Introduction to Non-Arc Welding Processes

Module 2B

Introduction to Non-Arc Welding Processes

- Non-Arc Welding processes refer to a wide range of processes which produce a weld without the use of an electrical arc
  - High Energy Density Welding processes
    - Main advantage – low heat input
    - Main disadvantage – expensive equipment
  - Solid-State Welding processes
    - Main advantage – good for dissimilar metal joints
    - Main disadvantage – usually not ideal for high production
  - Resistance Welding processes
    - Main advantage – fast welding times
    - Main disadvantage – difficult to inspect

Introduction to Non-Arc Welding Processes

- Brazing and Soldering
  - Main advantage – minimal degradation to base metal properties
  - Main disadvantage – requirement for significant joint preparation
- Thermite Welding
  - Main advantage – extremely portable
  - Main disadvantage – significant set-up time
- Oxyfuel Gas Welding
  - Main advantage - portable, versatile, low cost equipment
  - Main disadvantage - very slow

- In general, most non-arc welding processes are conducive to original fabrication only, and not ideal choices for repair welding (with one exception being Thermite Welding)

High Energy Density (HED) Welding

Module 2B.1

Types of HED Welding

- Electron Beam Welding
  - Process details
  - Equipment
  - Safety
- Laser Welding
  - Process details
  - Different types of lasers and equipment
  - Comparison to Electron Beam Welding
  - Hybrid Laser Welding
  - Safety

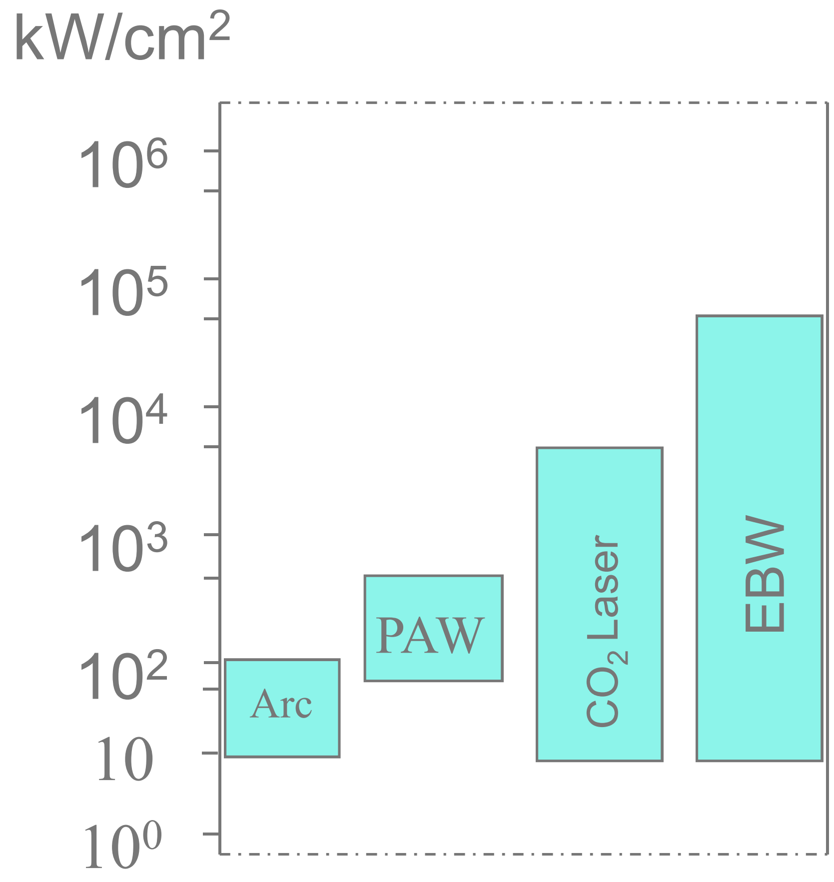
HED Welding

- Power density (power / area) is significantly higher than that achieved by the common arc welding processes

- In HED processes the power density is greater than 5 x 102 kW/cm2:
  - Electron Beam Welding
  - Laser Beam Welding
  - Plasma Arc Welding

Range of Power Densities

- Depends on the power and spot size
- Melting and vaporization processes will be dominant in the molten pool
- Vaporization may cause keyhole formation

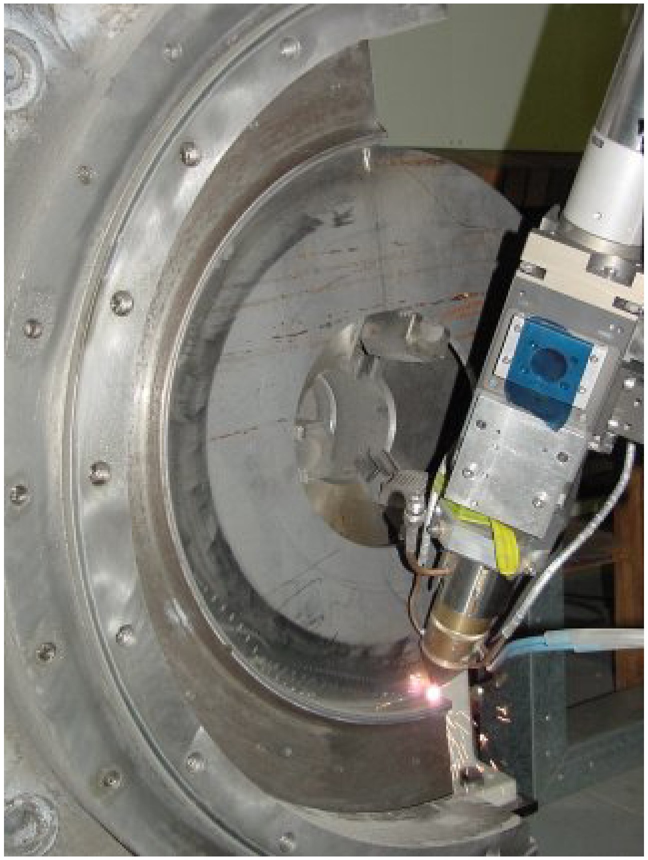


HED Welding

- Laser and electron beams can be focused to a very small spot size (the diameter of human hair, 0.05 mm)
- CW (constant wave) power density can reach as high as 10^5 kW/cm^2
- HED processes can melt and/or vaporize materials including:
  - Metals and alloys
  - Plastics and composites
  - Wood
  - Rubber
  - Ceramics and Concrete

HED Welding Applications

- Automotive
  - Transmission components
  - Structural
- Aerospace
  - Jet Engines
- Medical
  - Pacemakers
  - Batteries
- Electrical
  - Relays
  - Electronic Devices



[Source: Internet]

HED Welding

- Advantages (compared to Arc Welding processes)
  - Low overall heat input results in low distortion and minimal degradation to the base metal microstructure (small heat affected zone)
  - Very fast single pass weld speeds possible
  - Easily automated in the case of Laser Welding
  - Non-contact processes, no tool or electrode wear
  - No filler metal required
- Disadvantages
  - Accurate joint positioning and fit-up required
  - High equipment cost
  - Safety concerns

Welding Processes Comparison

Quality	LBW	EBW	Arc	Resistance
Welding Speed	++	++	-	+
Low Heat Input	++	++	-	+
Narrow HAZ	++	++	-	-
Weld Bead Appearance	+	+	-	
Deep Penetration	+	++	-	-
Equipment Cost	-	-	+	+
Equipment Reliability	+		+	+
	+ = Advantage		- = Disadvantage	

Relative Joining Efficiencies

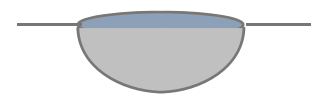
Process	Joining Efficiency mm^2/kJ
High Frequency Resistance Welding	65 - 100
Electron beam (EBW)	20 – 30
Laser (LBW)	15 - 25
Submerged arc welding (SAW)	4 – 10
Shielded metal arc (SMAW)	2 - 3
Gas tungsten arc welding (GTAW)	0.8 - 2
Oxyacetylene flame	0.2 - 0.5

[Ref: "Laser Material Processing", W. M. Steen]

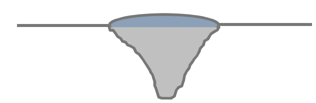
Power Densities and Weld Profiles

- Flux shielded arc welding — 0.5 - 50 kW/cm^2

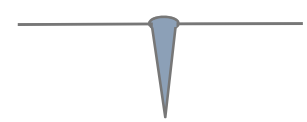
- Gas shielded arc welding — 0.5 -50 kW/cm^2



- Plasma — 50 - 5×10^3 kW/cm^2



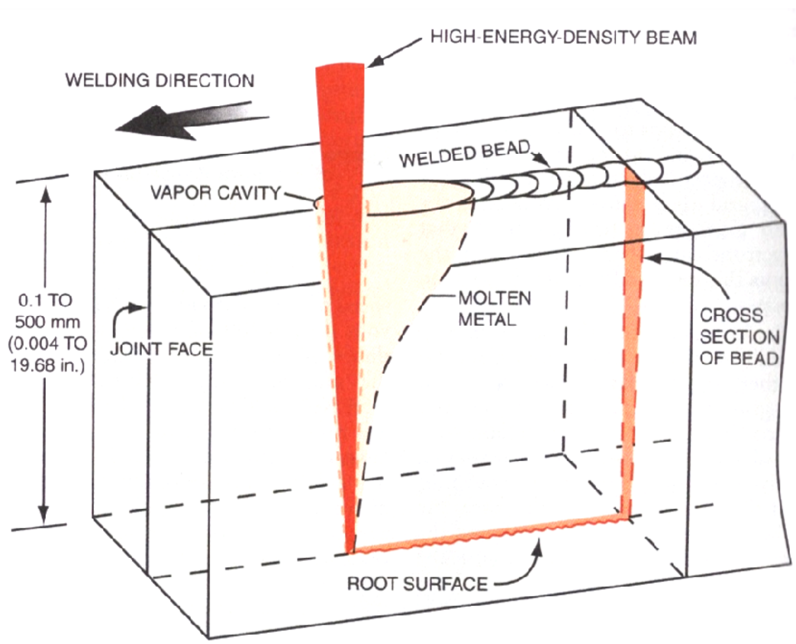
- Laser or electron beam — 5×10^3 - 5×10^5 kW/cm^2



[Ref: “Laser Material Processing”, W. M. Steen]

HED Welding Features

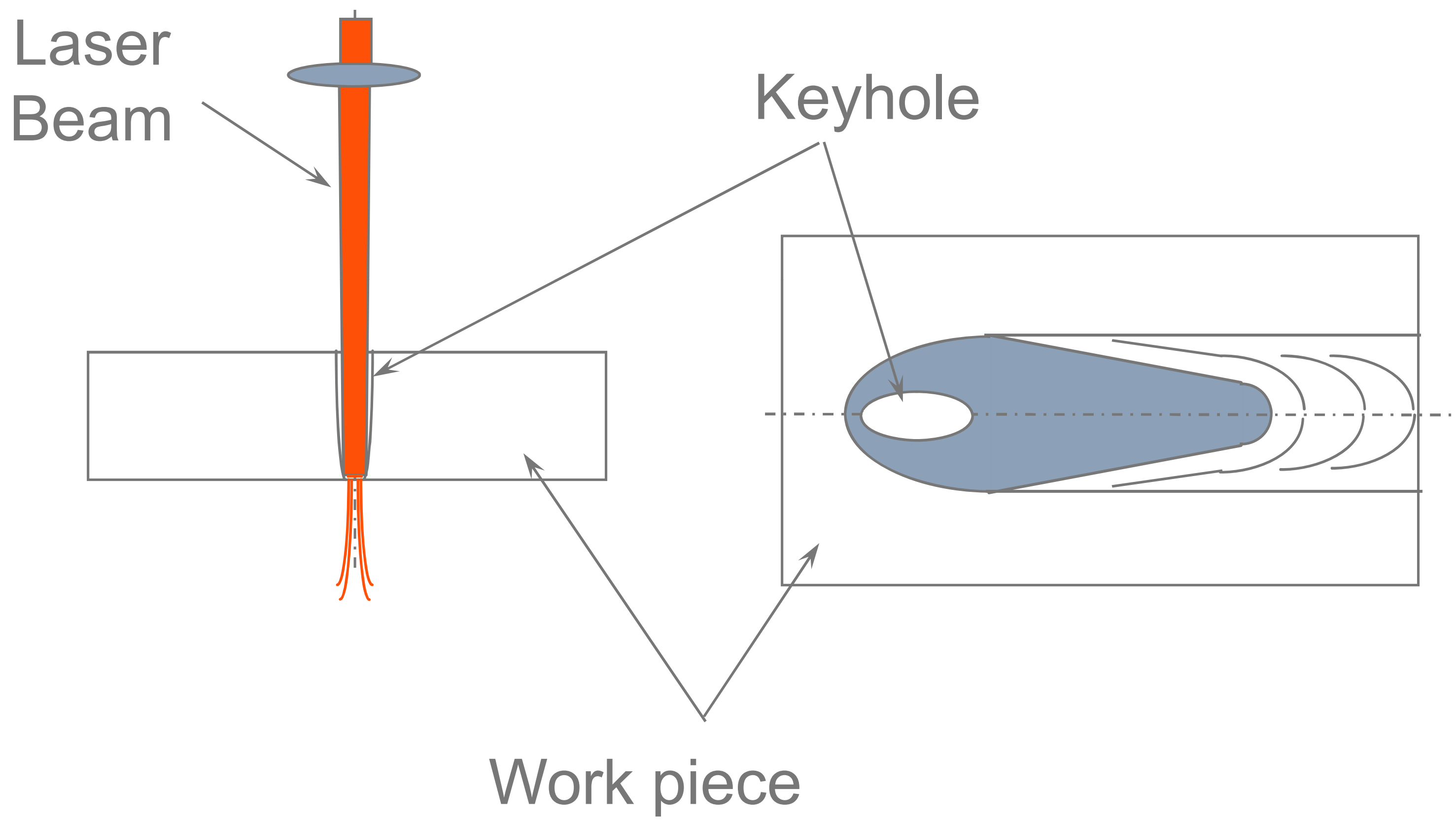
- Pressure on weld pool surface forms a deep depression (keyhole)
- Weld depth is generally significantly greater than width



Keyhole in Electron Beam Welding

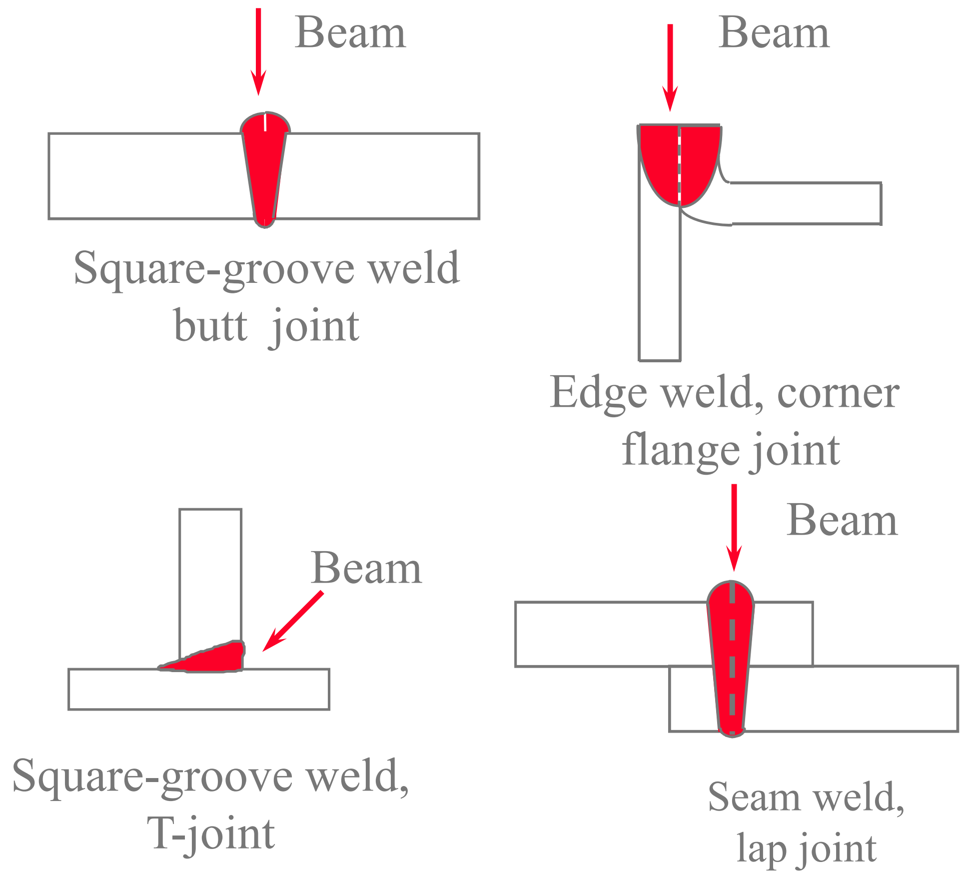
[Ref: "AWS Handbook, Vol. 3, Welding Processes, Part 2, 9th Ed.]

"Keyhole" Formation

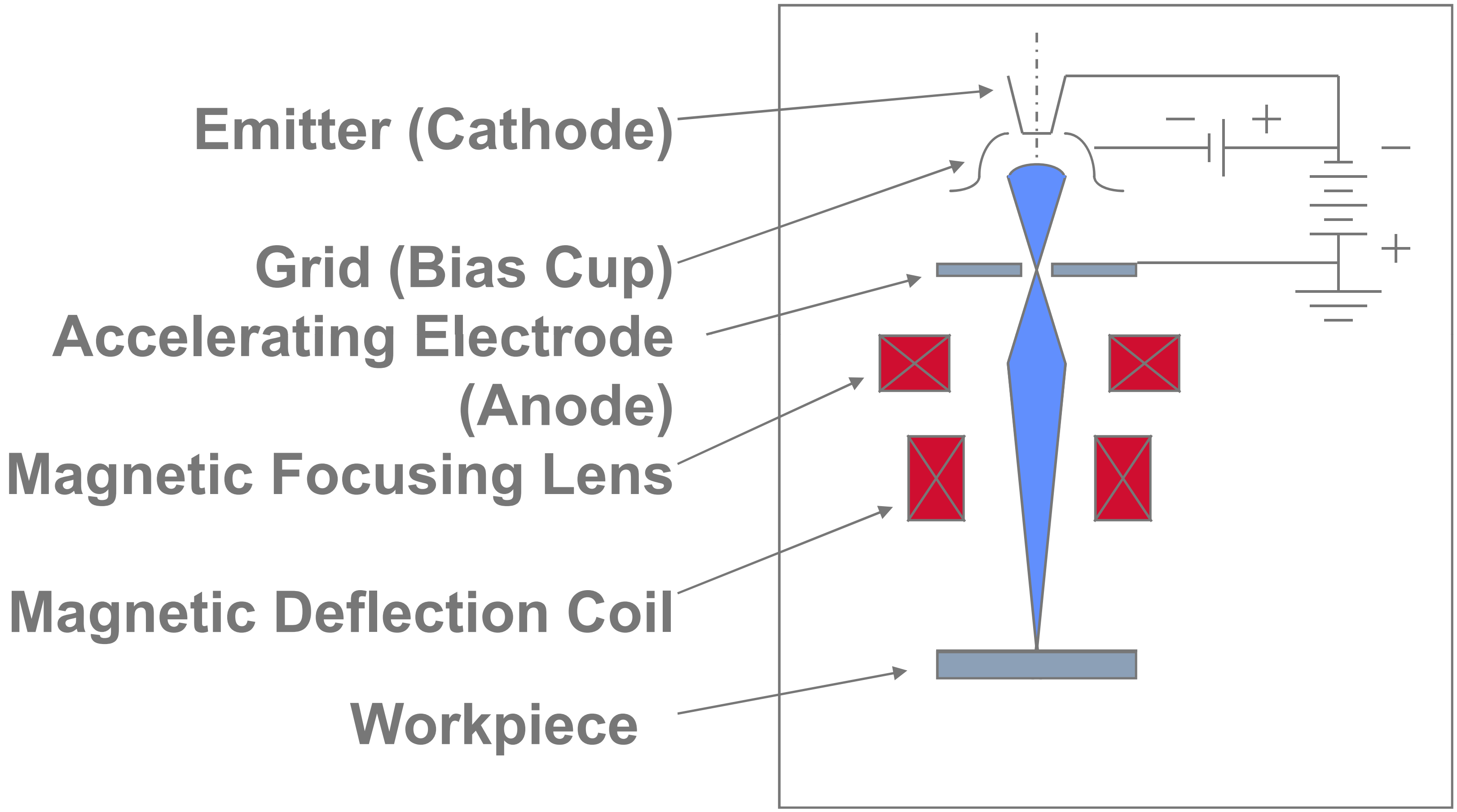


Weld Joint Design for HED Welding

- Butt, corner, lap, edge and T-joints can be made by electron beam welding using square-groove or seam welds.
- Fillet welds are difficult to make and are not generally used.

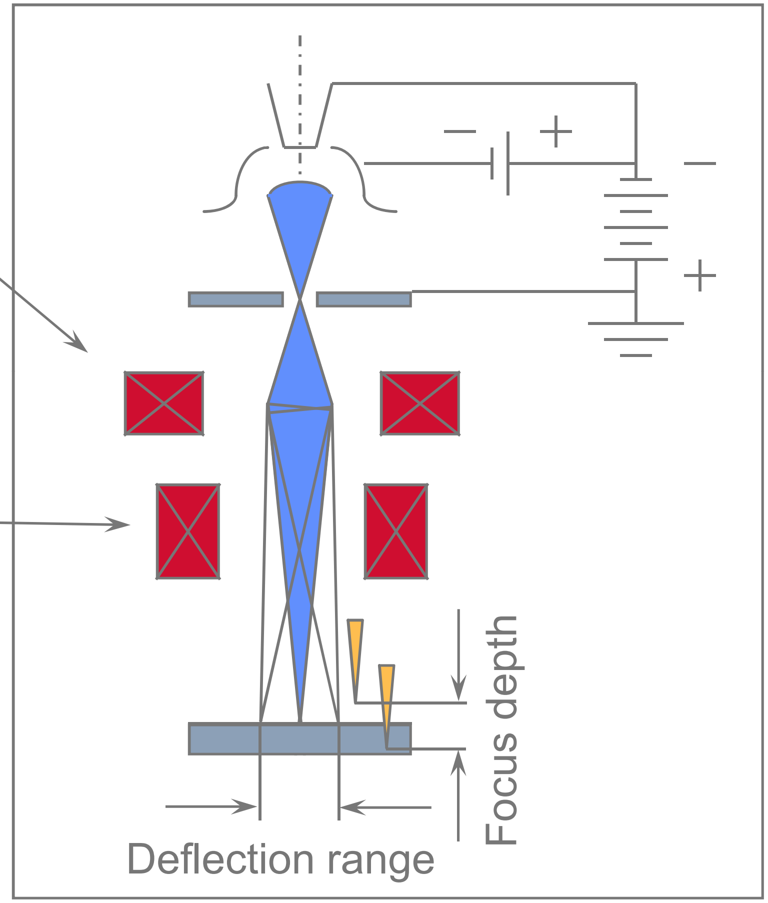


Electron Beam Welding (EBW) – Concept



Control of the Electron Beam

- Electron beam systems employ an electromagnetic lens to focus the electron beam into a small spot on the workpiece
- The deflection coils are generally positioned below the focusing lens, and are used to deflect the electron beam from its normal axial position

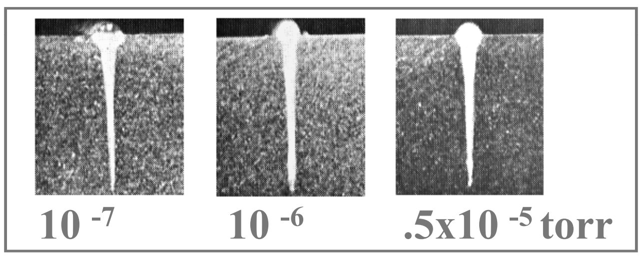


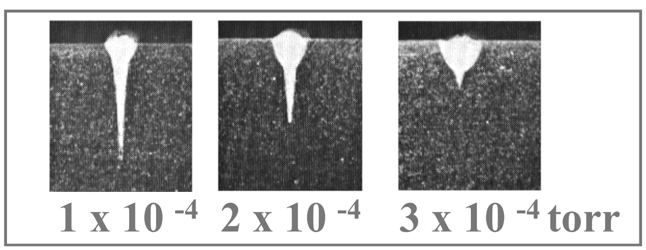
Electron Beam Welding – Key Variables

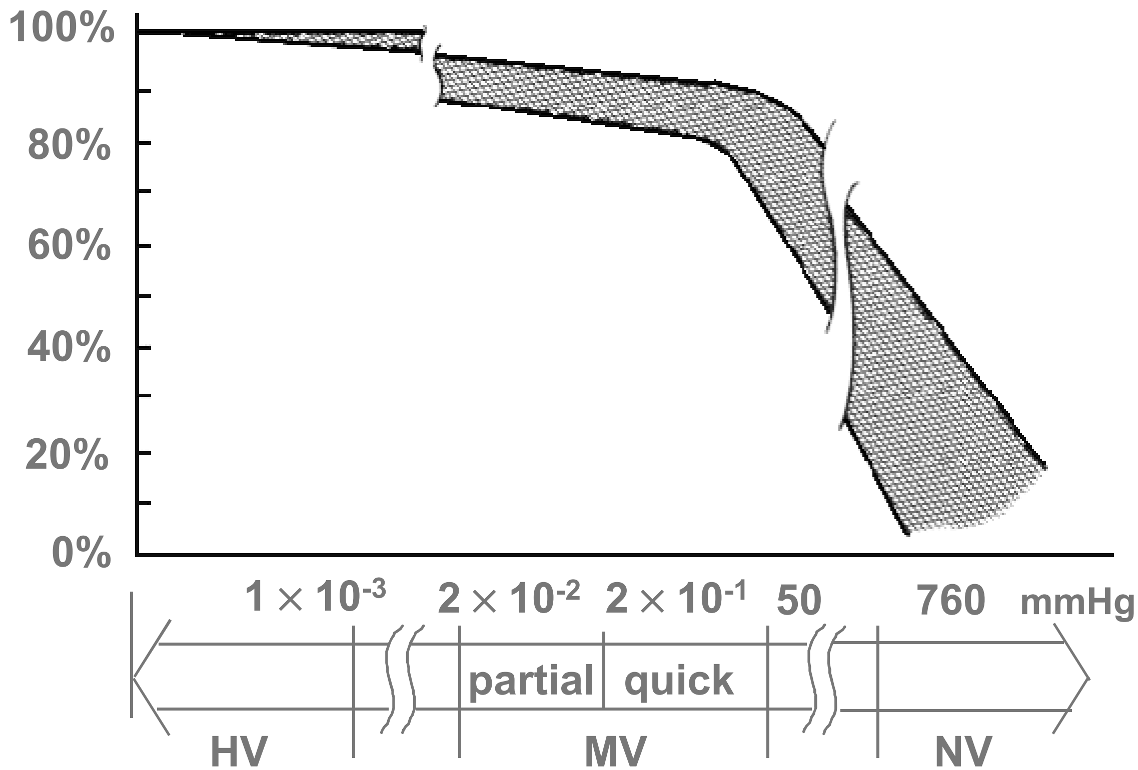
- Factors that affect electron beam welds
  - Electron-beam gun design
  - Focusing
  - Accelerating voltage
  - Beam current
  - Welding speed
  - Vacuum environment

Penetration as a Function of Operating Pressure in Electron Beam Welding

- HV – Hard Vacuum
- MV – Medium Vacuum
- NV – Non-Vacuum

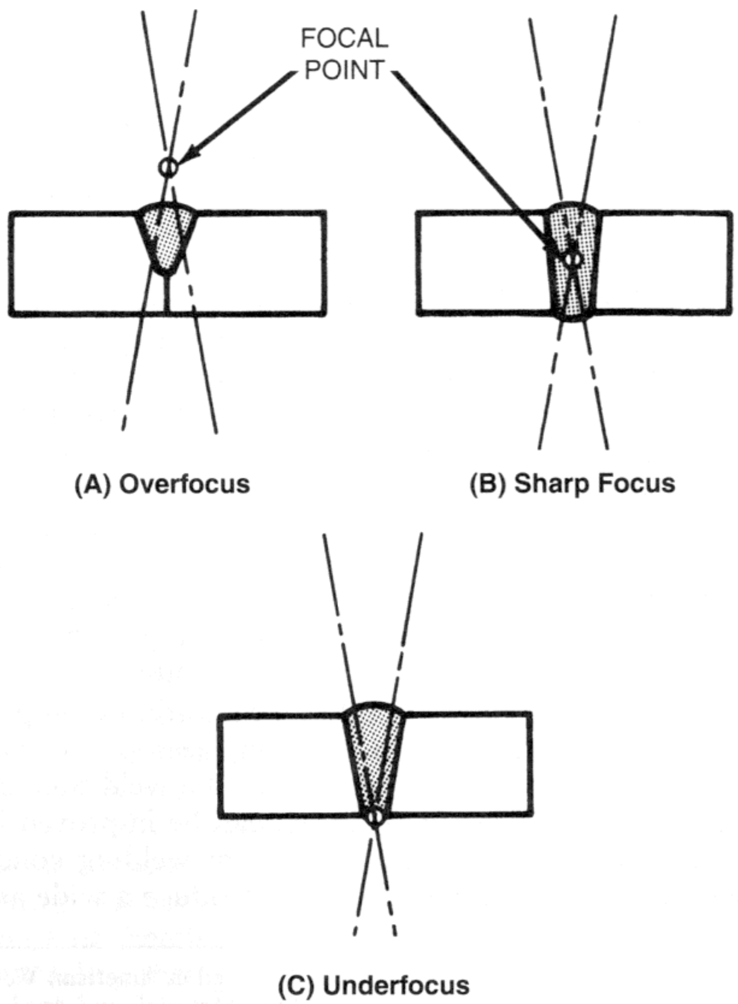






[Ref: “AWS Handbook, Vol. 3, Welding Processes, Part 2, 9th Ed.]

Effect of Electron Beam Focusing on Weld Bead Geometry and Penetration



[Ref: "AWS Handbook, Vol. 3, Welding Processes, Part 2, 9th Ed.]

Electron Beam Safety

- Electric shock risk due to extremely high voltages
- X-rays which are generated when beam contacts parts being welded
- Fumes and gases
- Visible radiation from intense heating

ASME Section IX – Electron Beam Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-404 Filler Metals	.1	φ Cross Section or Speed	X		
	.2	< t or φ Composition	X		
	.8	± or φ Composition	X		
	.14	± Filler	X		
	.20	φ Method of Addition	X		
	.21	φ Analysis	X		
	.33	φ Classification			X
QW-408 Gas	.6	φ Environment	X		

ASME Section IX – Electron Beam Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-409 Electrical Characteristics	.6	φ I, E, Speed, Distance, Osc.	X		
	.7	φ Pulsing Frequency	X		
QW-410 Technique	.5	φ Method of Cleaning			X
	.14	φ Angle or Beam Axis	X		
	.17	φ Type Equipment	X		
	.18	> Pressure of Vacuum	X		
	.19	φ Filament Type, Size, etc.	X		
	.20	+ Wash Pass	X		

Laser Beam Welding (LBW)

- The word “LASER” is an acronym for “light amplification by stimulated emission of radiation”
- A focused Laser Beam Welding (LBW) machine is an excellent source of concentrated power
- Three basic types of lasers are used in welding: gas (CO2), solid-state lasers (Nd:YAG), fiber

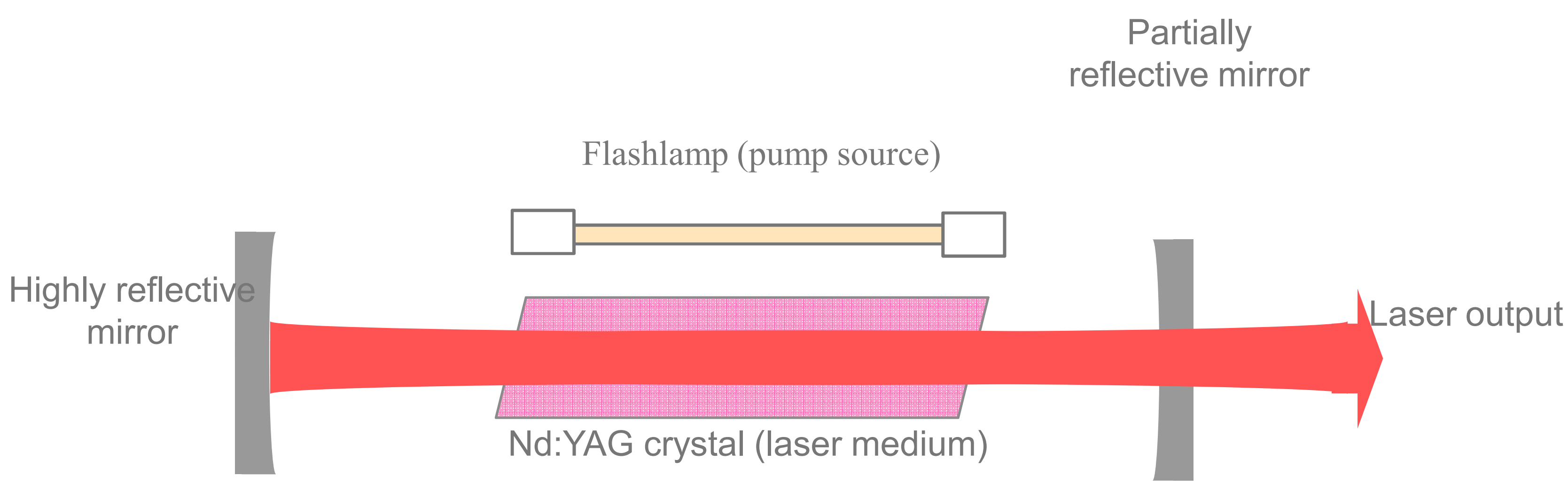
Comparison of LBW to EBW

- No vacuum requirement for LBW – much more conducive to high speed production
- Very flexible beam deliver systems with LBW – ease of automation
- No X-ray hazards with LBW, but eye safety is important
- EBW capable of welding much thicker cross-sections

Three Important Laser Components

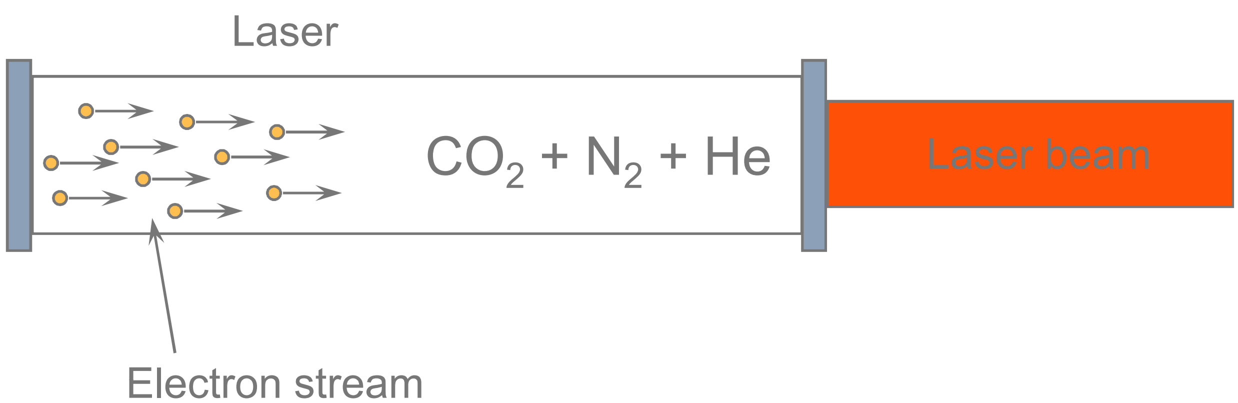
- Laser gain medium
- Pumping energy
- Optical resonator cavity

Nd: YAG solid-state laser



Optical resonator

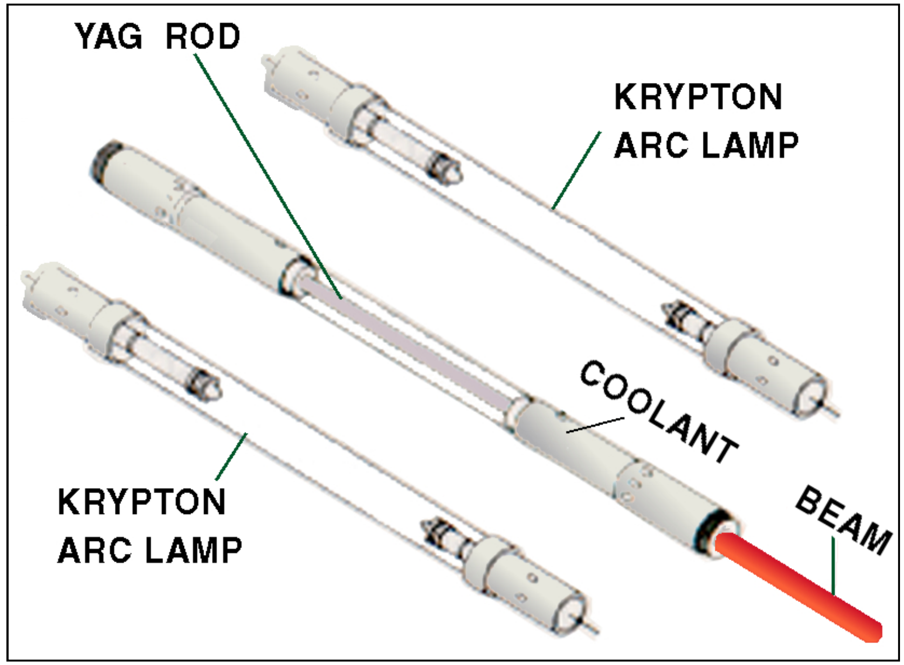
CO_2 Lasers



- Electrical current passes through a low pressure gas mixture of CO_2, nitrogen and helium to excite gas molecules, obtain a population inversion
- Most CO_2 lasers produce either a continuous wave (CW) or pulsed output.
  - The pulses are generated by periodically interrupting the energy input to the laser cavity

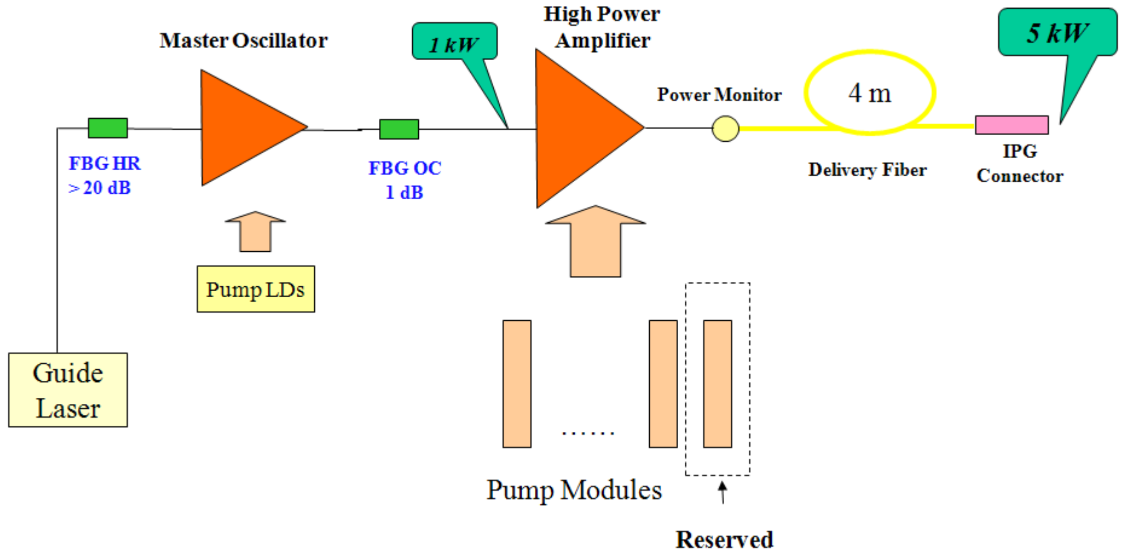
Nd:YAG Lasers

- Lasing medium for the Nd:YAG laser is a transparent rod of yttrium aluminum garnet crystal implanted with neodymium ions
- Laser cavity consists of lamps, mirror reflector and YAG rod
- Nd:YAG laser has a wavelength of 1.06 mm
- Advantages over CO2 laser output
  - Optical fiber delivery, easy to adapt to robotics
  - Increased absorption in metals

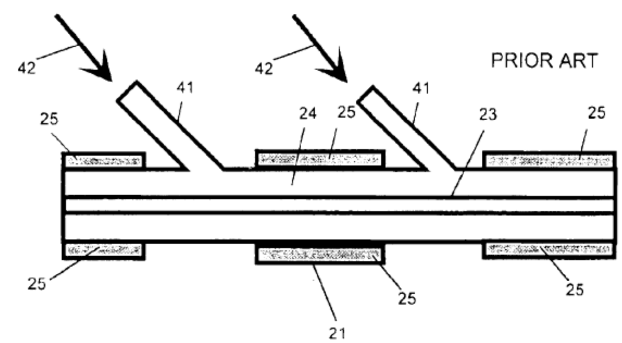


Fiber Lasers

5kW Single Mode



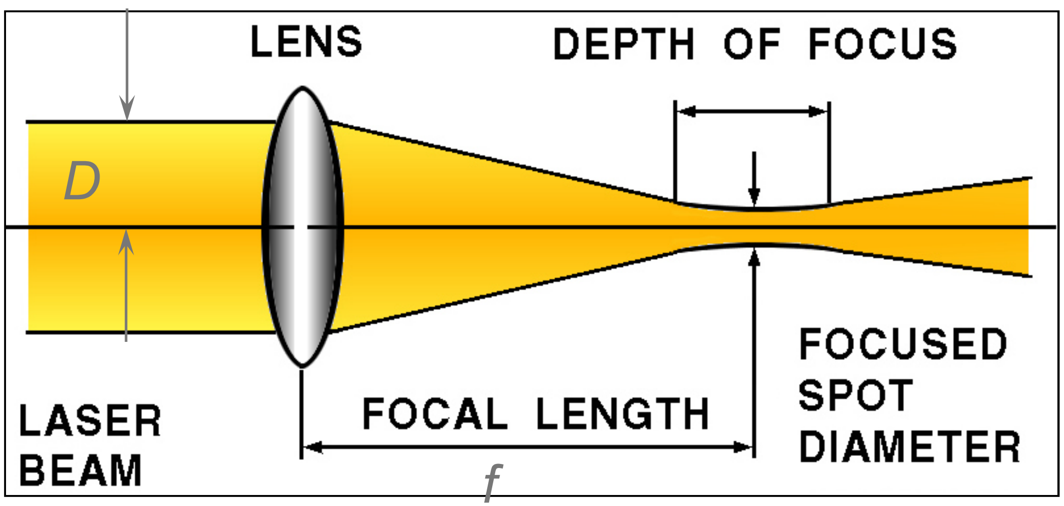
Multi-KW Multi-Mode



Multiple 1kW single mode fibers interfaced to a larger multi-mode fiber by a patented technique

Laser Beam Focusing

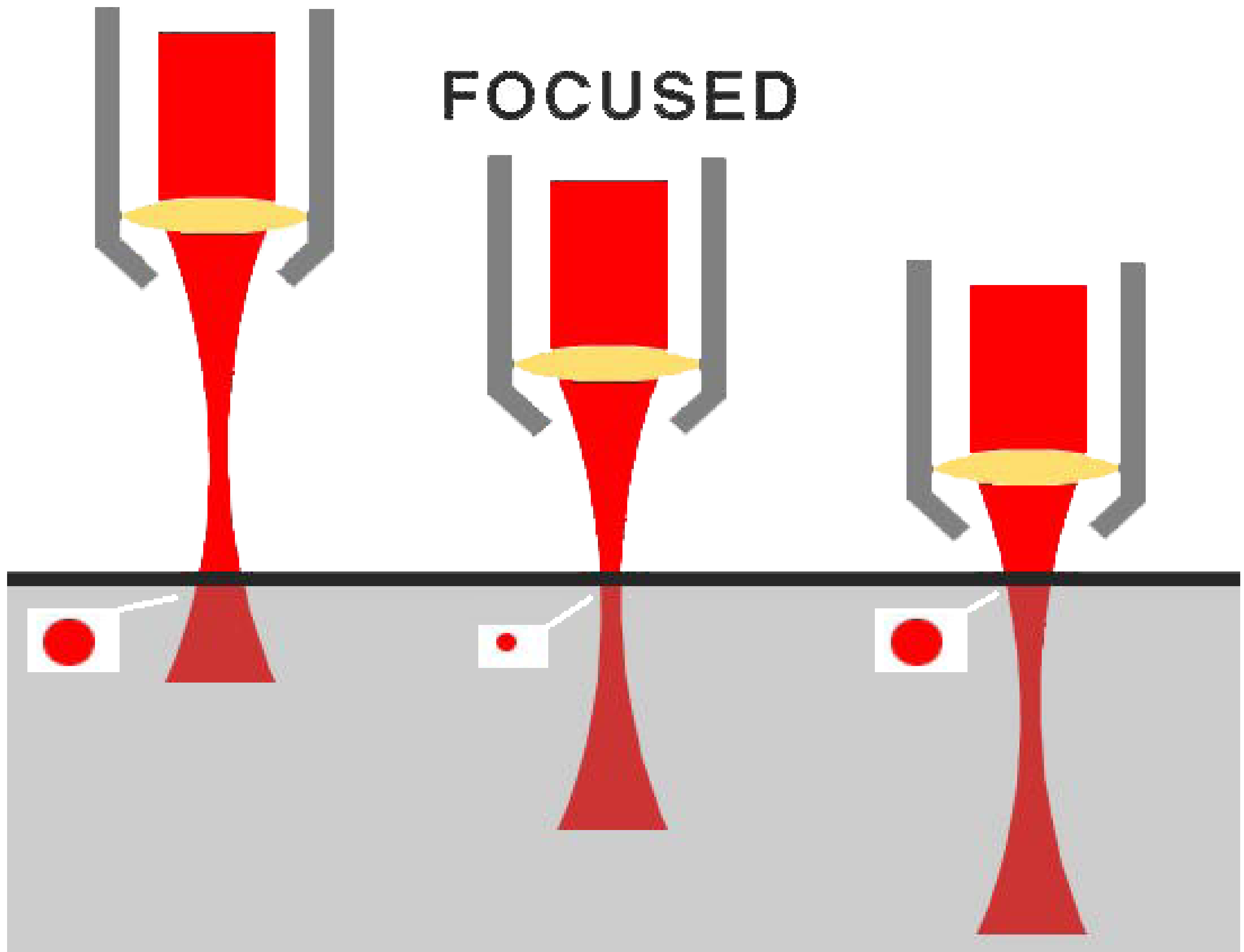
- Focal spot diameter of a high power laser beam is best measured with an optical instrument but can be estimated by spot welds or holes
- Standard optical formulae
  - Focal point diameter » M2 4lf/(pD)
  - Depth of focus = 4M2lf 2/(pD 2)



λ- Wavelength, M^2 – beam quality factor

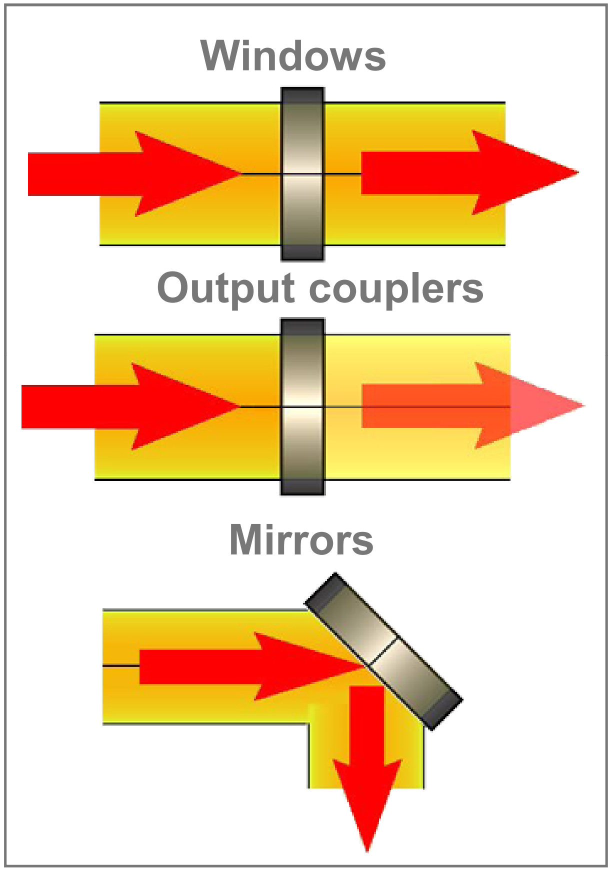
d_s – spot diameter,

Laser Beam Focusing



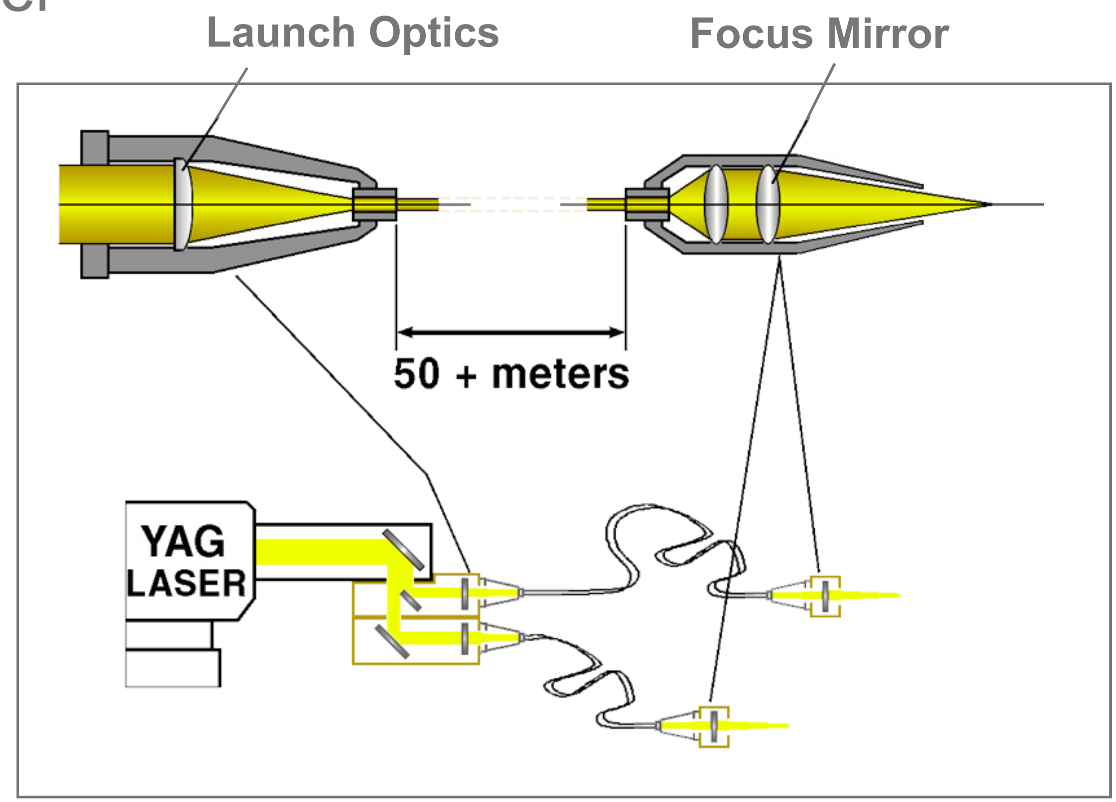
Types of Laser Optics

- The higher power lasers generally employ reflective style optics
  - Mirrors
- These mirrors are usually water cooled to withstand high incident powers
- They may be either bare or coated
- Highly polished, bare copper mirrors are commonly employed, but gold-coated mirrors will provide the highest reflectivity



Fiber Optics

- Working distances up to 150 m
- Can reach difficult-to-access places
- Can be taken under water
- Multi-station operation
- Robotics applications
- Flexibility



Laser Safety

- Carbon dioxide laser machines have a good industrial safety record
- Very few serious beam related accidents reported
- Certain lasers such YAG and Fiber Lasers require special eye protection to filter out their dangerous wavelength
- Danger associated with high voltage system used to generate the electrical discharge
- Lasers pose serious eye and burn hazards

ASME Section IX – LBW Process Procedure Variables

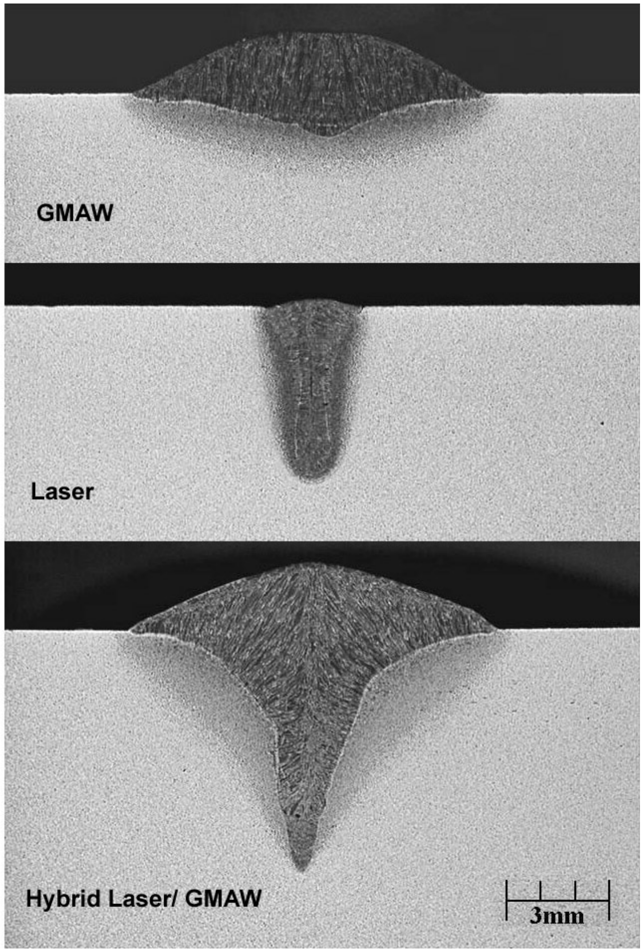
Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-404 Filler Metals	.1	φ Cross Section or Speed	X		
	.2	< t or φ Composition	X		
	.8	± or φ Composition	X		
	.14	± Filler	X		
	.20	φ Method of Addition	X		
	.21	φ Analysis	X		
	.33	φ Classification			X
QW-408 Gas	.2	φ Single, Mixture, or %	X		
	.6	φ Environment	X		
	.11	± Gases	X		
	.12	φ > 5% Gases	X		
	.13	φ Plasma Jet Position	X		

ASME Section IX – LBW Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-409 Electrical Characteristics	.19	φ Pulse	X		
	.20	φ Mode, Energy	X		
	.21	φ Power, Speed, D/fl, Distance	X		
QW-410 Technique	.5	φ Method of Cleaning			X
	.14	φ Angle or Beam Axis	X		
	.17	φ Type Equipment	X		
	.20	+ Wash Pass	X		

Hybrid Laser Welding

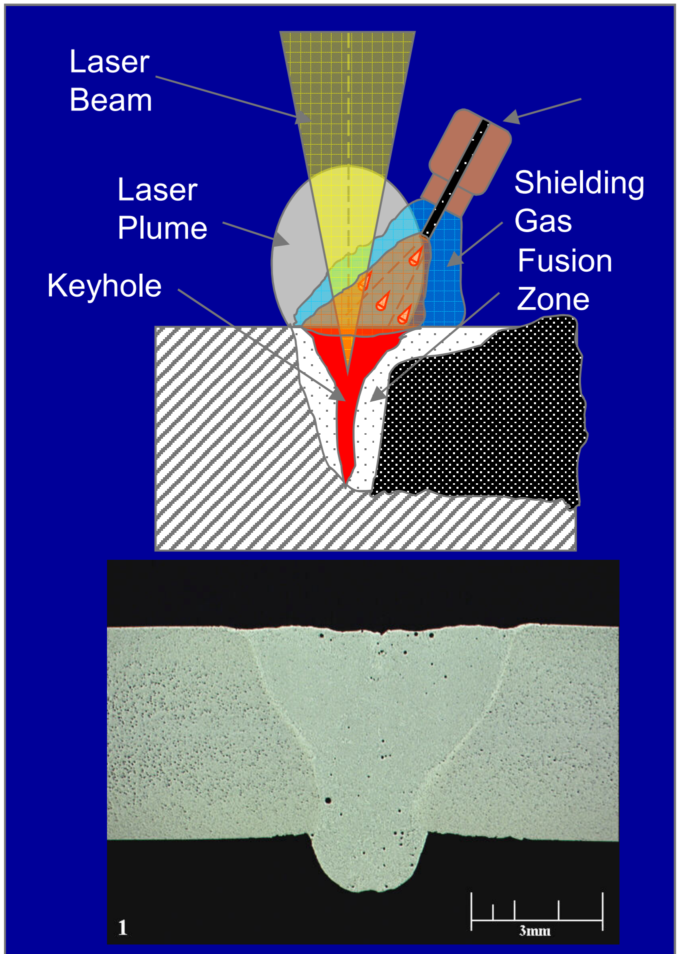
- Reflects a recent trend toward combining two welding processes into one
- Very common approach is to combine LBW and GMAW
- Utilizes the advantages of each process and minimizes the disadvantages
  - High welding speed of LBW
  - Wider weld profile of GMAW provides better tolerance to weld gap and alignment
  - Laser stabilizes arc
  - Flexibility of fiber delivery with LBW
  - Capability for weld reinforcement with GMAW



[Courtesy: EWI]

Hybrid Laser Welding

- Laser beam "leads" the weld puddle
- Laser spot stabilizes the arc
- Laser and GMAW is the most common hybrid process, but other combinations are being explored
- ASME Section IX is currently working to incorporate laser hybrid as a welding process



Hybrid Weld in Aluminum

[Courtesy: EWI]

Hybrid Laser GMAW

Solid-State Welding

Module 2B.2

Solid-State Welding Overview

- A group of welding processes that produces a metallurgical bond between two metals at temperatures below the melting point of the base metal”

- Fundamentals
  - Metallic bonding
  - Barriers to bonding
  - Overcoming barriers to bonding
  - Roll bonding theory
- Processes
  - Friction Welding
  - Diffusion Welding
  - Explosion Welding
  - Ultrasonic Welding

Advantages Compared to Arc Welding Processes

- Elimination of molten metal reduces the chance for forming weld defects
- Dissimilar metal joints are possible
- Usually produces very high quality, high strength weld joints
- Consumables such as filler metals and shielding gas are not required
- Often used for welding materials that cannot be welded with conventional welding processes

Disadvantages Compared to Arc Welding Processes

- Usually requires expensive equipment
- Not always conducive to high production
- Significant joint preparation is sometimes required
- Limited joint designs
- Non-destructive inspection can be difficult

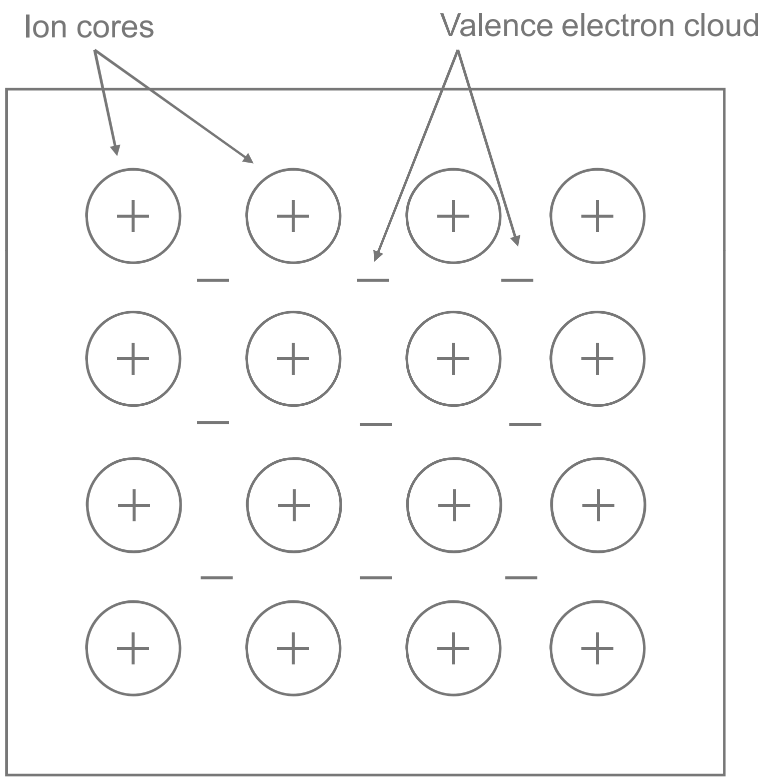
Applications

- Jet engines
- Automotive components
- Cookware
- Electrical devices
- Microelectronics
- Heat exchangers
- Medical products
- Many more!

[Source: Internet]

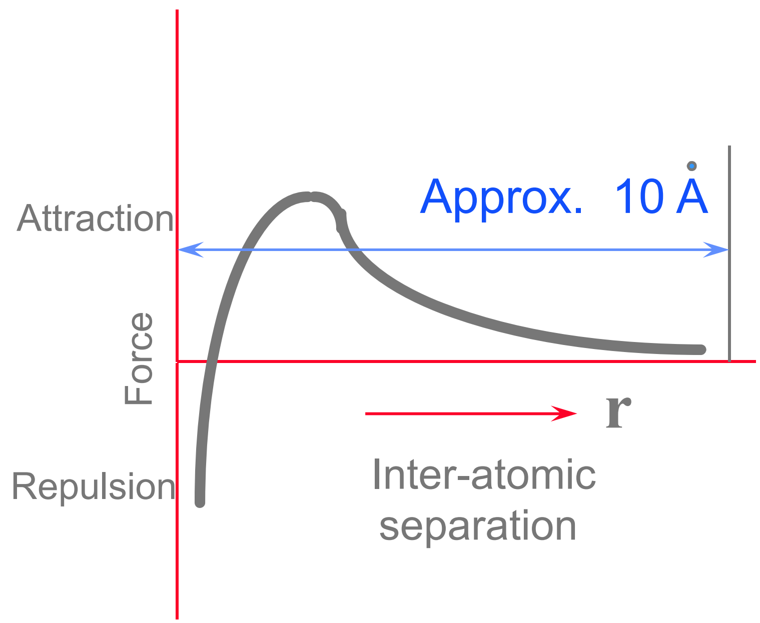
Metallic Bonding

- Valence electrons are not bound to a single atom and are free to drift (which is why metals conduct electricity) to form a “cloud” of electrons
- Remaining non-valence electrons and atomic nuclei form ion cores
- The binding forces between the ion cores and electron cloud hold the atoms together



Metallic Bonding

- Driving force for bonding of metals:
  - Adhesion, (formation of metallic bonds) between two metal surfaces can occur due to inter-atomic forces described previously
  - To occur, the two surfaces must be brought extremely close together ~ 10 A – a nearly perfectly smooth surface!
  - No industrial process is capable of achieving such a smooth surface

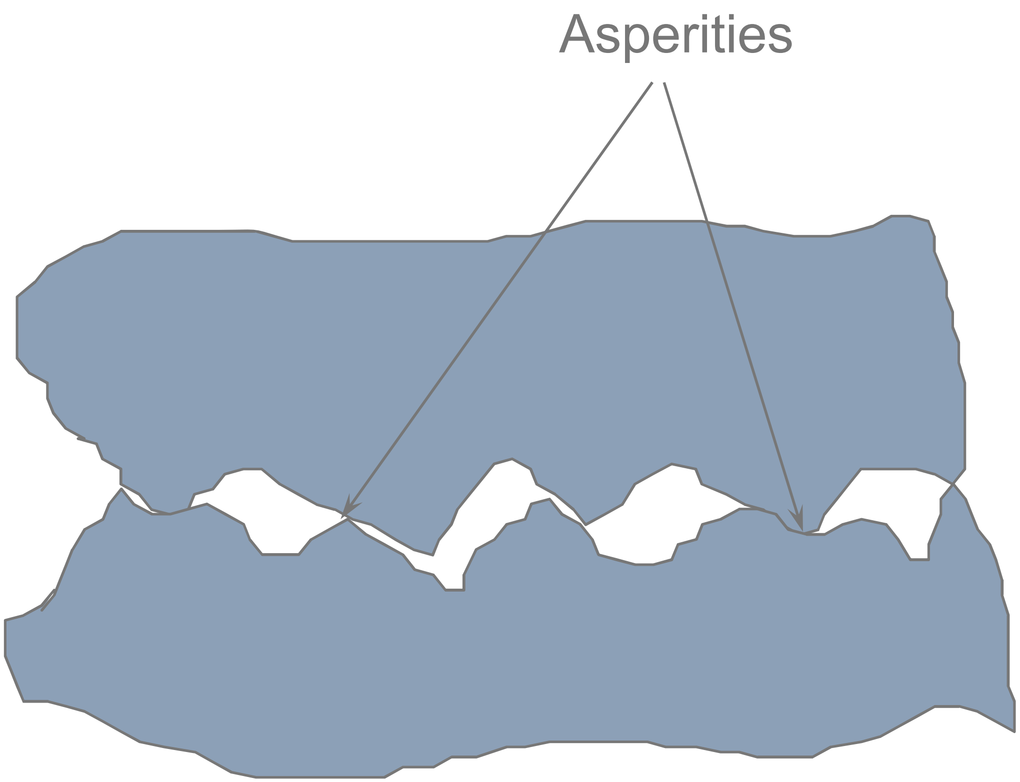


Metallic Bonding

- If there is a driving force for welding, why aren't metals easily welded with Solid-State Welding Processes?
  - Barriers to bonding hinder intimate contact:
    - Asperities (surface roughness)
    - Oxides
    - Surface contamination

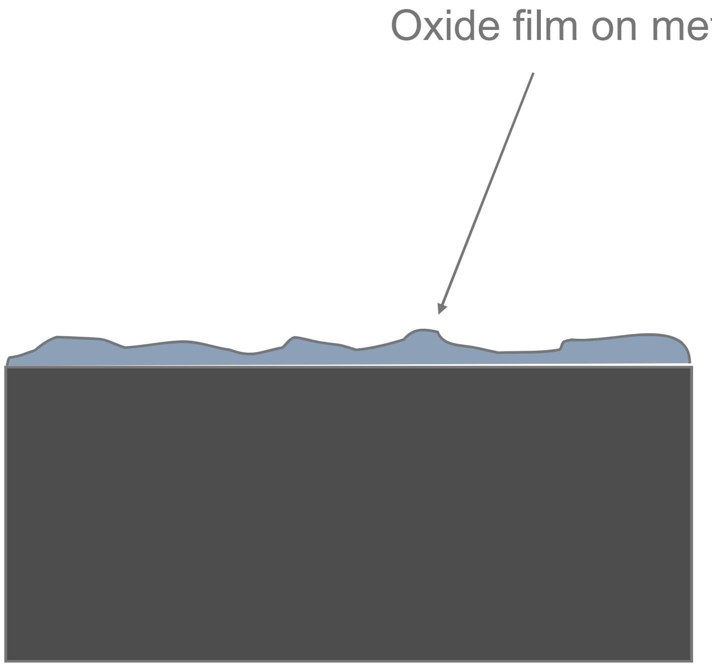
Interfaces - Asperities

- Barriers to Solid-State Welding – asperities
  - High and low areas of metal surfaces
  - Prevent intimate contact
  - All metals will have some surface roughness



Interfaces - Oxides

- Barriers to Solid-State Welding – oxides
  - Most metals react with atmosphere and form oxide films
  - Oxide films are hard and brittle and interfere with metal-to-metal contact
  - Sufficient deformation is required to break up oxide films during Solid-State Welding

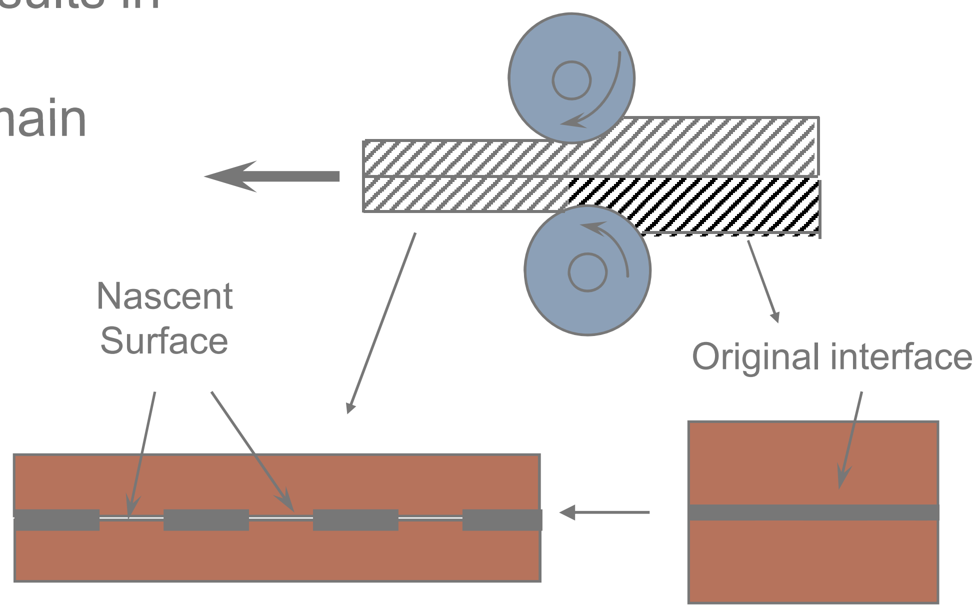


Interfaces - Contamination

- Barriers to Solid State Welding - surface contamination:
  - Oils, scales, grease, etc.
  - Adhere to surface by secondary bonding
  - Reduce metal-to-metal contact
  - Must be removed prior to welding, or during the Solid-State Welding process being utilized

Roll Bonding

- Roll bonding theory
  - Roll bonding introduces nascent surface – new metal-to-metal surfaces formed during plastic deformation
  - Asperities are collapsed and oxides broken up
  - Increased nascent surface results in increased weld strength
  - This theory is describes the main objective of most Solid-State Welding processes
    - Create nascent surfaces



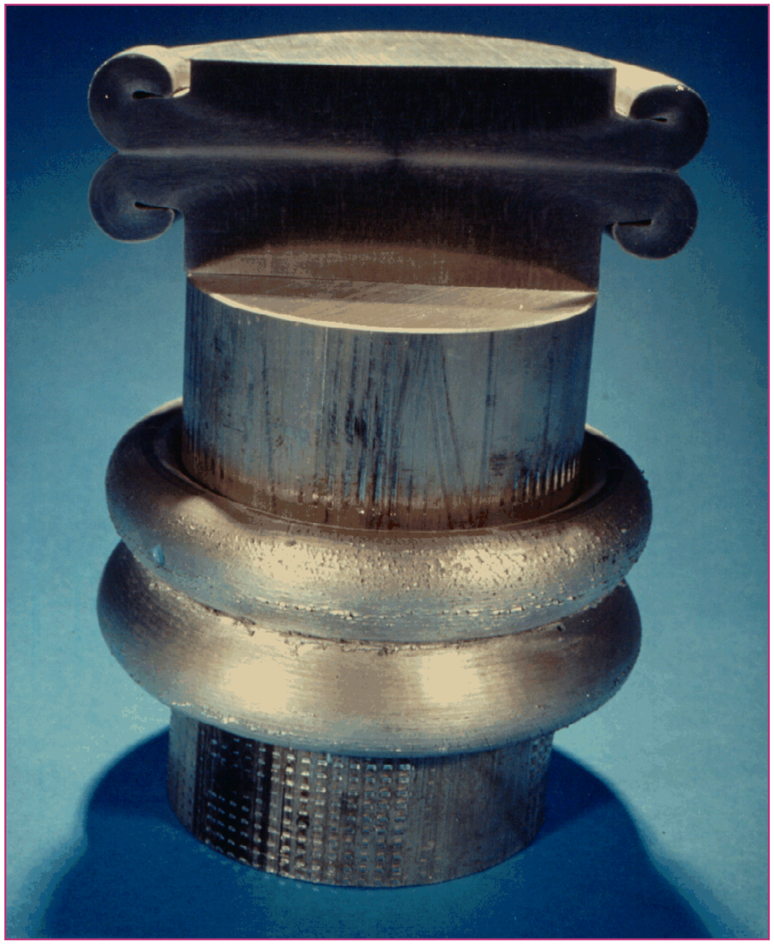
Roll bonding produces nascent surfaces needed for Solid-State Welding

Friction Welding Processes

- Processes – Friction Welding
  - Inertia Friction Welding
    - Inertia of rotating flywheel generates heat
  - Continuous Drive Friction Welding
    - Continuous drive system (i.e. hydraulic) for more precise control of rotational velocity and frictional heating
  - Friction Stir Welding
    - Non-consumable pin rotated along joint to produce frictional heating
  - Linear Friction Welding
    - Linear translation of parts in contact with each other produces frictional heating

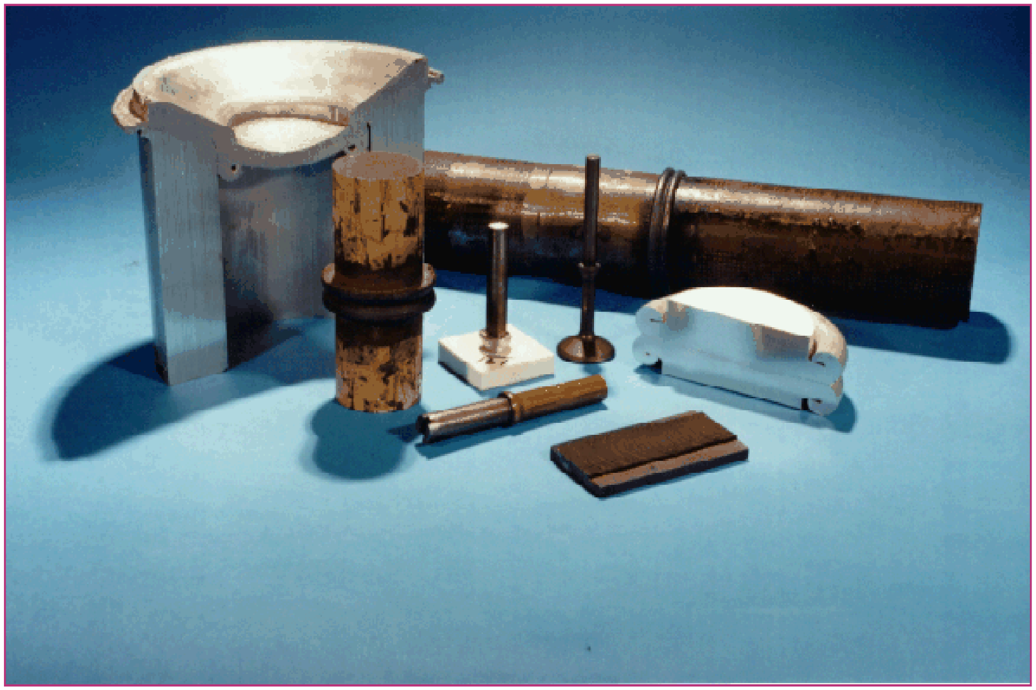
Friction Welding Processes

- Friction Welding – Advantages
  - Extremely reproducible, high quality joints
  - Fewer variables than most welding processes
  - Forging action reduces need for joint preparation
  - Ideal for joining dissimilar materials
  - Easily automated for high volume production
  - Can join plastics



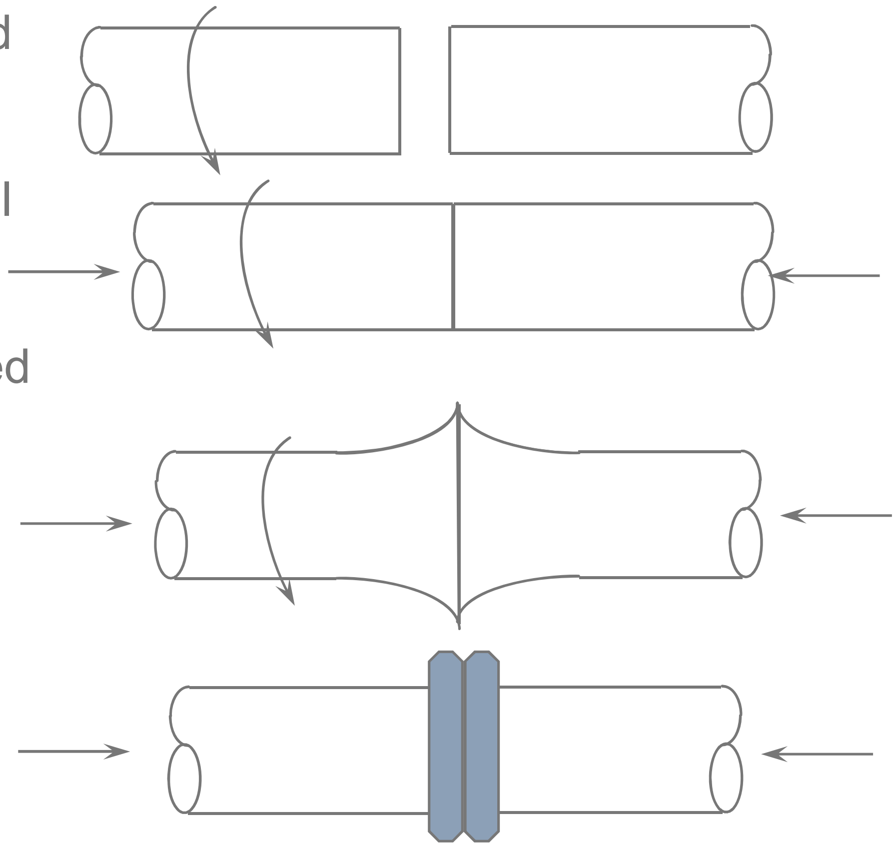
Friction Welding Processes

- Friction Welding – Disadvantages
  - Equipment cost is high
  - Application limited by part geometry and size
  - Some processes (i.e. Friction Stir Welding are slow)
  - Difficulty in joining dissimilar materials with large differences in properties



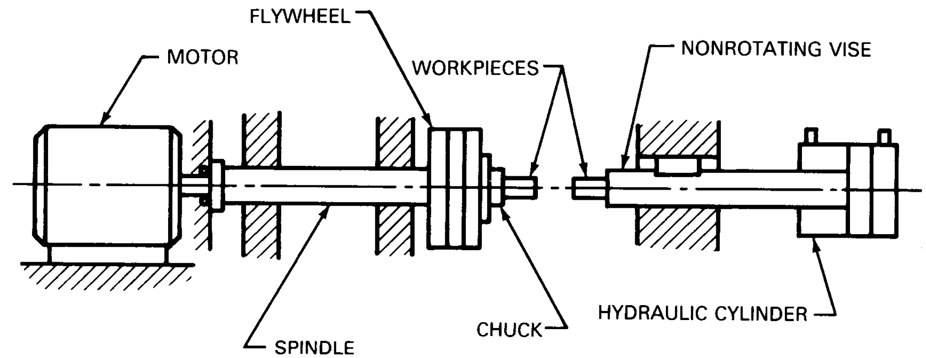
Friction Welding Processes

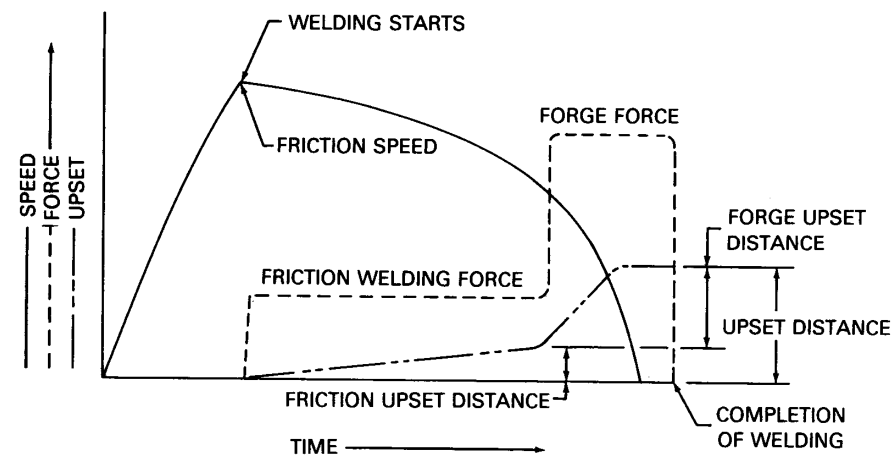
- Rotational Friction Welding Processes
  - Inertia and Continuous Drive Friction Welding
    - Ideal for round bars and shapes
    - One part is rotated at high speed relative to other part
    - Parts are brought together, axial force is applied creating frictional heating
    - Softened material is upset into the “flash”, which is later removed



Inertia Friction Welding (IFW)

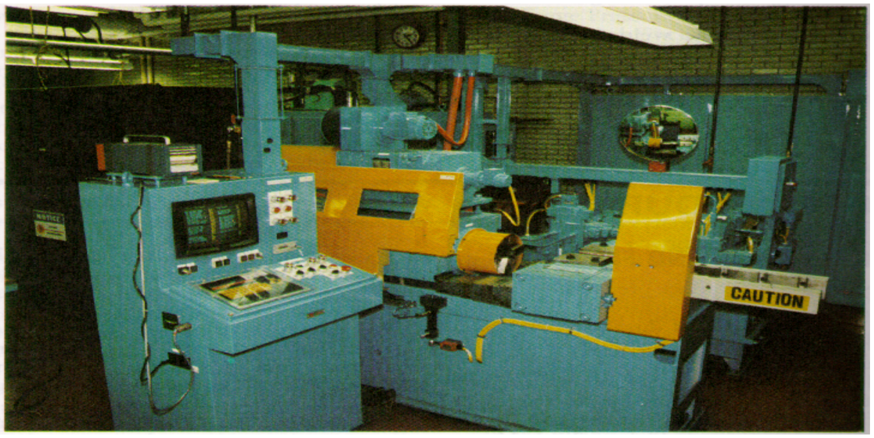
- Utilizes kinetic energy of rotating flywheel
- Flywheel connected to one part while other remains stationary
- Flywheel rotational velocity gradually decreases as joint cools and gains strength
- Additional forge force is added at the end of the cycle
- Ideal process for large parts
  - Common in jet engine manufacturing

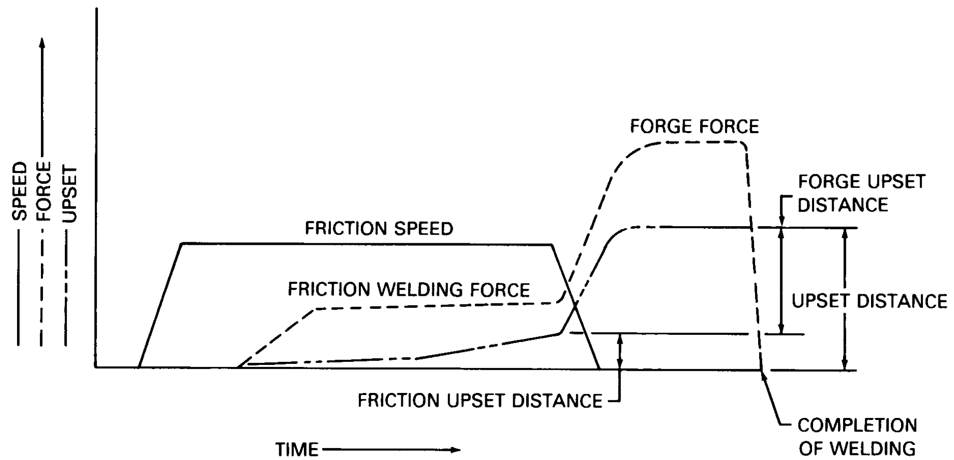




[Ref.: AWS Welding Handbook, Vol. 3, 9th Ed.]

Continuous Drive Friction Welding (CDFW)





[Ref.: AWS Welding Handbook, Vol. 3, 9th Ed.]

- Motor driven
- Rotational speed is controlled and held constant during the heating stage
- Provides better control of welding variables vs. Inertia Welding

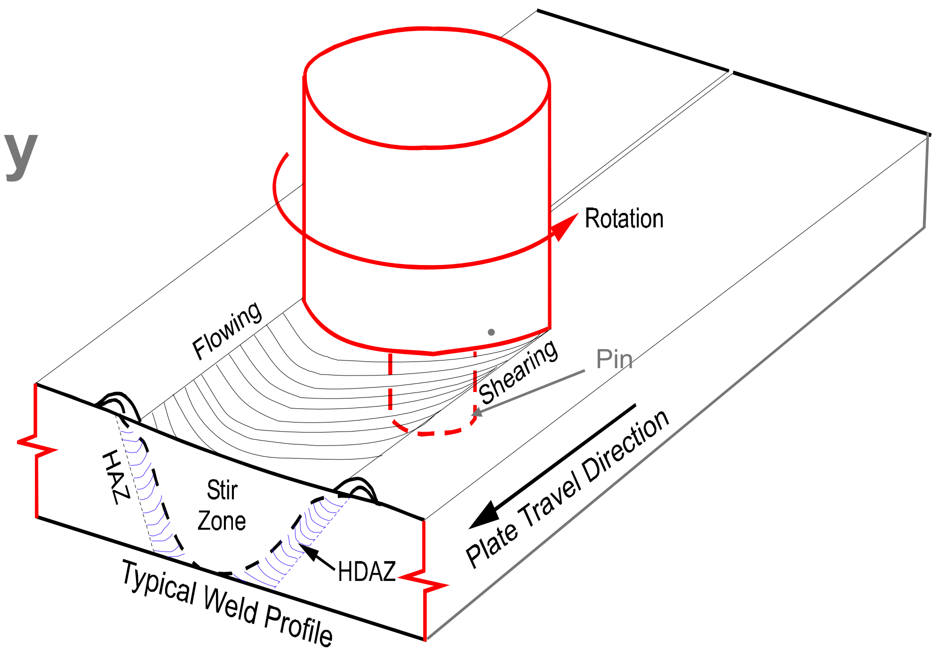
Also referred to as Direct Drive Friction Welding

ASME Section IX – IFW and CDFW Process Procedure Variables

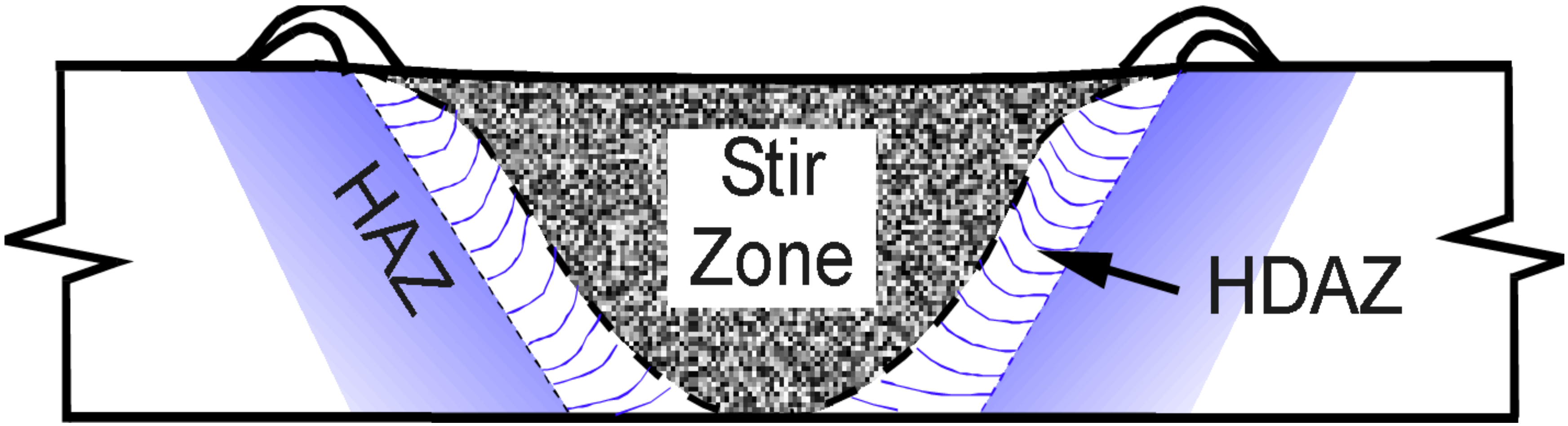
Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-402 Joint	.12	φ ± 10 deg	X		
		φ Cross Section > 10%	X		
		φ O.D. > ± 10%	X		
		φ Solid-to-tube	X		
QW-408 Gas	.6	φ Environment	X		
QW-410 Technique	.27	φ Spp. > ± 10%	X		
	.28	φ Load > ± 10%	X		
	.29	φ Energy > ± 10%	X		
	.30	φ Upset > ± 10%	X		

Friction Stir Welding

- Rotating tool is moved along top of the joint creating frictional heat and plasticized material in the stir zone
- Provides the ability to produce solid-state friction welds in a butt joint configuration between two plates
- Ideal for welding materials which are difficult to weld using fusion welding processes
- **ASME Section IX is currently working to incorporate friction stir as a welding process**

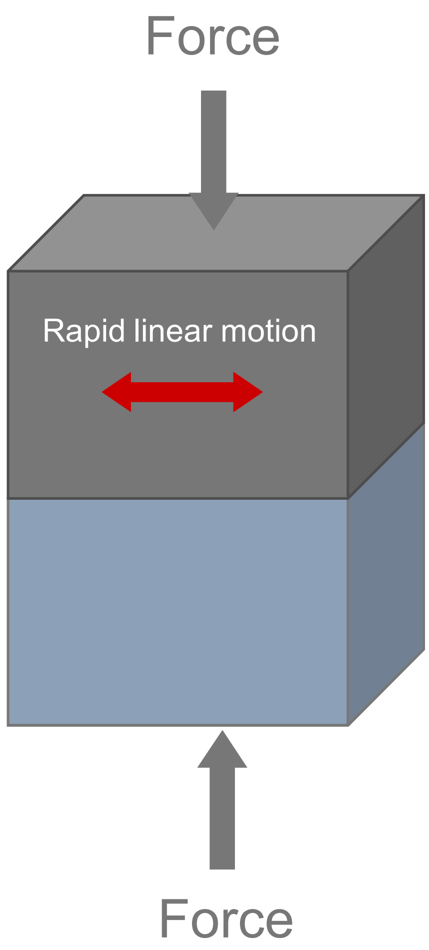


Friction Stir Welding



- Friction Stir welds consist of three distinct “zones”:
  - Stir zone or nugget
  - Heat and deformation affected zone (HDAZ) or thermo-mechanically affected zone (TMAZ)
  - Heat affected zone (HAZ)

Linear Friction Welding

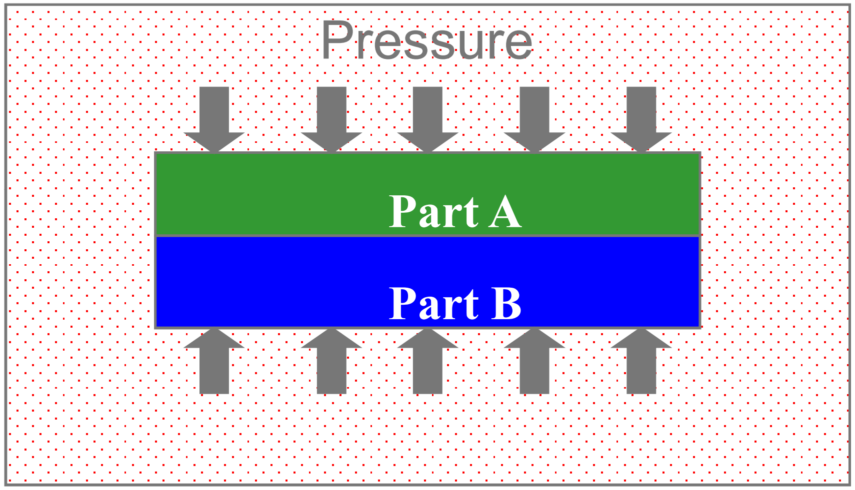


- Linear motion between two parts creates frictional heating and solid-state weld
- Provides for flexibility of part geometry
- Sometimes referred to as Translational Friction Welding
- Another variation utilizes orbital motion

Diffusion Welding

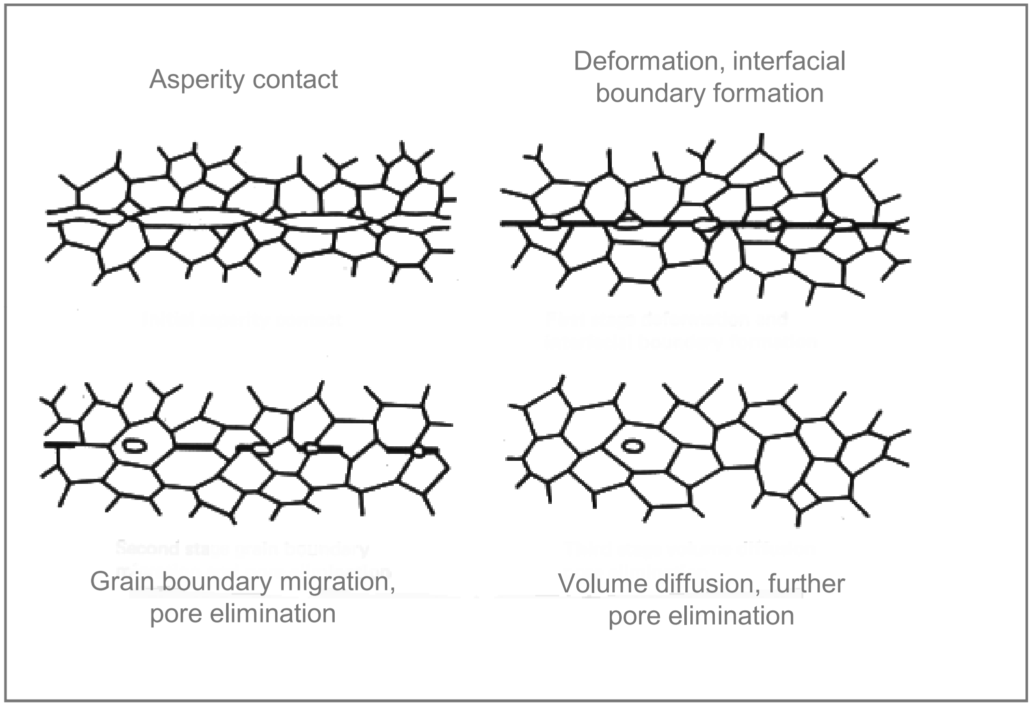
- A welding process that creates a solid-state weld through the application of pressure at elevated temperatures

- Advantages
  - Negligible deformation
  - Low heat process – minimal microstructure degradation
- Disadvantages
  - Significant surface preparation required
  - Long weld times



Elevated Temperature Furnace

Diffusion Welding

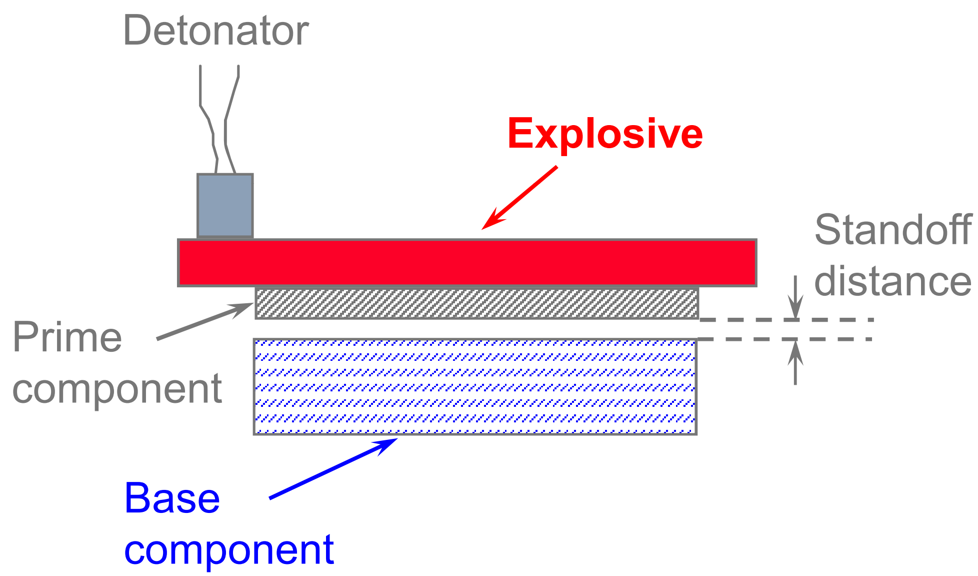


- Stage 1 – initial asperity contact
- Stage 2 – deformation and formation of interfacial boundary
- Stage 3 – grain boundary migration, elimination of interfacial boundary, pore elimination
- Stage 4 – volume diffusion, further elimination of interfacial boundary and pores

Explosion Welding

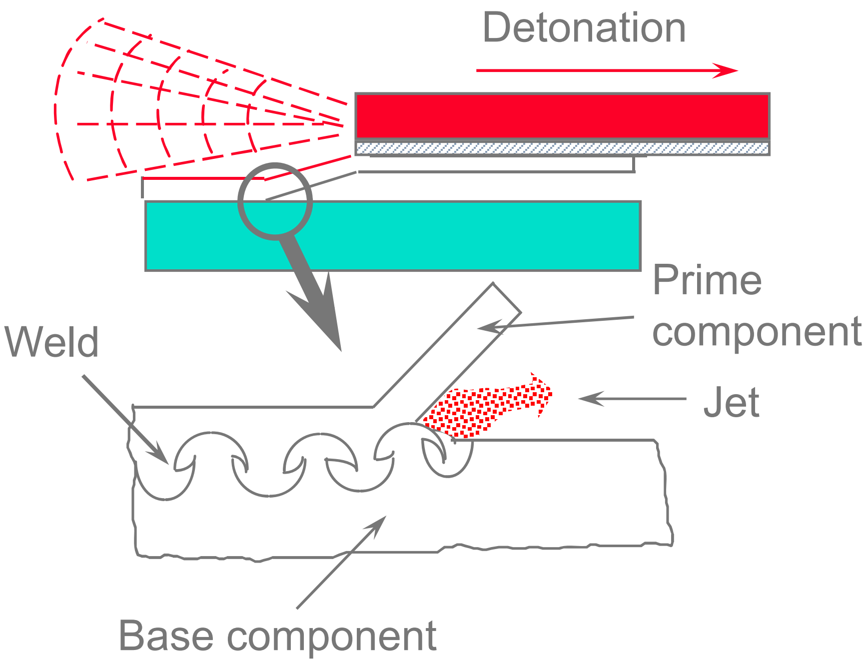
- A welding process that creates a solid-state weld through high velocity interaction of the work pieces by a controlled detonation

- Advantages
  - Minimal heating of the parts
  - Can produce almost any dissimilar metal combination
- Disadvantages
  - Not conducive to production
  - Limited joint designs



Arrangement for Explosion Welding

Explosion Welding



- Principals of Explosion Welding
  - Explosive is distributed over top surface of prime component
  - Upon detonation, high velocity collision occurs between prime and base component
  - “Jetting” provides for cleaning action and proper weld formation

Ultrasonic Welding

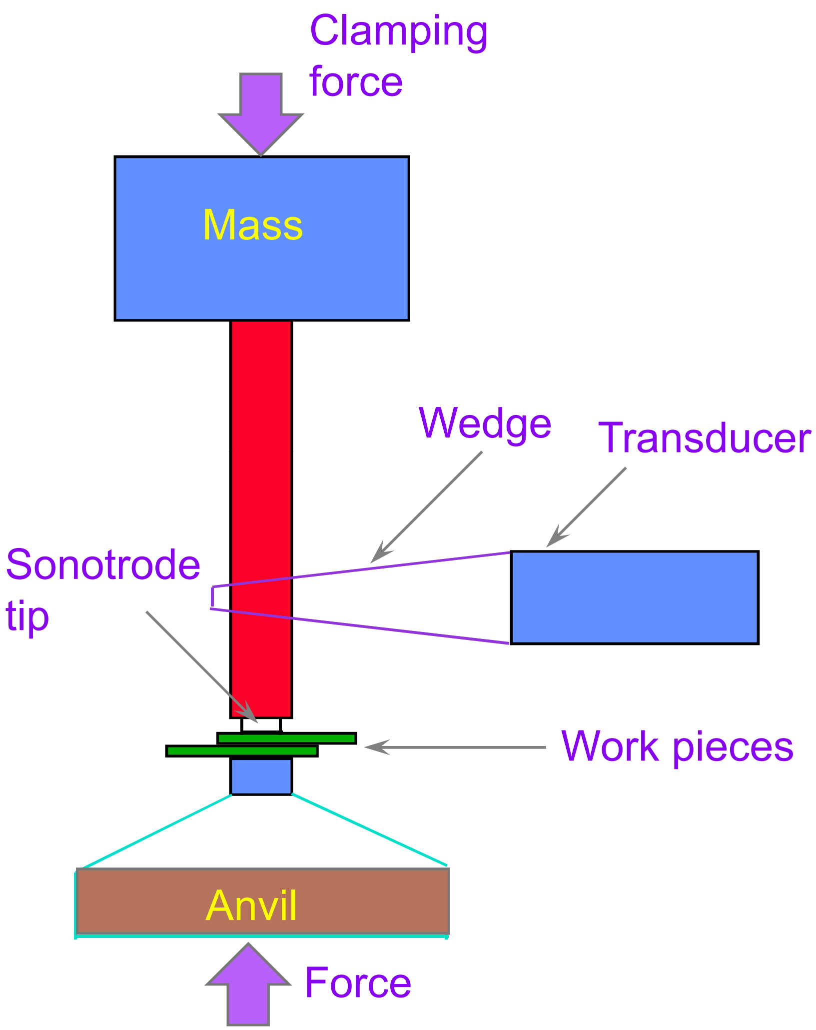
- A welding process that produces a solid-state weld through the application of high frequency vibrations combined with low pressure

- Advantages:
  - Negligible heating of parts
  - Minimal deformation
- Disadvantages
  - Limited to lap joints
  - At least one component must be very thin

Typical Ultrasonic Welding Machines

[Source: Internet]

Ultrasonic Welding



- Principals of Ultrasonic Welding
  - A static clamping force is applied perpendicular to the interface between the work pieces
  - The contacting sonotrode oscillates parallel to the interface
  - Combined effect of static and oscillating force produces deformation which promotes welding

Solid-State Welding

- Some applicable specifications and recommended practices
  - AWS C6.1, "Recommended Practices for Friction Welding"
  - AWS C6.2, "Specification for Friction Welding of Metals"
  - ASME Section IX currently has requirements for only IFW and CDFW solid-state welding processes
    - Requirements for Friction Stir Welding are being developed
- Very limited information in terms of codes, standards, and specifications
  - Solid-state weld development is typically based on applicable fusion welding codes

Resistance Welding

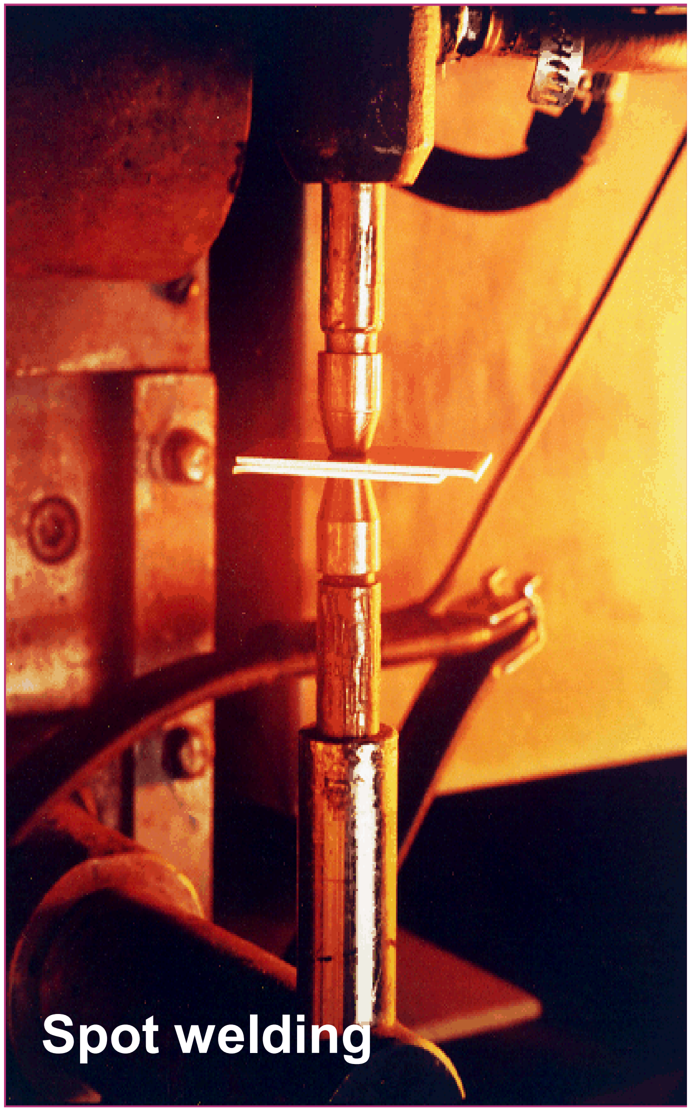
Module 2B.3

Resistance Welding Overview

- Fundamentals
  - Resistivity and Heat Generation
  - Heat Balance
- Common processes
  - Spot Welding
  - Projection Welding
  - Seam Welding
  - Flash Welding
- AWS has numerous resistance welding codes for different applications
  - AWS C1.1, "Recommended Practices for Resistance Welding"
  - AWS C1.4, "Specification for Resistance Welding of Carbon and Low Alloy Steels"
  - AWS D8.6, "Standard for Automotive Resistance Spot Welding Electrodes"

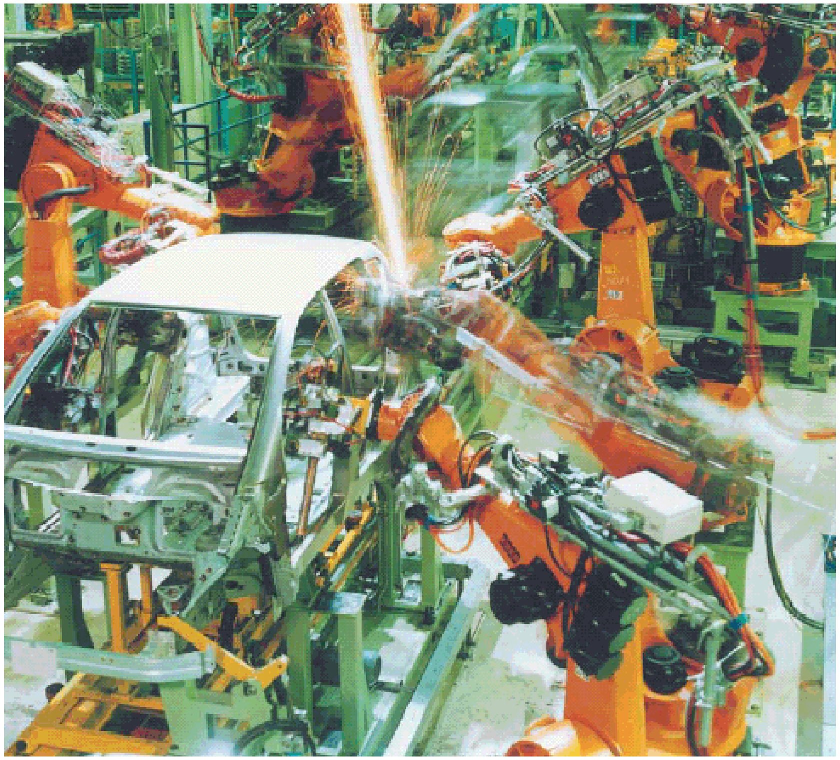
Definition of Resistance Welding

- The electrical resistance of metal and metal-to-metal contact area to the localized flow of current produces heat (Joule heating = $I^2 \times R_t$) at the joint
- This heating, combined with pressure produces a weld
- Welds may be fusion or solid-state welds



Resistance Welding Applications

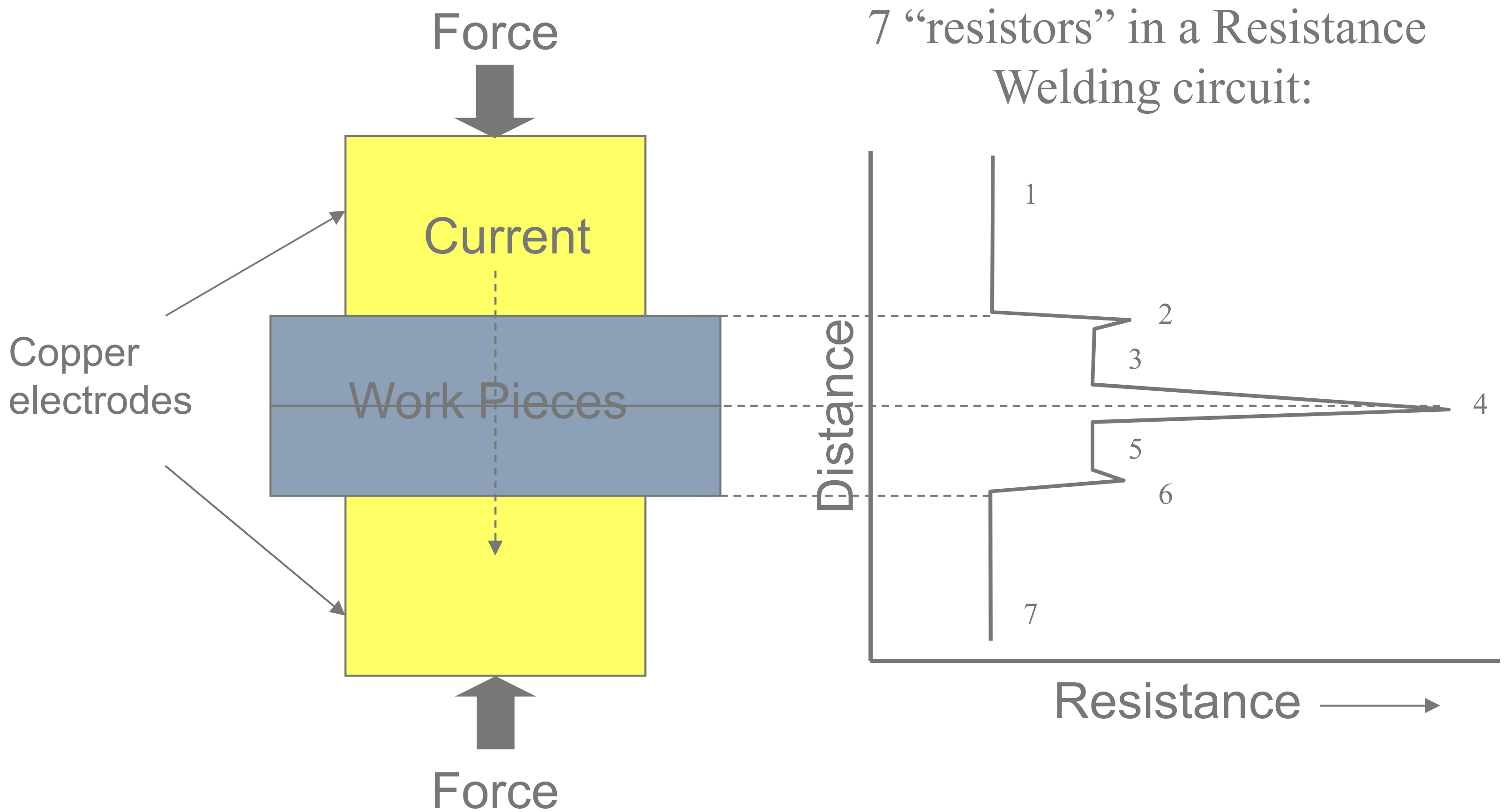
- Automotive
  - Bodies
  - Frames
  - Components
- Medical
- Tubing
- Appliances
- Electrical
- Light manufacturing
  - Fencing
  - Grills
  - Chains
  - Office products
- "Every metal product is a possible application" – RWMA Handbook



[Source: Internet]

Resistance Welding Fundamentals – Resistivity at Joint

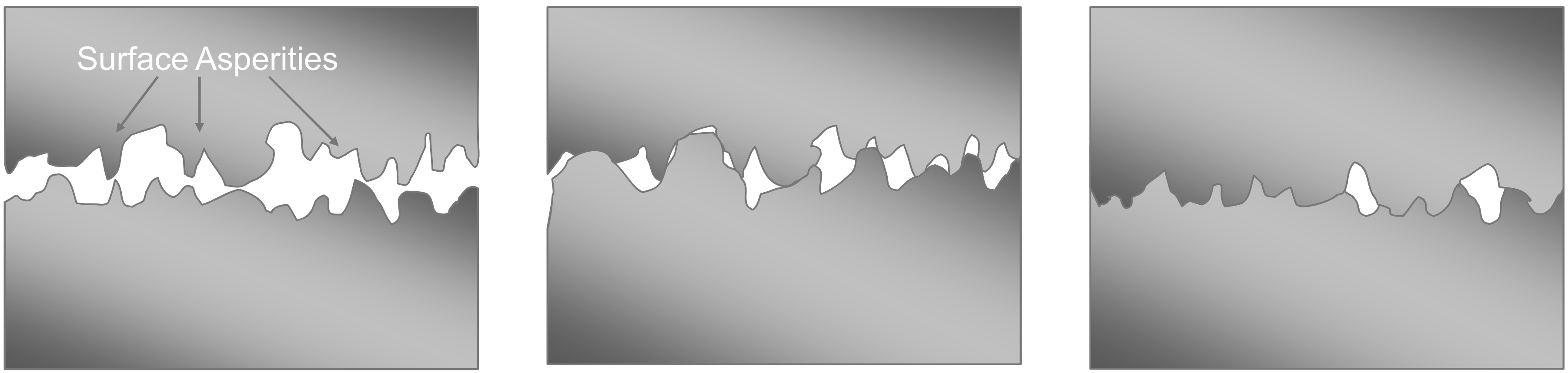
Ideal Resistance Welding conditions occur when resistance #4 is maximized relative to other 6:



Resistance Welding Fundamentals – Effect of Pressure

High Resistance

Low Resistance

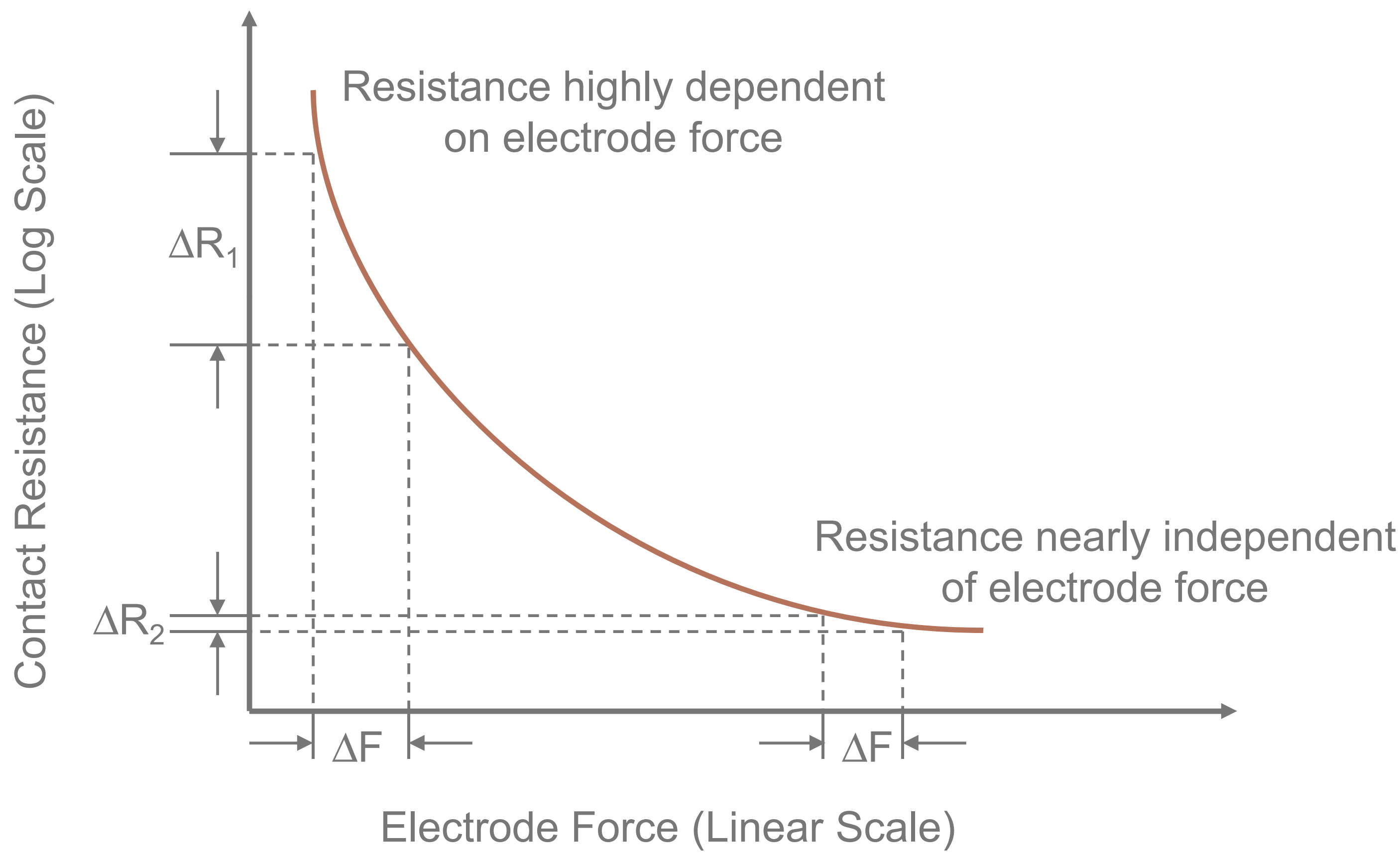


Low Pressure

Medium Pressure

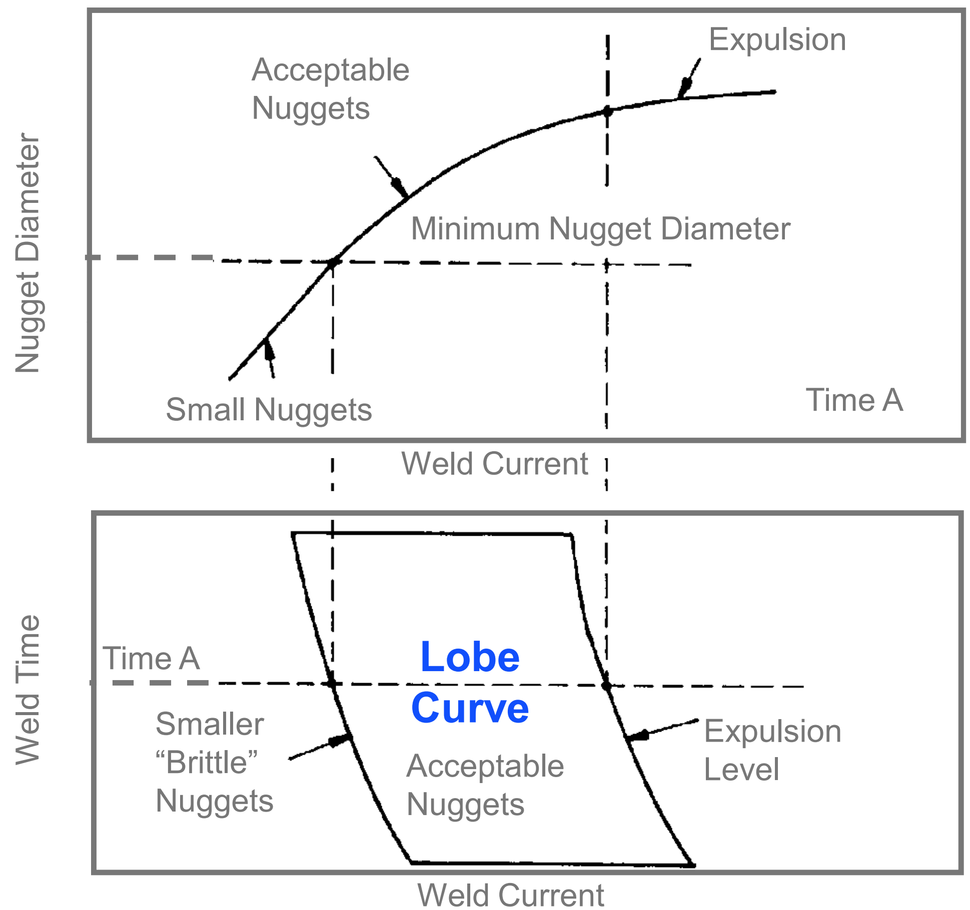
High Pressure

Resistance Welding Fundamentals – Effect of Pressure

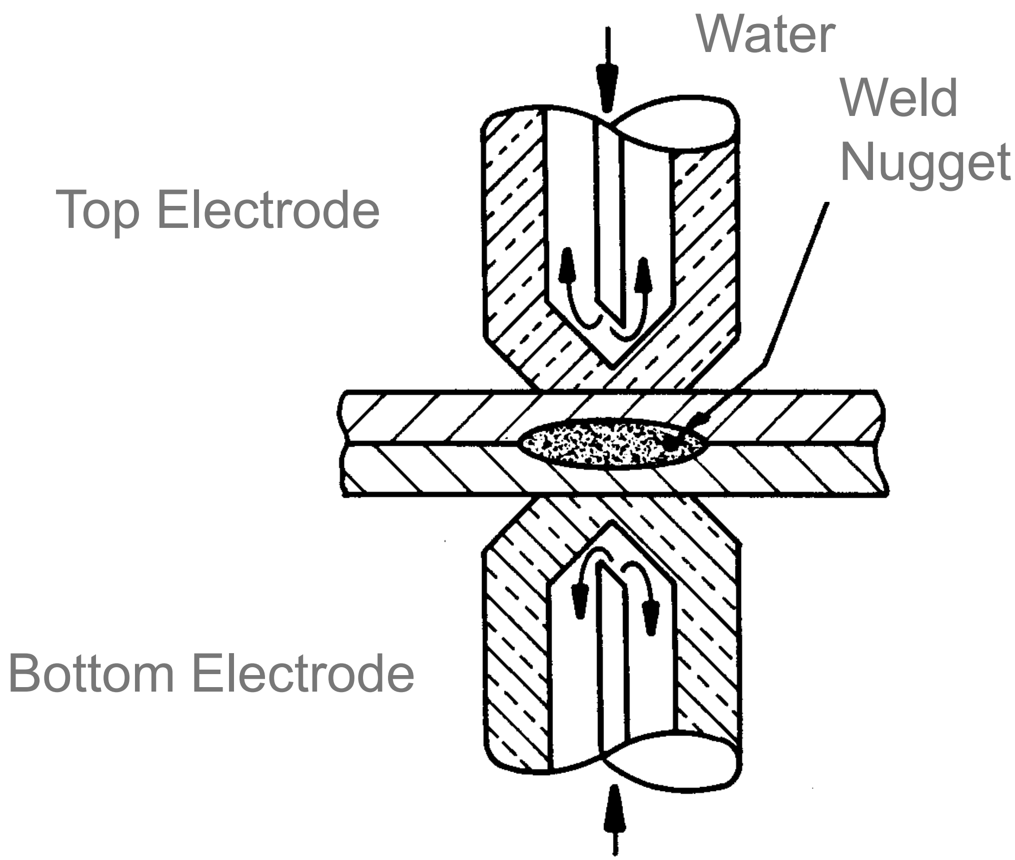


Resistance Welding Fundamentals – Lobe Curves

One method for generating Lobe Curves is to use nugget diameter as an indicator of weld quality



Resistance Spot Welding



Resistance Spot Welding

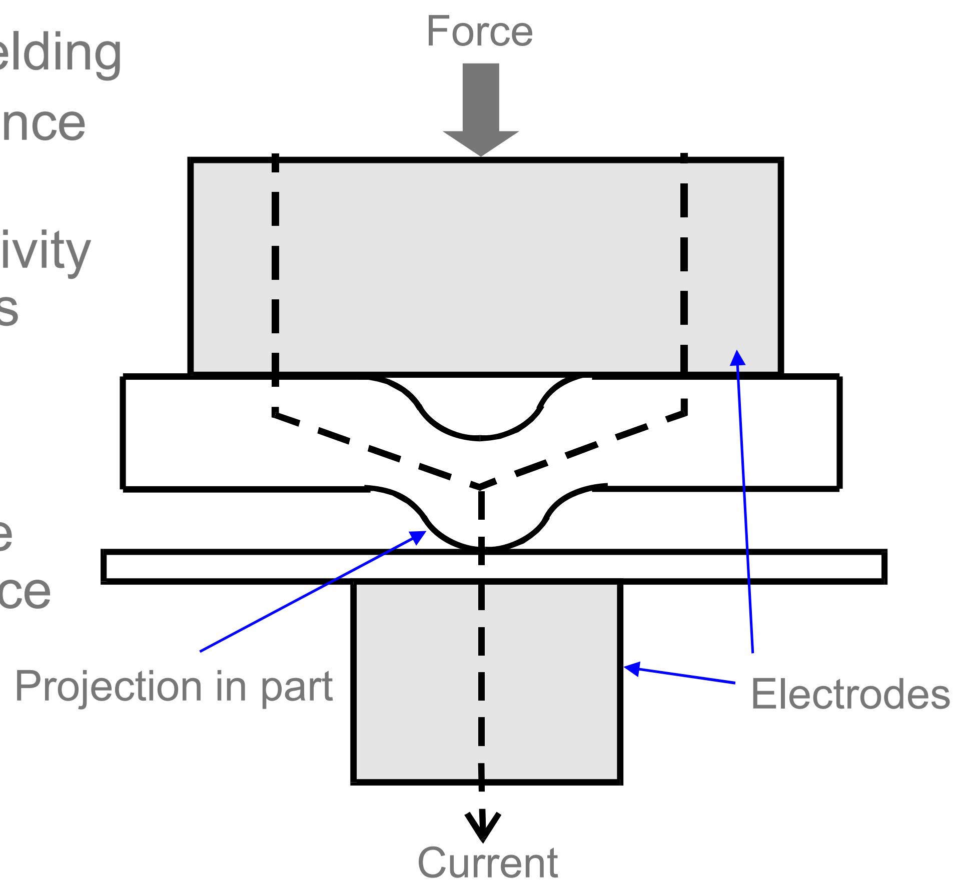
- Advantages
  - Ideal for high speed production of sheet metal assemblies
  - Easy to automate
  - Self-clamping
  - No filler materials required
  - Relatively inexpensive
  - "Aesthetics" of surface condition

Resistance Spot Welding

- Disadvantages
  - Overlapping joint adds weight
  - Need for sufficient joint access
  - Hidden weld location – quality control is difficult, highly dependent on Lobe curves
  - Poor mechanical properties due to notches and uneven load distributions
  - Expensive equipment
  - Weld repair difficult
  - Extreme power line demands

Resistance Projection Welding

- Applicability
  - Parts are too thick for Spot Welding
  - A significant (>5:1) size difference exists between parts
  - A significant electrical conductivity difference exists between parts
- Projection balances the heat
  - Concentrates current
  - Allows parts to reach the same temperature across the interface



Resistance Projection Welding

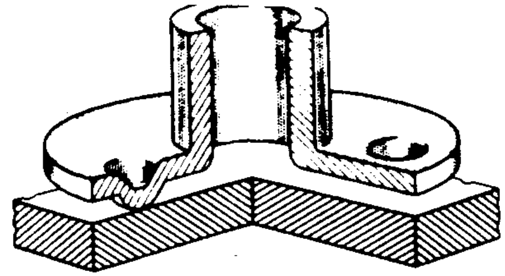
- Advantages
  - Ease of obtaining satisfactory heat balance for welding difficult combinations
  - Can weld greater thicknesses and thickness mismatches vs. Spot Welding
  - More uniform results in many applications
  - Increased output per machine because several welds are being made simultaneously
  - Longer electrode life
  - Welds may be placed more closely together
  - Parts are more easily welded in an assembly fixture
  - Finish, or surface appearance, is often improved on side without the projection
  - Parts may be projection welded that could not be otherwise resistance welded
  - Often replaces arc welding processes such as GMAW and results in much faster welding time

Resistance Projection Welding

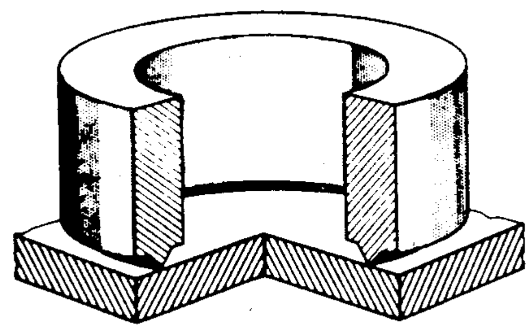
- Disadvantages
  - Requires an additional operation to form projections
  - Requires accurate control of projection height and precise alignment of the welding dies with multiple welds
  - Requires higher capacity equipment than Spot Welding

Resistance Projection Welding

- Common projection designs
  - Button or Bubble
    - Most common
    - Easy to form with punch and die
    - Usually involves forming multiple individual projections
  - Annular
    - Single “ring” projection centered on the part
- Approaches to producing projections
  - Embossing or forming
    - Least expensive
    - Usually results in melting but not always
  - Machining
    - Used when welding thicker parts
    - Referred to as solid projections
    - Always a solid-state weld



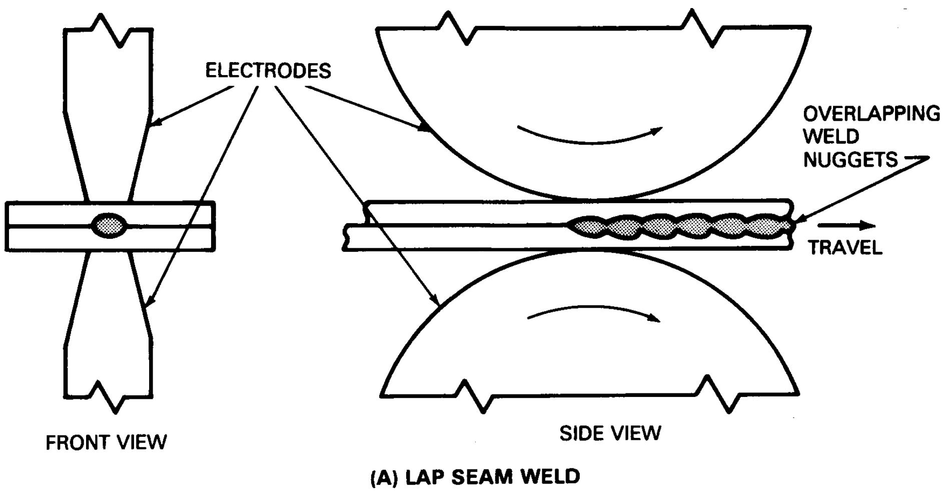
Button or Bubble Embossed Projection Design



Annular Solid Projection Design

Resistance Seam Welding

- Lap seam welding – same advantages as spot, but with ability to create continuous leak-tight joints – automotive gas tanks are a very common application
- Primary disadvantage is the requirement for straight or uniformly curved paths and uniform joint contours



[Ref.: AWS Welding Handbook, Vol. 3, 9th Ed.]

[Source: Internet]

ASME Section IX – Resistance Welding Process Procedure Variables

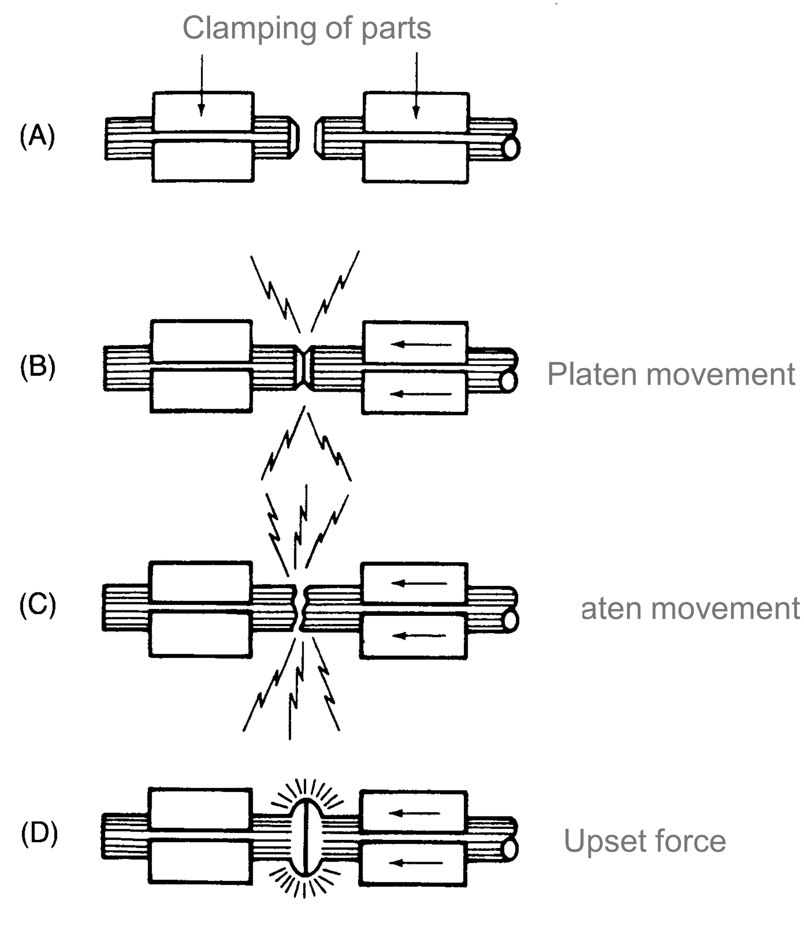
Paragraph		Brief of Variables	Essential	Nonessential
QW-402 Joints	.13	φ Spot, Projection, Seam	X	
	.14	φ Overlap, Spacing	X	
	.15	φ Project, Shape, Size	X	
QW-403 Base Materials	.21	± Coating, Plating	X	
	.22	± T	X	
QW-408 Gas	.23	- Gases	X	

ASME Section IX – Resistance Welding Process Procedure Variables

Paragraph		Brief of Variables	Essential	Nonessential
QW-409 Electrical Characteristics	.13	φ RWMA Class	X	
	.14	± φ Slope	X	
	.15	φ Pressure, Current, Time	X	
	.17	φ Power Supply		X
	.18	Tip Cleaning		X
QW-410 Technique	.31	φ Cleaning Method	X	
	.32	φ Pressure, Time	X	
	.33	φ Equipment	X	
	.34	φ Cooling Medium		X
	.35	φ Throat		X

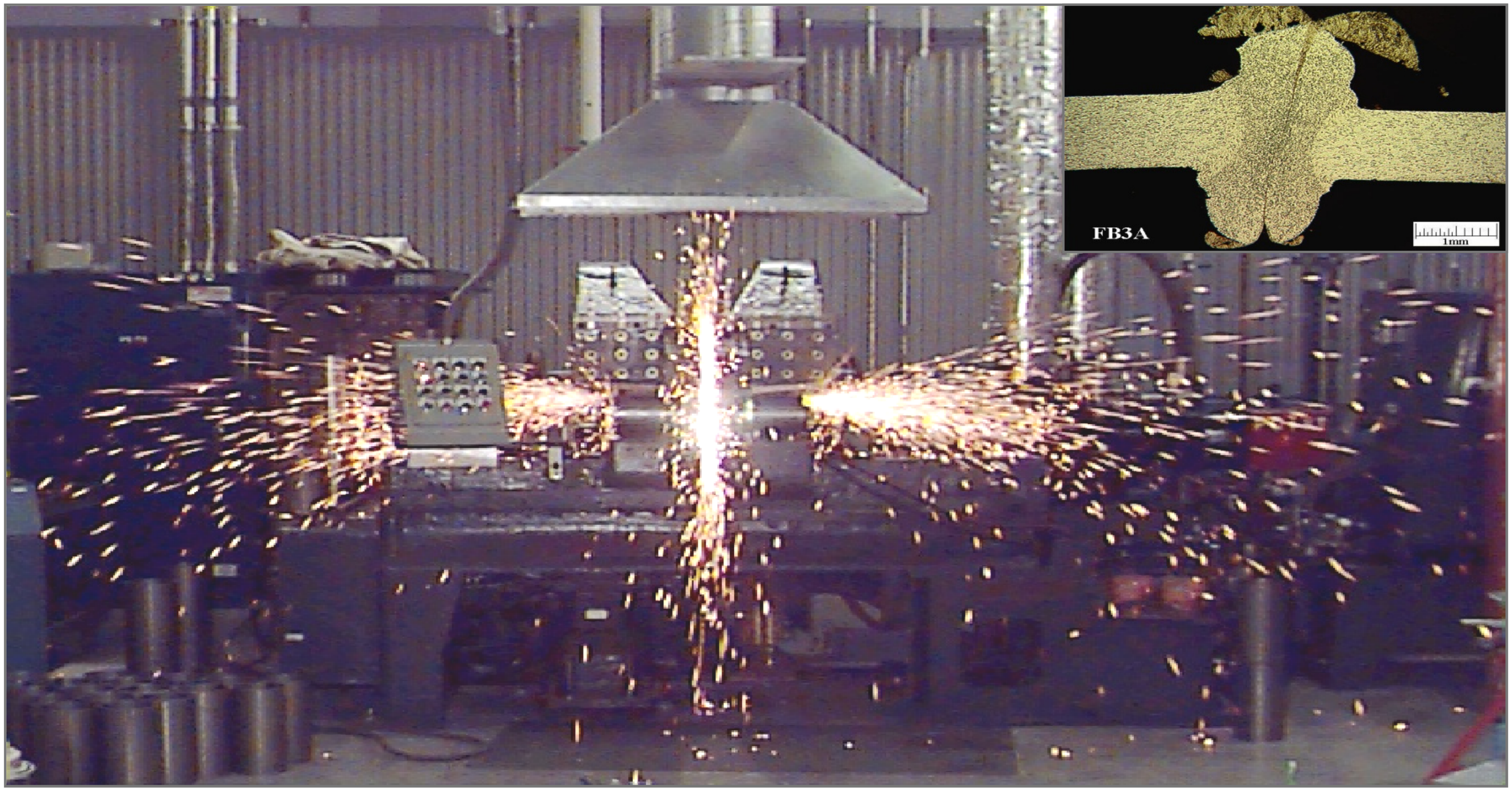
Resistance Flash Welding

- Not an arc welding process, but a continuous series of high current density "shorts"
- Flash Welding steps
  - Clamp parts
  - Apply flashing voltage and initiate platen motion
  - Continue flashing motion to achieve proper heating
  - Terminate flashing and apply upset force to create solid-state weld



[Ref.: AWS Handbook, Vol. 2, 8th Ed].

Resistance Flash Welding



Flash Welding of Steel Tubes

[Courtesy: EWI]

ASME Section IX – Flash Welding Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-402 Joint	.19	φ Diameter or Thickness	X		
	.20	φ Joint Configuration	X		
	.21	φ Method or Equip. used to Minimize ID Flash	X		
	.22	φ End Preparation Method	X		
QW-408 Gas	.22	φ Shielding Gas Composition, Pressure, or Purge Time	X		
QW-409 Electrical Characteristics	.27	φ > 10% Flashing Time	X		
	.28	φ > 10% Upset Current Time	X		

ASME Section IX – Flash Welding Process Procedure Variables

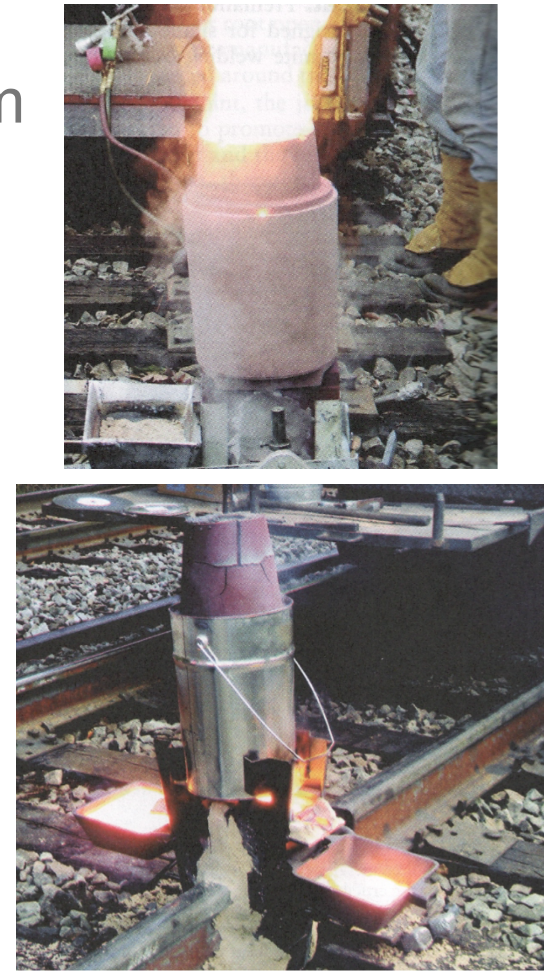
Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-410 Technique	.17	φ Type/Model of Equipment	X		
	.54	φ > 10% Upset Length or Force	X		
	.55	φ > 10% Distance Between Clamping Dies or Preparation of Clamping Area	X		
	.56	φ Clamping Force	X		
	.57	φ 10% Forward or Reverse Speed	X		

Thermite Welding

Module 2B.4

Thermite Welding

- A welding process that produces coalescence of metals by heating them with superheated metal from an exothermic reaction between a metal oxide and aluminum
- Very portable, minimal capital quipment cost
- Does not require external power source
- Common applications
  - Rail
  - Reinforcing bar

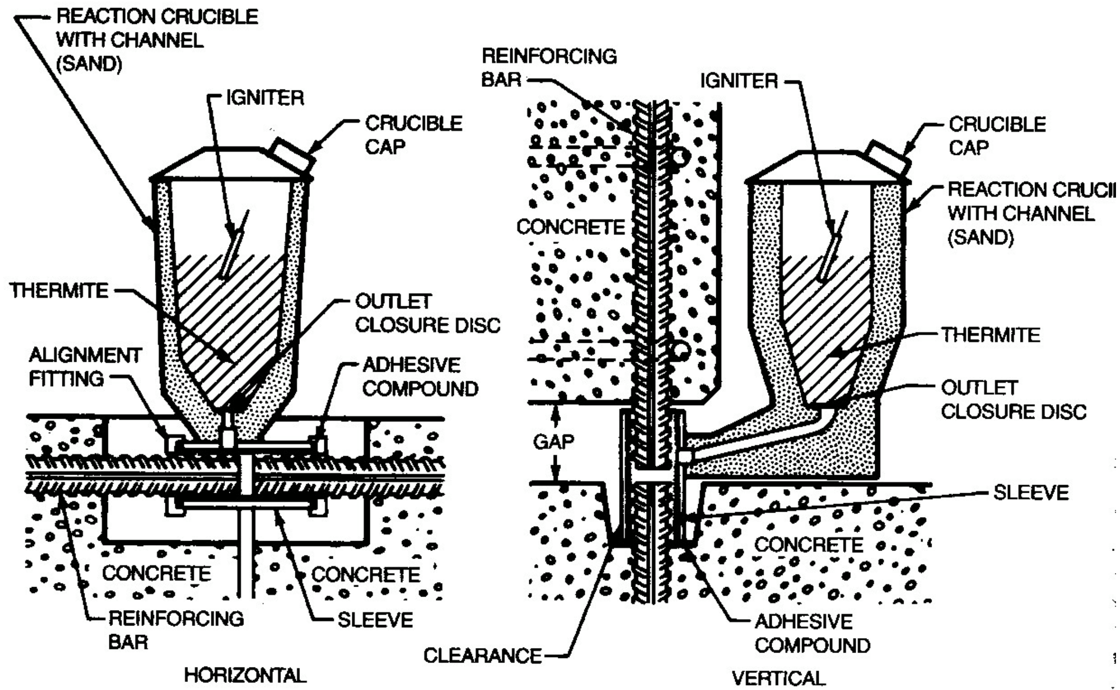


Thermite Welding of rails

[Ref: "AWS Handbook, Vol. 3, Welding Processes, Part 2, 9th Ed.]

Thermite Welding

- Welding steel reinforcing bar
  - Provides for design of smaller concrete columns and beams
  - Relies on a closure disc at the base of the crucible which melts, allowing the molten steel to flow into the joint
  - Can be welded in any position
  - Schematic shows a version in which bars are not melted



Thermite sleeve joint for reinforcing bars

[Ref: "AWS Handbook, Vol. 3, Welding Processes, Part 2, 9th Ed.]

Thermite Welding Safety

- Moisture must be minimized
- Work area should be free of combustible materials and well ventilated
- Personnel should wear appropriate protection – gloves, face shields with filter lenses, safety boots, and gloves
- No pockets or cuffs

Oxyfuel Gas Welding (OFW)

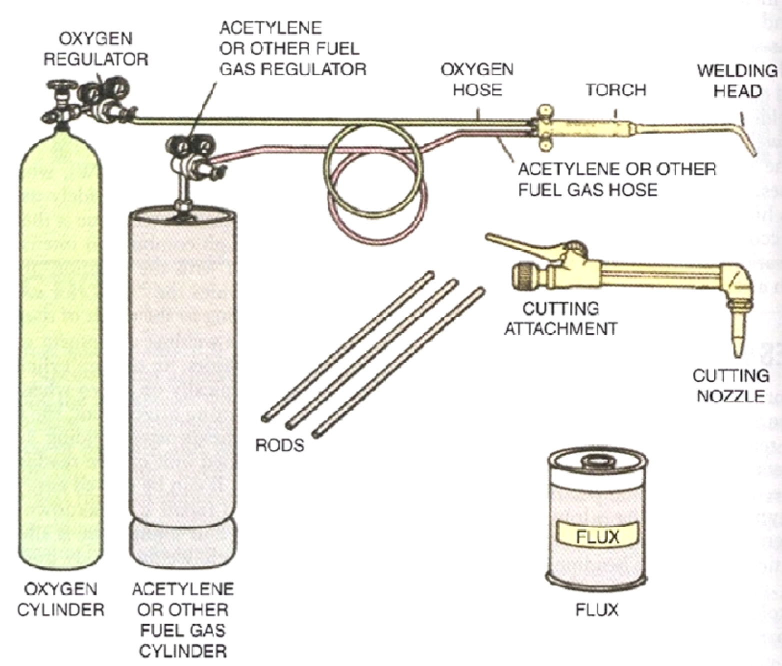
Module 2B.5

Oxyfuel Gas Welding

- A group of welding processes that achieve the coalescence of metals by heating them with an oxyfuel gas flame - may or may not use a filler metal
- One of the oldest welding techniques (early 1900's)
- Mostly replaced by arc welding processes today, but still offers portability, versatility, and low equipment cost
- Very slow welding speeds, cannot be used with reactive metals

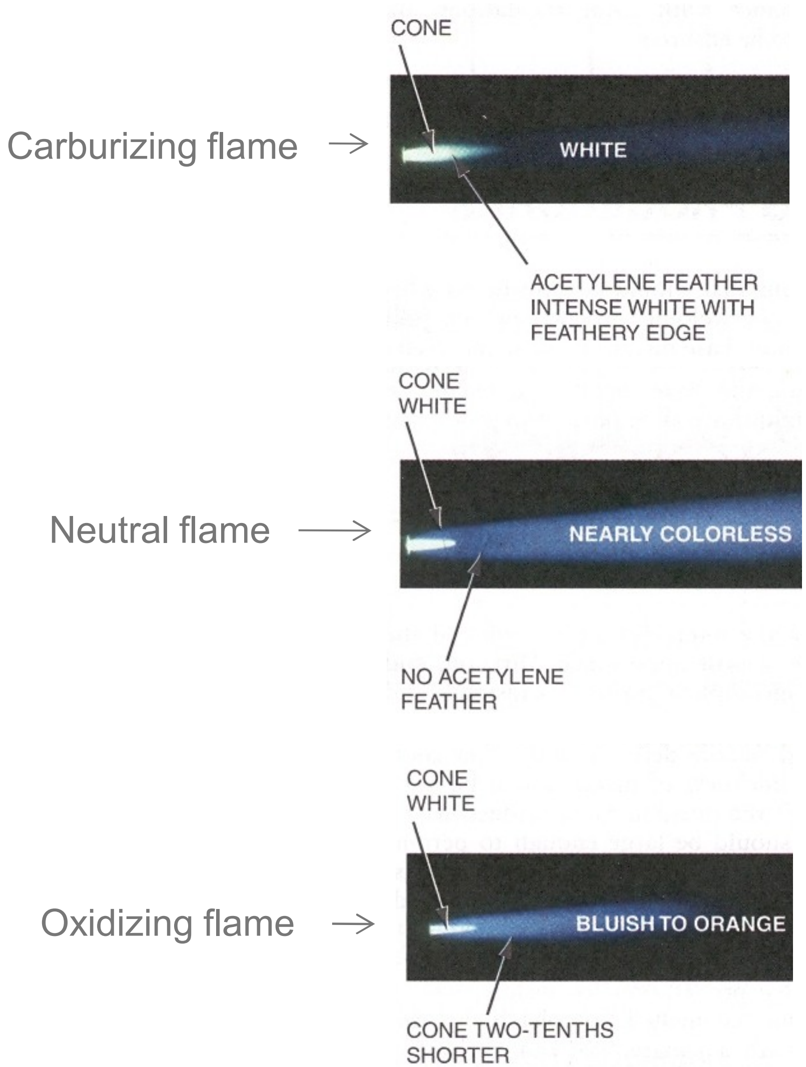
Oxyacetylene Welding

- Most widely used OFW process
- Acetylene (C_2H_2) produces the heat and oxygen supports combustion
- Acetylene offers high combustion intensity compared to other fuel gases
- Welding equipment can easily be converted to cutting equipment with attachment
- Filler metals that match base metal chemistry are typically used
- Fluxes are used to assist in oxide removal during welding



Oxyfuel Gas Welding

- Flame Adjustment
  - Neutral flame - decrease acetylene flow until feather disappears
  - Carburizing flame - contains acetylene "feather"
    - Can be used to increase carbon content or reduce melting point of weld metal
  - Oxidizing flame - contains a reduced cone length



Oxyfuel Gas Welding Safety

- Compressed gases
- Flammable fuel gases…keep away from sources of ignition
- Acetylene can react violently with copper
- Goggles with proper shielding must be worn
- Use proper ventilation

ASME Section IX – OFW Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-404 Filler Metals	.3	φ Size			X
	.4	φ F-Number	X		
	.5	φ A-Number	X		
	.12	φ Classification		X	
QW-405 Positions	.1	+ Position			X
QW-408 Gas	.7	φ Fuel Gas Type	X		
QW-410 Technique	.2	φ Flame Characteristics			X
	.4	φ ← → Technique			X
	.5	φ Method of Cleaning			X

Introduction to Brazing and Soldering

Module 2C

AWS Definition of Brazing and Soldering

- Joining processes which utilize a filler metal which melts below the melting temperature of the base metal
  - Brazing: filler metal liquidus > 450ºC
  - Soldering: filler metal liquidus < 450ºC
- Joint formation
  - Filler metal melting
  - Joint gap filled by capillary action
  - Filler metal solidifies
- ASME Section IX has an entire section dedicated to qualifying brazing procedures and brazers which is not covered in this course
  - Follows the same methodology as welding procedure and welder qualifications

Elements of Brazing and Soldering

- Materials
  - Base materials
    - Metals and alloys: ferrous and non-ferrous
    - Ceramics
    - Glasses
    - Composites
  - Filler metals
- Brazing and soldering processes
  - Heat sources: electrical, chemical (combustion, exothermic reactions)
  - Protection from oxidation: fluxes, controlled atmospheres
  - Equipment: torches, furnaces, inductors, baths, etc.
    - Brazing: Al, Mg, Ag, Au, Cu, Ni, Co, Ti, Mo, and Nb based alloys
    - Soldering: Sn, Pb, In, Au based, and Zn, Bi, and Cd containing alloys
- Joint design
  - Lap joints, butt joints
  - Joint clearance (gap)

Brazing and Soldering

- Advantages
  - No melting of base metal
  - Able to easily join dissimilar metals and metal-to-non-metal combinations
  - Economical for complex assemblies and large joint designs
  - Minimal distortion and residual stress
- Disadvantages
  - Formation of brittle intermetallics
  - May require highly skilled operators
  - Difficulties with fit-up and assembly

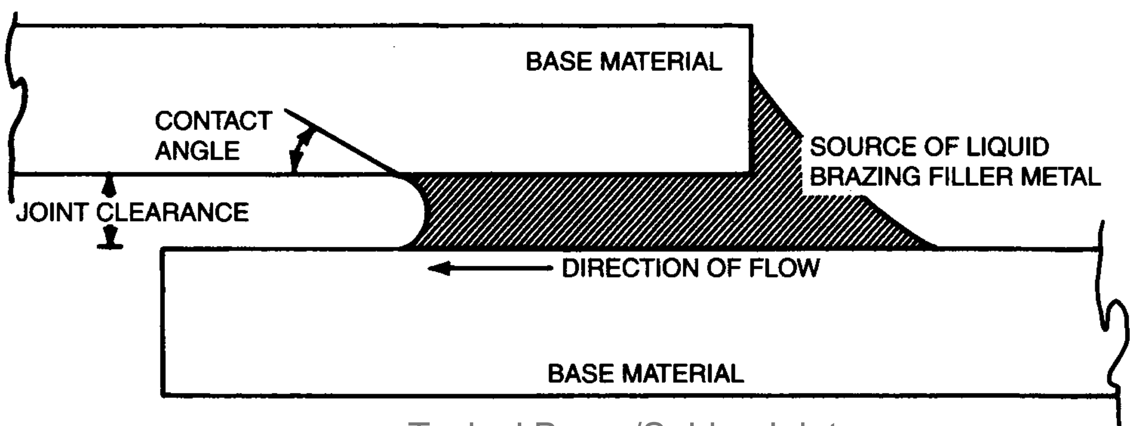
Brazing and Soldering – Applications

- Electrical and electronic components
- Automotive
- Aerospace
- Solar panels
- Nuclear systems
- Food processing equipment
- Pressure vessels
- Jewelry
- Toys

[Source: Internet]

Joint Formation

- Filler metal melting, wetting and gap filling, solidification
- Base/filler metal reactions
  - During brazing/soldering
  - During aging (at service temperature)
    - Dissolution
    - Diffusion
    - Formation of intermetallic compounds
    - Formation of solid solutions

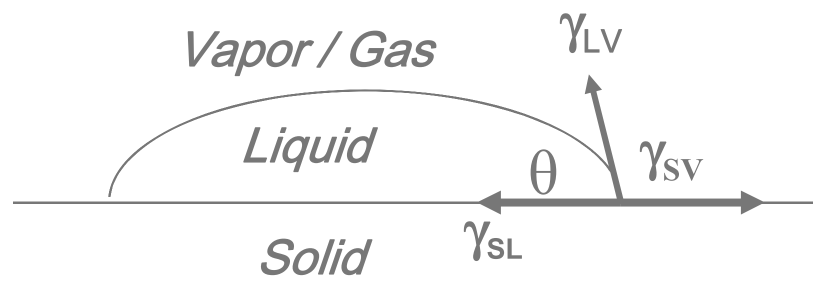


Typical Braze/Solder Joint

[Ref.: "Brazing Handbook, 5th Ed.", AWS]

Wetting

- Surface energy balance
- Assumptions
  - No chemical reactions
  - No gravity
- Spreading, if θ ~ 0º
- Wetting, if θ < 90º
- No wetting, if θ > 90º
- Brazing and soldering optimum: 10º ≤ θ ≤ 45º
- Effect of oxides and surface active impurities

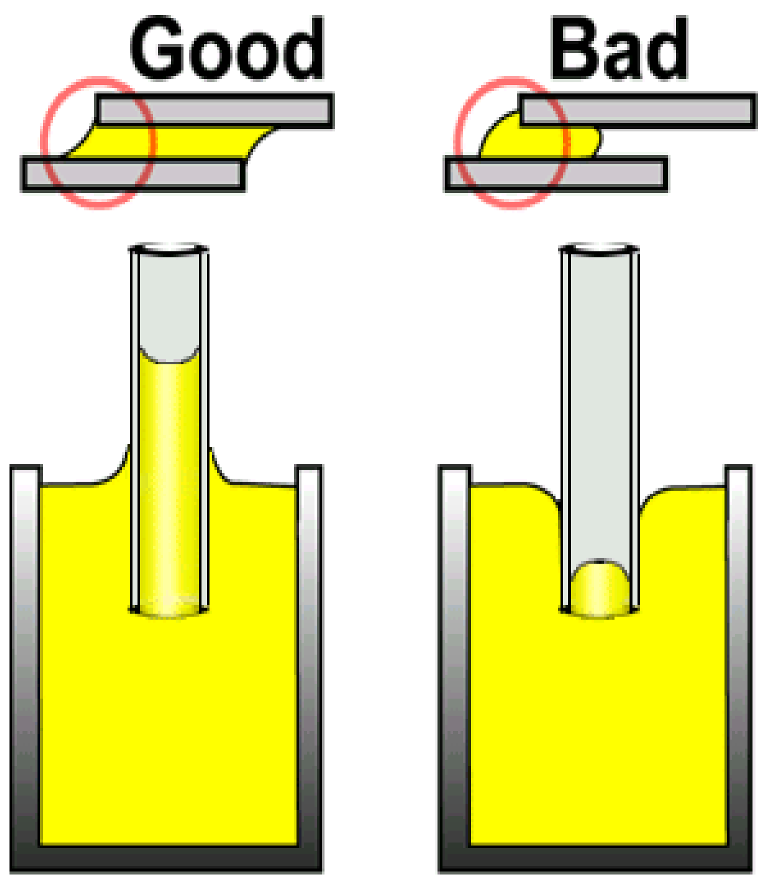


$$\cos\theta = \frac{(\gamma_{SV} - \gamma_{SL})}{\gamma_{LV}}$$

- θ – contact angle
- γ – surface energy

Capillary Action

- Factors controlling capillary action
  - Wetting (θ, γ_{LV})
  - Liquid density
  - Liquid viscosity
  - Gap distance and geometry
  - Surface cleanliness



Capillary Action Principle

Fluxes

- Functions
  - Remove surface oxides
  - Protect from surface oxidation during brazing / soldering
  - Reduce surface tension of molten filler metal
- Composition
  - Active component
    - Reducing or etching, acids or alkaline metals (F, Cl, Li, B)
  - Solvent
    - Water or alcohol
  - Wetting agents
    - Organic compounds

Brazing Fluxes

Brazing Fluxes: Examples from AWS A5.31 Specification

AWS Clas.	Form	Filler metal type	Ingredients	Temp. range, ^oC	Process	Base material
FB1-A	Powder	BAlSi	Fluorides, Chlorides	560-615	Torch, Furnace	Brazeable Al alloys
FB2-A	Powder	BMg	Fluorides, Chlorides	480-620	General purpose	Mg alloys designated with AZ
FB3-C	Paste	BAg, BCuP	Borates, Flourides, B	565-925	General purpose	Brazeable metallic alloys except containing Al and Mg, carbides
FB3-G	Slurry	BAg, BCuP	Borates, Flourides	565-870	General purpose	
FB3-K	Liquid	BAg, BCuP RBCuZn	Borates	760-1205	Torch flux applied by fuel gas	

Soldering Fluxes

Soldering Fluxes: Examples from ANSI/J-STD 004

Flux Material	Activity Level (% Halide)	Type	ANSI Designator
Rosin (RO)	Low (0%)	L0	ROL0
Resin (RE)	Low (<0.5%)	L1	REL1
Organic (OR)	Moderate (0.5-2.0%)	M1	ORM1
Inorganic (IN)	High (>2.0%)	H1	INH1

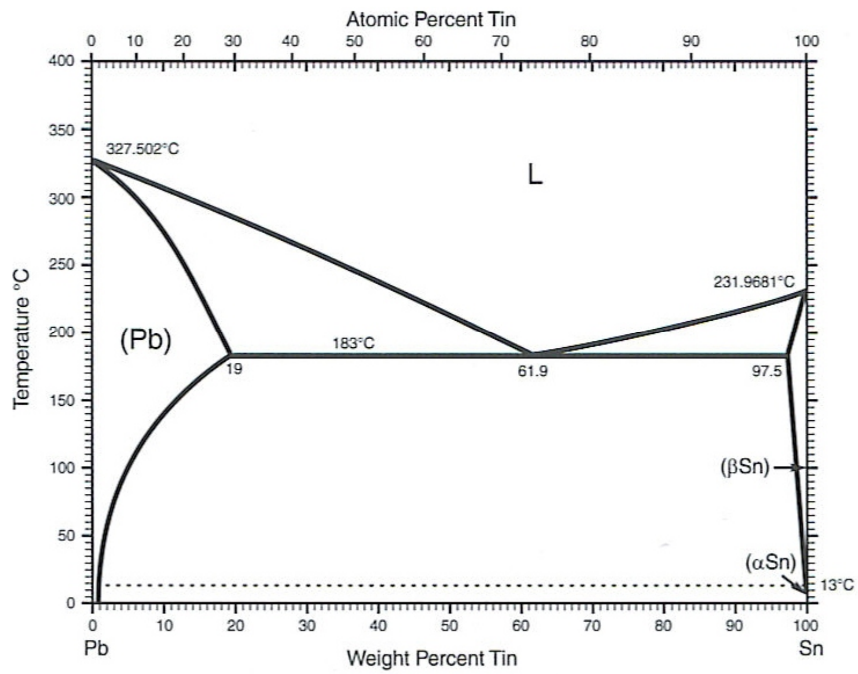
ISO classification: 122C
Resin–base flux
with halogen activator

Soldering Fluxes: Examples from ISO 9454-1

<table>
<tr><th>Flux Type</th><th>Flux Basis</th><th>Flux Activation</th><th>Flux Form</th></tr>
<tr><td rowspan="2">1 Resin</td><td>1 Rosin</td><td rowspan="4">1 Nonactivated
2 Halogen activated
3 Not halogen activated</td><td rowspan="9">A Liquid
B Solid
C Paste</td></tr>
<tr><td>2 Resin</td></tr>
<tr><td rowspan="2">2 Organic</td><td>1 Water Soluble</td></tr>
<tr><td>2 Not Water Soluble</td></tr>
<tr><td rowspan="5">3 Inorganic</td><td rowspan="2">1 Salts</td><td>1 With ammonium chloride</td></tr>
<tr><td>2 With ammonium chloride</td></tr>
<tr><td rowspan="2">2 Acids</td><td>1 Phosphoric acid</td></tr>
<tr><td>2 Other acids</td></tr>
<tr><td>3 Alkalis</td><td>1 Ammonia and/or amines</td></tr>
</table>

Brazing and Soldering Filler Metals

- Liquidus temperature
  - Lower than base material
  - > 450ºC in brazing filler metals
  - < 450ºC in soldering filler metals
- Requirements
  - Wetting
    - Spreading and adhering to substrate
  - Melting temperature range
    - Clearance filling by capillary action
  - Homogeneous composition
    - Avoid liquation
  - Mechanical and physical properties
  - Interactions with base material
    - Brittle compounds, erosion, etc.
    - Diffusion, chemical reactions



The Tin-Lead Binary Phase Diagram

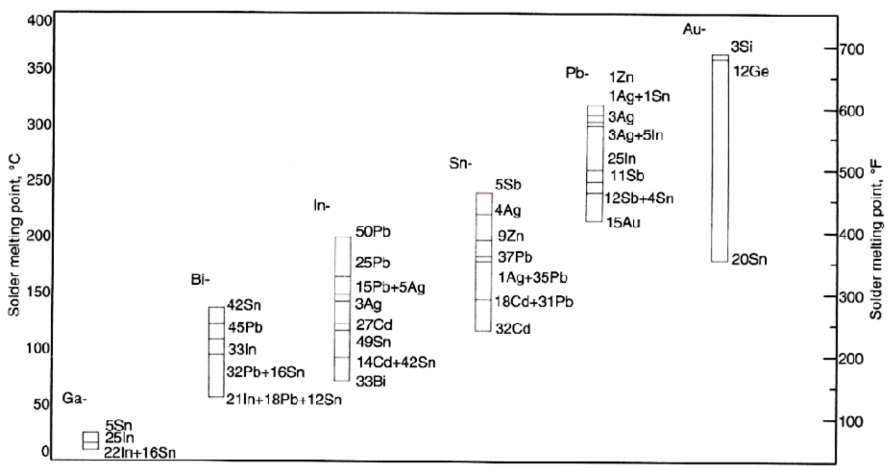
[Ref: "Soldering Handbook", 3rd Ed., AWS]

Brazing and Soldering Filler Metals

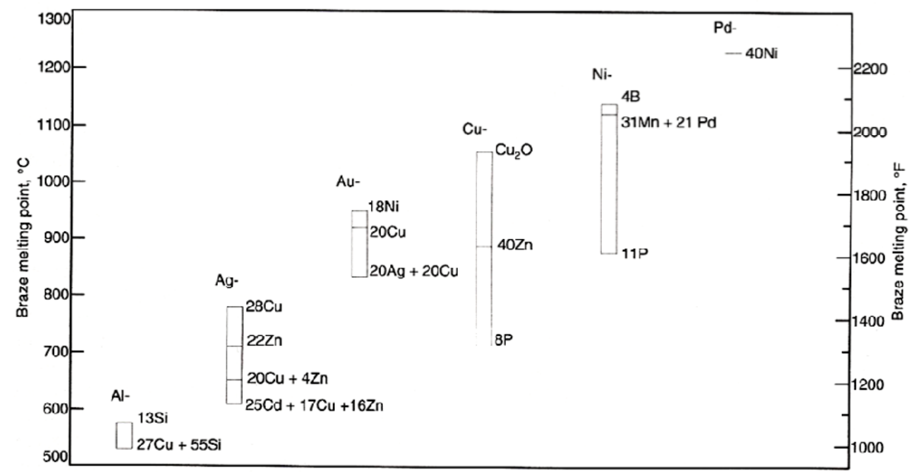
Melting Temperature

450^0C (840^0F)

Soldering Filler Metals



Brazing Filler Metals



[Ref: "Principles of Soldering and Brazing", ASM International]

Brazing Filler Metals

Classes of Brazing Filler Metals from AWS A5.8/A5.8M

Class	Alloy Family	AWS Des.	Materials Joined	Application Examples
1	Al-Si	BAlSi	Aluminum and aluminum to steel and beryllium	Car radiators, heat exchangers, aircraft honeycomb structure
2	Cu-X	BCu	Copper and copper to steel and stainless steel	Heat exchangers, automotive parts
3	Cu-Zn	RBCuZn		
-	Cu-Sn	None		
4	Cu-P	BCuP	Copper and copper to silver/oxide metal composites	Electrical components, heat exchangers
5	Cu-Ag	Bag	Most metals except aluminum and magnesium	Most widely used utility filler metal
6	TM-Si-B	BNi	Steels, copper, nickel, and cobalt-base alloys	Aircraft and automotive parts, heat exchangers, honeycomb
7	(Co,Cr)-Si-B	BCo	Steels, cobalt-base alloys	Aircraft engines, honeycomb marine structures
-	(Ni,Pd)-Si-B	None	Stainless steels, superalloys, and cemented carbide	Honeycomb, orthodontics, catalytic convertors
8	Au-Ni	BAu	Nickel-based alloys, steels	Honeycomb structures, turbine parts
-	Cu-(Ti,Zr)-Ni	None	Titanium and zirconium-based alloys	Aircraft components, chemical reactors

Soldering Filler Metals

ASTM B32-91: *Standard Specification for Solder Metal*

ISO/DIS 9453, ISO/CD 12226-1, ISO/CD 12224-1

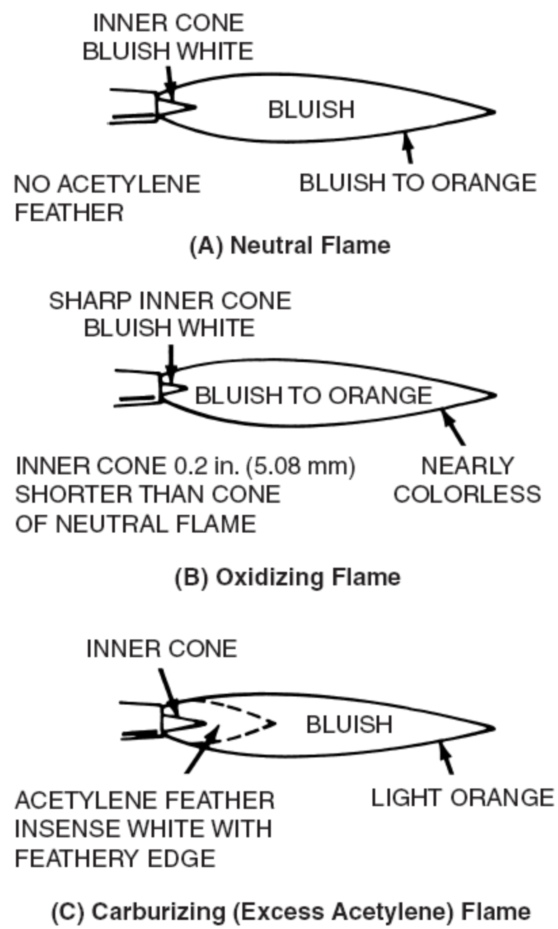
Compositions	Forms
Sn Based: Sn, Sn-Pb; Sn-Pb-Sb; Sn-Pb-Ag; Pb-Ag	Bars
SN Based, Pb Free: Sn-Sb; Sn-Sb-Ag-(Cu); Sn-Ag	Paste
Zn Containing: Sn-Zn; Zn-Al; etc.	Solid Wire
In Based: In; In-Sn; In-Pb; etc.	Flux Cored Wire
Bi Containing	Foil, Sheet, Ribbon
Au Based	Segment or Drop
Cd Containing	Cakes or ingots: 3 to 10 lb
	Pig: 50 to 100 lb

Brazing and Soldering Processes

Brazing Processes	Soldering Processes
Torch	Torch
Induction	Induction
Furnace	Furnace
Dip (Immersion)	Dip (Immersion)
Resistance	Vapor Phase
Diffusion	Resistance
Laser Beam	Laser Beam
Electron Beam	Hot Gas
Exothermic	Ultrasonic
Infrared	

Torch Brazing / Soldering

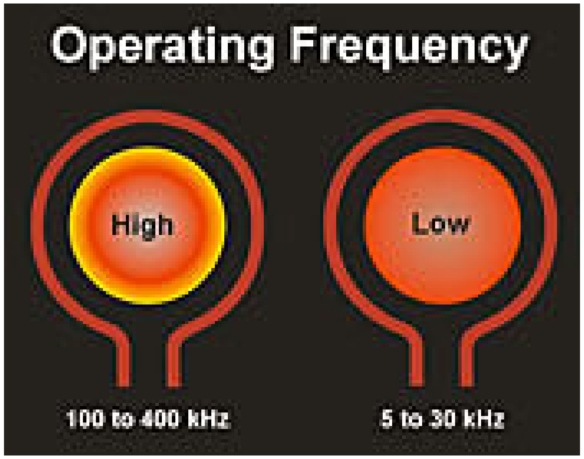
- Low to moderate capital cost
- Flexible component sizes
- Used with flux or self-fluxing alloys
- Manual and mechanized
- Applications
  - Carbon steel
  - Stainless steel
  - Cast iron
  - Copper
  - Aluminum
  - Carbides
- Flame characteristics



[Ref: "Brazing Handbook", 5th Ed., AWS]

Induction Brazing / Soldering

- Low to moderate capital cost
- Used with flux or atmospheres
- Best for small components
- High speed
- Localized heating
- Thermal cycle control
- Applications
  - Carbon and stainless steel
  - Cast iron
  - Copper
  - Aluminum
  - Titanium



$$d = 3160 \frac{\sqrt{\rho}}{\mu \cdot f}, in$$

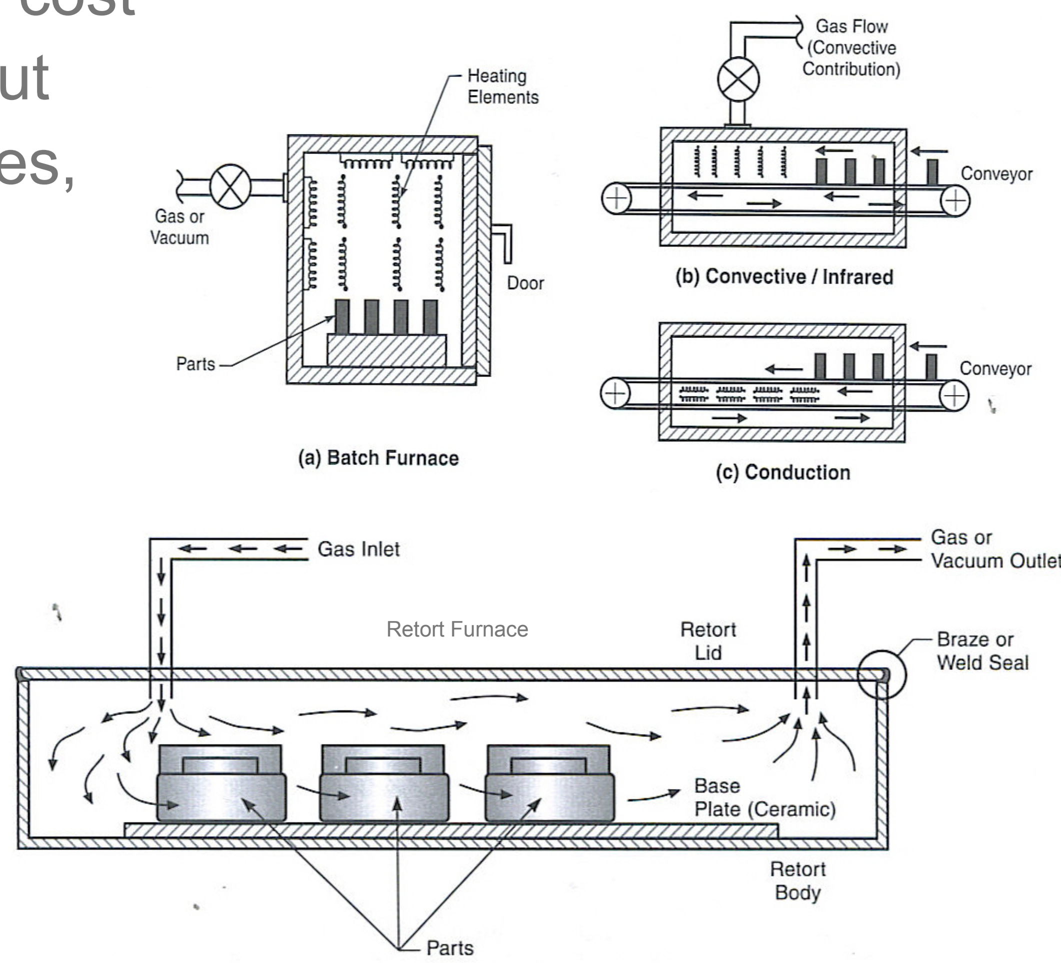
μ = 1 above curie temperature or for non-magnetic materials

ρ = electrical resistivity

f = frequency, Hz

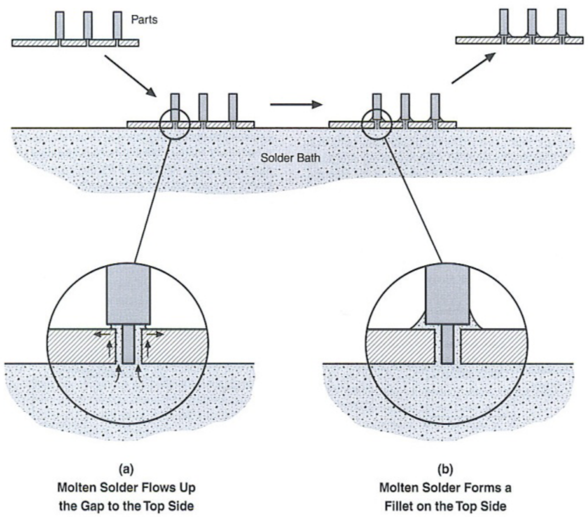
Furnace Brazing / Soldering

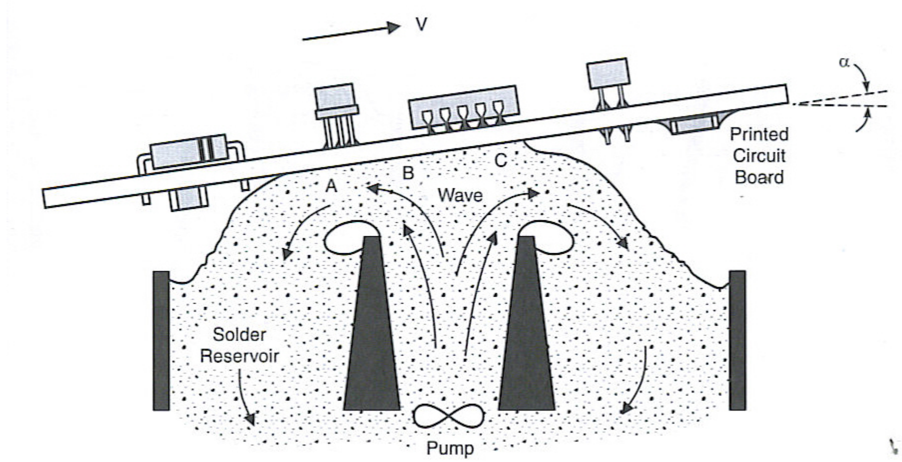
- High capital and operation cost
- High production through-put
- Used with flux, atmospheres, or vacuum
- Slow heating
- Pre-placed filler metal
- Generalized heating
- Thermal cycle control
- Applications
  - Carbon and stainless steel
  - Cast iron
  - Copper
  - Aluminum
  - Titanium
  - Ceramics



[Ref: "Soldering Handbook", 3rd Ed., AWS]

Immersion (Dip) Soldering



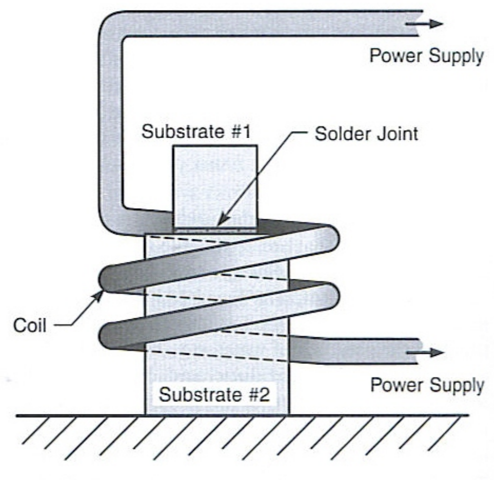


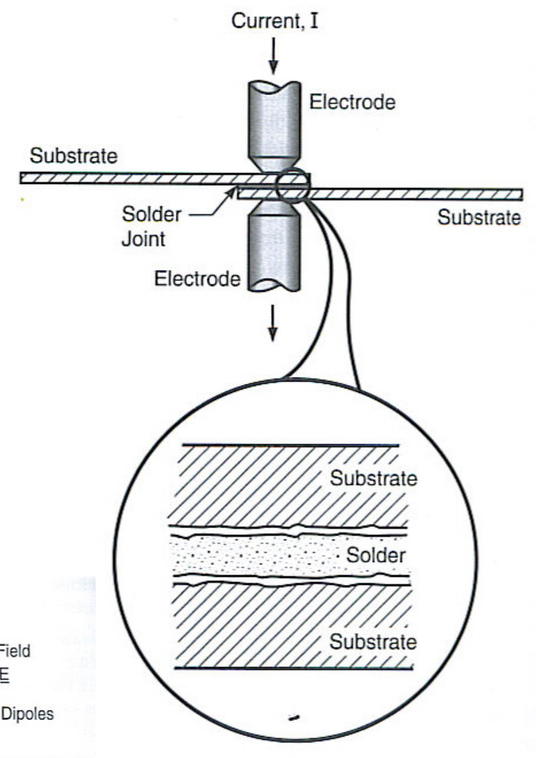
[Ref: "Soldering Handbook", 3rd Ed., AWS]

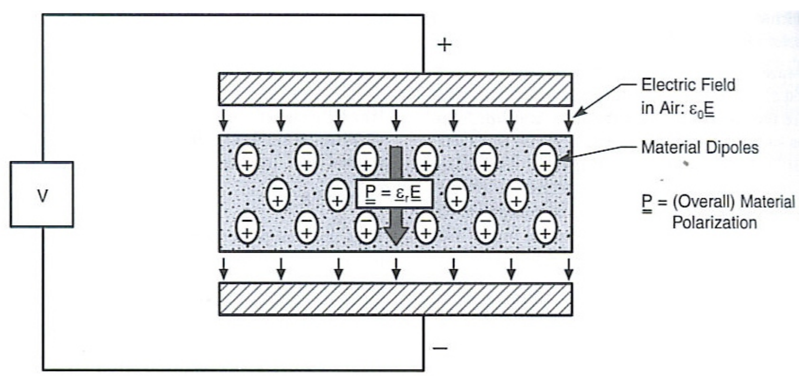
- Drag Soldering
  - Surface dragging and wetting
  - Capillary action
  - Heat transfer
  - Surface inclination
  - Dragging time 5 – 15 s
- Wave Soldering
  - Flux application
  - Preheat
  - Soldering
  - Peel back

Other Brazing and Soldering Processes

- Induction
- Infrared
- Resistance
- Laser beam
- Hot gas
- Microwave
- Ultrasonic





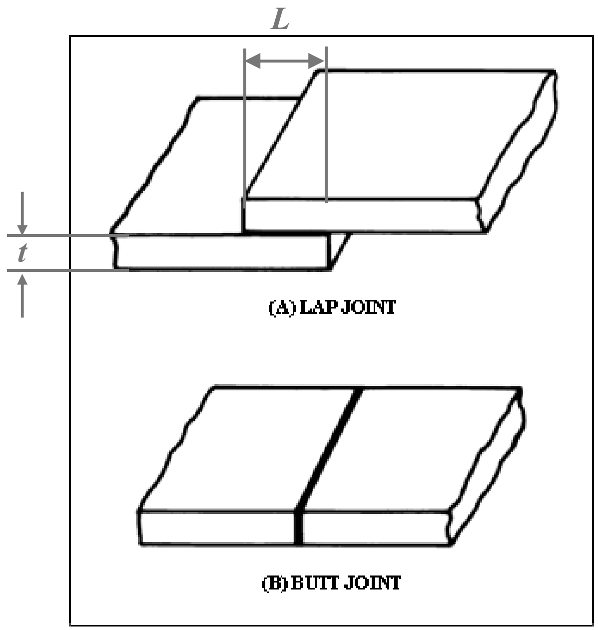


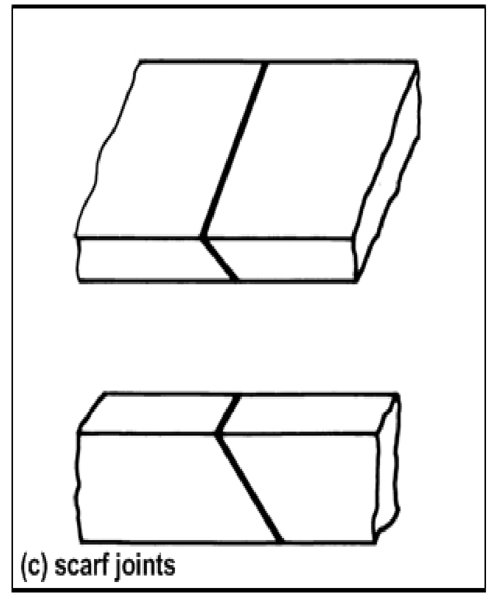
[Ref: "Soldering Handbook", 3rd Ed., AWS]

Design Criteria of Brazed and Soldered Joints

- Base material strength
- Base material/filler metal metallurgical compatibility
- Joint type and geometry
- Joint clearance geometry
- Fixturing of brazed/soldered parts
- Thermal expansion compatibility
- Filler metal form and placement
- Manufacturability
- Cost
- Safety

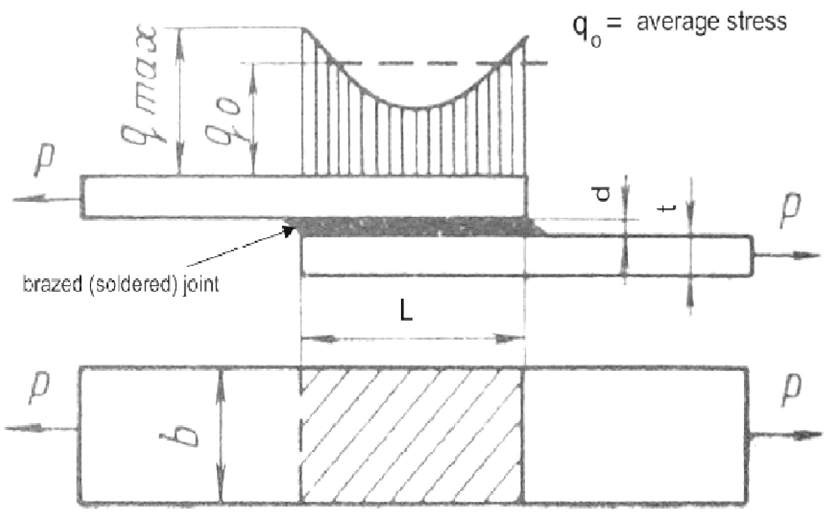
Joint Design





- Lap Joints
  - Best joint efficiency
  - Controlled by overlap length
    - Joint efficiency cam be higher than the weaker member
    - L > (3 - 4)t gives the maximum joint efficiency for steel, Cu, Ti, Al
  - Best manufacturability
- Other options include butt and scarf joints

Shear Strength of Lap Joints



- Desirable condition

$$b \cdot L \cdot \tau_{BR} \geq \sigma_{UTSBM} \cdot b \cdot t$$

- Realistic condition

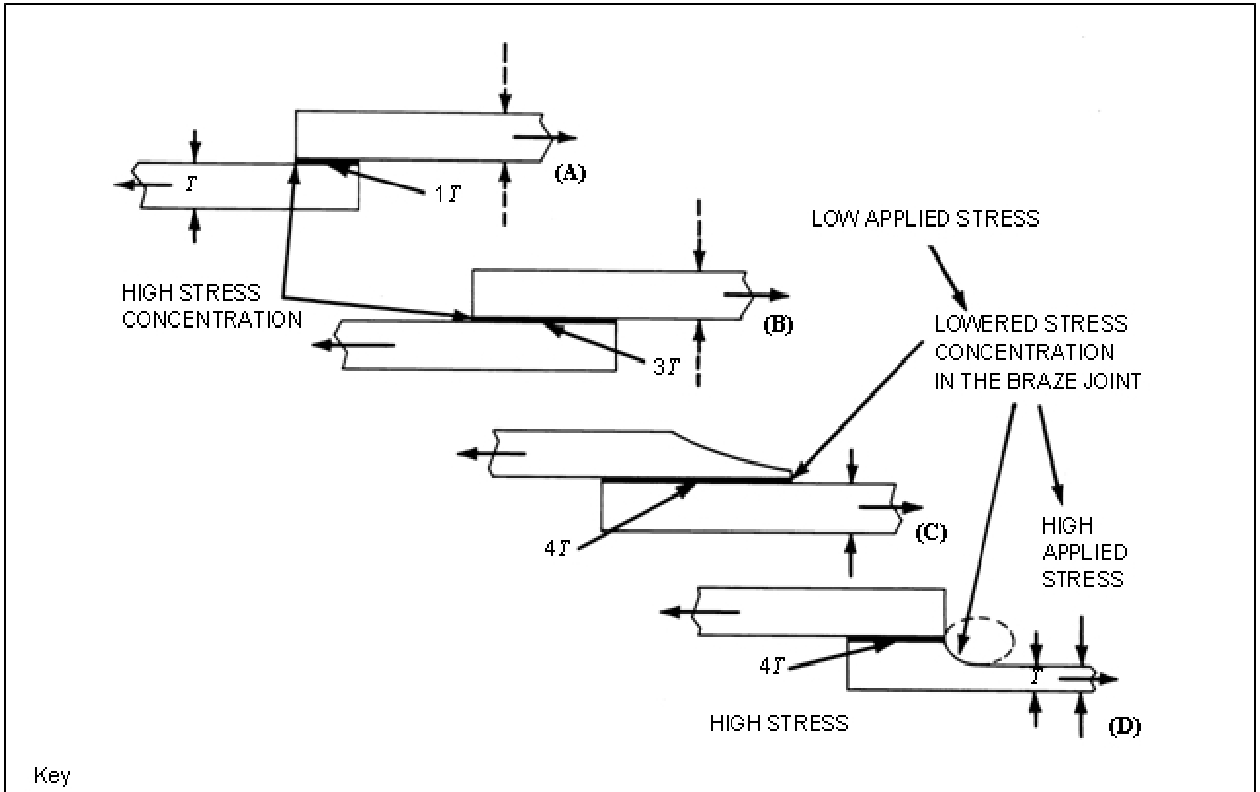
$$b \cdot L \cdot \tau_{BR} \leq \sigma_{UTS\ BM} \cdot b \cdot t$$

τ_{BR} - **Joint Shear strength**

σ_{BM} - **Base Metal Tensile Strength**

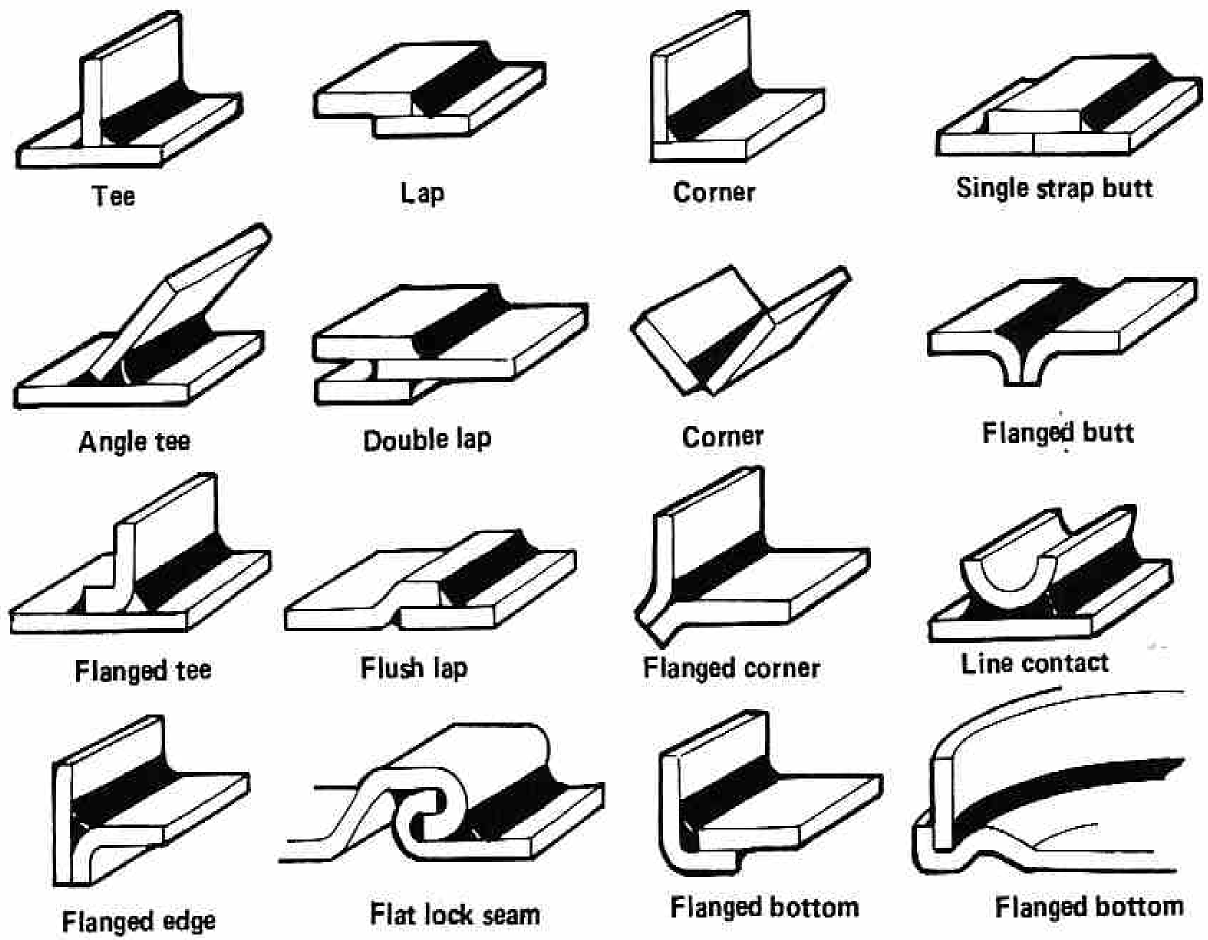
Joint Design

- Stresses in brazed and soldered joints
  - Avoid stress concentration
  - Apply load to base metal not to joints



Robert L. Peaslee, AWS Brazing Handbook, 2007, Chapter 2

Joint Design



[Ref: M.M. Schwartz, “Brazing”, 1987]

Introduction to Cutting Processes

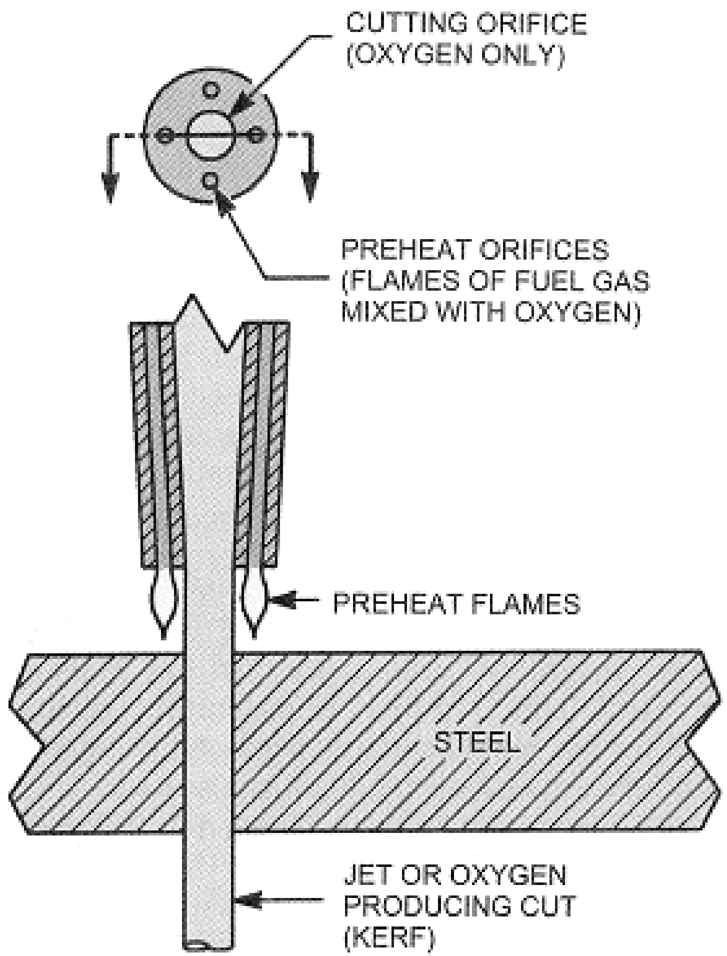
Module 2D

Definition of Thermal Cutting Process

- A concentrated heat source melts metal and high speed gas and/or plasma flow removes the melt to form a cut kerf
- Some thermal cutting processes
  - Oxyfuel cutting - OFC
  - Air carbon arc cutting or gouging – CAC-A
  - Plasma arc cutting - PAC
  - Laser beam – LBC
- Waterjet cutting is an alternative cutting technology to the thermal cutting processes

Oxyfuel Cutting

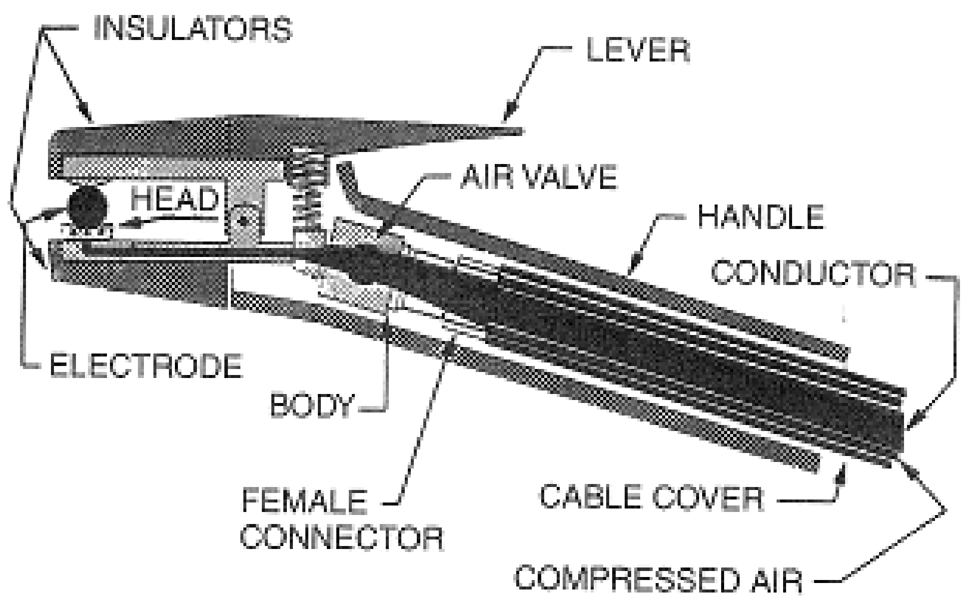
- Preheat flames produced by combustion of a fuel gas with oxygen
  - Acetylene, natural gas, propane, etc.
- Preheat flames increase metal temperature to allow burning by an oxygen jet
- Advantages
  - Inexpensive
  - Portable equipment
- Disadvantages
  - Only for oxidizing metals with a low melting point oxide



Courtesy of the AWS Welding Handbook, Volume 1, 9th Edition

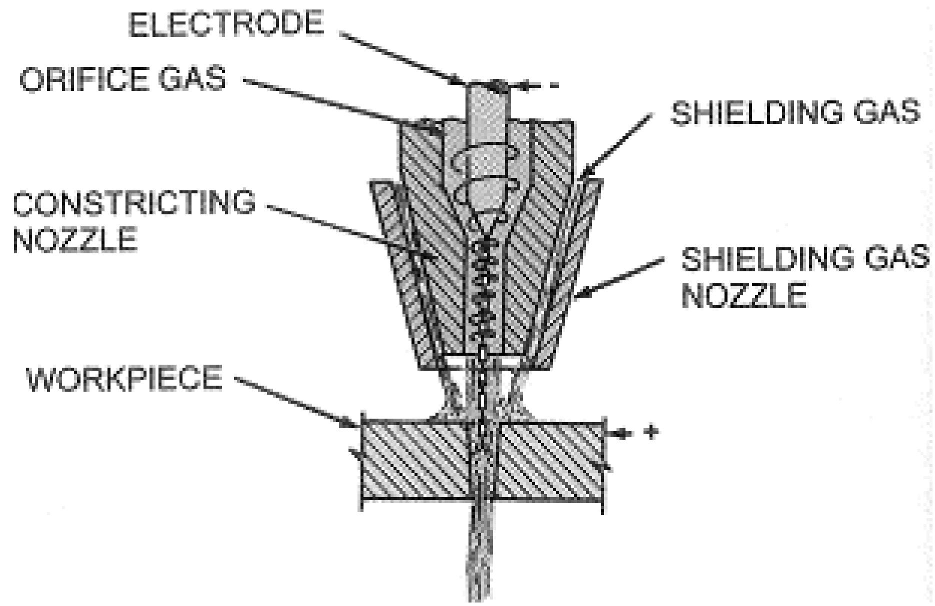
Air Carbon Arc Cutting or Gouging

- Electric arc between carbon electrode melts metal, expelled by pressurized air
- Advantages
  - Portable
  - Relatively inexpensive
- Disadvantages
  - Debris
  - Possible carbon deposition



Plasma Arc Cutting

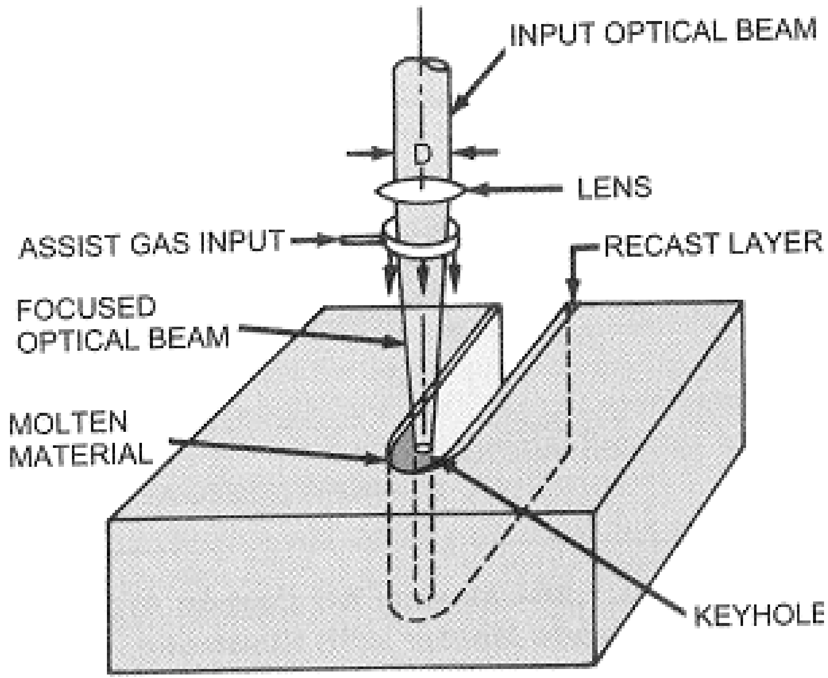
- Transferred arc plasma jet melts and expels metal from kerf
- Advantages
  - Works for all metals
  - High speed
- Disadvantages
  - Relatively expensive
  - Tapered kerf



Courtesy of the AWS Welding Handbook, Volume 1, 9th Edition

Laser Beam Cutting

- Focused high power laser beam melts material, expelled by assist gas flow
  - CO_2, Nd:YAG, fiber lasers
  - Air, oxygen, nitrogen, argon assist gases
- Advantages
  - High speed
  - Narrow kerf
- Disadvantages
  - Expensive



Courtesy of the AWS Welding Handbook, Volume 1, 9th Edition

Thermal Cutting Materials Effect

- Material heat-affected zone adjacent to kerf
  - In some materials, heat treatment may be required to restore material properties.
- Rapidly-solidified (recast) layer remains on sides of kerf, dross (slag) may be deposited at lower edge of kerf
  - Dross should be removed prior to welding
  - Recast layers may require heat treatment or removal by grinding, machining, etc.

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-410 Technique	.6	φ Method of Back Gouging			x
	.64	Use of Thermal Processes	X		

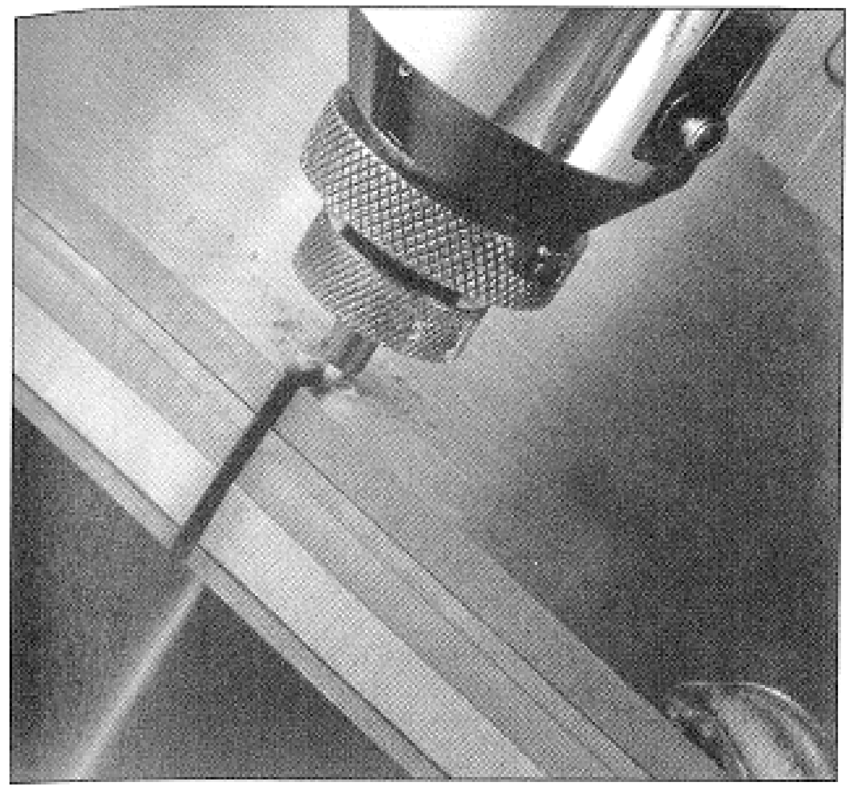
- ASME Section IX has a weld procedure variable defining thermal processing of low-alloy quench and tempered steels

Applicability of Thermal Cutting Processes

Material	Cutting Processes			
	OFC	PAC	CAC-A	LBC
Carbon steel	X	X	X	X
Stainless steel	X	X	X	X
Cast iron	X	X	X	X
Aluminum		X	X	X
Titanium	X	X	X	X
Copper		X	X	X
Refractory materials		X	X	X

Water Jet Cutting

- High pressure (P=30-60kPSI) water through a small orifice (f = 0.1-0.6mm) erodes material
- Abrasive grit usually added to water for metal cutting
- Advantages
  - Non-thermal
- Disadvantages
  - Slow
  - Expensive



Courtesy of the AWS Welding Handbook, Volume 1, 9th Edition

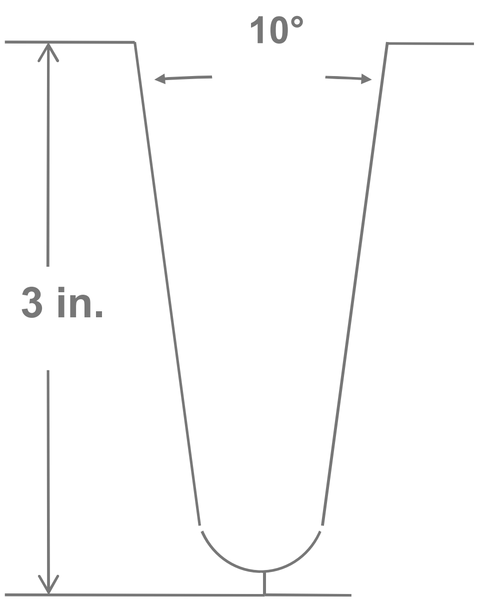
Welding Process Applications

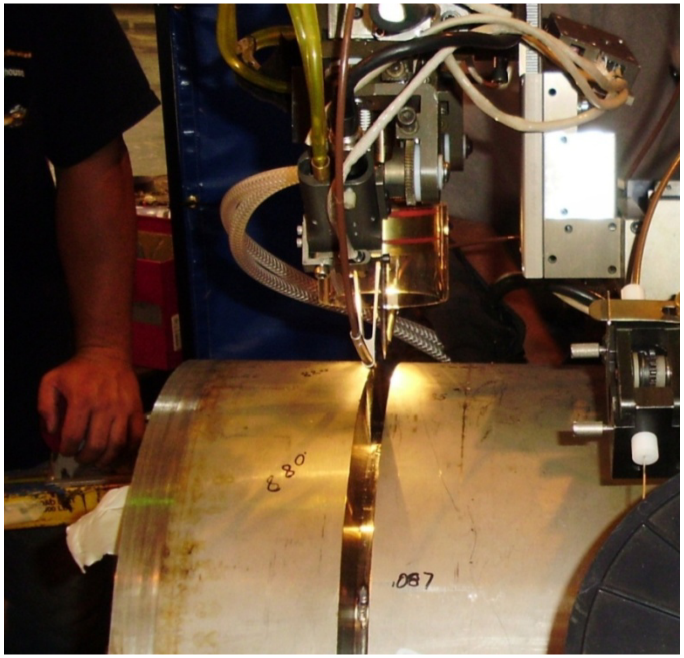
Module 2E

Welding Process Applications

Narrow Groove

- Often used for thick-wall pipe or nozzle to pipe applications
  - Weld prep angles as shallow as 1°
  - Typical GTAW joint preparation and welding setup are shown

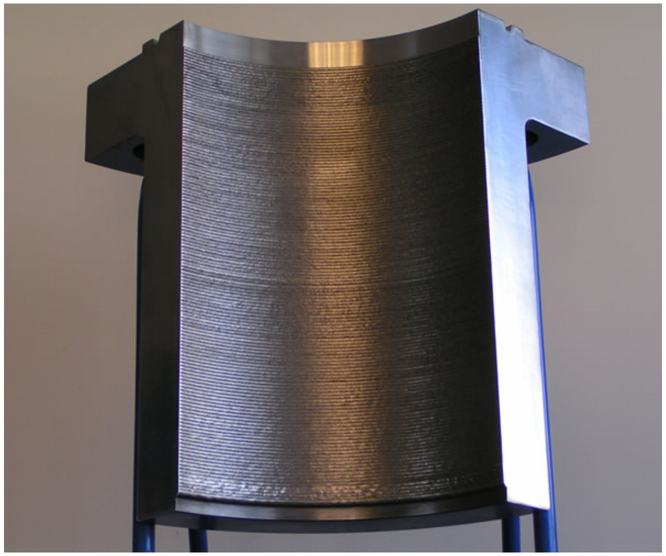




- Processes used in a narrow groove
  - GTAW
  - SAW
  - GMAW

Overlay

- Welding is used to deposit weld alloy cladding layers
- Provide improved properties of vessel walls, pipes, etc
  - Corrosion resistance
  - Wear
  - Structural integrity
- Process parameters are selected to maximize deposition rate, minimize dilution of clad metal with base metal



Cross section of tubing with internal weld cladding deposited by GTAW

ASME Section IX – Overlay Procedure Variables

- ASME Section IX provides welding procedure variables for overlay welding procedures
  - The additional welding procedure variables depend on the welding process used to deposit the weld overlay and the application of the overlay (i.e., Hard-Facing or Corrosion-Resistant Overlays)
    - Oxyfuel Welding, SMAW, SAW, GMAW, FCAW, GTAW, PAW, ESW and Laser Beam Welding have weld overlay procedure variables
    - Many of the variables are duplicates of typical procedure qualification variables
    - The variables are usually related to the dilution of the base material or the chemistry of the welding material
  - Overlay welding procedures require testing to assure the overlay is suitable for the intended purpose

ASME Section IX – GTAW Overlay Procedure Variables

Paragraph		Essential Variables: Hard-Facing Overlay	Essential Variables: Corrosion-Resistant Overlay	Nonessential Variables
QW-402 Joint	.16	< Finished t	< Finished t	
QW-403 Base Metals	.20	φ P-No.	φ P-No.	
	.23	φ T Qualified	φ T Qualified	
QW-404 Filler Metals	.3			φ Wire Size
	.12	φ Classification		
	.14	± Filler Metal	± Filler Metal	
	.23	φ Filler Metal Product Form	φ Filler Metal Product Form	
	.37		φ A-No.	
QW-405 Position	.4	+ Position	+ Position	
QW-406 Preheat	.4	Decrease > 100ºF Preheat > Interpass	Decrease > 100ºF Preheat > Interpass	

ASME Section IX – GTAW Overlay Procedure Variables

Paragraph		Essential Variables		Nonessential Variables
		Hard-Facing Overlay	Corrosion-Resistant Overlay	
QW-407 PWHT	.6	φ PWHT		
	.9		φ PWHT	
QW-408 Gas	.2	φ Single, Mixture, or %	φ Single, Mixture, or %	
	.3			φ Flow Rate
QW-409 Electrical Characteristics	.4	φ Current or Polarity	φ Current or Polarity	
	.12			φ Tungsten Electrode
	.26	1st Layer Heat Input > 10%	1st Layer Heat Input > 10%	

ASME Section IX – GTAW Overlay Procedure Variables

Paragraph		Essential Variables: Hard-Facing Overlay	Essential Variables: Corrosion-Resistant Overlay	Nonessential Variables
QW-410 Technique	.1			φ Stringer/weave
	.3			φ Orifice/Cup or Nozzle Size
	.5			φ Method of Cleaning
	.7			φ Oscillation
	.15			φ Electrode Spacing
	.25			φ Manual or Automatic
	.26			± Peening
	.38	φ Multiple to Single Layer	φ Multiple to Single Layer	
	.50	φ No. of Electrodes	φ No. of Electrodes	
	.52	φ Filler Metal Delivery	φ Filler Metal Delivery	φ Filler Metal Delivery

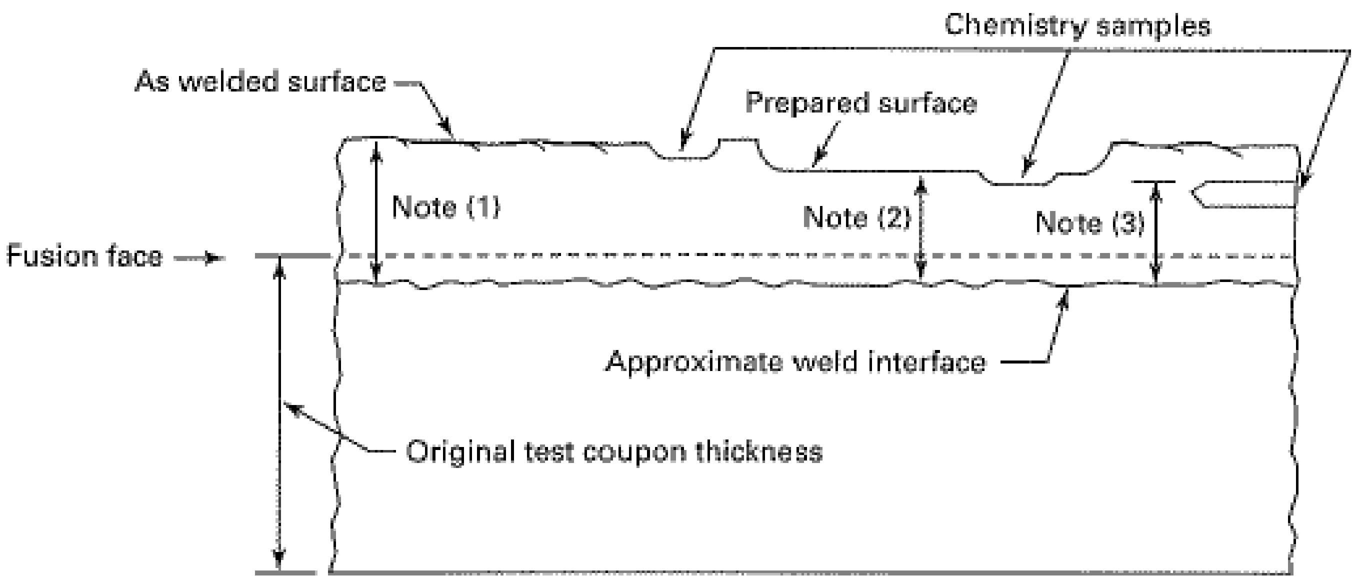
ASME Section IX – Overlay Qualification Requirements

QW-453
PROCEDURE/PERFORMANCE QUALIFICATION THICKNESS LIMITS AND TEST SPECIMENS FOR HARD-FACING (WEAR-RESISTANT) AND CORROSION-RESISTANT OVERLAYS

Thickness of Test Coupon (*T*)	Corrosion-Resistant Overlay [Note (1)]		Hard-facing Overlay (Wear-Resistant) [Note (2)]	
	Nominal Base Metal Thickness Qualified (*T*)	Type and Number of Tests Required	Nominal Base Metal Thickness Qualified (*T*)	Type and Number of Tests Required
Procedure Qualification Testing				
Less than 1 in. (25 mm) *T*	*T* qualified to unlimited	Notes (4), (5), and (9)	*T* qualified up to 1 in. (25 mm)	Notes (3), (7), (8), and (9)
1 in. (25 mm) and over *T*	1 in. (25 mm) to unlimited		1 in. (25 mm) to unlimited	
Performance Qualification Testing				
Less than 1 in. (25 mm) *T*	*T* qualified to unlimited	Note (6)	*T* qualified to unlimited	Notes (8) and (10)
1 in. (25 mm) and over *T*	1 in. (25 mm) to unlimited		1 in. (25 mm) to unlimited	

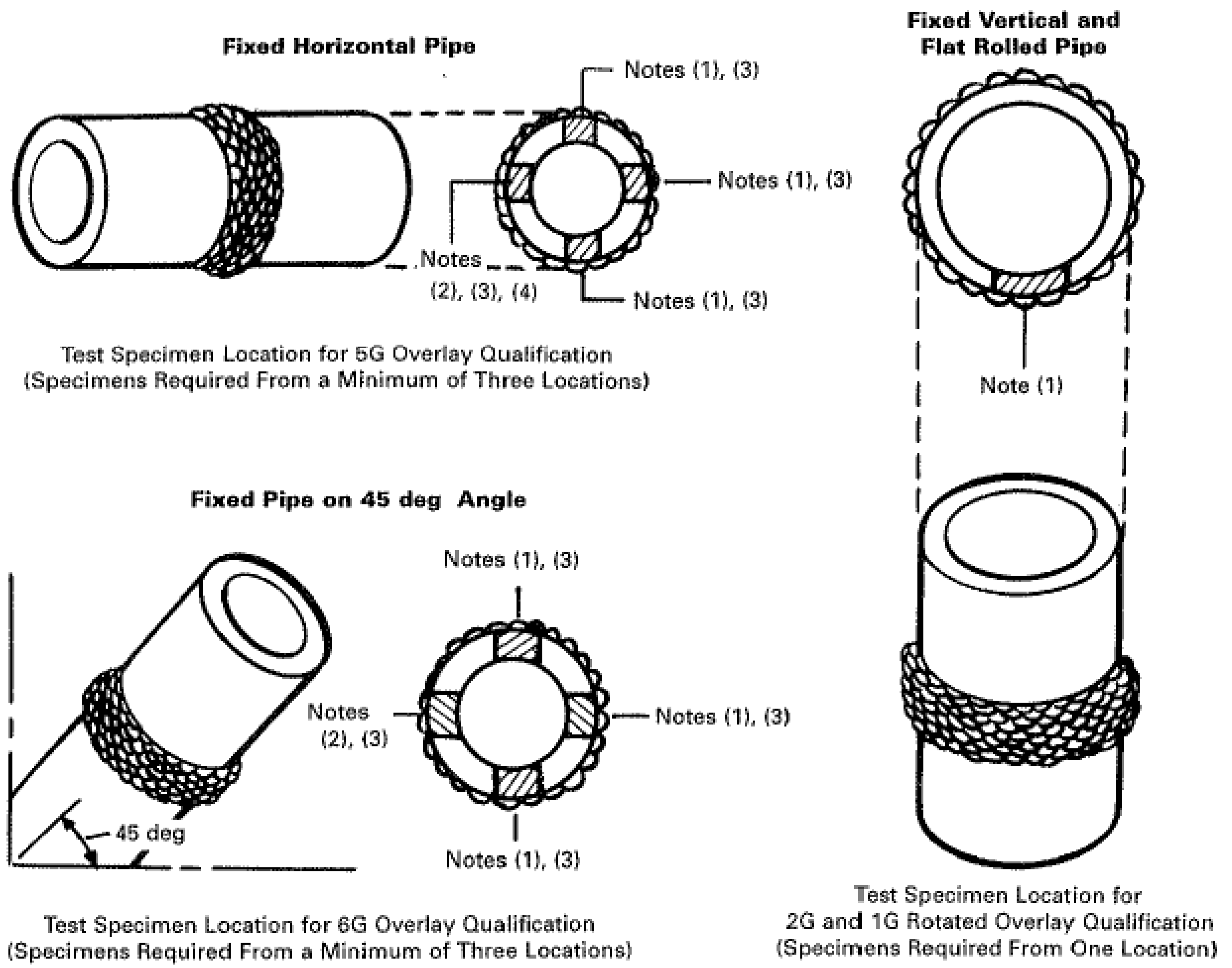
ASME Section IX – Overlay Qualification Requirements

QW-462.5(a) CHEMICAL ANALYSIS AND HARDNESS SPECIMEN CORROSION-RESISTANT AND HARD-FACING WELD METAL OVERLAY



ASME Section IX – Overlay Qualification Requirements

QW-462.5(b) CHEMICAL ANALYSIS SPECIMEN, HARD-FACING OVERLAY HARDNESS, AND MACRO TEST LOCATION(S) FOR CORROSION-RESISTANT AND HARD-FACING WELD METAL OVERLAY



Orbital Welding

- Specialized equipment used for pipe and overlay applications
- Can be used with several processes
  - GTAW
  - FCAW
  - GMAW
  - Hybrid
- Can be used in a narrow groove