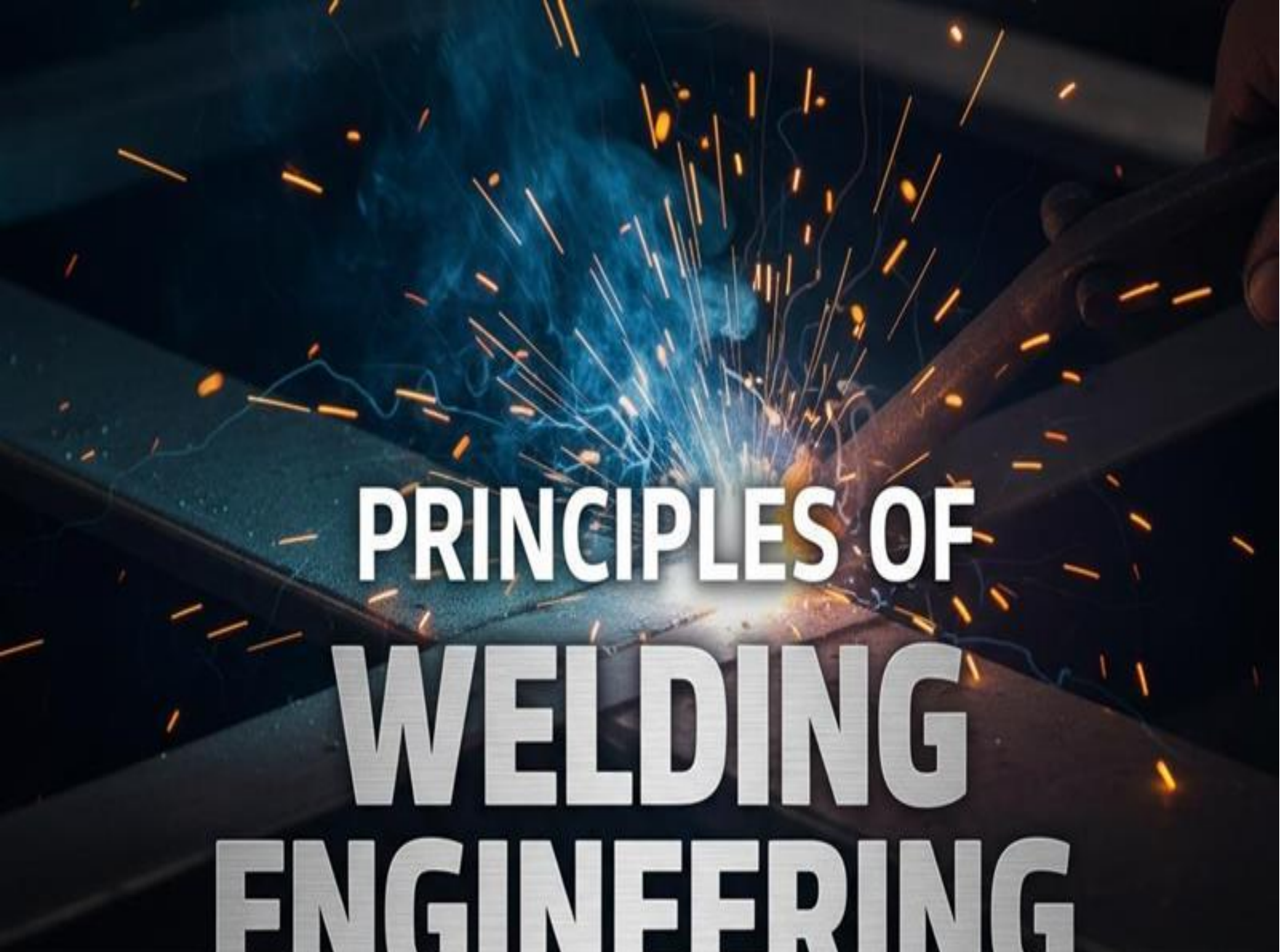

PRINCIPLES OF WELDING ENGINEERING

A Comprhensive Study

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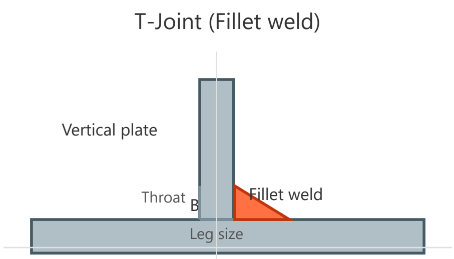
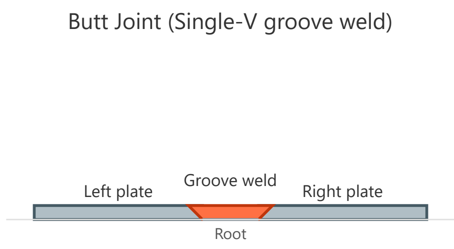
Welding

Welding is a fabrication process that joins materials, usually metals or thermoplastics, by using high temperature to melt the parts together and allow them to cool, creating a fusion bond. Alternative methods include solvent welding (for thermoplastics) and solid-state welding processes such as pressure welding, cold welding, and diffusion bonding.

Welding differs from lower-temperature bonding techniques such as brazing and soldering, which do not melt the base metal but instead use a filler metal to form the joint.

In most welding processes, a filler material is added to form a molten weld pool that solidifies into a strong joint. A shielding method is also required to protect the molten metal from contamination or oxidation.



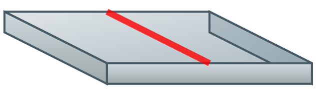


Energy Sources

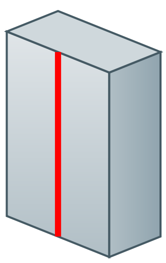
Welding can be performed using a variety of energy sources, including:

- Gas flame
- Electric arc
- Laser
- Electron beam
- Friction
- Ultrasound

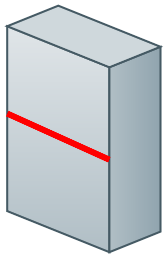
It can be carried out in diverse environments such as open air, underwater, and even in outer space.



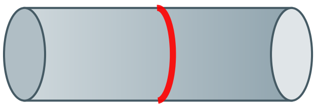
1G Weld Position



3G Weld Position



2G Weld Position



5G Weld Position

Safety

Welding is hazardous and requires precautions to prevent burns, electric shock, vision damage, inhalation of toxic fumes, and exposure to intense ultraviolet radiation.

History

Until the late 19th century, **forge welding** was the only known process, used by blacksmiths for millennia. Later developments included arc welding, oxy-fuel welding, and electric resistance welding.

During the early 20th century, demand from world wars accelerated welding technology. Modern methods emerged, such as:

- Shielded metal arc welding (SMAW)
- Gas metal arc welding (GMAW)
- Submerged arc welding (SAW)
- Flux-cored arc welding (FCAW)
- Electroslag welding (ESW)

Later innovations included laser beam welding, electron beam welding, magnetic pulse welding, and friction stir welding. Today, **robot welding** is common in industry, and research continues to improve weld quality and efficiency.

Welding Processes

Welding joins two pieces of metal using heat, pressure, or both. The most common modern methods melt the base metals and filler metal to form a weld pool, which must be shielded from oxygen and contaminants. Solid-state welding, by contrast, joins metals using pressure without melting.

Fusion Welding

- **Gas Welding** – Uses a flame (commonly oxy-fuel) to melt base and filler metals.
- **Arc Welding** – Uses an electric arc to generate heat. Includes SMAW, GMAW, GTAW, SAW, FCAW, PAW, and more.
- **Advanced Fusion Methods** – Electron beam welding, laser beam welding, and electroslag/electrogas welding.

Solid-State Welding

- **Resistance Welding** – Combines heat and pressure without filler material.
- **Diffusion Bonding** – Joins metals at high temperature and pressure without melting.

- **Friction Stir Welding** – Uses a rotating tool to join metals in the solid state.
- **Magnetic Pulse Welding** – Uses electromagnetic forces to bond metals.

Gas Welding

Gas welding, also known as oxyacetylene welding, uses an open flame to generate heat and shield the weld. The flame temperature is about 3100 °C (5600 °F), lower and less concentrated than arc welding. This slower cooling can cause residual stresses and distortion, but it also makes welding high-alloy steels easier. The outer flame envelope consumes oxygen before it reaches the molten weld pool, and flux may be applied when welding easily oxidized metals like stainless steel.

The equipment is simple and inexpensive, consisting of a torch, hoses, regulators, and tanks of oxygen and fuel (usually acetylene). Gas welding is one of the oldest and most versatile processes, though less common in modern industry. It remains widely used for pipe and tube welding, repair work, and related processes such as oxyfuel cutting and heating metal for bending or straightening.

Arc Welding

Arc welding uses a power supply to create and maintain an electric arc between an electrode and the base material, melting the metals at the weld point. Both alternating current (AC) and direct current (DC) can be used, with electrode polarity affecting the weld. Shielding gases or flux coatings protect the molten pool from contamination, and filler material is often added.

Arc Welding Processes

- **Shielded Metal Arc Welding (SMAW)** – Also called stick welding. Uses a consumable flux-coated electrode that provides filler metal and shielding gas. It is versatile, inexpensive, and widely used, though slower due to electrode changes and slag removal. Primarily used for ferrous metals, with special electrodes for cast iron, stainless steel, and aluminum.
- **Gas Metal Arc Welding (GMAW/MIG)** – A semi-automatic or automatic process using a continuous wire electrode and shielding gas. Faster than SMAW, with higher productivity, especially for long welds.
- **Flux-Cored Arc Welding (FCAW)** – Similar to MIG, but uses a tubular wire filled with flux. Provides deeper penetration and higher speed, though it generates more fumes and slag. Dual-shield versions combine flux with external shielding gas.
- **Gas Tungsten Arc Welding (GTAW/TIG)** – Uses a non-consumable tungsten electrode and separate filler rod. Produces high-quality, precise welds, especially for thin materials and non-ferrous metals, but requires more skill and is slower than other arc processes.

Gas Tungsten Arc Welding (GTAW / TIG)

Gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding, uses a non-consumable tungsten electrode, an inert or semi-inert shielding gas, and a separate filler material. It is especially useful for thin materials, producing stable arcs and high-quality welds, but requires significant operator skill and is relatively slow.

GTAW can be applied to nearly all weldable metals, most often stainless steel and light alloys. It is preferred where weld quality is critical, such as in bicycles, aircraft, and naval applications.

A related process, **plasma arc welding**, also uses a tungsten electrode but employs plasma gas to create a more concentrated arc. This allows faster welding and a wider range of thicknesses, though it is usually mechanized. A variation, **plasma cutting**, is widely used for efficient steel cutting.

Submerged Arc Welding (SAW)

Submerged arc welding (SAW) is a high-productivity process where the arc burns beneath a layer of flux. The flux shields the weld from contaminants, improves arc quality, and produces slag that usually detaches on its own. Combined with continuous wire feed, this results in high deposition rates and minimal smoke. SAW is widely used in industry for large products and welded pressure vessels.

Other related arc welding processes include atomic hydrogen welding, electroslag welding (ESW), electrogas welding, and stud arc welding. ESW is especially productive for thick materials (25–300 mm) in vertical positions.

Arc Welding Power Supplies

Arc welding requires electrical power, typically supplied by either constant current (CC) or constant voltage (CV) power sources:

- **Constant Current (CC)** – Used for manual processes like GTAW and SMAW. Maintains steady current despite voltage fluctuations caused by hand movement.
- **Constant Voltage (CV)** – Used for automated processes like GMAW, FCAW, and SAW. Maintains steady voltage while current adjusts automatically to keep arc length constant.

The type of current also matters:

- **Direct Current (DC)** – Common for consumable electrode processes. Positive polarity increases penetration; negative polarity produces shallower welds.
- **Alternating Current (AC)** – Alternates between positive and negative, giving medium penetration. Modern square-wave power units improve arc stability.

Resistance Welding

Resistance welding generates heat from electrical resistance in the base metals while electrodes apply pressure. Copper electrodes conduct current, creating small molten pools at the weld area. Current levels range from 1,000 to 100,000 A.

Types of Resistance Welding

- **Spot Welding** – Joins overlapping sheets up to 3 mm thick. Advantages include efficiency, high production rates, and easy automation. Widely used in the automotive industry, often with robots.
- **Seam Welding** – Uses wheel-shaped electrodes to create continuous welds along sheets. Formerly used in beverage can production, now more limited.
- **Other Methods** – Butt welding, flash welding, projection welding, and upset welding are specialized variations.

Energy Beam Welding

Energy beam welding processes use highly concentrated heat sources such as electron beams or lasers. These methods allow deep, narrow welds with minimal distortion and are especially useful in high-precision industries like aerospace and electronics.

Energy Beam Welding

Energy beam welding methods include **laser beam welding** and **electron beam welding**. Both use highly concentrated energy to achieve deep penetration and narrow weld zones:

- **Laser Beam Welding** – Uses a focused laser beam, fast and easily automated.

- **Electron Beam Welding** – Performed in a vacuum using an electron beam, also highly productive.

Advantages include high speed, deep penetration, and automation. Disadvantages are high equipment costs and susceptibility to thermal cracking. Developments include **laser-hybrid welding**, **laser cladding**, and experimental **x-ray welding**.

Solid-State Welding

Unlike fusion welding, **solid-state welding** does not melt the base materials. Instead, pressure, vibration, or other energy sources bond the materials together.

- **Ultrasonic Welding** – High-frequency vibrations join thin sheets or wires of metal or thermoplastic. Common in electrical connections and polymer welding.
- **Explosion Welding** – Extremely high pressure from an explosive impact bonds materials, often used for dissimilar metals (e.g., aluminum to steel in ship hulls).
- **Friction Welding** – Heat from friction joins materials. Variants include friction stir welding and friction stir spot welding.
- **Magnetic Pulse Welding** – Uses electromagnetic forces to bond metals.
- **Other Methods** – Cold welding, diffusion bonding, exothermic welding, high-frequency welding, induction welding, roll bonding, and hot pressure welding.

Weld Geometry: Detailed Explanation

Definition: Weld geometry refers to the shape, dimensions, and configuration of a weld joint and the resulting weld bead. It encompasses all physical aspects of the weld, including bead width, reinforcement height, penetration depth, groove angles, and contours. Proper weld geometry is critical for ensuring the mechanical strength, fatigue resistance, and service life of the welded structure. It also influences stress distribution, heat flow, and inspection accessibility.

Key Elements of Weld Geometry:

- **Weld Bead Profile:** This is the visible shape of the weld on the surface of the joint. It includes:
  - *Reinforcement height:* The amount the weld bead protrudes above the base metal surface. Excessive reinforcement can cause stress concentration, while insufficient reinforcement may reduce strength.
  - *Bead width:* The lateral spread of the weld. It should be consistent and proportional to joint design.
  - *Contour:* The smoothness and shape of the bead surface—convex, flat, or concave. A smooth, uniform contour indicates good fusion and minimal defects.
- **Penetration Depth:** The depth to which the weld metal fuses into the base metal. Full penetration is essential in critical joints to ensure complete fusion and load transfer. Incomplete penetration can lead to root defects and reduced joint strength.
- **Root Face:** The flat portion at the bottom of a groove joint that is not beveled. A thicker root face can restrict penetration, while a thinner one may lead to burn-through. It must be balanced to support the root pass and ensure fusion.
- **Root Gap:** The intentional space between the base metal pieces at the root. It allows the arc and filler metal to access the joint root. Too small a gap can cause lack of fusion; too large can lead to burn-through or excessive weld metal usage.
- **Groove Angle:** The included angle between the beveled edges of the joint. A wider groove angle improves access and visibility but increases filler metal consumption. A narrower angle saves filler but may hinder access and fusion, especially in thick sections.

- **Toe Angle:** The angle formed between the weld face and the base metal surface at the weld toe. A sharp toe angle can act as a notch and concentrate stress, increasing the risk of fatigue cracks. A smooth transition reduces stress concentration.
- **Leg Length:** In fillet welds, this is the distance from the weld root to the toe along each leg. It determines the weld size and directly affects the throat thickness and load-carrying capacity. Equal leg lengths are preferred for balanced stress distribution.
- **Throat Thickness:** The shortest distance from the root to the face of a fillet weld. It represents the effective area resisting shear or tensile loads. Undersized throat reduces strength; oversized throat increases weld volume and cost unnecessarily.

Types of Weld Geometry Based on Joint Design:

- **Butt Joint Geometry:** Formed when two plates are aligned in the same plane. Variants include:
  - *Square Butt:* No edge preparation; used for thin materials.
  - *Single V / Double V:* Beveled edges forming a V; double V is used for thicker sections to balance distortion.
  - *Single Bevel / Double Bevel:* One or both sides beveled; used when access is limited to one side.

  These geometries affect weld volume, penetration, and accessibility.
- **Fillet Weld Geometry:** Used in lap, T, and corner joints. The weld cross-section is approximately triangular. Key geometric parameters include leg length and throat thickness, which determine the weld's load-bearing capacity.
- **Groove Weld Geometry:** Designed for full penetration in thicker materials. Groove shapes include:
  - *V-groove:* Simple and widely used; requires moderate filler.
  - *U-groove:* Curved edges reduce filler volume but require machining.
  - *J-groove:* One side curved; used when access is limited to one side.

  Groove geometry affects weld accessibility, filler metal usage, and distortion control.
- **Plug and Slot Weld Geometry:** Used to join overlapping plates by filling circular (plug) or elongated (slot) holes with weld metal. The geometry—hole diameter, spacing, and depth—affects shear strength and load distribution across the joint.

Importance of Weld Geometry:

- **Ensures proper load transfer and structural integrity:** Well-designed geometry allows the weld to carry design loads without failure or deformation.
- **Minimizes stress concentration and fatigue failure:** Smooth transitions and correct angles reduce localized stress and improve fatigue life.
- **Improves aesthetic appearance and surface finish:** Uniform bead profile and clean contours enhance visual quality, especially in exposed structures.
- **Facilitates inspection and quality control:** Consistent geometry makes it easier to detect defects and verify compliance with standards.
- **Reduces material usage and welding time when optimized:** Efficient geometry minimizes filler metal consumption and reduces arc time, improving productivity and cost-effectiveness.

Factors Affecting Weld Geometry:

- **Welding process (e.g., SMAW, GMAW, TIG):** Each process produces different bead shapes and penetration characteristics. For example, TIG offers precise control and clean geometry, while FCAW may produce more reinforcement and spatter.
- **Joint design and preparation:** Proper beveling, root gap, and alignment are essential for achieving the desired geometry and avoiding defects like lack of fusion or excessive reinforcement.
- **Welding parameters such as current, voltage, and travel speed:** These control heat input, which directly affects bead size, penetration, and contour. High current increases penetration but may cause burn-through; low current may result in poor fusion.

- **Filler metal type and deposition rate:** The composition, diameter, and feed rate of filler metal influence bead shape, reinforcement, and dilution with base metal.
- **Welder skill and technique:** Consistent torch angle, arc length, and travel speed are crucial for maintaining uniform geometry. Skilled welders can adapt to joint variations and control bead formation effectively.

Inspection of Weld Geometry:

- Visual inspection for bead shape and uniformity.
- Dimensional checks using weld gauges and templates.
- Non-destructive testing (NDT) for internal geometry and defects.

Conclusion: Weld geometry is a fundamental aspect of welding engineering. It influences the strength, performance, and reliability of welded structures. Understanding and controlling weld geometry is essential for producing high-quality welds that meet design specifications and safety standards.

Weld Quality

Weld quality depends on many factors, including the welding process, filler and flux materials, shielding method, joint design, energy input, and the skill of the operator. Quality assurance ensures that welds are free of defects, have acceptable levels of residual stress and distortion, and meet the required mechanical properties.

Factors Affecting Quality

- Welding method and energy input
- Weldability of the base material
- Filler and flux materials
- Joint design and geometry
- Welding position (1G flat, 2G horizontal, 3G vertical, 4G overhead, 5G horizontal fixed pipe, 6G inclined fixed pipe)

Testing Methods

Weld quality is verified using destructive and nondestructive testing. These methods confirm that welds are free of defects, have acceptable residual stresses and distortion, and maintain proper heat-affected zone (HAZ) properties.

Common defects include cracks, distortion, porosity, inclusions, lack of fusion, incomplete penetration, lamellar tearing, and undercutting.

Inspection techniques include visual inspection, radiography, ultrasonic testing, phased-array ultrasonics, dye penetrant inspection, magnetic particle inspection, and industrial computed tomography.

Codes and Standards

The metalworking industry has established codes and specifications to guide welders, inspectors, and engineers in proper technique, weld design, and quality assurance. These standards also define how to evaluate welding procedure specifications and the skill of welders.

Extending Weld Life

The durability of dynamically loaded welded structures often depends on weld transitions. Treatments such as grinding, shot peening, high-frequency impact treatment, and ultrasonic impact treatment can significantly increase fatigue life and durability.

Heat-Affected Zone (HAZ)

The heat-affected zone (HAZ) is the region of base metal around a weld that is not melted, but whose properties are changed by the heat of welding. Uneven heating and cooling can alter hardness, strength, and toughness in this zone.

Factors Affecting HAZ Size

- **Material diffusivity:** High diffusivity → faster cooling → smaller HAZ; low diffusivity → slower cooling → larger HAZ.
- **Welding process:**
  - Oxyacetylene welding → large HAZ (diffuse heat).
  - Laser beam welding → very small HAZ (concentrated heat).
  - Arc welding → intermediate HAZ size, depending on process and parameters.

Heat Input Calculation

The heat input for arc welding can be estimated using:

$$Q = (V \times I \times 60) / (S \times 1000) \times Efficiency$$

where Q = heat input (kJ/mm), V = voltage (V), I = current (A), S = welding speed (mm/min). Typical process efficiencies are: SMAW = 0.75, GMAW/SAW = 0.9, GTAW = 0.8.

Controlling HAZ Properties

The HAZ can sometimes become brittle or prone to cracking, especially at the junction between the weld and base metal. This is caused by rapid expansion during heating and contraction during cooling. To reduce these risks:

- Use **pre-heating** to slow down cooling and reduce thermal stresses.
- Apply **post-heating** or controlled cooling to relieve stresses.
- Perform **stress relieving** or **tempering** to restore toughness and reduce brittleness.

Lifetime Extension with After-Treatment

The durability of dynamically loaded welded structures often depends on weld transitions. Treatments such as grinding, shot peening, high-frequency impact treatment (HiFIT), and ultrasonic impact treatment can significantly increase fatigue life and durability.

Metallurgical Analysis of Welding

Overview: Welding metallurgy involves the study of how heat, cooling rates, and chemical interactions affect the microstructure and mechanical properties of metals during and after welding. It is critical for understanding weld integrity, predicting performance, and preventing defects.

1. Thermal Cycle and Its Effects

During welding, the base metal undergoes rapid heating and cooling. This thermal cycle causes phase transformations, grain growth, and residual stress formation. The temperature gradient creates distinct zones:

- **Fusion Zone (FZ):** The region where the base metal melts and mixes with filler metal. Solidification here determines grain structure and segregation behavior.

- **Heat-Affected Zone (HAZ):** The area adjacent to the weld that experiences elevated temperatures but does not melt. Metallurgical changes here include grain coarsening, phase transformation, and precipitation dissolution.
- **Base Metal (BM):** The unaffected portion of the parent material retaining its original microstructure.

2. Solidification and Grain Structure

In the fusion zone, solidification begins at the fusion boundary and progresses inward. Grain morphology depends on cooling rate and alloy composition:

- **Columnar Grains:** Grow perpendicular to the fusion boundary due to directional heat flow.
- **Equiaxed Grains:** Form near the weld center if nucleation is promoted by alloying elements or inoculants.
- **Segregation:** Alloying elements may concentrate in interdendritic regions, affecting corrosion resistance and mechanical properties.

3. Phase Transformations in Steels

In carbon and alloy steels, welding induces critical phase changes:

- **Austenitization:** Occurs in HAZ when temperature exceeds the A_{c3} point, transforming ferrite and pearlite to austenite.
- **Martensite Formation:** Rapid cooling from austenite leads to hard, brittle martensite, especially in high-carbon steels.
- **Tempering:** Post-weld heat treatment can reduce brittleness by decomposing martensite into tempered structures.

4. Alloy Behavior and Precipitation

In precipitation-hardened alloys (e.g., aluminum, nickel-based), welding can dissolve strengthening precipitates in the HAZ:

- **Solutionizing:** High temperatures dissolve precipitates.
- **Overaging:** Slow cooling or post-weld heat can coarsen precipitates, reducing strength.
- **Reprecipitation:** Controlled aging after welding can restore properties.

5. Residual Stresses and Distortion

Thermal contraction during cooling generates residual stresses, which can lead to distortion or cracking. Metallurgical factors influencing stress include:

- Phase transformation volume changes (e.g., austenite to martensite).
- Coefficient of thermal expansion mismatch between weld and base metal.
- Grain boundary weakening due to segregation or inclusions.

6. Weld Defects and Metallurgical Origins

Common defects with metallurgical causes include:

- **Cracking:** Hot cracks from solidification shrinkage; cold cracks from hydrogen embrittlement or martensite formation.
- **Porosity:** Gas entrapment due to contamination or alloy volatility.
- **Inclusions:** Entrapped oxides, slag, or unmelted particles from poor fusion or flux behavior.

7. Metallurgical Testing and Analysis

Techniques used to evaluate weld metallurgy:

- **Optical Microscopy:** Reveals grain structure and phase distribution.
- **Scanning Electron Microscopy (SEM):** High-resolution imaging of microstructural features and inclusions.
- **Hardness Testing:** Maps hardness across weld zones to infer phase changes.
- **X-ray Diffraction (XRD):** Identifies crystalline phases and residual stress.

Conclusion: Metallurgical analysis of welding is essential for designing reliable joints, selecting appropriate materials and processes, and preventing failure. It integrates thermal behavior, phase transformations, alloy chemistry, and microstructural evolution to ensure weld quality and performance.

Unusual Welding Conditions

Welding is often performed in controlled environments, but some processes are used in challenging conditions:

- **Open Air** – Shielded metal arc welding (SMAW) is common for construction and repair.
- **Underwater** – SMAW, flux-cored arc welding, and GTAW are used for ship, platform, and pipeline repair.
- **Space** – First attempted in 1969 (Soyuz 6 mission). Tested processes include SMAW, plasma arc welding, and electron beam welding. Research continues into laser, resistance, and friction welding for future space structures like the ISS.

Safety Issues

Welding involves hazards such as fumes, ultraviolet radiation, heat, electric currents, and vibrations. Proper precautions, protective equipment, and safe practices are essential.

Fire and Burns

Welding is classified as a *hot work* process. Welders wear leather gloves and protective jackets. Synthetic fabrics should be avoided, as molten metal can melt through them.

Radiation and Eye Protection

Arc welding produces intense visible and UV light, which can cause *arc eye* (corneal inflammation) and retinal burns. Helmets with UV-filtering faceplates, often auto-darkening, are required. Welding curtains protect bystanders. Oxyfuel welding produces less intense light, so goggles are sufficient.

Noise and Vibration

Welding can produce noise levels above 100 dB(A). Hearing protection is required above 85 dB(A). Processes that cause harmful vibrations are automated, as PPE cannot fully protect against them.

Welding Fumes and Health Risks

Welders are often exposed to dangerous gases and particulate matter. Processes like flux-cored arc welding and shielded metal arc welding produce smoke containing oxides. Smaller particles are more toxic because they can cross the blood–brain barrier. Hazardous fumes may include carbon dioxide, ozone, and heavy metals. For example, manganese fumes, even at low levels, can cause neurological and organ damage. Nanoparticles can lodge in the lungs and cause pulmonary fibrosis. The use of compressed gases and flames also poses fire and explosion risks.

Fume Control Technologies

- **Local Exhaust Ventilation (LEV)** – Removes fumes and dust directly from the welding area. Includes downdraft benches, fume hoods, and fume extraction guns.
- **Respirators** – Provide additional protection. Half-mask elastomeric respirators significantly reduce particulate inhalation.

Costs and Trends in Welding

The cost of welding depends on equipment, labor, materials, and energy:

- **Equipment** – Inexpensive for SMAW and oxyfuel welding; very costly for laser and electron beam welding.
- **Labor** – Usually the largest cost in manual welding. Efficiency depends on deposition rate, operator skill, and setup time.
- **Materials** – Includes base metals, filler, and shielding gases. Costs rise when special properties are required.
- **Energy** – Typically a small percentage of total cost.

Automation and robotics are increasingly used to reduce labor costs, especially in automotive resistance spot welding and arc welding. Research focuses on welding dissimilar materials (e.g., steel to aluminum), advanced processes (friction stir, magnetic pulse, laser-hybrid), and improving understanding of weld microstructure, residual stresses, and cracking.

In steel erection, faster welding speeds can compromise weld integrity if fusion is insufficient. Inspectors must often witness puddle welds to ensure load capacity. Standards for these practices are under review by the American Welding Society.

Glass and Plastic Welding

Welding is not limited to metals. Glass and plastics can also be joined using specialized processes:

- **Glass Welding** – Glass tubes or cast-glass components can be fused together, leaving visible weld seams.
- **Plastic Welding** – Thermoplastics can be welded using heat, pressure, or ultrasonic energy, creating strong, seamless joints.

Glass and Plastic Welding

Glasses and certain plastics can be welded, but unlike metals (which have a sharp melting point), they soften over a range of temperatures known as the **glass transition**. Above this range, they become viscous liquids with low surface tension, allowing two softened surfaces to be pressed together and fused. Upon cooling, the materials solidify into a single piece of amorphous solid.

Glass Welding

Glass welding is common in glassblowing and glass casting, used in making lighting, neon signs, scientific equipment, bottles, and jars. The process involves heating glass through its transition range until it becomes a thick, formable liquid. Heating is usually done with gas or oxy-gas torches or furnaces, depending on the glass type:

- **Lead glass** – Weldable at ~870 °C (1600 °F), can be worked with a propane torch.
- **Quartz glass (fused silica)** – Requires >1650 °C (3000 °F), typically welded with an oxyhydrogen torch.

When two pieces of molten glass are pressed together, they readily fuse. More complex shapes (e.g., tubes) may require blowing, suction, and careful manipulation to ensure seals and prevent collapse. Glass is brittle when solid, so welded glass must be cooled slowly and evenly in a process called **annealing** to relieve internal stresses.

Different glasses have different thermal expansion rates, so welding dissimilar glasses often causes cracking. Matching coefficients of thermal expansion is critical. Glass can also be bonded to metals or ceramics, though usually by adhesion rather than mixing. Special alloys or coatings are often used to ensure compatibility.

Plastic Welding

Plastics are divided into two categories:

- **Thermosets** – Once set, they cannot be melted or welded (e.g., epoxy, silicone, vulcanized rubber, polyester, polyurethane).
- **Thermoplastics** – Can be softened and welded repeatedly. Examples include polyethylene, polypropylene, polystyrene, PVC, Teflon, and Spectralon.

Welding thermoplastics involves heating them through the glass transition until the interface becomes viscous, pressing the surfaces together, and allowing intermolecular diffusion. Upon cooling, the weld solidifies. A filler rod may be used for some joints. Plastics weld at much lower temperatures than glass but can burn if overheated, so controlled heating methods are essential.

Heating methods include ovens, electric tools, ultrasonic welding, laser welding, friction welding, induction heating, and hot gas welding (using heated inert gas to melt and shield the plastic simultaneously).

Solvent Welding
Solvent welding is another method for joining plastics. A solvent softens or partially dissolves the surfaces of the plastic pieces, which are then pressed together. As the solvent evaporates, the materials fuse into a single solid joint. This method is commonly used for plastics like PVC in piping systems.

Solvent Welding

Many thermoplastics can be welded using chemical solvents. When the solvent contacts the plastic, it softens the surface into a thick liquid solution. Pressing two softened surfaces together allows their molecules to mix and fuse. As the solvent evaporates, the joint solidifies into one piece.

Solvent welding is commonly used for joining PVC (polyvinyl chloride) or ABS (acrylonitrile butadiene styrene) pipes in plumbing, and for welding styrene and polystyrene plastics in model construction. It is especially effective on plastics like PVC, which burn at or below their glass transition, but less effective on resistant plastics such as Teflon or polyethylene.

Weldability

Weldability, also known as **joinability**, of a material refers to its ability to be welded. Many metals and thermoplastics can be welded, but some are easier to weld than others (see Rheological weldability). A material's weldability is used to determine the welding process and to compare the final weld quality to other materials.

Weldability is often hard to define quantitatively, so most standards define it qualitatively. For instance, the International Organization for Standardization (ISO) defines weldability in ISO standard 581-1980 as: *"Metallic material is considered to be susceptible to welding to an established extent with given processes and for given purposes when welding provides metal integrity by a corresponding technological process for welded parts to meet technical requirements as to their own qualities as well as to their influence on a structure they form."* Other welding organizations define it similarly.

Steels

For steel there are three major failure modes by which weldability can be measured: *hydrogen-induced cold cracking*, *lamellar tearing*, and *spot-weld peeling*. The most prominent of these is hydrogen-induced cold cracking.

Hydrogen-induced cold cracking

The weldability of steel, with regard to hydrogen-induced cold cracking, is inversely proportional to the hardenability of the steel, which measures the ease of forming martensite during heat treatment. Hardenability depends on chemical composition: greater quantities of carbon and alloying elements increase hardenability and thus reduce weldability.

To compare alloys, a measure known as the equivalent carbon content is used, relating their properties to plain carbon steel. Elements like chromium and vanadium have a stronger negative effect on weldability than copper or nickel. As equivalent carbon content rises, weldability decreases.

High-strength low-alloy steels (HSLA), developed in the 1970s, are generally easy to weld and have good strength, making them ideal for many applications.

Stainless steels, due to their high chromium content, behave differently. Austenitic stainless steels are the most weldable but are prone to distortion because of their high coefficient of thermal expansion. Some alloys are susceptible to cracking and reduced corrosion resistance. Hot cracking can occur if ferrite content is not controlled; electrodes that deposit small amounts of ferrite are used to alleviate this. Ferritic and martensitic stainless steels are less weldable and often require preheating and special electrodes.

Lamellar tearing

Lamellar tearing is a failure mode that occurs in rolled steel products. It has been virtually eliminated with the production of cleaner steels.

Spot-weld peeling

Excessive hardenability can occur when spot welding HSLA steels, leading to spot-weld peeling. The equivalent carbon content can be used to evaluate the propensity for this type of failure.

Aluminium

The weldability of aluminium alloys varies significantly depending on chemical composition. Aluminium alloys are susceptible to hot cracking. To combat this, welders increase welding speed to lower heat input. Preheating reduces temperature gradients and helps prevent hot cracking, but it can reduce the mechanical properties of the base material and should not be used when the base material is restrained.

Joint design can be modified, and more compatible filler alloys can be selected to decrease hot cracking. Aluminium alloys should also be cleaned prior to welding to remove oxides, oils, and loose particles. This is critical because aluminium welds are susceptible to porosity from hydrogen and dross from oxygen.

Process factors

While weldability can be generally defined for various materials, some welding processes work better for a given material than others. Even within a certain process, weld quality may vary greatly depending on parameters such as electrode material, shielding gases, welding speed, and cooling rate.

Types Of Welding

Oxy-Fuel Welding

Oxy–fuel welding (commonly called **oxyacetylene welding**, **oxy welding**, or **gas welding** in the United States) and **oxy–fuel cutting** are processes that use fuel gases (or liquid fuels such as gasoline, diesel, biodiesel, kerosene, etc.) and oxygen to weld or cut metals. French engineers Edmond Fouché and Charles Picard developed oxygen-acetylene welding in 1903. Pure oxygen, instead of air, is used to increase the flame temperature to allow localized melting of the workpiece material (e.g., steel) in a room environment.

A common propane/air flame burns at about 2,250 K (1,980 °C; 3,590 °F), a propane/oxygen flame burns at about 2,526 K (2,253 °C; 4,087 °F), an oxyhydrogen flame burns at 3,073 K (2,800 °C; 5,072 °F), and an acetylene/oxygen flame burns at about 3,773 K (3,500 °C; 6,332 °F).

During the early 20th century, before the development and availability of coated arc welding electrodes in the late 1920s, oxy–acetylene welding was the only process capable of making welds of exceptionally high quality in virtually all metals in commercial use at the time. These included carbon steel, alloy steels, cast iron, aluminium, and magnesium. In recent decades it has been superseded in most industrial uses by various arc welding methods offering greater speed and, in the case of gas tungsten arc welding, the capability of welding very reactive metals such as titanium.

Oxy–acetylene welding is still used for metal-based artwork and in smaller home-based shops, as well as situations where accessing electricity would present difficulties. The oxy–acetylene (and other oxy–fuel gas mixtures) welding torch remains a mainstay heat source for manual brazing, metal forming, preparation, and localized heat treating. In addition, oxy–fuel cutting is still widely used in both heavy industry and light industrial and repair operations.

In **oxy–fuel welding**, a welding torch is used to weld metals. Welding occurs when two pieces are heated to a temperature that produces a shared pool of molten metal. The molten pool is generally supplied with additional filler metal, selected based on the metals being welded.

In **oxy–fuel cutting**, a torch is used to heat metal to its kindling temperature. A stream of oxygen is then directed onto the metal, burning it into a metal oxide that flows out of the kerf as dross.

Torches that do not mix fuel with oxygen (instead combining with atmospheric air) are not considered oxy–fuel torches and can typically be identified by a single tank. Most metals cannot be melted with a single-tank torch. Consequently, single-tank torches are typically suitable for soldering and brazing but not for welding.

Uses

Oxy–fuel torches are or have been used for:

- Heating metal: in automotive and other industries for loosening seized fasteners.
- Neutral flame for joining and cutting of ferrous and non-ferrous metals (except brass).
- Depositing metal to build up a surface, as in hardfacing.
- Oxy-hydrogen flames are used:
  - In stone working for "flaming," where the stone is heated and the top layer crackles and breaks, leaving a textured surface.
  - In the glass industry for "fire polishing."
  - In jewelry production for "water welding" using a water torch (an oxyhydrogen torch whose gas supply is generated by electrolysis of water).
  - In automotive repair, for removing seized bolts.
  - Formerly, to heat lumps of quicklime to obtain limelight in theatres or lanterns.

- Formerly, in platinum works, as platinum is fusible only in the oxyhydrogen flame or an electric furnace.

In short, oxy–fuel equipment is versatile, not only for welding iron or steel but also for brazing, braze-welding, metal heating (annealing, tempering, bending, forming), rust or scale removal, loosening corroded fasteners, and cutting ferrous metals.

Apparatus

The apparatus used in gas welding consists of an oxygen source and a fuel gas source (usually in cylinders), two pressure regulators, two flexible hoses (one for each cylinder), and a torch. This torch can also be used for soldering and brazing. The cylinders are often carried in a wheeled trolley.

There have also been examples of oxyhydrogen cutting sets with small (scuba-sized) gas cylinders worn on the user's back in a harness, for rescue work and similar applications.

Fuels

Oxy–fuel processes may use a variety of fuel gases (or combustible liquids), the most common being acetylene. Other gases that may be used are propylene, liquified petroleum gas (LPG), propane, natural gas, hydrogen, and MAPP gas. Liquid fuel cutting systems use such fuels as gasoline (petrol), diesel, kerosene, and some aviation fuels.

Acetylene

Acetylene is the primary fuel for oxy–fuel welding and is the fuel of choice for repair work and general cutting and welding. Acetylene gas is shipped in special cylinders designed to keep the gas dissolved. The cylinders are packed with porous materials (e.g., kapok fibre, diatomaceous earth, or formerly asbestos), then filled to around 50% capacity with acetone, as acetylene is soluble in acetone. This method is necessary because above 207 kPa (30 psi) absolute pressure, acetylene is unstable and may explode.

There is about 1,700 kPa (247 psi) pressure in the tank when full. When combined with oxygen, acetylene burns at 3,200 to 3,500 °C (5,790 to 6,330 °F), the highest among commonly used gaseous fuels. Its primary disadvantage is its high price. Because acetylene is unstable at pressures equivalent to about 10 m (33 ft) underwater, submerged cutting and welding is reserved for hydrogen rather than acetylene.

Gasoline

Tests showed that an oxy-gasoline torch can cut steel plate up to 0.5 in (13 mm) thick at the same rate as oxy–acetylene. For plate thicknesses greater than 0.5 in (13 mm), the cutting rate was better than oxy–acetylene; at 4.5 in (110 mm) it was three times faster. The liquid fuel vapour is about four times the density of a gaseous fuel. A high-velocity cutting flame is produced by the large volume expansion as the liquid transitions to vapour, allowing the flame to cut across voids (air gaps between plates).

Oxy-gasoline torches can also cut through paint, dirt, rust, and other surface contaminants. This system provides nearly 100% oxidation during cutting, leaving almost no molten steel in the slag and preventing cut material from sticking together. Operating costs for a gasoline torch are typically 75–90% less than using propane or acetylene. The gasoline can be fed from a pressurized tank (hand-pumped or cylinder-fed) or a non-pressurized tank, with the fuel drawn into the torch by a venturi effect created by the oxygen flow. A low-cost approach used by jewelry makers in Asia involves bubbling air through a gasoline container with a foot pump and burning the fuel-air mixture in a specialized torch.

Hydrogen

Hydrogen has a clean flame and is suitable for use on aluminium. It can be used at higher pressures than acetylene and is therefore useful for underwater welding and cutting. It is also effective for heating large amounts of material. The flame temperature is about 2,000 °C in air and up to 2,800 °C when pre-mixed with oxygen in a 2:1 ratio (oxyhydrogen). Hydrogen is not used for welding steels and other ferrous materials because it causes hydrogen embrittlement.

For some oxyhydrogen torches, the oxygen and hydrogen are produced by electrolysis of water in an apparatus connected directly to the torch. Types include:

- Oxygen and hydrogen led separately from the electrolysis cell into a standard oxy-gas torch (as in water torches used in jewelry and electronics).
- Mixed oxygen and hydrogen drawn from the electrolysis cell into a special torch designed to prevent flashback.

MPS and MAPP gas

Methylacetylene-propadiene (MAPP) gas and LPG gas are similar fuels, as LPG is liquefied petroleum gas mixed with MPS. MAPP has storage and shipping characteristics like LPG and a heat value slightly lower than acetylene. Because it can be shipped in small containers, it is popular with hobbyists and industries. Unlike acetylene, it does not polymerize at pressures above 15 psi, making it safer.

MAPP gas can be stored in larger quantities due to its compressibility. It can be used at pressures up to 40–50 psi in high-volume oxy–fuel cutting torches, capable of cutting steel up to 300 mm (12 in) thick. MPS and MAPP are recommended primarily for cutting rather than welding. After the closure of the Petromont Varennes plant in 2008, which was the only North American producer, substitutes (mainly propylene) became common.

Propylene and fuel gas

Propylene is used in production welding and cutting, with performance similar to propane. When using propylene, torch tips rarely need cleaning. Cutting with an injector torch is often more effective than with an equal-pressure torch. Many North American suppliers market propylene under proprietary names such as FG2 and Fuel-Max.

Butane, propane and butane/propane mixes

Butane, like propane, is a saturated hydrocarbon. Butane and propane do not react with each other and are regularly mixed. Butane boils at 0.6 °C (33.1 °F). Propane is more volatile, with a boiling point of −42 °C (−44 °F). Vaporization is rapid at temperatures above the boiling points. The calorific (heat) values of the two are almost equal. Both are thus mixed to attain the vapor pressure required by the end user and depending on the ambient conditions. If the ambient temperature is very low, propane is preferred to achieve higher vapor pressure at the given temperature.

Propane does not burn as hot as acetylene in its inner cone, and so it is rarely used for welding. Propane, however, has a very high number of BTUs per cubic foot in its outer cone, and so with the right torch (injector style) can make a faster and cleaner cut than acetylene, and is much more useful for heating and bending than acetylene.

The maximum neutral flame temperature of propane in oxygen is 2,822 °C (5,112 °F).

Propane is cheaper than acetylene and easier to transport.

Operating costs

The following is a comparison of operating costs in cutting 13 mm (0.5 in) plate. Costing is based on an average cost for oxygen and different fuels in May 2012. The operating expense with gasoline was 25% that of propane and 10% that of acetylene. Numbers will vary depending on source of oxygen or fuel and on the type of cutting and the cutting environment or situation.

The role of oxygen

Oxygen is not the fuel. It is the oxidizing agent, which chemically combines with the fuel to produce the heat for welding. This is called 'oxidation', but the more specific and more commonly used term in this context is 'combustion'. In the case of hydrogen, the product of combustion is simply water. For the other hydrocarbon fuels, water and carbon dioxide are produced. The heat is released because the molecules of the products of combustion have a lower energy state than the molecules of the fuel and oxygen. In oxy–fuel cutting, oxidation of the metal being cut (typically iron) produces nearly all of the heat required to "burn" through the workpiece.

Oxygen is usually produced elsewhere by distillation of liquefied air and shipped to the welding site in high-pressure vessels (commonly called "tanks" or "cylinders") at a pressure of about 21,000 kPa (3,000 psi = 200 atmospheres). It is also shipped as a liquid in Dewar type vessels (like a large Thermos jar) to places that use large amounts of oxygen.

It is also possible to separate oxygen from air by passing the air, under pressure, through a zeolite sieve that selectively adsorbs the nitrogen and lets the oxygen (and argon) pass. This gives a purity of oxygen of about 93%. This method works well for brazing, but higher-purity oxygen is necessary to produce a clean, slag-free kerf when cutting.

Types of flame

The welder can adjust the oxy–acetylene flame to be carburizing (reducing), neutral, or oxidizing. Adjustment is made by adding more or less oxygen to the acetylene flame. The neutral flame is the flame most generally used when welding or cutting. The welder uses the neutral flame as the starting point for all other flame adjustments because it is so easily defined. This flame is attained when welders, as they slowly open the oxygen valve on the torch body, first see only two flame zones. At that point, the acetylene is being completely burned in the welding oxygen and surrounding air. The flame is chemically neutral.

The two parts of this flame are the light blue inner cone and the darker blue to colorless outer cone. The inner cone is where the acetylene and the oxygen combine. The tip of this inner cone is the hottest part of the flame. It is approximately 6,000 °F (3,320 °C) and provides enough heat to easily melt steel. In the inner cone the acetylene breaks down and partly burns to hydrogen and carbon monoxide, which in the outer cone combine with more oxygen from the surrounding air and burn.

An excess of acetylene creates a reducing (carbonizing) flame. This flame is characterized by three flame zones: the hot inner cone, a white-hot "acetylene feather", and the blue-colored outer cone. This is the type of flame observed when oxygen is first added to the burning acetylene. The feather is adjusted and made smaller by adding increasing amounts of oxygen. A welding feather is measured as 2X or 3X, with X being the length of the inner flame cone.

The unburned carbon insulates the flame and drops the temperature to approximately 5,000 °F (2,760 °C). The reducing flame is typically used for hardfacing operations or backhand pipe welding techniques. The feather is caused by incomplete combustion of the acetylene, producing excess carbon in the flame. Some of this carbon is dissolved by the molten metal, carbonizing it. The carbonizing flame also tends to remove oxygen from iron oxides present, hence the name "reducing flame".

The oxidizing flame is the third possible flame adjustment. It occurs when the ratio of oxygen to acetylene required for a neutral flame has been changed to give an excess of oxygen. This flame type is observed when welders add more oxygen to the neutral flame. This flame is hotter than the other two flames because the combustible gases do not need to search as far for oxygen. It is called an oxidizing flame because of its effect on metal. This flame adjustment is generally not preferred, as it creates undesirable oxides that reduce the structural and mechanical properties of most metals. In an oxidizing flame, the inner cone acquires a purplish tinge, becomes pinched and smaller at the tip, and the flame sound becomes harsh. A slightly oxidizing flame is used in braze-welding and bronze-surfacing, while a strongly oxidizing flame is used in fusion welding certain brasses and bronzes.

The size of the flame can be adjusted to a limited extent by the valves on the torch and by the regulator settings, but mainly depends on the size of the orifice in the tip. The tip should be chosen first according to the job at hand, and then the regulators set accordingly.

Welding

The flame is applied to the base metal and held until a small puddle of molten metal is formed. The puddle is moved along the path where the weld bead is desired. Usually, more metal is added to the puddle as it is moved along by dipping metal from a welding rod or filler rod into the molten metal puddle. The molten puddle will travel toward the hottest area of the flame. This is accomplished through torch manipulation by the welder.

The amount of heat applied to the metal is a function of the welding tip size, the speed of travel, and the welding position. The flame size is determined by the welding tip size. The proper tip size is determined by the metal thickness and the joint design.

Welding gas pressures using oxy–acetylene are set in accordance with the manufacturer's recommendations. The welder will modify the speed of welding travel to maintain a uniform bead width. Uniformity is a quality attribute indicating good workmanship. Trained welders are taught to keep the bead the same size at the beginning of the weld as at the end. If the bead gets too wide, the welder increases the speed of welding travel. If the bead gets too narrow or if the weld puddle is lost, the welder slows down the speed of travel. Welding in the vertical or overhead positions is typically slower than welding in the flat or horizontal positions.

The welder must add the filler rod to the molten puddle. The welder must also keep the filler metal in the hot outer flame zone when not adding it to the puddle to protect filler metal from oxidation. The welding flame should not be allowed to burn off the filler metal. If this occurs, the filler will not wet into the base metal and will appear as a series of cold dots on the base metal, resulting in a weak weld. When filler metal is properly added to the molten puddle, the resulting weld will be stronger than the original base metal.

Welding lead or 'lead burning' was much more common in the 19th century to make some pipe connections and tanks. Great skill is required, but it can be quickly learned. In building construction today some lead flashing is welded, but soldered copper flashing is much more common in America. In the automotive body repair industry before the 1980s, oxyacetylene gas torch welding was seldom used to weld sheet metal, since warping and excess heat were common byproducts. Automotive body repair methods at the time were crude and yielded poor results until MIG welding became the industry standard. Since the 1970s, when high-strength steel became the standard for automotive manufacturing, electric welding became the preferred method. After the 1980s, oxyacetylene torches fell out of use for sheet metal welding in the industrialized world.

Cutting

For cutting, the setup is slightly different. A cutting torch has a 60- or 90-degree angled head with orifices placed around a central jet. The outer jets are for preheat flames of oxygen and acetylene. The central jet carries only oxygen for cutting. The use of several preheating flames rather than a single flame makes it possible to change the direction of the cut without altering the nozzle position or angle, while also providing better preheat balance. Manufacturers have developed custom tips for MAPP, propane, and propylene gases to optimize the flames from these alternate fuel gases.

The flame is not intended to melt the metal, but to bring it to its ignition temperature. The torch's trigger blows extra oxygen at higher pressures down the torch's third tube out of the central jet into the workpiece, causing the metal to burn and blowing the resulting molten oxide through to the other side. The ideal kerf is a narrow gap with sharp edges; overheating the workpiece and melting through it causes a rounded edge.

Cutting is initiated by heating the edge or leading face of the steel to ignition temperature (approximately bright cherry red) using the preheat jets only, then using the separate cutting oxygen valve to release oxygen from the central jet. The oxygen chemically combines with the iron in the ferrous material to oxidize it rapidly into molten iron oxide, producing the cut. Initiating a cut in the middle of a workpiece is known as piercing.

Key considerations during cutting include:

- **Oxygen flow rate** is critical. Too little produces a slow, ragged cut; too much wastes oxygen and produces a wide concave cut. Cutting oxygen pressure must match the tip orifice, as specified by the manufacturer.
- The oxidation of iron is highly exothermic. Once started, steel can be cut at a surprising rate, far faster than if it were merely melted. Preheat jets then serve mainly as assistance.
- Since molten metal flows out of the workpiece, there must be clearance on the opposite side for the spray to exit. Workpieces are often cut on a grate to allow molten metal to fall freely.

For a basic oxy–acetylene rig, cutting speed in light steel sections is nearly twice as fast as a petrol-driven cut-off grinder. Advantages when cutting large sections include light weight, low noise, and minimal operator effort compared to heavy, noisy grinders that cause vibration and fatigue. Oxy–acetylene torches can cut ferrous materials in excess of 200 mm (7.9 in). Oxygen lances are used in scrapping operations to cut sections thicker than 200 mm.

Robotic oxy–fuel cutters sometimes use a high-speed divergent nozzle, which produces a high-velocity oxygen jet that spreads less than a parallel-bore nozzle, allowing a cleaner cut. These are not used by hand but are valuable in industries such as shipbuilding for producing complex shapes from large steel plates.

Oxy-propane torches are often used for cutting scrap to save money, as LPG is much cheaper per joule than acetylene, though propane does not produce acetylene's neat cut profile. Propane is also used in production for cutting very large sections.

Oxy–acetylene can cut only low- to medium-carbon steels and wrought iron. High-carbon steels are difficult to cut because the slag's melting point is close to that of the base metal, preventing proper ejection. In cast iron, graphite between grains interferes with cutting. Stainless steels cannot be cut because they do not burn readily.

Safety

Oxyacetylene welding/cutting is generally considered not to be difficult, but there are a good number of subtle safety points that should be learned such as:

- No more than 1/7 the capacity of the cylinder should be used per hour. Exceeding this causes the acetone inside the acetylene cylinder to come out and contaminate the hose and possibly the torch.
- Acetylene is dangerous above 1 atm (15 psi) pressure. It is unstable and explosively decomposes.
- Proper ventilation when welding will help to avoid large chemical exposure.

Eye protection

Proper protection such as welding goggles should be worn at all times, including to protect the eyes against glare and flying sparks. Special safety eyewear must be used—both to protect the welder and to provide a clear view through the yellow-orange flare given off by the incandescing flux. In the 1940s cobalt melters' glasses were borrowed from steel foundries and were still available until the 1980s.

However, the lack of protection from impact, ultraviolet, infrared, and blue light caused severe eyestrain and eye damage. Didymium eyewear, developed for glassblowers in the 1960s, was also borrowed—until many complained of eye problems from excessive infrared, blue light, and insufficient shading. Today, specialized eye protection is available for gas-welding aluminum that cuts the sodium orange flare completely and provides the necessary protection from ultraviolet, infrared, blue light, and impact, according to ANSI Z87-1989 safety standards for a Special Purpose Lens.

Safety with cylinders

Fuel and oxygen tanks should be fastened securely and upright to a wall, post, or portable cart. An oxygen tank is especially dangerous because the gas is stored at a pressure of 21 MPa (3,000 psi; 210 atm) when full. If the tank falls over and damages the valve, the tank can be propelled by the escaping oxygen with enough force to break through a brick wall. For this reason, an oxygen tank should never be moved without its valve cap screwed in place.

On an oxyacetylene torch system there are three types of valves: the tank valve, the regulator valve, and the torch valve. Each gas in the system will have each of these three valves. The regulator converts the high-pressure gas inside the tanks to a low-pressure stream suitable for welding. Acetylene cylinders must be maintained upright to prevent the internal acetone and acetylene from separating in the filler material.

Chemical exposure

A less obvious hazard of welding is exposure to harmful chemicals. Exposure to certain metals, metal oxides, or carbon monoxide can often lead to severe medical conditions. Damaging chemicals can be produced from the fuel, from the workpiece, or from protective coatings. Increasing ventilation around the welding environment significantly reduces exposure.

The most common fuel used in welding is acetylene, which has a two-stage reaction. The primary chemical reaction involves acetylene disassociating in the presence of oxygen to produce heat, carbon monoxide, and hydrogen gas: $C_2H_2 + O_2 \rightarrow 2CO + H_2$. A secondary reaction follows where the carbon monoxide and hydrogen combine with more oxygen to produce carbon dioxide and water vapor. If the secondary reaction does not consume all reactants, large amounts of carbon monoxide may be produced.

Almost every piece of metal is an alloy. Copper, aluminum, and other base metals are sometimes alloyed with beryllium, a highly toxic metal. Welding or cutting such alloys releases toxic beryllium fumes. Long-term exposure may cause shortness of breath, chronic cough, weight loss, fatigue, and weakness. Other alloying elements such as arsenic, manganese, silver, and aluminum can also cause sickness.

Anti-rust coatings on many manufactured components often contain zinc, cadmium, and fluorides. Galvanized metals have heavy zinc coatings. Exposure to zinc oxide fumes can cause "metal fume fever", a condition resembling influenza with fever, chills, nausea, cough, and fatigue. It usually lasts less than 24 hours but can be severe or fatal in extreme cases.

Flashback

Flashback is the condition of the flame propagating down the hoses of an oxy–fuel welding and cutting system. To prevent this, a flashback arrestor is usually employed. The flame burns backwards into the hose, causing a popping or squealing noise. It can cause an explosion in the hose with the potential to injure or kill the operator. Using a lower pressure than recommended can cause a flashback.

Shielded metal arc welding (SMAW)

Shielded metal arc welding (SMAW), also known as **manual metal arc (MMA/MMAW)** or **stick welding**, is a manual arc welding process that uses a consumable, flux-coated electrode to lay the weld. An electric current (AC or DC) from a welding power supply forms an arc between the electrode and the workpiece. The electrode and base metal melt to create a weld pool, which solidifies into the joint. As the weld is made, the flux coating decomposes, releasing shielding gases and forming a slag layer that protect the molten metal from atmospheric contamination.

Owing to its versatility and simple equipment, SMAW is one of the world's most widely used welding processes. It dominates maintenance and repair work and is extensively applied in heavy steel construction and industrial fabrication. While primarily used for iron and steels (including stainless steel), it can also weld aluminium, nickel, and copper alloys.

Development

After early arc discoveries (short-pulsed in 1800 and continuous in 1802), progress accelerated in the late 19th century with carbon arc welding and consumable metal electrodes. Early coated electrodes (using clay, lime, carbonates, and silicates) improved arc stability but were costly until extrusion processes (1927) reduced production costs and enabled tailored coatings. Iron powder added to flux in the 1950s further increased welding speed. Variants such as gravity welding and firecracker welding saw limited use.

Operation

To initiate, the electrode briefly touches and lifts from the workpiece to strike the arc. The consumable electrode melts, transferring droplets into the weld pool. Flux decomposition provides shielding gases and forms protective slag, which is removed after solidification. Frequent electrode changes and slag removal reduce arc-on time relative to continuous wire processes, but SMAW's portability and all-position capability (flat, vertical, overhead) make it well suited for site work and varied materials.

Operation

To strike the electric arc, the electrode is lightly touched to the base metal and then withdrawn slightly. This initiates the arc, melts both the workpiece and the consumable electrode, and transfers droplets of molten electrode into the weld pool. Striking an arc can be challenging for beginners: if the electrode is held perpendicular, it may stick to the workpiece and overheat. A lower angle allows the weld pool to flow more smoothly. As the electrode melts, the flux covering disintegrates, releasing shielding gases that protect the weld from oxygen and other atmospheric gases. The flux also produces molten slag, which covers the filler as it travels into the weld pool. Once solidified, the slag must be chipped away to reveal the finished weld. Because electrodes are consumed quickly, the welder must frequently stop to replace them and remove slag, reducing efficiency. The operator factor (time actually spent welding) is typically around 25%.

The welding technique depends on the electrode, workpiece composition, and joint position. Flat welds require the least skill and allow higher speeds with electrodes that melt quickly but solidify slowly. Vertical, overhead, or sloped welds demand more skill and often require electrodes that solidify quickly to prevent molten metal from flowing out of the weld pool, though this reduces deposition rate.

Quality

Common quality issues in SMAW include weld spatter, porosity, poor fusion, shallow penetration, and cracking.

- **Weld spatter** – Affects appearance and increases cleaning costs. Caused by high current, long arc length, or arc blow.
- **Porosity** – Weakens the weld, often detectable only by nondestructive testing. Caused by inadequate shielding, contamination, or excessive arc length.
- **Poor fusion** – Results from low current, contaminated surfaces, or improper electrode use.
- **Shallow penetration** – Produces weak welds; mitigated by reducing speed, increasing current, or using a smaller electrode.
- **Cracking** – Influenced by high carbon, alloy, or sulfur content, residual stresses, or insufficient preheating with low-hydrogen electrodes.

Safety

SMAW, like all welding methods, poses hazards if precautions are not taken. The open arc can cause burns, prevented by protective clothing such as leather gloves and jackets. The intense brightness can lead to arc eye or flash burns; welding helmets with dark or auto-darkening faceplates are essential. Translucent welding curtains protect nearby workers from ultraviolet radiation.

Fumes and gases from vaporized metal and flux can be harmful. They contain oxides and fine particulates, with smaller particles posing greater risks. Gases such as carbon dioxide and ozone may form if ventilation is poor. Modern helmets may include powered fans to help disperse fumes.

Applications and Materials

SMAW remains one of the most widely used welding processes worldwide. Its low equipment cost and versatility make it dominant in maintenance, repair, and construction of steel structures. Although flux-cored and gas metal arc welding are increasingly popular in industry, SMAW continues to be favored by small businesses and amateurs.

It is commonly used for carbon steels, alloy steels, stainless steels, cast iron, and ductile iron. It can also weld nickel and copper alloys, and occasionally aluminium. Thickness is limited on the low end by operator skill (rarely below 1.5 mm), but with proper preparation and multiple passes, virtually unlimited thicknesses can be joined. SMAW can be performed in all positions depending on electrode type and welder skill.

Equipment

Shielded metal arc welding equipment typically consists of a constant current welding power supply and an electrode, with an electrode holder, a ground clamp, and welding cables connecting the two.

Power Supply

The power supply used in SMAW provides constant current output, ensuring that the heat remains relatively stable even if arc distance and voltage vary. This is important because SMAW is a manual process, and maintaining a steady arc length is difficult with constant voltage sources. Skilled welders can intentionally vary arc length to fine-tune current and penetration.

The preferred polarity depends on the electrode and desired weld properties:

- **DCEN (Direct Current Electrode Negative)** – Increases electrode melting rate, reduces penetration.
- **DCEP (Direct Current Electrode Positive)** – Increases penetration, reduces electrode melting rate.
- **AC (Alternating Current)** – Provides balanced heat distribution and stable operation.

Most SMAW equipment uses a step-down transformer and, for DC models, a rectifier to convert AC to DC. Typical output ranges from 17–45 V at currents up to 600 A. Transformer types include tap-type, movable coil/core, and inverter machines. Inverters are smaller and more portable, using electronics to control current characteristics.

Engine-driven generators and alternators are also used as portable power supplies, especially in field work where mains power is unavailable. While less efficient and more costly to maintain, they eliminate the need for a separate rectifier and can provide both AC and DC. High-frequency alternators (e.g., 400 Hz) make arc striking and stability easier compared to grid-frequency units.

Electrode

The choice of electrode depends on the base material, welding position, and desired weld properties. Electrodes are flux-coated, providing shielding gases, slag formation, arc stability, and alloying elements. They are classified as:

- **Fast-fill** – Melt quickly for high welding speed.
- **Fast-freeze** – Solidify quickly, suitable for vertical and overhead positions.
- **Fill-freeze** (or fast-follow) – Intermediate characteristics.

Electrode cores are usually similar in composition to the base material, but variations are used to achieve specific properties. For example, stainless steel electrodes may be used to weld carbon steel to stainless steel. Non-ferrous electrodes are available for aluminium, copper, and their alloys.

Common electrode coatings include:

- **Rutile (TiO_2)** – Easy to use, good appearance, but higher hydrogen content can cause embrittlement.
- **Calcium fluoride (basic/low-hydrogen)** – Produce strong welds, hygroscopic, must be kept dry.

- **Cellulose** – Provide deep penetration, often combined with rutile, but require special handling to avoid cracking.
- **Iron powder** – Increases deposition rate, up to twice as fast.

Electrode Identification

The American Welding Society (AWS) established a system to identify electrodes using a four- or five-digit number. Covered electrodes made of mild or low-alloy steel carry the prefix *E*, followed by their number. The first two or three digits specify the tensile strength of the weld metal in thousands of pounds per square inch (ksi). The penultimate digit indicates the welding positions permitted with the electrode, typically:

- **1** – Fast-freeze electrodes, suitable for all positions.
- **2** – Fast-fill electrodes, generally limited to horizontal welding.

The final two digits together specify the welding current and type of electrode covering. When applicable, a suffix denotes the alloying element contributed by the electrode.

Common examples include:

- **E6010** – Fast-freeze, all-position electrode with 60 ksi (410 MPa) tensile strength. Operated using DCEP, it provides deep penetration and can burn through light rust or oxides.
- **E6011** – Similar to E6010 but usable with AC as well as DCEP.
- **E7024** – Fast-fill electrode, used mainly for flat or horizontal fillet welds with AC, DCEN, or DCEP.
- **E6012, E6013, E7014** – Fill-freeze electrodes, offering a balance between welding speed and all-position capability.

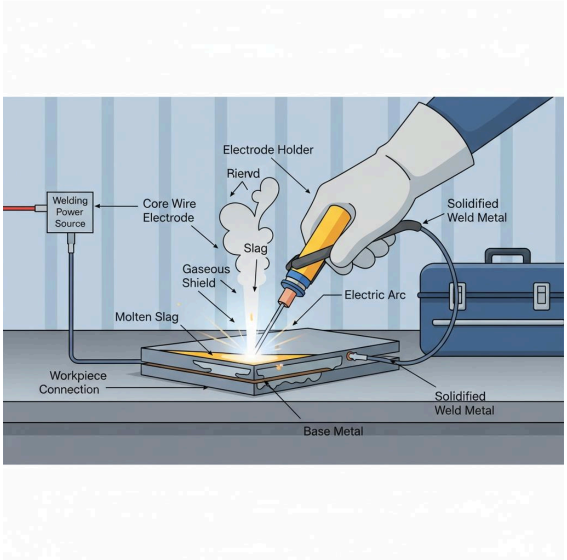
Process Variations

Although SMAW is almost exclusively a manual process, one notable variation is **gravity welding** (or gravity arc welding). In this automated method, the electrode holder is attached to an inclined bar along the weld length. Once started, the electrode feeds itself until consumed, allowing operators to manage multiple systems simultaneously. Electrodes used are heavily flux-coated, typically 71 cm (28 in) long and 6.35 mm (0.25 in) thick, such as E6027 or E7024. A constant current power supply is used, with either DC negative polarity or AC.

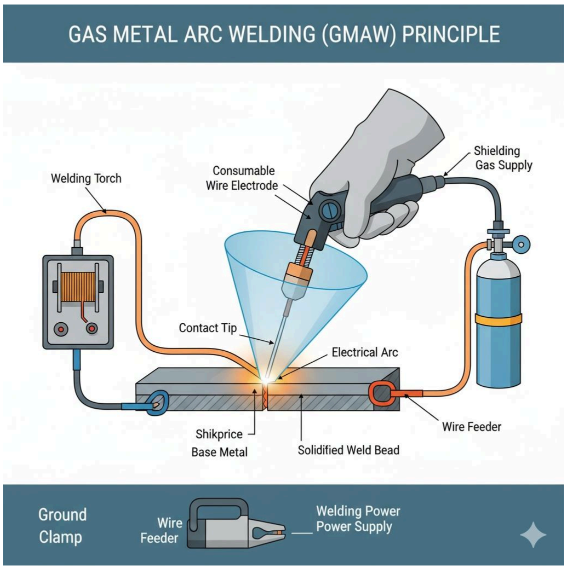
With the rise of semiautomatic processes like flux-cored arc welding, gravity welding has declined due to limited economic advantage. Other rarely used SMAW-related methods include:

- **Firecracker welding** – An automatic method for butt and fillet welds.
- **Massive electrode welding** – Used for large components, capable of depositing up to 27 kg (60 lb) of weld metal per hour.

Shielded Metal Arc Welding (SMAW)



Gas Metal Arc Welding (GMAW)



Gas Metal Arc Welding

Gas metal arc welding (GMAW), sometimes referred to by its subtypes **metal inert gas (MIG)** and **metal active gas (MAG)**, is a welding process in which an electric arc forms between a consumable wire electrode and the workpiece metal(s). The arc heats the workpiece, causing the metals to fuse. Along with the wire electrode, a shielding gas is fed through the welding gun to protect the weld from atmospheric contamination.

The process can be semi-automatic or automatic. A constant-voltage, direct-current power source is most commonly used with GMAW, though constant-current systems and alternating current can also be employed. There are four primary methods of metal transfer in GMAW: globular, short-circuiting, spray, and pulsed-spray, each with distinct properties, advantages, and limitations.

Originally developed in the 1940s for welding aluminium and other non-ferrous materials, GMAW was soon applied to steels because it provided faster welding times compared to other processes. Initially, the high cost of inert gases limited its use in steels, but the introduction of semi-inert gases such as carbon dioxide made it more economical. Further developments during the 1950s and 1960s gave the process more versatility, and it became a highly used industrial process. Today, GMAW is the most common industrial welding process, preferred for its versatility, speed, and adaptability to robotic automation. Unlike welding processes that do not employ a shielding gas, such as shielded metal arc welding, it is rarely used outdoors or in areas of moving air. A related process, flux cored arc welding, often does not use a shielding gas but instead employs a hollow electrode wire filled with flux.

Development

The principles of gas metal arc welding began to be understood in the early 19th century, after Humphry Davy discovered short pulsed electric arcs in 1800. Vasily Petrov independently produced the continuous electric arc in 1802. By the 1880s, the technology was being developed for industrial use. At first, carbon electrodes were used in carbon arc welding. By 1890, metal electrodes had been invented by Nikolay Slavyanov and C. L. Coffin. In 1920, P. O. Nobel of General Electric invented an early predecessor of GMAW using direct current with a bare electrode wire, though it lacked shielding gas. In 1926 another forerunner appeared, but it was not practical.

In 1948, GMAW was developed by the Battelle Memorial Institute. It used a smaller diameter electrode and a constant voltage power source. Although it offered a high deposition rate, the high cost of inert gases limited its use to non-ferrous materials. In 1953, the use of carbon dioxide as a welding atmosphere was developed, making welding steel more economical. In 1958–59, the short-arc variation of GMAW was released, which increased versatility and enabled welding of thin materials. It quickly became the most popular variation.

The spray-arc transfer variation was developed in the early 1960s, when small amounts of oxygen were added to inert gases. More recently, pulsed current has been applied, giving rise to the pulsed spray-arc variation.

GMAW is widely used in industrial environments, especially in the sheet metal and automobile industries. It is often employed for arc spot welding, replacing riveting or resistance spot welding. It is also popular for automated welding, where robots handle the workpieces and welding gun. GMAW is less suitable outdoors, since drafts can dissipate the shielding gas; flux cored arc welding is better for construction. Likewise, GMAW is not suited to underwater welding, which is more commonly performed via shielded metal arc welding, flux cored arc welding, or gas tungsten arc welding.

Equipment

To perform gas metal arc welding, the basic necessary equipment is a welding gun, a wire feed unit, a welding power supply, a welding electrode wire, and a shielding gas supply.

The typical GMAW welding gun has several key parts: a control switch, a contact tip, a power cable, a gas nozzle, an electrode conduit and liner, and a gas hose. The control switch, or trigger, when pressed by the operator, initiates the wire feed, electric power, and shielding gas flow, causing an electric arc to be struck. The contact tip, normally made of copper and sometimes chemically treated to reduce spatter, is connected to the welding power source through the power cable and transmits the electrical energy to the electrode while directing it to the weld area. It must be firmly secured and properly sized, since it must allow the electrode to pass while maintaining electrical contact. On the way to the contact tip, the wire is protected and guided by the electrode conduit and liner, which help prevent buckling and maintain an uninterrupted wire feed. The gas nozzle directs the shielding gas evenly into the welding zone. Inconsistent flow may not adequately protect the weld area. Larger nozzles provide greater shielding gas flow, which is useful for high-current welding operations that develop a larger molten weld pool. A gas hose from the shielding gas tanks supplies the gas to the nozzle. Sometimes, a water hose is also built into the welding gun, cooling the gun in high-heat operations.

The wire feed unit supplies the electrode to the work, driving it through the conduit and on to the contact tip. Most models provide the wire at a constant feed rate, but more advanced machines can vary the feed rate in response to the arc length and voltage. Some wire feeders can reach feed rates as high as 30 m/min (1200 in/min), but feed rates for semiautomatic GMAW typically range from 2 to 10 m/min (75–400 in/min).

Tool style

The most common electrode holder is a semiautomatic air-cooled holder. Compressed air circulates through it to maintain moderate temperatures. It is used with lower current levels for welding lap or butt joints. The second most common type is a semiautomatic water-cooled holder, where water replaces air. It is used with higher current levels for welding T or corner joints. The third type is a water-cooled automatic electrode holder, typically used with automated equipment.

Power supply

Most applications of gas metal arc welding use a constant-voltage power supply. Any change in arc length (directly related to voltage) results in a large change in heat input and current. A shorter arc length causes greater heat input, which makes the wire electrode melt more quickly and thereby restores the original arc length. This helps operators keep the arc length consistent even when manually welding with hand-held guns. Sometimes a constant-current power source is used with an arc voltage-controlled wire feed unit. In this case, a change in arc length makes the wire feed rate adjust to maintain a relatively constant arc length. In rare cases, a constant-current power source and a constant wire feed rate unit are coupled, especially for welding metals with high thermal conductivity such as aluminum. This grants the operator additional control over heat input but requires significant skill.

Alternating current is rarely used with GMAW; instead, direct current is employed and the electrode is generally positively charged. Since the anode tends to have a greater heat concentration, this results in faster melting of the feed wire, which increases weld penetration and welding speed. The polarity can be reversed only when special emissive-coated electrode wires are used, but since these are uncommon, a negatively charged electrode is rarely employed.

Electrode

The electrode is a metallic alloy wire, called a MIG wire. Its selection—composition, alloy, and size—is based primarily on the base metal, process variation, joint design, and surface conditions. Electrode selection greatly influences the mechanical properties of the weld and is a key factor in weld quality. In general, the finished weld metal should have properties similar to those of the base material, with no defects such as discontinuities, contaminants, or porosity. To achieve this, all commercially available electrodes contain deoxidizing metals such as silicon, manganese, titanium, and aluminum in small percentages to prevent oxygen porosity. Some also contain denitriding metals such as titanium and zirconium to avoid nitrogen porosity. Depending on the process variation and base material, electrode diameters typically range from 0.7 to 2.4 mm (0.028–0.095 in) but can be as large as 4 mm (0.16 in). The smallest electrodes, up to 1.14 mm (0.045 in), are associated with short-circuiting transfer, while spray-transfer electrodes are usually at least 0.9 mm (0.035 in).

Shielding gas

Shielding gases are necessary in GMAW to protect the welding area from atmospheric gases such as nitrogen and oxygen, which can cause fusion defects, porosity, and embrittlement if they contact the electrode, arc, or weld metal. Unlike SMAW, where the electrode coating produces a protective gas, GMAW uses a separate shielding gas. This eliminates slag, the hard residue from flux that must be chipped away after welding.

The choice of shielding gas depends on the material and process variation. Pure inert gases such as argon and helium are used for nonferrous welding; with steel, argon provides poor penetration and helium causes an erratic arc. Pure carbon dioxide allows deep penetration but encourages oxide formation and spatter, making it less suitable for thin materials. Its low cost, however, makes it attractive. For this reason, argon–carbon dioxide mixtures (typically 75/25 to 90/10) are common. In short-circuit GMAW, higher carbon dioxide content increases weld heat and energy. However, above 20% CO_2, spray transfer becomes problematic, especially with smaller electrodes.

Argon is also commonly mixed with other gases such as oxygen, helium, hydrogen, and nitrogen. The addition of up to 5% oxygen can be helpful in welding stainless steel, though in most applications carbon dioxide is preferred. Increased oxygen oxidizes the electrode, which can lead to porosity in the deposit if the electrode does not contain sufficient deoxidizers. Excessive oxygen, especially when used improperly, can cause brittleness in the heat-affected zone. Argon–helium mixtures are extremely inert and are used on nonferrous materials. A helium concentration of 50–75% raises the required voltage and increases arc heat due to helium's higher ionization temperature. Hydrogen is sometimes added to argon in small concentrations (up to about 5%) for welding nickel and thick stainless steel workpieces. In higher concentrations (up to 25%), it may be used for welding conductive materials such as copper. However, it should not be used on steel, aluminum, or magnesium because it can cause porosity and hydrogen embrittlement.

Shielding gas mixtures of three or more gases are also available. Mixtures of argon, carbon dioxide, and oxygen are marketed for welding steels. Other mixtures add a small amount of helium to argon–oxygen combinations, allowing higher arc voltages and welding speed. Helium can also serve as the base gas with small amounts of argon and carbon dioxide added. However, because helium is less dense than air, it is less effective at shielding the weld than argon, which is denser. Helium can also cause arc stability and penetration issues, as well as increased spatter, due to its energetic arc plasma. In addition, helium is substantially more expensive than other shielding gases. Other specialized and proprietary gas mixtures claim further benefits for specific applications.

Despite being poisonous, trace amounts of nitric oxide can be used to prevent the formation of ozone in the arc.

The desirable rate of shielding-gas flow depends on weld geometry, speed, current, gas type, and metal transfer mode. Welding flat surfaces requires higher flow than welding grooved materials, since gas disperses more quickly. Faster welding speeds generally require more gas for adequate coverage. Higher current also requires greater flow, and helium generally requires more flow than argon. The four primary variations of GMAW have differing shielding gas flow requirements: for short-circuiting and pulsed spray modes, about 10 L/min (20 ft^3/h) is generally suitable; for globular transfer, around 15 L/min (30 ft^3/h) is preferred; and for spray transfer, 20–25 L/min (40–50 ft^3/h) is typical.

GMAW-based 3-D printing

GMAW has also been used as a low-cost method to 3-D print metal objects. Various open-source 3-D printers have been developed to use GMAW. Components fabricated from aluminum can compete with traditionally manufactured parts in mechanical strength. By deliberately forming a weak weld on the first layer, GMAW 3-D printed parts can be removed from the substrate with a hammer.

Operation

For most applications, gas metal arc welding is a relatively simple process to learn, requiring no more than a week or two to master basic technique. Even with trained operators, weld quality can fluctuate since it depends on external factors. All GMAW is hazardous, though somewhat less so than some other welding methods, such as shielded metal arc welding.

Technique

The techniques required to weld successfully with GMAW are not complicated, and most individuals can achieve reasonable proficiency in a few weeks with proper training and practice. Because much of the process is automated, GMAW relieves the operator of maintaining a precise arc length and feeding filler metal at the correct rate—tasks that are required in manual processes such as shielded metal arc welding.

Producing a sound weld requires correct gun orientation relative to the joint, as well as a uniform travel rate to ensure adequate penetration and bead buildup. Movement along the joint may also require weaving, especially when welding vertically or overhead. Trainees are advised to watch the trailing edge of the weld puddle, not the arc, to gauge progress.

The orientation of the gun affects how arc energy is directed into the workpieces. Ideally, 100% penetration would be achieved, producing a weld stronger than the base materials, but in practice full penetration is not always desirable. Penetration is deepest when the electrode is perpendicular to the surface. In most cases, the gun is angled to bisect the joint. For example, in a 90° fillet joint, a 45° wire angle provides good penetration and filler deposition. In a horizontal lap joint, a shallower angle directs more energy into the lower piece, preventing melting of the upper edge.

The travel (lead) angle is the angle of the gun relative to the direction of travel. It should generally remain near vertical. Most guns are designed so that when the handle is parallel to the work surface, a suitable lead angle results. However, the best angle varies with shielding gas type. With pure argon, the bottom of the torch is often slightly ahead of the top, while with carbon dioxide the opposite is true.

Maintaining a stable contact tip-to-work distance (stick-out) is important. Excessive stick-out may cause the wire to melt too far from the weld, leading to sputtering, shallow penetration, and poor deposition. It may also reduce shielding gas effectiveness, allowing contamination and porosity.

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Further developments in welding steel with GMAW led to a variation known as short-circuit transfer (SCT) or short-arc GMAW, in which the current is lower than for the globular method. As a result of the lower current, the heat input for the short-arc variation is considerably reduced, making it possible to weld thinner materials while decreasing distortion and residual stress in the weld area. As in globular welding, molten droplets form on the tip of the electrode, but instead of dropping to the weld pool, they bridge the gap between the electrode and the weld pool as a result of the lower wire feed rate. This causes a short circuit and extinguishes the arc, but it is quickly reignited after the surface tension of the weld pool pulls the molten metal bead off the electrode tip. This process is repeated about 100 times per second, making the arc appear constant to the human eye. This type of metal transfer provides better weld quality and less spatter than the globular variation, and allows for welding in all positions, albeit with slower deposition of weld material. Setting the weld process parameters (volts, amps, and wire feed rate) within a relatively narrow band is critical to maintaining a stable arc: generally between 100 and 200 amperes at 17 to 22 volts for most applications. However, short-arc transfer can result in lack of fusion and insufficient penetration when welding thicker materials, due to the lower arc energy and rapidly freezing weld pool. Like the globular variation, it can only be used on ferrous metals.

Cold metal transfer

For thin materials, cold metal transfer (CMT) is used by reducing the current when a short circuit is registered, producing many drops per second. CMT can be used for aluminum.

Spray

Spray transfer GMAW was the first metal transfer method used in GMAW, and is well-suited to welding aluminium and stainless steel while employing an inert shielding gas. In this process, the weld electrode metal is rapidly passed along the stable electric arc from the electrode to the workpiece, essentially eliminating spatter and resulting in a high-quality weld finish. As the current and voltage increase beyond the range of short-circuit transfer, the weld electrode metal transfer transitions from larger globules through small droplets to a vaporized stream at the highest energies. Since this vaporized spray transfer variation requires higher voltage and current, and produces a larger weld pool, it is generally used only on workpieces thicker than about 6.4 mm (0.25 in).

Because of the large weld pool, spray transfer is often limited to flat and horizontal welding positions, and sometimes vertical-down welds. It is generally not practical for root pass welds. When a smaller electrode is used with lower heat input, its versatility increases. The maximum deposition rate for spray arc GMAW is relatively high—about 600 mm/s (1500 in/min).

Pulsed-spray

A variation of the spray transfer mode, pulsed-spray is based on the principles of spray transfer but uses a pulsing current to melt the filler wire and allow one small molten droplet to fall with each pulse. The pulses allow the average current to be lower, decreasing the overall heat input and thereby reducing the size of the weld pool and heat-affected zone, making it possible to weld thin workpieces. The pulse provides a stable arc and no spatter, since no short-circuiting takes place. This also makes the process suitable for nearly all metals, and thicker electrode wire can be used as well. The smaller weld pool gives the variation greater versatility, making it possible to weld in all positions.

In comparison with short-arc GMAW, pulsed-spray has a somewhat slower maximum speed (85 mm/s or 200 in/min) and requires that the shielding gas be primarily argon with a low carbon dioxide concentration. Additionally, it requires a special power source capable of providing current pulses with a frequency between 30 and 400 pulses per second. However, the method has gained popularity, since it requires lower heat input and can be used to weld thin workpieces as well as nonferrous materials.

Comparison with flux-cored wire-fed arc welding

Flux-cored, **self-shielding**, or **gasless** wire-fed welding was developed for simplicity and portability. This avoids the gas system of conventional GMAW and uses a cored wire containing a solid flux. The flux vaporizes during welding and produces a plume of shielding gas. Although described as a “flux,” this compound has little activity and acts mostly as an inert shield. The wire is of slightly larger diameter than for a comparable gas-shielded weld, to allow room for the flux. The smallest available is 0.8 mm diameter, compared to 0.6 mm for solid wire. The shield vapor is slightly active, rather than inert, so the process is always MAG (active gas shield) but not MIG (inert gas shield). This limits the process to steel and not aluminium.

These gasless machines operate as DCEN, rather than the DCEP usually used for GMAW solid wire. DCEP, or DC Electrode Positive, makes the welding wire the positively charged anode, which is the hotter side of the arc. Provided that it is switchable from DCEN to DCEP, a gas-shielded wire-feed machine may also be used for flux-cored wire.

Flux-cored wire has advantages for outdoor welding on-site, as the shielding gas plume is less likely to be blown away by wind than shield gas from a conventional nozzle. A drawback is that, like SMAW (stick) welding, there may be some flux deposited over the weld bead, requiring cleaning between passes.

Flux-cored welding machines are popular at the hobbyist level, as the machines are slightly simpler and avoid the cost of providing shield gas, either through a rented cylinder or with the high cost of disposable cylinders.

Gas Tungsten Arc Welding

Gas tungsten arc welding (**GTAW**, also known as **tungsten inert gas welding** or **TIG**, **tungsten argon gas welding** or **TAG**, and **heliarc welding** when helium is used) is an arc welding process that uses a non-consumable tungsten electrode to produce the weld. The weld area and electrode are protected from oxidation or other atmospheric contamination by an inert shielding gas (argon or helium). A filler metal is normally used, though some welds, known as autogenous welds or fusion welds, do not require it. A constant-current welding power supply produces electrical energy, which is conducted across the arc through a column of highly ionized gas and metal vapors known as a plasma.

The process grants the operator greater control over the weld than competing processes such as shielded metal arc welding and gas metal arc welding, allowing stronger, higher-quality welds. However, TIG welding is comparatively more complex and difficult to master, and furthermore, it is significantly slower than most other welding techniques.

TIG welding is most commonly used to weld thin sections of stainless steel and non-ferrous metals such as aluminium, magnesium, and copper alloys.

A related process, plasma arc welding, uses a slightly different welding torch to create a more focused welding arc and as a result is often automated.

Development

After the discovery of the short pulsed electric arc in 1801 by Humphry Davy and of the continuous electric arc in 1802 by Vasily Petrov, arc welding developed slowly. C. L. Coffin had the idea of welding in an inert gas atmosphere in 1890, but even in the early 20th century, welding non-ferrous materials such as aluminum and magnesium remained difficult because these metals react rapidly with the air, resulting in porous, dross-filled welds. Processes using flux-covered electrodes did not satisfactorily protect the weld area from contamination. To solve the problem, bottled inert gases were used in the beginning of the 1930s. A few years later, a direct current, gas-shielded welding process emerged in the aircraft industry for welding magnesium.

In the early 1940s, Northrop Aircraft was developing an experimental aircraft from magnesium designated XP-56, for which Vladimir Pavlecka, Tom Piper, and Russell Meredith developed a welding process named Heliarc because it used a tungsten electrode arc and helium as a shielding gas (the torch design was patented by Meredith in 1941). It is now often referred to as tungsten inert gas welding (TIG), especially in Europe, but the American Welding Society's official term is gas tungsten arc welding (GTAW). Linde Air Products developed a wide range of air-cooled and water-cooled torches, gas lenses to improve shielding, and other accessories that increased the use of the process. Initially, the electrode overheated quickly and, despite tungsten's high melting temperature, particles of tungsten were transferred to the weld. To address this problem, the polarity of the electrode was changed from positive to negative, but the change made it unsuitable for welding many non-ferrous materials. Finally, the development of alternating current units made it possible to stabilize the arc and produce high-quality aluminum and magnesium welds.

Developments continued during the following decades. Linde developed water-cooled torches that helped prevent overheating when welding with high currents. During the 1950s, as the process continued to gain popularity, some users turned to carbon dioxide as an alternative to the more expensive welding atmospheres consisting of argon and helium, but this proved unacceptable for welding aluminum and magnesium because it reduced weld quality, so it is rarely used with GTAW today. The use of any shielding gas containing an oxygen compound, such as carbon dioxide, quickly contaminates the tungsten electrode, making it unsuitable for the TIG process.

In 1953, a new process based on GTAW was developed, called plasma arc welding. It affords greater control and improves weld quality by using a nozzle to focus the electric arc, but is largely limited to automated systems, whereas GTAW remains primarily a manual, hand-held method. Development within the GTAW process has continued as well, and today a number of variations exist. Among the most popular are the pulsed-current, manual programmed, hot-wire, dabber, and increased penetration GTAW methods.

Operation

Manual gas tungsten arc welding is a relatively difficult welding method, due to the coordination required by the welder. Similar to torch welding, GTAW normally requires two hands, since most applications require that the welder manually feed a filler metal into the weld area with one hand while manipulating the welding torch in the other. Maintaining a short arc length, while preventing contact between the tungsten electrode and the workpiece, is also important.

To strike the welding arc, a high-frequency generator (similar to a Tesla coil) provides an electric spark. This spark is a conductive path for the welding current through the shielding gas and allows the arc to be initiated while the electrode and the workpiece are separated, typically about 1.5–3 mm (0.06–0.12 in) apart.

Once the arc is struck, the welder moves the torch in a small circle to create a welding pool, the size of which depends on the size of the electrode and the amount of current. While maintaining a constant separation between the electrode and the workpiece, the operator then moves the torch back slightly and tilts it backward about 10–15 degrees from vertical. Filler metal is added manually to the front end of the weld pool as it is needed.

Welders often develop a technique of rapidly alternating between moving the torch forward (to advance the weld pool) and adding filler metal. The filler rod is withdrawn from the weld pool each time the electrode advances, but it is always kept inside the gas shield to prevent oxidation of its surface and contamination of the weld. Filler rods composed of metals with a low melting temperature, such as aluminum, require that the operator maintain some distance from the arc while staying inside the gas shield. If held too close to the arc, the filler rod can melt before it makes contact with the weld puddle. As the weld nears completion, the arc current is often gradually reduced to allow the weld crater to solidify and prevent the formation of crater cracks at the end of the weld.

The physics of GTAW involves several complex processes, including thermodynamics, plasma physics, and fluid dynamics. The non-consumable tungsten electrode can be operated as a cathode or anode and is used to produce an electric arc between the electrode and the workpiece. In order to initially create the arc, the welding area is flooded with inert gas and a high strike voltage (typically 1 kV per 1 mm) is generated by the welding machine to overcome the electric resistivity of the atmosphere surrounding the welding area. With the arc established, the voltage is lowered and current flows between the workpiece and electrode. Despite the high temperatures of this electric arc, the main heat transfer mechanism in GTAW is joule heating resulting from this current flow.

Safety

Welders wear protective clothing, including light and thin leather gloves and protective long sleeve shirts with high collars, to avoid exposure to strong ultraviolet light. Due to the absence of smoke in GTAW, the electric arc light is not covered by fumes and particulate matter as in stick welding or shielded metal arc welding, and thus is much brighter, subjecting operators to strong ultraviolet light. Potential arc light damage includes accidental flashes to the eye (arc eye) and skin damage similar to severe sunburn. Operators wear opaque helmets with dark eye lenses and full head and neck coverage to prevent this exposure. Modern helmets often feature a liquid crystal-type face plate that self-darkens upon exposure to the bright light of the arc. Translucent welding curtains, made of strongly colored polyvinyl chloride plastic film, are often used to shield nearby workers and bystanders from UV exposure.

Welders are also often exposed to dangerous gases and particulate matter. While the process does not produce smoke, the brightness of the arc in GTAW can break down surrounding air to form ozone and nitric oxides. These react with lung tissue and moisture to create nitric acid and ozone burn. Exposure levels are moderate, but duration, repetition, and ventilation quality must be monitored. Unsafe practices can lead to emphysema and pulmonary oedema. Additionally, the heat from the arc can cause poisonous fumes to form from cleaning and degreasing agents. Such cleaning operations should not be performed near welding, and proper ventilation is essential.

Applications

The aerospace industry is one of the primary users of GTAW, but the process is widely applied elsewhere. Many industries use GTAW for welding thin workpieces, especially nonferrous metals. It is used extensively in the manufacture of space vehicles and is frequently employed to weld small-diameter, thin-wall tubing such as that used in the bicycle industry. GTAW is also used to make root or first-pass welds for piping of various sizes. In maintenance and repair work, the process is commonly used to repair tools and dies, especially components made of aluminum and magnesium. Because the weld metal is not transferred directly across the arc, a wide variety of filler metals can be used. This flexibility allows welding of many alloys in diverse configurations. GTAW welds are highly resistant to corrosion and cracking, making the process ideal for critical applications such as sealing spent nuclear fuel canisters before burial.

Quality

Gas tungsten arc welding, because it affords greater control over the weld area than other welding processes, can produce high-quality welds when performed by skilled operators. Maximum weld quality is assured by maintaining cleanliness—all equipment and materials must be free from oil, moisture, dirt, and other impurities, as these cause weld porosity and reduce strength. Oil and grease can be removed with alcohol or similar solvents, while oxides on metals like aluminum can be removed with a stainless steel wire brush or chemical process. Rust on steels can be removed by grit blasting followed by brushing. These steps are especially important when negative polarity direct current is used, since it provides no cleaning action during welding, unlike positive polarity DC or AC. To maintain a clean weld pool, shielding gas flow must be sufficient and consistent. GTAW in windy or drafty environments requires more shielding gas, increasing cost and making the process less suitable outdoors.

The level of heat input also affects weld quality. Low heat input, caused by low welding current or high welding speed, can limit penetration and cause the weld bead to lift away from the surface. Excessive heat input, however, can widen the weld bead and increase the risk of excessive penetration and spatter. If the welding torch is too far from the workpiece, the shielding gas becomes ineffective, causing porosity within the weld. This results in a weld with pinholes, which is weaker than a typical weld.

If the amount of current used exceeds the capability of the electrode, tungsten inclusions in the weld may result. Known as tungsten spitting, this can be identified with radiography and can be prevented by changing the type of electrode or increasing the electrode diameter. In addition, if the electrode is not well protected by the gas shield or the operator accidentally allows it to contact the molten metal, it can become dirty or contaminated. This often causes the welding arc to become unstable, requiring that the electrode be ground with a diamond abrasive to remove the impurity.

Equipment

The equipment required for the gas tungsten arc welding operation includes a welding torch utilizing a non-consumable tungsten electrode, a constant-current welding power supply, and a shielding gas source.

Welding torch

GTAW welding torches are designed for either automatic or manual operation and are equipped with cooling systems using air or water. The automatic and manual torches are similar in construction, but the manual torch has a handle while the automatic torch normally comes with a mounting rack. The angle between the centerline of the handle and the centerline of the tungsten electrode, known as the head angle, can be varied on some manual torches according to the preference of the operator. Air cooling systems are most often used for low-current operations (up to about 200 A), while water cooling is required for high-current welding (up to about 600 A). The torches are connected with cables to the power supply and with hoses to the shielding gas source and, where used, the water supply.

The internal metal parts of a torch are made of hard alloys of copper or brass so they can transmit current and heat effectively. The tungsten electrode must be held firmly in the center of the torch with an appropriately sized collet, and ports around the electrode provide a constant flow of shielding gas. Collets are sized according to the diameter of the tungsten electrode they hold. The body of the torch is made of heat-resistant, insulating plastics covering the metal components, providing insulation from heat and electricity to protect the welder.

The size of the welding torch nozzle depends on the amount of shielded area desired. The size of the gas nozzle depends upon the diameter of the electrode, the joint configuration, and the availability of access to the joint by the welder. The inside diameter of the nozzle is preferably at least three times the diameter of the electrode, but there are no hard rules. The welder judges the effectiveness of the shielding and increases the nozzle size to increase the area protected by the external gas shield as needed. The nozzle must be heat resistant and is normally made of alumina or a ceramic material, but fused quartz, a high-purity glass, offers greater visibility. Devices can be inserted into the nozzle for special applications, such as gas lenses or valves to improve shielding gas flow and reduce turbulence. Hand switches to control welding current can also be added to manual GTAW torches.

Power supply

Gas tungsten arc welding uses a constant current power source, meaning that the current (and thus the heat flux) remains relatively constant, even if the arc distance and voltage change. This is important because most applications of GTAW are manual or semiautomatic, requiring that an operator hold the torch. Maintaining a suitably steady arc distance is difficult if a constant voltage power source is used instead, since it can cause dramatic heat variations and make welding more difficult.

The preferred polarity of the GTAW system depends largely on the type of metal being welded. Direct current with a negatively charged electrode (DCEN) is often employed when welding steels, nickel, titanium, and other metals. It can also be used in automatic GTAW of aluminum or magnesium when helium is used as a shielding gas. The negatively charged electrode generates heat by emitting electrons, which travel across the arc, causing thermal ionization of the shielding gas and increasing the temperature of the base material. The ionized shielding gas flows toward the electrode, not the base material, and this can allow oxides to build on the surface of the weld.

Direct current with a positively charged electrode (DCEP) is less common, and is used primarily for shallow welds since less heat is generated in the base material. Instead of flowing from the electrode to the base material, as in DCEN, electrons go the other direction, causing the electrode to reach very high temperatures. To help it maintain its shape and prevent softening, a larger electrode is often used. As the electrons flow toward the electrode, ionized shielding gas flows back toward the base material, cleaning the weld by removing oxides and other impurities and thereby improving its quality and appearance.

Alternating current, commonly used when welding aluminum and magnesium manually or semi-automatically, combines the two direct currents by making the electrode and base material alternate between positive and negative charge. This causes the electron flow to switch directions constantly, preventing the tungsten electrode from overheating while maintaining the heat in the base material. Surface oxides are still removed during the electrode-positive portion of the cycle, and the base metal is heated more deeply during the electrode-negative portion. Some power supplies enable operators to use an unbalanced alternating current wave by modifying the exact percentage of time that the current spends in each state of polarity, giving them more control over the amount of heat and cleaning action supplied by the power source. In addition, operators must be wary of rectification, in which the arc fails to reignite as it passes from straight polarity (negative electrode) to reverse polarity (positive electrode). To remedy the problem, a square wave power supply can be used, as can high-frequency to encourage arc stability.

Electrode

The electrode used in GTAW is made of tungsten or a tungsten alloy, because tungsten has the highest melting temperature among pure metals, at 3,422 °C (6,192 °F). As a result, the electrode is not consumed during welding, though some erosion (called burn-off) can occur. Electrodes can have either a clean finish or a ground finish—clean finish electrodes have been chemically cleaned, while ground finish electrodes have been ground to a uniform size and have a polished surface, making them optimal for heat conduction. The diameter of the electrode can vary between 0.5 and 6.4 millimetres (0.02 and 0.25 in), and their length can range from 75 to 610 millimetres (3.0 to 24.0 in).

A number of tungsten alloys have been standardized by the International Organization for Standardization and the American Welding Society in ISO 6848 and AWS A5.12, respectively, for use in GTAW electrodes, and are summarized below:

- **Pure tungsten electrodes** (WP or EWP): General purpose, low cost, poor heat resistance and electron emission. Limited use in AC welding of magnesium and aluminum.
- **Thorium oxide (thoria) alloy electrodes**: Excellent arc performance and starting, popular general purpose electrodes. However, thorium is radioactive, creating health and environmental risks.
- **Cerium oxide (ceria) alloy electrodes**: Improve arc stability and ease of starting while decreasing burn-off. Less effective than thorium but non-radioactive.
- **Lanthanum oxide (lanthana) alloy electrodes**: Similar benefits to cerium, also non-radioactive.
- **Zirconium oxide (zirconia) alloy electrodes**: Increase current capacity, improve arc stability and starting, and extend electrode life.

Filler metals are also used in nearly all applications of GTAW, except for welding very thin materials. Filler metals are available in different diameters and materials. Typically, filler rods are added manually to the weld pool, but some applications use automatically fed filler metals stored on spools or coils.

Shielding gas

As with other welding processes such as gas metal arc welding, shielding gases are necessary in GTAW to protect the welding area from atmospheric gases such as nitrogen and oxygen, which can cause fusion defects, porosity, and weld metal embrittlement. The gas also transfers heat from the tungsten electrode to the metal and helps start and maintain a stable arc.

The selection of shielding gas depends on the material, joint design, and desired weld appearance:

- **Argon**: Most common, prevents arc length defects, produces high weld quality and good appearance, especially with AC.
- **Helium**: Increases penetration and welding speed, useful for high-conductivity metals like copper and aluminum. Disadvantage: harder arc starting and variable quality.
- **Argon-helium mixtures**: Combine benefits, often 75%+ helium with argon balance. Improve AC welding of aluminum and arc striking.
- **Argon-hydrogen mixtures**: Used in mechanized welding of light gauge stainless steel. Limited use due to porosity risks.
- **Argon-nitrogen mixtures**: Sometimes used to stabilize austenite in stainless steels and increase penetration in copper. Limited use in ferritic steels due to porosity.

Materials

GTAW is most commonly used to weld stainless steel and nonferrous materials such as aluminum and magnesium, but it can be applied to nearly all metals, with the notable exception of zinc and its alloys. Applications involving carbon steels are limited not by process restrictions but by the availability of more economical techniques such as gas metal arc welding and shielded metal arc welding. GTAW can also be performed in a variety of positions, depending on the welder’s skill and the material.

Aluminum and magnesium

Aluminum and magnesium are most often welded using alternating current, though direct current is also possible depending on desired properties. Before welding, the work area should be cleaned and may be preheated to 175–200 °C (347–392 °F) for aluminum or up to 150 °C (302 °F) for thick magnesium to improve penetration and travel speed. AC provides a self-cleaning effect, removing the refractory aluminum oxide layer that forms quickly in air. Pure tungsten or zirconiated tungsten electrodes are preferred for AC welding, as thoriated electrodes are more likely to spit particles into the weld. Blunt electrode tips are preferred, and pure argon shielding gas is recommended for thin workpieces. Adding helium improves penetration in thicker workpieces but makes arc starting more difficult.

Direct current can also be used:

- **DCEN (negative electrode)**: Provides high penetration. Argon is common, with helium-rich gases for thicker materials. Thoriated electrodes are suitable.
- **DCEP (positive electrode)**: Used for shallow welds, especially joints under 1.6 mm (0.063 in). Thoriated tungsten electrodes with pure argon shielding are common.

Steels

For GTAW of carbon and stainless steels, the selection of filler material is important to prevent excessive porosity. Oxides on the filler material and workpieces must be removed before welding to prevent contamination, and immediately prior to welding, alcohol or acetone should be used to clean the surface. Preheating is generally not necessary for mild steels less than one inch thick, but low alloy steels may require preheating to slow the cooling process and prevent the formation of martensite in the heat-affected zone. Tool steels should also be preheated to prevent cracking in the heat-affected zone.

Austenitic stainless steels do not require preheating, but martensitic and ferritic chromium stainless steels do. A DCEN power source is normally used, and thoriated electrodes, tapered to a sharp point, are recommended. Pure argon is used for thin workpieces, but helium can be introduced as thickness increases.

Dissimilar metals

Welding dissimilar metals often introduces new difficulties to GTAW welding, because most materials do not easily fuse to form a strong bond. However, welds of dissimilar materials have numerous applications in manufacturing, repair work, and the prevention of corrosion and oxidation. In some joints, a compatible filler metal is chosen to help form the bond, and this filler metal can be the same as one of the base materials (for example, using a stainless steel filler metal with stainless steel and carbon steel as base materials), or a different metal (such as the use of a nickel filler metal for joining steel and cast iron). Very different materials may be coated or "buttered" with a material compatible with a particular filler metal, and then welded. In addition, GTAW can be used in cladding or overlaying dissimilar materials.

When welding dissimilar metals, the joint must have an accurate fit, with proper gap dimensions and bevel angles. Care should be taken to avoid melting excessive base material. Pulsed current is particularly useful for these applications, as it helps limit the heat input. The filler metal should be added quickly, and a large weld pool should be avoided to prevent dilution of the base materials.

Process variations

Pulsed-current

In the pulsed-current mode, the welding current rapidly alternates between two levels. The higher current state is known as the pulse current, while the lower current level is called the background current. During the period of pulse current, the weld area is heated and fusion occurs. Upon dropping to the background current, the weld area is allowed to cool and solidify. Pulsed-current GTAW has a number of advantages, including lower heat input and consequently a reduction in distortion and warpage in thin workpieces. In addition, it allows for greater control of the weld pool, and can increase weld penetration, welding speed, and quality. A similar method, manual programmed GTAW, allows the operator to program a specific rate and magnitude of current variations, making it useful for specialized applications.

Dabber

The dabber variation is used to precisely place weld metal on thin edges. The automatic process replicates the motions of manual welding by feeding a cold or hot filler wire into the weld area and dabbing (or oscillating) it into the welding arc. It can be used in conjunction with pulsed current, and is used to weld a variety of alloys, including titanium, nickel, and tool steels. Common applications include rebuilding seals in jet engines and building up saw blades, milling cutters, drill bits, and mower blades.

Submerged Arc Welding

Submerged arc welding (**SAW**) is a common arc welding process. The first SAW patent was taken out in 1935. The process requires a continuously fed consumable solid or tubular (metal cored) electrode. The molten weld and the arc zone are protected from atmospheric contamination by being "submerged" under a blanket of granular fusible flux consisting of lime, silica, manganese oxide, calcium fluoride, and other compounds. When molten, the flux becomes conductive and provides a current path between the electrode and the work. This thick layer of flux completely covers the molten metal, preventing spatter and sparks as well as suppressing the intense ultraviolet radiation and fumes that are a part of the shielded metal arc welding (SMAW) process.

SAW is normally operated in the automatic or mechanized mode; however, semi-automatic (hand-held) SAW guns with pressurized or gravity flux feed delivery are available. The process is normally limited to the flat or horizontal-fillet welding positions (although horizontal groove position welds have been done with special arrangements to support the flux). Deposition rates approaching **45 kg/h (100 lb/h)** have been reported — compared to ~5 kg/h (10 lb/h) for SMAW. Although currents ranging from 300 to 2000 A are commonly utilized, currents of up to 5000 A have also been used (multiple arcs).

Single or multiple (2 to 5) electrode wire variations of the process exist. SAW strip-cladding utilizes a flat strip electrode (e.g., 60 mm wide × 0.5 mm thick). DC or AC power can be used, and combinations of DC and AC are common on multiple electrode systems. Constant voltage welding power supplies are most commonly used; however, constant current systems in combination with a voltage-sensing wire feeder are available.

Features

Welding head

The welding head feeds flux and filler metal to the joint. The electrode (filler metal) is energized here.

Flux hopper

The flux hopper stores the flux and controls the rate of flux deposition on the welding joint.

Flux

The granulated flux shields and protects molten weld metal from atmospheric contamination. The flux cleans the weld metal and can also modify its chemical composition. It is granulated to a definite size and may be fused, bonded, or mechanically mixed. Flux may consist of fluorides of calcium and oxides of calcium, magnesium, silicon, aluminium, and manganese compounds. Alloying elements may be added as required. Substances that release large amounts of gas during welding are never mixed with flux. Fine particle flux is recommended for thinner materials, while coarser flux is used for heavier sections.

Electrode

SAW filler material is usually a standard wire, though other forms exist. Wire thickness typically ranges from 1.6 mm to 6 mm (1/16 in. to 1/4 in.). In some cases, twisted wire is used to give the arc an oscillating movement, helping fuse the weld toe to the base metal. The electrode composition depends on the material being welded, and alloying elements may be added. Electrodes are available for mild steels, high carbon steels, low and special alloy steels, stainless steel, and some nonferrous metals such as copper and nickel. Electrodes are generally copper-coated to prevent rusting and to increase electrical conductivity. They are available in straight lengths and coils, with diameters of 1.6, 2.0, 2.4, 3.0, 4.0, 4.8, and 6.4 mm. Approximate current ranges: 150–350 A for 1.6 mm, 250–800 A for 3.2 mm, and 650–1350 A for 6.4 mm electrodes.

Welding Operation

During welding, flux is deposited on the joint. Since cold flux is not electrically conductive, the arc may be struck by touching the electrode to the workpiece, by placing steel wool between electrode and job before switching on the current, or by using a high-frequency unit. In all cases, the arc is struck under a cover of flux. Once melted by the arc, the flux becomes highly conductive, maintaining current flow between electrode and workpiece. The upper portion of the flux, in contact with the atmosphere, remains granular and can be reused. The lower, melted flux solidifies into slag, which must be removed after welding.
The electrode is continuously fed to the joint to be welded at a predetermined speed. In semi-automatic welding sets, the welding head is moved manually along the joint. In automatic welding, a separate drive moves either the welding head over the stationary job or the job moves/rotates under the stationary welding head.

The arc length is kept constant by using the principle of a self-adjusting arc. If the arc length decreases, arc voltage will increase, arc current and therefore burn-off rate will increase, thereby causing the arc to lengthen. The reverse occurs if the arc length increases more than normal.

A backing plate of steel or copper may be used to control penetration and to support large amounts of molten metal associated with the process.

Key SAW process variables

- Wire feed speed (main factor in welding current control)
- Arc voltage
- Travel speed
- Electrode stick-out (ESO) or contact tip to work (CTTW)
- Polarity and current type (AC or DC) and variable balance AC current

Material applications

- Carbon steels (structural and vessel construction)
- Low alloy steels
- Stainless steels
- Nickel-based alloys
- Surfacing applications (wear-facing, build-up, and corrosion-resistant overlay of steels)

Advantages

- High deposition rates (over 45 kg/h or 100 lb/h have been reported).
- High operating factors in mechanized applications.
- Deep weld penetration.
- Sound welds are readily made with good process design and control.
- High-speed welding of thin sheet steels up to 5 m/min (16 ft/min) is possible.
- Welding fumes and arc flash are eliminated or minimized.
- Minimal edge preparation required depending on joint configuration and penetration needs.
- Suitable for both indoor and outdoor works.
- Welds produced are sound, uniform, ductile, corrosion-resistant, and have good impact value.
- Single-pass welds can be made in thick plates with normal equipment.
- The arc is always covered under a blanket of flux, eliminating spatter.
- 50% to 90% of the flux is recoverable, recycled, and reused.

Limitations

- Limited to ferrous (steel or stainless steels) and some nickel-based alloys.
- Normally limited to the 1F, 1G, and 2F positions.
- Generally restricted to long straight seams or rotated pipes/vessels.
- Requires relatively complex flux handling systems.
- Flux and slag residue can present health and safety concerns.
- Requires inter-pass and post-weld slag removal.
- Requires backing strips for proper root penetration.
- Limited to high-thickness materials.

Electron-Beam Welding (EBW)

Electron-beam welding (EBW) is a **fusion welding** process in which a beam of high-velocity electrons is applied to two materials to be joined. The workpieces melt and flow together as the kinetic energy of the electrons is transformed into heat upon impact. EBW is often performed under vacuum conditions to prevent dissipation of the electron beam.

History

Electron-beam welding was developed by German physicist Karl-Heinz Steigerwald in 1949, who was working on electron-beam applications. He conceived and developed the first practical electron-beam welding machine, which began operation in 1958. American inventor James T. Russell was also credited with designing and building the first electron-beam welder.

Physics

Electrons are elementary particles with mass $m = 9.1 \times 10^{-31}$ kg and charge $e = -1.6 \times 10^{-19}$ C. They exist either bound to an atomic nucleus, as conduction electrons in the crystal lattice of metals, or as free electrons in vacuum.

Free electrons in vacuum can be accelerated and controlled by electric and magnetic fields, forming beams of high kinetic energy. Upon collision with atoms in solids, their kinetic energy transforms into heat. EBW provides excellent welding conditions because it involves:

- Strong electric fields that accelerate electrons to high speeds, producing beam power equal to current × voltage. By increasing current and voltage, beam power can be raised to very high values.
- Magnetic lenses that shape the beam into a narrow cone and focus it to a small diameter, achieving very high power density on the surface to be welded.
- Penetration depths on the order of hundredths of a millimeter, with volumetric power densities sufficient to raise local temperatures extremely rapidly.

Beam effectiveness depends on the physical properties of the materials being welded, especially their melting and vaporization behavior under low pressure. At moderate power densities, evaporation is negligible, but at higher values the material may vaporize, shifting the process from welding to machining.

Beam Formation

Cathode

Conduction electrons move in the crystal lattice of metals with velocities distributed according to temperature. They cannot leave the metal unless their kinetic energy exceeds the surface potential barrier. The number of electrons able to escape increases exponentially with temperature, following Richardson's rule.

As a source of electrons for EBW, the cathode material must:

- Provide high emission current density at elevated temperature,
- Have low vapor pressure in vacuum,
- Be mechanically stable and chemically resistant to residual gases.

These requirements limit cathode materials to high-melting-point metals such as tantalum and tungsten. Tungsten cathodes can achieve emission current densities of about 100 mA/mm², though only a fraction contributes to beam formation. The most common cathode is a tungsten strip about 0.05 mm thick, with width chosen according to required emission current. For beam powers up to about 2 kW, a width of 0.5 mm is typical.

Acceleration

Electrons emitted from the cathode are low energy, only a few electronvolts (eV). To give them the required speed, they are accelerated by an electric field applied between the emitter and the anode. The accelerating field must also direct the electrons to form a narrow converging bundle around an axis. This can be achieved by an electric field near the cathode with both radial and axial components, forcing the electrons toward the axis. As a result, the electron beam converges to a small diameter in a plane close to the anode.

For practical applications, the power of the electron beam must be controllable. This can be accomplished by another electric field produced by a second cathode negatively charged with respect to the first. At least this part of the electron gun must be evacuated to high vacuum, to prevent cathode damage and electrical discharges.

Focusing

After leaving the anode, the divergent electron beam does not have sufficient power density for welding and must be focused. This is accomplished by a magnetic field produced by electric current in a cylindrical coil.

The focusing effect of a rotationally symmetrical magnetic field on electrons results from the Lorentz force, proportional to the magnetic induction B and electron velocity v. The vector product of the radial component of induction (B_r) and axial velocity (v_a) produces a force perpendicular to both, causing electrons to spiral around the axis. This helical trajectory leads to focusing. Variations in focal length (coil current) also cause slight rotation of the beam cross-section.

Beam deflection system

The beam spot must be precisely positioned with respect to the joint. This is usually accomplished mechanically by moving the workpiece, but sometimes it is preferable to deflect the beam. A system of four coils positioned symmetrically around the gun axis behind the focusing lens produces a magnetic field perpendicular to the axis, allowing beam deflection.

Penetration

Electron penetration

When electrons impact a solid surface, some are reflected (backscattered), while others penetrate and collide with atoms. In inelastic collisions they lose kinetic energy, which is converted into heat. Electrons can travel only a short distance below the surface before losing energy. This distance is proportional to their initial energy and inversely proportional to the density of the solid, typically on the order of hundredths of a millimeter.

Beam penetration

By increasing the beam current, the beam power can be raised to any desired value. By focusing the beam to a small diameter, planar power densities as high as 10^7–10^8 W/mm^2 can be achieved. Because electrons deposit energy in a thin surface layer, the volumetric power density can be extremely high, raising local temperatures at rates of 10^6–10^8 K/s.

Results

The results of beam application depend on several factors:

> 1. **Beam power** – Product of accelerating voltage (kV) and beam current (mA). Controlled by beam current at constant voltage.
> 2. **Power density** – Determined by cathode size, lens quality, beam alignment, accelerating voltage, and focal length.
> 3. **Welding speed** – Adjustable between ~2 and 50 mm/s.
> 4. **Material properties** – Evaporation varies with conditions; at moderate power densities, evaporation is negligible for most metals.
> 5. **Joint geometry** – Shape and dimensions influence weld quality.

The final effect depends on the combination of these parameters:

- Low power density or short exposure melts only a thin surface layer.
- A defocused beam heats by conduction, producing a hemispherical melted zone.
- High power density and low speed produce a deeper, conical melt zone.
- A tightly focused, high-power beam penetrates deeply in proportion to total power.

Welding process

Weldability

For welding thin-walled parts, special welding aids are generally required. These fixtures ensure perfect contact of the parts and prevent movement during welding, and are usually designed individually for each workpiece.

Not all materials can be welded by EBW in vacuum. Materials with high vapor pressure at melting temperature, such as zinc, cadmium, magnesium, and most non-metals, are unsuitable. Another limitation is the change in material properties induced by rapid cooling during welding.

Joining dissimilar materials

Some metal components cannot be welded by melting both materials at the joint if their properties differ significantly. However, it is still possible to create joints that are mechanically compact and vacuum-tight. The principal approach is to melt the material with the lower melting point while the other remains solid. The advantage of electron-beam welding is its ability to localize heating precisely and control the energy input. High vacuum conditions substantially improve results. A general rule is that the part with the lower melting point should be directly accessible to the beam.

Local vacuum

Local vacuum systems allow workpieces to be welded without enclosing the entire workpiece in a chamber. Instead, a vacuum is established by sealing the chamber to one section of the workpiece, welding that section, and then moving the chamber or workpiece to additional sections until the weld is complete. This method enables welding of thick materials in a single pass, with minimal shrinkage and fewer flaws. Welds avoid oxide or nitride contamination, retain strength better, and require less non-destructive examination (NDE).

Challenges

If the melted material shrinks during cooling, cracking, deformation, and shape changes may occur. Butt welds of two plates may bend because more material melts at the head than at the root, though this effect is less severe than in arc welding. Cracks may also appear if both parts are rigid, as weld shrinkage can produce high stresses that fracture brittle materials.

Equipment

Many types of EBW machines exist, differing in construction, chamber volume, manipulators, and beam power. Electron guns can supply beams from a few watts to over 100 kW. Both micro-welds of tiny components and deep welds up to 300 mm are possible. Vacuum chamber volumes range from a few liters to hundreds of cubic meters.

The major EBW components are:

- Electron gun (beam generator)
- Vacuum chamber
- Workpiece manipulator
- Power supply
- Control and monitoring electronics

Electron gun

Emitter
The electron gun generates, accelerates, and focuses the beam. Free electrons are produced by thermo-emission from a hot metal strap or wire.

Accelerator
Electrons are accelerated and formed into a narrow beam by an electric field between three electrodes: the emitter, the cathode (connected to the negative pole of the high-voltage supply), and the anode. A third control electrode (Wehnelt) is negatively charged relative to the cathode, regulating the beam current. After passing the anode opening, electrons move at constant speed in a slightly divergent cone.

Focuser
The divergent beam is focused by a magnetic coil (focusing lens). The beam must be aligned with the optical axes of the accelerating and focusing lenses. This is achieved by a correction system of two pairs of coils, whose currents are adjusted to produce the required field.

Deflector
After focusing, the beam can be applied directly or deflected by a deflection system. Two pairs of coils (for x and y directions) provide static or dynamic deflection. Static deflection allows precise positioning, while dynamic deflection (computer-controlled) enables applications beyond welding, such as surface hardening, annealing, imaging, and engraving.

Working chamber

Welding typically takes place in a vacuum chamber, either high or low vacuum, though some systems operate without a chamber. Chamber volumes range from a few liters to hundreds of cubic meters.

Workpiece manipulator

Electron-beam welding cannot be hand-manipulated due to strong X-radiation. Relative motion between beam and workpiece is achieved by rotating or moving the workpiece or the beam.

Power supply

EBW equipment requires a high-voltage power supply, with accelerating voltages ranging from tens to hundreds of kilovolts. Higher voltages increase technical challenges and cost. Additional supplies provide low-voltage current for cathode heating, negative voltage for the control electrode, and low-voltage power for correction, focusing, and deflection systems.

Control and monitoring

Electronics control the manipulator, monitor the welding process, and adjust voltages for specific applications.

Applications

Reactor pressure vessels

EBW has been applied to welding reactor pressure vessels for small modular reactors, with significant savings in time and cost compared to arc welding. Materials up to substantial thickness can be welded in a single pass, with minimal shrinkage, fewer flaws, and less NDE required.

Wind turbine

Offshore wind turbines require extensive welding hours. Local vacuum EBW can replace conventional methods at lower cost and time, with improved weld quality.

Laser Beam Welding

Laser beam welding (LBW) is a welding technique used to join metals or thermoplastics using a laser. The concentrated heat source enables narrow, deep welds and high welding rates. It is widely applied in high-volume, precision industries such as automotive and aeronautics, typically in keyhole or penetration mode.

Operation

Like electron-beam welding (EBW), LBW has high power density (~1 MW/cm^2), producing small heat-affected zones and rapid heating/cooling. Spot sizes range from 0.2–13 mm, though only smaller sizes are used for welding. Penetration depends on power and focal point location, maximized when focused slightly below the surface.

Continuous lasers are used for deep welds, while pulsed lasers (millisecond pulses) weld thin materials. LBW can weld carbon steels, HSLA steels, stainless steel, aluminum, and titanium. High cooling rates may cause cracking in high-carbon steels. Weld quality is comparable to EBW. Welding speed depends on power, material type, and thickness. Gas lasers are especially suited for high-volume applications, making LBW dominant in the automotive industry.

Advantages over EBW:

- Laser beam transmitted through air (no vacuum required)
- Easily automated with robotic machinery
- No x-ray generation
- High weld quality

Laser-hybrid welding combines LBW with arc welding (e.g., GMAW), improving positioning flexibility, welding speed, and reducing undercutting.

Equipment

Automation and CAM

Most LBW systems are automated, using computer-aided manufacturing (CAM) based on CAD models. Laser welding can be integrated with milling for finished parts. Open-source projects have also developed cost-effective laser welding systems.

Lasers

- **Solid-state lasers:** Ruby, Nd:glass, and Nd:YAG. Operate at ~1 µm wavelength. Nd:YAG can run in pulsed or continuous mode. Typical power: 10–20 W (ruby), 0.04–6000 W (Nd:YAG). Fiber optics usually deliver the beam.
- **Gas lasers:** Use helium, nitrogen, and CO_2 mixtures. Operate at 10.6 µm (infrared). Require rigid lens/mirror delivery (fiber optics unsuitable). Power up to 25 kW.
- **Fiber lasers:** Use optical fiber as the medium. Power up to 50 kW. Increasingly used in robotic industrial welding.

Laser Beam Delivery

Two main types: (1) traditional systems where the laser output follows the seam (robot-controlled), and (2) remote laser welding, where a laser scanner moves the beam along the seam. Remote welding offers higher speed and precision.

Thermal Modeling of Pulsed-Laser Welding

Pulsed-laser welding offers advantages over continuous wave (CW) welding, including lower porosity and reduced spatter. However, it can cause hot cracking in aluminum alloys. Thermal analysis helps predict parameters such as depth of fusion, cooling rates, and residual stresses. Due to process complexity, a development cycle is required: constructing a mathematical model, calculating thermal cycles using FEM, FDM, or simplified analytical models, and validating results experimentally.

General methodology:

> 1. Determine power absorption efficiency.
> 2. Calculate recoil pressure using the Clausius-Clapeyron relation.
> 3. Compute fluid flow velocities with the Volume of Fluid (VOF) method.
> 4. Calculate temperature distribution.
> 5. Increment time and repeat steps 1–4.
> 6. Validate results experimentally.

Step 1: Absorption Efficiency

Not all radiant energy is absorbed; some is lost in plasma formation. Absorptivity depends on wavelength, material surface composition, angle of incidence, and temperature. Gaussian energy distribution is often assumed instead of a point source, allowing more accurate modeling of temperature-dependent properties. In keyhole welding, Fresnel reflection enhances absorption due to multiple reflections inside the cavity.

Step 2: Recoil Pressure

Welding occurs in conduction or keyhole mode depending on power density. In keyhole mode, recoil pressure from vaporized metal counteracts gravity and surface tension. Recoil pressure is derived from the Clausius-Clapeyron equation, relating equilibrium vapor pressure to surface temperature and latent heat of vaporization.

Step 3: Fluid Flow

Keyhole profiles require fluid flow analysis. Velocities are determined from momentum equations involving pressure, density, viscosity, thermal expansion, gravity, and fluid fraction within the simulation grid.

Step 4: Temperature Distribution

Boundary temperature at the laser impingement surface is modeled using conduction, convection, and radiation terms. Pulsed welding introduces multiple overlapping thermal cycles, modeled by step functions or time-dependent modifiers applied to the heat flux. Fourier's second law is then solved for internal temperature distribution.

Step 5: Time Increment

Numerical discretization is applied to governing equations, advancing in time and space steps.

Step 6: Validation

Models are validated against experimental data, such as metallographic verification of fusion depth.

Consequences of Simplifying Assumptions

Simplifications (e.g., ignoring temperature dependence of material properties) reduce computation time but may overestimate liquid temperatures if vaporization losses are neglected.

Plasma Arc Welding

Plasma arc welding (PAW) is an arc welding process similar to gas tungsten arc welding (GTAW). The electric arc is formed between an electrode (usually sintered tungsten) and the workpiece. The key difference from GTAW is that in PAW, the electrode is positioned within the body of the torch, so the plasma arc is separated from the shielding gas envelope. The plasma is forced through a fine-bore copper nozzle, which constricts the arc. The plasma exits the orifice at high velocity (approaching the speed of sound) and at temperatures up to 28,000 °C (50,000 °F) or higher.

Arc plasma is a temporary state of gas ionized by electric current, making it conductive. In this state, atoms are broken into electrons (−) and cations (+), forming a mixture of ions, electrons, and excited atoms. The degree of ionization may range from 1% to greater than 100% (double or triple ionization). Plasma jet energy and temperature depend on the electrical power used. A plasma jet torch typically reaches ~28,000 °C, compared to ~5,500 °C in an ordinary welding arc. All welding arcs are plasmas, but PAW uses a constricted arc plasma.

Just as oxy-fuel torches can be used for welding or cutting, plasma torches can also serve both purposes.

Concept

Plasma arc welding produces coalescence by heat from a constricted arc, either between a tungsten electrode and the water-cooled nozzle (non-transferred arc) or between the electrode and the workpiece (transferred arc). Two inert gases are used: one forms the plasma, the other shields it. Filler metal may or may not be added.

History

Plasma arc welding and cutting was invented by Robert M. Gage in 1953 and patented in 1957. It enabled precision cutting and welding of both thin and thick metals, and could also spray-coat hardening metals onto other metals. One application was coating turbine blades of the Saturn V rocket.

Principle of operation

Plasma arc welding is an advanced form of TIG welding. In TIG, an open arc is shielded by argon or helium. In PAW, the arc is constricted by a water-cooled nozzle, while shielding gas is supplied separately. The constricted arc has higher pressure, temperature, and stability, improving heat transfer.

Plasma arcs can be laminar (low pressure/flow) or turbulent (high pressure/flow). Gases used include argon, helium, hydrogen, or mixtures. Laminar flow is preferred in welding to avoid blowing molten metal out of the weld zone.

The non-transferred (pilot) arc initiates the process, formed between the electrode (−) and the constricting nozzle (+). A high-frequency unit starts the arc, after which a low-current pilot arc is maintained. Once the main arc is struck, the nozzle becomes neutral. In micro plasma welding, a continuous pilot arc may be used. The transferred arc has high energy density and velocity, suitable for cutting and welding.

Micro plasma (0.1–10 A): used for foils, bellows, and thin sheets; usually autogenous, without filler.

Medium plasma (10–100 A): used for plates up to 6 mm thick, with or without filler; also for hardfacing using powder feeders.

High-current plasma (>100 A): used with filler wires at high travel speeds.

Other applications include plasma cutting, heating, deposition of diamond films, metallurgy, plasma spraying, and underwater cutting.

Equipment

Essential equipment for PAW includes:

- **Current and gas decay control**: Ensures proper keyhole closure when terminating welds.
- **Fixture**: Prevents atmospheric contamination of molten metal.
- **Materials**: Suitable for steel, aluminium, and others.
- **High-frequency generator and resistors**: Used for arc ignition.
- **Plasma torch**: For transferred or non-transferred arcs; usually automated; water-cooled to extend nozzle and electrode life.
- **Power supply**: A DC source (generator or rectifier) with drooping characteristics and open-circuit voltage ≥70 V. Rectifiers are preferred. Helium requires higher voltage, which can be achieved by series operation of two sources or by starting with argon and switching to helium.

Typical parameters: Current 50–350 A, voltage 27–31 V, gas flow 2–40 L/min (lower for orifice gas, higher for shielding gas). DCEN is normally used, except for aluminium, where DCEP with a water-cooled electrode is preferable.

- **Shielding gases**: Two inert gases or gas mixtures are employed. The orifice gas at lower pressure and flow rate forms the plasma arc. Its pressure is intentionally kept low to avoid weld metal turbulence, but this low pressure cannot provide proper shielding of the weld pool. To achieve adequate shielding, the same or another inert gas is supplied through the outer shielding ring of the torch at higher flow rates. Most materials can be welded with argon, helium, argon+hydrogen, or argon+helium mixtures. Argon is most common. Helium is preferred where a broad heat input pattern and flatter cover pass are desired without keyhole mode. Argon+hydrogen mixtures provide higher heat energy, enabling keyhole welds in nickel-base alloys, copper-base alloys, and stainless steels.

For cutting, argon+hydrogen (10–30%) or nitrogen may be used. Hydrogen dissociates into atomic form and recombines, generating higher temperatures than argon or helium alone. It also provides a reducing atmosphere, preventing oxidation of the weld and surrounding area. However, hydrogen diffusion into the metal can cause embrittlement in some steels and alloys.

- **Voltage control**: Required in contour welding. In normal keyhole welding, arc length variations up to 1.5 mm do not significantly affect penetration or bead shape, so voltage control is not essential.

Process description

Workpiece cleaning and filler-metal addition are similar to TIG welding. Filler metal is added at the leading edge of the weld pool, but is not required for root-pass welds.

Type of joints: For thicknesses up to 25 mm, square butt, J, or V joints are used. PAW can produce both keyhole and non-keyhole welds.

Non-keyhole welds: Suitable for workpieces ≤2.4 mm thick.

Keyhole welds: Plasma arc welding can produce keyhole welds in materials 2.5–25 mm thick. Proper current, nozzle diameter, and travel speed create a plasma jet that penetrates completely without expelling molten metal. Advantages include rapid penetration of thick root sections, uniform underbeads without backing, and a high depth-to-width ratio, resulting in narrow welds and smaller heat-affected zones. As the weld progresses, base metal ahead of the keyhole melts, flows around, solidifies, and forms the bead. For thicker pieces, filler metal is added while reducing plasma jet force by adjusting orifice gas.

PAW is an advancement over GTAW, using a non-consumable tungsten electrode and a constricted arc through a fine-bore copper nozzle. It can weld all metals weldable by GTAW, though bronze, cast iron, lead, and magnesium are more difficult.

PAW process variations (by current, gas flow, and orifice size):

- Micro-plasma (<15 A)

- Melt-in mode (15–100 A)
- Keyhole mode (>100 A)
- Greater energy concentration than GTAW
- Deep, narrow penetration (12–18 mm depending on material)
- Greater arc stability and tolerance to arc-length changes
- Requires more complex and expensive equipment than GTAW
- Procedures are less tolerant to fit-up variations
- Operator skill required is slightly greater than GTAW
- Orifice replacement is necessary

Process variables

Gases

At least two (sometimes three) gas flows are used in PAW:

- Plasma gas – flows through the orifice and becomes ionized
- Shielding gas – flows through the outer nozzle to protect the weld pool
- Back-purge/trailing gas – used for certain materials and applications

Key process variables

- Current type and polarity: DCEN from a CC source is standard
- AC square-wave is common for aluminum and magnesium
- Welding current: 0.5–1200 A; can be constant or pulsed (up to 20 kHz)
- Gas-flow rate: must be carefully controlled based on current, orifice size, gas mixture, and base material

Other plasma arc processes

Depending on torch design, electrode type, gas composition, and current, several plasma process variations exist:

- Plasma arc cutting (PAC)
- Plasma arc gouging
- Plasma arc surfacing
- Plasma arc spraying

Plasma arc cutting

In cutting, plasma gas flow is increased so the jet penetrates and removes molten material as dross. PAC differs from oxy-fuel cutting: PAC melts metal with the arc, while oxy-fuel oxidizes it and uses exothermic heat. PAC can cut metals forming refractory oxides (stainless steel, cast iron, aluminum, non-ferrous alloys). Since its introduction in 1954, PAC has seen many refinements in process, gases, and equipment.

Ultrasonic Welding

Ultrasonic welding is an industrial process whereby high-frequency ultrasonic acoustic vibrations are locally applied to work pieces being held together under pressure to create a solid-state weld. It is commonly used for plastics and metals, and especially for joining dissimilar materials. In ultrasonic welding, there are no connective bolts, nails, soldering materials, or adhesives necessary to bind the materials together. When used to join metals, the temperature stays well below the melting point of the involved materials, preventing any unwanted properties which may arise from high temperature exposure of the metal.

History

Practical application of ultrasonic welding for rigid plastics was completed in the 1960s. At this point only hard plastics could be welded. The patent for the ultrasonic method for welding rigid thermoplastic parts was awarded to Robert Soloff and Seymour Linsley in 1965. Soloff, the founder of Sonics & Materials Inc., was a lab manager at Branson Instruments where thin plastic films were welded into bags and tubes using ultrasonic probes. He unintentionally moved the probe close to a plastic tape dispenser and observed that the halves of the dispenser welded together. He realized that the probe did not need to be manually moved around the part, but that the ultrasonic energy could travel through and around rigid plastics and weld an entire joint. He went on to develop the first ultrasonic press. The first application of this new technology was in the toy industry.

The first car made entirely out of plastic was assembled using ultrasonic welding in 1969. The automotive industry has used it regularly since the 1980s, and it is now used for a multitude of applications.

Process

For joining complex injection molded thermoplastic parts, ultrasonic welding equipment can be customized to fit the exact specifications of the parts being welded. The parts are sandwiched between a fixed shaped nest (anvil) and a sonotrode (horn) connected to a transducer, and a ~20–70 kHz low-amplitude acoustic vibration is emitted. When welding plastics, the interface of the two parts is specially designed to concentrate the melting process. One of the materials usually has a spiked or rounded energy director which contacts the second plastic part. The ultrasonic energy melts the point contact between the parts, creating a joint. Ultrasonic welding of thermoplastics causes local melting of the plastic due to absorption of vibrational energy along the joint to be welded. In metals, welding occurs due to high-pressure dispersion of surface oxides and local motion of the materials. Although there is heating, it is not enough to melt the base materials.

Ultrasonic welding can be used for both hard and soft plastics, such as semicrystalline plastics, and metals. The understanding of ultrasonic welding has increased with research and testing. The invention of more sophisticated and inexpensive equipment and increased demand for plastic and electronic components has led to a growing knowledge of the fundamental process. However, many aspects of ultrasonic welding still require more study, such as the relationship of weld quality to process parameters.

Scientists from the Institute of Materials Science and Engineering (WKK) of University of Kaiserslautern, with support from the German Research Foundation (Deutsche Forschungsgemeinschaft), have shown that ultrasonic welding can produce highly durable bonds between light metals and carbon-fiber-reinforced polymer (CFRP) sheets.

A benefit of ultrasonic welding is that there is no drying time as with conventional adhesives or solvents, so the workpieces do not need to remain in a fixture for longer than it takes for the weld to cool. The welding can easily be automated, making clean and precise joints; the site of the weld is very clean and rarely requires any touch-up work. The low thermal impact on the materials involved enables a greater number of materials to be welded together. The process is a good automated alternative to glue, screws, or snap-fit designs.

Ultrasonic welding is typically used with small parts (e.g. cell phones, consumer electronics, disposable medical tools, toys, etc.) but it can be used on parts as large as a small automotive instrument cluster. Ultrasonics can also be used to weld metals, but are typically limited to small welds of thin, malleable metals such as aluminum, copper, and nickel. Ultrasonics would not be used in welding the chassis of an automobile or in welding pieces of a bicycle together, due to the power levels required.

Components

All ultrasonic welding systems are composed of the same basic elements:

- A press, usually with a pneumatic or electric drive, to assemble two parts under pressure
- A nest or anvil or fixture where the parts are placed and allowing the high frequency vibration to be directed to the interfaces
- An ultrasonic stack composed of a converter or piezoelectric transducer, an optional booster, and a horn. All three elements of the stack are specifically tuned to resonate at the same ultrasonic frequency (typically 15, 20, 30, 35 or 40 kHz)
    - **Converter**: Converts the electrical signal into a mechanical vibration using the piezoelectric effect.
    - **Booster**: Modifies the amplitude of the vibration mechanically. It is also used in standard systems to clamp the stack in the press.
    - **Horn**: Takes the shape of the part, modifies the amplitude mechanically, and applies the vibration to the parts to be welded.
- An electronic ultrasonic generator (power supply) delivering a high power electric signal with frequency matching the resonance frequency of the stack.
- A controller managing the movement of the press and the delivery of ultrasonic energy.

Applications

The applications of ultrasonic welding are extensive and are found in many industries including electrical and computer, automotive and aerospace, medical, and packaging. Whether two items can be ultrasonically welded is determined by their thickness. If they are too thick this process will not join them. This is the main obstacle in the welding of metals. However, wires, microcircuit connections, sheet metal, foils, ribbons, and meshes are often joined using ultrasonic welding. Ultrasonic welding is a very popular technique for bonding thermoplastics. It is fast and easily automated with weld times often below one second and there is no ventilation system required to remove heat or exhaust. This type of welding is often used to build assemblies that are too small, too complex, or too delicate for more common welding techniques.

Safety

Hazards of ultrasonic welding include exposure to high temperatures and voltages. This equipment should always be operated using the safety guidelines provided by the manufacturer to avoid injury. For instance, operators must never place hands or arms near the welding tip when the machine is activated. Operators should also be provided with hearing protection and safety glasses. In addition, operators should be informed of government agency regulations for ultrasonic welding equipment, and these regulations should be enforced.

Ultrasonic welding machines require routine maintenance and inspection. Panel doors, housing covers, and protective guards may need to be removed for maintenance. This should only be done when the power to the equipment is off and by trained professionals servicing the machine.

Sub-harmonic vibrations, which can create annoying audible noise, may be caused in larger parts near the machine due to the ultrasonic welding frequency. This noise can be damped by clamping these large parts at one or more locations. High-powered welders with frequencies of 15 kHz and 20 kHz typically emit a potentially damaging high-pitched squeal in the range of human hearing. Shielding this radiating sound can be achieved using an acoustic enclosure.

Welding Defects

1. Porosity

Definition: Porosity is a welding defect characterized by the presence of small holes or cavities in the weld metal. These voids are formed when gases become trapped in the molten weld pool and fail to escape before solidification. Porosity can compromise the mechanical strength and corrosion resistance of the weld.

Types of Porosity:

- **Surface Porosity:** Visible holes on the weld surface.
- **Subsurface Porosity:** Hidden voids beneath the surface, detectable by radiographic or ultrasonic testing.
- **Scattered Porosity:** Randomly distributed pores throughout the weld.
- **Cluster Porosity:** Grouped pores in a localized area.
- **Linear Porosity:** Pores aligned along the weld axis, often indicating continuous gas entrapment.

Cause:

- Contaminants such as oil, rust, paint, or dirt on the base metal or filler material.
- Moisture in the electrode coating or shielding gas.
- Improper shielding gas flow or composition, allowing atmospheric gases to enter the weld pool.
- Excessive welding speed that prevents gas escape before solidification.
- Incorrect arc length or technique causing turbulence and gas entrapment.

Control:

- Clean the base metal and filler thoroughly to remove contaminants.
- Store electrodes in dry conditions and use baking ovens if necessary to remove moisture.
- Ensure proper shielding gas selection and flow rate; avoid welding in windy or drafty environments.
- Use correct welding parameters including arc length, travel speed, and current.
- Apply proper welding techniques to allow gases to escape before the weld solidifies.
- Preheat the material if required to reduce moisture and improve gas escape.

Inspection: Porosity can be detected using visual inspection, ultrasonic testing, radiographic (X-ray) testing, or dye penetrant testing depending on its location and severity.

Impact: If not controlled, porosity can lead to reduced mechanical strength, increased risk of corrosion, and potential failure of the welded structure under load.

2. Cracks

Definition: Cracks are serious welding defects characterized by a separation or fracture in the weld metal or heat-affected zone (HAZ). They can occur during or after welding and significantly compromise the structural integrity of the joint.

Types of Cracks:

- **Hot Cracks:** Form during solidification due to high thermal stresses. Common in materials with a wide solidification range.
- **Cold Cracks:** Appear after the weld has cooled, often due to hydrogen embrittlement or residual stress.
- **Longitudinal Cracks:** Run parallel to the weld axis, often caused by shrinkage stress.
- **Transverse Cracks:** Run perpendicular to the weld axis, typically due to high restraint or poor ductility.
- **Crater Cracks:** Small cracks at the end of a weld bead caused by abrupt arc termination.

Cause:

- High residual stress from rapid cooling or poor welding sequence.
- Improper joint design that concentrates stress in specific areas.
- Use of incompatible or low-ductility filler material.
- Presence of hydrogen in the weld zone, especially in high-strength steels.
- Improper termination of the weld bead leading to crater cracks.

Control:

- Preheat the base material to reduce thermal gradients and slow cooling.
- Use filler metals compatible with the base material and suitable for the welding process.
- Control the cooling rate by adjusting welding parameters and using post-weld heat treatment if necessary.
- Design joints to distribute stress evenly and avoid sharp corners or abrupt transitions.
- Use proper welding techniques to fill craters and avoid abrupt arc stops.
- Apply controlled welding sequences to minimize residual stress buildup.

Inspection: Cracks can be detected using visual inspection, magnetic particle testing (for ferromagnetic materials), dye penetrant testing, ultrasonic testing, or radiographic (X-ray) methods.

Impact: Cracks are among the most dangerous welding defects. If not addressed, they can propagate under load, leading to catastrophic failure of the welded structure.

3. Undercut

Definition: Undercut is a groove or depression that forms at the toe of the weld, where the base metal is melted away but not filled with weld metal. This defect reduces the cross-sectional thickness of the base metal and can act as a stress concentrator, leading to fatigue failure or cracking under load.

Visual Appearance: It appears as a sharp notch or groove along the edge of the weld bead, often visible to the naked eye during inspection.

Cause:

- Excessive welding current that causes the base metal to melt excessively without proper filler deposition.
- Incorrect electrode angle that directs the arc away from the joint edges, leading to poor fusion and metal removal.
- High travel speed that prevents adequate filler metal from filling the melted edges.
- Improper weaving technique or arc manipulation that fails to distribute heat evenly.
- Use of inappropriate electrode size or type for the joint configuration.

Control:

- Use recommended welding current settings based on electrode type and material thickness.
- Maintain proper electrode angle—typically 5° to 15° from vertical for manual welding processes.
- Reduce travel speed to allow sufficient filler metal deposition at the weld toe.
- Apply consistent weaving or stringer bead technique to ensure uniform heat distribution.
- Select appropriate electrode size and type for the joint and welding position.

Inspection: Undercut can be detected through visual inspection, and its depth can be measured using weld gauges. For critical applications, non-destructive testing (NDT) methods like ultrasonic or radiographic testing may be used.

Impact: If left uncorrected, undercut can significantly reduce the fatigue strength of the weld joint and may lead to premature failure, especially in dynamic or cyclic loading conditions.

4. Lack of Fusion

Definition: Lack of fusion is a welding defect where the weld metal fails to properly fuse with the base metal or with a preceding weld pass. This results in weak bonding and can severely compromise the mechanical integrity of the joint.

Visual Appearance: It may appear as a visible gap between the weld and base metal, or be hidden internally and only detectable through non-destructive testing methods.

Cause:

- Insufficient heat input that prevents the base metal from reaching melting temperature.
- Improper welding technique, such as incorrect torch angle or poor electrode manipulation.
- Contamination on the base metal surface, including rust, oil, paint, or moisture, which acts as a barrier to fusion.
- Too fast travel speed, which limits the time for proper melting and bonding.
- Incorrect joint preparation or fit-up, leading to gaps or misalignment.

Control:

- Increase heat input by adjusting current, voltage, or travel speed to ensure full melting of the base metal.
- Clean the base metal thoroughly to remove all contaminants before welding.
- Use proper welding technique, including correct torch/electrode angle and consistent travel speed.
- Ensure proper joint design and fit-up to promote full access and fusion.
- Use suitable filler material and electrode size for the joint configuration.

Inspection: Lack of fusion can be detected using ultrasonic testing, radiographic (X-ray) inspection, or destructive testing methods like bend tests. Visual inspection may not reveal subsurface fusion issues.

Impact: This defect can lead to premature failure under load, especially in structural or pressure-containing applications. It reduces the effective cross-section of the weld and can act as a crack initiation site.

5. Incomplete Penetration

Definition: Incomplete penetration is a welding defect where the weld metal fails to fully penetrate the joint thickness. This results in a weak weld root and reduces the overall strength of the joint, especially in load-bearing applications.

Visual Appearance: It may appear as a visible gap at the root of the weld or be hidden internally, detectable only through radiographic or ultrasonic testing.

Cause:

- Low welding current that does not generate enough heat to melt through the joint thickness.
- Incorrect joint preparation, such as inadequate root opening, improper bevel angle, or poor fit-up.
- Use of an electrode or filler metal that is too small or unsuitable for the joint configuration.
- Improper welding technique, including incorrect travel speed or torch angle.
- High travel speed that limits the time for full penetration.

Control:

- Use appropriate welding current and voltage settings to ensure full root fusion.
- Prepare joints with correct root gap, bevel angle, and alignment to facilitate penetration.
- Select suitable electrode size and type based on joint thickness and welding position.
- Apply proper welding technique, including correct torch/electrode angle and travel speed.
- Use backing strips or perform root passes with stringer beads to improve penetration.

Inspection: Incomplete penetration is typically detected using radiographic (X-ray) or ultrasonic testing. Visual inspection may not reveal internal root defects.

Impact: This defect can lead to joint failure under tensile or bending loads. It reduces the effective cross-sectional area of the weld and may act as a stress riser, especially in dynamic loading conditions.

6. Slag Inclusion

Definition: Slag inclusion is a welding defect where non-metallic solid material (slag) becomes trapped in the weld metal or between weld passes. Slag is a byproduct of flux used in processes like SMAW and FCAW, and if not properly removed, it can compromise weld integrity.

Visual Appearance: Slag inclusions may appear as dark lines or irregular shapes within the weld bead or beneath the surface. They are often detected using radiographic or ultrasonic testing.

Cause:

- Failure to clean slag between successive weld passes, especially in multi-pass welding.
- Incorrect welding angle that prevents slag from escaping the weld pool.
- Low welding current that results in poor fusion and incomplete slag melting.
- Improper electrode manipulation or weaving technique that traps slag.
- Use of contaminated or damp electrodes that produce excessive slag.

Control:

- Thoroughly clean each weld pass using a wire brush, chipping hammer, or grinder before applying the next pass.
- Maintain correct electrode or torch angle to allow slag to flow out of the weld pool.
- Use appropriate welding current to ensure complete melting and fusion of the slag and base metal.
- Apply proper welding technique with consistent travel speed and arc control.
- Store electrodes in dry conditions and inspect for damage or contamination before use.

Inspection: Slag inclusions are typically detected using radiographic (X-ray) or ultrasonic testing. Visual inspection may reveal surface inclusions, but subsurface defects require NDT methods.

Impact: Slag inclusions reduce the mechanical strength of the weld and can act as initiation points for cracks or corrosion. In critical applications, they may lead to premature failure under stress or fatigue loading.

7. Spatter

Definition: Spatter refers to small droplets of molten metal that are ejected from the weld pool during welding and land on the surrounding surface. These droplets solidify and form unwanted projections that can affect the appearance and quality of the weld and nearby surfaces.

Visual Appearance: Spatter appears as scattered metallic particles or blobs around the weld bead. It can adhere to the base metal, tools, or fixtures, and often requires grinding or cleaning to remove.

Cause:

- Excessive welding current that creates turbulence in the weld pool.
- Incorrect polarity settings, especially in processes like GMAW or FCAW.
- Poor shielding gas composition or flow rate, leading to arc instability.
- Contaminated base metal or electrode causing erratic arc behavior.
- Improper arc length or electrode manipulation that disrupts the molten pool.

Control:

- Adjust welding current to recommended levels for the electrode and process.
- Use correct polarity settings as specified for the welding method (e.g., DCEN or DCEP).
- Optimize shielding gas composition (e.g., argon-CO_2 mix) and maintain proper flow rate.
- Clean base metal and electrodes to remove oil, rust, or moisture.
- Maintain consistent arc length and use smooth, controlled electrode movement.

Inspection: Spatter is usually identified through visual inspection. While it may not affect weld strength directly, excessive spatter can indicate poor welding parameters and may require post-weld cleaning.

Impact: Although spatter is primarily a cosmetic defect, it can lead to surface contamination, interfere with coatings or paint, and increase post-weld cleanup time. In precision applications, it may also affect dimensional accuracy or component fit.

8. Overlap

Definition: Overlap is a welding defect where the weld metal flows over the base metal surface without fusing properly. It creates a weak joint and can act as a stress riser, leading to cracking or failure under load.

Visual Appearance: It appears as a rounded protrusion or lip at the toe of the weld bead, often with poor blending into the base metal.

Cause:

- Low travel speed that allows excess molten metal to accumulate and spill over the base metal.
- Excessive filler metal deposition without proper fusion.
- Poor welding technique, such as incorrect torch angle or arc manipulation.
- Improper joint design or fit-up that restricts access and control.

Control:

- Increase travel speed to prevent excessive buildup of molten metal.
- Control filler metal deposition by adjusting current and electrode feed rate.
- Use proper welding technique with correct torch/electrode angle and consistent movement.
- Ensure joint design allows for smooth weld transitions and full fusion.

Inspection: Overlap is typically identified through visual inspection. For critical applications, dye penetrant or ultrasonic testing may be used to assess fusion quality.

Impact: Overlap reduces the effective bonding area and can lead to fatigue failure or cracking, especially in dynamic loading conditions.

9. Burn Through

Definition: Burn through is a welding defect where the weld metal completely penetrates and creates a hole in the base metal. It is common when welding thin materials and results in loss of structural integrity.

Visual Appearance: It appears as a visible hole or crater in the weld zone, often surrounded by irregular edges and excessive heat discoloration.

Cause:

- Excessive heat input due to high current or slow travel speed.
- Welding thin base metals without proper control or backing support.
- Incorrect electrode size or type for the material thickness.
- Poor technique, such as lingering too long in one spot or improper arc control.

Control:

- Reduce welding current and voltage to match the material thickness.
- Use backing bars or chill blocks to support and absorb excess heat.
- Adjust travel speed to avoid overheating and allow controlled fusion.
- Select appropriate electrode size and type for thin materials.
- Apply precise welding technique with short arc length and smooth movement.

Inspection: Burn through is easily detected by visual inspection. For internal damage assessment, radiographic or ultrasonic testing may be used.

Impact: Burn through severely compromises the weld joint and may require complete rework. It can lead to leaks, structural failure, or rejection in quality-critical applications.

10. Cold Lap

Definition: Cold lap is a welding defect where the weld metal fails to fuse smoothly with the base metal, resulting in a weak and poorly bonded joint. It typically appears as a rolled-over edge or a visible boundary between the weld and base metal.

Visual Appearance: The weld bead may appear to sit on top of the base metal without blending in, often with a rounded toe and lack of penetration.

Cause:

- Low heat input that prevents proper melting and fusion of the base metal.
- Improper torch or electrode angle that directs the arc away from the joint edges.
- Slow travel speed that allows the weld metal to pile up without fusing.
- Contaminated base metal surface that inhibits bonding.

Control:

- Increase heat input by adjusting current and voltage to ensure full fusion.
- Maintain correct torch or electrode angle to direct heat into the joint edges.
- Use appropriate travel speed to promote smooth fusion and avoid excessive buildup.
- Clean the base metal thoroughly to remove rust, oil, or other contaminants.

Inspection: Cold lap can be detected using visual inspection, dye penetrant testing, or ultrasonic testing. It often appears as a visible boundary or lack of blending at the weld toe.

Impact: Cold lap reduces the mechanical strength of the weld and can lead to cracking or failure under load, especially in cyclic or dynamic conditions.

11. Arc Strikes

Definition: Arc strikes are localized areas of damage caused by accidental contact of the welding electrode or arc outside the intended weld zone. These marks can alter the microstructure of the base metal and act as stress concentrators.

Visual Appearance: Arc strikes appear as small, irregular burn marks or craters on the surface of the base metal, often with discoloration or pitting.

Cause:

- Accidental initiation of the arc outside the weld area.
- Careless handling of the electrode or torch during setup or repositioning.
- Inadequate control of arc start and stop procedures.

Control:

- Use proper arc initiation techniques such as scratch start or lift start in controlled areas.
- Avoid striking the arc outside the designated weld zone.
- Train operators to handle electrodes and torches carefully during setup and repositioning.
- Use protective barriers or covers to shield adjacent surfaces from accidental arc contact.

Inspection: Arc strikes are typically identified through visual inspection. In critical applications, magnetic particle or dye penetrant testing may be used to detect subsurface damage.

Impact: Arc strikes can lead to localized hardening, cracking, or corrosion. In pressure vessels or structural components, they may require grinding and reinspection or complete rejection of the part.

12. Weld Distortion

Definition: Weld distortion refers to the deformation or warping of the base metal caused by uneven heating and cooling during welding. As the metal expands and contracts, internal stresses can lead to bending, twisting, or dimensional changes in the welded component.

Types of Distortion:

- **Longitudinal Distortion:** Shrinkage along the length of the weld.
- **Transverse Distortion:** Shrinkage across the width of the weld.
- **Angular Distortion:** Rotation or bending due to asymmetrical weld placement.
- **Buckling:** Warping of thin plates due to compressive stresses.

Cause:

- Uneven heating and cooling rates across the weld zone.
- Poor clamping or fixturing that allows movement during welding.
- Incorrect welding sequence that concentrates heat in one area.
- Excessive heat input or multiple passes without balancing.

Control:

- Use proper clamping and fixturing to hold components securely during welding.
- Apply a balanced welding sequence to distribute heat evenly.
- Control heat input by adjusting current, voltage, and travel speed.
- Use techniques like backstep welding or skip welding to minimize distortion.
- Preheat or post-weld heat treat if necessary to relieve residual stresses.

Inspection: Distortion is typically identified through dimensional inspection using measuring tools or templates. In precision applications, laser scanning or coordinate measuring machines (CMM) may be used.

Impact: Weld distortion can affect fit-up, alignment, and structural integrity. It may require rework, machining, or straightening, increasing production time and cost.

13. Excess Reinforcement

Definition: Excess reinforcement refers to the condition where the weld bead is too large or protrudes excessively above the base metal surface. While some reinforcement is necessary, too much can lead to stress concentration and poor appearance.

Visual Appearance: The weld bead appears bulky or raised significantly above the joint surface, often with uneven contour.

Cause:

- Excessive filler metal deposition due to high feed rate or large electrode size.
- Slow travel speed that allows buildup of molten metal.
- Improper welding technique or lack of control over bead shape.
- Incorrect joint design that encourages overfilling.

Control:

- Control filler metal deposition by adjusting electrode feed rate and current.
- Increase travel speed to prevent excessive buildup.
- Use proper welding technique to maintain bead shape and size.
- Design joints with appropriate groove dimensions to avoid overfilling.

Inspection: Excess reinforcement is identified through visual inspection and measured using weld gauges. Standards often specify maximum allowable reinforcement height.

Impact: Excess reinforcement can lead to stress concentration, poor fatigue performance, and difficulty in applying coatings or machining. It may also require grinding or rework to meet specifications.

14. Root Concavity

Definition: Root concavity is a welding defect characterized by a depression or underfill at the root of the weld. It occurs when the root pass fails to adequately fill the joint, leaving a concave surface that can reduce weld strength and act as a stress concentrator.

Visual Appearance: The root of the weld appears sunken or hollow when viewed from the backside or through radiographic inspection.

Cause:

- Improper root pass technique, such as poor torch/electrode manipulation or incorrect arc positioning.
- Low heat input that prevents full fusion and adequate filler deposition at the root.
- Excessive root gap or poor joint fit-up that makes it difficult to bridge the joint properly.
- Inadequate backing or purging in processes like TIG welding of stainless steel or pipe joints.

Control:

- Use correct root pass technique with proper arc control and electrode angle.
- Ensure adequate heat input by adjusting current and travel speed to achieve full fusion.
- Prepare joints with appropriate root gap and alignment to facilitate smooth root filling.
- Use backing bars, purge gas, or chill rings as needed to support the root and prevent oxidation.

Inspection: Root concavity is typically detected using radiographic (X-ray) or ultrasonic testing. In some cases, visual inspection from the backside may reveal the defect.

Impact: Root concavity can reduce the effective throat thickness of the weld and act as a stress riser, leading to fatigue failure or cracking under cyclic loading.

15. Surface Irregularities

Definition: Surface irregularities refer to inconsistencies or roughness on the weld bead surface. These may include ripples, uneven contours, pits, or rough textures that affect the appearance and may indicate underlying issues with weld quality.

Visual Appearance: The weld bead may appear wavy, rough, or inconsistent in shape and texture. These irregularities are usually visible to the naked eye.

Cause:

- Poor welding technique, such as erratic torch movement or inconsistent arc length.
- Inconsistent travel speed that leads to uneven filler deposition.
- Contamination on the base metal or filler material, causing arc instability.
- Improper shielding gas flow or composition affecting arc stability and bead shape.

Control:

- Maintain consistent welding technique with smooth and controlled torch/electrode movement.
- Use steady travel speed to ensure uniform bead formation.
- Clean base metal and filler material thoroughly to remove oil, rust, or moisture.
- Ensure proper shielding gas selection and flow rate for stable arc performance.

Inspection: Surface irregularities are typically identified through visual inspection. In critical applications, surface profile gauges or replicas may be used to assess bead geometry.

Impact: While primarily cosmetic, surface irregularities can indicate poor weld quality and may lead to stress concentration, coating failure, or difficulty in machining or fitting components.

16. Inclusions (Tungsten, Oxide, etc.)

Definition: Inclusions are welding defects where foreign materials such as tungsten particles, oxides, slag, or other non-metallic substances become trapped within the weld metal. These inclusions disrupt the homogeneity of the weld and can severely affect its mechanical properties and integrity.

Types of Inclusions:

- **Tungsten Inclusions:** Occur in TIG welding when the tungsten electrode accidentally contacts the weld pool and breaks off.
- **Oxide Inclusions:** Result from surface contamination or poor shielding, especially in aluminum and stainless steel welding.
- **Slag Inclusions:** Entrapment of flux residue between weld passes, common in SMAW and FCAW processes.

Cause:

- Contaminated electrode or base metal containing rust, oil, paint, or moisture.
- Improper cleaning between weld passes, allowing slag or oxides to remain.
- Accidental contact of tungsten electrode with the weld pool during TIG welding.
- Inadequate shielding gas coverage, allowing atmospheric contamination.
- Incorrect welding technique or arc manipulation that traps foreign particles.

Control:

- Use clean, dry electrodes and thoroughly clean base metals before welding.
- Avoid touching the tungsten electrode to the weld pool; maintain proper arc length and angle.
- Ensure complete removal of slag between passes using wire brushes or chipping tools.
- Maintain proper shielding gas flow and composition to prevent oxidation.
- Apply correct welding technique with smooth, controlled movements to avoid turbulence.

Inspection: Inclusions are typically detected using radiographic (X-ray) or ultrasonic testing. Visual inspection may reveal surface inclusions, but subsurface defects require non-destructive testing methods.

Impact: Inclusions reduce the strength and ductility of the weld, and can act as crack initiation points under stress or fatigue. In critical applications, they may lead to weld rejection or structural failure.

Comparison of Welding Processes

Process	Electrode / Filler	Shielding	Heat-Affected Zone (HAZ)	Weld Quality	Productivity	Cost	Applications
SMAW (Stick)	Consumable coated stick electrode	Flux coating → gas + slag	Medium; depends on current & electrode	Good, but slag removal needed	Low (frequent electrode changes)	Low equipment cost	Maintenance, construction, field work
GMAW (MIG/MAG)	Continuous wire electrode	External shielding gas (Ar/CO_2)	Moderate; controlled by parameters	High, clean welds, minimal slag	High (continuous wire feed)	Medium (gas + wire)	Fabrication, automotive, automation
FCAW	Tubular flux-cored wire	Self-shielded or dual-shield	Moderate	Good, but more fumes/slag	High deposition rate	Medium–High	Heavy fabrication, outdoor welding
GTAW (TIG)	Non-consumable tungsten + filler rod	Inert gas (Ar/He)	Small, precise HAZ	Excellent, highest precision	Low–Medium (slow process)	Medium (gas + skill)	Aerospace, thin sections, critical welds
SAW	Continuous wire electrode	Granular flux blanket	Moderate; arc submerged under flux	High, clean welds, deep penetration	Very high (long seams, thick plates)	Medium–High	Pressure vessels, shipbuilding

Process	Electrode / Filler	Shielding	Heat-Affected Zone (HAZ)	Weld Quality	Productivity	Cost	Applications
Resistance Welding	No filler (base metal only)	None (pressure + current)	Very small, localized HAZ	Good for sheet metals	Very high (automated)	High equipment cost	Automotive, sheet joining
Laser / Electron Beam	No filler or optional wire	Inert gas (laser) / Vacuum (EBW)	Very small, narrow HAZ	Excellent, deep penetration	High (fast, automated)	Very high equipment cost	Aerospace, electronics, precision
Friction Stir	No filler (solid-state)	None	Minimal (solid-state, low heat)	Excellent, defect-free	High (continuous process)	High setup cost	Aluminum alloys, rail, aerospace

Practice Quiz: Welding Fundamentals

1. **Which zone in a welded joint experiences phase transformation without melting?**
    - A. Fusion Zone
    - B. Heat-Affected Zone
    - C. Base Metal
    - D. Weld Face

   Answer: *B* — The HAZ undergoes microstructural changes due to heat but does not melt.

2. **In fillet weld geometry, the throat thickness is defined as:**
    - A. The longest leg of the triangle
    - B. The shortest distance from root to weld face
    - C. The width of the weld bead
    - D. The depth of penetration

   Answer: *B* — Throat thickness is the shortest distance from the root to the weld face.

3. **Which welding process typically uses a non-consumable electrode?**
    - A. SMAW
    - B. GMAW
    - C. TIG
    - D. FCAW

   Answer: *C* — TIG welding uses a non-consumable tungsten electrode.

4. **Which defect is caused by insufficient heat input or poor technique?**
    - A. Porosity
    - B. Slag Inclusion
    - C. Lack of Fusion
    - D. Spatter

   Answer: *C* — Lack of fusion results from inadequate heat or improper manipulation.

5. **In welding metallurgy, martensite forms when:**
    - A. Austenite cools slowly
    - B. Ferrite is reheated
    - C. Austenite cools rapidly
    - D. Pearlite transforms under pressure

Answer: *C* — Rapid cooling of austenite forms hard, brittle martensite.

6. **Which of the following best describes weldability?**
   - A. The ability to melt metal
   - B. The ease with which a metal can be joined by welding without defects
   - C. The strength of the weld bead
   - D. The rate of heat input during welding

   Answer: *B* — Weldability refers to how easily and reliably a metal can be welded.

7. **What is the typical groove angle for a single V butt joint?**
   - A. 30°
   - B. 45°
   - C. 60°
   - D. 90°

   Answer: *C* — A 60° groove angle is standard for single V joints to balance access and filler volume.

8. **Which defect is most likely to occur when welding thin sheets with high current?**
   - A. Incomplete penetration
   - B. Burn through
   - C. Cold lap
   - D. Arc strike

   Answer: *B* — Excessive heat on thin materials causes burn through.

9. **Which of the following is a non-destructive testing method for weld inspection?**
   - A. Bend test
   - B. Radiographic test
   - C. Tensile test
   - D. Impact test

   Answer: *B* — Radiographic testing uses X-rays to inspect internal weld quality without damaging the part.

10. **In welding, the heat input Q is calculated using:**
    - A. $Q = \frac{V \cdot I}{S}$
    - B. $Q = V + I$
    - C. $Q = V \cdot I \cdot S$
    - D. $Q = \frac{V + I}{S}$

Answer: *A* — Heat input is proportional to voltage and current, and inversely to travel speed.

11. **Which weld geometry type is used for deep penetration in thick plates?**
    - A. Fillet weld
    - B. Plug weld
    - C. Groove weld
    - D. Spot weld

    Answer: *C* — Groove welds are designed for full penetration in thick sections.

12. **Which element in steel increases hardenability and promotes martensite formation?**
    - A. Chromium
    - B. Nickel
    - C. Carbon
    - D. Manganese

    Answer: *C* — Carbon is the key element controlling martensite formation and hardenability.