Oxyfuel Welding Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast iron</td>
<td>Recommended with cast iron filler rods; braze welding recommended if there are no corrosion objections</td>
</tr>
<tr>
<td>Carbon and low-alloy steels</td>
<td>Recommended for low-carbon and low-alloy steels, using rods of the same material; more difficult for higher carbon</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Common for thinner material; more difficult for thicker</td>
</tr>
<tr>
<td>Aluminum and magnesium</td>
<td>Common for aluminum thinner than 1 in.; difficult for magnesium alloys</td>
</tr>
<tr>
<td>Copper and copper alloys</td>
<td>Common for most alloys; more difficult for some types of bronzes</td>
</tr>
<tr>
<td>Nickel and nickel alloys</td>
<td>Common for nickel, Monels, and Inconels</td>
</tr>
<tr>
<td>Titanium</td>
<td>Not recommended</td>
</tr>
<tr>
<td>Lead and zinc</td>
<td>Recommended</td>
</tr>
<tr>
<td>Thermoplastics, thermosets, and elastomers</td>
<td>Hot-gas welding used for thermoplastics, not used with thermosets and elastomers</td>
</tr>
<tr>
<td>Ceramics and glass</td>
<td>Seldom used with ceramics, but common with glass</td>
</tr>
<tr>
<td>Dissimilar metals</td>
<td>Difficult; best if melting points are within 50°F; concern for galvanic corrosion</td>
</tr>
<tr>
<td>Metals to nonmetals</td>
<td>Not recommended</td>
</tr>
<tr>
<td>Dissimilar nonmetals</td>
<td>Difficult</td>
</tr>
</tbody>
</table>
Oxyacetelyn Flame Cutting

- Melts metal and gas blows the metal away from the gap creating the kerf
- In ferrous metals iron actually burns (oxidizes at high temperatures)

**Advantages - Disadvantages**
- Low rate of heat input, large heat affected zone, slow process
- Not suited for operations where finish and tolerance are critical
- Large area of metal heated (distortion).
- Used only metals that oxidize readily. SS, aluminum alloys are difficult
- Low cost of equipment
Arc welding

• 1880s - Arc used as heat source. Carbon, electrode, filler rod.
• Now shielded metal arc welding is most common form of welding.
• Circuit – Basic (1-4000 Amps of current and 20 to 50 V)
• Arc is formed between an electrode and a workpiece, different polarities.
• Arc consists of thermally emitted e⁻ and positive ions from the electrode and workpiece. e⁻s and ions are accelerated by the potential field (voltage) between the source and the work. Heat is produced when e⁻s and ions collide with opposite charged element.
• e⁻s are much smaller than +ve ions but have higher kinetic energy (higher velocities).
Arc welding

- **Consumable Electrode**: Electrode is consumed, providing filler metal to fill voids. $T_{\text{Melting}} < T_{\text{arc}}$.
- Droplets from arc are transferred to the workpiece.
- Maintain stable arc by moving electrode towards workpiece at the same time as moving electrode along workpiece (gap or joint).
- Schematic of modes of molten metal transfer in arc welding:
  - (a) drop globular
  - (b) spray
  - (c) short-circuiting.
Arc Welding

- Automatic - may use continuous bare metal wire, fed automatically but continuously controlled to control arc and shielding.
- Non-Consumable Electrode: Separate wire used as filler
- Arc electrode is Tungsten.
- Still require shielding.
- Selection: variety of processes available, requires based on application, voltage, current, polarity (straight, reversed or alternating)
- Arc length, speed, arc atmosphere, filler metal, flux
- Quality also depends on the skilled operator – reduce dependence by robotic welding or automation of process
Current Modes

• Different current modes can be used:
  • DC – direct current
  • EN – electrode negative
  • EP – electrode positive
  • AC – alternating current
• When using DC supply:
  • When work is +ve (ANODE)
    • Direct current straight polarity – DCSP/SPDC
    • or Direct current electrode negative – DCEN
  • When work is -ve (CATHODE)
    • Direct current reversed polarity – DCRP/RPDC
    • or Direct current electrode positive – DCEP
Current Modes

DCSP (EN)
No cleaning action
70% heat at work
30% heat at W
Excellent electrode
Current capacity

DCRP (EP)
Strong cleaning action
30% heat at work
70% heat at W
Poor electrode
Current capacity

AC
Cleaning every half cycle
50% heat at work
50% heat at W
Good electrode
Current capacity

Summary of characteristics of various modes for arc welding process.
Current Modes

• In DCSP (DCEN), e−s are emitted from the electrode and accelerated to very high speeds and kinetic energies while traveling through the arc.
• These high-energy e−s collide with the workpiece, give up their kinetic energy, and generate considerable heat in the workpiece.
• Consequently, DCSP results in deep penetrating, narrow welds, but with higher workpiece heat input. About two-thirds of the net heat available from the arc (after losses from various sources) enters the workpiece.
• High heat input may or may not be desirable, depending on factors such as required weld penetration, weld width, workpiece mass, susceptibility to heat-induced defects or degradation, and concern for distortion or residual stress.
Current Modes

• In DCRP (DCEP), the heating effect of the electrons is on the (tungsten) electrode rather than on the workpiece. Consequently, larger water-cooled electrode holders are required, shallow welds are produced, and workpiece heat input can be kept low.

• This operating mode is good for welding thin sections or heat-sensitive metals and alloys. This mode also results in a scrubbing action on the workpiece by the large positive ions that strike its surface, removing oxide and cleaning the surface.

• This mode is thus preferred for welding metals and alloys that oxidize easily, such as aluminum or magnesium.
Current Modes

• The DCSP mode is much more common with nonconsumable electrode arc processes than the DCRP mode.

• Many of these effects are far less pronounced with other electric arc welding processes employing consumable electrodes than with GTAW. Most particularly, there is little difference in penetration between DCSP and DCRP.

• This is so since the concentration of heat at the electrode with RP aids in melting the consumable electrode, as is desired, but this heat is returned to the weld when the molten metal droplets transfer to the pool. On the other hand, the cleaning action of the RP mode at the workpiece still takes place.
Current Modes

• Third mode, employing alternating current or AC.
• The AC mode tends to result in some of the characteristics of both of the DC modes, during the corresponding half cycles, but with some bias toward the straight polarity half-cycle due to the greater inertia (i.e., lower mobility) and, thus, greater resistance of large positive ions.
• During this half-cycle, the current tends to be higher due to the extra emission of electrons from the smaller, hotter electrode versus larger, cooler workpiece. In the AC mode, reasonably good penetration is obtained, along with some oxide cleaning action.
Arc Welding Variables

- Welding voltage and current
- Welding arc polarity and arc length
- Welding speed
- Arc atmosphere
- Electrode material
- Filler material
- Flux

- So quite a few things to get right (or conversely, it doesn’t take much to produce a bad weld!)
Shielded Metal Arc Welding - SMAW

• (aka Stick Welding).

• Very common, very versatile - low cost.

• Heat from arc between tip of flux-coated, discontinuous, consumable ("stick") electrode and the surface of the work.

• Core wire conducts current from constant current power supply and provides filler metal to joint.

• Some arc heat is lost by conduction and as resistance heating.

• SMAW can operate in DCEP or DCEN and also in AC mode depending on coating.

• Typical currents: 50-300 A, 10-30V

• Deposition rates of 1 – 10 kg/hr.
Shielded Metal Arc Welding - SMAW

Schematic of the shielded-metal arc welding (SMAW) process, including electrode holder and electrode, weld, and electrical hookup.
Shielded Metal Arc Welding - SMAW

- Electrode covering is very important. Surrounding the wire electrode is bonded coating having chemical components that adds characteristics.
  - Provides a protective atmosphere (gas shield)
  - Stabilizes the arc (readily ionized compounds)
  - Acts as flux to deoxidize and/or remove contaminants
  - Provides slag coating - impurities, oxidation protection, slows cooling rate.
  - Reduces spatter
  - Adds alloying elements and/or grain refiners
  - Affects arc penetration
  - Affects shape of weld bead
  - Adds additional filler metal
Shielded Metal Arc Welding - SMAW

- Classified by:
  - tensile strength of deposited metals
  - position can be used in
  - type of polarity
- E7016 means tensile strength of 70,000 psi, used in all positions, AC DC or RP, with low hydrogen + potassium coating

![Designation system for arc-welding electrodes.](image)

<table>
<thead>
<tr>
<th>Current</th>
<th>Polarity</th>
<th>Type of coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC or DC</td>
<td></td>
<td>0 Cellulosic</td>
</tr>
<tr>
<td></td>
<td>Straight or reversed</td>
<td>1 Cellulosic + Ca and K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 Titania</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 High titania–potassium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 Titania + iron powder</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 Low hydrogen (lime)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 Low hydrogen + potassium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7 Cellulosic + iron powder</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 Low hydrogen + iron powder</td>
</tr>
</tbody>
</table>

- Minimum tensile strength, in 1,000 psi, as-deposited weld metal in nonstress-relieved condition.
- Welding position:
  - 1 All
  - 2 Flat and horizontal
  - 3 Flat only

Lecture 8
# Shielded Metal Arc Welding - SMAW

## Usability of the Electrode Based on Last Digit

<table>
<thead>
<tr>
<th>Classification</th>
<th>Welding—Type of Covering</th>
<th>Position</th>
<th>Arc Type</th>
<th>Approximate Iron Powder&lt;sup&gt;a&lt;/sup&gt; (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWS</td>
<td>ASME</td>
<td>Current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6010</td>
<td>F-3</td>
<td>DCEP</td>
<td>Cellulose—sodium</td>
<td>All</td>
</tr>
<tr>
<td>6011</td>
<td>F-3</td>
<td>Ac and DCEP</td>
<td>Cellulose—potassium</td>
<td>All</td>
</tr>
<tr>
<td>6012</td>
<td>F-2</td>
<td>Ac and DCEN</td>
<td>Rutile—sodium</td>
<td>All</td>
</tr>
<tr>
<td>6013</td>
<td>F-2</td>
<td>Ac and dc</td>
<td>Rutile—potassium</td>
<td>All</td>
</tr>
<tr>
<td>6019</td>
<td>F-2</td>
<td>Ac and dc</td>
<td>Iron oxide rutile—potassium</td>
<td>All</td>
</tr>
<tr>
<td>6020</td>
<td>F-1</td>
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<td>Iron oxide—iron powder</td>
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<sup>a</sup>Iron powder percentage based on weight of the covering.
## Shielded Metal Arc Welding - SMAW

<table>
<thead>
<tr>
<th>AWS Classification</th>
<th>Minimum Tensile Strength (ksi, MPa)</th>
<th>Minimum Yield Strength at 0.2% Offset (ksi, MPa)</th>
<th>Elongation (%)</th>
<th>Radiographic Standard (AWS Grade)</th>
<th>Minimum V-Notch Impact (20 ft-lb at –20°F = 27 joules at –29°C and 20 ft-lb at 0°F = 27 joules at –18°C)</th>
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<td>1</td>
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</tbody>
</table>

Abridged specifications for mild steel covered electrodes.
Shielded Metal Arc Welding - SMAW

- **Electrode coatings:** The cellulose and titania (rutile) coatings contain SiO$_2$ & TiO$_2$ (small amounts of FeO, MgO, Na$_2$O) + volatiles
  - On decomposition, volatile matter release hydrogen that dissolve the weld metal leading to cracking
  - Cellulosic generates H$_2$, CO, H$_2$O, CO$_2$
  - Rutile (TiO$_2$) generates up to 40% H$_2$,
  - Limestone (CaCO$_3$) generates CO$_2$ and CaO slag with little or no H$_2$
- Low hydrogen electrodes are available that provide shielding without hydrogen release
- Electrodes can absorb water and become another source of hydrogen, so baking electrodes to remove water is done
Shielded Metal Arc Welding - SMAW

- **To start weld:** touch electrode tip to metal quickly & raise short distance (striking an arc) - “frizzling” begins.
- **Tip should not touch workpiece again.**
- **Arc heat melts tip of wire, & coating & metal.**
- **Glassy slag formed can be chipped off once the weld is cooled.**
- **For heavier depositions, coating can contain iron (or alloy) powder.**
- **Other alloying elements can be used to alter the chemistry of the weld**
- **Commonly used to weld Carbon steels, Alloy steels, SS, Cast irons**
- **Temperature of Arc: ~ 5000°C, 15 - 45 V, 10 - 500 A.**
Shielded Metal Arc Welding - SMAW

- Simple, inexpensive, Quick, portable, versatile
- limited to short electrodes (heating) - not always suited to mass prod’n.
- Discontinuous processes
- Welder has to stop, chip slag and change electrodes when down to last 2 inches of electrode.
- Limits production rate. (duty cycle).

FIGURE 34-4 Schematic diagram of shielded metal arc welding (SMAW). (Courtesy of American Iron and Steel Institute, Washington, D.C.)
Flux-Cored Arc Welding - FCAW

- (a.k.a Open-arc welding) Opposite of shielded electrode - Tube of metal with flux powder inside. “Inside-out” electrode.

- Same principle as SMAW electrode (filler provides shielding, slag, arc stabilizers etc). Slag formed (chipped off).

- Better shielding than SMAW. Continuous electrode – no binder required. Good for welding in the field.

- Can use gas shielding as well (often CO₂ with DCEP for ferrous metals).

- DCEN or DCEP. No problems of electrode overheating (up to 500A)
Flux-Cored Arc Welding - FCAW

- Larger, better contoured welds than SMAW. Better penetration as well
- Easier for automation - continuous feed
- High deposition rates (2-15 kg/hr)
- Portable

FIGURE 34-11 Schematic representation of the flux-cored arc welding process (FCAW). (Courtesy of The American Welding Society, New York.)
Gas Metal Arc Welding - GMAW

• If gas flowing through can protect, there is no need for flux coating

• Formerly known as (MIG - Metal Inert Gas) - Arc between workpiece
  + automatically fed, continuous, consumable, bare-wire
  electrode/filler (no separate filler rod required).

• Inert gas shielding. Argon, helium or mixture of both for reactive metals (Ti, Al, Mg).

• Ferrous metals - up to 20% CO$_2$ or 2% O$_2$ to stabilize arc & contour

• Wire is automatically fed by wire feeder & trigger

• Variety of control methods & other variations.
Gas Metal Arc Welding - GMAW

- Generally, FAST, economical, no flux or slag, so multiple pass immediately after first, automated, lightweight.
- DCRP (Reverse Polarity) is most popular mode. Electrons from workpiece (-ve) strike wire (+ve) causing heating and melting of wire.
- Heat is recovered as molten drops fall onto workpiece. (good penetration).
- Other modes can be used – DCSP, AC.
- Smooth welds produced.
Gas Metal Arc Welding - GMAW

- **Short-circuiting mode GMAW-S** – globules periodically touch workpiece to form short-circuit (50 times per second). Good for welding thin sheets and out of position (Used for steels only). DCEN. (Causes splatter)

- **Spray transfer GMAW-ST** – very stable metal transfer, directional and free from spatter. Use DCEP (DCRP) at high voltages. Can also be used for out-of-position welding (not flat).

- Limited use for thin sheet metal as high energy & heat.

- **Globular transfer** – large globules form on electrode tip and fall by gravity to workpiece. Slower, more spatter. DCEN
Gas Metal Arc Welding - GMAW

- Pulsed Spray Transfer GMAW-P – invented in 1960 to overcome limitations of conventional ST.

- Low currents are passed to create metallic globules. Then high current bursts "explode" globules of molten metal onto workpiece –

- Lower workpiece temperatures, thinner metals, less distortion, less discolouration, less spatter, fine microstructure. Allows use of spray transfer on thinner metals at lower currents.

- All positions, safer, high speed, lower energy (reduced cost)

- DCEN mode usually used.
Gas Metal Arc Welding - GMAW

- GMAW is fast, economical, flexible. No changing of electrode, no flux formed, multi-pass welding without intermediate cleaning.
- Readily automated.
- Requires less manipulative skill than GTAW and SMAW.
- High deposition rates (5 – 20 kg/hr)
- High efficiencies (80 - 90%)
- Power supplies relatively expensive.
- Advanced – GMAW - Wire is pre-heated as enters nozzle; less arc energy required, less base metal melted, less penetration.

Lecture 9
Submerged Arc Welding - SAW

- No shielding gas is used. Deposit thick layer of granular flux where joint is to be made just ahead of bare-wire consumable electrode. Arc maintained under surface of flux.

- Some flux melts, removes impurities from weld pool; unmelted gives thermal shielding; melted slag/flux forms glass on cooling.

- Flux provides thermal insulation - slow cooling, soft, ductile welds. Cold flux cracks off easily, unmelted flux recycled.
Submerged Arc Welding - SAW

- Best for flat, butt or fillet welds in < 0.3%C steels (with pre & post-heating - Med. C steels / alloy steels / CI / SS, copper, nickel alloys).
- Not for high-C steels, tool steels, Al, Mg, Ti, Pb, Zn.
- High currents - so speed, high deposition rates (27 – 45 kg/hr), clean.
- 1½” deep single pass (38 mm). Fewer passes required.
- Good for automation. Horizontal position only.
- Electrodes classified by composition
- Solid wire (wire is alloyed)
- Plain carbon steel wire (alloy additions in flux)
Submerged Arc Welding - SAW

- Tubular steel wire (alloy additions in centre)
- Larger electrodes carry more current – rapid deposition but shallow welds
- Flux need to have low MP and brittleness but high fluidity
- Limitation of submerged arc welding:
  - Flux handling and maintaining flux quality (moisture etc).
  - Large volumes of slag to be removed.
  - High heat inputs – large grain size structure.
  - Slow cooling rate (segregation, hot-cracking).
  - Horizontal position only; Mechanized only.