Different techniques of metal joining

Subjects of Interest

- Conventional joining techniques
- Oxyacetylene welding
- Shielded metal arc welding
- Gas-tungsten arc welding
- Gas-metal arc welding
- Flux-core arc welding
- Plasma arc welding
- Submerged arc welding
- Electroslag welding
- Electron beam welding
- Laser beam welding
- Resistance welding
- Friction (stir) welding
Objectives

This chapter provides information on metal joining processes, for example, fusion welding and other high energy beam welding techniques.

Students are required to indicate advantages and disadvantages of different methods of metal joining.

Students should be able to select appropriate methods of metal joining for the required applications.
Introduction to metal joining

- Types of metal joining
- Power density of heat source
- Type of joint and weld position
- Welding processes and materials
Types of metal joining

Fusion welding

Gas welding
- Oxyacetylene welding

Arc welding
- Shielded metal arc welding (SMAW)
- Gas-tungsten arc welding (GTAW)
- Gas-metal arc welding (GMAW)
- Flux-core arc welding (FCAW)
- Plasma arc welding (PAW)
- Submerged arc welding (SAW)
- Electroslag welding (ESW)

High energy beam welding
- Electron beam welding (EBW)
- Laser beam welding (LBW)

Other joining techniques

- Bolting
- Riveting
- Brazing
- Soldering
- Adhesive joining
As the power density of the heat source increases, the heat input to the workpiece that is required for welding decreases.

- Deeper weld penetration
- Higher welding speeds
- Better weld quality
- Less damage to the workpiece
TABLE 1.1  Overview of Welding Processes

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
<th>SMAW</th>
<th>SAW</th>
<th>GMAW</th>
<th>FCAW</th>
<th>GTAW</th>
<th>PAW</th>
<th>ESW</th>
<th>OPW</th>
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* Process code: SMAW, shielded metal arc welding; SAW, submerged arc welding; GMAW, gas-metal arc welding; FCAW, flux-cored arc welding; GTAW, gas-tungsten arc welding; PAW, plasma arc welding; ESW, electron beam welding; OPW, oxyfuel gas welding; EBW, electron beam welding; LBW, laser beam welding.

* Abbreviations: S, sheet, up to 3mm (0.12in.); I, intermediate, 3–6mm (0.12–0.24in.); M, medium, 6–19mm (0.24–0.75in.); T, thick, 19mm (0.75in.) and up; X, recommended.

Types of joints and welding positions

Five basic types of weld joint designs.

- The surface of the weld is called **the face**.
- The two junctions between the face and the workpiece surface are called **the toes**.
- The portion of the weld beyond the workpiece surface is called **the reinforcement**.
Conventional joining techniques

• Bolting

A fastening method using a **threaded pin** or rod with a head at one end (bolt), designed to be inserted through holes in assembled parts and secured by a **mated nut**, that is tightened by applying **torque**.

![Bolting components diagram](image)

- thread
- nut
- runout
- shank
- head
- thread length
- grip length
- nominal length

![Bolting types](image)
Conventional joining techniques

• Riveting

Two or more pieces are jointed by inserting a headed shank through a hole and closed by forming a head on the projecting part of the shank.

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Conventional joining techniques

• **Soldering**

  • A joining method using a low melting point *lead-tin alloy* (solder) to fill in a small gap between sheets.
  • The *solder* wets the metal and produce an intermetallic bond.
  • T ~ 183–275 °C depending on compositions.
Conventional joining techniques

• Blazing

  • *Blazing* is similar to *soldering* but uses *fillers of higher T<sub>m</sub>* (450-800°C).
  • Give *better strength* than soldering but might get oxidation problems or discoloration.
  • *Heating methods* such as gas torch, furnace, molten-flux bath, induction heating resistance heating are used.
Gas welding

- Gas welding is a welding process that melts and joins metals by **heating them with a flame** caused by a reaction of fuel gas and oxygen.
- The most commonly used method is **Oxyacetylene welding**, due to its high flame temperature.
- The **flux** may be used to deoxidize and cleanse the weld metal.
- The flux melts, solidifies and forms a **slag skin** on the resultant weld metal.
There are three types of flame in oxyacetylene welding:

- **Neutral flame**
  Acetylene ($\text{C}_2\text{H}_2$) and $\text{O}_2$ are mixed in equal amounts and burn at the tip of the welding torch. The *inner cone* gives $2/3$ of heat whereas the *outer envelope* provides $1/3$ of the energy.

- **Reducing flame**
  The excess amount of acetylene is used, giving a reducing flame. The combustion of acetylene is incomplete (greenish) between the *inner cone* and the *outer envelope*. Good for welding aluminium alloys, high carbon steels.

- **Oxidizing flame**
  The excess amount of $\text{O}_2$ is used, giving an oxidizing flame. Good for welding brass.
Chemical reactions and temperature distribution in a neutral oxyacetylene

The secondary combustion is also called the **protection envelope** since CO and H₂ here consume the O₂ entering from surrounding air, thereby **protecting the weld from oxidation**.
## Advantages and disadvantages

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Simple equipment</td>
<td>• Limited power density</td>
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<tr>
<td>• Portable</td>
<td>• Very low welding speed</td>
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<tr>
<td>• Inexpensive</td>
<td>• High total heat input per unit length</td>
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<tr>
<td>• Easy for maintenance and repair</td>
<td>• Large heat affected zone</td>
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<td></td>
<td>• Severe distortion</td>
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<td></td>
<td>• Not recommended for welding reactive metals such as titanium and zirconium.</td>
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</tbody>
</table>
Shield metal arc welding (SMAW) is a process that melts and joins metals by heating them with an arc established between a sticklike covered electrode and the metals.

- The core wire conducts the electric current to the arc and provides filler metal for the joint.
- The electrode holder is essentially a metal clamp with an electrically insulated outside shell for the welder to hold safely.
- The heat of the arc melts the core wire and the flux covering at the electrode tip into metal droplets.
- Molten metal in the weld pool solidifies into the weld metal while the lighter molten flux floats on the top surface and solidifies as a slag layer.

**Shielding gas** Mixture of $H_2$, $CO$, $H_2O$ and $CO_2$
**Functions of electrode (flux) covering**

**Protection**

Provide the gaseous shield to protect the molten metal from air.

- **Cellulose-type electrode** \((C_6H_{10}O_5)_x\), providing gas mixture of \(H_2\), \(CO\), \(H_2O\) and \(CO_2\).
- **Limestone-type electrode** \((CaCO_3)\) – low in hydrogen and it is used for welding metals that are susceptible to hydrogen cracking such as high-strength steels.

**Deoxidation**

Provide deoxidizers and fluxing agent to deoxidize and cleanse the weld metal. The solid slag also protects the weld metal from oxidation.

**Arc stabilization**

Provide arc stabilizers which are compounds such as potassium oxalate and lithium carbonate. They readily decompose into ions in an arc, which increase electrical conductivity.

**Metal addition**

Provide alloying elements (for composition control) and metal powder (increase deposition rate) to the weld pool.
Advantages and disadvantages

**Advantages**

- Simple welding equipment
- Portable
- Inexpensive
- Used for maintenance, repair, and field construction

**Disadvantages**

- Not clean enough for reactive metals such as aluminium and titanium.
- The deposition rate is limited because the electrode covering tends to overheat and fall off.
- The electrode length is ~ 35 mm and requires electrode changing → lower the overall production rate.
Gas-tungsten arc welding (GTAW) is a process that melts and joins metals by heating them with an arc established between a nonconsumable tungsten electrode and the metals.

- The **tungsten electrode** is normally contacted with a water cooled copper tube, which is connected to the welding cable. → prevent **overheating**.

- The **shielding gas** (Ar, He) goes through the torch body and nozzle toward the weld pool to protect it from air.

- **Filler metal** (for joining of thicker materials) can be fed manually or automatically to the arc.

- Also called **tungsten inert gas (TIG)** welding.
Electrodes

Tungsten electrodes with 2% cerium or thorium give better electron emissivity, current-carrying capacity, and resistance to contamination than pure electrodes. → the arc is more stable.

Shielding gases

Ar is heavier and offers more effective shielding and cheaper than He.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Chemical Symbol</th>
<th>Molecular Weight (g/mol)</th>
<th>Specific Gravity with Respect to Air at 1 atm and 0°C</th>
<th>Density (g/L)</th>
<th>Ionization Potential (eV)</th>
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Source: Reprinted from Lyttle (6).
Advantages and disadvantages

**Advantages**

- Suitable for joining thin section due to its limited heat inputs.
- Can weld metals without fillers (autogenous welding).
- Very clean welding process, which can be used for welding reactive metals such as titanium, zirconium, aluminium and magnesium.

**Disadvantages**

- Deposition rate is low.
- Excessive welding current causes melting of the tungsten electrode and results in brittle tungsten in the weld pool.
- Multiple passes
- Low welding speed
Plasma arc welding (PAW) is a process that melts and joins metals by heating them with a constricted arc established between a tungsten electrode and the metals.

- **PAW** is similar to **GTAW** but an orifice gas and an shielding gas is used.
- The arc is constricted due to the covering action of the orifice gas nozzle.
- The **tungsten electrode** is recessed in the orifice gas nozzle and the arc is initiated by a **high frequency generator** between the electrode tip and the water-cooled orifice gas nozzle.
- The arc is then transferred to between the electrode tip and the workpiece.
• **Keyholing** is a positive indication of full penetration and allow *higher welding speed* (for thickness 2.5-6.4 mm).

• Requires proper combinations of the orifice gas flow, the travel speed, and the welding current.

• A wine cup shape is common in **PAW**.
Advantages and disadvantages

Advantages
- The electrode is recessed in the nozzle, therefore no contamination to the weld metal.
- Less sensitive to arc length variation.
- Full penetration.
- High welding speed.

Disadvantages
- More complicated.
- Require proper electrode tip configuration and positioning and orifice selection.
- Equipment is more expensive.
Gas metal arc welding (GMAW) is a process that melts and joins metals by heating them with an arc established between a continuously fed filler wire electrode and the metals.

- \textit{Ar} and \textit{He} are also used as \textbf{inert shielding gases} to protect the molten weld pool. \textrightarrow{} often called metal inert gas (MIG). However, non-inert gases, i.e., \textit{CO}_2 are also used for carbon and low alloy steels.

- \textit{Ar}, \textit{He} or Mixtures of (25\%)\textit{Ar}, (75\%)\textit{He} are used for non-ferrous (mostly \textit{Al}) as well as stainless and alloy steels.

- The \textit{Ar arc plasma} is stable and beneficial for transferring \textbf{metal droplets} through the arc plasma.
Modes of metal transfer

The molten metal at the electrode tip can be transferred to the weld pool by

1. **Globular transfer**
   - Metal droplets travel across the arc gap under the influence of gravity.
   - Often not smooth and cause spatter.
   - *Low welding current* (180A).

2. **Spray transfer**
   - Occur above a critical current level (280-320A).
   - Small metal droplets travel across the gap under the influence of the electromagnetic force at much higher frequency and speed than in the globular mode.
   - More stable and spatter free.

3. **Short-circuit transfer**
   - Molten metal droplets are transferred from electrode tip to the weld pool when it touches the pool surface (short-circuit).
   - Require *very low current* and electrode diameter, giving *small and fast-freezing weld pool* desirable for welding thin section or out of position welding.
Advantages and disadvantages

**Advantages**

- Very clean due to inert shielding gas used.
- Much higher deposition rate.
- Can weld thicker weld sections at higher weld speeds.
- Can use dual-touch and twin-wire processes to further increase the deposition rate.
- Short and stable arc make it easier to weld (skill is not required).

**Disadvantages**

- The GMAW gun is quite bulky and difficult to reach small areas or corners.

![Ar shielding](image1.png) ![75%He-25%Ar shielding](image2.png)

*Papillary (nipple) type penetration pattern*
Submerged arc welding (SAW) is a process that melts and joins metals by heating them with an arc established between a *consumable wire electrode* and the *metals*, with the arc being shielded by a *molten slag and granular flux*.

- The arc is **submerged** and invisible.
- The **flux** is supplied from a hopper, which travel with the torch.
- The **shielding gas** may not be required because the molten metal is separated from the air by the molten slag and granular flux.
Advantages and disadvantages

**Advantages**

• Clean welds are obtained due to protecting and refining action of the slag.

• At high welding current, spatter and heat loss are eliminated because the arc is submerged.

• Alloyming elements and metal powders can be added to the granular flux to control the composition and increase the deposition rate respectively.

• The deposition rate can be increased by using two or more electrodes in tandem.

• Can weld thick section.

**Disadvantages**

• Cannot weld in a flat-position and circumferential (pipe).

• High heat input can reduce the weld quality and increase distortions.
Electroslag welding (ESW) is a process that melts and joins metals by heating them with a pool of molten slag held between the metals and continuously feeding a filler wire electrode into it.

- The **weld pool** is covered with molten slag and move upward as welding progresses.
- A pair of **water-cooled copper shoes** keeps the weld pool and the molten slag from breaking out.
- The **molten slag** protects the weld metal from air and refine it.
- The arc is only used during the **initiation process**.
Advantages and disadvantages

**Advantages**

- Extremely high deposition rate.
- One single pass no matter how thick the workpiece is.
- No angular distortion because the weld is symmetrical with respect to its axis.

**Disadvantages**

- Very high heat input → weld quality could be poor due to coarse grain in the fusion zone or heat affected zone.
- Strict to vertical position due to very large weld pools.

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*Transverse cross section of electroslag weld in 70-mm thick steel.*
Comparison of deposition rate in different arc welding processes

![Graph showing deposition rate in different arc welding processes](image-url)

- **SMAW**
- **GTAW/PAW**
- **GMAW**
- **FCAW**
- **SAW**
- **ESW**

Deposition Rate, Lb/hr

Deposition Rate, Kg/hr

Welding Process (100% Duty Cycle)

- 6010
- 6012
- 7018
- 7024
- Cold wire
- Fine wire spray
- CO₂ shielded
- Iron powder
- With iron powder added
- 1 electrode
- 2 electrodes
- 3 electrodes
- 4 electrodes
- 5 electrodes
Electron beam welding (EBW) is a process that melts and joins metals by heating them with an electron beam.

- When the filament in the electron gun is negatively charged, it emits electrons which is accelerated by the electric field.
- These electrons go through the anode and are focused by an electromagnetic coil to point at the workpiece surface ($\phi \sim 0.3-0.8$ mm, due to a high power density ($\sim 10^{10}$ W/m$^2$)).
- The high intensity electron beam can vapourise the metal and form a deep penetrating keyhole.
- A single pass electron beam can be obtained.
- EBW is not intended for incompletely degassed materials such as rimmed steels because high speed welding does not allow gas bubbles to escape in time.
Electron beam welding

Dispersion of electron beam at various ambient pressures.

Welds in 13 mm-thick 2219 aluminium (a) Electron beam weld and (b) gas tungsten arc weld.

Vacuum operation
### Advantages

- High power density to produce a full-penetration keyhole even in thick specimens.
- Produce a single pass welding at a high welding speed.
- Very narrow heat affected zone (HAZ) and little distortion due to lower heat input per unit length than in arc welding.
- Reactive and refractory metals can be welded in vacuum (no contamination).
- Very rapid cooling can prevent coarse, brittle intermetallic compounds.
- Dissimilar metals can be welded.

### Disadvantages

- Very high equipment cost.
- High vacuum ($10^{-3} – 10^{-6}$ torr) is inconvenient. → medium vacuum ($10^{-3} – 25$ torr) and non vacuum (1 atm) EBW have also been developed.
- Precise alignment of the joints and the gun is required due to small beam size.
- Missed jointed of dissimilar metal can be obtained due to beam deflection.
Laser beam welding is a process that melts and joins metals by heating them with a laser beam.

- The laser beam can be produced by a solid state laser (YAG-Yttrium-aluminium garnet crystal) or a gas ($\text{CO}_2$) laser, which can be focused and directed by optical means to achieve high power densities.
- $\text{CO}_2$ laser gives higher power than YAG.
- Laser is produced when excited electrons return to their normal state.
- A plasma (an ionic gas) produced during welding can absorb and scatter the laser beam, which reduces the weld penetration.
- Inert gas (He, Ar) is required to increase weld penetration.
Laser beam welding with CO₂ laser in 13-mm thick A633 steel.

- Surface melting produces a full penetration.

- **High reflectivity** can cause problems in **LBW** → Surface modifications, i.e., roughening, oxidizing and coating can significantly reduce reflectivity.

- **Laser beam** can be used in combination with arc welding such as **GMAW** to provide greater penetration.
Advantages and disadvantages

**Advantages**
- Produce deep and narrow welds at high welding speeds.
- Narrow heat-affected zone.
- Little distortion.
- Can be used for welding dissimilar metals in varying sizes.

**Disadvantages**
- Very high reflectivity of a laser beam by the metal surface.
- High equipment cost.
- Require precise joint and laser beam alignment.
Resistance welding is used to join two or more metal parts together in a localised area by the application of heat and pressure. The heat is produced by the resistance of the material to carry a high amperage current.

There are at least seven different types of resistance welding:

- Flash welding
- High-frequency resistance welding
- Percussion welding
- Projection welding
- Resistance seam welding
- Resistance spot welding
- Upset welding
Friction welding is a mechanical solid-phase welding process in which heat generated by friction is used to create high-integrity joint between similar or dissimilar metals.

Can be used for round and rectangular sections.
Inertia Friction welding

The energy required to make the weld is supplied primarily by the stored rotational kinetic energy of the welding machine.

- One piece is attached to a flywheel and the other is restrained from rotating.
- The flywheel is accelerated by a motor to a predetermined rotational speed, storing the energy.
- The motor is disengaged and the work pieces are forced together by the friction welding force.
- The surfaces rub together under pressure producing heat through friction at the weld interface.
- The flywheel speed decreases and stop when the stored kinetic energy has used up.
- Forge force may be applied before the rotation ceases.
Friction welding

Friction welding for rectangular sections

Friction welding process.

Weld structure obtained from friction welding.

- The heat generated due to frictional motions of the two workpieces, creating a columnar microstructure as shown in figure.
Friction stir welding

- Friction stir welding is a solid phase bonding process used mostly in welding aluminium.

- A cylindrical, shouldered tool with a profiled probe is rotated and slowly plunged into the joint line between two pieces of sheet or plate material, which are butted together.

- Frictional heat ($<T_m$) is generated between the wear resistant welding tool and the material of the workpieces.

- High cost of welding machines.
- Can use to join dissimilar metals.
- Very small distortion.
- Limited to non-round and non-complex component.