WELDING PROCESSES

1. Arc Welding
2. Resistance Welding
3. Oxyfuel Gas Welding
4. Other Fusion Welding Processes
5. Solid State Welding
6. Weld Quality
7. Weldability
8. Design Considerations in Welding

Syllabus

- **WELDING**
- Welding introduction and classification of welding, processes, welding terminology,
- general principles, welding positions, filler metals.
- Gas welding and gas cutting, principle, oxyacetylene welding equipment
- oxyhydrogen
- welding. Flame cutting.

- Electric are welding. Principle, equipment, types-MIG, TIG submerged arc and others.
- Welding electrodes, classification and selection of electrodes, welding arc and its
- characteristics, arc stability, arc blow. Thermal effects on weldment. Heat affected zone , grain size and its control.

- Resistance welding- principle and their types i.e. spot, seam, projection, upset and flash
- Thermit welding, electro slag welding, friction welding, plasma are welding electron, beam welding, atomic hydrogen hydrogen welding. Basic considerations in joint design,
- Welding defects, their cases and remedies.
- Brazing, braze welding and soldering.

Two Categories of Welding Processes

- Fusion welding - coalescence is accomplished by melting the two parts to be joined, in some cases adding filler metal to the joint
  - Examples: arc welding, resistance spot welding, oxyfuel gas welding
- Solid state welding - heat and/or pressure are used to achieve coalescence, but no melting of base metals occurs and no filler metal is added
  - Examples: forge welding, diffusion welding, friction welding

Arc Welding (AW)

A fusion welding process in which coalescence of the metals is achieved by the heat from an electric arc between an electrode and the work

- Electric energy from the arc produces temperatures ~ 10,000 F (5500 C), hot enough to melt any metal
- Most AW processes add filler metal to increase volume and strength of weld joint

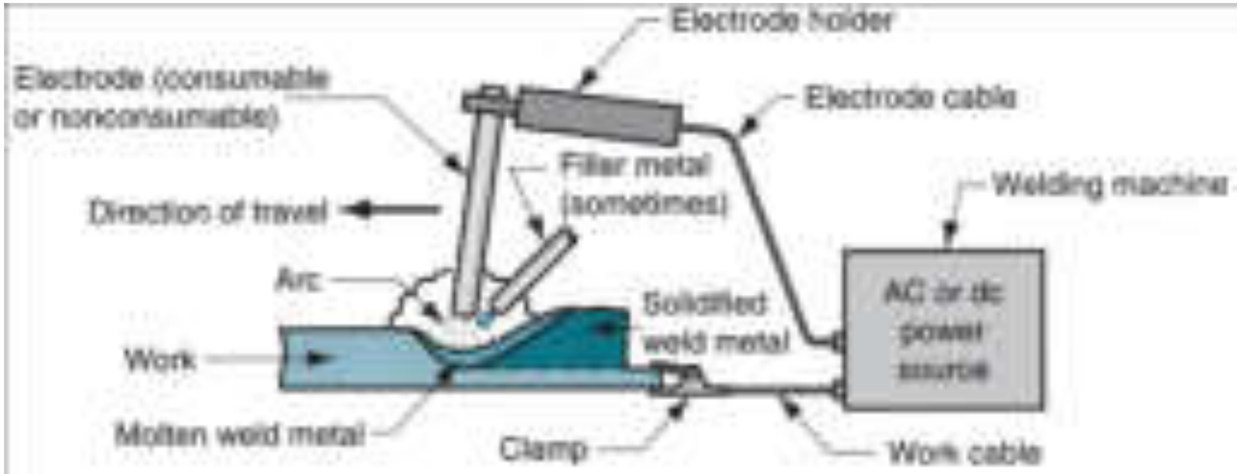
What is an Electric Arc?

An electric arc is a discharge of electric current across a gap in a circuit

- It is sustained by an ionized column of gas (*plasma*) through which the current flows
- To initiate the arc in AW, electrode is brought into contact with work and then quickly separated from it by a short distance

Arc Welding

- A pool of molten metal is formed near electrode tip, and as electrode is moved along joint, molten weld pool solidifies in its wake



Manual Arc Welding and Arc Time

- Problems with manual welding:
  - Weld joint quality
  - Productivity
- Arc Time = (time arc is on) divided by (hours worked)
  - Also called “arc-on time”
  - Manual welding arc time = 20%
  - Machine welding arc time ~ 50%

Two Basic Types of AW Electrodes

- Consumable – consumed during welding process
  - Source of filler metal in arc welding
- Nonconsumable – not consumed during welding process
  - Filler metal must be added separately if it is added

Consumable Electrodes

- Forms of consumable electrodes
  - Welding rods (a.k.a. sticks) are 9 to 18 inches and 3/8 inch or less in diameter and must be changed frequently
  - Weld wire can be continuously fed from spools with long lengths of wire, avoiding frequent interruptions
- In both rod and wire forms, electrode is consumed by the arc and added to weld joint as filler metal

Nonconsumable Electrodes

- Made of tungsten which resists melting
- Gradually depleted during welding (vaporization is principal mechanism)
- Any filler metal must be supplied by a separate wire fed into weld pool

Arc Shielding

- At high temperatures in AW, metals are chemically reactive to oxygen, nitrogen, and hydrogen in air
  - Mechanical properties of joint can be degraded by these reactions
  - To protect operation, arc must be shielded from surrounding air in AW processes
- Arc shielding is accomplished by:
  - Shielding gases, e.g., argon, helium, CO_2
  - Flux

Flux

A substance that prevents formation of oxides and other contaminants in welding, or dissolves them and facilitates removal

- Provides protective atmosphere for welding
- Stabilizes arc
- Reduces spattering

Various Flux Application Methods

- Pouring granular flux onto welding operation
- Stick electrode coated with flux material that melts during welding to cover operation
- Tubular electrodes in which flux is contained in the core and released as electrode is consumed

Power Source in Arc Welding

- Direct current (DC) vs. Alternating current (AC)
  - AC machines less expensive to purchase and operate, but generally restricted to ferrous metals
  - DC equipment can be used on all metals and is generally noted for better arc control

Consumable Electrode AW Processes

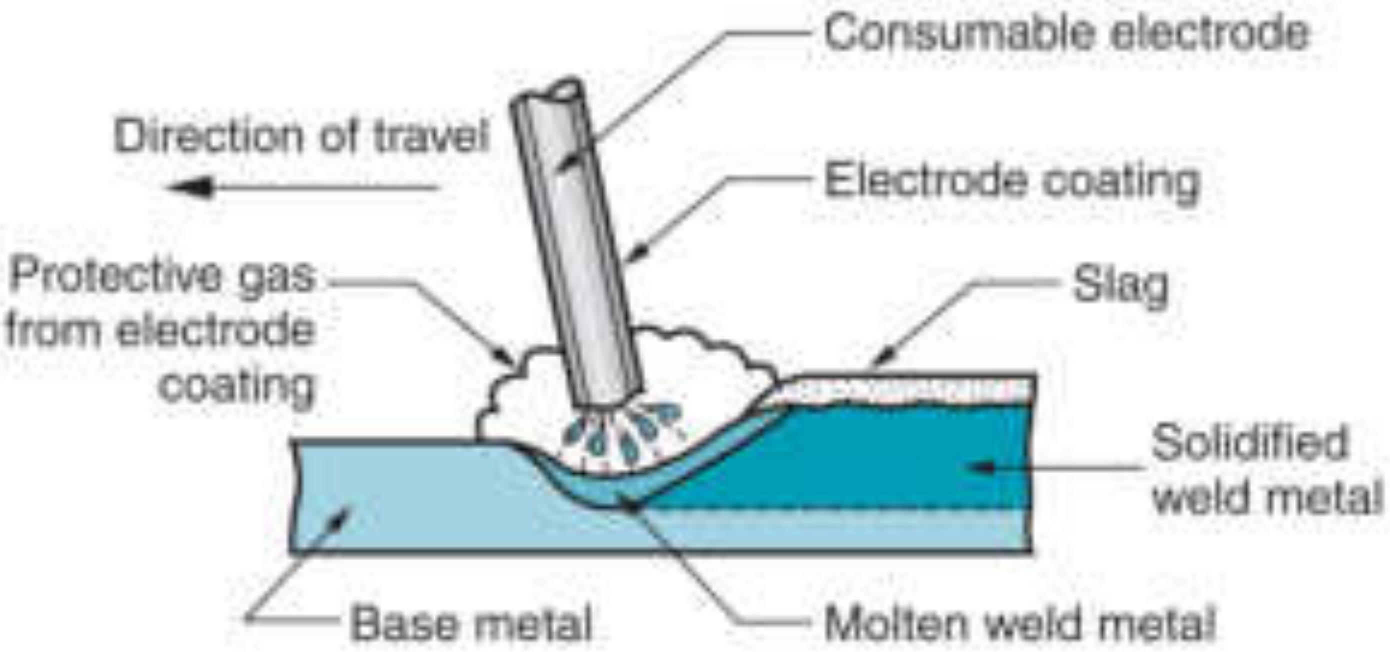
- Shielded Metal Arc Welding
- Gas Metal Arc Welding
- Flux-Cored Arc Welding
- Electrogas Welding
- Submerged Arc Welding

Shielded Metal Arc Welding (SMAW)

Uses a consumable electrode consisting of a filler metal rod coated with chemicals that provide flux and shielding

- Sometimes called "stick welding"
- Power supply, connecting cables, and electrode holder available for a few thousand dollars

Shielded Metal Arc Welding (SMAW)



Welding Stick in SMAW

- Composition of filler metal usually close to base metal
- Coating: powdered cellulose mixed with oxides and carbonates, and held together by a silicate binder
- Welding stick is clamped in electrode holder connected to power source
- Disadvantages of stick welding:
  - Sticks must be periodically changed
  - High current levels may melt coating prematurely

Shielded Metal Arc Welding

- Shielded metal arc welding (stick welding) performed by a human welder (photo courtesy of Hobart Brothers Co.)

SMAW Applications

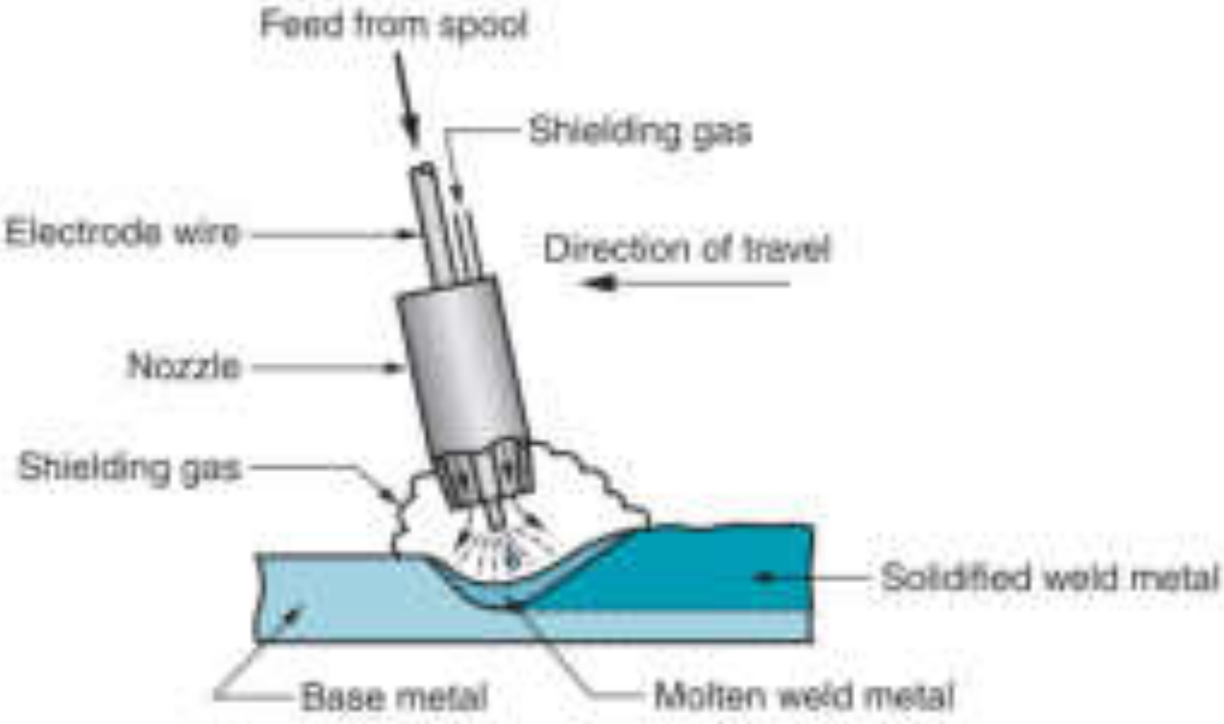
- Used for steels, stainless steels, cast irons, and certain nonferrous alloys
- Not used or rarely used for aluminum and its alloys, copper alloys, and titanium

Gas Metal Arc Welding (GMAW)

Uses a consumable bare metal wire as electrode with shielding by flooding arc with a gas

- Wire is fed continuously and automatically from a spool through the welding gun
- Shielding gases include argon and helium for aluminum welding, and CO_2 for steel welding
- Bare electrode wire plus shielding gases eliminate slag on weld bead
  - No need for manual grinding and cleaning of slag

Gas Metal Arc Welding



GMAW Advantages over SMAW

- Better arc time because of continuous wire electrode
  - Sticks must be periodically changed in SMAW
- Better use of electrode filler metal than SMAW
  - End of stick cannot be used in SMAW
- Higher deposition rates
- Eliminates problem of slag removal
- Can be readily automated

Flux-Cored Arc Welding (FCAW)

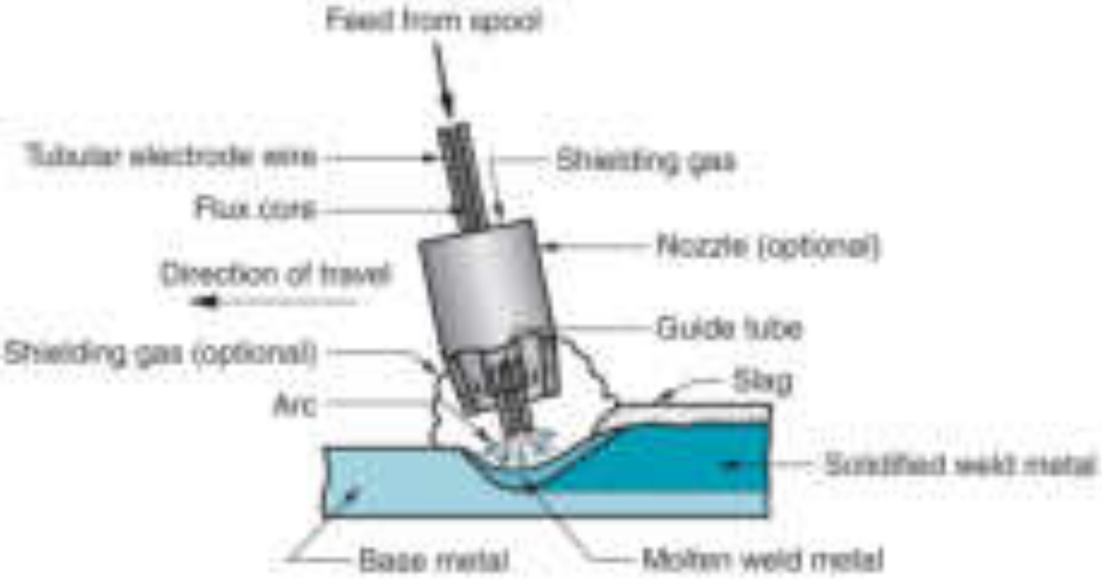
Adaptation of shielded metal arc welding, to overcome limitations of stick electrodes - two versions

  - Self-shielded FCAW - core includes compounds that produce shielding gases
  - Gas-shielded FCAW - uses externally applied shielding gases

- Electrode is a continuous consumable tubing (in coils) containing flux and other ingredients (e.g., alloying elements) in its core

Flux-Cored Arc Welding

Presence or absence of externally supplied shielding gas distinguishes: (1) self-shielded - core provides ingredients for shielding, (2) gas-shielded - uses external shielding gases



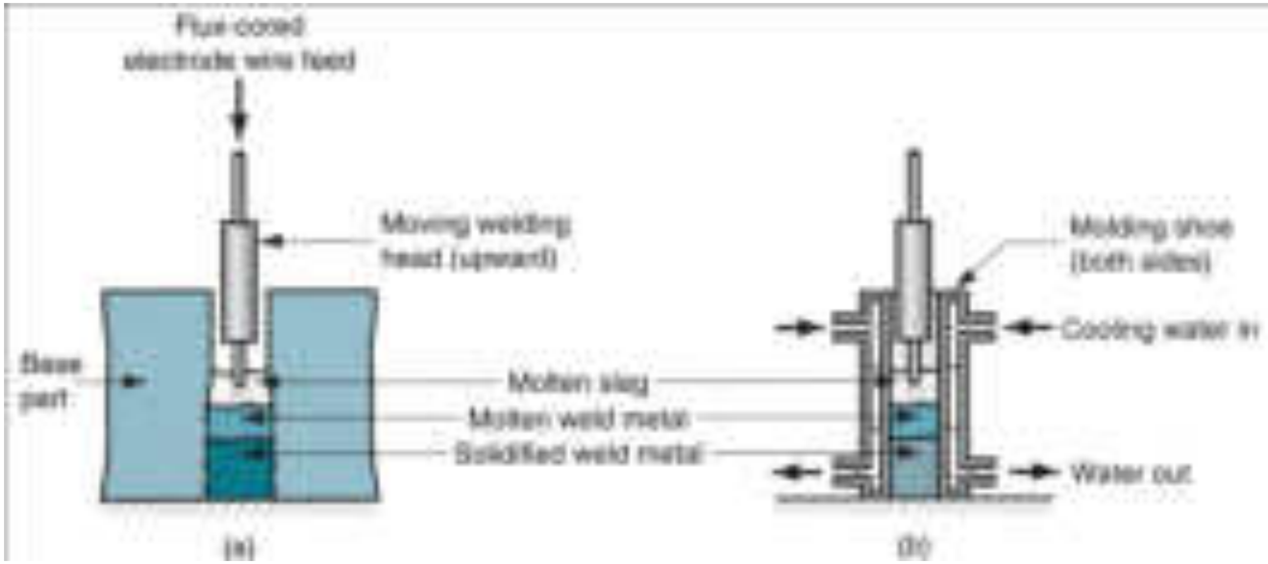
Electrogas Welding (EGW)

Uses a continuous consumable electrode, flux-cored wire or bare wire with externally supplied shielding gases, and molding shoes to contain molten metal

- When flux-cored electrode wire is used and no external gases are supplied, then special case of self-shielded FCAW
- When a bare electrode wire used with shielding gases from external source, then special case of GMAW

Electrogas Welding

- Electrogas welding using flux-cored electrode wire: (a) front view with molding shoe removed for clarity, and (b) side view showing molding shoes on both sides

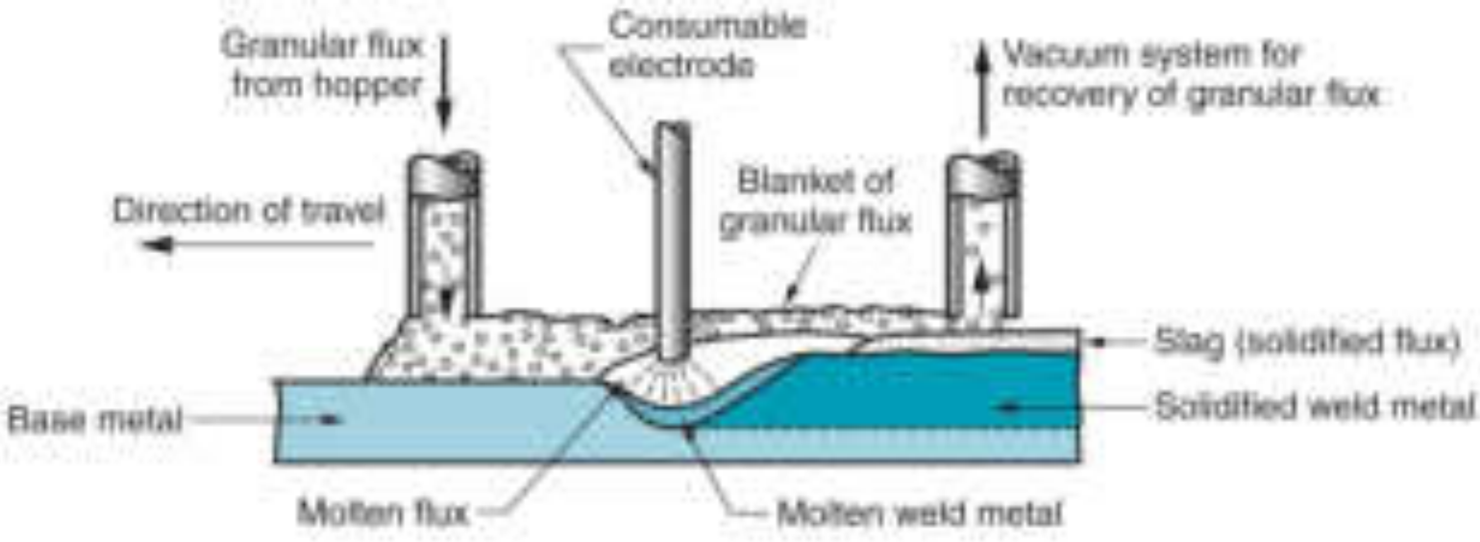


Submerged Arc Welding (SAW)

Uses a continuous, consumable bare wire electrode, with arc shielding by a cover of granular flux

- Electrode wire is fed automatically from a coil
- Flux introduced into joint slightly ahead of arc by gravity from a hopper
  - Completely submerges operation, preventing sparks, spatter, and radiation

Submerged Arc Welding



SAW Applications and Products

- Steel fabrication of structural shapes (e.g., I-beams)
- Seams for large diameter pipes, tanks, and pressure vessels
- Welded components for heavy machinery
- Most steels (except hi C steel)
- Not good for nonferrous metals

Nonconsumable Electrode Processes

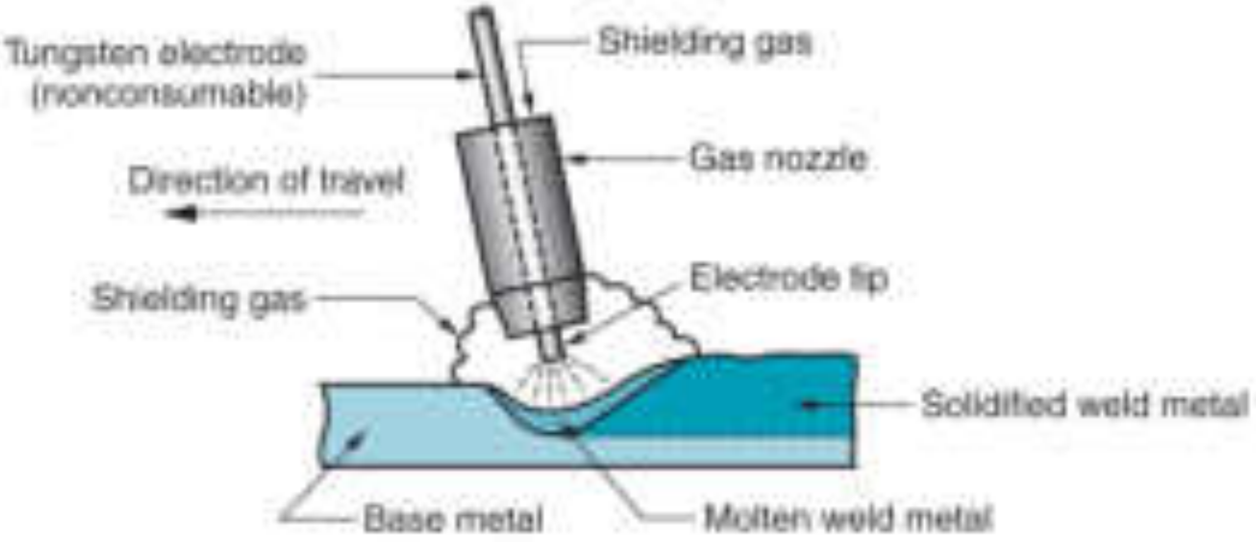
- Gas Tungsten Arc Welding
- Plasma Arc Welding
- Carbon Arc Welding
- Stud Welding

Gas Tungsten Arc Welding (GTAW)

Uses a nonconsumable tungsten electrode and an inert gas for arc shielding

- Melting point of tungsten = 3410°C (6170°F)
- A.k.a. Tungsten Inert Gas (TIG) welding
  - In Europe, called "WIG welding"
- Used with or without a filler metal
  - When filler metal used, it is added to weld pool from separate rod or wire
- Applications: aluminum and stainless steel mostly

Gas Tungsten Arc Welding



Advantages and Disadvantages of GTAW

Advantages:

- High quality welds for suitable applications
- No spatter because no filler metal through arc
- Little or no post-weld cleaning because no flux

Disadvantages:

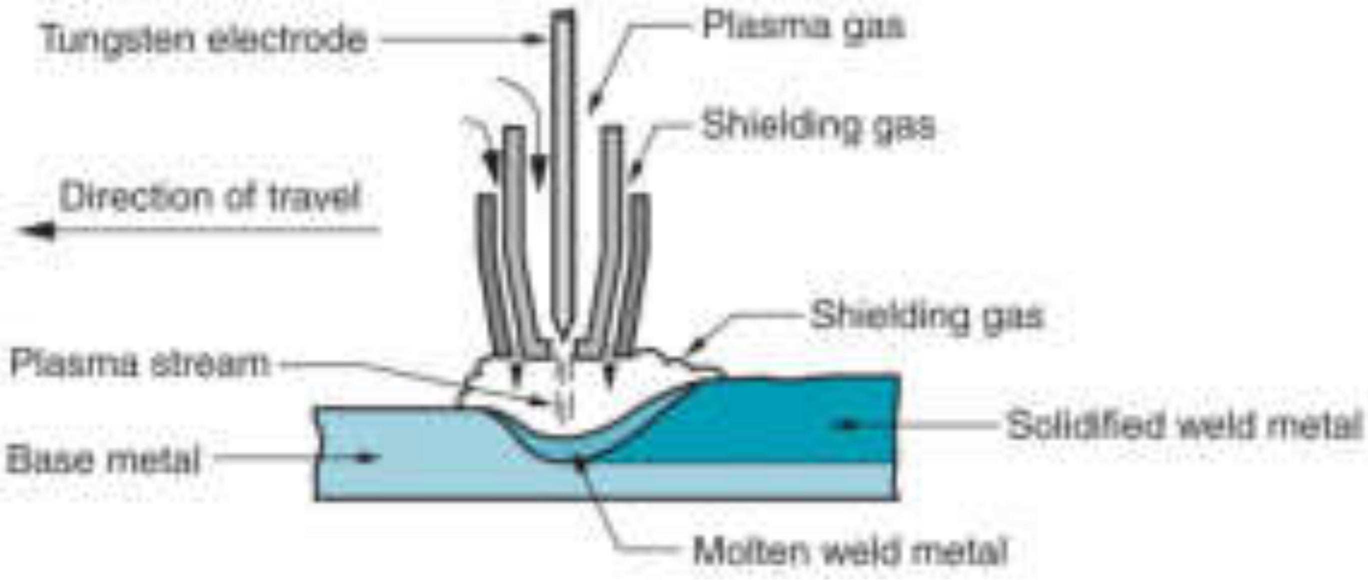
- Generally slower and more costly than consumable electrode AW processes

Plasma Arc Welding (PAW)

Special form of GTAW in which a constricted plasma arc is directed at weld area

- Tungsten electrode is contained in a nozzle that focuses a high velocity stream of inert gas (argon) into arc region to form a high velocity, intensely hot plasma arc stream
- Temperatures in PAW reach 28,000°C (50,000°F), due to constriction of arc, producing a plasma jet of small diameter and very high energy density

Plasma Arc Welding



Advantages and Disadvantages of PAW

Advantages:

- Good arc stability and excellent weld quality
- Better penetration control than other AW processes
- High travel speeds
- Can be used to weld almost any metals

Disadvantages:

- High equipment cost
- Larger torch size than other AW processes
  - Tends to restrict access in some joints

Resistance Welding (RW)

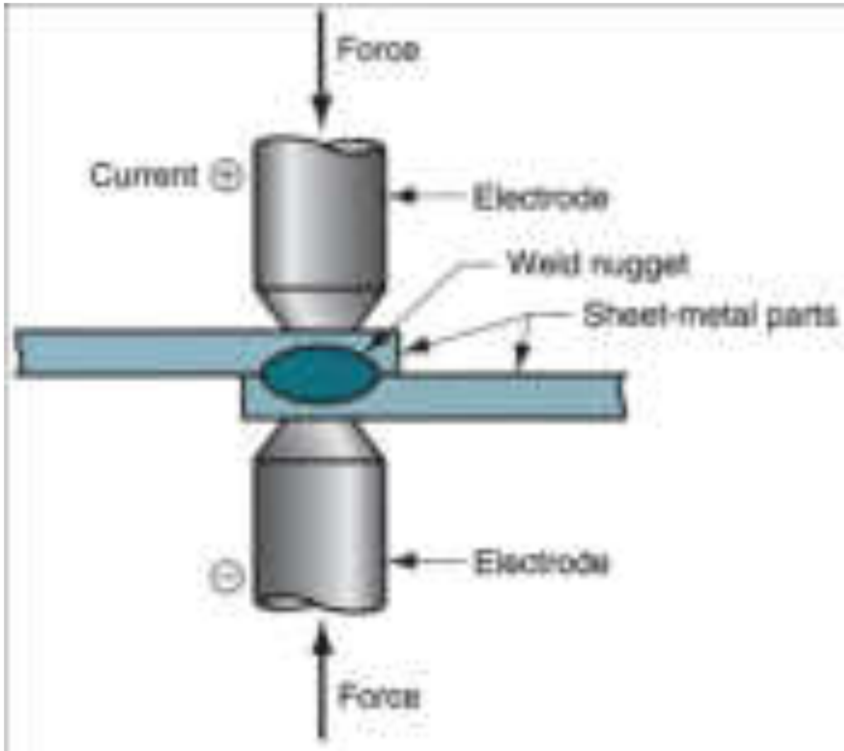
A group of fusion welding processes that use a combination of heat and pressure to accomplish coalescence

- Heat generated by electrical resistance to current flow at junction to be welded
- Principal RW process is resistance spot welding (RSW)

Figure 31.12.

Resistance Welding

- Resistance welding, showing components in spot welding, the main process in the RW group



Components in Resistance Spot Welding

- Parts to be welded (usually sheet metal)
- Two opposing electrodes
- Means of applying pressure to squeeze parts between electrodes
- Power supply from which a controlled current can be applied for a specified time duration

Advantages and Drawbacks of Resistance Welding

Advantages:

- No filler metal required
- High production rates possible
- Lends itself to mechanization and automation
- Lower operator skill level than for arc welding
- Good repeatability and reliability

Disadvantages:

- High initial equipment cost
- Limited to lap joints for most RW processes

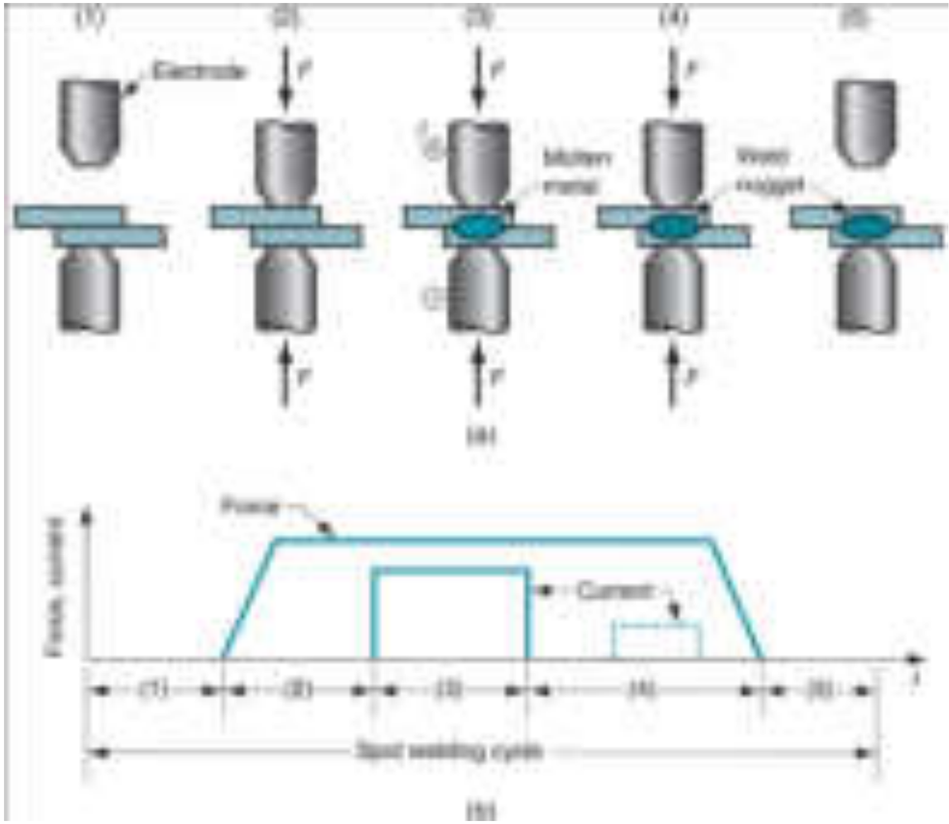
Resistance Spot Welding (RSW)

Resistance welding process in which fusion of faying surfaces of a lap joint is achieved at one location by opposing electrodes

- Used to join sheet metal parts
- Widely used in mass production of automobiles, metal furniture, appliances, and other sheet metal products
  - Typical car body has ~ 10,000 spot welds
  - Annual production of automobiles in the world is measured in tens of millions of units

Spot Welding Cycle

- (a) Spot welding cycle
- (b) Plot of force and current
- Cycle: (1) parts inserted between electrodes, (2) electrodes close, (3) current on, (4) current off, (5) electrodes opened

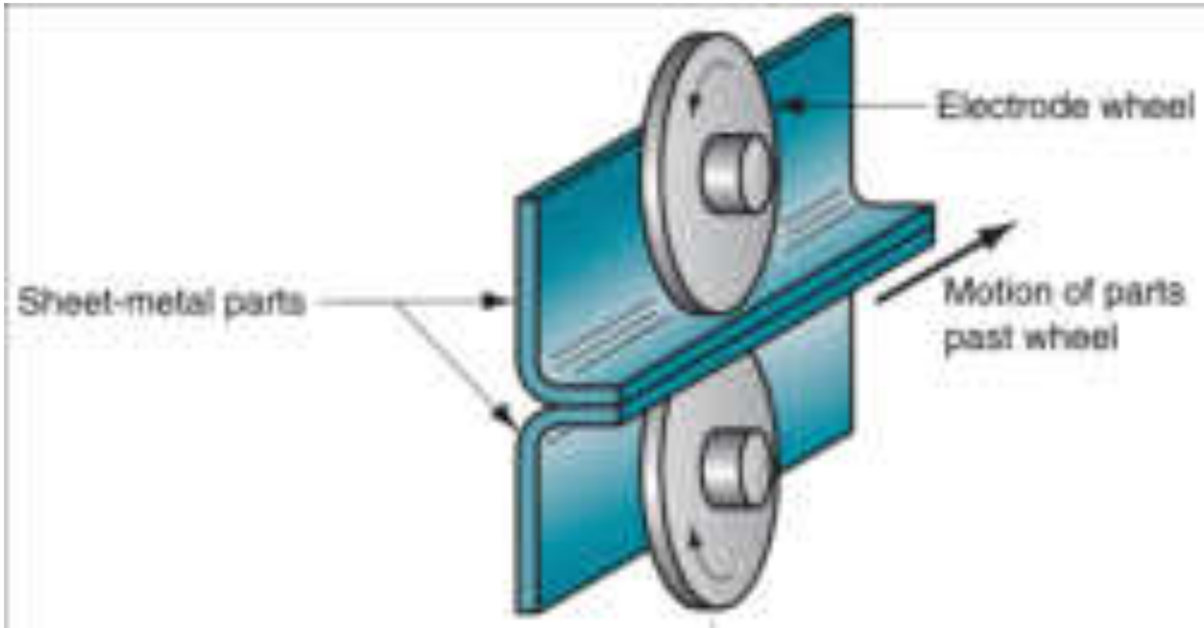


Resistance Seam Welding (RSEW)

Uses rotating wheel electrodes to produce a series of overlapping spot welds along lap joint

- Can produce air-tight joints
- Applications:
  - Gasoline tanks
  - Automobile mufflers
  - Various sheet metal containers

Resistance Seam Welding



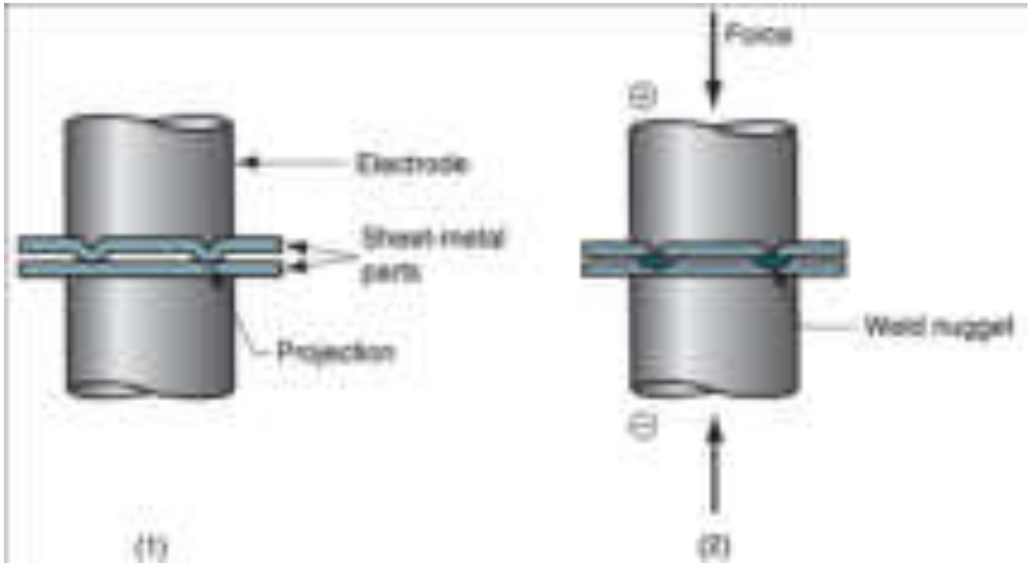
Resistance Projection Welding (RPW)

A resistance welding process in which coalescence occurs at one or more small contact points on the parts

- Contact points determined by design of parts to be joined
  - May consist of projections, embossments, or localized intersections of parts

Resistance Projection Welding

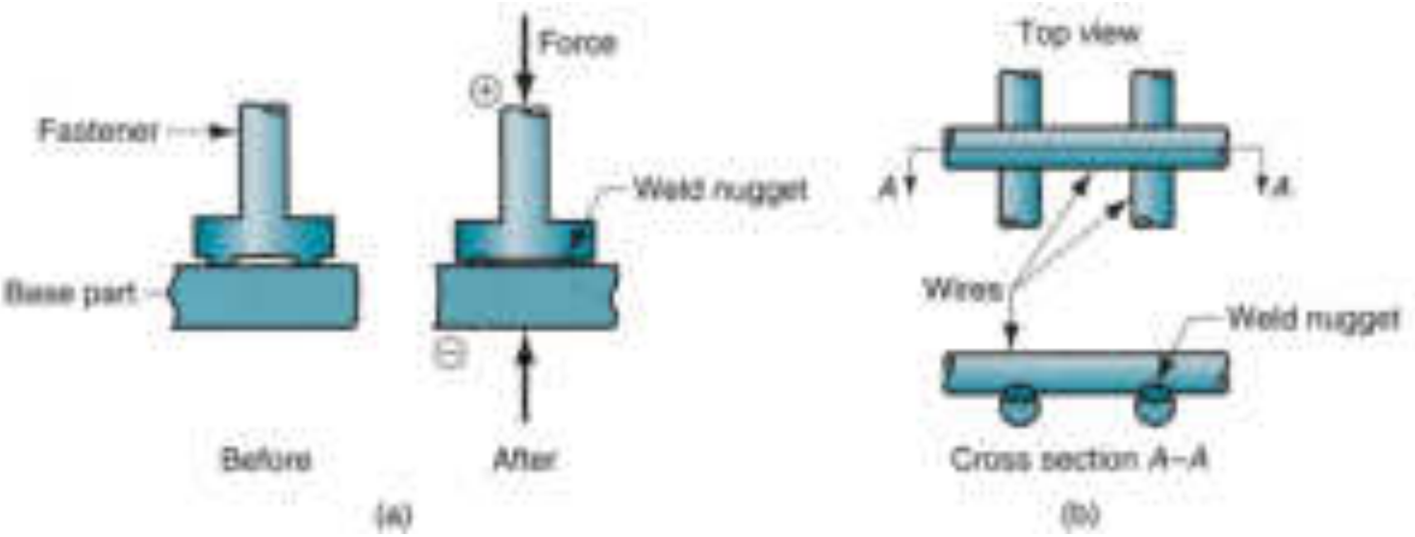
- (1) Start of operation, contact between parts is at projections; (2) when current is applied, weld nuggets similar to spot welding are formed at the projections



Cross-Wire Welding

Other Resistance Projection Welding Operations

- (a) Welding of fastener on sheetmetal and (b) cross-wire welding



Oxyfuel Gas Welding (OFW)

Group of fusion welding operations that burn various fuels mixed with oxygen

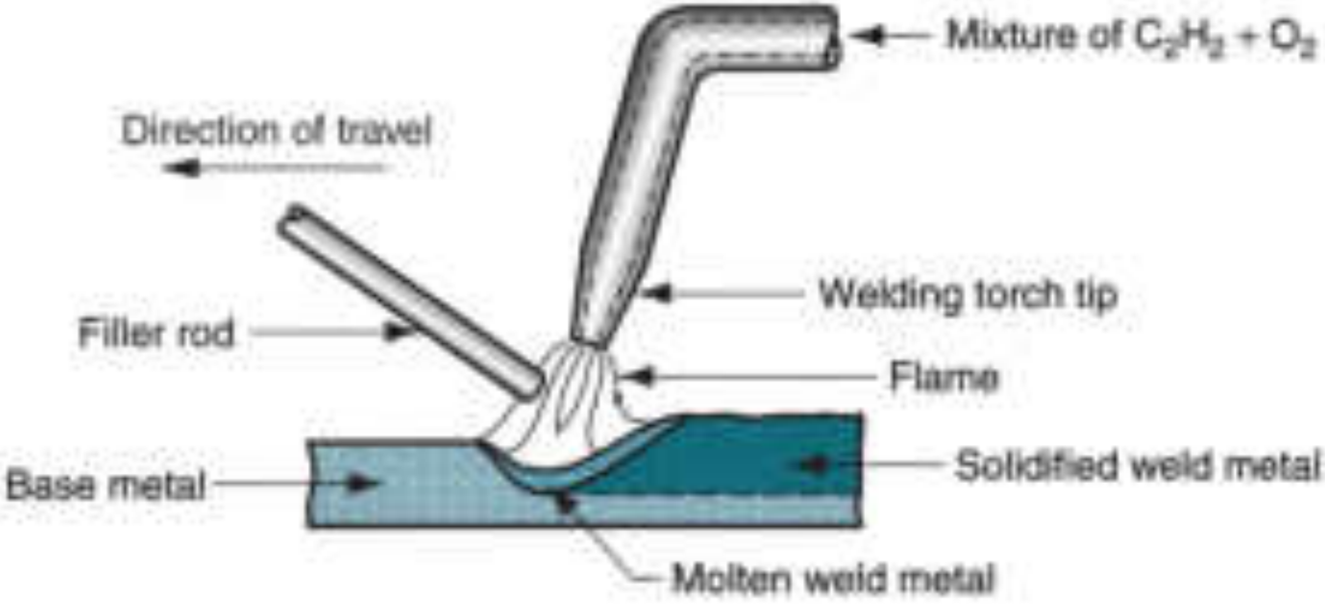
- OFW employs several types of gases, which is the primary distinction among the members of this group
- Oxyfuel gas is also used in flame cutting torches to cut and separate metal plates and other parts
- Most important OFW process is oxyacetylene welding

Oxyacetylene Welding (OAW)

Fusion welding performed by a high temperature flame from combustion of acetylene and oxygen

- Flame is directed by a welding torch
- Filler metal is sometimes added
    - Composition must be similar to base metal
    - Filler rod often coated with *flux* to clean surfaces and prevent oxidation

Oxyacetylene Welding



Acetylene (C_2H_2)

- Most popular fuel among OFW group because it is capable of higher temperatures than any other
  - Up to 3480°C (6300°F)
- Two stage reaction of acetylene and oxygen:
  - First stage reaction (inner cone of flame)

$$C_2H_2 + O_2 \rightarrow 2CO + H_2 + \text{heat}$$

  - Second stage reaction (outer envelope)

$$2CO + H_2 + 1.5O_2 \rightarrow 2CO_2 + H_2O + \text{heat}$$

Oxyacetylene Torch

- Maximum temperature reached at tip of inner cone, while outer envelope spreads out and shields work surface from atmosphere
- Shown below is neutral flame of oxyacetylene torch indicating temperatures achieved

Safety Issue in OAW

- Together, acetylene and oxygen are highly flammable
- C_2H_2 is colorless and odorless
    - It is therefore processed to have characteristic garlic odor

OAW Safety Issue

- C_2H_2 is physically unstable at pressures much above 15 lb/in^2 (about 1 atm)
    - Storage cylinders are packed with porous filler material saturated with acetone (CH_3COCH_3)
    - Acetone dissolves about 25 times its own volume of acetylene
- Different screw threads are standard on C_2H_2 and O_2 cylinders and hoses to avoid accidental connection of wrong gases

Alternative Gases for OFW

- Methylacetylene-Propadiene (MAPP)
- Hydrogen
- Propylene
- Propane
- Natural Gas

Other Fusion Welding Processes

FW processes that cannot be classified as arc, resistance, or oxyfuel welding

- Use unique technologies to develop heat for melting
- Applications are typically unique
- Processes include:
  - Electron beam welding
  - Laser beam welding
  - Electroslag welding
  - Thermit welding

Electron Beam Welding (EBW)

Fusion welding process in which heat for welding is provided by a highly-focused, high-intensity stream of electrons striking work surface

- Electron beam gun operates at:
  - High voltage (e.g., 10 to 150 kV typical) to accelerate electrons
  - Beam currents are low (measured in milliamps)
- Power in EBW not exceptional, but power density is

EBW Vacuum Chamber

- When first developed, EBW had to be carried out in a vacuum chamber to minimize disruption of electron beam by air molecules
  - Serious inconvenience in production
    - Pumpdown time can take as long as an hour

Three Vacuum Levels in EBW

1. High-vacuum welding – welding in same vacuum chamber as beam generation to produce highest quality weld
2. Medium-vacuum welding – welding in separate chamber but partial vacuum reduces pump-down time
3. Non-vacuum welding – welding done at or near atmospheric pressure, with work positioned close to electron beam generator - requires vacuum divider to separate work from beam generator

EBW Advantages and Disadvantages of EBW

Advantages:

- High-quality welds, deep and narrow profiles
- Limited heat affected zone, low thermal distortion
- No flux or shielding gases needed

Disadvantages:

- High equipment cost
- Precise joint preparation & alignment required
- Vacuum chamber required
- Safety concern: EBW generates x-rays

Laser Beam Welding (LBW)

Fusion welding process in which coalescence is achieved by energy of a highly concentrated, coherent light beam focused on joint

- LBW normally performed with shielding gases to prevent oxidation
- Filler metal not usually added
- High power density in small area
  - So LBW often used for small parts

Comparison: LBW vs. EBW

- No vacuum chamber required for LBW
- No x-rays emitted in LBW
- Laser beams can be focused and directed by optical lenses and mirrors
- LBW not capable of the deep welds and high depth-to-width ratios of EBW
  - Maximum LBW depth = ~ 19 mm (3/4 in), whereas EBW depths = 50 mm (2 in)

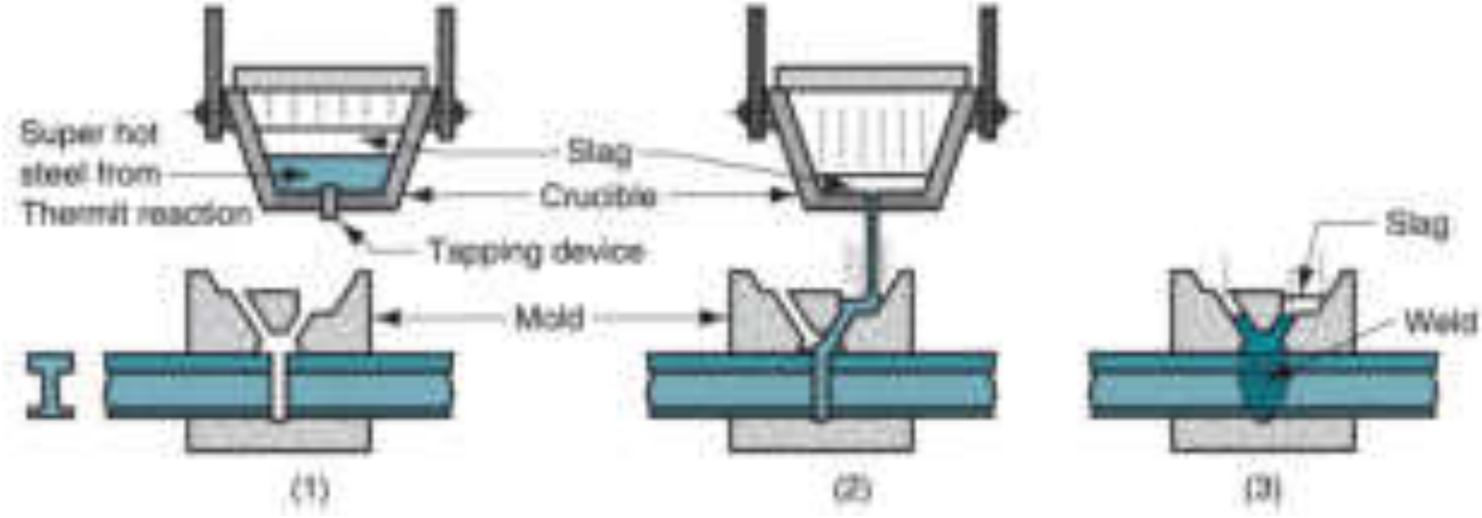
Thermit Welding (TW)

FW process in which heat for coalescence is produced by superheated molten metal from the chemical reaction of thermite

- *Thermite* = mixture of Al and Fe_3O_4 fine powders that produce an exothermic reaction when ignited
- Also used for incendiary bombs
- Filler metal obtained from liquid metal
- Process used for joining, but has more in common with casting than welding

Thermit Welding

- (1) Thermit ignited; (2) crucible tapped, superheated metal flows into mold; (3) metal solidifies to produce weld joint



TW Applications

- Joining of railroad rails
- Repair of cracks in large steel castings and forgings
- Weld surface is often smooth enough that no finishing is required

Solid State Welding (SSW)

- Coalescence of part surfaces is achieved by:
  - Pressure alone, or
  - Heat and pressure
    - If both heat and pressure are used, heat is not enough to melt work surfaces
  - For some SSW processes, time is also a factor
- No filler metal is added
- Each SSW process has its own way of creating a bond at the faying surfaces

Success Factors in SSW

- Essential factors for a successful solid state weld are that the two faying surfaces must be:
  - Very clean
  - In very close physical contact with each other to permit atomic bonding

SSW Advantages over FW Processes

- If no melting, then no heat affected zone, so metal around joint retains original properties
- Many SSW processes produce welded joints that bond the entire contact interface between two parts rather than at distinct spots or seams
- Some SSW processes can be used to bond dissimilar metals, without concerns about relative melting points, thermal expansions, and other problems that arise in FW

Solid State Welding Processes

- Forge welding
- Cold welding
- Roll welding
- Hot pressure welding
- Diffusion welding
- Explosion welding
- Friction welding
- Ultrasonic welding

Forge Welding

Welding process in which components to be joined are heated to hot working temperature range and then forged together by hammering or similar means

- Historic significance in development of manufacturing technology
  - Process dates from about 1000 B.C., when blacksmiths learned to weld two pieces of metal
- Of minor commercial importance today except for its variants

Cold Welding (CW)

SSW process done by applying high pressure between clean contacting surfaces at room temperature

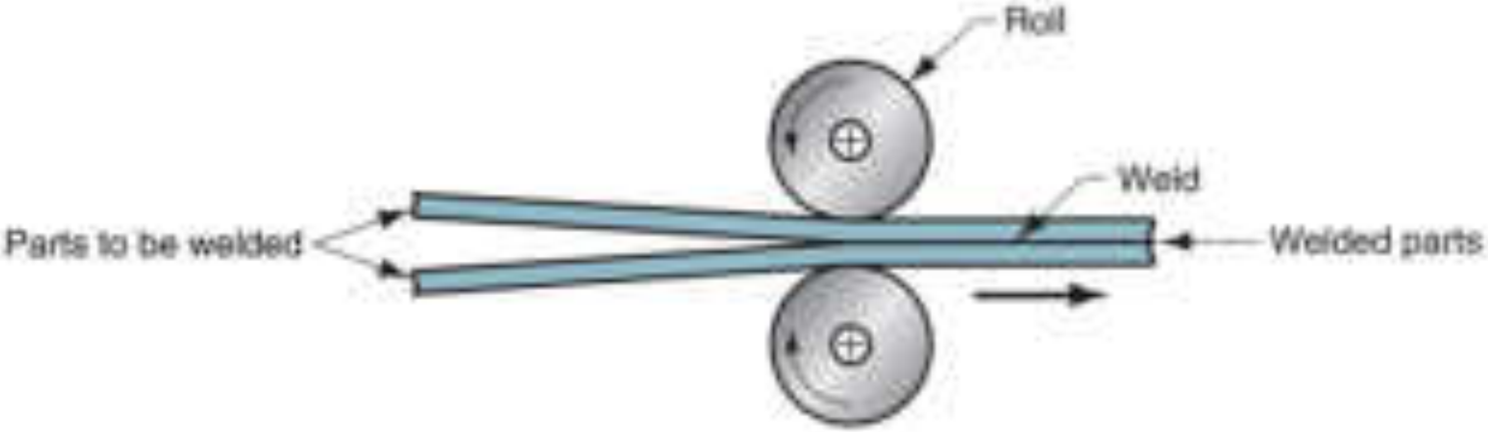
- Cleaning usually done by degreasing and wire brushing immediately before joining
- No heat is applied, but deformation raises work temperature
- At least one of the metals, preferably both, must be very ductile
  - Soft aluminum and copper suited to CW
- Applications: making electrical connections

Roll Welding (ROW)

SSW process in which pressure sufficient to cause coalescence is applied by means of rolls, either with or without external heat

- Variation of either forge welding or cold welding, depending on whether heating of workparts is done prior to process
  - If no external heat, called *cold roll welding*
  - If heat is supplied, *hot roll welding*

Roll Welding



Roll Welding Applications

- Cladding stainless steel to mild or low alloy steel for corrosion resistance
- Bimetallic strips for measuring temperature
- "Sandwich" coins for U.S mint

Diffusion Welding (DFW)

SSW process uses heat and pressure, usually in a controlled atmosphere, with sufficient time for diffusion and coalescence to occur

- Temperatures $\leq 0.5\ T_m$
- Plastic deformation at surfaces is minimal
- Primary coalescence mechanism is solid state diffusion
- Limitation: time required for diffusion can range from seconds to hours

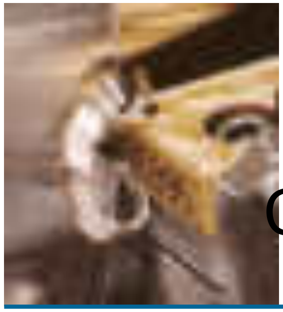
DFW Applications

- Joining of high-strength and refractory metals in aerospace and nuclear industries
- Can be used to join either similar and dissimilar metals
  - For joining dissimilar metals, a filler layer of different metal is often sandwiched between base metals to promote diffusion

Explosion Welding (EXW)

SSW process in which rapid coalescence of two metallic surfaces is caused by the energy of a detonated explosive

- No filler metal used
- No external heat applied
- No diffusion occurs - time is too short
- Bonding is metallurgical, combined with mechanical interlocking that results from a rippled or wavy interface between the metals

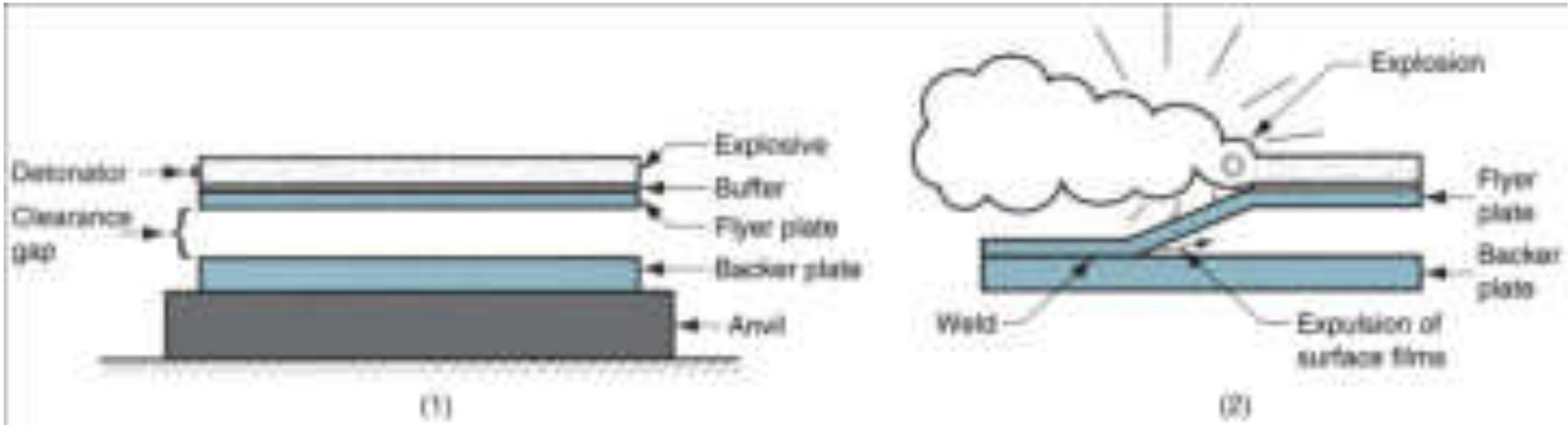


Explosive Welding

Commonly used to bond two dissimilar metals, in particular to clad one metal on top of a base metal over large areas

Explosive Welding

- Commonly used to bond two dissimilar metals, e.g., to clad one metal on top of a base metal over large areas
- (1) Setup in parallel configuration, and (2) during detonation of the explosive charge



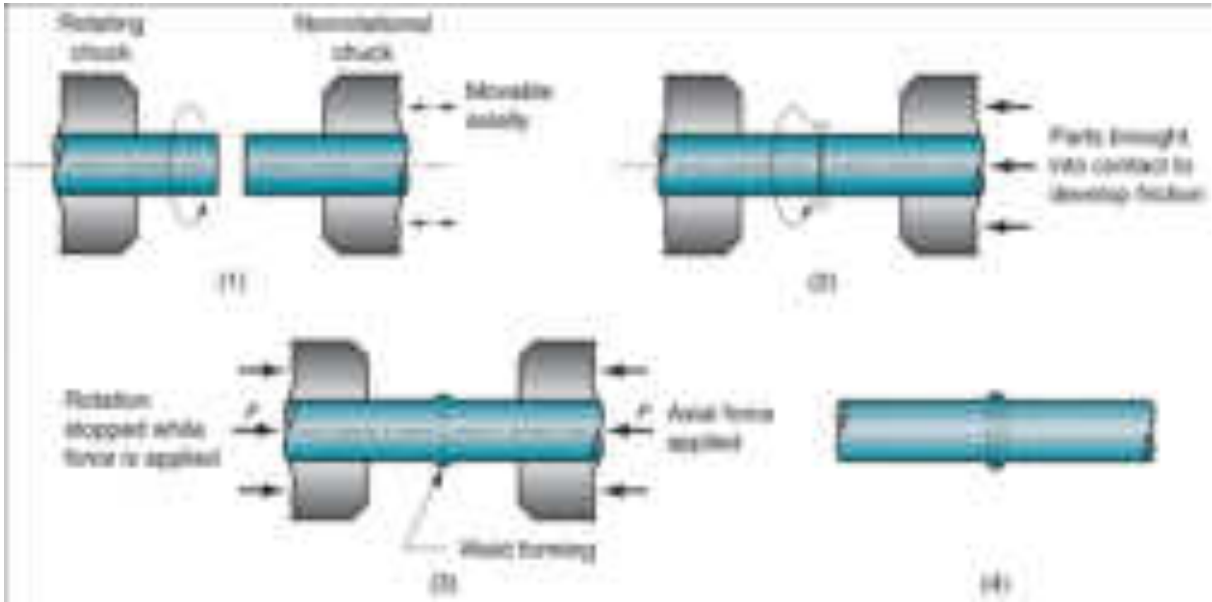
Friction Welding (FRW)

SSW process in which coalescence is achieved by frictional heat combined with pressure

- When properly carried out, no melting occurs at faying surfaces
- No filler metal, flux, or shielding gases normally used
- Process yields a narrow HAZ
- Can be used to join dissimilar metals
- Widely used commercial process, amenable to automation and mass production

Friction Welding

- (1) Rotating part, no contact; (2) parts brought into contact to generate friction heat; (3) rotation stopped and axial pressure applied; and (4) weld created



Applications and Limitations of Friction Welding

Applications:

- Shafts and tubular parts
- Industries: automotive, aircraft, farm equipment, petroleum and natural gas

Limitations:

- At least one of the parts must be rotational
- Flash must usually be removed (extra operation)
- Upsetting reduces the part lengths (which must be taken into consideration in product design)

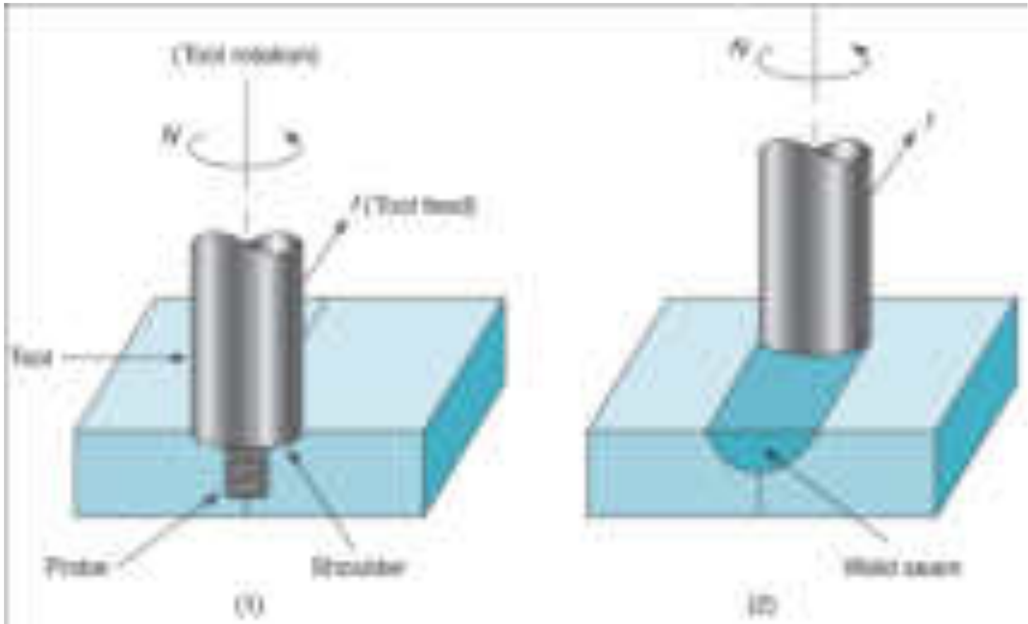
Friction Stir Welding (FSW)

SSW process in which a rotating tool is fed along a joint line between two workpieces, generating friction heat and mechanically stirring the metal to form the weld seam

- Distinguished from FRW because heat is generated by a separate wear-resistant tool rather than the parts
- Applications: butt joints in large aluminum parts in aerospace, automotive, and shipbuilding

Friction Stir Welding

- (1) Rotating tool just before entering work, and (2) partially completed weld seam



Advantages and Disadvantages of Friction Stir Welding

- Advantages
  - Good mechanical properties of weld joint
  - Avoids toxic fumes, warping, and shielding issues
  - Little distortion or shrinkage
  - Good weld appearance
- Disadvantages
  - An exit hole is produce when tool is withdrawn
  - Heavy duty clamping of parts is required

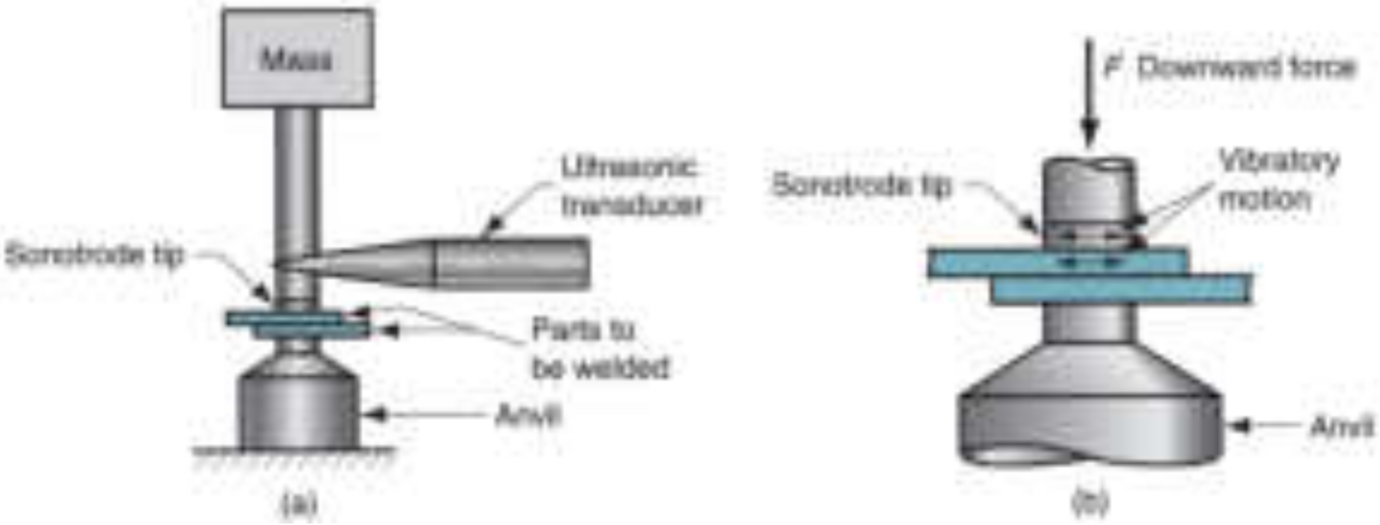
Ultrasonic Welding (USW)

Two components are held together, and oscillatory shear stresses of ultrasonic frequency are applied to interface to cause coalescence

- Oscillatory motion breaks down any surface films to allow intimate contact and strong metallurgical bonding between surfaces
- Temperatures are well below T_m
- No filler metals, fluxes, or shielding gases
- Generally limited to lap joints on soft materials

Ultrasonic Welding

- (a) General setup for a lap joint; and (b) close-up of weld area



USW Applications

- Wire terminations and splicing in electrical and electronics industry
  - Eliminates need for soldering
- Assembly of aluminum sheet metal panels
- Welding of tubes to sheets in solar panels
- Assembly of small parts in automotive industry

Weld Quality

Concerned with obtaining an acceptable weld joint that is strong and absent of defects

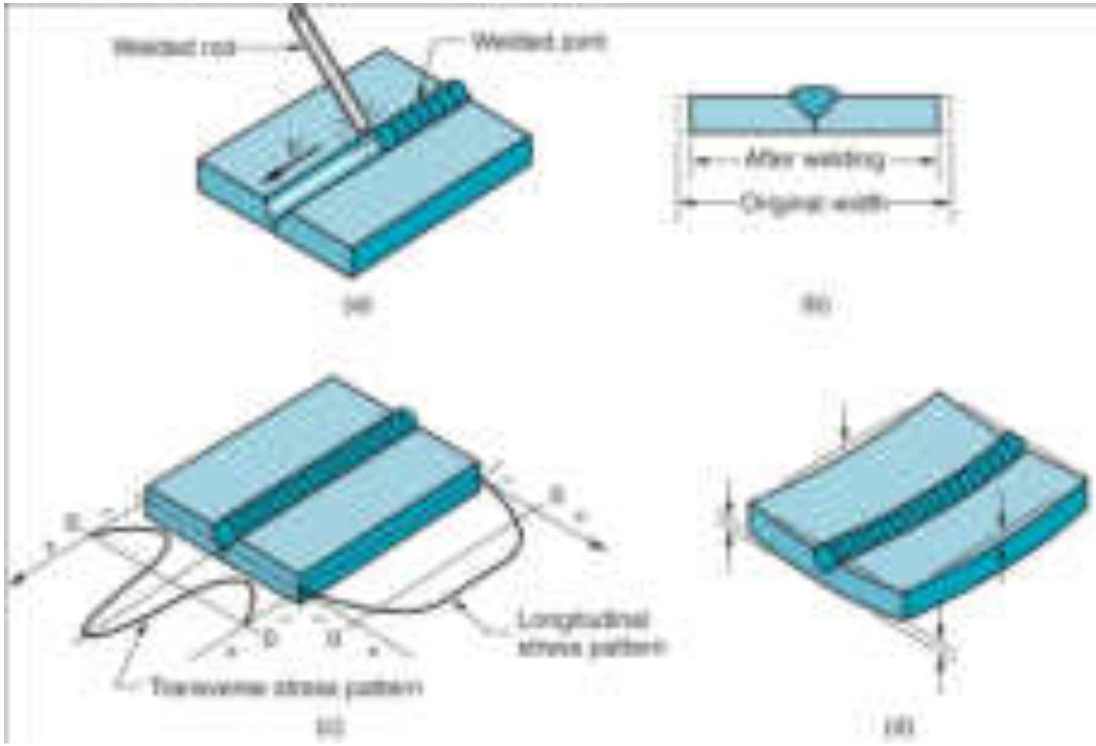
- Also concerned with the methods of inspecting and testing the joint to assure its quality
- Topics:
  - Residual stresses and distortion
  - Welding defects
  - Inspection and testing methods

Residual Stresses and Distortion

- Rapid heating and cooling in localized regions during FW result in thermal expansion and contraction that cause residual stresses
- These stresses, in turn, cause distortion and warpage
- Situation in welding is complicated because:
  - Heating is very localized
  - Melting of base metals in these regions
  - Location of heating and melting is in motion (at least in AW)

Residual Stresses and Distortion

- (a) Butt welding two plates
- (b) Shrinkage
- (c) Residual stress patterns
- (d) Likely warping of weldment



Techniques to Minimize Warpage

- Welding fixtures to physically restrain parts
- Heat sinks to rapidly remove heat
- Tack welding at multiple points along joint to create a rigid structure prior to seam welding
- Selection of welding conditions (speed, amount of filler metal used, etc.) to reduce warpage
- Preheating base parts
- Stress relief heat treatment of welded assembly
- Proper design of weldment

Welding Defects

- Cracks
- Cavities
- Solid inclusions
- Imperfect shape or unacceptable contour
- Incomplete fusion
- Miscellaneous defects

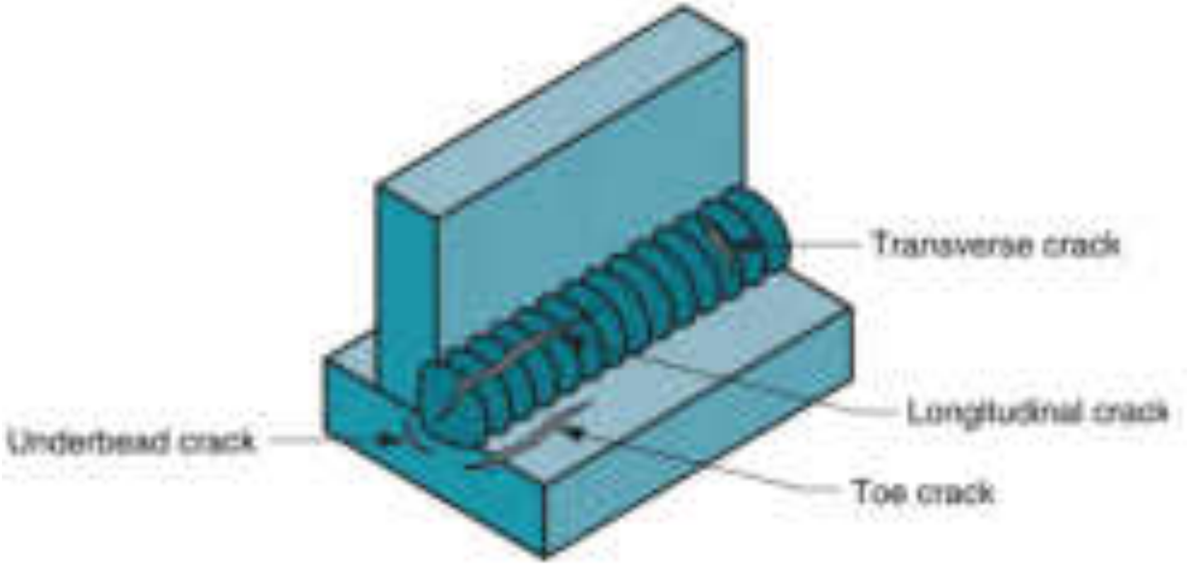
Welding Cracks

Fracture-type interruptions either in weld or in base metal adjacent to weld

- Serious defect because it is a discontinuity in the metal that significantly reduces strength
- Caused by embrittlement or low ductility of weld and/or base metal combined with high restraint during contraction
- In general, this defect must be repaired

Welding Cracks

- Various forms of welding cracks



Cavities

Two defect types, similar to defects found in castings:

1. Porosity - small voids in weld metal formed by gases entrapped during solidification
   - Caused by inclusion of atmospheric gases, sulfur in weld metal, or surface contaminants
2. Shrinkage voids - cavities formed by shrinkage during solidification

Solid Inclusions

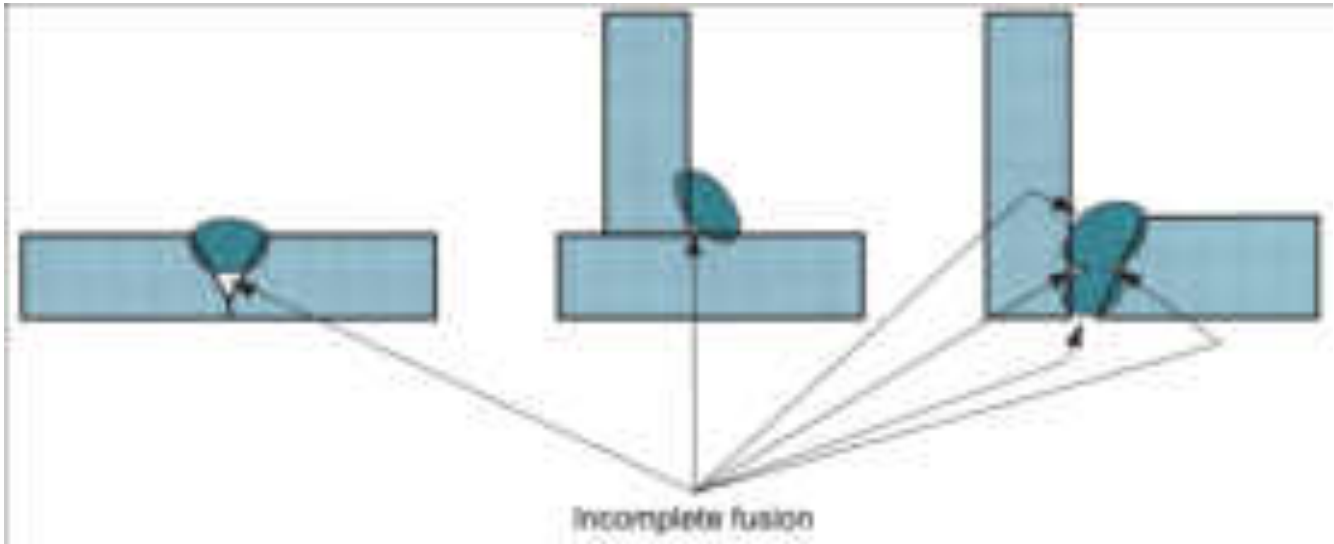
Nonmetallic material entrapped in weld metal

- Most common form is slag inclusions generated during AW processes that use flux
  - Instead of floating to top of weld pool, globules of slag become encased during solidification
- Other forms: metallic oxides that form during welding of certain metals such as aluminum, which normally has a surface coating of Al_2O_3

Incomplete Fusion

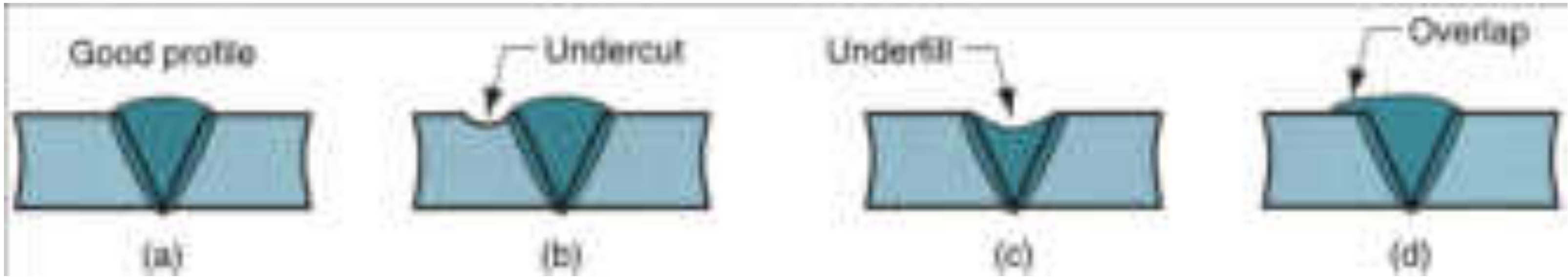
A weld bead in which fusion has not occurred throughout entire cross section of joint

- Several forms of incomplete fusion are shown below



Weld Profile in AW

- (a) Desired profile for single V-groove weld joint, (b) undercut - portion of base metal melted away, (c) underfill - depression in weld below adjacent base metal surface, and (d) overlap - weld metal spills beyond joint onto part surface but no fusion occurs



Inspection and Testing Methods

- Visual inspection
- Nondestructive evaluation
- Destructive testing

Visual Inspection

- Most widely used welding inspection method
- Human inspector visually examines for:
  - Conformance to dimensions, wWarpage
  - Cracks, cavities, incomplete fusion, and other surface defects
- Limitations:
  - Only surface defects are detectable
  - Welding inspector must also decide if additional tests are warranted

Nondestructive Evaluation (NDE) Tests

- Ultrasonic testing - high frequency sound waves through specimen to detect cracks and inclusions
- Radiographic testing - x-rays or gamma radiation provide photograph of internal flaws
- Dye-penetrant and fluorescent-penetrant tests - to detect small cracks and cavities at part surface
- Magnetic particle testing – iron filings sprinkled on surface reveal subsurface defects by distorting magnetic field in part

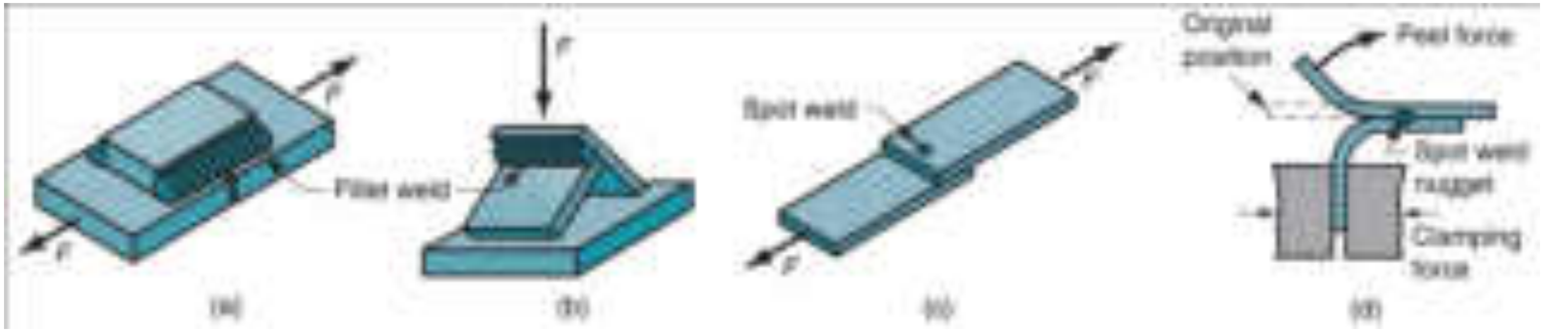
Destructive Testing

Tests in which weld is destroyed either during testing or to prepare test specimen

- Mechanical tests - purpose is similar to conventional testing methods such as tensile tests, shear tests, etc
- Metallurgical tests - preparation of metallurgical specimens (e.g., photomicrographs) of weldment to examine metallic structure, defects, extent and condition of heat affected zone, and similar phenomena

Mechanical Tests in Welding

- (a) Tension-shear test, (b) fillet break test, (c) tension-shear of spot weld, and (d) peel test for spot weld



Weldability

Capacity of a metal or combination of metals to be welded into a suitable structure, and for the resulting weld joint(s) to possess the required metallurgical properties to perform satisfactorily in intended service

- Good weldability characterized by:
  - Ease with which welding is accomplished
  - Absence of weld defects
  - Strength, ductility, and toughness in welded joint

Weldability Factors – Welding Process

- Some metals or metal combinations can be readily welded by one process but are difficult to weld by others
    - Example: stainless steel readily welded by most AW and RW processes, but difficult to weld by OFW

Weldability Factors – Base Metal

- Some metals melt too easily; e.g., aluminum
- Metals with high thermal conductivity transfer heat away from weld, which causes problems; e.g., copper
- High thermal expansion and contraction in metal causes distortion problems
- Dissimilar metals pose problems in welding when their physical and/or mechanical properties are substantially different

Other Factors Affecting Weldability

- Filler metal
  - Must be compatible with base metal(s)
  - In general, elements mixed in liquid state that form a solid solution upon solidification do not cause a problem
- Surface conditions
  - Moisture can result in porosity in fusion zone
  - Oxides and other films on metal surfaces can prevent adequate contact and fusion

Design Considerations in Welding

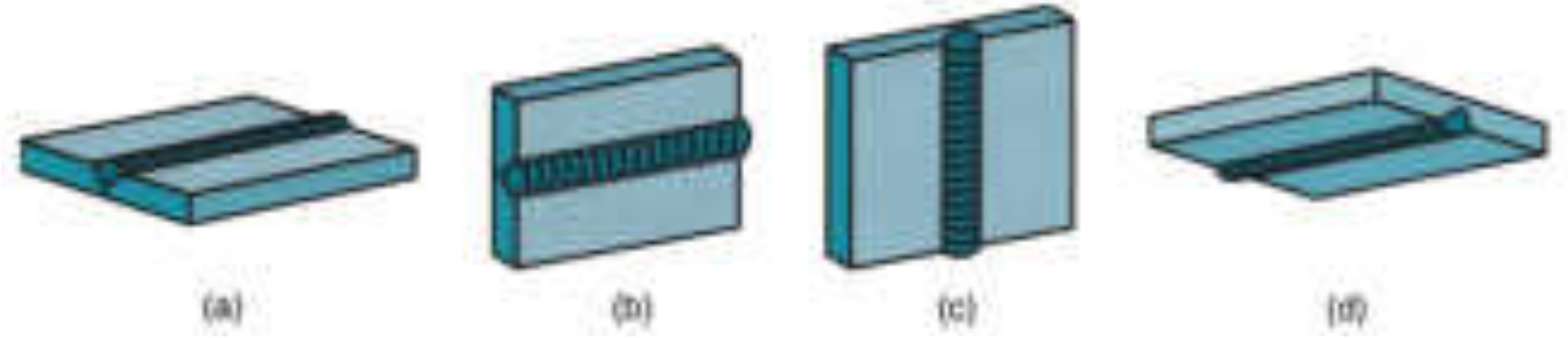
- Design for welding - product should be designed from the start as a welded assembly
    - Not as a casting or forging or other formed shape
- Minimum parts - welded assemblies should consist of fewest number of parts possible
    - Example: usually more cost efficient to perform simple bending operations on a part than to weld an assembly from flat plates and sheets

Arc Welding Design Guidelines

- Good fit-up of parts - to maintain dimensional control and minimize distortion
  - Machining is sometimes required to achieve satisfactory fit-up
- Assembly must allow access for welding gun to reach welding area
- Design of assembly should allow flat welding to be performed as much as possible, since this is the fastest and most convenient welding position

Arc Welding Positions

- Welding positions defined here for groove welds: (a) flat, (b) horizontal, (c) vertical, and (d) overhead



Design Guidelines - RSW

- Low-carbon sheet steel up to 0.125 (3.2 mm) is ideal metal for RSW
- How additional strength and stiffness can be obtained in large flat sheet metal components
  - Spot welding reinforcing parts into them
  - Forming flanges and embossments
- Spot welded assembly must provide access for electrodes to reach welding area
- Sufficient overlap of sheet metal parts required for electrode tip to make proper contact

Welding Technology

JOINING

- Soldering
  - Produces coalescence of materials by heating to soldering temperature (***below solidus of base metal***) in presence of filler metal with liquidus < 450°C
- Brazing
  - Same as soldering ***but*** coalescence occurs at > 450°C
- Welding
  - Process of achieving complete coalescence of two or more materials through melting & re-solidification of the base metals and filler metal

Soldering & Brazing

- Advantages
  - Low temperature heat source required
  - Choice of permanent or temporary joint
  - Dissimilar materials can be joined
  - Less chance of damaging parts
  - Slow rate of heating & cooling
  - Parts of varying thickness can be joined
  - Easy realignment
- Strength and performance of structural joints need careful evaluation

Welding

- Advantages
  - Most efficient way to join metals
  - Lowest-cost joining method
  - Affords lighter weight through better utilization of materials
  - Joins all commercial metals
  - Provides design flexibility

Weldability

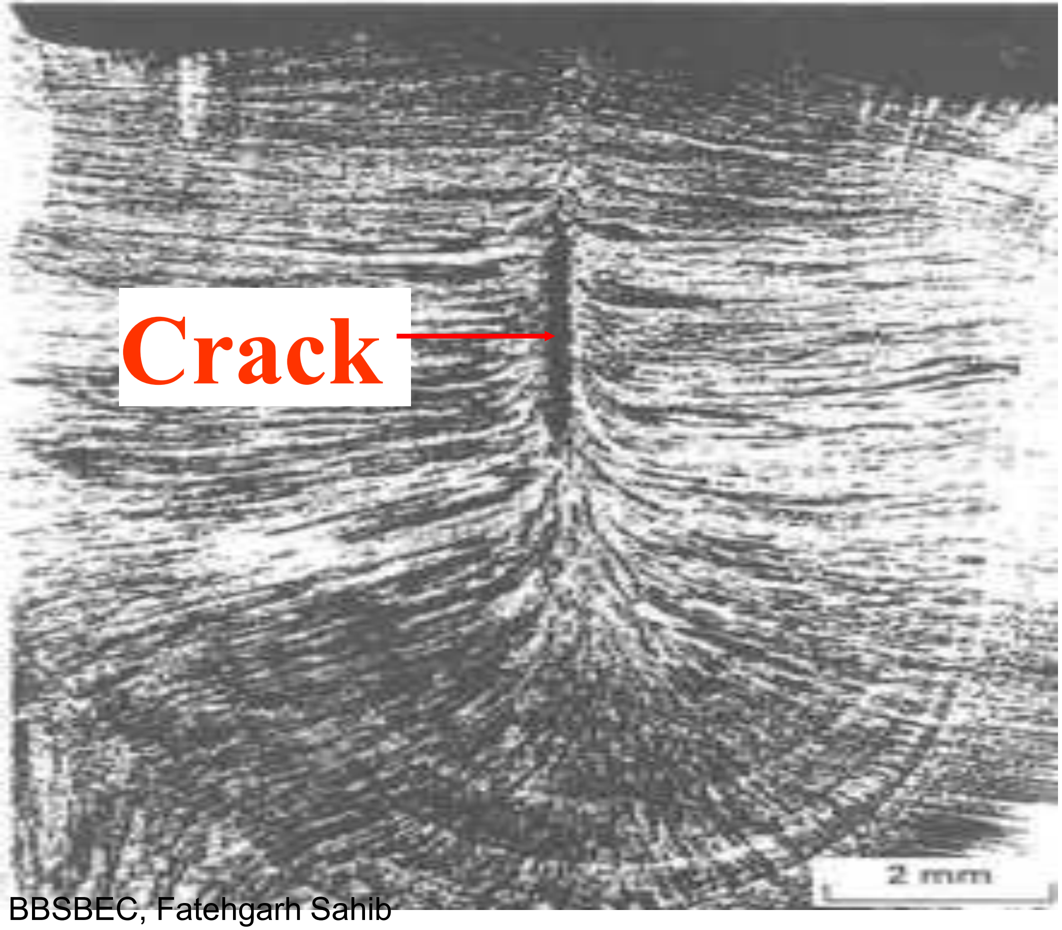
- Weldability is the ease of a material or a combination of materials to be welded under fabrication conditions into a specific, suitably designed structure, and to perform satisfactorily in the intended service
- **Common Arc Welding Processes**
  - Shielded Metal Arc Welding (SMAW)
  - Gas Tungsten Arc Welding (GTAW) or, TIG
  - Gas Metal Arc Welding (GMAW) or MIG/MAG
  - Flux Cored Arc Welding (FCAW)
  - Submerged Arc Welding (SAW)

WELDABILITY OF STEELS

- Cracking & Embrittlement in Steel Welds
  - Cracking
    - Hot Cracking
    - Hydrogen Assisted Cracking
    - Lamellar Tearing
  - Reheat Cracking
  - Embrittlement
    - Temper Embrittlement
    - Strain Age Embrittlement

Hot Cracking

- Solidification Cracking
  - During last stages of solidification
- Liquation Cracking
- Ductility Dip Cracking
  - Ductility ≈ 0
  - Caused by segregation of alloying elements like S, P etc.
  - Mn improves resistance to hot cracking
    - Formation of (Fe, Mn)S instead of FeS



Prediction of Hot Cracking

- **H**ot **C**racking **S**ensitivity
  - **HCS** = $$\frac{(S + P + Si/25 + Ni/100) \times 10^3}{3Mn + Cr + Mo + V}$$
    - HCS $<$ 4, ***Not sensitive***
- **U**nit of **C**rack **S**usceptibility
  [for **S**ubmerged **A**rc **W**elding (SAW)]
  - **UCS** = $230C + 90S + 75P + 45Nb – 12.3Si – 4,5Mn – 1$
    - UCS $\leq$ 10, ***Low risk***
    - UCS $>$ 30, ***High risk***

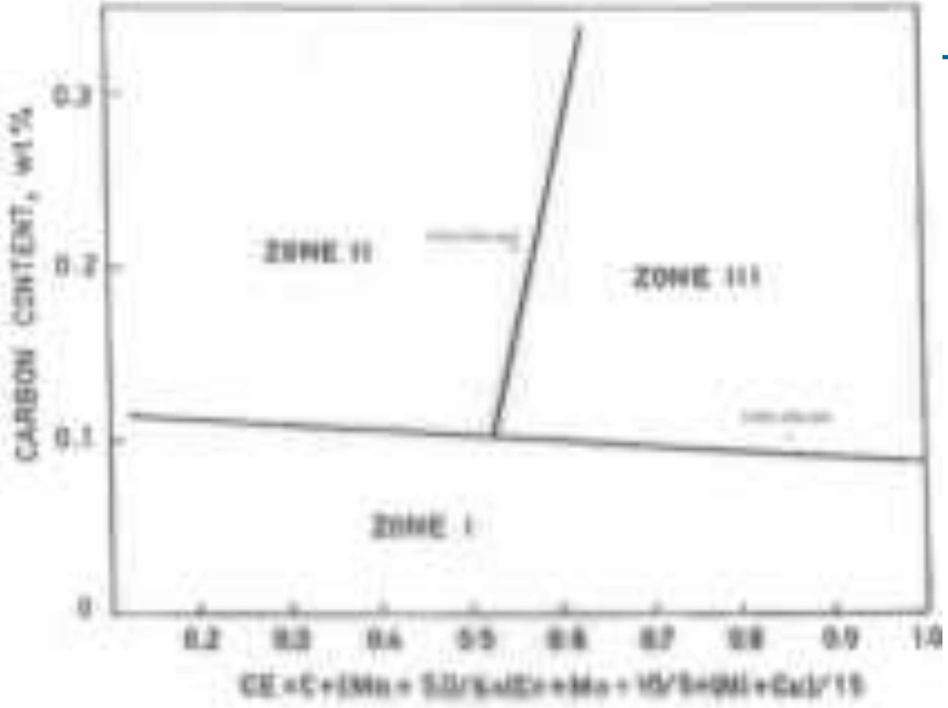
Hydrogen Assisted Cracking (HAC)

- Cold / Delayed Cracking
  - Serious problem in steels
    - In carbon steels
      - HAZ is more susceptible
    - In alloy steels
      - Both HAZ and weld metal are susceptible
  - Requirements for HAC
    - Sufficient amount of hydrogen (H_D)
    - Susceptible microstructure (*hardness*)
      - Martensitic > Bainitic > Ferritic
    - Presence of sufficient restraint
  - Problem needs careful evaluation
    - Technological solutions possible

Methods of Prevention of HAC

- By reducing hydrogen levels
  - Use of low hydrogen electrodes
  - Proper baking of electrodes
  - Use of welding processes without flux
  - Preheating
- By modifying microstructure
  - Preheating
  - Varying welding parameters
- Thumb rule (*based on experience / experimental results*):
  - No preheat if:
    - CE < 0.4 & thickness < 35 mm
  - Not susceptible to HAC if
    - HAZ hardness < 350 VHN

Graville Diagram



- Zone I
  - C < ~0.1%
- Zone II
  - C > ~0.1%
  - CE < ~0.5
- Zone III
  - C > ~0.1%
  - CE > ~0.5

Determination of Preheat Temperature (#1/2)

- **Hardness Control Approach**
  - Developed at The Welding Institute (TWI) UK
  - Considers
    - Combined Thickness
    - H_D Content
    - Carbon Equivalent (CE)
    - Heat Input
  - Valid for steels of limited range of composition
    - In Zone–II of Graville diagram

Determination of Preheat Temperature (#2/2)

- **Hydrogen Control Approach**
  - **For steels in Zones – I & III of Graville diagram**
  - **Cracking Parameter**
    - **$P_W = P_{cm} + (H_D/60) + (K/40) \times 10^4$, where**

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn+Cu+Cr}{20} + \frac{Ni}{60} + \frac{V}{15} + 5B$$

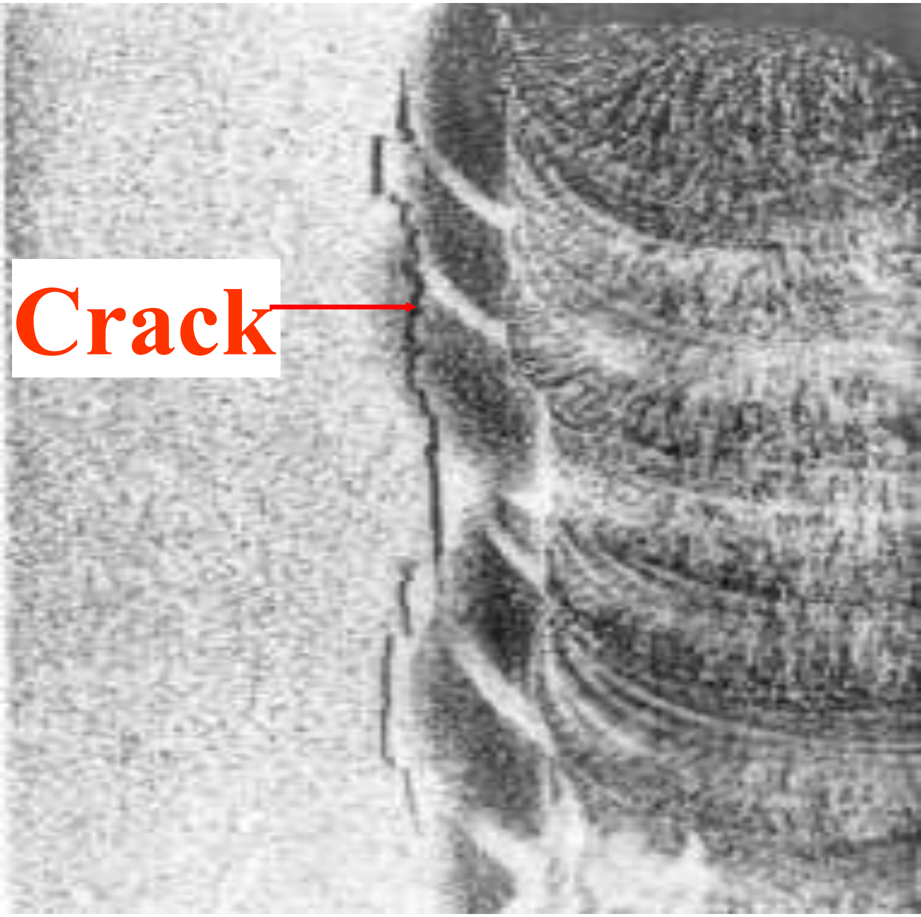
      - ***Weld restraint*, $K = K_o \times h$, with**
        - **h = combined thickness**
        - **$K_o \approx 69$**
    - **T (°C) = $1440\ P_W - 392$**

HAC in Weld Metal

- If H_D levels are high
- In Microalloyed Steels
  - Where carbon content in base metal is low
    - Due to lower base metal strength
- In High Alloy Steels (like Cr-Mo steels)
  - Where matching consumables are used
    - Cracking can take place even at hardness as low as 200 VHN

Lamellar Tearing

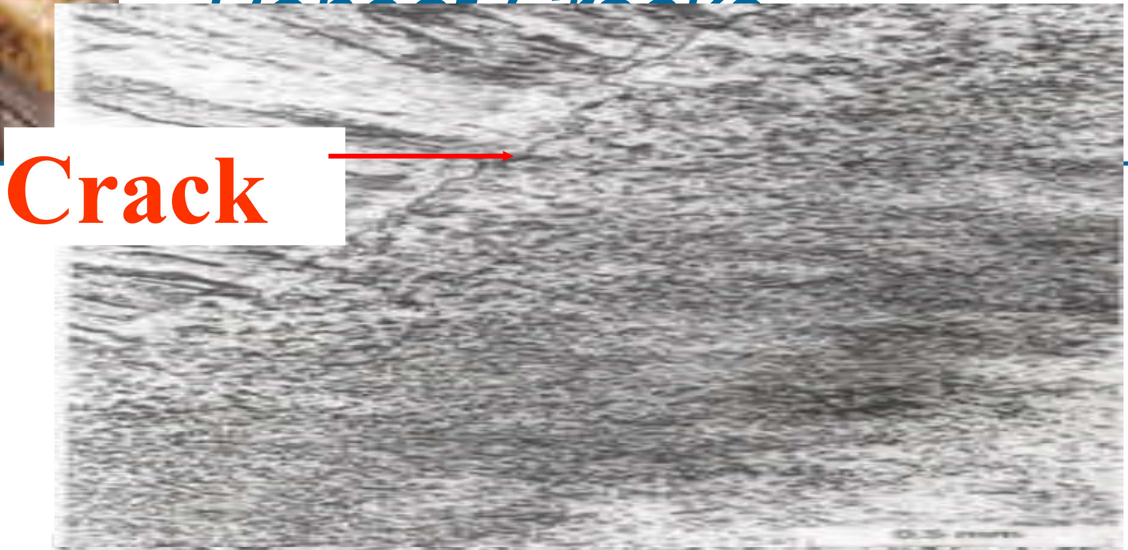
- Occurs in rolled or forged (thick) products
    - When fusion line is parallel to the surface
    - Caused by elongated sulphide inclusions (FeS) in the rolling direction
- Susceptibility determined by *Short Transverse Test*
    - If Reduction in Area
        - >15%, ***Not susceptible***
        - < 5%, ***Highly susceptible***



Reheat Cracking

- Occurs during PWHT
  - Coarse-Grain HAZ most susceptible
  - Alloying elements Cr, Mo, V & Nb promote cracking
    - In creep resistant steels due to primary creep during PWHT !
- Variation:
  - Under-clad cracking in pipes and plates clad with stainless steels

Reheat Cracks

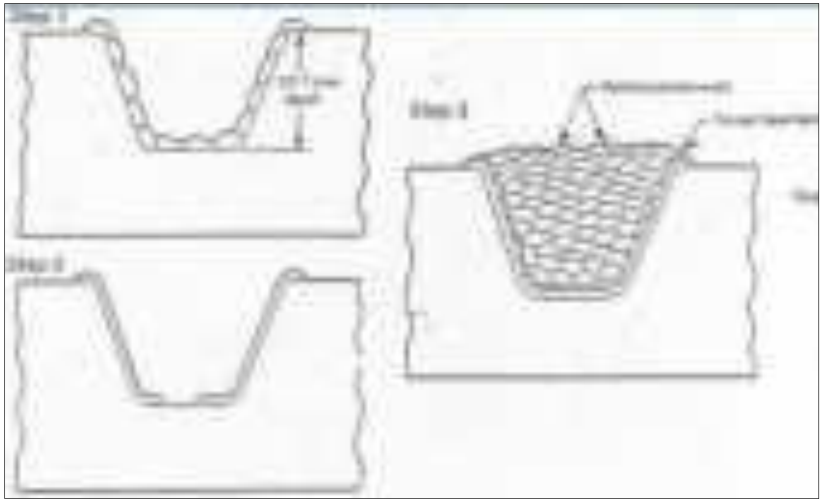


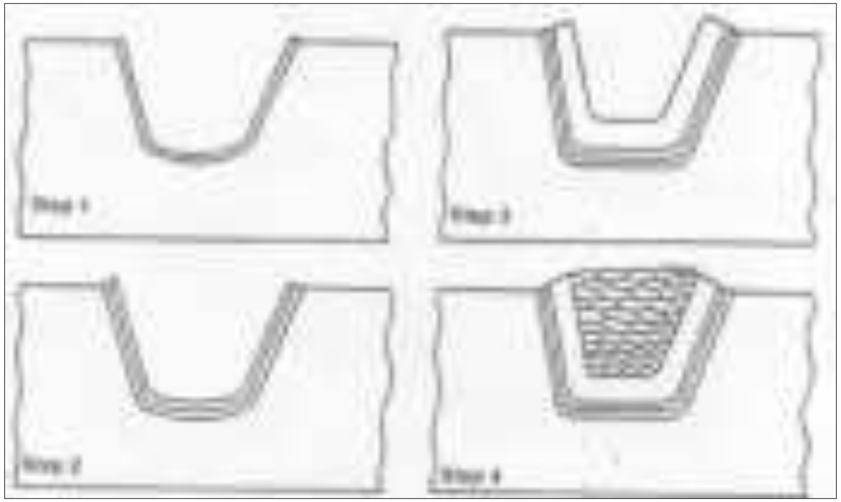
Reheat Cracking

(contd.…)

- **Prediction of Reheat Cracking**
  - $\Delta G =$ Cr + 3.3 Mo + 8.1V + 10C – 2
  - $P_{sr} =$ Cr + Cu + 2Mo + 10V + 7Nb + 5Ti – 2
    - If ΔG, $P_{sr} > 0$, *Material susceptible to cracking*
- **Methods of Prevention**
  - Choice of materials with low impurity content
  - Reduce / eliminate CGHAZ by proper welding technique
    - Buttering
    - Temper-bead technique
    - Two stage PWHT

Temper-bead Techniques

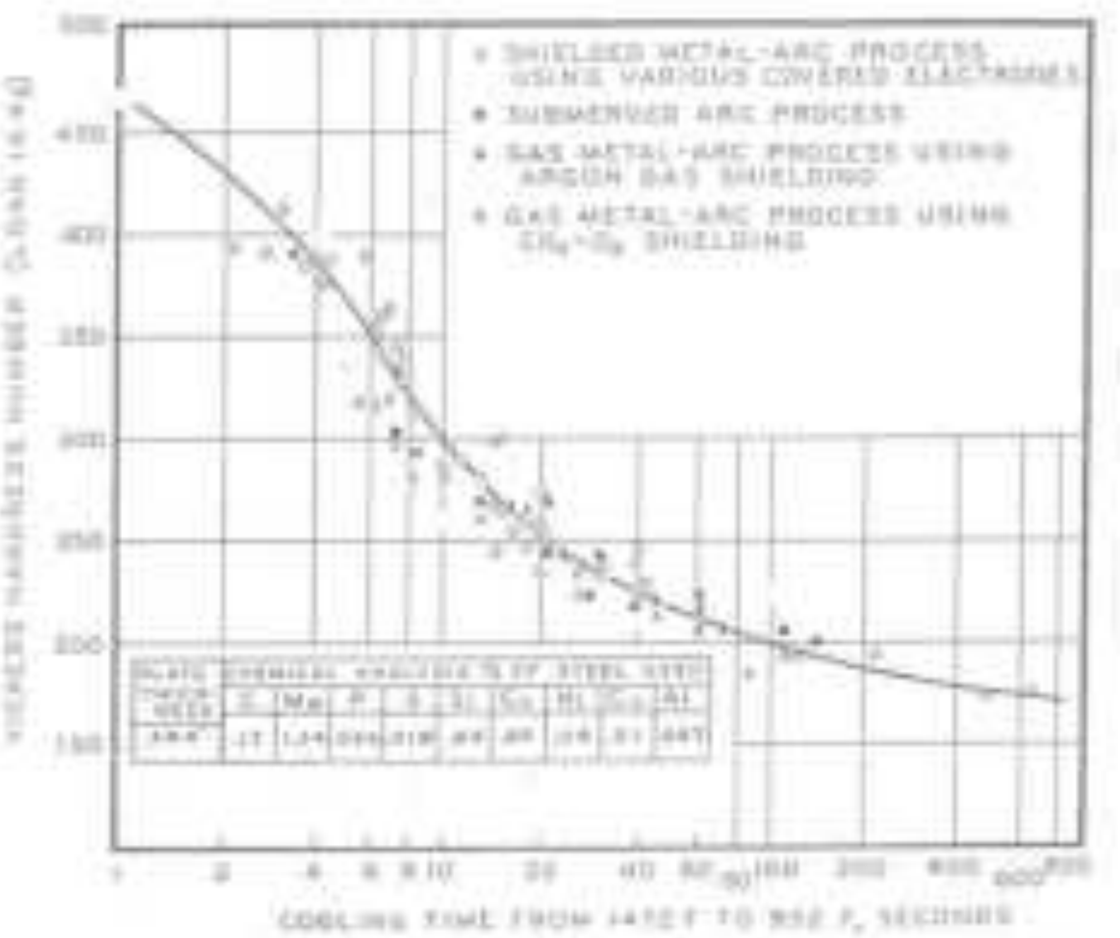




Temper Embrittlement

- Caused by segregation of impurity elements at the grain boundaries
  - Temperature range: 350–600 °C
  - Low toughness
- ***Prediction***
  - $J = (Si + Mn)(P + Sn) \times 10^4$
    - If $J \leq 180$, ***Not susceptible***
  - For weld metal
    - $P_E = C + Mn + Mo + Cr/3 + Si/4 + 3.5(10P + 5Sb + 4Sn + As)$
      - $P_E \leq 3$ ***To avoid embrittlement***

HAZ Hardness Vs. Heat Input



- **Heat Input** is ***inversely proportional*** to **Cooling Rate**

Cr-Mo Steels

- Cr: 1–12 wt.-%
  Mo: 0.5–1.0 wt.-%
- High oxidation & creep resistance
  - Further improved by addition of V, Nb, N etc.
- Application temp. range:
  - 400–550 °C
- Structure
  - Varies from ***Bainite*** to ***Martensite*** with increase in alloy content

- **Welding**
  - Susceptible to
    - Cold cracking &
    - Reheat cracking
      - Cr < 3 wt.-%
  - PWHT required:
    - 650–760 °C

Nickel Steels

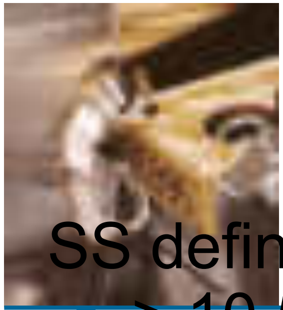
- Ni: 0.7–12 wt.-%
- C: Progressively reduced with increase in Ni

- For cryogenic applications
  - High toughness
  - Low DBTT
- Structure
  - Mixture of fine ferrite, carbides & retained austenite
- **Welding**
  - For steels with ≤ 1% Ni
    - HAZ softening & toughness reduction in multipass welds
    - Consumables: 1–2.5%Ni
- **Welding** (*contd.*)
  - For steels with 1–3.5% Ni
    - Bainite/martensite structure
    - Low H_D consumables
      - Matching / austenitic SS
    - No PWHT
    - Temper-bead technique
    - Low heat input
  - For steels with > 3.5% Ni
    - Martensite+austenite HAZ
    - Low heat input
    - PWHT at 650 °C
    - Austenitic SS / Ni-base consumable

HSLA Steels

- **Yield strength > 300 MPa**
  - **High strength by**
    - **Grain refinement through**
      - **Microalloying with**
        - **Nb, Ti, Al, V, B**
      - **Thermo-mechanical processing**
  - **Low impurity content**
  - **Low carbon content**
  - **Sometimes Cu added to provide precipitation strengthening**

- **Welding problems**
  - Dilution from base metal
    - Nb, Ti, V etc.
  - Grain growth in CGHAZ
  - Softening in HAZ
  - Susceptible to HAC
  - CE and methods to predict preheat temperature are of limited validity



STAINLESS STEELS

- SS defined as Iron-base alloy containing
  - > 10.5% Cr & < 1.5%C
- Based on microstructure & properties
  - 5 major families of SS
    - Austenitic SS
    - Ferritic SS
    - Martensitic SS
    - Precipitation-hardening SS
    - Duplex ferritic-austenitic SS
  - Each family requires
    - Different weldability considerations
      - Due to varied phase transformation behaviour on cooling from solidification

Stainless Steels

(contd. …1)

- All SS types
  - Weldable by virtually all welding processes
    - Process selection often dictated by available equipment
    - Simplest & most universal welding process
      - Manual SMAW with coated electrodes
        - Applied to material > 1.2 mm
      - Other very commonly used arc welding processes for SS
        - GTAW, GMAW, SAW & FCAW
- Optimal filler metal (FM)
  - Does not often closely match base metal composition
  - Most successful procedures for one family
    - Often markedly different for another family

Stainless Steels

(contd. …2)

- SS base metal & welding FM chosen based on
    - Adequate **corrosion resistance** for intended use
        - Welding FM must match/over-match BM content w.r.t
            - Alloying elements, e.g. Cr, Ni & Mo
    - **Avoidance of cracking**
        - Unifying theme in FM selection & procedure development
        - **Hot cracking**
            - At temperatures < bulk solidus temperature of alloy(s)
        - **Cold cracking**
            - At rather low temperatures, typically < 150 °C

Stainless Steels

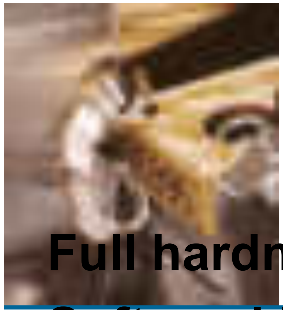
(contd. …3)

- **Hot cracking**
  - As large Weld Metal (WM) cracks
    - Usually along weld centreline
  - As small, short cracks (*microfissures*) in WM/HAZ
    - At fusion line & usually perpendicular to it
  - Main concern in ***Austenitic*** WMs
  - Common remedy
    - Use mostly ***austenitic*** FM with small amount of ferrite
      - Not suitable when requirement is for
        - Low magnetic permeability
        - High toughness at cryogenic temperatures
        - Resistance to media that selectively attack ferrite (e.g. urea)

Stainless Steels

(contd. …4)

- **Cold cracking**
  - Due to interaction of
    - High welding stresses
    - High-strength metal
    - Diffusible hydrogen
  - Commonly occurs in ***Martensitic*** WMs/HAZs
  - Can occur in ***Ferritic*** SS weldments embrittled by
    - Grain coarsening and/or second-phase particles
  - <u>Remedy</u>
    - Use of mostly austenitic FM (*with appropriate corrosion resistance*)



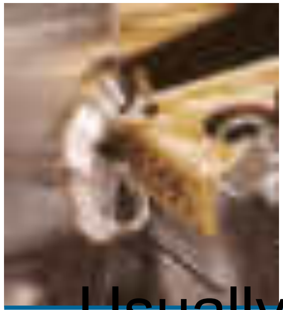
Martensitic Stainless Steels

- Full hardness on air-cooling from ~ 1000 ºC
- Softened by tempering at 500–750 ºC
  - Maximum tempering temperature reduced
    - If Ni content is significant
  - On high-temperature tempering at 650–750 ºC
    - Hardness generally drops to < ~ R_C 30
      - Useful for softening martensitic SS before welding for
        - Sufficient bulk material ductility
        - Accommodating shrinkage stresses due to welding
    - Coarse Cr-carbides produced
      - Damages corrosion resistance of metal
      - To restore corrosion resistance after welding

Martensitic Stainless Steels

For use in As-Welded Condition

- Not used in as-welded condition
  - Due to very brittle weld area
    - Except for
      - Very small weldments
      - Very low carbon BMs
      - Repair situations
  - Best to avoid
    - Autogenous welds
    - Welds with matching FM
    - *Except*
      - Small parts welded by GTAW as
        - Residual stresses are very low
        - Almost no diffusible hydrogen generated



Martensitic Stainless Steels
For use after PWHT

- Usually welded with martensitic SS FMs
        - Due to under-matching of WM strength / hardness when welded with austenitic FMs
- Followed by PWHT
        - To improve properties of weld area
    - PWHT usually of ***<u>two</u>*** forms
        - (1) Tempering at < A_s
        - (2) Heating at > A_f (*to austenitise*) +
Cooling to ~ RT (*to fully harden*) +
Heating to < A_s (*to temper metal to desired properties*)

Ferritic Stainless Steels

- Generally requires rapid cooling from hot-working temperatures
  - To avoid grain growth & embrittlement from α phase
  - Hence, most ferritic SS used in relatively thin gages
    - Especially in alloys with high Cr
    - “Super ferritics” (e.g. type 444) limited to thin plate, sheet & tube forms
- To avoid embrittlement in welding
  - General rule is “***weld cold***” i.e., weld with
    - No / low preheating
    - Low interpass temperature
    - Low level of welding heat input
      - Just enough for fusion & to avoid cold

Ferritic Stainless Steels

For use in As-Welded Condition

- Usually used in as-welded condition
  - Weldments in ferritic SS
    - Stabilised grades (e.g. types 409 & 405)
    - “Super-ferritics”
      - In contrast to martensitic SS
  - If “***weld cold***” rule is followed
    - Embrittlement due to grain coarsening in HAZ avoided
  - If WM is fully ferritic
    - Not easy to avoid coarse grains in fusion zone
      - Hence to join ferritic SS, considerable amount of austenitic filler metals (usually containing considerable amount of ferrite) are used

Ferritic Stainless Steels

For use in PWHT Condition

- Generally used in PWHT condition
  - Only unstabilised grades of ferritic SS
    - Especially type 430
  - When welded with matching / no FM
    - Both WM & HAZ contain fresh martensite in as-welded condition
    - Also C gets in solution in ferrite at elevated temperatures
      - Rapid cooling after welding results in ferrite in both WM & HAZ being supersaturated with C
    - Hence, joint would be quite brittle
    - Ductility significantly improved by
      - PWHT at 760 ºC for 1 hr. & followed by rapid cooling to avoid the 475 ºC embrittlement

Austenitic Stainless Steels

For use in As-Welded Condition

- Most weldments of austenitic SS BMs
  - Used in service in as-welded condition
  - Matching/near-matching FMs available for many BMs
- FM selection & welding procedure depend on
  - Whether ferrite is possible & acceptable in WM
    - If ferrite in WM possible & acceptable
      - Then broad choice for suitable FM & procedures
    - If WM solidifies as primary ferrite
      - Then broad range of acceptable welding procedures
    - If ferrite in WM not possible & acceptable
      - Then FM & procedure choices restricted
        - Due to hot-cracking considerations

Austenitic Stainless Steels

(As-Welded) *(contd. …1)*

- If ferrite possible & acceptable
  - Composite FMs tailored to meet specific needs
    - For SMAW, FCAW, GMAW & SAW processes
    - E.g. type 308/308L FMs for joining 304/304L BMs
      - Designed within AWS specification for 0 – 20 FN
    - For GMAW, GTAW, SAW processes
      - Design optimised for 3–8 FN (as per WRC-1988)
      - Availability limited for ferrite > 10 FN
    - Composition & FN adjusted via alloying in
      - Electrode coating of SMAW electrodes

Austenitic Stainless Steels

For use in PWHT Condition

- Austenitic SS weldments given PWHT
  1) When ***non-low-C grades are welded & Sensitisation by Cr-carbide precipitation cannot be tolerated***
     - Annealing at 1050–1150 ºC + water quench
       - To dissolve carbides/intermetallic compounds (σ-phase)
         - Causes much of ferrite to transform to austenite
  2) For ***Autogenous welds in high-Mo SS***
       - E.g. longitudinal seams in pipe
     - Annealing to diffuse Mo to erase micro-segregation
       - To match pitting / crevice corrosion resistance of WM & BM
         - No ferrite is lost as no ferrite in as-welded condition

Austenitic SS (after PWHT)

(contd. …1)

- **Austenitic SS –to– carbon / low-alloy steel joints**
  - **Carbon from mild steel / low-alloy steel adjacent to fusion line migrates to higher-Cr WM producing**
    - **Layer of carbides along fusion line in WM & Carbon-depleted layer in HAZ of BM**
      - **Carbon-depleted layer is weak at elevated temperatures**
        - **Creep failure can occur (at elevated service temp.)**
  - **Coefficient of Thermal Expansion (CTE) mismatch between austenitic SS WM & carbon / low-alloy steel BM causes**
    - **Thermal cycling & strain accumulations along interface**
      - **Leads to premature failure in creep**
  - **In dissimilar joints for elevated-temperature service**
    - **E.g. Austenitic SS –to– Cr-Mo low-alloy steel joints**
      - **Ni-base alloy filler metals used**

Austenitic SS (after PWHT)

(contd. …2)

- PWHT used for
  - Stress relief in austenitic SS weldments
    - YS of austenitic SS falls slowly with rising temp.
      - Than YS of carbon / low-alloy steel
        - Carbide pptn. & σ phase formation at 600–700 ºC
- Relieving residual stresses without damaging corrosion resistance on
  - Full anneal at 1050–1150 ºC + rapid cooling
    - Avoids carbide precipitation in <u>unstabilised grades</u>
    - Causes Nb/Ti carbide pptn. (*stabilisation*) in <u>stabilized grades</u>
    - Rapid cooling – *Reintroduces residual stresses*
    - At annealing temp. – *Significant surface oxidation in air*
      - Oxide tenacious on SS
        - Removed by pickling + water rinse + passivation

Precipitation-Hardening SS

For use in As-Welded Condition

- Most applications for
  - Aerospace & other high-technology industries
- PH SS achieve high strength by heat treatment
  - Hence, not reasonable to expect WM to match properties of BM in as-welded condition
  - Design of weldment for use in as-welded condition assumes WM will ***under-match*** the BM strength
    - If acceptable
      - Austenitic FM (types 308 & 309) suitable for martensitic & semi-austenitic PH SS
        - Some ferrite in WM required to avoid hot cracking

Precipitation-Hardening SS **For use in PWHT Condition**

- PWHT to obtain comparable WM & BM strength
  - WM must also be a PH SS
    - As per AWS classification
      - Only martensitic type 630 (17-4 PH) available as FM
    - As per Aerospace Material Specifications (AMS)
      - Some FM (*bare wires* only) match BM compositions
        - Used for GTAW & GMAW
    - Make FM by shearing BM into narrow strips for GTAW
  - Many PH SS weldments light-gage materials
    - Readily welded by ***autogenous GTAW***
      - WM matches BM & responds similarly to heat treatment

Duplex Ferritic-Austenitic Stainless Steels

- **Optimum phase balance**
  - **Approximately equal amounts of ferrite & austenite**
    - **BM composition adjusted as equilibrium structure at ~1040ºC**
      - **After hot working and/or annealing**
    - **Carbon undesirable for reasons of corrosion resistance**
    - **All other elements (except N) – diffuse slowly**
      - **Contribute to determine equilibrium phase balance**
        - **N most impt. (for near-equilibrium phase balance)**
  - **Earlier duplex SS (e.g. types 329 & CD-4MCu)**
    - **N not a deliberate alloying element**
  - **Under normal weld cooling conditions**
    - **Weld HAZ & matching WMs reach RT with very little γ**
      - **Poor mechanical properties & corrosion resistance**
    - **For useful properties**
      - **welds to be annealed + quenching**
        - **To avoid embrittlement of ferrite by σ /**

Duplex SS

(contd. …1)

- Over-alloying of weld metal with Ni causes
  - Transformation to begin at higher temp. (*diffusion very rapid*)
      - Better phase balance obtained in as-welded WM
      - Nothing done for HAZ
- Alloying with N (*in newer duplex SS)*
  - Usually solves the HAZ problem
  - With normal welding heat input & ~0.15%Ni
    - Reasonable phase balance achieved in HAZ
    - N diffuses to austenite
      - Imparts improved pitting resistance
  - If cooling rate is too rapid
    - N trapped in ferrite
      - Then Cr-nitride precipitates
        - Damages corrosion resistance
    - Avoid low welding heat inputs with duplex SS

Duplex SS

For use in As-Welded Condition

- Matching composition WM
  - Has inferior ductility & toughness
    - Due to high ferrite content
    - Problem less critical with GTAW, GMAW (but significant)
      - Compared to SMAW, SAW, FCAW
- Safest procedure for as-welded condition
  - Use FM that matches BM
    - With higher Ni content
  - Avoid autogenous welds
  - With GTAW process (esp. root pass)
    - Welding procedure to limit dilution of WM by BM
      - Use wider root opening & more filler metal in the root
        - Compared to that for an austenitic SS

Duplex SS (As-Welded)

(contd. …1)

- SAW process
  - Best results with high-basicity fluxes
    - WM toughness
      - Strongly sensitive to O_2 content
        - Basic fluxes provide lowest O_2 content in WM
- GTAW process
  - Ar-H_2 gas mixtures used earlier
    - For better wetting & bead shape
    - But causes significant hydrogen embrittlement
      - Avoid for weldments used in as-welded condition
- SMAW process (*covered electrodes*)
  - To be treated as low-hydrogen electrodes for low alloy steels

Duplex SS

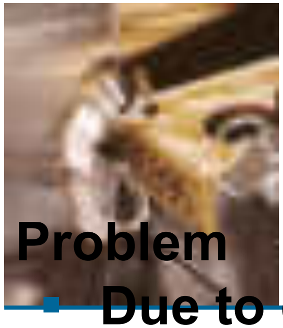
For use in PWHT Condition

- **Annealing after welding**
    - **Often used for longitudinal seams in pipe lengths, welds in forgings & repair welds in castings**
  - **Heating to > 1040 ºC**
    - ***Avoid* slow heating**
      - **Pptn. of σ / other phases occurs in few minutes at 800 ºC**
        - **Pipes produced by very *rapid induction heating***
    - ***Brief hold* near 1040 ºC necessary for phase balance control**
  - **Followed by rapid cooling (water quench)**
    - **To avoid σ phase formation**
  - **Annealing permits use of exactly matched / no FM**
    - **As annealing adjusts phase balance to near equilibrium**

Duplex SS (after PWHT)

(contd. …1)

- Furnace annealing
  - Produce slow heating
    - σ phase expected to form during heating
      - Longer hold (> 1 hour) necessary at annealing temp.
        - To dissolve all σ phase
  - Properly run continuous furnaces
    - Provide high heating rates
      - Used for light wall tubes & other thin sections
    - If σ phase pptn. can be avoided during heating
      - Long anneals not necessary
  - Distortion during annealing can be due to
    - Extremely low creep strength of duplex SS at annealing temp.



Major Problem with welding of Al, Ti & Zr alloys

- Problem
  - Due to great affinity for oxygen
    - Combines with oxygen in air to form a high melting point oxide on metal surface
- Remedy
  - Oxide must be cleaned from metal surface before start of welding
  - Special procedures must be employed
    - Use of large gas nozzles
    - Use of trailing shields to shield face of weld pool
    - When using GTAW, thoriated tungsten electrode to be used
    - Welding must be done with direct current electrode positive with matching filler wire
      - Job is negative (cathode)
        - Cathode spots, formed on weld pool, scavenges the oxide film

ALUMINUM ALLOYS

- Important Properties
  - High electrical conductivity
  - High strength to weight ratio
  - Absence of a transition temperature
  - Good corrosion resistance
- Types of aluminum alloys
  - Non-heat treatable
  - Heat treatable (age-hardenable)

Non-Heat Treatable Aluminum Alloys

- Gets strength from cold working
- Important alloy types
  - Commercially pure (>98%) Al
  - Al with 1% Mn
  - Al with 1, 2, 3 and 5% Mg
  - Al with 2% Mg and 1% Mn
  - Al with 4, 5% Mg and 1% Mn
- Al-Mg alloys often used in welded construction

Heat-treatable Aluminum Alloys

- Cu, Mg, Zn & Li added to Al
  - Confer age-hardening behavior after suitable heat-treatment
    - On solution annealing, quenching & aging
- Important alloy types
  - Al-Cu-Mg
  - Al-Mg-Si
  - Al-Zn-Mg
  - Al-Cu-Mg-Li
- Al-Zn-Mg alloys are the most easily welded

Welding of Aluminum Alloys

- Most widely used welding process
    - Inert gas-shielded welding
- For thin sheet
    - Gas tungsten-arc welding (GTAW)
- For thicker sections
    - **Gas metal-arc welding (GMAW)**
        - GMAW preferred over GTAW due to
            - High efficiency of heat utilization
            - Deeper penetration
            - High welding speed
            - Narrower HAZ
            - Fine porosity
            - Less distortion

Welding of Aluminum Alloys

(contd...1)

- Other welding processes used
  - Electron beam welding (EBW)
    - Advantages
      - Narrow & deep penetration
        - High depth/width ratio for weld metal
        - Limits extent of metallurgical reactions
      - Reduces residual stresses & distortion
      - Less contamination of weld pool
  - Pressure welding

TITANIUM ALLOYS

- Important properties
  - High strength to weight ratio
  - High creep strength
  - High fracture toughness
  - Good ductility
  - Excellent corrosion resistance

Titanium Alloys

(contd...1)

- Classification of Titanium alloys
        - Based on annealed microstructure
    - Alpha alloys
        - Ti-5Al-2.5Sn
        - Ti-0.2Pd
    - Near Alpha alloys
        - Ti-8Al-1Mo-1V
        - Ti-6Al-4Zr-2Mo-2Sn
    - Alpha-Beta alloys
        - Ti-6Al-4V
        - Ti-8Mn
        - Ti-6Al-6V-2Sn
    - Beta alloys
        - Ti-13V-11Cr-3Al

Welding of Titanium alloys

- Most commonly used processes
  - GTAW
  - GMAW
  - Plasma Arc Welding (PAW)
- Other processes used
  - Diffusion bonding
  - Resistance welding
  - Electron welding
  - Laser welding

ZIRCONIUM ALLOYS

- Features of Zirconium alloys
  - Low neutron absorption cross-section
    - Used as structural material for nuclear reactor
  - Unequal thermal expansion due to anisotropic properties
  - High reactivity with O, N & C
  - Presence of a transition temperature

Zirconium Alloys

(contd.…1)

- Common Zirconium alloys
  - Zircaloy-2
    - Containing
      - Sn = 1.2–1.7%
      - Fe = 0.07–0.20%
      - Cr = 0.05–0.15%
      - Ni = 0.03–0.08%
  - Zircaloy-4
    - Containing
      - Sn = 1.2–1.7%
      - Fe = 0.18–0.24%
      - Cr = 0.07–0.13%
  - Zr-2.5%Nb

Weldability Demands For Nuclear Industries

- Weld joint requirements
    - To match properties of base metal
    - To perform equal to (or better than) base metal
- Welding introduces features that degrade mechanical & corrosion properties of weld metal
        - Planar defects
            - Hot cracks, Cold cracks, Lack of bead penetration (LOP), Lack of side-wall fusion (LOF), etc.
        - Volumetric defects
            - Porosities, Slag inclusions
    - Type, nature, distribution & locations of defects affect design critical weld joint properties
        - Creep, LCF, creep-fatigue interaction, fracture toughness, etc.

Welding of Zirconium Alloys

- Most widely used welding processes
  - Electron Beam Welding (EBW)
  - Resistance Welding
  - GTAW
  - Laser Beam Welding (LBW)
- For Zircaloy-2, Zircaloy-4 & Zr-2.5%Nb alloys in PHWRs, PWRs & BWRs
  - By resistance welding
    - Spot & Projection welding
    - EBW
    - GTAW

Welding Zirconium Alloys in Nuclear Industry

- For PHWR components
  - End plug welding by resistance welding
  - Appendage welding by resistance welding
  - End plate welding by resistance welding
  - Cobalt Absorber Assemblies by EBW & GTAW
  - Guide Tubes, Liquid Poison Tubes etc by circumferential EBW
  - Welding of Zirconium to Stainless steel by Flash welding