Welding and Cutting Processes

Module 2

Module 2 – Welding and Cutting Processes

- 2A – Introduction to Arc Welding Processes
- 2B – Introduction to Non-Arc Welding Processes
- 2C – Brazing and Soldering
- 2D – Introduction to Cutting Processes
- 2E – Welding Process Applications

Module 2 Learning Objectives

- Definitions and terminology associated with arc welding
  - Description of welding arcs
  - Arc welding power supply types and characteristics
- Basic operational concepts of SMAW, GTAW, GMAW, FCAW, SAW, ESW, and EGW welding
- Overview of specialized welding processes including narrow groove welding, low hydrogen practices, overlays (HFWMO, CRWMO, structural) and stud welding
- Code requirements (essential, supplementary essentials, and non-essential variables)
- Welding Safety
- Practical Experience (SMAW, GTAW, and GMAW)
- Welding Process Demonstrations

Module 2 Learning Objectives

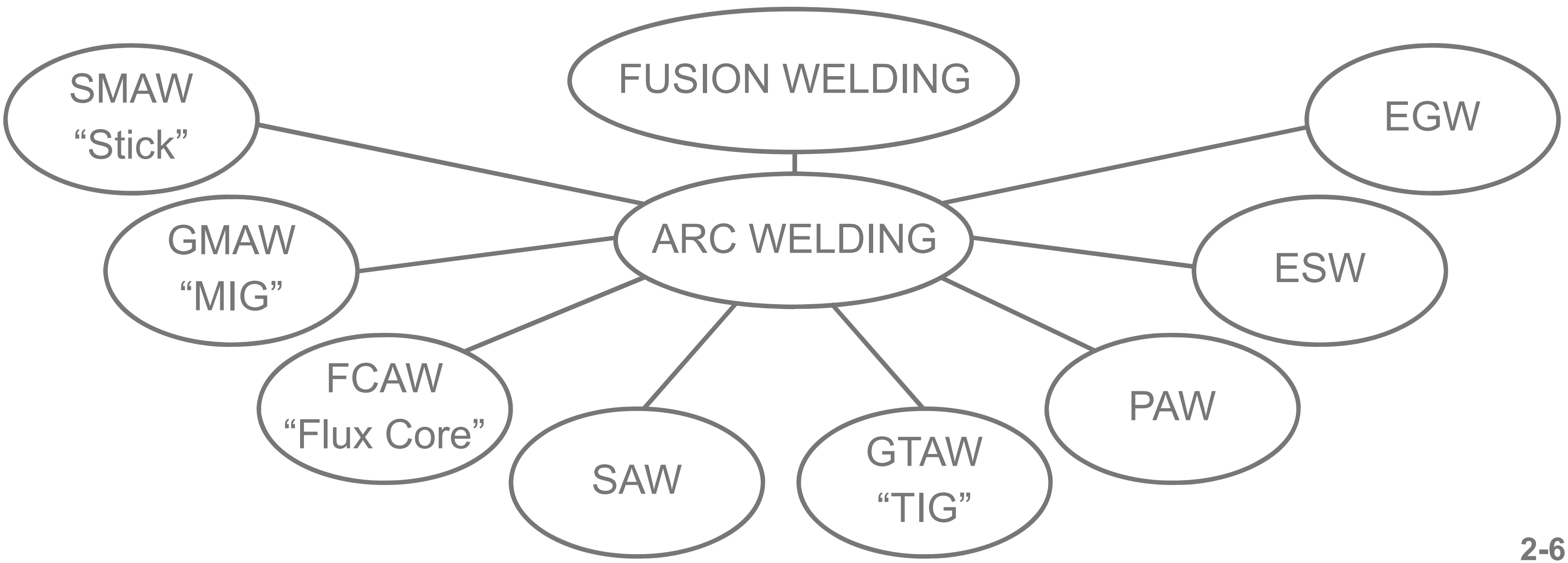
- Definitions and terminology associated with non-arc welding processes
- Descriptions and capabilities of non-arc welding processes
- Advantages, disadvantages, and applications of non-arc welding processes
- Important operating parameters of non-arc welding processes
- Safety issues
- Applicable codes, standards, and specifications
- Demonstrations

Introduction to Arc Welding Processes

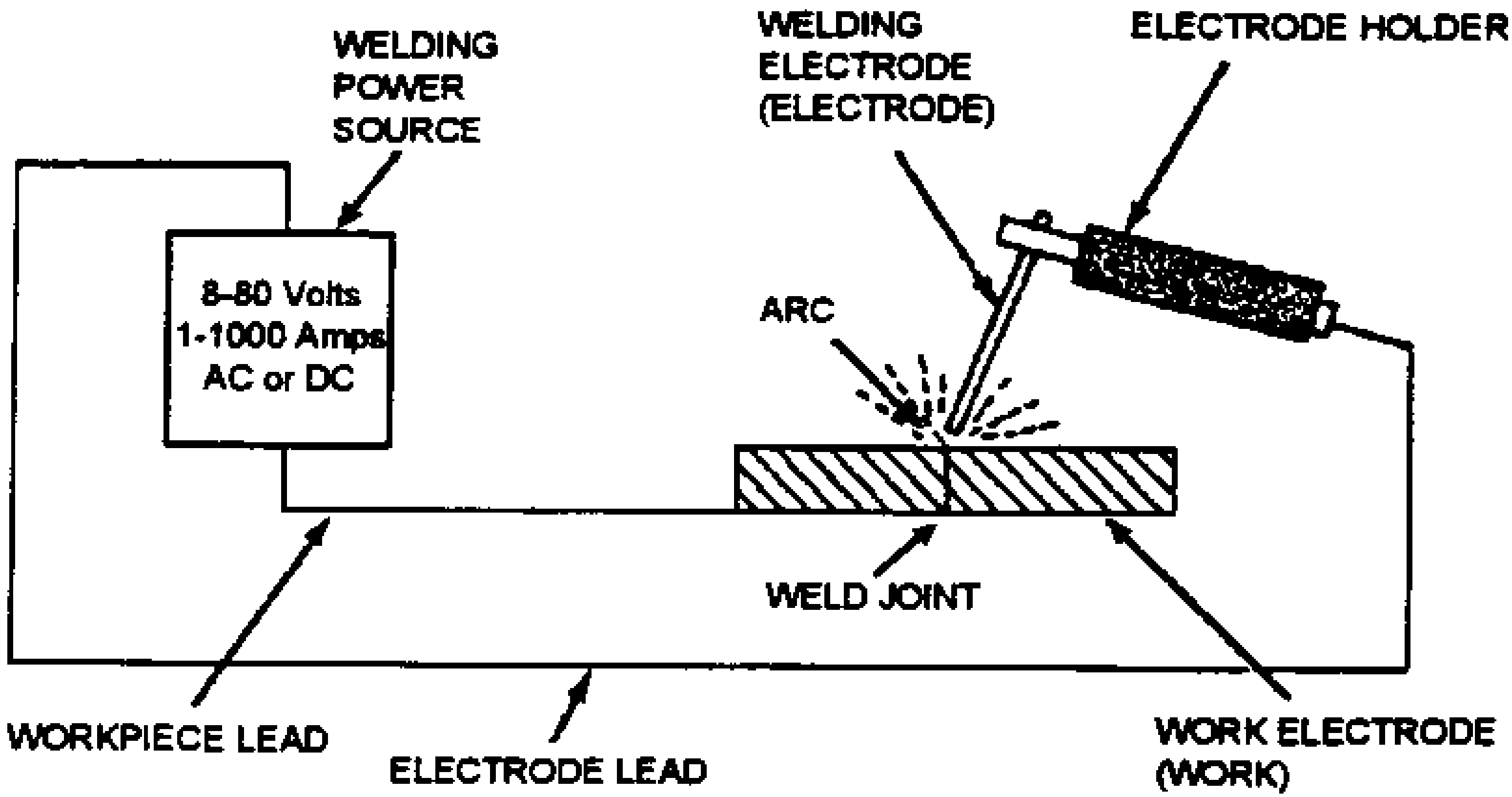
Module 2A

Process Definition

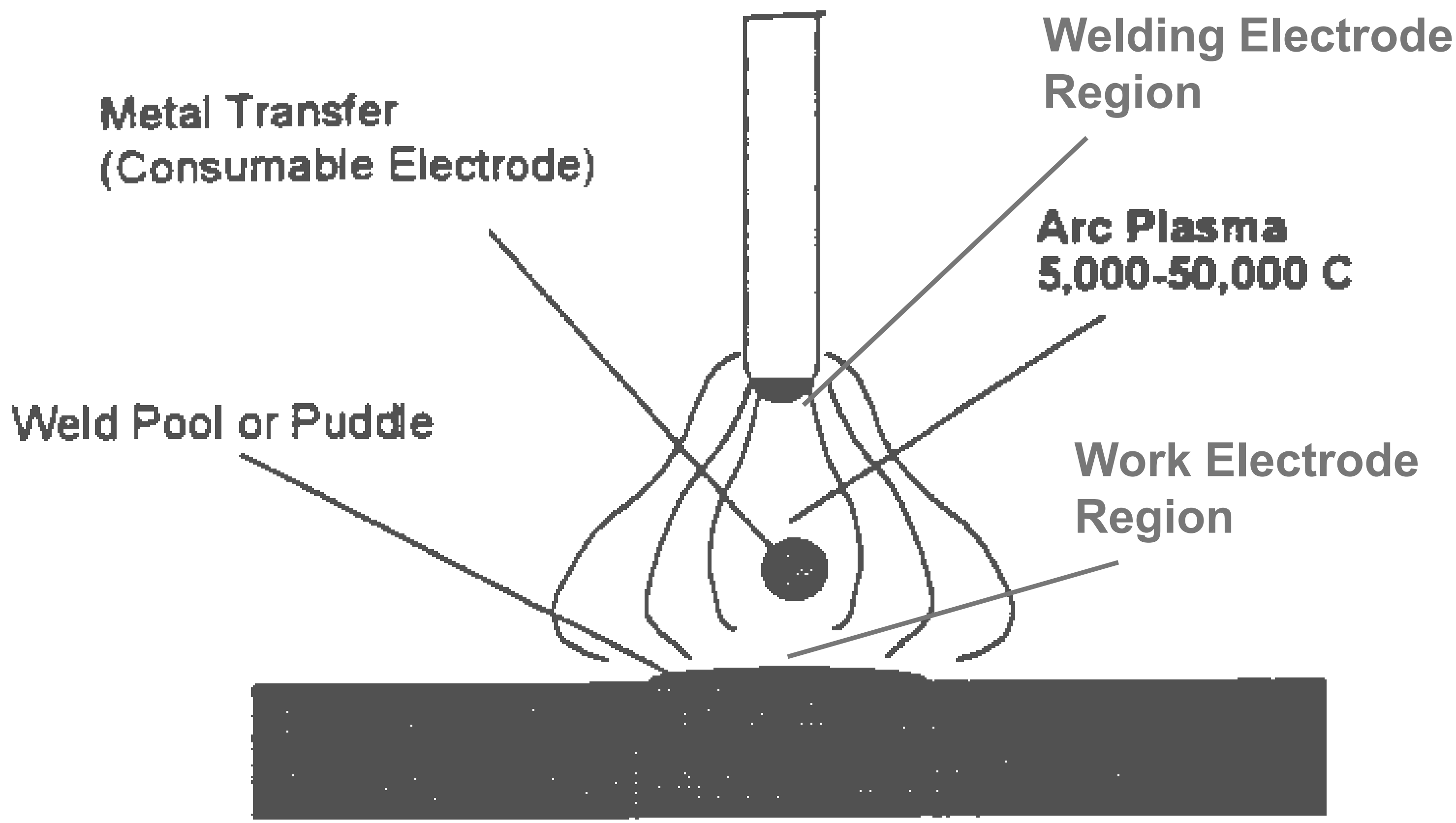
- Forms of arc welding vary by means of:
  - Controlling the arc
  - Shielding of the molten metal
  - Filler metal addition (if used)
- Upper: Standard terminology - AWS
- Lower: Commonly used trade names



Basic Arc Welding Circuit



Welding Arc


Metal Transfer
(Consumable Electrode)
Welding Electrode
Region
Arc Plasma
5,000-50,000 C
Weld Pool or Puddle
Work Electrode
Region

Electrode Types

- Consumable Electrodes
  - Melt and transfer to the weld for filling joint
    - Carbon steel
    - Low-alloy steel
    - Stainless steel
    - Aluminum
    - Magnesium
    - Copper
    - Titanium
  - Filler metal
- Nonconsumable Electrodes
  - Provide electrode for arc and **do not melt**
    - Tungsten
    - Carbon
  - Filler material, when used, is provided separately

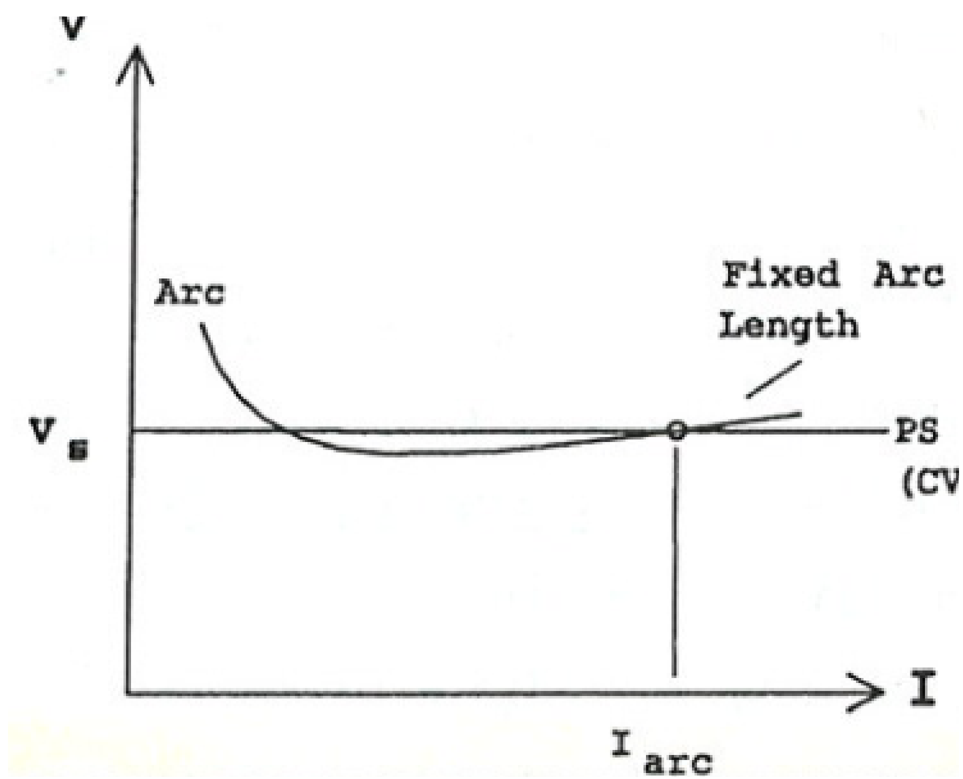
Consumable Electrode Classification (Filler Metal)

- Prefix
  - E = Electrode, R = Rod
- Carbon and Low Alloy Steels
  - First 2 or 3 digits indicate minimum UTS in KSI
  - Examples ER70S-1, E-7018 are 70 KSI UTS
- Other information maybe specified
  - Chemistry (ex. Cr, Mo, Mn, and Ni additions)
  - Process information (ex. S: solid, F: flux, T: tubular)
  - Primary welding positions
- Stainless Steels Use AISI Numbers
- Specific details contained in the electrode designation are dependent on the process

Arc Welding Power Sources

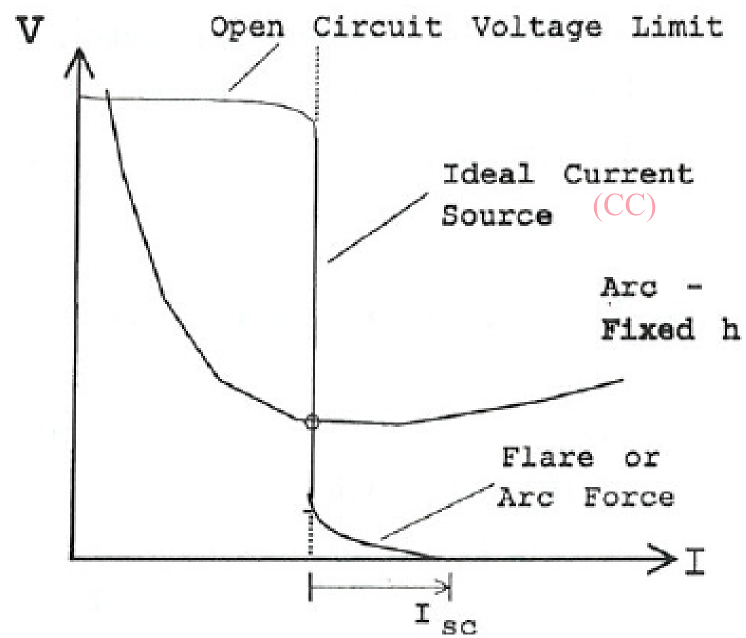
- Two types: constant voltage (CV) and constant current (CC)
  - Some power supplies are capable of both CC and CV operation

- Constant voltage
  - Generally used with welding processes that employ a continuously fed consumable electrode, typically in the form of wire (ex. GMAW, FCAW)



Arc Welding Power Sources

- Constant current
  - Slight variations in voltage due to changes in arc length have a minimal effect on current
  - Generally used for manual welding with a covered electrode or a tungsten electrode, where variations in arc length are unavoidable (ex. SMAW, GTAW)
    - When used in a semi-automated or automated application, external control devices are needed (ex. GMAW, FCAW)



Primary Operating Parameters

- Arc Voltage/Arc Length
- Arc Current
- Electrode Feed Rate (Consumable)
- Welding Travel Speed
- Polarity

Arc Voltage

- Mainly related to arc length
- Affects concentration of arc heat
  - Shorter arc, more heat concentration
  - Longer arc, less heat concentration
- Voltage can be regulated to control arc length
- Varies little with arc current and welding speed
  - Has little affect on energy input and amount of melting
- Typical arc voltages: 8- to 40-volts

Arc Current

- Mainly affects amount of arc heat
- Determines electrode melting rate (consumable)
- Directly affects energy input to work and melting
  - More current, more melting
  - Less current, less melting
- Often regulated to control arc and energy input
- Arc currents: 1- to 1000-amperes
  - More typically, 50- to 500-amperes

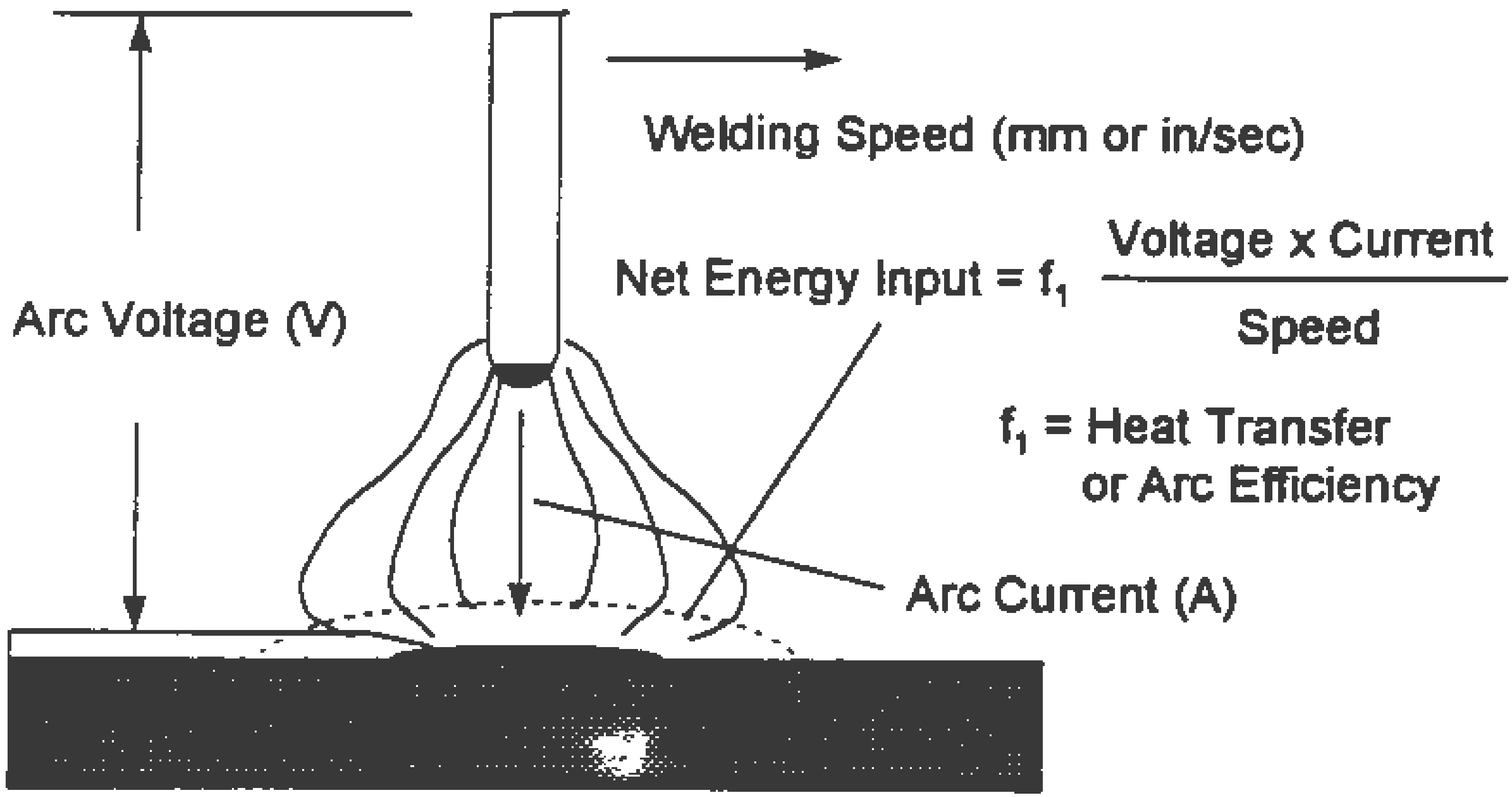
Electrode Feed Rate

- Directly determines amount of metal deposited
- Closely related to current
  - Current must provide equal melt-off rate
- May be supplied manually or via an automatic feed system
- Typically, 10’s to 100’s of inches-per-minute (ipm)

Welding Travel Speed

- Has little affect on arc and electrode melting
- Directly affects metal deposition per length of weld
- Mainly affects energy input to work
  - Faster travel, less energy input and base metal melting
  - Slower travel, more energy input and base metal melting
- An important parameter to productivity
- May be provided manually or mechanized
- Typical range is 5- to 100-in/min

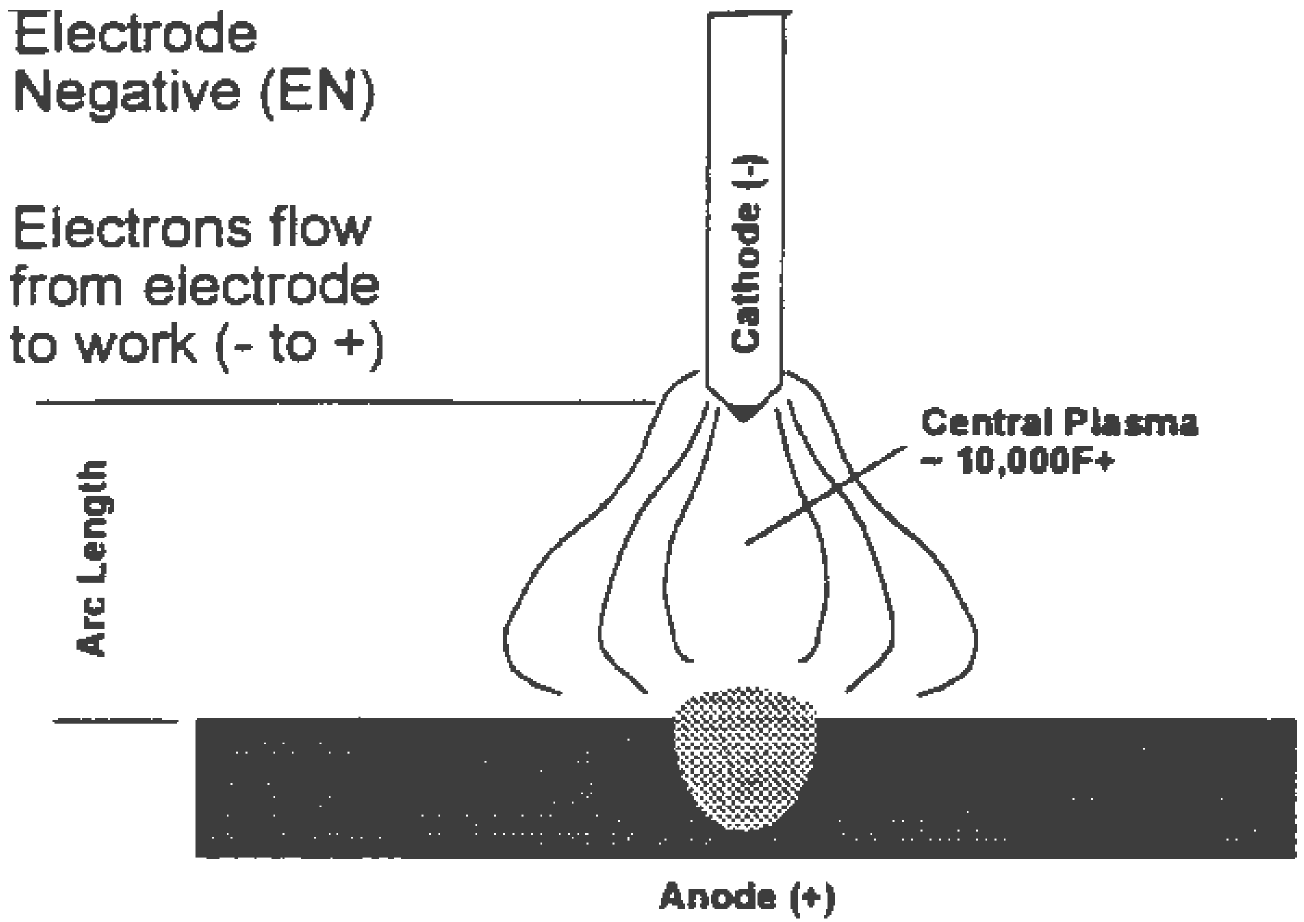
Energy Input



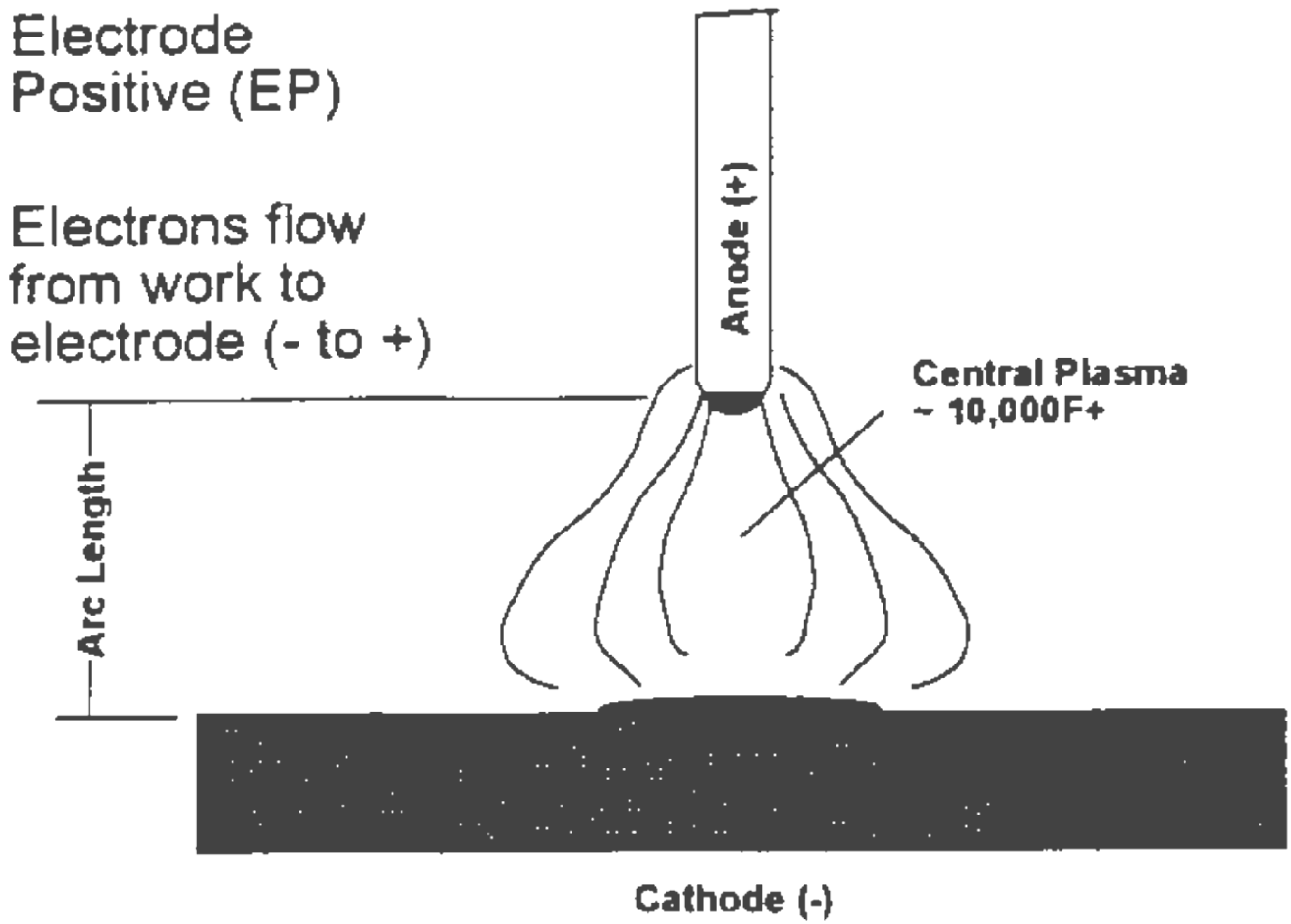
Electrical Polarity

- Electrical polarity is important to arc operation
- Electrode positive
  - DCEP
  - DCRP (reverse polarity)
- Electrode negative
  - DCEN
  - DCSP (straight polarity)
- Alternating polarity
  - AC
  - VP (variable polarity)

The DCEN Arc


Electrode
Negative (EN)
Electrons flow
from electrode
to work (- to +)
Cathode (-)
Central Plasma
~ 10,000F+
Arc Length
Anode (+)

The DCEP Arc


Electrode
Positive (EP)
Electrons flow
from work to
electrode (- to +)
Anode (+)
Central Plasma
~ 10,000F+
Arc Length
Cathode (-)

Need for Shielding from Atmosphere

- Molten metal reacts with the atmosphere to form oxides and nitrides
  - Porosity can result
  - Metallurgical changes can occur
- Weld mechanical properties are generally reduced

- Note that the weld should be free of dirt, grease, paint, scale, and other foreign objects to ensure weld quality
  - Fluxes and shielding gasses are not designed to scavenge these components from the solidifying weld metal

Flux Shielding

- Provides a gas to shield the arc and prevent excessive atmospheric contamination of the molten filler metal and weld pool.
- Provides scavengers, deoxidizers, and fluxing agents to cleanse the weld and prevent excessive grain growth in the weld metal.
- Establishes the electrical characteristics of the electrode.
- Provides a slag blanket to protect the hot weld metal from the air and enhance the mechanical properties, bead shape, and surface cleanliness of the weld metal.
- Provides a means of adding alloying elements to change the mechanical properties of the weld metal.

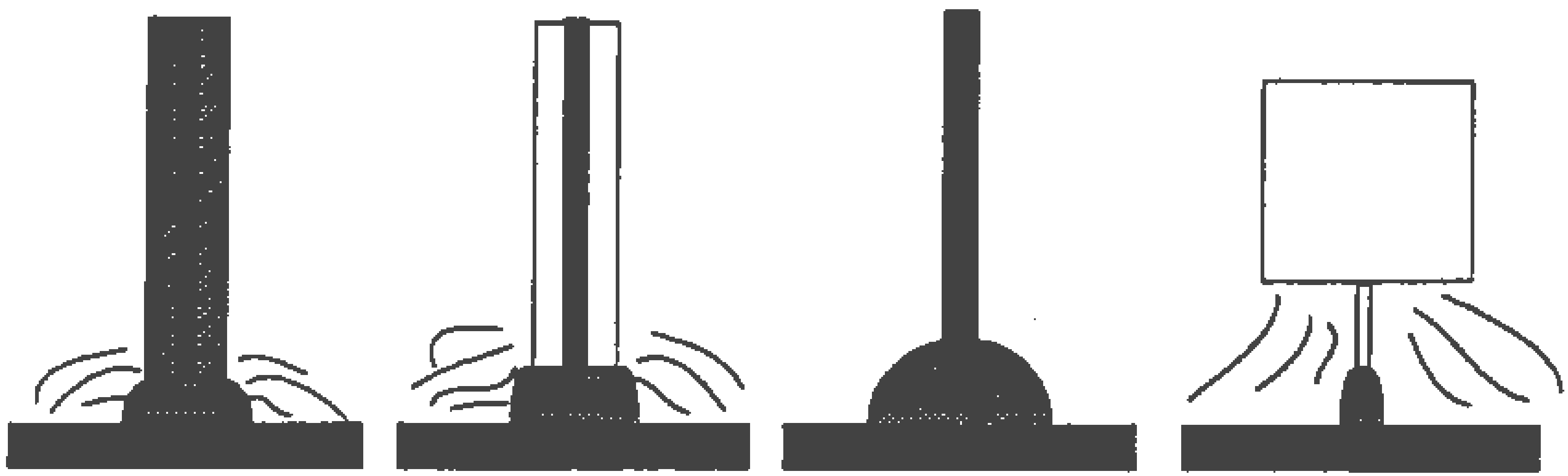
Welding Fluxes

Ingredient	Function
Iron oxide	Slag former, arc stabilizer
Titanium oxide	Alloy
Calcium fluoride	Slag former, arc stabilizer
Magnesium oxide	Fluxing agent
Potassium silicate	Slag, binder, fluxing agent
Other silicates	Gas former, arc stabilizer
Calcium carbonates	Gas former
Cellulose	Alloy, deoxidizer
Ferro-chrome	Alloy
Other carbonates	Gas former
Ferro-manganese	Alloy
Ferro-silicon	Deoxidizer

Gas Shielding

- Mainly purges the weld area to shield it from the atmosphere
- Argon is the most common inert gas
- Carbon dioxide is sometimes used
  - Less expensive
  - Similar to gases produced from fluxes
- CO2 and O2 are commonly mixed with argon
  - Oxidation stabilizes arc and metal transfer
  - Improves weld bead wetting
- H2 can be added to increase arc heat in some cases
- Helium may also be used to increase arc heat
- Require addition of deoxidizers to filler materials

Sources of Shielding



Covered Electrode	Flux Cored	Submerged Arc	Gas Shielded
Covering forms CO_2 & slag	Core forms gasses & slag	Flux shields arc	Ar, CO_2 & mixes

Arc Welding Hazards

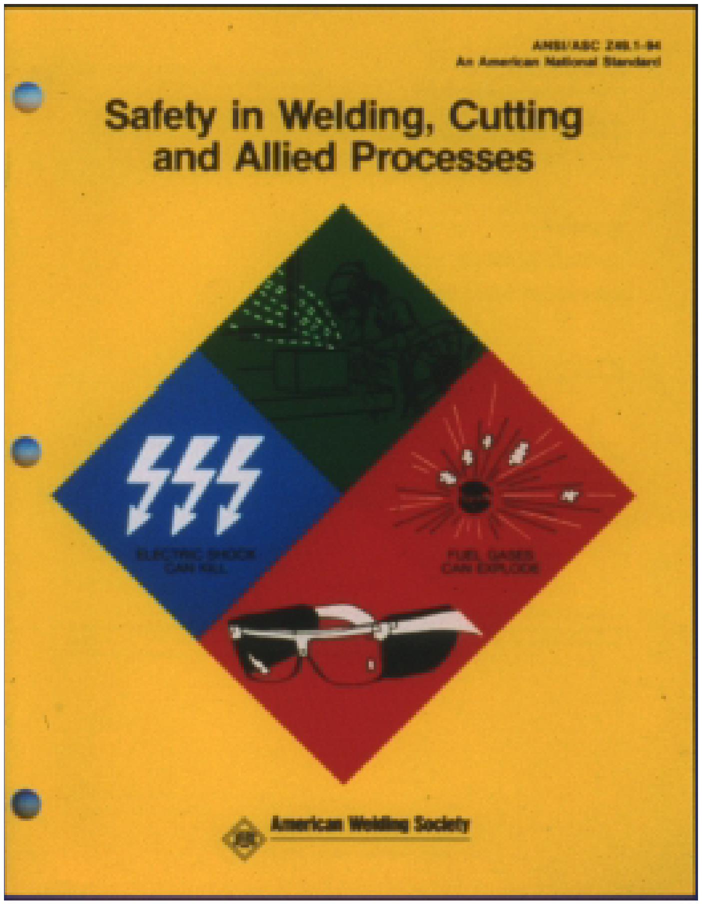
- Arc Radiation
  - UV damage to skin and eyes
- Electrical Shock
  - Welding voltages are generally safe
  - Anomalous conditions can arise
- Fumes and Gases
  - Suffocation
  - Long term breathing of fume
- Compressed Gases
  - Explosion of cylinders
- Burns - Hot Metal
- Fire - Ignition of Nearby Flammable Materials

Arc Welding Safety

- AWS Z49.1: 2005
  - Safety in Welding, Cutting, and Allied processes
  - Training (mandated under provisions of the U.S. Occupational Safety and Health Act (OSHA), especially those of the Hazard Communication Standard, 29 CFR 1910.1200)
- Management Support
- Ventilation
- General Housekeeping
- Eye and Skin Protection from Radiation
- Hot Work Permit System

Reference: AWS Z49-1 or WHB, V1, Ch16

ANSI/ASC Z49.1 Safety in Welding, Cutting and Allied Processes



- A document outlining safe practices for welding and cutting operations
- Is referenced almost in all AWS welding codes
- When the code is mandated by the contract or laws, ANSI/ASC Z49.1 is also invoked.

Management Support

- Evidenced by:
  - Stating clear safety objectives
  - Showing commitment to safety
  - Designating safe work areas
  - Developing safety procedures
  - Providing safe equipment
  - Implementing safety training

Personal Protective Equipment

- Sturdy boots, no laces
- Clean clothing
- Woolen is best
- Treated cotton acceptable
- No synthetics
- Pants without cuffs
- Pants outside boots
- Flaps on shirt pockets
- Cap
- Gloves
- Leathers

Eye, Ear, Face, and Head Protection

Lens Shade Selector

Key Words—Eye protection and lens shade

Table 2.1—Lens Shade Selector
Shade numbers are given as a guide only and may be varied to suit individual needs

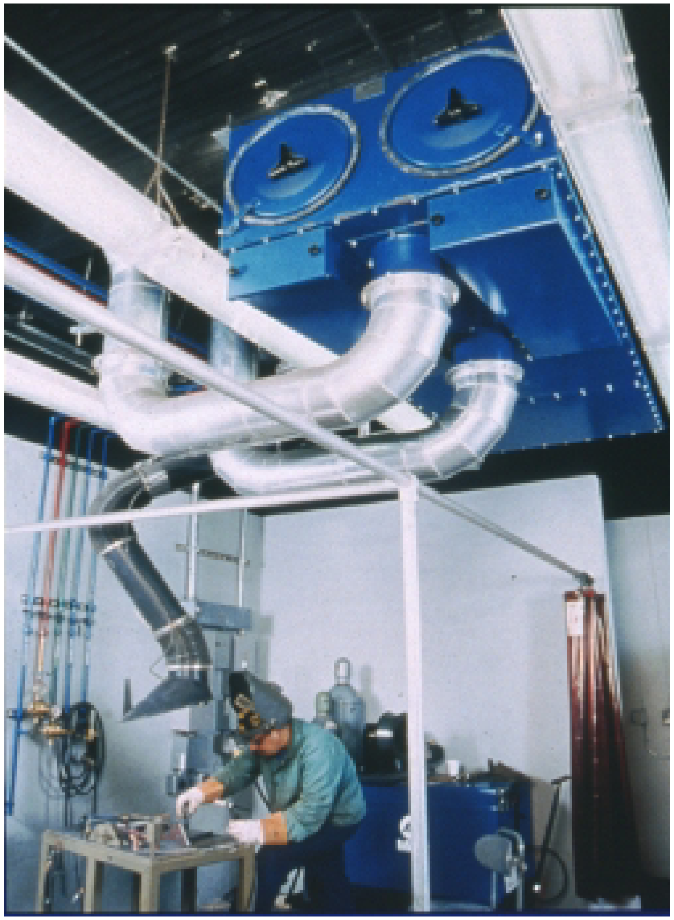
Operation	Electrode Size, mm (1/32 in.)	Arc Current (Amperes)	Minimum Protective Shade	Suggested[1] Shade No. (Comfort)
Shielded Metal Arc Welding (SMAW)	less than 2.5 (3)	less than 60	7	—
	2.5–4 (3–5)	60–160	8	10
	4–6.4 (5–8)	>160–250	10	12
	more than 6.4 (8)	>250–500	11	14
Gas Metal Arc Welding and Flux Cored Arc Welding (GMAW and FCAW)		less than 60	7	—
		60–160	10	11
		>160–250	10	12
		>250–500	10	14
Gas Tungsten Arc Welding (GTAW)		Less than 50	8	10
		50–100	8	12
		>150–250	10	14
Air Carbon Arc Cutting (light) (CAC-A)		less than 500	10	12
(heavy)		500–1000	11	14
Plasma Arc Welding (PAW)		less than 20	6	6 to 8
		20–100	8	10
		>100–400	10	12
		>400–800	11	14
Plasma Arc Cutting (PAC)				
Light[2]		less than 300	8	9
Medium		300–400	9	12
Heavy		>400–800	10	14
Torch Brazing (TB)		—	—	3 or 4
Torch Soldering (TS)		—	—	2
Carbon Arc Welding (CAW)		—	—	14

Operation	Plate Thickness mm	Plate Thickness in.	Suggested[1] Shade No. (Comfort)
Gas Welding (GW)			
Light[2]	under 3.2	under 1/8	4 or 5
Medium	3.2 to 13	1/8 to 1/2	5 or 6
Heavy	over 13	over 1/2	6 to 8
Oxygen Cutting (OC)			
Light[2]	under 25	under 1	3 or 4
Medium	25 to 150	1 to 6	4 or 5
Heavy	over 150	over 6	5 or 6

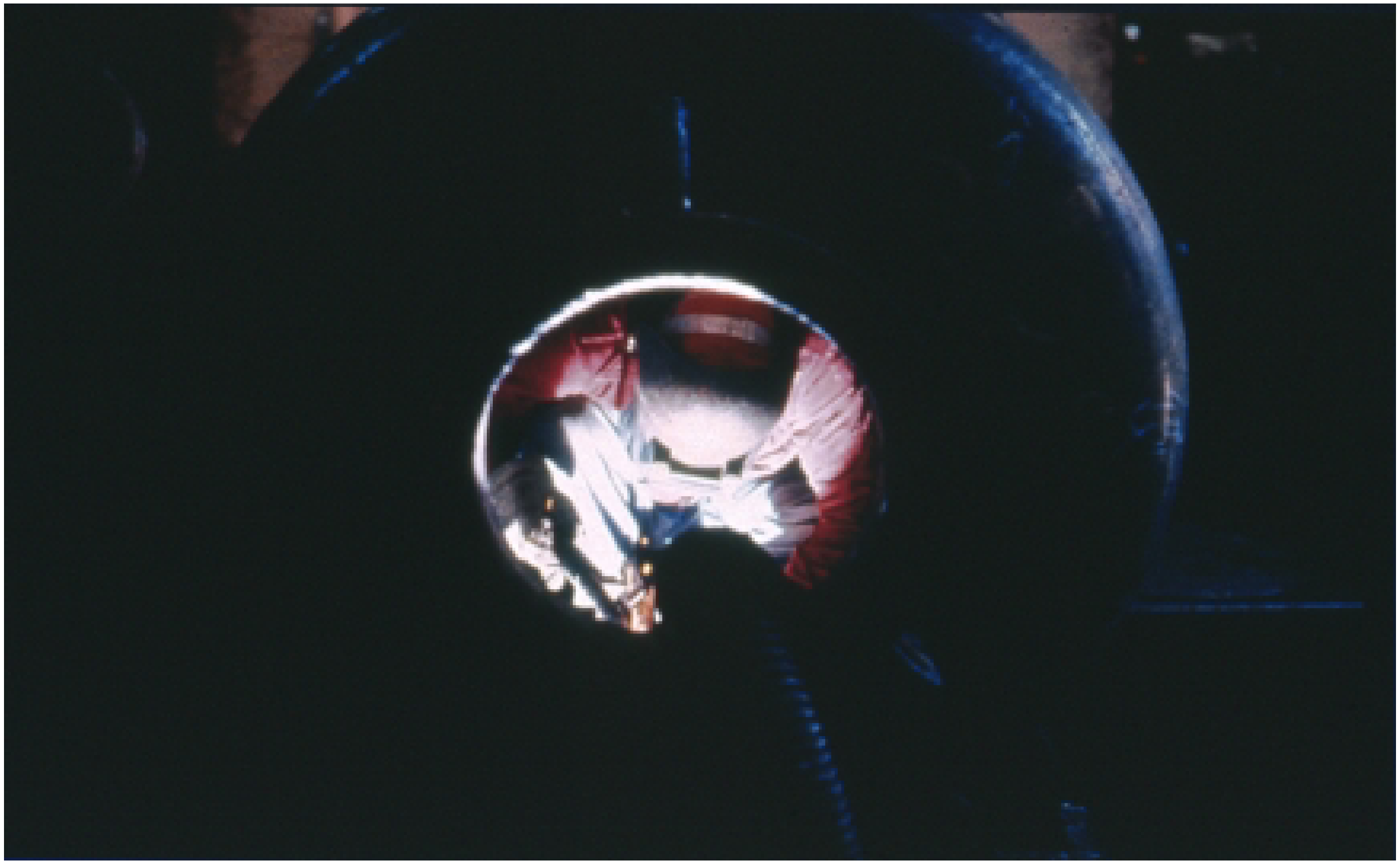
1. Shade numbers are given as a rule of thumb. It is recommended to begin with a shade that is too dark to see the weld zone. Then one should go to a lighter shade which gives sufficient view of the weld zone without going below the minimum. In gas welding or oxygen cutting where the torch produces a high yellow light, it is desirable to use a filter lens that adsorbs the yellow or sodium line in the visible light (spectrum) of the operation.
2. These values apply where the actual arc is clearly seen. Experience has shown that lighter filters may be used when the arc is hidden by the workpiece.

Fume Exposure and Ventilation

note head position



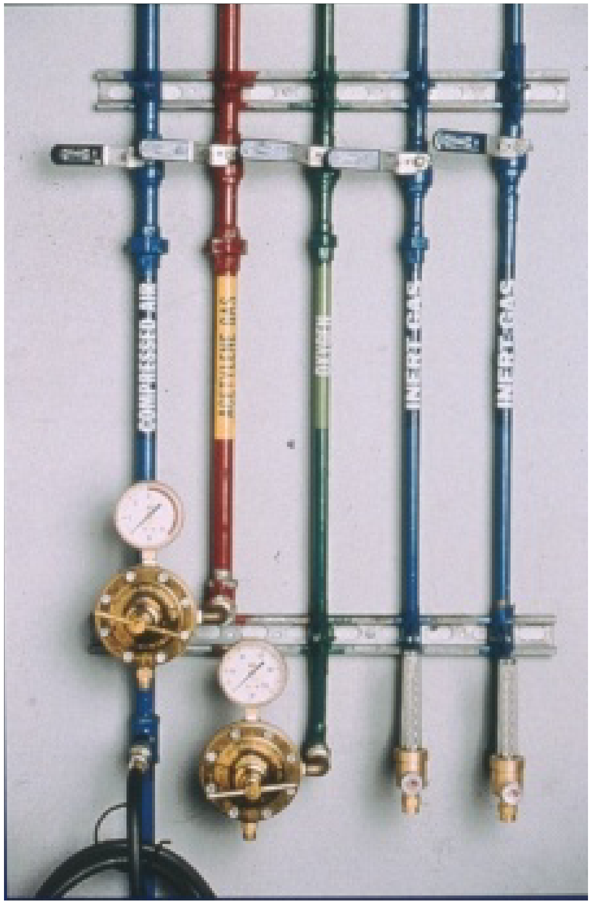
Welding in Confined Space



Shield Gases

- Argon, Helium – Inert
- Nitrogen, Carbon dioxide – Reactive
- Odorless
- Colorless
- Can displace oxygen

Safe Welding and Cutting of Containers

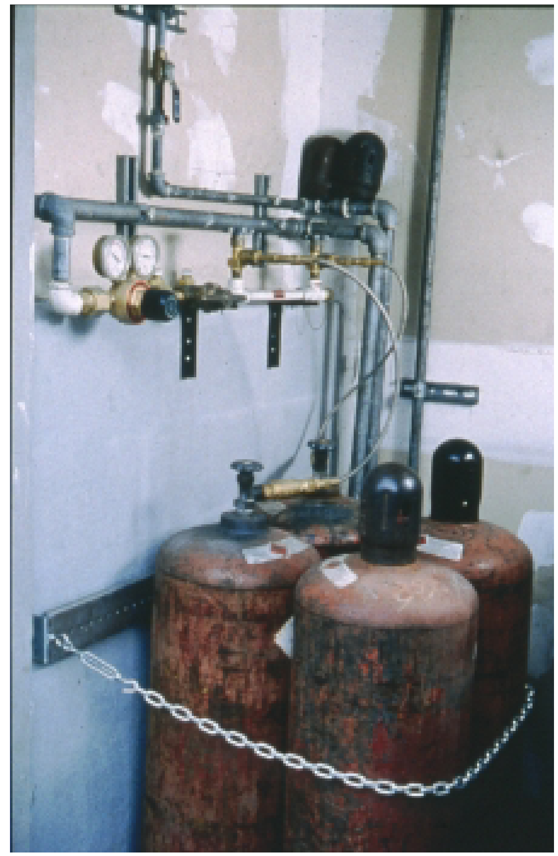


Manifold/Piping System

Compressed Gas

Compressed Gases Cylinder Safety

Oxygen Manifold System
- Oxygen Supports Combustion



Acetylene Manifold System
– A Fuel Gas

Arc Welding Power Sources

Module 2A.1

Arc Welding Power Source

- Provide suitably conditioned electrical power for the arc
  - Reduce line voltage to arc voltage
  - Provide suitable output characteristic for a stable arc
- Allow operator input of weld parameters/sequences
- Interfaces to/from other equipment
  - Wire feeders
  - Controllers
  - Robot systems

Sources of Electricity

- Engine driven generator/alternator
- Utility power

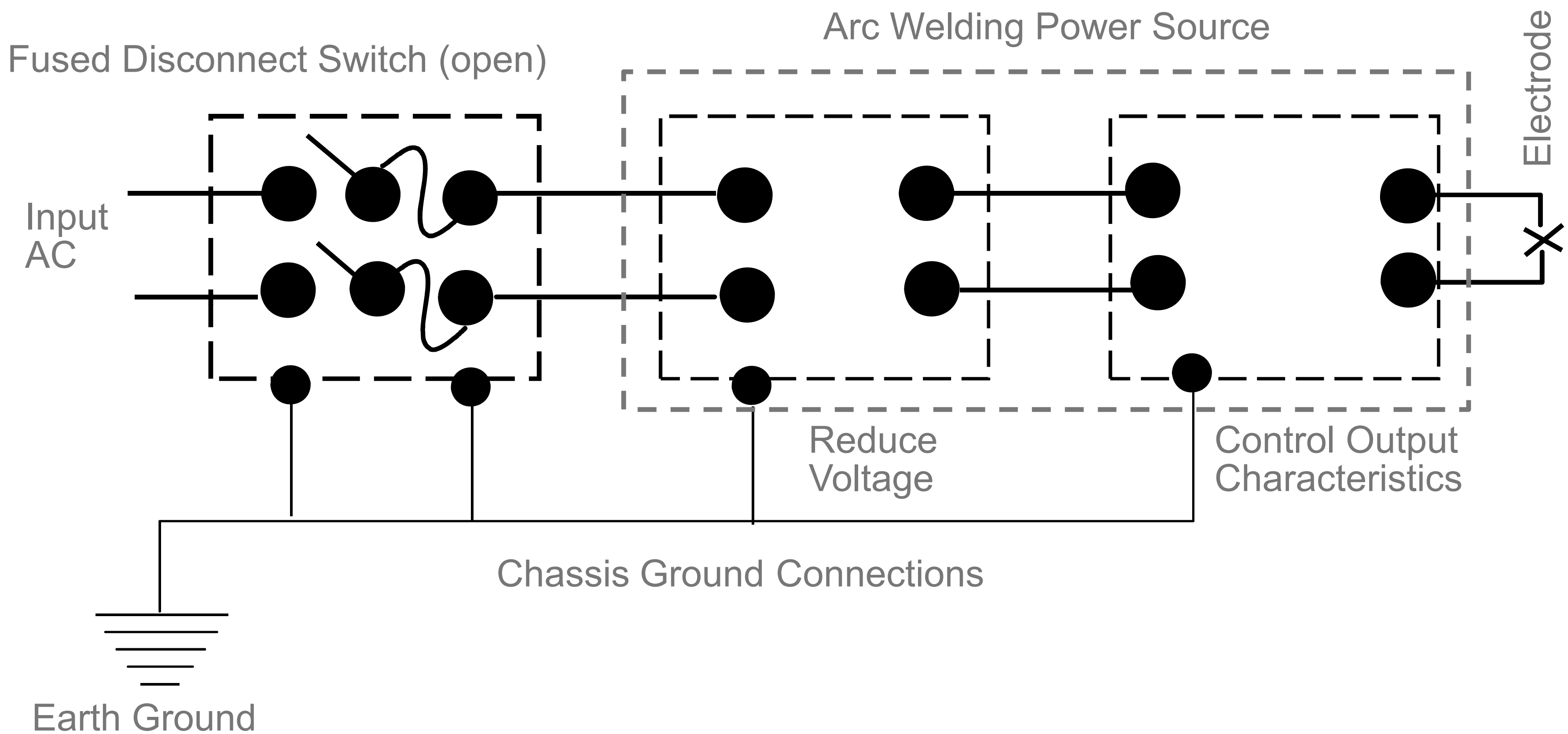
Usable Arc Welding Voltage, Current Range

- Industrial line voltages are 208VAC to 480VAC
- Voltage range for a welding arc is 20V to 80V
- Welding power sources need a transformer to convert line voltage to welding voltage
- Motor driven generators (for field use) directly output voltages that are usable for arc welding
- Typical welding arc currents range from 100A to 1000A
- 2kVA to 80kVA of electrical power is needed

Arc Welding Power Source Characteristics

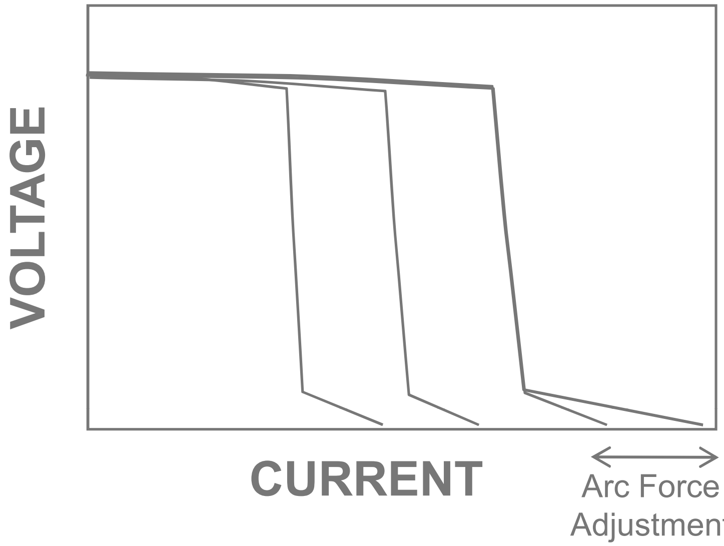
- Type of current
  - Transformers - AC
  - Transformers with rectifiers - AC/DC
- Welding current rating
- Duty cycle
- Service classification
- Input power requirements
- Special features
  - Remote control
  - High frequency
  - Pulsation
  - Start and finish schedules
  - Wave balancing and line voltage compensation

Line-Powered Welding Power Source Components

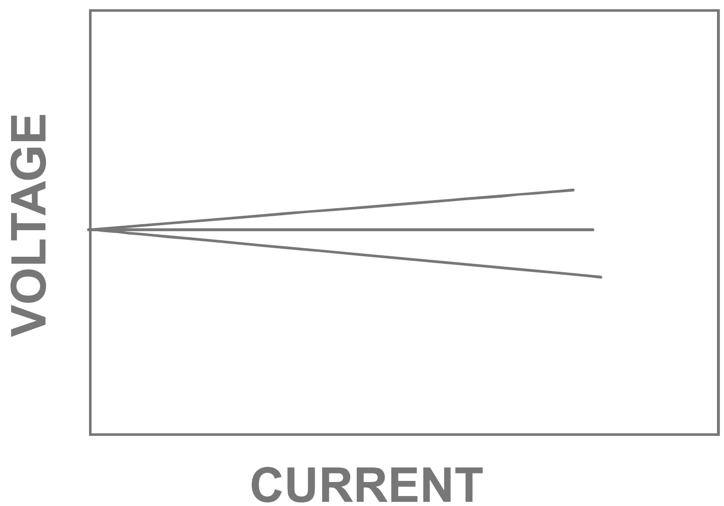


Basic Characteristics of Power Sources

- Constant Current
  - Transistor switching inverter supplies provide a relatively constant current at a given setting



- Constant Voltage
  - Voltage remains relatively stable and current varies to maintain an arc voltage



Output Control Methods

- Transformers
  - Tapped secondary
  - Movable coil or shunt
- Reactor (inductor, older technology)
  - Movable reactor core
  - Saturable reactor (magnetic amplifier)
- Silicon Controlled Rectifier (SCR, newer technology)
- Transistor (newest technology)
  - Linear
  - Switching - inverter

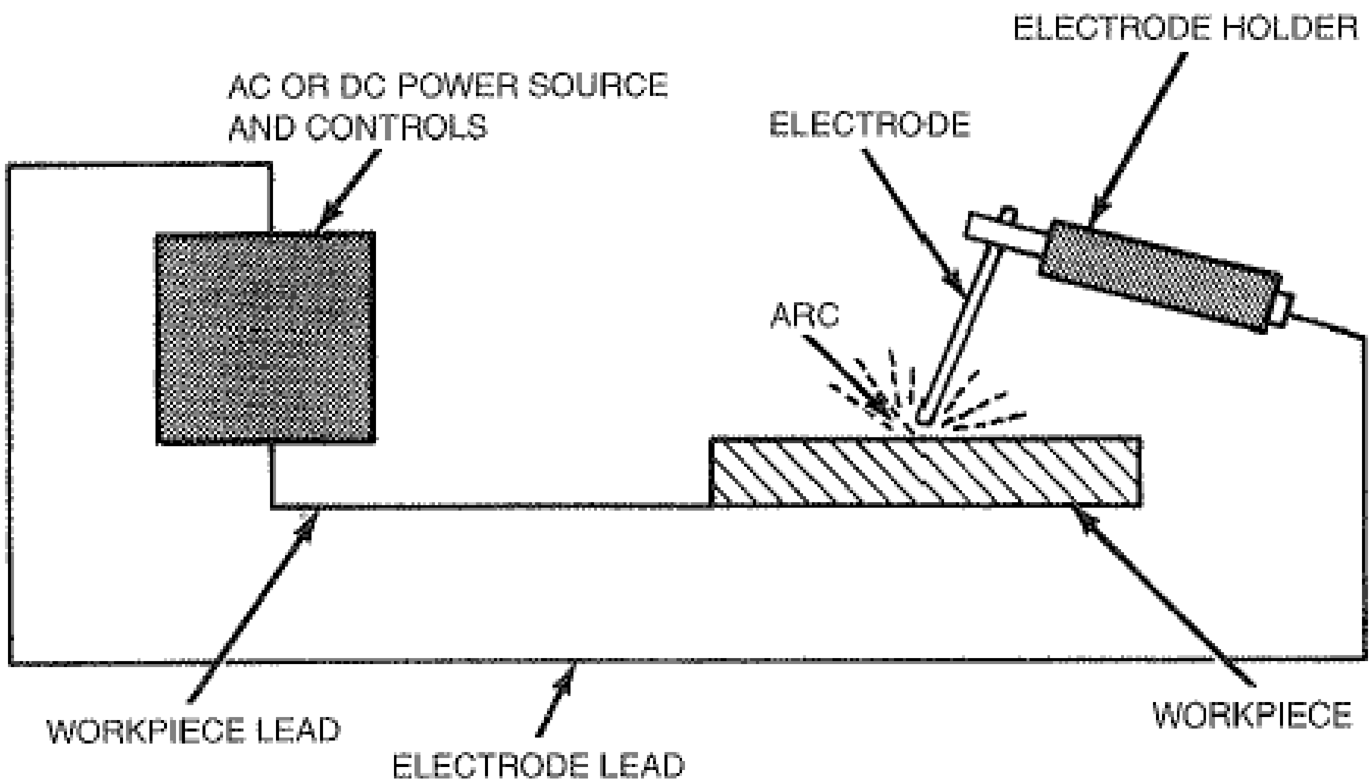
Other Features

- Single phase
- Three phase
- Remote control
- Pulsation
- Variable polarity AC
- High frequency
- Synergic controls
- Start control
- Arc force control
- Finish - down slope

Shielded Metal Arc Welding (SMAW)

Module 2A.2

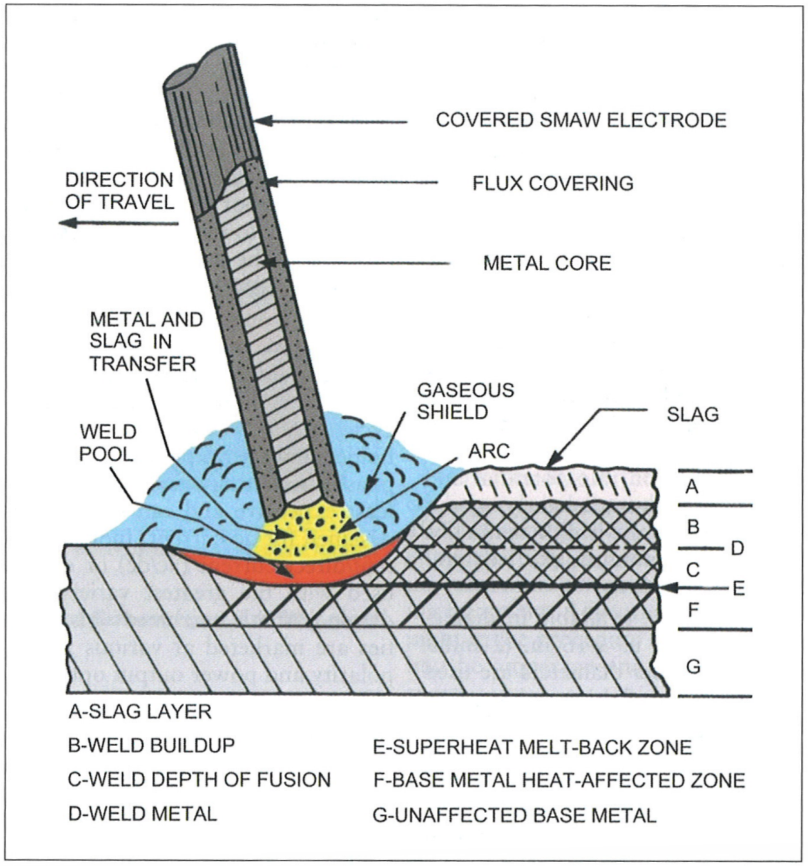
Elements of a Typical Welding Circuit for SMAW



Source: AWS Handbook, 9th ed., Vol. 2

Definition of SMAW

- An arc welding process in which coalescence of metals is produced by heat from an electric arc that is maintained between the tip of a covered electrode and the surface of the base metal in the joint being welded



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.8.

Figure 1.1—Schematic Representation of Shielded Metal Arc Welding

Source: AWS Handbook 9th ed. Vol. 2

SMAW

Medium arc length

170A, 12V, T=5.5 IPM

Long arc length

170A, 14V, T=5.5 IPM

6012 electrode was used
Recording rate was 125 frames per second

Electrode Covering

- Depending on the type, the covering performs one or more of the following:
  - Provide a gas cover to shield the arc and prevent excessive atmospheric contamination of the molten filler metal
  - Provide scavengers, deoxidizers, and fluxing agents to cleanse the weld and (potentially) prevent excessive grain growth in the weld metal
  - Establishes the electrical characteristics of the arc.
  - Provides a slag blanket to protect the hot weld metal from the air and enhance the mechanical properties, bead shape, and surface cleanliness of the weld metal
  - Provides a means of adding alloying elements to weld metal to alter the microstructure and mechanical properties of the weld metal

Characteristics of SMAW

- Outgrowth of original welding process developed in the early 20th century
- Most widely used process worldwide
- Normally performed manually by skilled welders
- Equipment and consumable costs are low
- Extremely versatile
- Productivity is low
- Fume generation rates are high
- Generally considered “low tech”

SMAW Advantages

- Most widely used process worldwide – broad skill-base
- Equipment and consumable costs are low – "low-tech"
- Extremely versatile
- Easily implemented for field welding
- Relatively adaptable to part fit-up variances
  - Operator skill is required

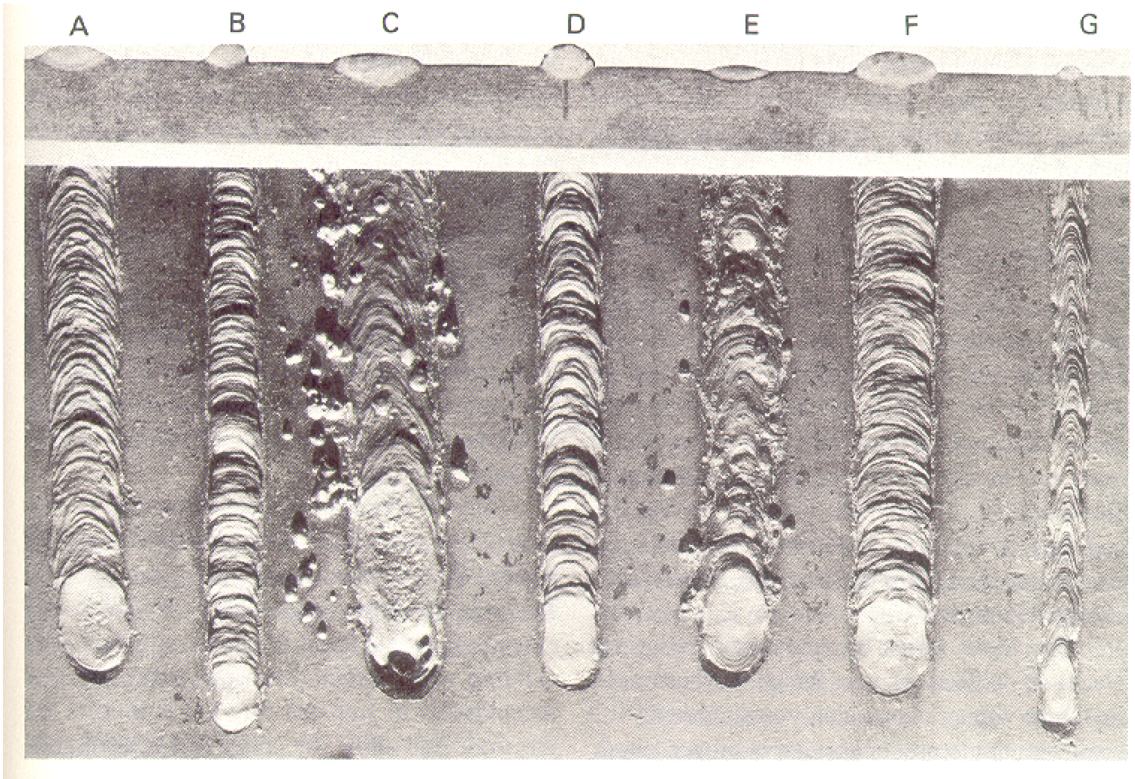
Underwater welding with SMAW

Limitations

- Requires relatively high-skilled manual welder
- Deposition rate is low
- Defect rates are relatively high
- Fume generation rates are high

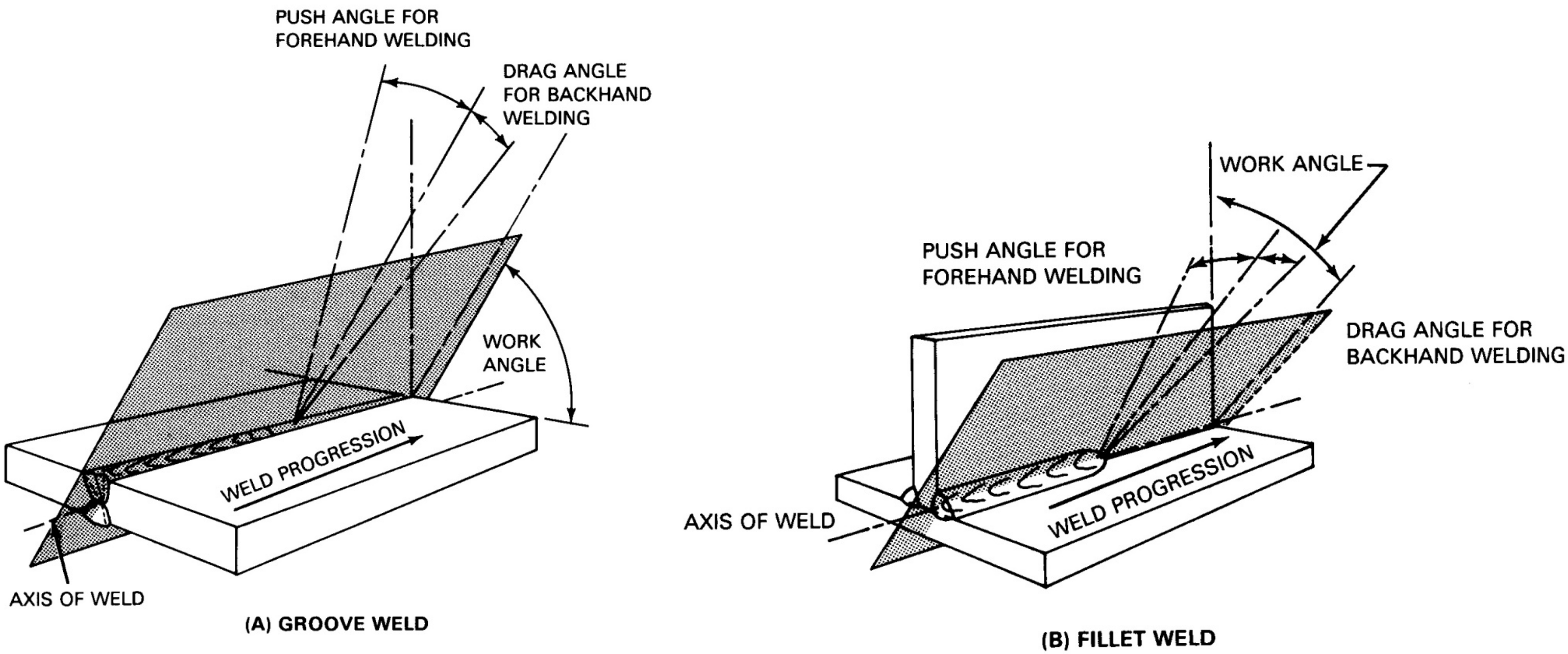
Effect of Welding Parameters on Bead Profile

A) Proper amperage, arc length, and travel speed
B) Amperage too low
C) Amperage too high
D) Arc length too short
E) Arc length too long
F) Travel speed too slow
G) Travel speed too fast



Courtesy AWS Handbook, 8th Edition, Volume 2, page 64

Orientation of the Electrode



Courtesy AWS Handbook, 8th Edition, Volume 2, page 66

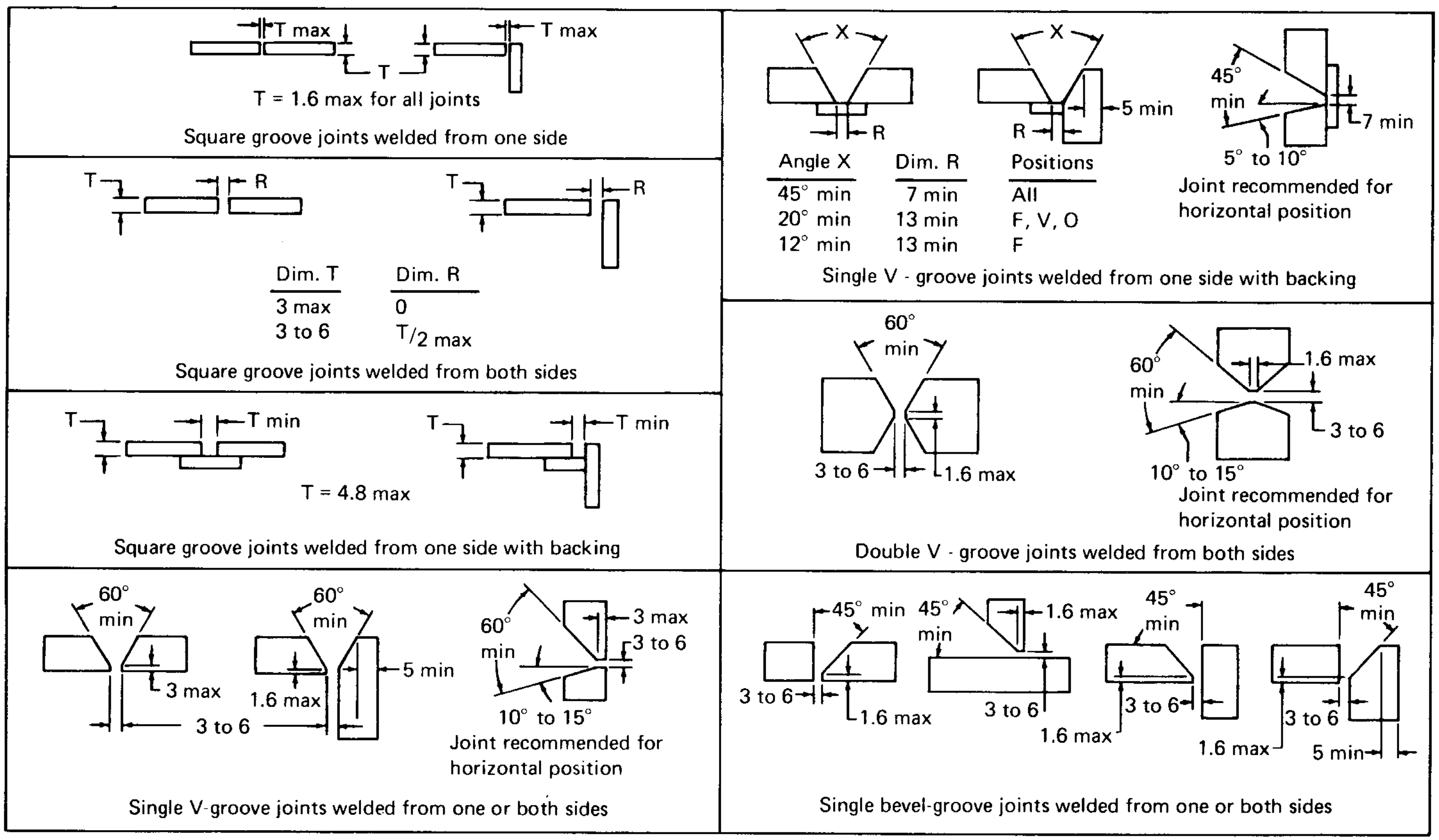
Typical Electrode Orientation and Welding Technique for Carbon Steel Electrodes

Type of Joint	Welding Position	Work Angle (degrees)	Travel Angle (degrees)	Welding Technique
Groove	Flat	90	5-10*	Backhand
Groove	Horizontal	80-100	5-10	Backhand
Groove	Vertical - Up	90	5-10	Forehand
Groove	Overhead	90	5-10	Backhand
Fillet	Horizontal	45	5-10*	Backhand
Fillet	Vertical - Up	35-55	5-10	Forehand
Fillet	Overhead	30-45	5-10	Backhand

* Travel angle may be 10- to 30-degrees for electrodes with heavy iron powder coatings

From AWS Handbook, 8th Edition, Volume 2, page 65

Recommended Dimensions of Grooves for Shielded Metal Arc Welding of Steel



All dimensions in millimeters except angles

From AWS Handbook, 8th Edition, Volume 2, page 59

AWS A5.1 Specification for Carbon Steel Electrodes for SMAW

- E-XXXX
  - E = Electrode (coated)
  - First 2 digits = Ultimate tensile strength (UTS) in ksi
  - Third digit = position
    - 1 is all positions
    - 2 is flat or horizontal
    - 4 is flat, overhead, horizontal or vertical-down
  - Fourth digit = type of coating
    - 0 is DCEP Cellulose-sodium silicate
    - 1 is AC/DCEP, Cellulose, potassium
    - 2 is AC/DCEN, Rutile, sodium
    - 3 is AC/DC, Rutile, potassium
    - 4 is AC/DC, Rutile/iron powder
    - 5 is DCEP, Lime, sodium
    - 6 is AC/DCEP, Lime, potassium
    - 7 is AC/DC, Iron oxide/iron powder
    - 8 is AC/DCEP, lime/iron powder

SMAW Electrode Classification Example

- E7018
  - "E" indicates "stick" electrode
  - 70 indicates nominal tensile strength of 70-ksi
  - 1 indicates use for welding in all positions
  - 8 indicates low hydrogen coating
- E6010
  - "E" indicates "stick" electrode
  - 60 indicates nominal tensile strength of 60-ksi
  - 1 indicates use for welding in all positions
  - 0 indicates cellulose coating

AWS A5.4 Specification for Stainless Steel Electrodes for SMAW

- Uses AISI number to denote alloy and suffix for coating type
  - -15 = DCEP
  - -16 = AC/DC
- Examples
  - E-308-15 is a 308 alloy with DCEP lime coating
  - E-312-16 is a 312 alloy with AC/DC rutile coating

AWS A5.5 Specification for Low Alloy Steel Covered Electrodes

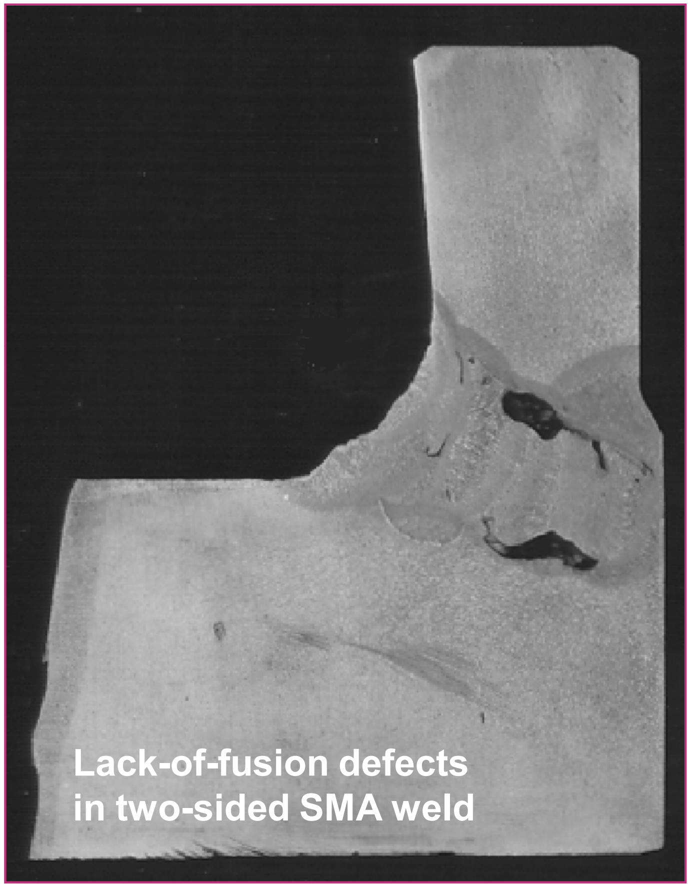
- Similar to AWS A5.1
- May be five digits
- Suffix denotes type of alloy
  - A C-Mo
  - B Cr-Mo
  - C Ni
  - D Mn-Mo
  - E Ni-Mo
  - G General
  - M Military
  - W Weathering
- E-8018-B2
  - 80,000-ksi UTS
  - All positions
  - Alloyed with Cr-Mo
  - Lime, AC/DC

ASME Classifications

- ASME classifies electrodes by F-No. and ASME Specification
  - The same F-No. are electrodes with the same usability characteristics
    - All cellulosic electrodes are F-No. 3
    - All low-hydrogen electrodes are F-No. 4
  - ASME specifications are the same as AWS specifications with the addition of “SF”
    - AWS Specification A5.1 is ASME Specification SFA-5.1
- Electrodes can be in the same ASME specifications but in different F-no. groups and vice versa
  - E6010 is SFA-5.1 and F-No. 3
  - E7018 is SFA-5.1 and F-No. 4
  - E8018-B2 is SFA-5.5 and F-No. 4

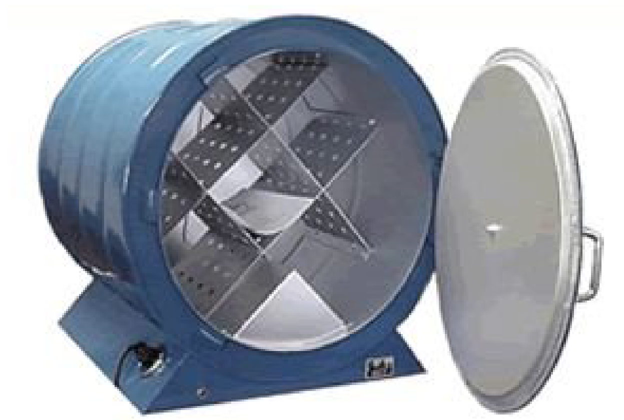
Quality Issues

- Discontinuities associated with manual welding process that utilizes flux for pool shielding
  - Slag inclusions
  - Lack of fusion
- Other possible effects on quality are porosity and hydrogen cracking



Low Hydrogen Practice

- Hydrogen embrittlement is a common problem in medium- and high-carbon steel alloys
  - Causes delayed cracking in HAZ
  - Worse in thick sections, restrained parts
- Low hydrogen welding practices keep electrodes and weldment dry, prevent introduction of hydrogen into the weld metal
  - Preheat, minimum interpass temperatures
- Rod ovens and portable rod containers prevent moisture from being absorbed in electrode coatings



ASME Section IX – SMAW Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-404 Filler Metals	.4	φ F-Number	X		
	.5	φ A-Number	X		
	.6	φ Diameter			X
	.7	φ Diameter > 1/4 in.		X	
	.12	φ Classification		X	
	.30	φ t	X		
	.33	φ Classification			X

ASME Section IX – SMAW Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-405 Positions	.1	+ Position			X
	.2	φ Position		X	
	.3	φ ↑↓ Vertical Welding			X
QW-409 Electrical Characteristics	.1	> Heat Input		X	
	.4	φ Current or Polarity		X	X
	.8	φ I & E Range			X
QW-410 Technique	.5	φ Method of Cleaning			
	.25	φ Manual or Automatic			X

Gas Tungsten Arc Welding (GTAW)

Module 2A.3

GTAW Process Description

- An arc is formed between a nonconsumable (tungsten) electrode and the workpiece electrode
- The energy from the arc melts the workpiece, and the molten metal solidifies to form a weld bead
- Shielding gas provides the medium for arc formation and protects the molten pool and electrode from oxidation

Basic Components of GTAW

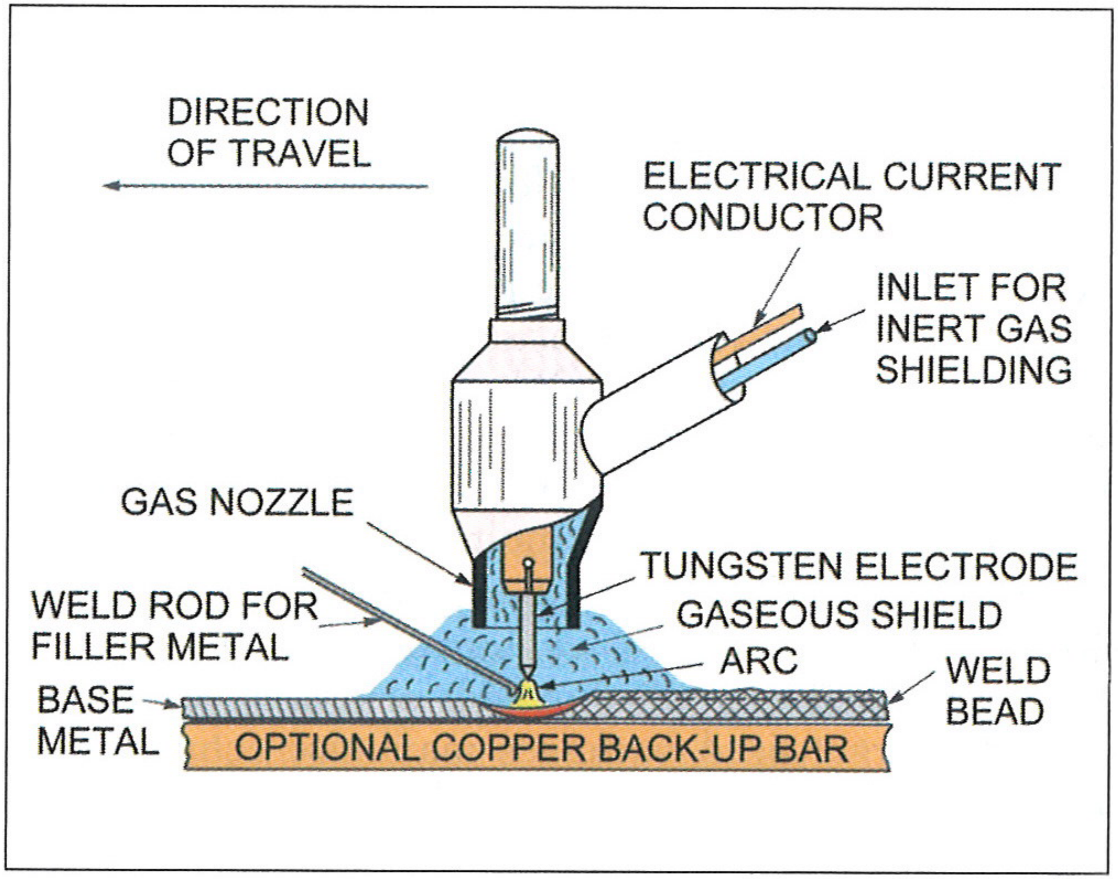


Figure 1.4—Schematic Representation of Gas Tungsten Arc Welding

Source: AWS Handbook 9th ed. Vol. 1

Autogeneous GTAW

250A 11.5V 10 IPM

Recording rate was 125 Hz

170A 10.5V, T=5.5 IPM

170A 11.5V, T=5.5 IPM

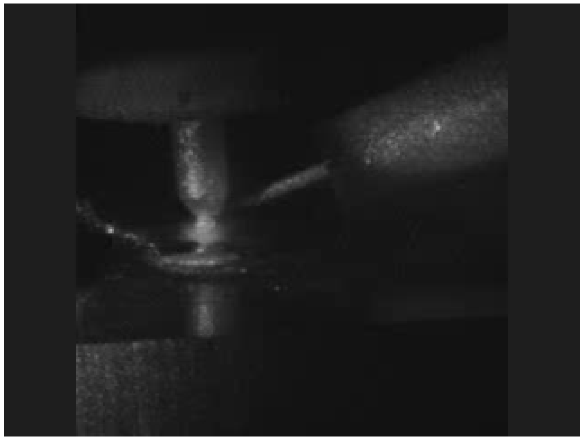
GTAW Filler Metal

Good wire position

170A 14.5V 5.5 IPM 35.4 IPM

Recording rate: 250 Hz

Bad wire position – off target



170A 12.5V 5.5IPM 35.4 IPM

Bad wire position – too high

170A 16.5V 5.5 IPM 35.4 IPM

GTAW - Range of Operation

- Current: <1- to 500-amps, typically 30 to 150
- Voltage: 9- to 20-volts, typically 10- to 12-volts for argon
- Arc Gap: 0.02- to ¼-in., typically 1/16-in.
- Welding Speed: 1- to 40-in/min, typically 3- to 6-in/min.
- Shielding Gas: argon, argon hydrogen mixtures, helium, argon helium mixtures
- Thickness: 0.004-in. upwards, typically up to 0.1-in. in a single pass or ¼-in. with multiple passes
- May be without filler (autogenous) or with added filler, usually as wire, 1/32- to 3/32-in. diameter

GTAW Process Description: Terminology

- Gas Tungsten Arc Welding: GTAW - AWS Definition
- Tungsten Inert Gas Welding: TIG - Europe and worldwide, also often used in the U.S.
- Wolfram Inert Gas Welding: WIG - Used in Germany
- Heliarc: Original name in U.S.
- Argonarc: Original name in U.K.

GTAW Applications

- Full penetration welds, typically up to 0.1-in.
- Root runs, particularly in pipe welds
- Autogenous welds (no filler)
- High quality welds
- Fill runs, typically up to 0.5-in.
- Most metals
  - Stainless steels and nickel-based alloys
  - Carbon and low alloy steels
  - Aluminum and magnesium alloys
  - Titanium and reactive metals

GTAW Applications

- Small components - sensors, medical and electronic
- Tube to tube welds, orbital or rotated tube
- Tube to tube plate welds, condensers, heat exchangers
- Repairs, all industries (e.g., aerospace)
- Process equipment, food industry
- Cladding, overlays
- Sheet metal applications

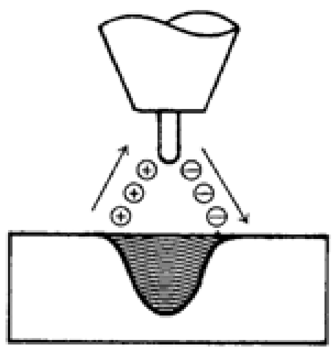
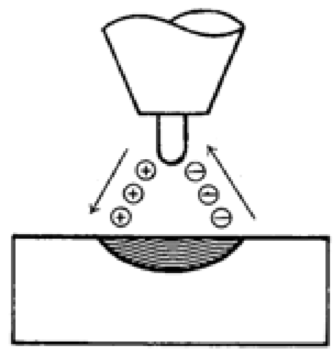
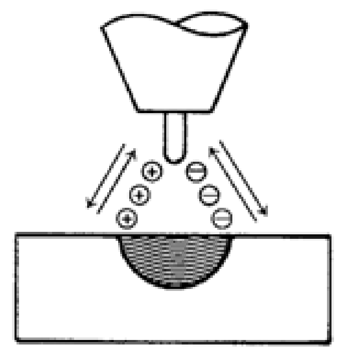
GTAW Process Advantages

- Can be used in all positions, manual or mechanized
- Provides excellent control on thin and intricate parts
- No slag or spatter; post weld cleaning often not required
- Use with or without filler wire
- Welds almost all metals
- Precise control of weld heat
- High quality

GTAW Process Limitations

- Lower deposition rates than consumable electrode processes
- Requires more dexterity and coordination for manual welding than consumable electrode processes
- Requires high gas purity, low tolerance for drafty environments means it cannot be used outdoors without special precautions
- Low tolerance to contaminants
- Generally requires arc starting system
- Requires precise positioning of electrode

Characteristics of Current Types for GTAW

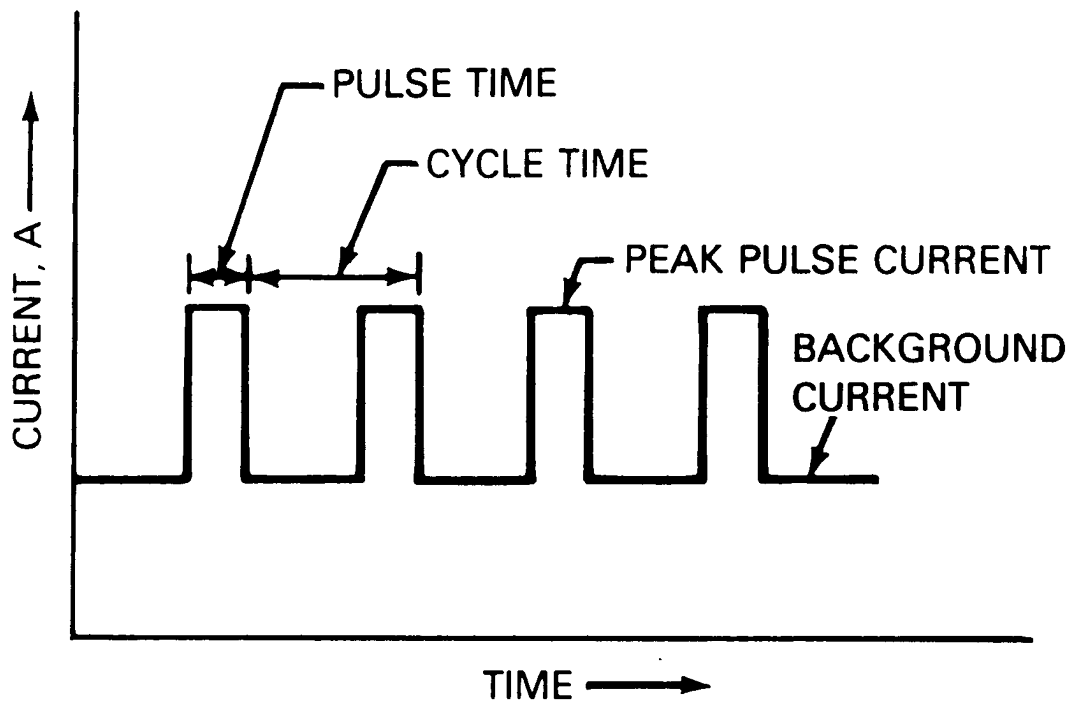
Current type	DC	DC	AC (balanced)
Electrode polarity	Negative	positive	balanced
Electrode and ion flow Penetration characteristics			
Oxide cleaning action	No	Yes	Yes-once every half cycle
Heat balance in the arc (approx.)	70% at work end; 30% at electrode end	30% at work end; 70% at electrode end	50% at work end; 50% at electrode end
penetration	Deep; narrow	Shallow; wide	medium
Electrode capacity	Excellent e.g.1/8in-400A	Poor e.g.1/4-120A	Good e.g.1/8in-225A

Courtesy of the AWS Welding Handbook Volume 2, 7th Edition

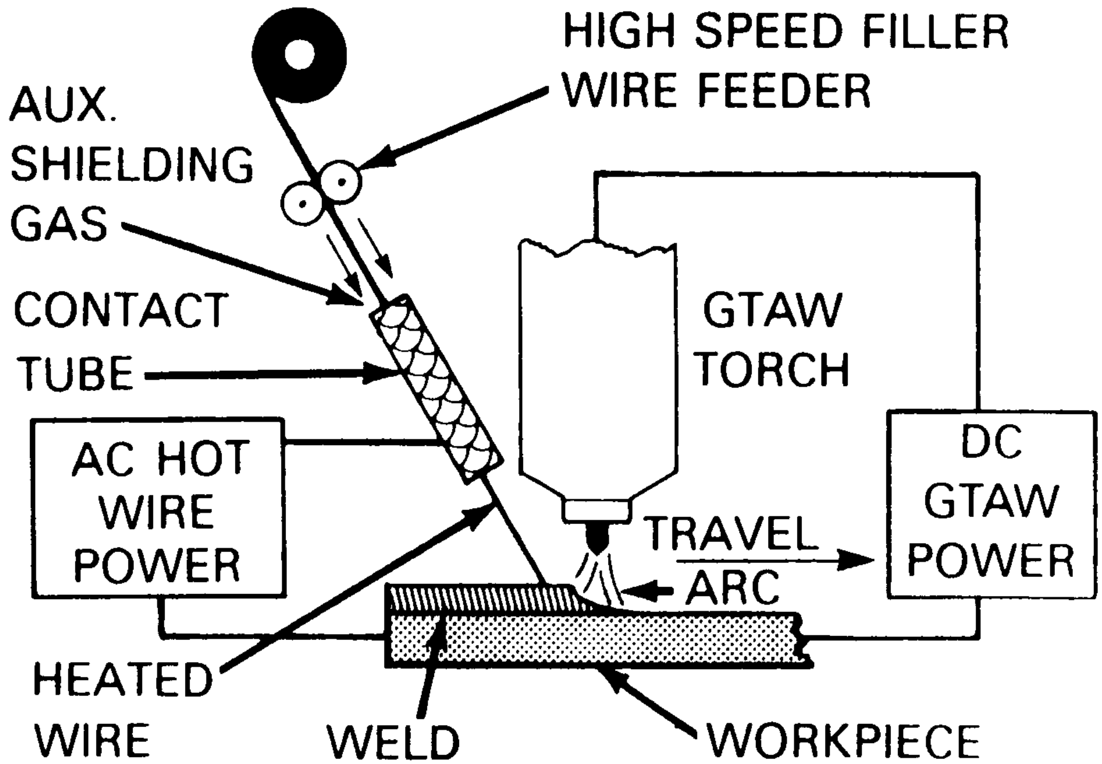
Shielding Gas for GTAW

- Argon is used most extensively
  - Lower cost and flow rate than helium
  - Easier arc starting
  - Better cross draft resistance
- Helium is preferred for some applications
  - Transfers more heat to workpiece - useful for metals with high thermal conductivity and for high speed welding
  - Argon-helium mixtures are used to gain advantages of both gases
- Argon-Helium mixtures
  - Used to increase penetration on stainless steels, along with up to 15% hydrogen

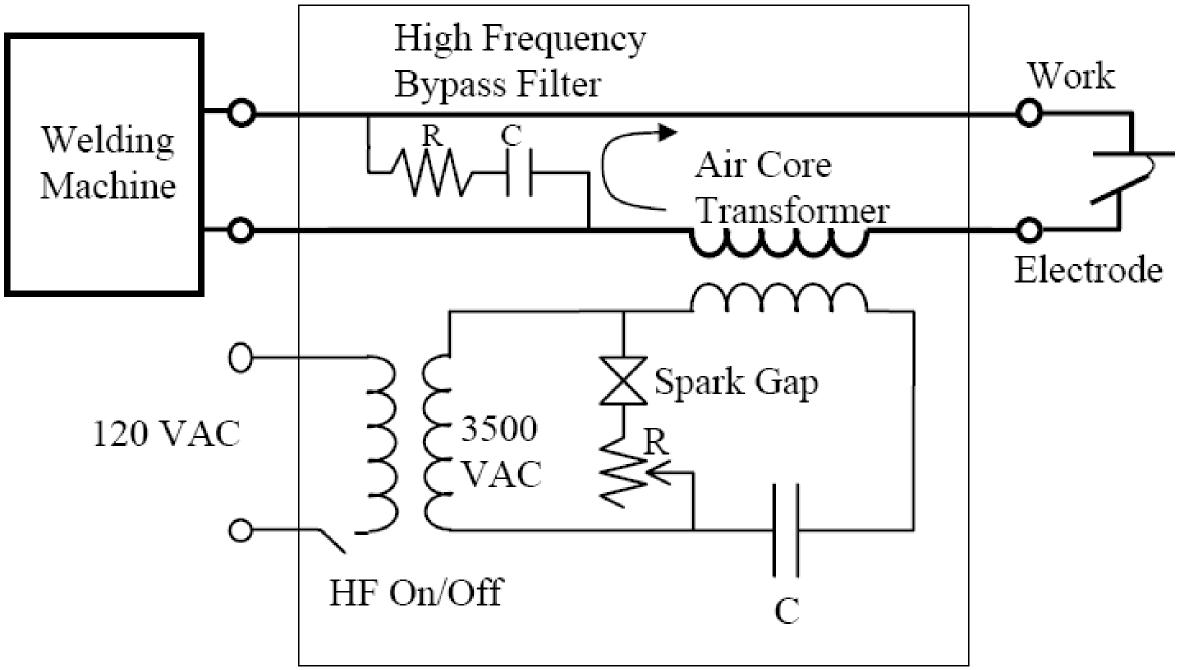
Pulsed Gas Tungsten Arc Welding



Hot Wire GTAW



High Frequency (HF) Arc Starting



- Spark gap oscillator generates HF (VRMS ~ 3500 V, f ~ 10kHz)
- Air core transformer couples HF to welding electrode
- HF bypass filter prevents HF current from passing back into welding machine (and causing possible damage to electronics

Specifications and Practices

- Electrode and filler metal specifications
  - AWS A5.12, Specification for Tungsten and Tungsten Alloy Electrodes for Metal Arc Welding and Cutting
  - AWS A5.18, Specification for Carbon Steel Filler Metals for Gas Shielded Arc Welding
  - ASME uses the same labeling system for GTAW filler metals as SMAW electrodes
    - SF labeling
- Recommended practice documents
- C5.5, Recommended Practices for Gas Tungsten Arc Welding
- C5.10, Recommended Practices for Shielding Gases for Arc Welding and Cutting

ASME Section IX – GTAW 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	
	.14	± Filler	X		
	.22	± Consumable Insert			X
	.23	φ Filler Metal Product Form	X		
	.30	φ t	X		
	.33	φ Classification			X
	.50	± Flux			X

ASME Section IX – GTAW Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-405 Positions	.1	+ Position			X
	.2	φ Position		X	
	.3	φ ↑↓ Vertical Welding			X
QW-408 Gas	.1	± Trail or φ Composition			X
	.2	φ Single, Mixture, or %	X		
	.3	φ Flow Rate			X
	.5	± or φ Backing Flow			X
	.9	- Backing or φ Composition	X		
	.10	φ Shielding or Trailing	X		

ASME Section IX – GTAW Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-409 Electrical Characteristic	.1	> Heat Input		X	
	.3	± Pulsing I			X
	.4	φ Current or Polarity		X	X
	.8	φ I & E Range			X
	.12	φ Tugsten Electrode			X
QW-410 Technique	.3	φ Orifice, Cup, or Nozzle Size			X
	.5	φ Method of Cleaning			X
	.10	φ Single to Multi Electrodes		X	X
	.11	φ Closed to Out Chamber	X		
	.15	φ Electrode Spacing			X
	.25	φ Manual to Automatic			X

Plasma Arc Welding (PAW)

Module 2A.4

Plasma Arc Welding (PAW) Definition

- Nonconsumable electrode
- Heat is produced from a plasma jet
  - Arc can be transferred or nontransferred
- Shielding is obtained from the ionized gas
  - Usually supplemented by an auxiliary source of shielding gas
- Filler metal may of may not be used
- Pressure is not used
- Variables
  - Plasma current
  - Orifice diameter and shape
  - Type of orifice gas
  - Flow rate of orifice gas
  - Type of shielding gas

Plasma Arc Torch

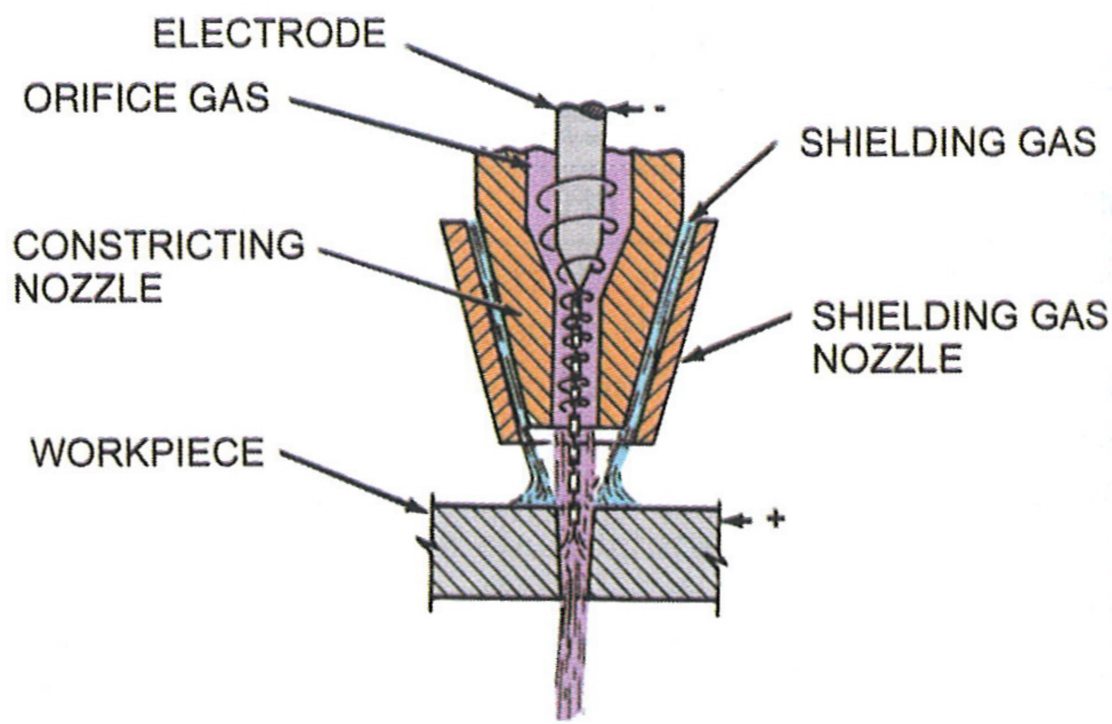
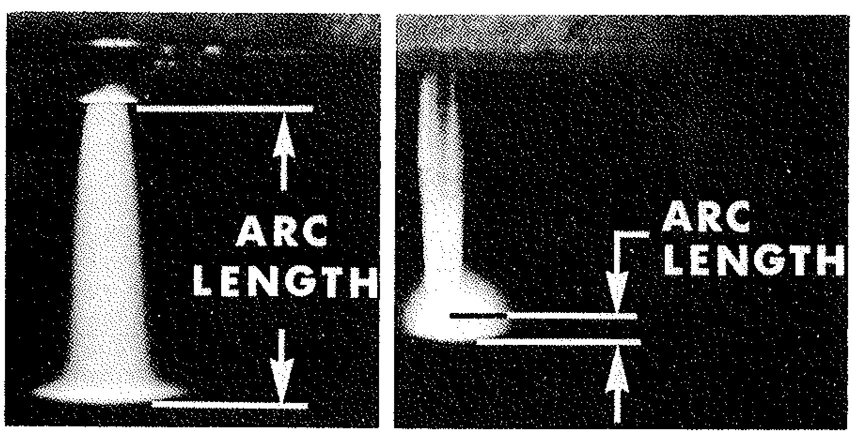


Figure 1.54—Schematic Representation of Plasma Arc Cutting

Source: AWS Handbook 9th ed. Vol. 1

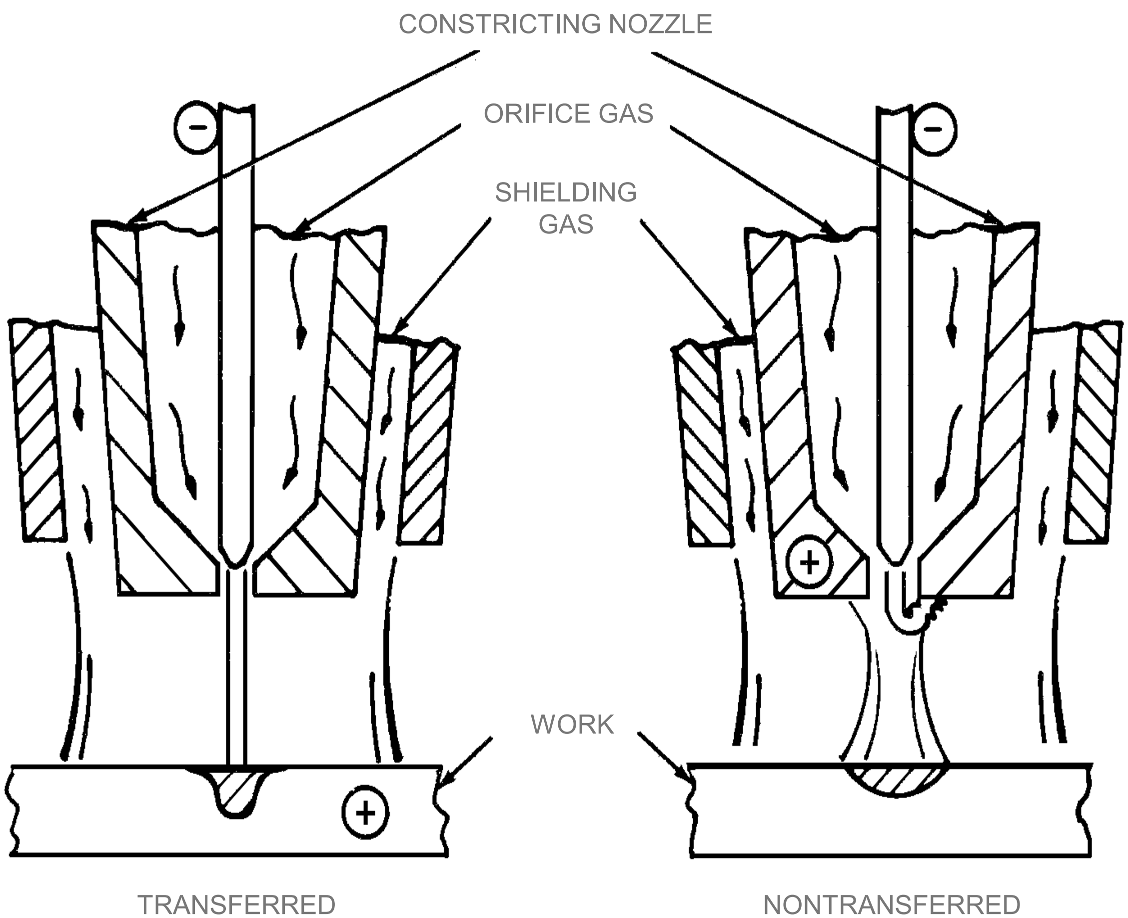
Why Arc Constriction?

- Columnar shaped plasma jet
  - Significantly reduces sensitivity to variations in arc length
  - More stable plasma jet
  - Permits the use of longer arc lengths
  - Less welder skill is required (compared to GTAW)
- Higher energy density
  - Increased penetration and travel speeds



Courtesy of the AWS Welding Handbook, Volume 2, 8th Edition

Transferred and Nontransferred Plasma Arc Modes



Courtesy of the AWS Welding Handbook, Volume 2, 8th Edition

Consumables

- Techniques for adding filler metal
  - Cold wire feed
    - Filler wire is introduced at the leading edge of the weld pool
    - May be done manually or by conventional GTAW wirefeeders
  - Hot wire feed
    - Wirefeeder introduces wire at the trailing edge of the weld pool
  - Dabber technique
    - Filler wire feed is pulsed in synchronization with the pulsing of the plasma arc current
- AWS specifications for consumables used for PAW are the same as those used for GTAW
  - Filler wires, electrodes, and shielding gases

Advantages and Disadvantages

- Advantages
  - Columnar plasma jet
    - Higher energy density enables faster welding speeds, lower heat input, and less distortion
    - Improved arc stability and tolerance to variations in torch-to-work distance
    - Permits the use of longer torch-to-work distances
    - Less welder skill is required (compared to GTAW)
- Disadvantages
  - Higher equipment cost
  - Lower tolerance to variations in fit-up
  - Manual PAW torches are more difficult to manipulate than manual GTAW torches

Applications

- Process techniques
  - Keyhole mode
  - Melt-in mode
- Applicable to all metals weldable by the GTAW process
  - All metals except aluminum and magnesium are welded with DCEN
- Applications
  - Build-ups for aerospace components
  - Medical pacemakers
  - Electronic components
  - Bellows and seals
  - Motors and transformers
  - Tube mills
  - Cladding, wire mesh, process piping

ASME Section IX – PAW 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	
	.14	± Filler	X		
	.22	± Consumable Insert			X
	.23	φ Filler Metal Product Form	X		
	.27	φ Alloy Elements	X		
	.30	φ t	X		
	.33	φ Classification			X

ASME Section IX – PAW Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-405 Positions	.1	+ Position			X
	.2	φ Position		X	
	.3	φ ↑↓ Vertical Welding			X
QW-408 Gas	.1	± Trail or φ Composition			X
	.4	φ Composition	X		
	.5	± or φ Backing Flow			X
	.9	- Backing or φ Composition	X		
	.10	φ Shielding or Trailing	X		
	.21	φ Flow Rate			X

ASME Section IX – PAW Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-409 Electrical Characteristics	.1	> Heat Input		X	
	.4	φ Current or Polarity		X	X
	.8	φ I & E Range			X
	.12	φ Tugsten Electrode			X
QW-410 Technique	.3	φ Orifice, Cup, or Nozzle Size			X
	.5	φ Method of Cleaning			X
	.10	φ Single to Multi Electrodes		X	X
	.11	φ Closed to Out Chamber	X		
	.12	φ Melt-in to Keyhole		X	
	.15	φ Electrode Spacing			X

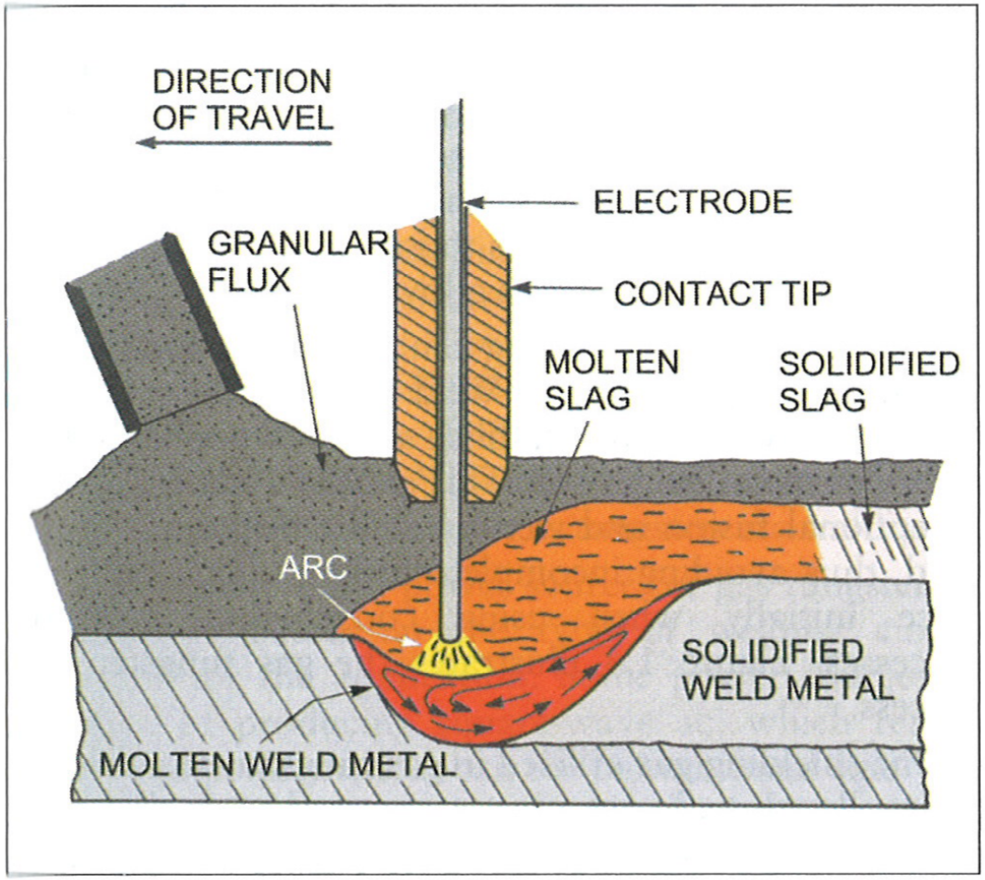
Submerged Arc Welding (SAW)

Module 2A.5

SAW Definition

- At least one consumable bare metal electrode
- Arc(s) produce heat
- Shielded by granular, fusible material on workpieces
- Used without the application of pressure

SAW Components



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.18.

Figure 1.2—Schematic of Submerged Arc Welding

Source: AWS Handbook 9th ed. Vol. 1

SAW Definitions and Variables

Definitions	Variables
Machine	Welding amperage
Automatic	Welding voltage
Semiautomatic	Travel speed
Tandem arc	Electrode size
Flux	Electrode extension
Flux recovery units	Width and depth of flux
Tractors	
Manipulators	
Positioners	

Consumables for SAW

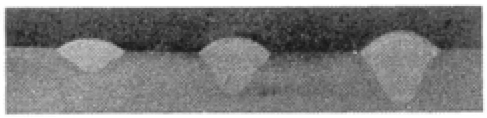
- AWS A5.17, Specification for Carbon Steel Electrodes and Fluxes for Submerged Arc Welding
  - F7A6-EM12K - 70,000 psi UTS, Charpy toughness of 20 ft-lb @ -60F, with EM12K Medium Mn, 0.12%C, Killed
    - F - Flux
    - 7 - Tensile Strength in 10,000 psi
    - A - Condition of heat treatment
    - 6 - Lowest temperature (x -10°C) with Charpy toughness of 20ft-lb
    - E - Solid electrode, EC - cored electrode
    - M - Classification of manganese content
    - L - Low, M - Medium, H - High
    - 12 - Carbon content in hundredths of a percent
    - K - Killed

Selection and Application Criteria for SAW

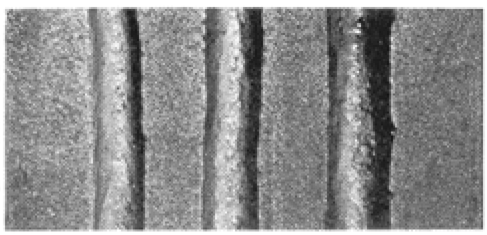
- Advantages
  - Superior weld quality
  - Often self cleaning
  - High deposition rates
  - Minimum edge preparation
  - No radiant energy
  - Minimum fume problem
- Disadvantages
  - Flux housekeeping
  - Usable only in flat position

Effect of Amperage Variation on Weld Bead Shape and Penetration

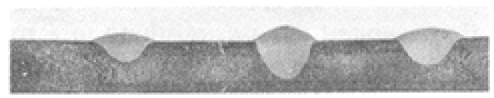
Semiautomatic welding
3/32 in. wire, 35V, 24in./s



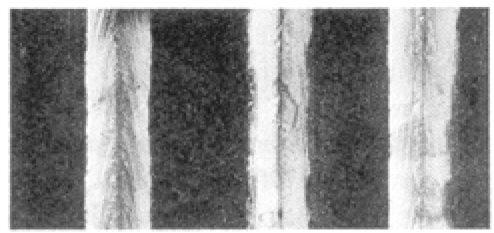
350 A   500 A   650 A



Machine welding
7/32 in. wire, 34V, 30in./s



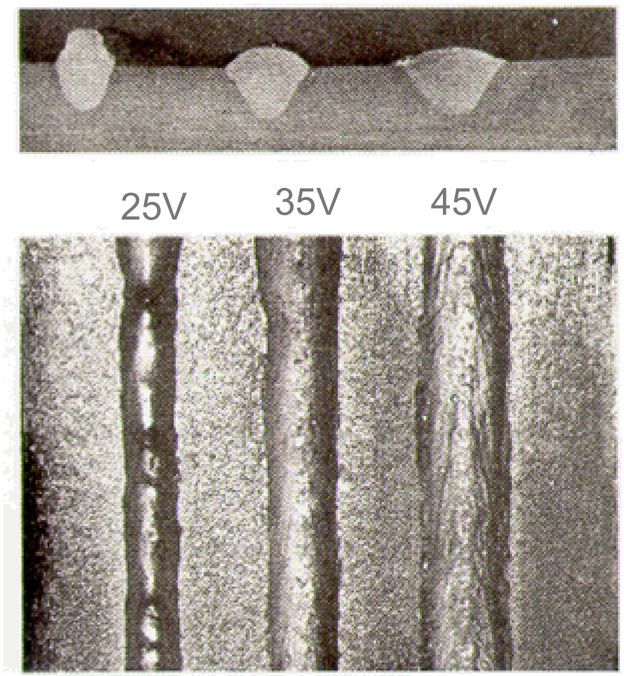
700 A   1000 A   850 A



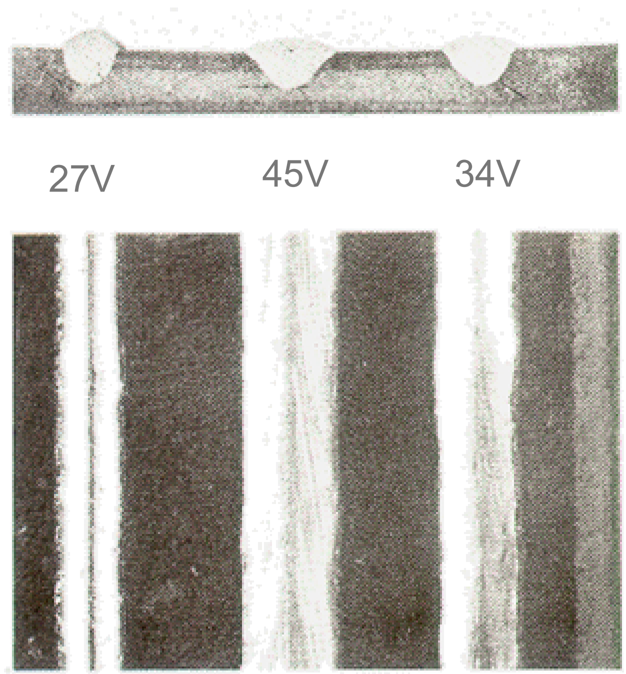
Welding Processes -- Arc and Gas Welding and Cutting, Brazing and Soldering, AWS Welding Handbook, 7th Ed, Vol. 2, p. 203, fig. 6.5.

Effect of Arc Voltage Variations on Weld Bead Shape and Penetration

Semiautomatic welding
3/32 in. wire, 500A, 24in./s



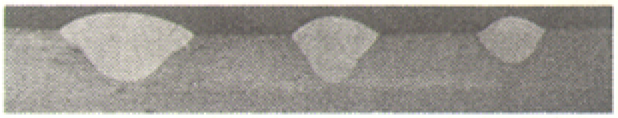
Machine welding
7/32 in. wire, 850A, 30in./s



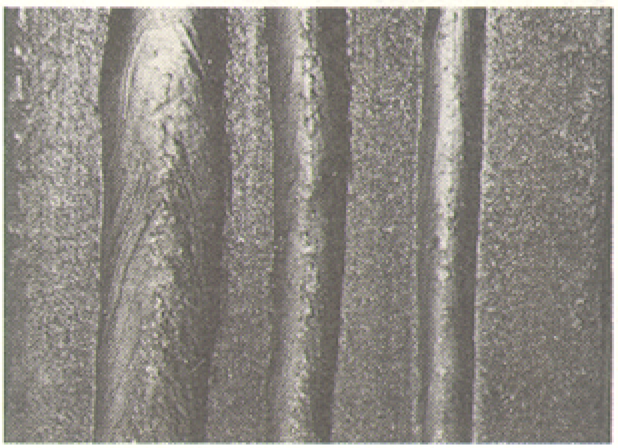
Welding Processes -- Arc and Gas Welding and Cutting, Brazing and Soldering, AWS Welding Handbook, 7th Ed, Vol. 2, p. 203, fig. 6.6.

Effect of Travel Speed Variation on Weld Bead Shape and Penetration

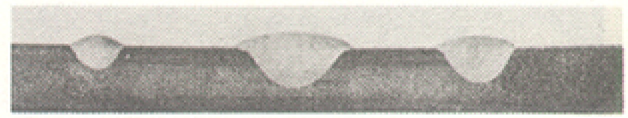
Semiautomatic welding
3/32 in. wire, 500A, 35V



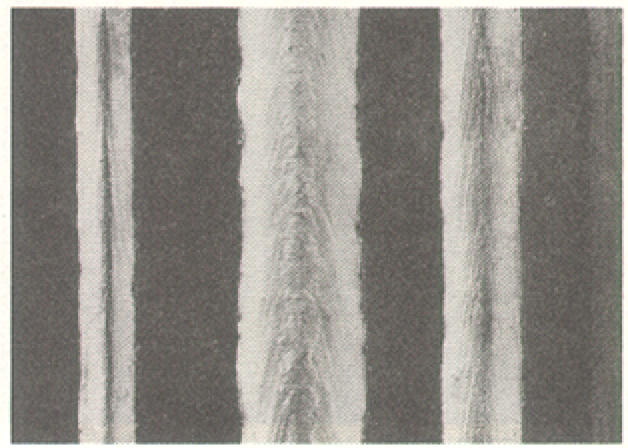
12 in./min | 24 in./min | 48 in./min



Machine welding
7/32 in. wire, 850A, 34V



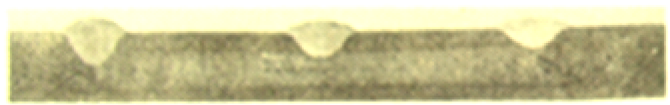
60 in./min | 15 in./min | 30 in./min



Welding Processes -- Arc and Gas Welding and Cutting, Brazing and Soldering, AWS Welding Handbook, 7th Ed, Vol. 2, p. 204, fig. 6.7.

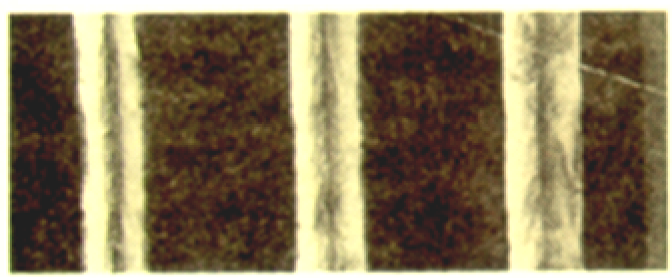
Effect of Electrode Size on Weld Bead Shape and Penetration

Machine welding
600A, 30V , 30in./min



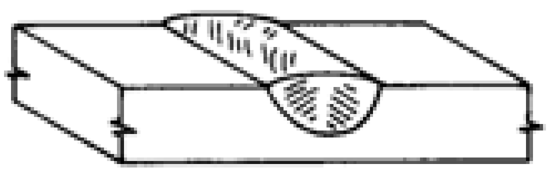
Electrode size

1/8in. 5/32in. 7/32in.



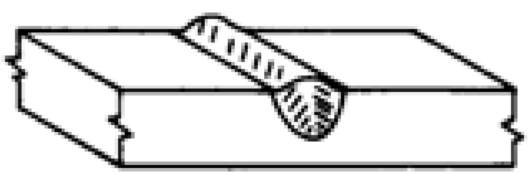
Welding Processes -- Arc and Gas Welding and Cutting, Brazing and Soldering, AWS Welding Handbook, 7th Ed, Vol. 2, p. 205, fig. 6.8.

Effect of Work Inclination on Weld Bead Shape in 13-mm (1/2 in.) Plate



Flat position weld

Downhill weld (1/8 slope)



Uphill weld (1/8 slope)

Lateral weld (1/19 slope)

Welding Processes -- Arc and Gas Welding and Cutting, Brazing and Soldering, AWS Welding Handbook, 7th Ed, Vol. 2, p. 215, fig. 6.12.

ASME Section IX – SAW Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-404 Filler Metals	.4	φ F-Number	X		
	.5	φ A-Number	X		
	.6	φ Diameter			X
	.9	φ Flux/Wire Classification	X		
	.10	φ Alloy Flux	X		
	.24	± or φ Supplemental	X		
	.27	φ Alloy Elements	X		
	.29	φ Flux Designation			X
	.30	φ t	X		
	.33	φ Classification			X
	.34	φ Flux Type	X		
	.35	φ Flux/Wire Classification		X	X
	.36	Recrushed Slag	X		

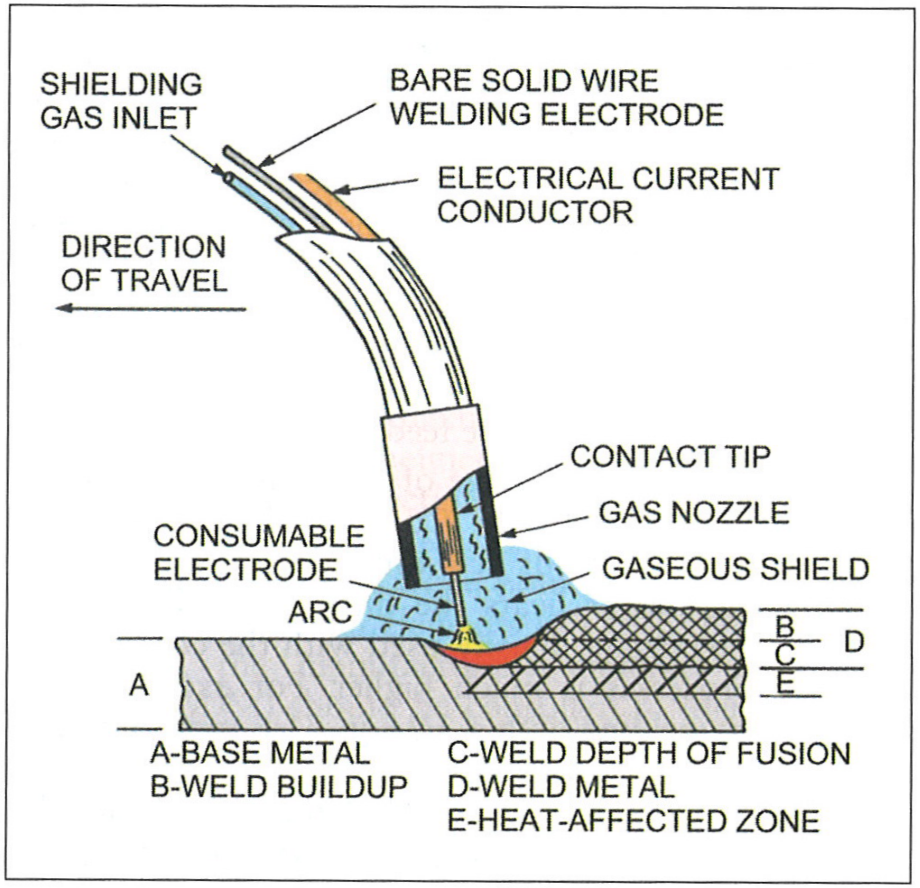
ASME Section IX – SAW Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-405 Positions	.1	+ Position			X
QW-409 Electrical Characteristics	.1	> Heat Input		X	
	.4	φ Current or Polarity		X	X
	.8	φ I & E Range			X
QW-410 Technique	.5	φ Method of Cleaning			X
	.8	φ Tube-Work Distance			X
	.10	φ Single to Multi Electrodes		X	X
	.15	φ Electrode Spacing			X
	.25	φ Manual or Automatic			X

Gas Metal Arc Welding
and Flux Cored Arc Welding
(GMAW & FCAW)

Module 2A.6

Gas Metal Arc Welding

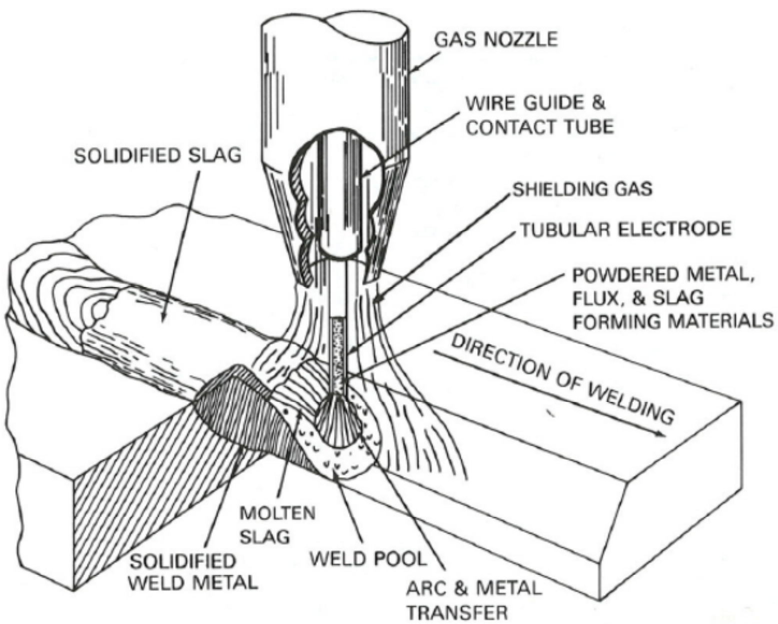


Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.12.

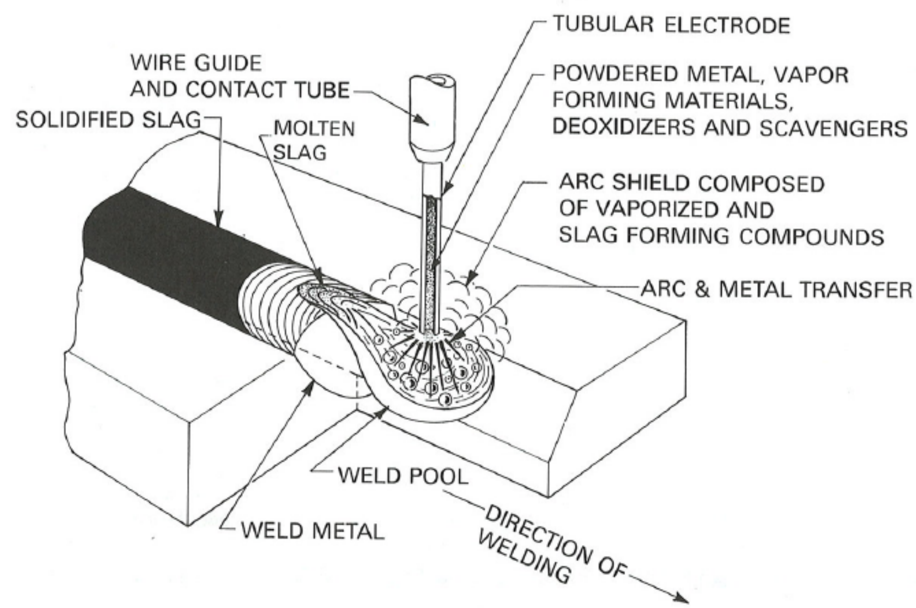
Figure 1.6—Schematic Representation of Gas Metal Arc Welding

Source: AWS Handbook 9th ed. Vol. 1

Flux Cored Arc Welding



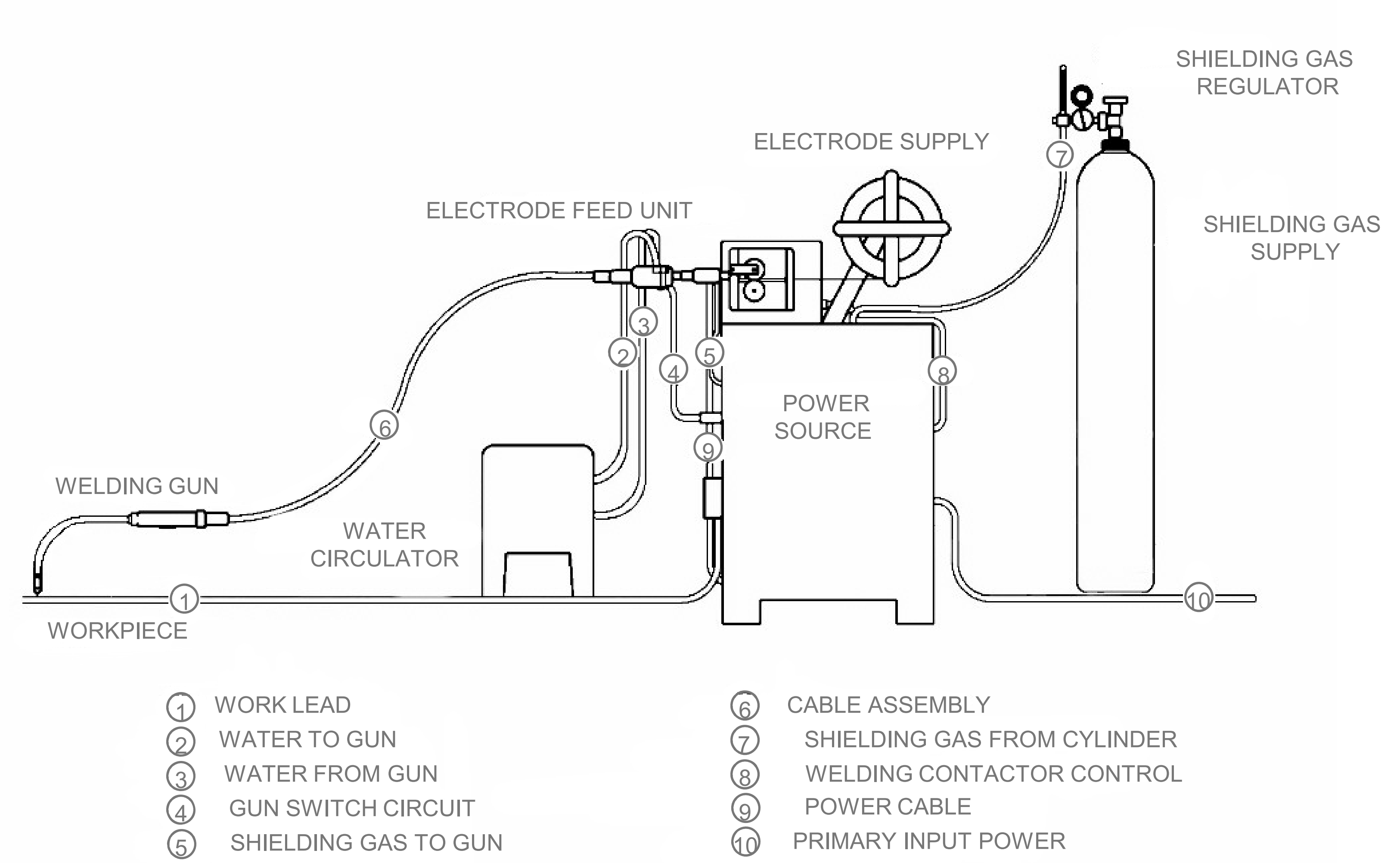
Self-Shielded FCAW



Gas-Shielded FCAW

Courtesy of the AWS Welding Handbook, Volume 2, 8th Edition

GMAW/FCAW Equipment



Courtesy of the AWS Welding Handbook, Volume 2, 8th Edition

Consumables for GMAW

- Primary consumables are the wire and the shielding gas
- A5.18 Specification for Carbon Steel Electrodes and Rods for Gas Shielded Arc Welding
- C5.10 Recommended Practices for Shielding Gases for Arc Welding and Plasma Cutting
- ERxxS-y
  - ER – Electrode or rod
  - xx - Two or three digits for tensile strength in KSI
  - S - Solid wire
  - y - Suffix for specifying chemistry and other details

Consumables for FCAW

- A5.20 Specification for Carbon Steel Electrodes for Flux Cored Arc Welding
- C5.10 Recommended Practices for Shielding Gases for Arc Welding and Plasma Cutting
- ExyT-ab
  - E - Electrode
  - x – One or two digits for tensile strength in 10's of KSI
  - y - Welding position (0 = flat or horizontal, 1 – all)
  - T - Tubular
  - a - Usability, performance

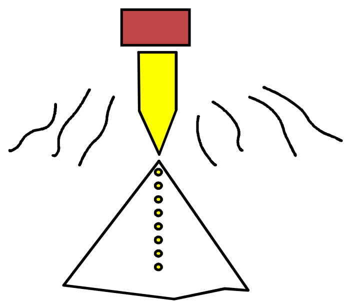
GMAW/FCAW Variables

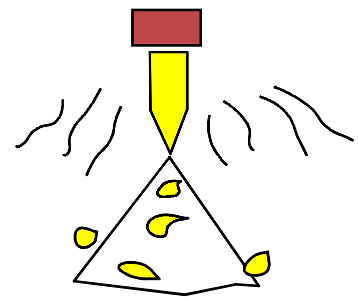
- Wire feed speed (WFS)
  - Controls the welding current
- Arc voltage
- Polarity
- Travel speed
- Electrode extension
- Torch angles
  - Work and travel angles
- Joint design
- Electrode diameter
- Shielding gas

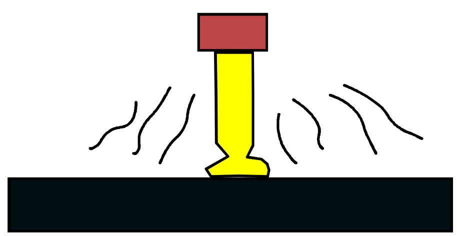
WFS, Voltage, and CTWD

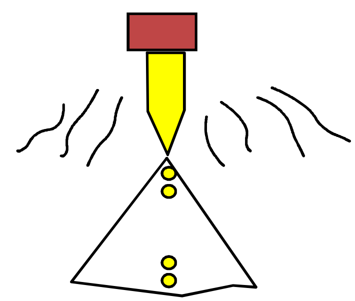
- WFS
  - Primary variable that controls heating and melting power to the electrode
  - Increasing the WFS increases the deposition rate and weld penetration
- Voltage
  - Impacts the melting efficiency at the workpiece and the weld shape
  - Improper voltage can result in arc instabilities and inadequate welds
- Contact Tip to Word Distance (CTWD)
  - Longer CTWDs result in greater preheating in the electrode stick-out, lower heat input into the workpiece, and a more crowned weld bead
    - Secondary affect on heat input to the workpiece compared to current, voltage, and travel speed

Modes of Metal Transfer


Spray

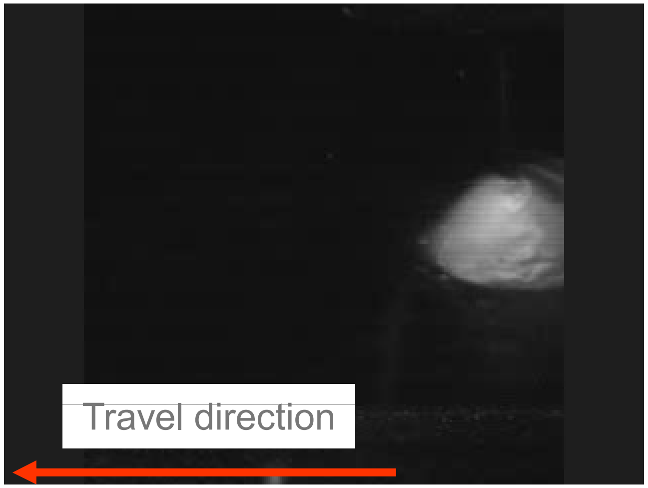

Globular


Short-circuiting


Pulse-spray

GMAW (transfer mode)

Globular mode



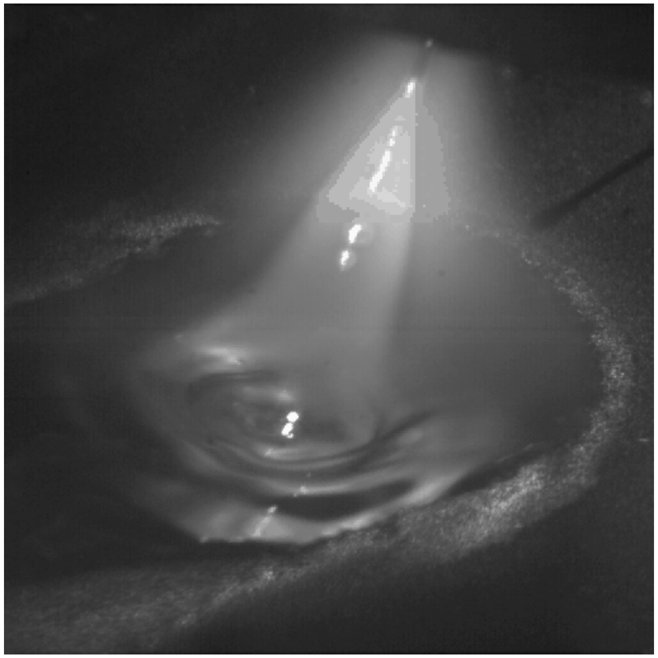
WFS=200 IPM, 29V, T=10 IPM

ER70S-3, 0.052” welding wire was used

Ar-10%CO_2 shielding gas was used

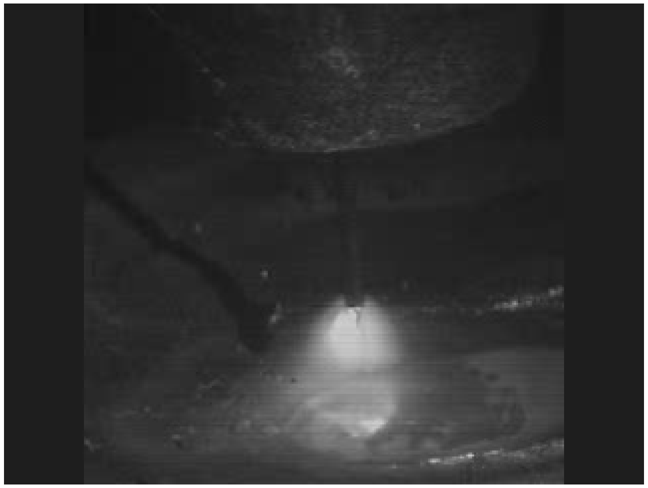
Recording rate
125 Hz for globular and spray modes

Spray mode



Stainless Wire ER308L

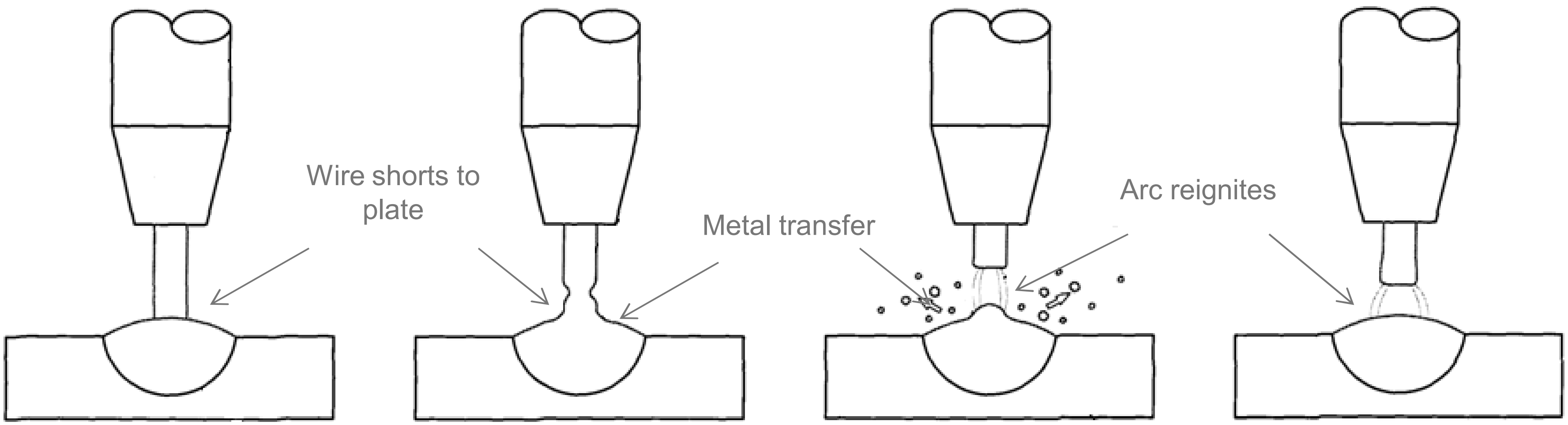
FCAW



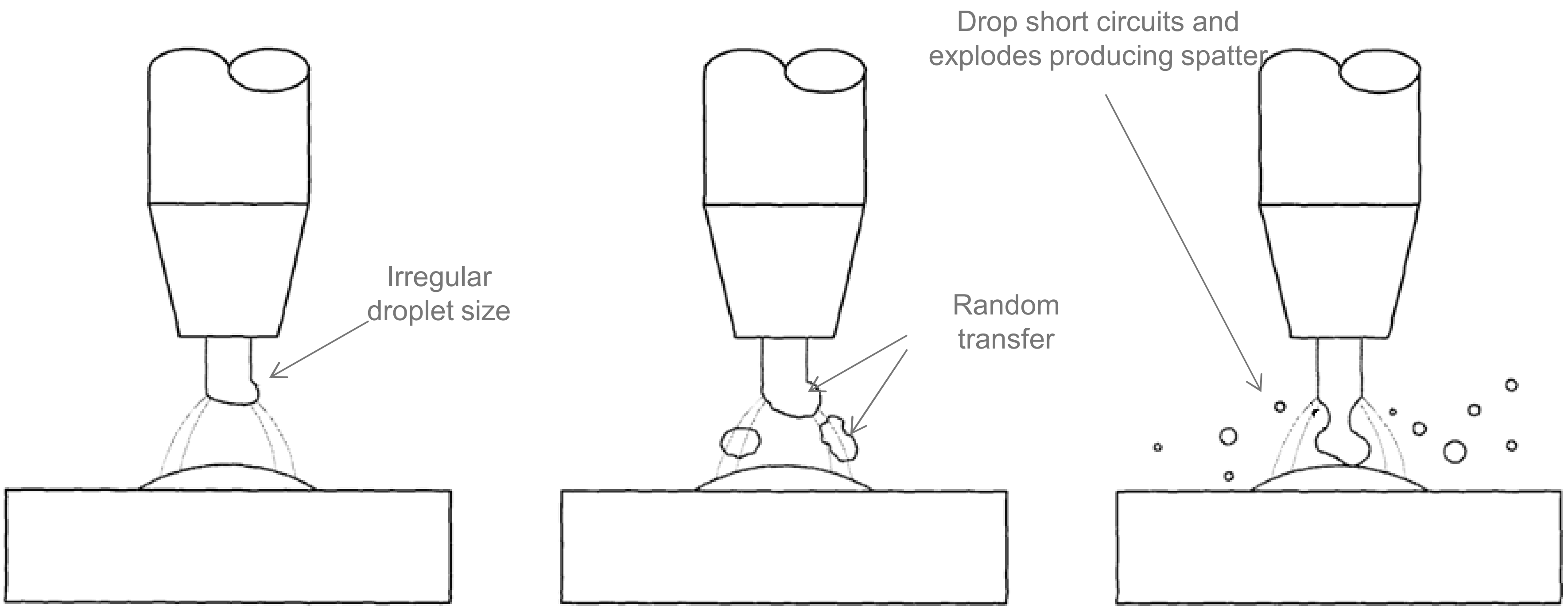
WFS= 225 IPM, V= 29V , T= 10 IPM

0.045” welding wire was used
Ar-10%CO_2 shielding gas was used
Recording rate was 1125 Hz

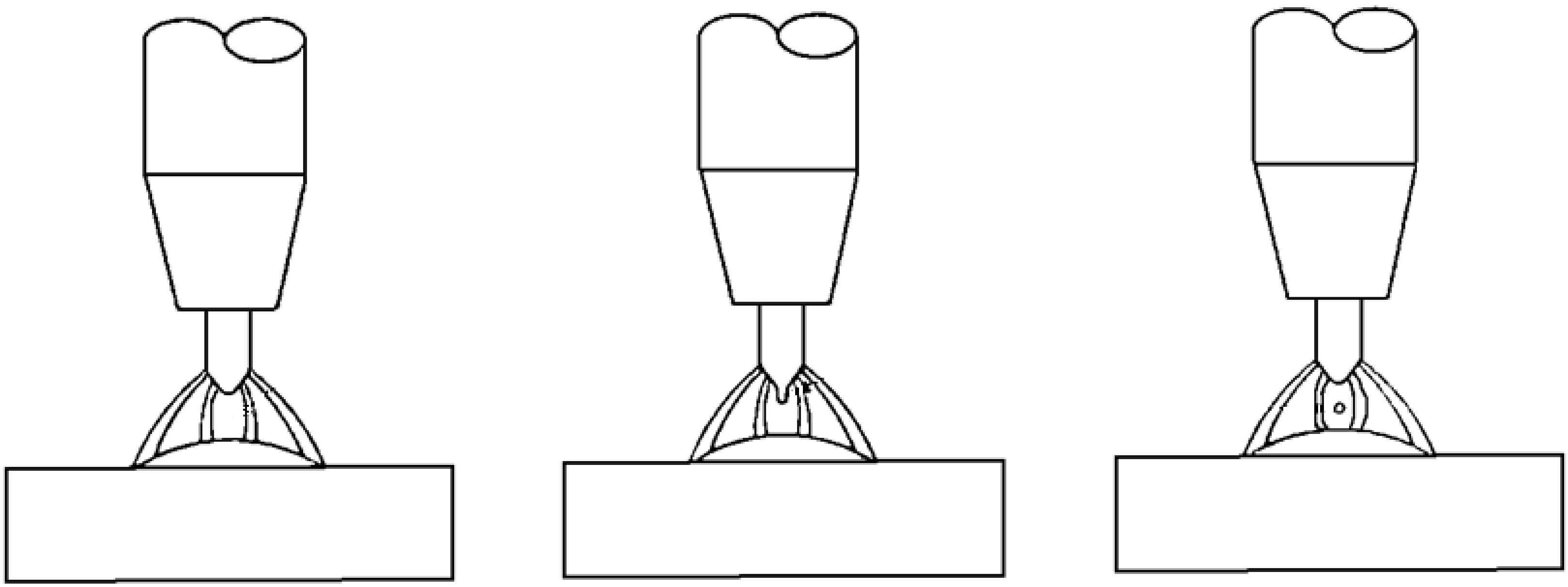
Short Circuit Transfer



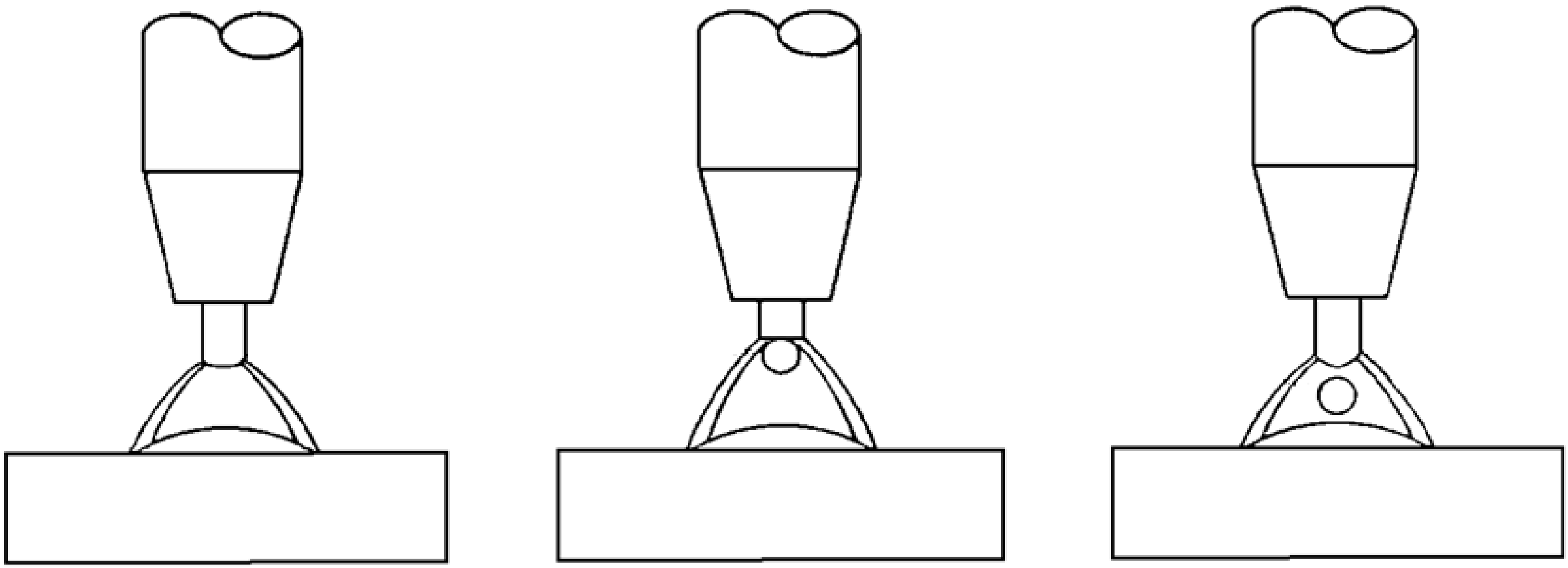
Globular Transfer



Spray Transfer



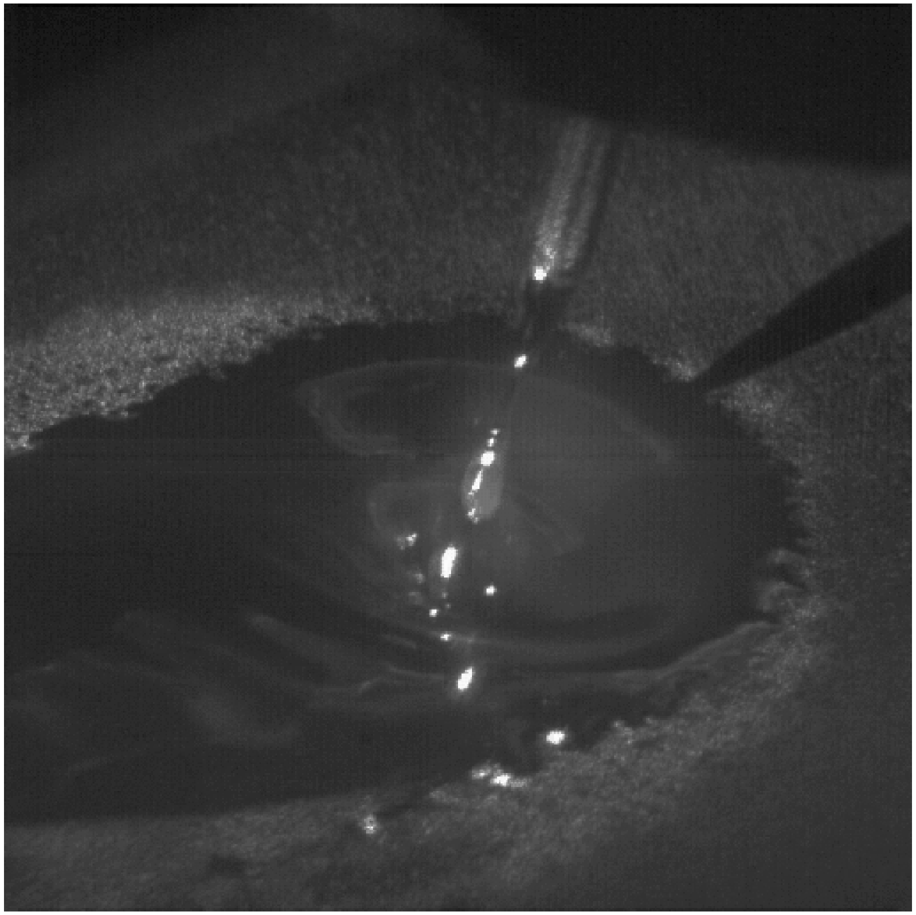
Pulse Spray Transfer



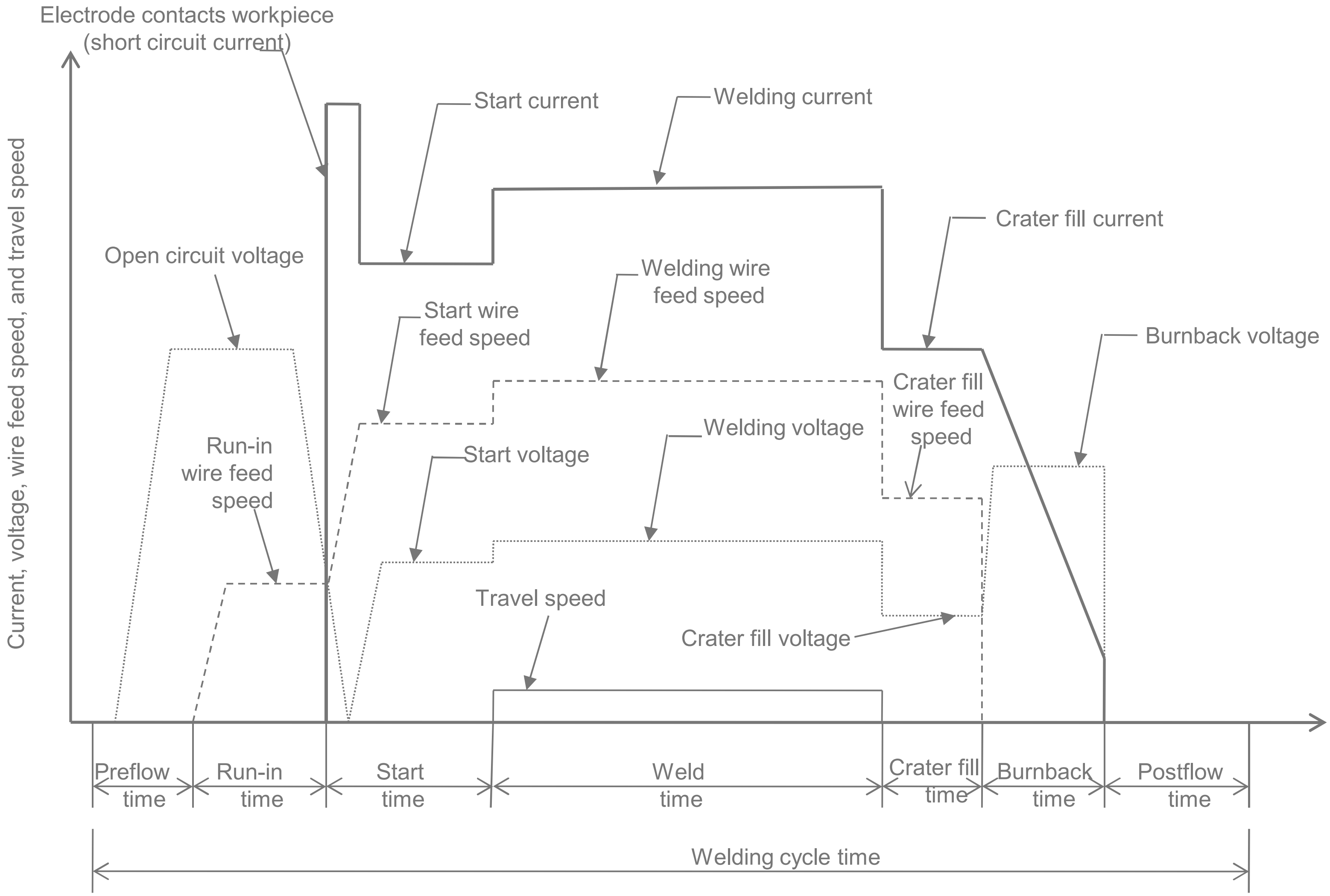
- Synergic control: in modern supplies, pulse waveforms are automatically adjusted to accommodate a wire feed rate set by the user

GMAW (transfer mode)

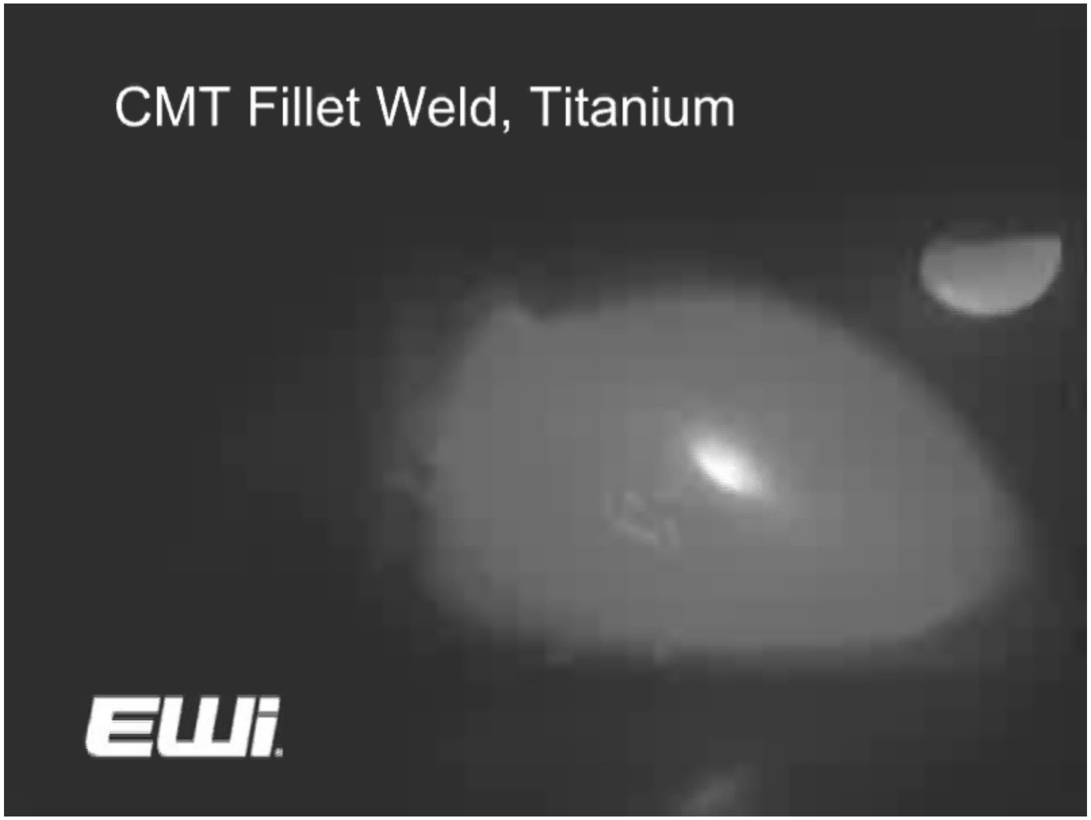
Pulsed mode



Typical Weld Cycle



Reciprocating Wire Feed GMAW



Selection and Application Criteria for GMAW

- Advantages
  - Welds all commercial metals
  - All positions
  - High deposition rates compared to GTAW and SMAW
    - Continuously fed filler wire
  - Long welds without stops and starts
  - Minimal post-weld and inter-pass cleaning
- Limitations
  - Welding equipment is more complex than that for SMAW
    - More difficult to use in hard to reach places
    - Welding torch size
  - Welding torch must be kept in close proximity to the workpieces in order to achieve adequate shielding
  - Arc must be protected against air drafts

Selection and Application Criteria for FCAW

- Advantages
  - High deposition rates
  - Deeper penetration than SMAW
  - High quality welds
  - Less pre-cleaning than GMAW
  - Slag covering helps with out-of-position welds
  - Self-shielded FCAW is draft tolerant
- Disadvantages
  - Slag must be removed
  - Higher fume generation than GMAW and SAW
  - Spatter
  - Equipment is more expensive and complex than SMAW
  - FCAW wire is more expensive

ASME Section IX – GMAW & FCAW Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-404 Filler Metals	.4	φ F-Number	X		
	.5	φ A-Number	X		
	.6	φ Diameter			X
	.12	φ Classification		X	
	.23	φ Filler Metal Product Form	X		
	.24	± or φ Supplemental	X		
	.27	φ Alloy Elements	X		
	.30	φ t	X		
	.32	t Limits (S.Cir. Arc)	X		
	.33	φ Classification			X

ASME Section IX – GMAW & FCAW Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-405 Positions	.1	+ Position			X
	.2	φ Position		X	
	.3	φ ↑↓ Vertical Welding			X
QW-408 Gas	.1	± Trail or φ Composition			X
	.2	φ Single, Mixture, or %	X		
	.3	φ Flow Rate			X
	.5	± or φ Backing Flow			X
	.9	- Backing or φ Composition	X		
	.10	φ Shielding or Trailing	X		

ASME Section IX – GMAW & FCAW Process Procedure Variables

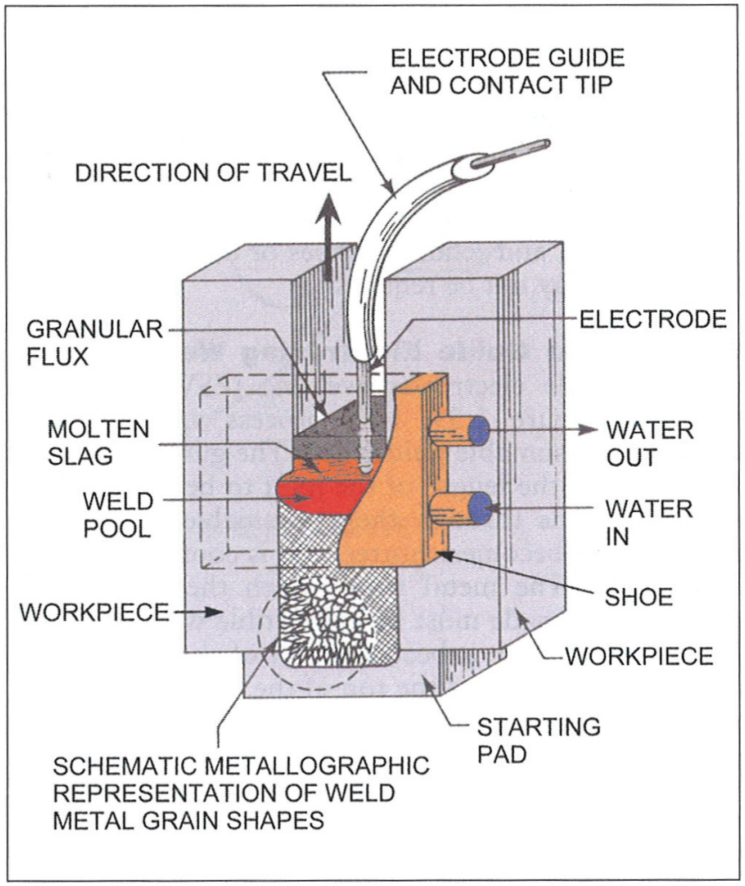
Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-409 Electrical Characteristics	.1	> Heat Input		X	
	.2	φ Transfer Mode	X		
	.4	φ Current or Polarity		X	X
	.8	φ I & E Range			X
QW-410 Technique	.3	φ Orifice, Cup, or Nozzle Size			X
	.5	φ Method of Cleaning			X
	.8	φ Tube-Work Distance			X
	.10	φ Single to Multi Electrodes		X	X
	.15	φ Electrode Spacing			X
	.25	φ Manual or Automatic			X

Other Arc Welding Processes

Module 2A.7

Electroslag Welding (ESW) Definition

- Pieces welded by molten slag that melts the filler metal and the surfaces of the workpieces to be welded
- ESW is not a "true" arc process



Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.51.

Figure 1.38—Schematic Representation of Electroslag Welding

Source: AWS Handbook 9th ed. Vol. 1

Advantages of ESW

- Deposition rates of 35- to 45-lbs/hr
- Sections with thicknesses ≥ ¾-in
- Preheating and post-heating are normally not required
- Long molten time allows gas and slag to escape
- High duty cycle with little operator fatigue
- Minimum material handling
- Minimum distortion
- No spatter
  - 100% of filler metal is transferred to the weld
- Fastest welding process for large, thick materials

Limitations of ESW

- Limited to carbon, low alloy, and some stainless steels
- Only applicable to vertically positioned joints
- Single pass welding only
  - Process cannot be interrupted, or else weld will contain discontinuities and flaws
- Minimum base metal thickness of approximately ¾-in
- Complex material shapes may be difficult or impossible to weld

Application of ESW

- Used for welding carbon, low alloy, and some stainless steels in a single pass
- Recognized by all of the important national codes
  - Several have requirements that differ from other welding processes
- Widely used for structural applications
  - Transition joint between different flange thicknesses
  - Stiffeners in box columns and wide flanges
- Large presses and machinery with large, heavy plate
- Pressure vessels

Safety and Health of ESW

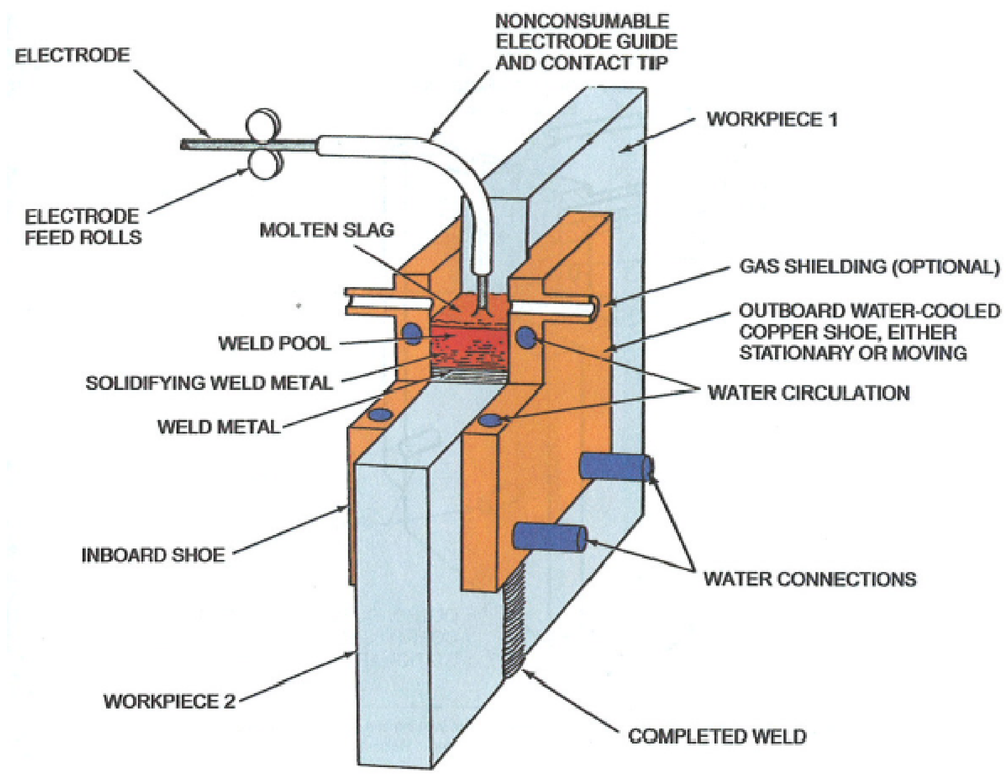
- Refer to Z49.1 of AWS and OSHA Title 29 Part 1910 for details
- Safety glasses with side shields are recommended
- Electrical safety due to all parts of operation being electrically "HOT"
- Stay away from fumes
- Slag leakage may be a problem
- Be cautious with hot shoes, sumps, and run-off blocks

ASME Section IX – ESW Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-404 Filler Metals	.4	φ F-Number	X		
	.5	φ A-Number	X		
	.6	φ Diameter			X
	.12	φ Classification		X	
	.17	φ Flux Type or Composition	X		
	.18	φ Wire to Plate	X		
	.19	φ Consumable Guide	X		
	.33	φ Classification			X
QW-409 Electrical Characteristics	.5	φ ± 15% I & E Range	X		
QW-410 Technique	.5	φ Method of Cleaning			X
	.10	φ Single to Multi Electrodes		X	X
	.15	φ Electrode Spacing			X

Electrogas Welding (EGW) Definition

- Arc welding process that uses an arc between a continuous filler metal electrode and the weld pool
- Employs vertical position welding with backing to confine the molten weld pool
- Externally applied shielding gas may or may not be used
  - No granular flux



Courtesy of the AWS Welding Handbook, Volume 2, 9th Ed.

Application of EGW

- Storage tanks, ship hulls, structural members, and pressure vessels
  - High heat input gives large grain size
  - Used for 3/8- to 4-in. thicknesses
  - Reduced need for preheat
  - Reduced need for PWHT
  - Reduced distortion
- Problem may be low notch toughness
- High voltages are needed to melt into sidewalls

ASME Section IX – EGW Process Procedure Variables

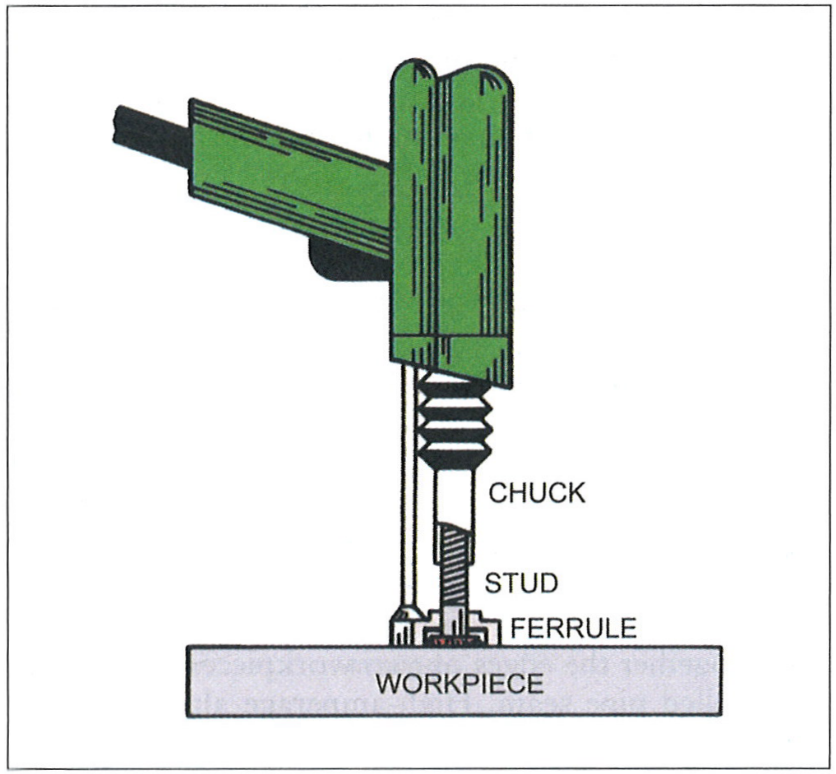
Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-404 Filler Metals	.4	φ F-Number	X		
	.5	φ A-Number	X		
	.6	φ Diameter			X
	.12	φ Classification		X	
	.23	φ Filler Metal Product Form	X		
	.33	φ Classification			X
QW-408 Gas	.2	φ Single, Mixture, or %	X		
	.4	φ Flow Rate			X

ASME Section IX – EGW Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-409 Electrical Characteristics	.1	> Heat Input		X	
	.4	φ Current or Polarity		X	X
	.8	φ I & E Range			X
QW-410 Technique	.5	φ Method of Cleaning			X
	.8	φ Tube-Work Distance			X
	.10	φ Single to Multi Electrodes		X	X
	.15	φ Electrode Spacing			X

Arc Stud Welding Definition

- Attachment of threaded studs to base plate
- Local melting at interface by ~0.1-2 second arc
- Metal expulsion during plunging
- Capacitor discharge is a less common process for stud welding



Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.63.

Figure 1.15—Schematic Representation of Stud Welding

Source: AWS Handbook 9th ed. Vol. 1

ASME Section IX – Arc Stud Process Procedure Variables

Paragraph		Brief of Variables	Essential	Supplementary Essential	Nonessential
QW-402 Joints	.8	φ Stud Shape Size	X		
	.9	- Flux or Ferrule	X		
QW-405 Positions	.1	+ Position	X		
QW-408 Gas	.2	φ Single, Mixture, or %	X		
QW-409 Electrical Characteristics	.4	φ Current or Polarity			X
	.8	φ I & E Range			X
	.9	φ Arc Timing	X		
	.10	φ Amperage	X		
	.11	φ Power Source	X		
QW-410 Technique	.22	φ Gun Model or Lift	X		