Joining processes: Introduction

According to the classification made by the American Welding Society, joining processes fall into three major categories:

- Welding
- Adhesive bonding
- Mechanical fastening

A variety of welding methods exist, including arc and gas welding, as well as brazing and soldering. Generally welding processes can be classified into three basic categories:

- Fusion welding
- Solid-state welding
- Brazing and soldering

In welding, two or more metal parts are joined to form a single piece when one-part fabrication is expensive or inconvenient.

- Both similar and dissimilar metals may be welded.
- The joining bond is metallurgical (involving some diffusion) rather than just mechanical, as with riveting and bolting.
- During arc and gas welding, the workpieces to be joined and the filler material are heated to a sufficiently high temperature to cause both to melt; upon solidification, the filler material forms a fusion joint between the workpieces.

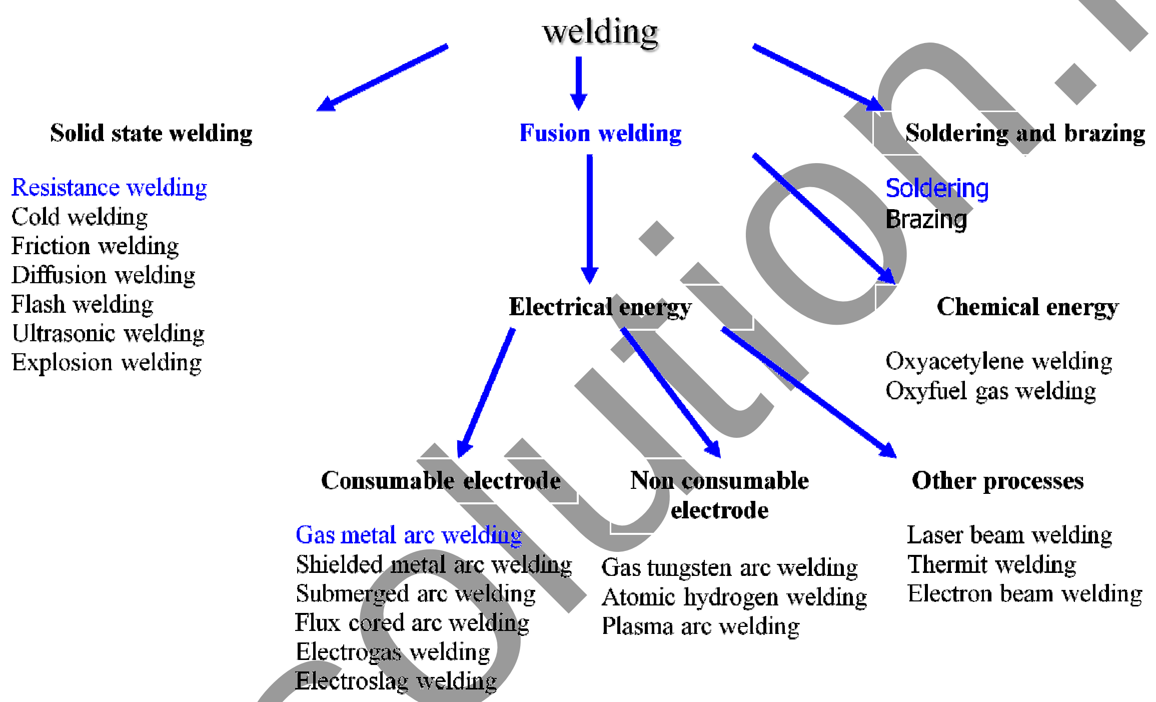
Main advantages of welding

- Welding has replaced riveting in many applications including:
- steel structures, boilers tanks, and motor car chassis
- Cost effectiveness
- Strong and tight joining
- Simplicity of welded structure design
- Welding process can be mechanised and automated

Some disadvantages of welding

- Internal stresses, distortions and changes of structures in the weld region
- HAZ is formed
- Harmful effects: light, ultra violate radiation, fumes, high temperature
- Permanent joint

Classification of welding processes



As seen from the Figure 1, the welding processes fall under larger categories. We will describe main methods in detail in the following sections.

Oxy-fuel gas welding

- OFW is a general term used to describe any welding processes that uses a fuel gas combined with oxygen to produce a flame.
- This flame is the source of the heat that is used to melt the materials at the joint.
- The most common gas welding processes uses acetylene, is known as oxy-acetylene gas welding (OAW).
- OAW is used typically for structural-sheet metal fabrication, automotive bodies and various repair works.

Type of flames on OAW

Different types of flames obtained from oxyacetylene welding are shown in Figure 2.

- ***Neutral flame***: Acetylene and oxygen mix at the ratio of 1:1.
- ***Oxidizing flame***: A flame with excess oxygen is known as oxidising flame
- ***Reducing flame***: If oxygen is insufficient for full combustion, the flame is known as a reducing or carburising flame

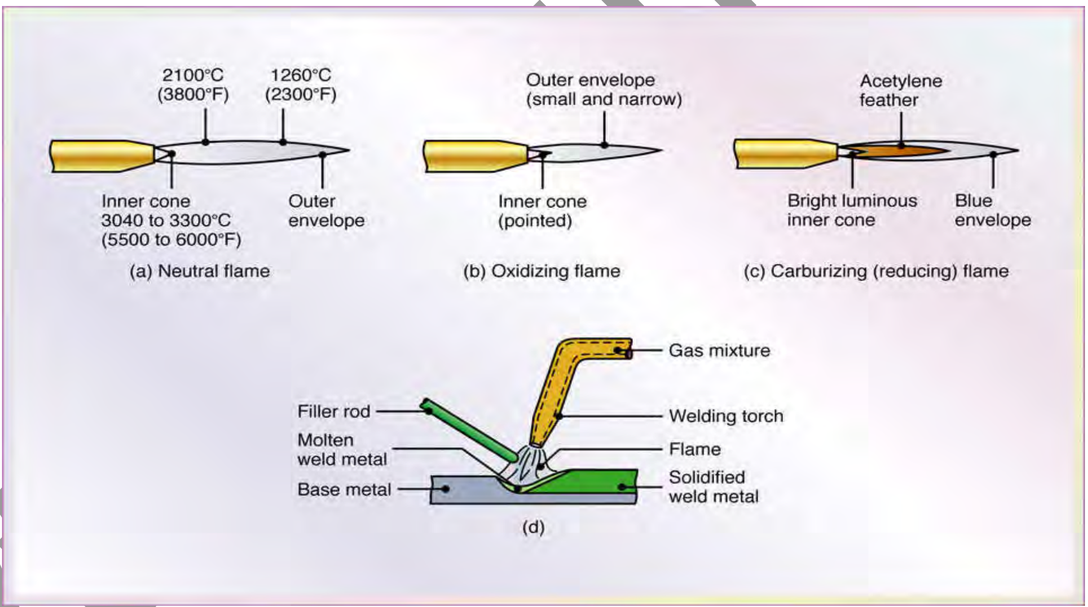


Figure 2: Schematic illustration of three basic oxyacetylene flames (a-c), (d) The principle of oxyfuel-gas welding operation (Source: Manufacturing Engineering and Technology, Fifth Edition, by Serope Kalpakjian and Steven Schmid. ISBN 0-13-148965-8. 2006 Pearson Education, Inc. PP 942

Oxy-acetylene welding practice and equipment

- Prepare the edges to be joined and establish and maintain their proper position by using clamps and fixtures
- Open main valves
- Adjust pressure
- Crack open acetylene needle valve.
- Ignite,
- Adjust flame.
- Crack open oxygen needle valve.
- Adjust flame. Hold the torch at 45^{o} and filler rod at about $30\text{-}40^{o}$ and control its movement
- Shut down in reverse order; finally, open needle valves to bleed off gases.

Oxy-fuel gas cutting

- The cutting takes place mainly by the oxidation (burning) of the steel; some melting also takes place. This process generates a kerf. With oxy-acetylene gas, 300 – 600 mm and thickness 1.5 to 10 mm.
- OFC is similar to oxyfuel welding, but the heat source now is used to remove a narrow zone from a metal plate or sheet. In this process, the metal is preheated with fuel gas, and oxygen is introduced later.
- The higher the carbon content of the steel, the higher the preheating temperature required

Arc welding

Arc welding processes fall under a larger category labeled as fusion welding, with an electrical energy source (Figure 1).

General characteristics of arc welding processes

- These processes are associated with molten metal
- Arc welding processes use an electric arc as a heat source to melt metal. The arc is struck between an electrode and the workpiece to be joined. The electrode can consist of consumable wire or rod, or may be a non-consumable tungsten electrode.
- The process can be manual, mechanized, or automated. The electrode can move along the work or remain stationary while the workpiece itself is moved. A flux or shielding gas is employed to protect the molten metal from atmosphere.
- If no filler metal is added, the melted weld is referred to as autogenous. If the filler metal matches the base metal, it is referred to as homogenous. If the filler metal is different from the base metal, it is referred to as heterogeneous.

The common arc welding processes used to weld metals are: shielded metal arc welding or SMAW, gas metal arc welding GMAW, sometimes called MIG welding; flux cored arc welding FCAW; submerged arc welding SAW; and gas tungsten arc welding GTAW, sometimes called TIG welding.

- Shielded Metal Arc Welding (SMAW)
- Gas Metal Arc Welding (GMAW)
- Flux Cored Arc Welding (FCAW)
- Submerged Arc Welding (SAW)
- Gas Tungsten Arc Welding (GTAW)

Shielded metal arc welding (SMAW)

- Arc is developed between electrode and the component
- Flux creates a gas shield and the metal slag prevents oxidation of the underlying metal.
- Typical uses: Pressure vessels, structural steel, and in general engineering
- Economics: Versatile and low cost (easy to transport) but can't be automated.
- SMAW is the most widely used welding process for joining metal parts because of its versatility, its less complex, more portable and less costly equipment

Metals commonly welded by SMAW

- Carbon and low alloy steels
- Stainless steels and heat resistance steels
- DCEN (Direct Current Electrode Negative) (reverse polarity) can be used of all steels. Melting and deposition rates are higher than with DCEP (Direct Current Electrode Positive) (straight polarity).
- The multiple-pass approach requires that the slag be cleaned after each weld bed. 3-20 mm thick

A schematic illustration of SMAW is shown in Figure 3. This is typically a manual welding process where the heat source is an electric arc which is formed between a consumable electrode and the base material. The electrode is covered by a coating, which is extruded on the surface of the electrode. During welding, the electrode coating decomposes and melts, providing the protective atmosphere around the weld area and forming a protective slag over the weld pool.

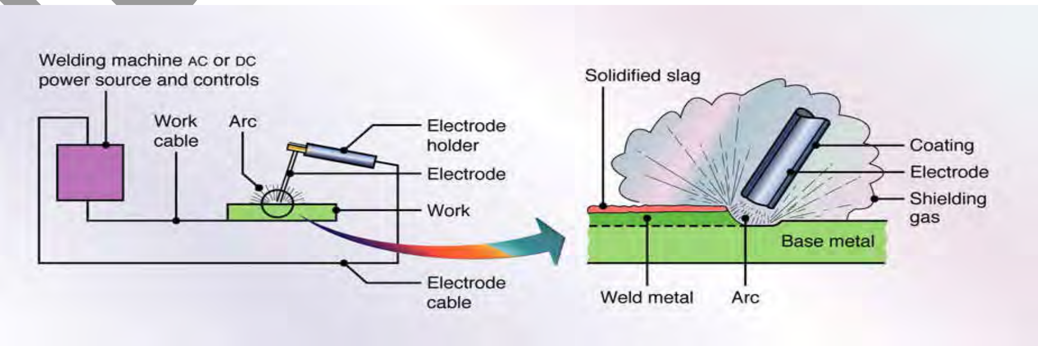


Figure 3: Schematic illustration of shielded metal arc welding
(Source: Manufacturing Engineering and Technology, Fifth Edition, by Serope Kalpakjian and Steven Schmid. ISBN 0-13-148965-8. 2006 Pearson Education, Inc. PP 949

Advantages of SMAW

- Equipment relatively easy to use, inexpensive, portable
- Filler metal and means for protecting the weld puddle are provided by the covered electrode
- Less sensitive to drafts, dirty parts, poor fit-up
- Can be used on carbon steels, low alloy steels, stainless steels, cast irons, copper, nickel, aluminum

Disadvantages of SMAW

Discontinuities associated with manual welding process that utilise flux for pool shielding

- Slag inclusions
- Lack of fusion

Other possible effects on quality are porosity, and hydrogen cracking. These points would be discussed separately in the welding defects section.

Limitations of SMAW

SMAW has a low weld metal deposition rate compared to other processes. This is because each welding rod contains a finite amount of metal. As each electrode is used, welding must be stopped and a new rod inserted into the holder. A 12-inch electrode may be able to deposit a bead 6-8 inches long.

The overall productivity of the process is affected by:

- Frequent changing of electrodes,
- Inter pass cleaning (grinding, brushing, etc.),
- Grinding of arc initiation points and stopping points,

Slag inclusions which require removal of the defect and re-welding of the defective area. The heat of the welding arc is too high for some lower melting metals. And the shielding of metals that react aggressively with the atmosphere is inadequate.

Gas metal arc welding (GMAW)

In GMAW, formerly known as metal inert-gas (MIG) welding is an arc welding process in which the heat for welding is generated by an arc between a consumable electrode and the work metal. The consumable bare wire is fed automatically through a nozzle into the weld arc by a wire-feed drive motor. In GMAW, the weld area is shielded by an effectively inert atmosphere of argon, helium, carbon dioxide or various other gas mixtures. Schematic illustration of GMAW is illustrated in Figure 4.

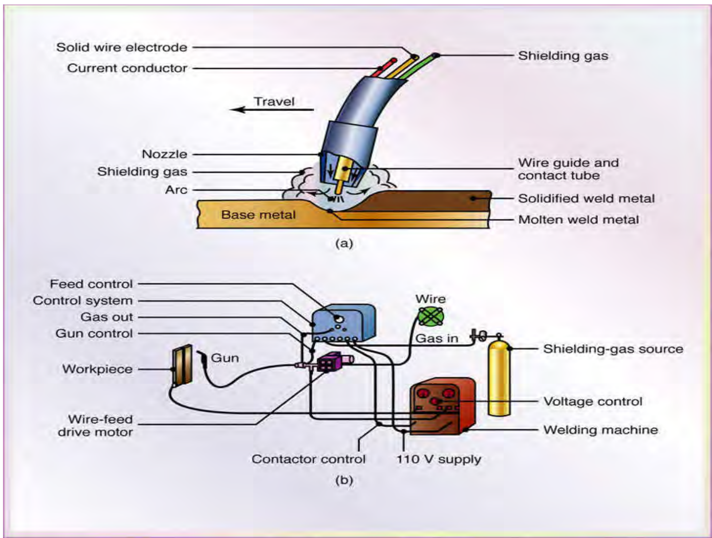


Figure 4: Schematic illustration of GMAW (Source: Manufacturing Engineering and Technology, Fifth Edition, by Serope Kalpakjian and Steven Schmid. ISBN 0-13-148965-8. 2006 Pearson Education, Inc. PP 951

Advantages if GMAW

- Can weld almost all metals and alloys, aluminum and aluminum alloys, stainless steel
- All positions of welding
- DCEP which provides stable arc, smooth metal transfer, relatively low spatter and good weld bed characteristics
- Due to automatic feeding of the filling wire (electrode) the process is referred to as a semi-automatic. The operator controls only the torch positioning and speed.
- No slag produced
- High level of operator skill is not required.

Further advantages of GMAW

- High productivity
- All positions of welding and reliability
- Wide area applications
- All ferrous and nonferrous can be welded

Limitations of GMAW

- Expensive and non-portable equipment
- Less skilled workers can operate this process, however this can lead to poor setup of the welding parameters, in turn this can lead to defects in the finished weld such as lack of fusion and porosity.
- More heat is generated in MIG than TIG; this will mean that the HAZ is larger around a weld of this type.
- Equipment is heavy and not particularly portable; the operator is limited to about 4.5m to 6m from the power source due to potential complications with the wire feed. Extended-reach wire feeders are now available which means the operator can be up to 15m away from the power source (Smith, 1986), but the extra equipment means that portability is further restricted.

Methods of metal transfer in GMAW

Spray transfer**:** small, molten metal droplets from the electrode are transferred to the weld area at a rate of several hundred droplets per second. Spray is achieved at higher welding currents and voltages with argon or argon- rich gas mixture Helium based shielding gas (over 80% Ar). The average current required in GMAW process can be reduced by using a ***pulsed arc,*** which superimposes high-amplitude pulses onto a low, steady current. Pulsing the current allows for better control for out of position welding. This mode produces little or no spatter and is known for the high deposition rate (higher productivity).

Globular transfer**:** carbon-dioxide rich gases are utilised, and globules are propelled by the forces of the electric arc transfer of the metal, resulting in considerable spatter. High currents are used, making it possible for greater weld penetration and higher welding speed than are achieved in spray transfer. Heavier sections commonly are joined by this method.

Short circuiting transfer: the metal is transferred in individual droplets (more than 50 per second), as electrode tip touches the molten weld metal and short circuits. At low current and voltages, short circuit transfer occurs. The weld is a shallow penetrating weld with low heat input. Using GMAW in this mode allows welding in all positions since the weld puddle is so small. In comparison to the other modes of transfer, this method is slowest (low productivity). Used primarily for sheet metal applications. This mode produces large amounts of spatter if welding variables are not optimized. This mode is also known as short arc or dip transfer.

Shielded gases

Contamination of the weld pool, by the atmosphere, can cause weld defects. These defects can have an adverse effect on the joint efficiency, which may lead to failure. Therefore, the weld pool should be protected from the atmosphere until it has completely solidified. The primary purpose of shielding gases is to protect the molten weld metal and the HAZ from oxidisation and other contamination.

- Shielding gas forms a protective atmosphere over the molten weld pool to prevent contamination
- *Inert* shielding gases, argon or helium, keep out oxygen, nitrogen, and other gases
- *Active* gases, such as oxygen and carbon dioxide, are sometimes added to improve variables such as arc stability and spatter reduction
- Shielding gas can be a single pure gas or a mixture of two or more gases.
- Inert gases, as the name implies, do not react with the weld metal. Argon is often used in the flat and horizontal position, since it is heavier than air. Helium can be used in the overhead position, since it is lighter than air. Helium has a characteristic of producing a “hotter” arc than argon.
- Active gases, such as oxygen and carbon dioxide, are often added to inert gases in order to improve arc properties. These properties include arc stability and spatter reduction.
- Shielding gases should be free of moisture, which decompose to hydrogen and oxygen in the arc. Moisture in the gas can result in porosity, and in steels, hydrogen can lead to cracking.

Main shielded gases used in GMAW

- *Argon*: Argon is 38% heavier than air, which is advantageous for welding in flat and horizontal fillet positions. Pure argon virtually can be used in all metals.
- *Helium*: It is lighter than air and because of this, high gas flow rate must be used to maintain adequate shielding. Helium is used primarily on Aluminum, magnesium and copper.
- *Carbon-dioxide*: This is widely used in the welding of steel by the short circuiting mode of metal transfer.
- *Mixtures*: Argon-carbon dioxide mixtures, argon helium mixtures, argon oxygen mixtures, helium-argon-carbon dioxide mixtures.

Flux- cored arc welding (FCAW)

Flux Cored Arc Welding (FCAW) (Figure 5) uses a tubular wire that is filled with a flux. FCAW is similar to GMAW, except the electrode is tubular in shape and filled with flux (hence the term flux-cored). The arc is initiated between the continuous wire electrode and the workpiece. The flux, which is contained within the core of the tubular electrode, melts during welding and shields the weld pool from the atmosphere. Direct current, electrode positive (DCEP) is commonly employed as in the FCAW process. Cored electrode produces a more stable arc, improve weld contour, and produce a better mechanical properties of the weld metal.

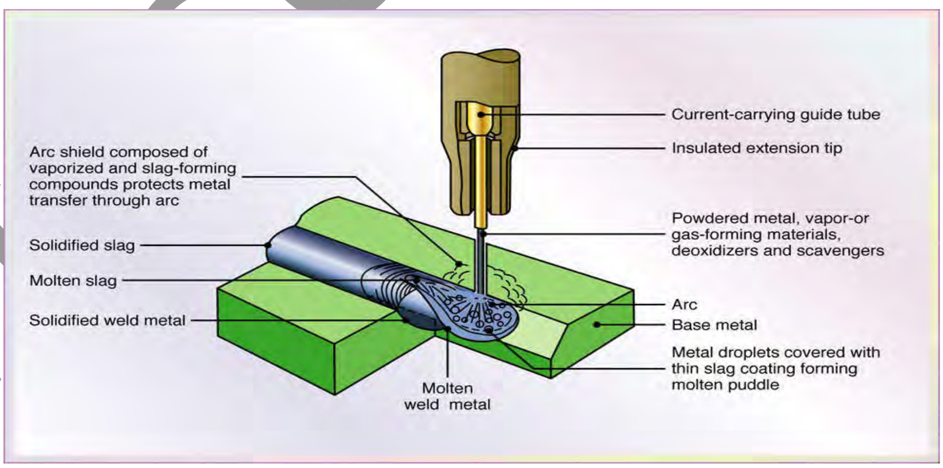


Figure 5: Schematic illustration of the flux-cored arc-welding process

(Source: Manufacturing Engineering and Technology, Fifth Edition, by Serope Kalpakjian and Steven Schmid. ISBN 0-13-148965-8. 2006 Pearson Education, Inc. PP 952

The FCAW process combines the versatility of SMAW with the continuous and automatic electrode-feeding feature of GMAW. A schematic illustration of FCAW is shown in Figure 6.

Advantages of FCAW

- Specific weld-metal chemistries can be developed
- By adding alloying elements to the flux core, all alloy composition can be produced
- Easy to automate and readily adaptable to flexible manufacturing and robotics

Disadvantages of FCAW

- The slag formed during welding must be removed between passes on multipass welds. This can reduce the productivity and result in possible slag inclusion discontinuities. For gas shielded FCAW, porosity can occur as a result of insufficient gas coverage.
- Large amounts of fume are produced by the FCAW process due to the high currents, voltages, and the flux inherent with the process. Increased costs could be incurred through the need for ventilation equipment for proper health and safety.
- FCAW is more complex and more expensive than SMAW because it requires a wire feeder and welding gun. The complexity of the equipment also makes the process less portable than SMAW.

Submerged-arc welding (SAW)

In SAW, the weld arc is shielded by a granular flux consisting of lime, silica, manganese oxide, calcium fluoride, and other compounds. A schematic illustration of submerged-arc welding process is shown in Figure 6.

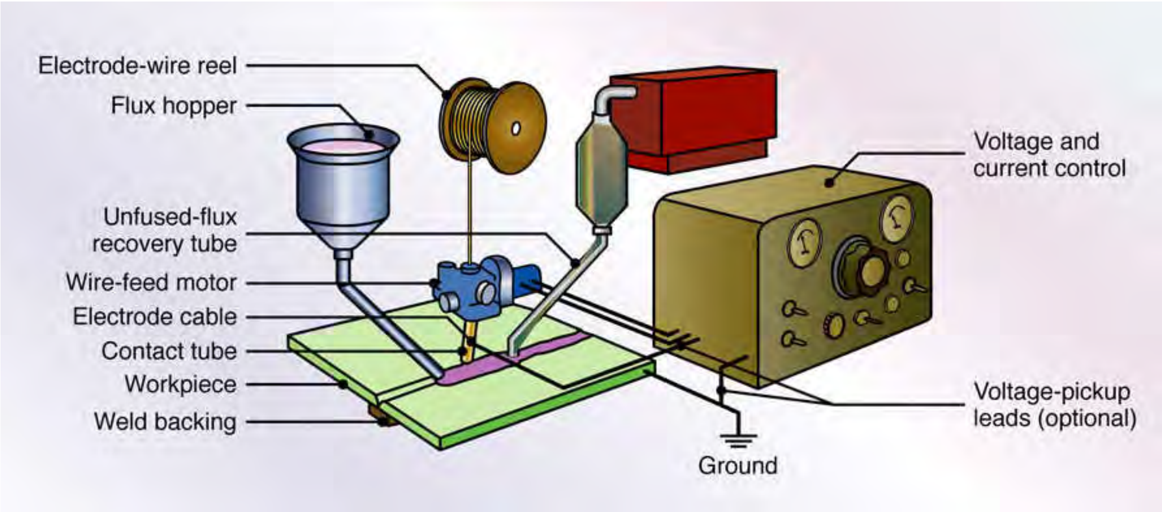


Figure 6: Schematic illustration of submerged-arc-welding (Source: Manufacturing Engineering and Technology, Fifth Edition, by Serope Kalpakjian and Steven Schmid. ISBN 0-13-148965-8. 2006 Pearson Education, Inc. PP 950)

Characteristics of submerged-arc welding

- The flux is fed into the weld zone from a hopper by gravity through a nozzle:
- The functions of the flux:
- Prevents spatter and sparks;
- Suppresses the intense ultraviolet radiation and fumes characteristics of the SMAW.
- It acts as a thermal insulator by promoting deep penetration of heat into the workpiece.
- The unused flux can be recovered, treated and reused.

The filler metal is a continuously-fed wire electrode like GMAW and FCAW. However, higher deposition rates can be achieved using SAW by using larger diameter electrodes and higher currents (650-1500 Amperes). Since the process is almost fully mechanized, several variants of the process can be utilized such as multiple torches and narrow gap welding.

- Because of the flux is gravity fed, the SAW process is limited largely to welds in flat or horizontal position
- This process can be automated and use to weld a variety of carbon and alloy steel and stainless steel sheets or plates as high as 5m/min.
- The quality of weld is very high, provides high productivity in ship building and for pressure vessels.

Advantages of submerged welding (SAW)

- This process can be automated and use to weld a variety of carbon and alloy steel and stainless steel sheets or plates as high as 5m/min.
- The quality of weld is very high, provides high productivity in ship building and for pressure vessels.
- High deposition rates
- No arc flash or glare
- Minimal smoke and fumes
- Flux and wire added separately - extra dimension of control
- Easily automated
- Joints can be prepared with narrow grooves
- Can be used to weld carbon steels, low alloy steels, stainless steels, chromium-molybdenum steels, nickel base alloys
- SAW has the highest deposition rate of the entire deep penetrating arc welding processes making it ideal for thick section and multi-pass welding. Variations of the process can utilize dual arc welding, twin arc welding, multiple torches, and narrow groove welding to increase productivity.
- Since the arc is completely submerged in the flux, there is no arc radiation. Screens or light filtering lenses are not needed. Additionally, the smoke and fumes are trapped within the flux and thus minimizing smoke and fumes.
- Since the process is simple to mechanize and easily automated, it is extremely consistent once a procedure is qualified. And it can be used on a wide variety of materials.

Limitations of submerged welding (SAW)

- Because of the flux is gravity fed, the SAW process is limited largely to welds in flat or horizontal position
- The flux which shields the arc and weld pool in SAW also obstruct the operator’s view of the joint and molten weld pool. This makes observation of the pool and joint impossible during welding; thus, correction of problems during welding can be very difficult.
- Because of the high current levels common to this process, it is normally not suited for thinner materials.
- Due to the presence of a granulated flux, submerged arc welding is limited to the flat and horizontal positions. As with SMAW and FCAW, SAW produces a slag which must be completely removed after each pass.
- Finally, additional flux handling equipment is required.

Gas tungsten arc welding (GTAW)

In gas tungsten arc welding (GTAW), formerly known as TIG welding (for "tungsten inert gas"), the filler metal is supplied from a filler wire as shown in Figure 7. In non-consumable-electrode welding process, the electrode is typically a tungsten electrode.

- An externally supplied shielding gas is necessary because of the high temperatures involved in order to prevent oxidisation of the weld zone.
- Typically direct current is used, and its polarity is important.

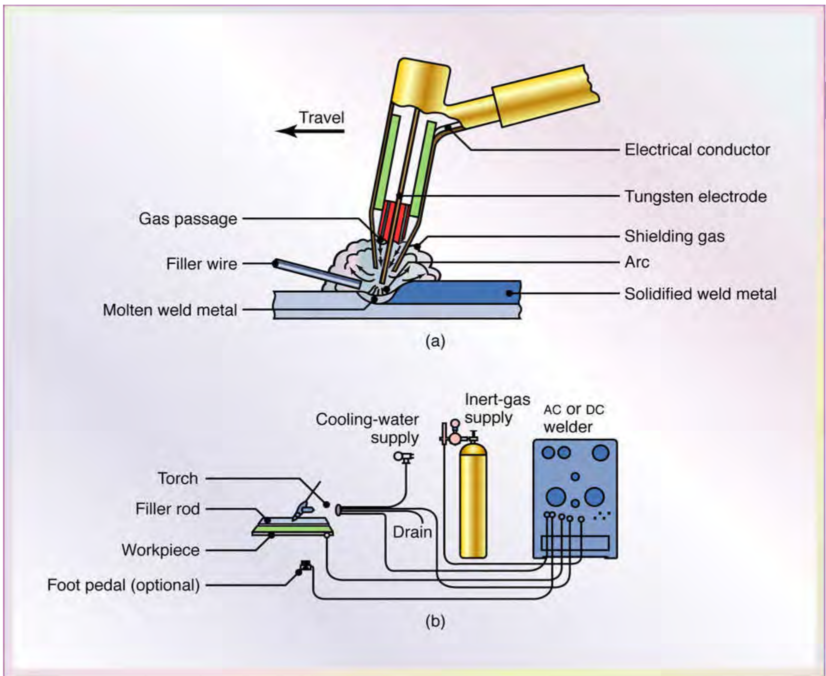


Figure 7: Schematic illustration of GTAW (Source: Manufacturing Engineering and Technology, Fifth Edition, by Serope Kalpakjian and Steven Schmid. ISBN 0-13-148965-8. 2006 Pearson Education, Inc. PP 951

- TIG is an arc welding process in which the heat is produced between a non-consumable electrode and the work metal.
- Because the tungsten electrode is not consumed in this operation, a constant and stable arc gap is maintained at a constant current level.
- The filler metals are similar to the metals to be welded, and flux is not used.
- The shielding gas is usually argon or helium (or a mixture of the two).
- TIG welding process is used for a wide variety of metals and applications.
- Metals that can be welded by TIG are aluminum, magnesium, titanium and copper and its alloy.

Applications of GTAW welding

TIG welding process is used for a variety of metals and applications in all industrial sectors. TIG is especially for welding aluminum, magnesium, titanium, and refractory metals. It is suitable for welding thin metals. The cost of the inert gas makes this process makes more expensive than SMAW but provides welds with very high quality and surface finish.

Advantages of GTAW

- Uses a lower temperature than either MIG or gas welding (Finch, 1997) subsequently this will produce a smaller HAZ (Heat Affected Zone) within which defects and weakness can occur.
- Produces very high quality welds of satisfactory quality for even the rigorous standards set by the aerospace industry. (Pritchard, 1996)
- Suitable for welding thin materials due to the lower temperature and the precise nature of the process.
- The equipment used is smaller than that of MIG and is subsequently more portable and thus more versatile. Also can weld in any position i.e. flat, horizontal, or overhead.

Limitations of GTAW

- The process is manual and requires a highly skilled operator, of which there is a shortage in the work force (Smith, 1986).
- TIG cannot be automated and is significantly slower than MIG welding and therefore less suitable for mass production.

Electrodes for arc welding

Electrodes for consumable arc-welding processes are classified according to:

- Strength of the deposited weld metal
- Current (AC or DC)
- Type of coating

Electrodes are identified by numbers and letters or by colour code, particularly if they are too small to imprint with identification. Typical coated-electrode dimensions are in the range of 150 to 460 mm in length and 1.5 to 8 mm in diameter.

A specification for electrodes and filler metals for welding According to American Welding Society (AWS) is presented in Table 1.

Table 1: AWS A5.1-69 and A5.5 – 69 designations for manual electrodes

a. The prefix "E" designates arc welding electrode.
b. The first two digits of four-digit numbers and the first three digits of five-digit numbers indicate minimum tensile strength:

E60XX	60,000 psi minimum tensile strength
E70XX	70,000 psi minimum tensile strength
E110XX	110,000 psi minimum tensile strength

c. The next-to-last digit indicates positions:

EXX1X	All positions
EXX2X	Flat position and horizontal fillets

d. The last two digits together indicate the type of covering and the current to be used.

The suffix (Example: EXXXX-A1) indicates the approximate alloy in the weld deposit:

-A1	0.5% Mo
-B1	0.5% Cr, 0.5% Mo
-B2	1.25% Cr, 0.5% Mo
-B3	2.25% Cr, 1%Mo
-B4	2% Cr, 0.5% Mo
-B5	0.5% Cr, 1% Mo
-C1	2.5% Ni
-C2	3.25% Ni
-C3	1% Ni, 0.35% Mo, 0.15% Cr
-D1 and D2	0.25-0.45% Mo, 1.75% Mn
-G	0.5% min. Ni, 0.3% min. Cr, 0.2% min Mo, 0.1% min. V, 1% min. Mn (only one element required.

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Type of electrodes for arc welding

- Gas shielded (cellulosic) electrodes
- Rutile electrodes
- Iron-oxide/silicate electrodes
- Basic electrodes

Factors to be considered while selecting the electrodes

- Compromise between the requirements of weld quality and the overall cost of fabrication.
- Skill of the operator and the conditions of the electrode storage and uses must also be considered.
- For the highest quality weld in mild steel and low alloy steel, basic electrodes are selected.

Metal arc welding electrodes consist of a core wire surrounded by a flux coating. The flux coating on arc welding electrode serves a number of purposes:

- To provide a gaseous shield for the weld metal and preserve it from contamination by the atmosphere whilst in a molten state
- To provide a steady arc
- To remove oxygen from the weld metal
- Control the rate at which the electrode melts
- Add alloying elements to the weld zone to enhance the properties of the joint

Friction Stir Welding (FSW)

FSW is a relatively new process developed and patented in England by The Welding Institute of Cambridge (TWI UK). The process works by lowering the pin of a shouldered tool into the gap between the two materials to be welded at a high rotational speed and under significant down force (see Figure 8). This creates friction between the tool and work, generating enough heat for the metal to change to a plasticised state. Subsequently the plasticised shaft of metal around the pin is stirred together to create a forged bond, or weld, between the materials (NASA Technology Applications Team, 2001).

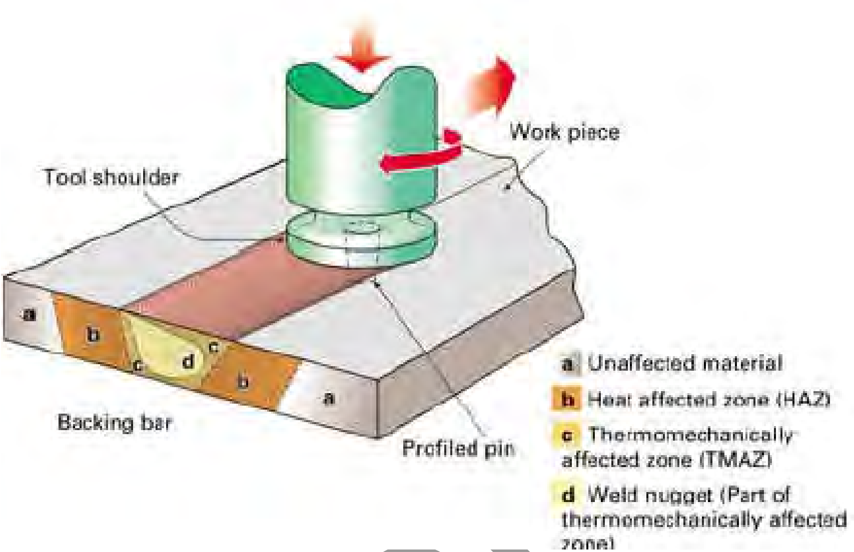

Figure 8: Schematic diagram of FSW (Nicholas et al 2002)

Advantages of FSW

Since gravity has no influence on the solid-phase welding process, it can be used in all positions, viz:

- Horizontal
- Vertical
- Overhead
- Orbital

The process advantages result from the fact that the FSW process (as all friction welding of metals) takes place in the solid phase below the melting point of the materials to be joined. The benefits therefore include the ability to join materials which are difficult to fusion weld, for example 2000 and 7000 aluminium alloys. Friction stir welding can use purpose-designed equipment or modified existing machine tool technology. The process is also suitable for automation and adaptable for robot use.

Main characteristics/advantages of FSW

- The FSW process works below the melting temperature of the weld material in the solid state phase (Nicholas et al, 2002). This means that the work has a significantly smaller heat affected zone (HAZ) than conventional fusion welding techniques where weld defects can occur.
- In tests by TWI UK, the fatigue performance of butt welds in aluminium alloys has been found to be comparable to that of the parent material (Nicholas et al, 2002).
- Post-process natural ageing of 7000 series aluminium also led to FSW welds having an average of 95% of the tensile strength of the parent material (Nicholas et al, 2002).
- FSW creates a very strong bond between materials. In shear tests done by USC Research in the USA riveted panels failed at a load of approximately 32,300lbs, whereas the equivalent FSW panels failed at an average of 35,100lbs (USC Research and Health Sciences). FSW can weld alloys that were previously very difficult to weld using the established welding techniques of the time.
- FSW can be easily automated and subsequently can be programmed to perform complex shape welds (NASA Technology Applications Team, 2001). This also means that FSW is not as dependent on highly skilled operators.
- Defects such as solidification cracking and gas porosity caused by absorption of hydrogen during welding do not occur in FSW, although they are common in fusion welding processes (Leal et al, 2004)

Limitations of FSW

Two drawbacks to the FSW procedure are the requirement for different length pin tools when using the process on materials which vary in thickness, and the fact that a keyhole is left at the end of the weld where the welding tool is removed. This is particularly a problem when welding cylindrical items such as pipe which require a continuous weld. However, NASA Marshall have developed a retractable pin tool which removes the pin at the end of the weld, leaving no keyhole (NASA Technology Applications Team, 2001). The workpiece in FSW also requires to be clamped rigidly. If metal deposition is required, this process is not good.

Electron-Beam Welding (EBW)

In EBW, developed in 1960s, the heat used for welding the two materials is generated by high velocity narrow-beam (concentrated) electrons is fired through the work, this transfers kinetic energy to the particles of metal causing them to heat up and melt to form a weld. A schematic illustration of EBW is shown in Figure 9. EBW process requires special equipment to focus the beam on the workpiece, typically in a vacuum. The higher the vacuum, the more the beam penetrates, and the greater the depth-to-width ratio can be achieved. There are three methods in EBW as far as vacuum is concerned:

- EBW-HV (for high vacuum)
- EBW-MV (medium vacuum)
- EBW-NV (no vacuum)

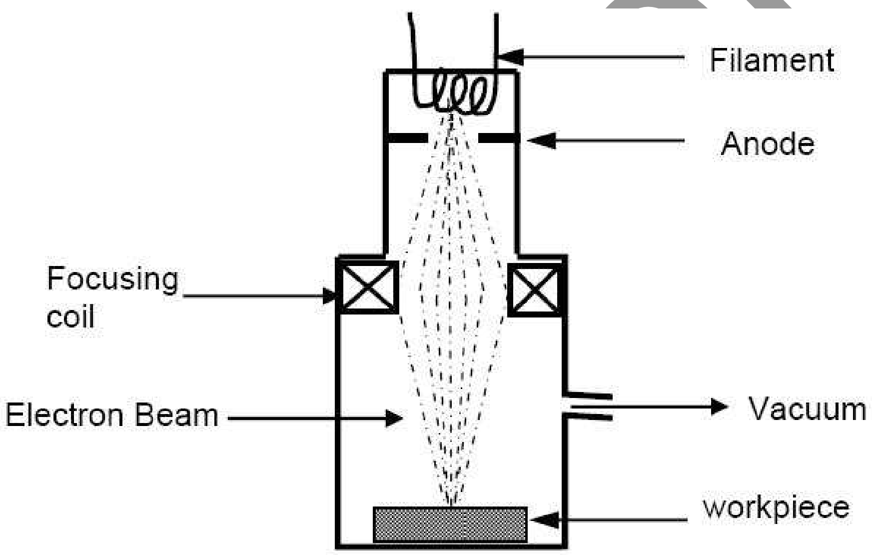

Figure 9: Schematic illustration of Electron Beam Welding (EBW) (Source: MAS 2007)

Some characteristics of EBW

- In aircraft industry alloy grade Ti is used. Electron Beam Welding (EBW) is extensively employed. TIG welding is adopted only in a few cases.
- Much better joints can be obtained by EBW of alloy grade Ti. By welding in a vacuum chamber, gas absorption is prevented.
- The HAZ is very narrow and influence of welding on structure is minimal.
- Complicated work-pieces can be welded without distortion.
- Components with large wall thickness as well as thin walled components can also be successfully welded.

Advantages of EBW

- Narrow welds can be made on thicker sections with deeper penetration with minimal thermal disturbances.
- This makes the process suitable for welding in titanium, niobium, tungsten, tantalum, beryllium, nickel alloys and magnesium, mostly in aerospace and space research sectors.
- Because welding is performed in a vacuum, there is no atmospheric contamination; accurate control of welding parameters is possible by controlling the electron beam power and accurate beam focus.
- Excellent welds can be made even on more reactive metals.
- Lack of thermal disturbance in the process means that there is minimum shrinkage and distortion.

EBW is suitable for welding many materials which are either complicated or impossible to weld using fusion welding techniques such as titanium, magnesium, tungsten, and aluminium alloys (MAS, 2007).

Both very thin and very thick work pieces can be welded by EBW in just a single pass, with a very high depth/width ratio compared to TIG welding as shown in Figure 10 (Electron Beam Industries, 2007). A small HAZ means that there are fewer defects in materials welded by EBW than there would potentially be in an equivalent fusion weld. The process can be automated in order to produce complex and intricate welds.

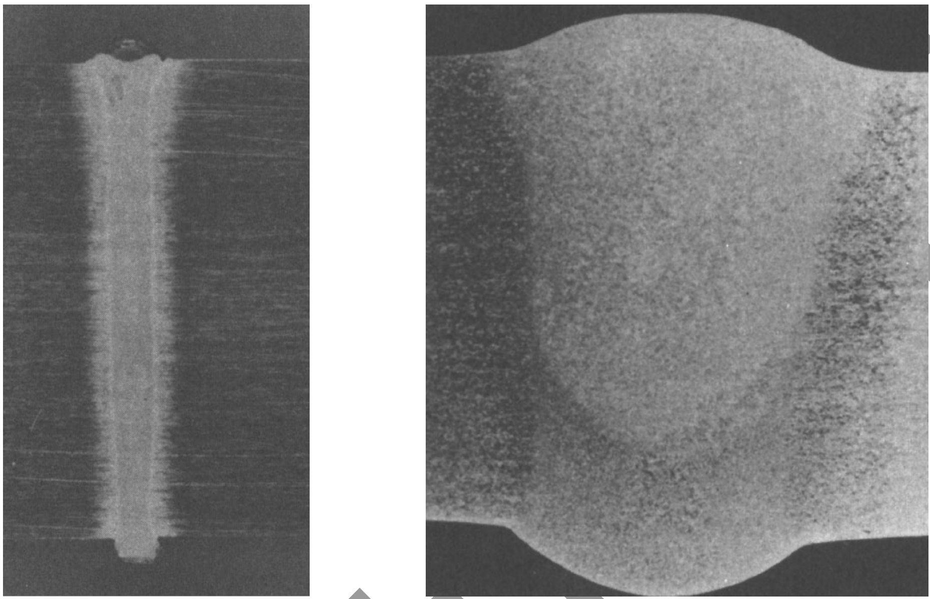

Figure 10: Comparison of the size of weld beads: (a) Laser beam or electron beam welding (b) Tungsten arc welding (Source: Manufacturing Engineering and Technology, Fifth Edition, by Serope Kalpakjian and Steven Schmid. ISBN 0-13-148965-8. 2006 Pearson Education, Inc. PP 957)

Limitations of EBW

- The process usually takes place in a vacuum; this means that the work piece must be setup in a vacuum chamber which then must be evacuated before the welding can take place. This can be time consuming and reduces the production efficiency of the system.
- The workforce must be protected while the system is in process due to the radiation which is generated by the electrons impacting with the work piece (MAS, 2007). Expensive safety measures must be in place.
- Electron beam equipment is very expensive compared to conventional welding equipment.
- If welding in a vacuum the size of the material to weld must be smaller than that of the vacuum chamber, meaning larger and more expensive equipment is required to

weld large pieces (Wikipedia, 2007). Welding in a chamber also means that the welding hardware is not easily portable.

- The pumps required to remove the air from the vacuum chamber completely are expensive (Wikipedia, 2007).

Laser Beam Welding (LBW)

LBW utilizes a high-power laser beam as the source of heat, to produce a fusion weld. Because the beam can be focused on to a very small area, it has high energy density and deep-penetrating capability. A schematic illustration of laser welding of titanium allows is shown in Figure 11.

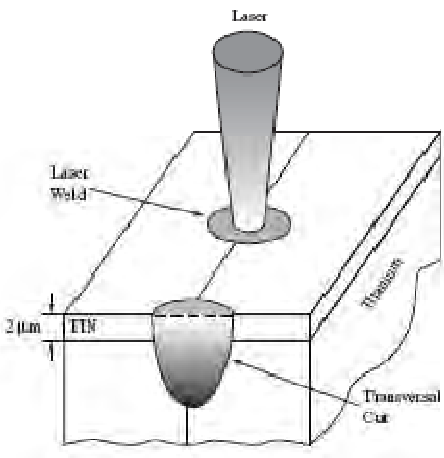

Figure 11: Schematic illustration of laser welding (Sergio and Lima 2005)

Advantages of LBW

- LBW produces welds of good quality with minimum shrinkage and distortion
- Laser welds have good strength, generally low hardness (ductile) and free of porosity
- The process can be automated
- Narrow welding seam
- Low energy input per seam length
- Reduced heat affected zone (HAZ)
- Very high welding speed (ranges from 2.5 m/min to as high as 80 m/min)

Resistance welding (RW)

Resistance Welding is a welding process in which work pieces are welded due to a combination of a pressure applied to them and a localized heat generated by a high electric current flowing through the contact area of the weld.

Different metals and alloys such as low carbon steels, aluminium alloys, alloy steels, medium carbon and high carbon steels can be welded by resistance welding. However, for high carbon contained steels, the weld bed can be harder (less brittle).

Resistance Welding (RW) is used for joining vehicle body parts, fuel tanks, domestic radiators, pipes of gas oil and water pipelines, wire ends, turbine blades, railway tracks.

The most popular methods of Resistance Welding are:

- Spot welding
- Flash welding
- Resistance butt welding
- Seam welding

Advantages of resistance welding

- High welding rates;
- Low fumes;
- Cost effectiveness;
- Easy automation;
- No filler materials are required;
- Low distortions.

Disadvantages of resistance welding

- High equipment cost;
- Low strength discontinuous welds;
- Thickness of welded sheets is limited - up to 6 mm.

Spot welding

Spot Welding is a Resistance Welding process, in which two or more overlapped metal sheets are joined by spot welds. The method uses pointed copper electrodes providing passage of electric current. The electrodes also transmit pressure required for formation of strong weld. Diameter of the weld spot is in the range 3 - 12 mm. Spot welding is widely used in automotive industry for joining vehicle body parts.

Flash welding

Flash Welding is a Resistance welding process, in which ends of rods (tubes, sheets) are heated and fused by an arc struck between them and then (brought into a contact under a pressure) producing a weld. The welded parts are held in electrode clamps, one of which is stationary and the second is movable.

Flash Welding method permits fast (about 1 min.) joining of large and complex parts. Welded parts are often annealed for improvement of toughness of the weld. Steels, Aluminium, Copper alloys, Magnesium alloys and Nickel alloys may be welded by flash welding. Thick pipes, ends of band saws, frames, and aircraft landing gears are produced by Flash Welding.

Resistance butt welding

Resistance Butt Welding is a Resistance Welding process, in which ends of wires or rods are held under a pressure and heated by an electric current passing through the contact area and producing a weld. The process is similar to Flash Welding however in Butt Welding pressure and electric current are applied simultaneously in contrast to Flash Welding where electric current is followed by forging pressure application.

Resistance seam welding

Seam welding is a Resistance Welding process of continuous joining of overlapping sheets by passing them between two rotating electrode wheels. Heat generated by the electric current flowing through the contact area and pressure provided by the wheels are sufficient to produce a leak-tight weld.

Friction welding

Friction welding uses pressure and frictional heat caused by mechanical rubbing, usually by rotation. In this process, the parts are rotated at high speed and brought together. The heat generated on contact causes the parts to fuse together.

Typical use: Automotive components, agriculture equipment, joining high speed steel ends and twist drills.

Process can be automated. Economics: Capital costs are high but tooling costs are low.

The weld joint and quality of welding

There are three distinct zones formed in a typical weld joint.

Fusion zone

The area of base metal and filler metal that has been completely melted

Weld interface

A thin area of base metal that was melted or partially melted but did not mix with the filler metal

Heat affected zone

The surrounding area of base metal that did not melt, but was heated enough to affect its grain structure

The metallurgy and properties of the heat affected and weld quality greatly depend on the type of metals joined, the particular joining process, the filler metals used (if any), and welding process available. Characteristics of s typical fusion weld zone in oxyfuel-gas and arc welding is shown in Figure 12.

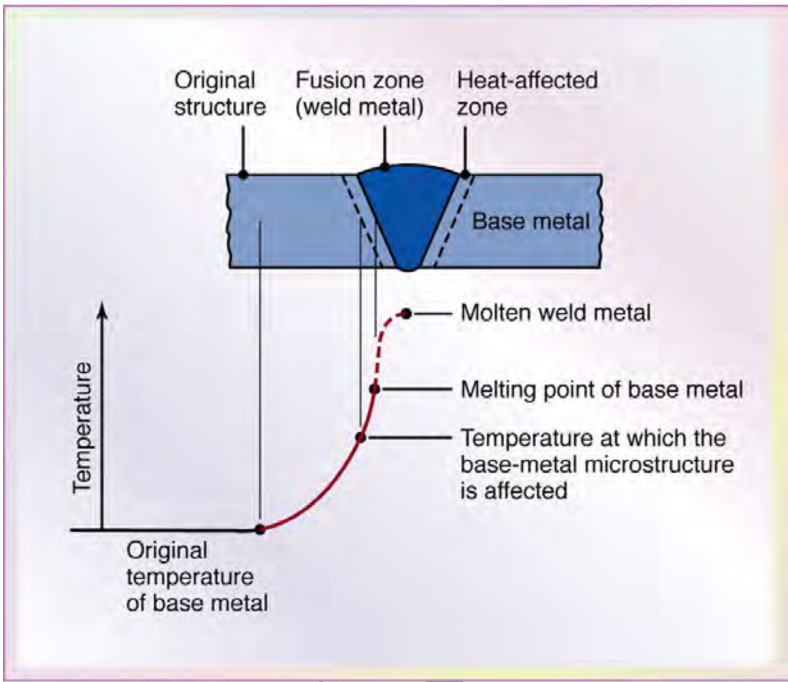

Figure 12: Characteristics of typical fusion welding (Source: Manufacturing Engineering and Technology, Fifth Edition, by Serope Kalpakjian and Steven Schmid. ISBN 0-13-148965-8. 2006 Pearson Education, Inc. PP 960)

Heat affected zone

- The heat-affected zone is the narrow region of the base metal adjacent to the weld bead, which is metallurgically altered by the heat of welding. It has a microstructure different from that of base metal prior to welding.
- The heat-affected zone is usually the major source of metallurgical problems in welding.
- The width of the heat-affected zone depends on the amount of heat input during welding and increases with the heat input.
- The properties and microstructure of the HAZ depends on the rate of heat input and cooling and the temperature to which this zone was raised.

Effect of HAZ

- If the workpiece material was previously cold worked, this HAZ may have experienced recrystallization and grain growth, and thus a diminishment of strength, hardness, and toughness. The strength and hardness of HAZ depend partly on how the original strength and hardness of the base metal was developed prior to the welding.
- Upon cooling, residual stresses may form in this region that weakens the joint.
- It can also lead to loss of corrosion resistance in stainless steels and nickel-base alloys.
- For steels, the material in this zone may have been heated to temperatures sufficiently high so as to form austenite. Upon cooling to room temperature, the microstructural products that form depend on cooling rate and alloy composition
- For plain carbon steels, normally pearlite and a proeutectoid phase will be present
- For alloy steels, one micro-structural product phase may be martensite, which is ordinarily undesirable because it is so brittle

Failures of welded joints

Weldaments failures may occur due to various reasons. One of the main reasons of failure in welding arises as a result of thermal cycling and its attendant microstructural changes, causing to develop various ***discontinuities***. Failures in service may arise from fracture, wear, corrosion or deformation. Poor workmanship and improper selection of welding procedures and filler-metal composition account for numerous arc-weld failures.

According to Glover and Hauser [ ], some discontinuities that can serve as failure origins of arc welded parts are found only in welds made by a particular process, but most discontinuities may be produced by any of the welding processes.

The major discontinuities found in arc welded joints are:

- Slag inclusions
- Porosity
- Grove overfill or underfill
- Cracks
- Lamellar tears
- Embrittlement

Slag inclusions

Slag inclusions are compounds such as pieces of slag trapped inside solidified weld pool; may result from excessive stirring in weld pool, or failure to remove slag from prior weld. If shielding gases are not effective during welding, contamination from the environment also may contribute to such inclusions.

Slag inclusions can be prevented by:

- Cleaning weld bed surface before the next layer deposited
- By providing sufficient shielded gases
- Proper designing of joints

Porosity

Porosity or fine holes or pores within the weld metal can occur by absorption of evolved gases and chemical reaction. Metals susceptible to porosity are those which can dissolve large quantities of gas contaminates (hydrogen, oxygen, nitrogen etc) in the molten weld pool and subsequently reject most of the gas during solidification. Aluminium alloys are more susceptible to porosity than any other structural material. Weld cooling rates substantially affects the volume of porosity.

- At fast cooling rates, the level of porosity can be low
- Similarly, at slow cooling rates, porosity is minimal because bubbles have ample time to coalesce, float, and escape from the weld pool.
- At intermediate cooling rates, the greatest volume of porosity in a weld is observed, as conditions are optimum for both formation and entrapment of virtually all of the evolved gases in the weld.

Types of porosity

According to According to Glover and Hauser [ ], porosity can be grouped into three different types:

Isolated: caused by a phenomenon similar to boiling when the arc power is too far avbove the ideal level.

Linear: caused from interaction of components of the shielding gas, such as oxygen, hydrogen, or carbon dioxide, with the weld puddle to evolve a gas, such as hydrogen sulphide.

Cluster: caused when cover of shielding gas is inadequate or when welding is done on wet base metal.

Sources of porosity:

Moisture, oils, paints, rust, mill scale, oxygen and hydrogen and their chemical reaction are the major sources of porosity.

How to avoid porosity

- Following standard of workmanship
- Following standard welding codes
- Improved welding techniques such as preheating the weld area and increasing the rate of heat input
- Reduce welding speed to allow gas to escape
- Electrodes are dried

Incomplete fusion and penetration

Incomplete fusion is termed as fusion which does not occur over the entire base metal surfaces intended for welding and between adjoining weld beads. Incomplete fusion can result from insufficient heat input or the improper manipulation of the welding electrode. While it is a discontinuity more commonly associated with weld technique, it could also be caused by the presence of contaminants on the surface being welded. Incomplete penetration occurs when the depth of welded joint is insufficient. A schematic illustration of various discontinuities in fusion welds is shown in Figure 13.

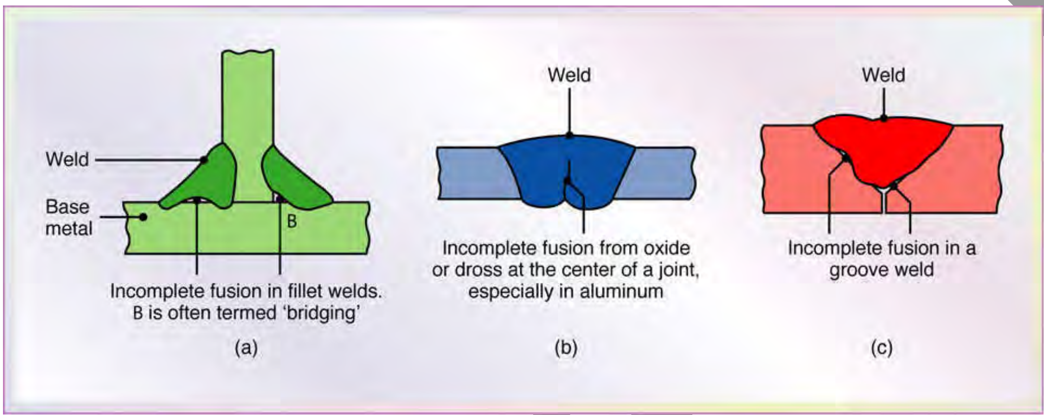

Figure 13: Examples of various discontinuities in fusion welding (Source: Manufacturing Engineering and Technology, Fifth Edition, by Serope Kalpakjian and Steven Schmid. ISBN 0-13-148965-8. 2006 Pearson Education, Inc. PP 963)

Incomplete fusion and penetration can be improved by:

- By raising the temperature
- Cleaning the weld area before welding
- Modifying the weld design
- Providing sufficient shielding gases
- Reducing the travel speed during the welding

Cracks

Cracks in welding occur is various locations and directions in the weld area as a result from hot tearing or cold cracking.

- Hot tearing or hot cracks (solidification crack) occurs when shrinkage during solidification tears mushy (liquid – solid) weld – physical constraints against shrinkage may exacerbate the problem. Hot cracking results from internal stress developed on cooling following solidification. This defect occurs at a temperature above the solidus of an alloy.
- Cold cracking or hydrogen cracking typically occurs after weld freezes, and residual stresses are sufficient to cause cracks – hours/days later.

Cause of crack formation

- by welding fixtures that do not permit contraction of the weld during cooling,
- by narrow joints with large depth-to-width ratios,
- by poor ductility of the deposited weld metal,
- or by a high coefficient of thermal expansion coupled with low-heat conductivity in the parent metal

Methods to minimize hot cracking

- Maintenance of adequate manganese-to-sulfur ratio
- Reduction of sulfur, phosphorus, carbon and niobium to minimal amounts
- Reduction of the tensile restraint exerted on the weld

Hydrogen cracking or **cold cracking** occurs in the heat-affected zone of some steels as hydrogen diffuses into this region when the weld cools. Hydrogen cracking is caused by atomic hydrogen.

The sources of atomic hydrogen are

- organic material,
- chemically bonded water in the electrode coating,
- absorbed water in the electrode coating,
- and moisture on the steel surface at the location of the weld

Methods of minimising hydrogen cracking

- Using low-hydrogen electrodes, which includes baking and storing them in a low-temperature oven
- Preheating the surface of the steel before welding to remove moisture
- Post-weld heat treating immediately to force the hydrogen to escape
- Peening immediately after each pass is also beneficial because it induces compressive stresses and offsets the tendency toward cracking.

Undercut and underfill

Undercut – combination of underfill and overly aggressive arc; leaves a sharp- edged hole in surface. Underfill – insufficient filler metal used in welding; may result from excessive welding velocity.

Residual stresses

Due to localised heating and cooling during welding, the expansion and contraction of the weld area causes residual stresses. At completion of the weld thermal cycle the weldament either distorts or if restrained will contain residual stress. Residual stress fields are complex, Stresses may need to be removed by a stress relief heat treatment process.

Mechanical fasteners advantages

- Fairly easy application
- Low capital for equipment needed to apply
- Nominal labor and provides good product aesthetics
- Dissimilar materials
- Different thicknesses

Disadvantages of mechanical fasteners

- Higher component costs leads pre-fabricated fasteners inventory
- Expensive preparation
- Smaller contact limits bond to materials lowers the load performance
- Prone to loosening, weakening, rusting increases noise source
- High stress around the holes

Adhesive bonding advantages

- Permits joining of materials with dissimilar coefficients of expansion and contraction
- Allows components to be designed with an "invisible" means of attachment
- No localised stresses as in welding-distributes joint stresses
- Flexible surface preparation
- Can be made electrically conductive or non-conductive
- Absorbs vibrations
- Reduces the weight of assembly
- Fills voids

Disadvantages of adhesive bonding

- Complicates quality control of bonds
- May not withstand high or low temperatures (most adhesives cannot be used at service temperature above 300 ^{o}C)
- Bonded joints are weaker under cleavage and peel loading than under tension or shear (Poor joint design = failure)
- Some require mixing of two or more components
- Requires careful surface preparation
- Parts need to be held in place (fixtured) during bond formation
- Adhesive materials are perishable
- Adhesives are susceptible to environmental degradation
- Shortage of design data
- Lack of code of practice
- Lack of confidence in use

Adhesive bonding design guidelines

Maximise these forces:

- **Shear,**
- **tension or compression**

Minimise these forces:

- **Peel, cleavage**
- **Increase bond area**
- **Wider is better than overlap**
- **Minimise thickness gap**

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