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12. REFERENCES
1. Welding

Welding is a metal-joining process in which coalescence is obtained by heat and pressure. It may also be defined as a metallurgical bond accomplished by the attracting forces between atoms. Before these atoms can be bonded together, absorbed vapors and oxides on contacting surfaces must be overcome. The number one enemy to welding is oxidation, and, consequently, many welding processes are performed in a controlled environment or shielded by an inert atmosphere. If force is applied between two smooth metal surfaces to be joined, some crystals will crush through the surfaces and be in contact. As more and more pressure is applied, these areas spread out and other contacts are made. The brittle oxide layer is broken and fragmented as the metal is deformed plastically. Coalescence is obtained when the boundaries between the two surfaces are mainly crystalline planes. This process, known as cold welding, will be discussed further in this chapter. The breaking through or elimination of surface oxide layers happens when a weld is made.

If temperature is added to pressure the welding of two surfaces will be facilitated, and coalescence is obtained in the same manner as cold-pressure welding. As temperature is increased the ductility of the base metal is increased and atomic diffusion progresses more rapidly. Nonmetallic materials on interfacial surfaces are softened, permitting them to be removed or broken up by plastic flow of the base materials. Hot-pressure welds are more efficient but not necessarily stronger if the atom-to-atom bond is the same.

Many welding processes have been developed. They differ widely in the manner that heat is applied and in the equipment used. The principal processes are listed here.

**WELDING PROCESSES**

1. Braze welding
   A. Torch
   B. Furnace
   C. Induction
   D. Resistance
   E. Dip
   F. Infrared

II. Forge welding
   A. Manual
   B. Machine
   1. Rolling
   2. Hammer
   3. Die

III. Gas welding
   A. Oxyacetylen
   B. Oxyhydrogen
   C. Air acetylene
   D. Pressure

IV. Resistance welding
   A. Spot
   B. Projection
   C. Seam
   D. Butt
   E. Flash
2. Welding processes

2.1. Arc welding

These processes use a welding power supply to create and maintain an electric arc between an electrode and the base material to melt metals at the welding point. They can use either direct (DC) or alternating (AC) current, and consumable or non-consumable electrodes. The welding region is sometimes protected by some type of inert or semi-inert gas, known as a shielding gas, and filler material is sometimes used as well. To supply the electrical energy necessary for arc welding processes, a number of different power supplies can be used. The most common classification is constant current power supplies and constant voltage power supplies. In arc welding, the voltage is directly related to the length of the arc, and the current is related to the amount of heat input. Constant current power supplies are most often used for manual welding processes such as gas tungsten arc welding and shielded metal arc welding, because they maintain a relatively constant current even as the voltage varies. This is important because in manual welding, it can be difficult to hold the
electrode perfectly steady, and as a result, the arc length and thus voltage tend to fluctuate. Constant voltage power supplies hold the voltage constant and vary the current, and as a result, are most often used for automated welding processes such as gas metal arc welding, flux cored arc welding, and submerged arc welding. In these processes, arc length is kept constant, since any fluctuation in the distance between the wire and the base material is quickly rectified by a large change in current. For example, if the wire and the base material get too close, the current will rapidly increase, which in turn causes the heat to increase and the tip of the wire to melt, returning it to its original separation distance. [2]

The type of current used in arc welding also plays an important role in welding. Consumable electrode processes such as shielded metal arc welding and gas metal arc welding generally use direct current, but the electrode can be charged either positively or negatively. In welding, the positively charged anode will have a greater heat concentration, and as a result, changing the polarity of the electrode has an impact on weld properties. If the electrode is positively charged, it will melt more quickly, increasing weld penetration and welding speed. Alternatively, a negatively charged electrode results in more shallow welds. [7] Nonconsumable electrode processes, such as gas tungsten arc welding, can use either type of direct current, as well as alternating current. However, with direct current, because the electrode only creates the arc and does not provide filler material, a positively charged electrode causes shallow welds, while a negatively charged electrode makes deeper welds. Alternating current rapidly moves between these two, resulting in medium-penetration welds. One disadvantage of AC, the fact that the arc must be re-ignited after every zero crossing, has been addressed with the invention of special power units that produce a square wave pattern instead of the normal sine wave, making rapid zero crossings possible and minimizing the effects of the problem.

2.1.2. Processes

![Shielded metal arc welding](image)

Fig. Shielded metal arc welding

One of the most common types of arc welding is shielded metal arc welding (SMAW), which is also known as manual metal arc welding (MMA) or stick welding. Electric current is used to strike an arc between the base material and consumable electrode rod, which is made of steel and is covered with a flux that protects the weld area from oxidation and contamination by producing CO₂ gas during the welding process. The electrode core itself acts as filler material, making a separate filler unnecessary.

The process is versatile and can be performed with relatively inexpensive equipment, making it well suited to shop jobs and field work. [6] An operator can become
reasonably proficient with a modest amount of training and can achieve mastery with experience. Weld times are rather slow, since the consumable electrodes must be frequently replaced and because slag, the residue from the flux, must be chipped away after welding. Furthermore, the process is generally limited to welding ferrous materials, though speciality electrodes have made possible the welding of cast iron, nickel, aluminium, copper, and other metals. Inexperienced operators may find it difficult to make good out-of-position welds with this process.

Gas metal arc welding (GMAW), also known as metal inert gas or MIG welding, is a semi-automatic or automatic process that uses a continuous wire feed as an electrode and an inert or semi-inert gas mixture to protect the weld from contamination. As with SMAW, reasonable operator proficiency can be achieved with modest training. Since the electrode is continuous, welding speeds are greater for GMAW than for SMAW. Also, the smaller arc size compared to the shielded metal arc welding process makes it easier to make out-of-position welds (e.g., overhead joints, as would be welded underneath a structure).

The equipment required to perform the GMAW process is more complex and expensive than that required for SMAW, and requires a more complex setup procedure. Therefore, GMAW is less portable and versatile, and due to the use of a separate shielding gas, is not particularly suitable for outdoor work. However, owing to the higher average rate at which welds can be completed, GMAW is well suited to production welding. The process can be applied to a wide variety of metals, both ferrous and non-ferrous.

A related process, flux-cored arc welding (FCAW), uses similar equipment but uses wire consisting of a steel electrode surrounding a powder fill material. This cored wire is more expensive than the standard solid wire and can generate fumes and/or slag, but it permits even higher welding speed and greater metal penetration.

Gas tungsten arc welding (GTAW), or tungsten inert gas (TIG) welding (also sometimes erroneously referred to as heliarc welding), is a manual welding process that uses a nonconsumable tungsten electrode, an inert or semi-inert gas mixture, and a separate filler material. Especially useful for welding thin materials, this method is characterized by a stable arc and high quality welds, but it requires significant operator skill and can only be accomplished at relatively low speeds.

GTAW can be used on nearly all weldable metals, though it is most often applied to stainless steel and light metals. It is often used when quality welds are extremely
important, such as in bicycle, aircraft and naval applications. A related process, plasma arc welding, also uses a tungsten electrode but uses plasma gas to make the arc. The arc is more concentrated than the GTAW arc, making transverse control more critical and thus generally restricting the technique to a mechanized process. Because of its stable current, the method can be used on a wider range of material thicknesses than can the GTAW process, and furthermore, it is much faster. It can be applied to all of the same materials as GTAW except magnesium, and automated welding of stainless steel is one important application of the process. A variation of the process is plasma cutting, an efficient steel cutting process.

Submerged arc welding (SAW) is a high-productivity welding method in which the arc is struck beneath a covering layer of flux. This increases arc quality, since contaminants in the atmosphere are blocked by the flux. The slag that forms on the weld generally comes off by itself, and combined with the use of a continuous wire feed, the weld deposition rate is high. Working conditions are much improved over other arc welding processes, since the flux hides the arc and almost no smoke is produced. The process is commonly used in industry, especially for large products and in the manufacture of welded pressure vessels. Other arc welding processes include atomic hydrogen welding, carbon arc welding, electroslag welding, electrogas welding, and stud arc welding.

![Fig. Gas welding a steel armature using the oxy-acetylene process.](image)

**Electrode.**

An electrode is an electrical conductor used to make contact with a metallic part of a circuit (e.g. a semiconductor, an electrolyte or a vacuum). The word was coined by the scientist Michael Faraday from the Greek words *elektron* (meaning amber, from which the word electricity is derived) and *hodos*, a way.

**2.1.3. Anode and cathode in electrochemical cells**
An electrode in an electrochemical cell is referred to as either an anode or a cathode, words that were also coined by Faraday. The anode is now defined as the electrode at which electrons leave the cell and oxidation occurs, and the cathode as the electrode at which electrons enter the cell and reduction occurs. Each electrode may become either the anode or the cathode depending on the voltage applied to the cell. A bipolar electrode is an electrode that functions as the anode of one cell and the cathode of another cell.

2.1.4. Primary cell

A primary cell is a special type of electrochemical cell in which the reaction cannot be reversed, and the identities of the anode and cathode are therefore fixed. The anode is always the negative electrode. The cell can be discharged but not recharged.

2.1.5. Secondary cell

The case in an electrolytic cell. When the cell is being discharged, it behaves like a primary or voltaic cell, with the anode as the negative electrode and the cathode as the positive.

2.1.6. Other anodes and cathodes

In a vacuum tube or a semiconductor having polarity (diodes, electrolytic capacitors) the anode is the positive (+) electrode and the cathode the negative (−). The electrons enter the device through the cathode and exit the device through the anode.

In a three-electrode cell, a counter electrode, also called an auxiliary electrode, is used only to make a connection to the electrolyte so that a current can be applied to the working electrode. The counter electrode is usually made of an inert material, such as a noble metal or graphite, to keep it from dissolving.
2.1.7. Welding electrodes

In arc welding an electrode is used to conduct current through a workpiece to fuse two pieces together. Depending upon the process, the electrode is either consumable, in the case of gas metal arc welding or shielded metal arc welding, or non-consumable, such as in gas tungsten arc welding. For a direct current system the weld rod or stick may be a cathode for a filling type weld or an anode for other welding processes. For an alternating current arc welder the welding electrode would not be considered an anode or cathode.

2.1.8. Alternating current electrodes

For electrical systems which use alternating current the electrodes are the connections from the circuitry to the object to be acted upon by the electrical current but are not designated anode or cathode since the direction of flow of the electrons changes periodically, usually many times per second.

2.1.9. Types of electrode

- Electrodes for medical purposes, such as EEG, ECG, ECT, defibrillator
- Electrodes for electrophysiology techniques in biomedical research
- Electrodes for execution by the electric chair
- Electrodes for electroplating
- Electrodes for arc welding
- Electrodes for cathodic protection
- Inert electrodes for electrolysis (made of platinum)

2.2. Gas welding

Gas welding includes all he processes in which gases are used in combination to obtain a hot flame. Those commonly used are acetylene, natural gas, and hydrogen in combination with oxygen. Oxyhydrogen welding was the first gas process to be commercially developed. The maximum temperature developed by this process is 3600 F (1980 C). Hydrogen is produced by either the electrolysis of water or passing steam over coke(1). The most used combination is the oxyacetylene process, which has a flame temperature of 6300 F (3500 C).

Oxyacetylene Welding. An oxyacetylene weld is produced by heating with a flame obtained from the combustion of oxygen and acetylene with or without the use of a filler metal. Most often the joint is heated to a state of fusion and as a rule no pressure is used. Oxygen is produced by both electrolysis and liquification of air. Electrolysis separates water into hydrogen and oxygen by passing an electric current through it. Most commercial oxygen is made by liquefying air and separating the oxygen from the nitrogen. It is stored in steel cylinders at a pressure of 2000 psi (14 MPa).

Acetylene gas (C₂H₂) is obtained by dropping lumps of calcium carbide in water. The gas bubbles through the water, and any precipitate is slaked lime. The reaction that takes place in an acetylene generator is

\[ \text{CaC}_2 + 2\text{H}_2\text{O} = \text{Ca(OH)}_2 + \text{C}_2\text{H}_2 \]
The perfect gas laws describe the amount of gas available at a regulated pressure from a pressurized cylinder\(^{(1)}\). That is;
\[ P_1V_1/T_1 = P_2V_2/T_2 \]
Where \( P_1, V_1, \) and \( T_1 \) refer to the pressure, volume, and absolute temperature in the cylinder; \( P_2, V_2, T_2 \) refer to the regulated pressure, volume, and temperature. The absolute temperature is \( T = 460 + t \) F. If the cylinder and regulated temperatures are the same or nearly so, then
\[ P_1V_1 = P_2V_2 \]

### 2.2.1. Equipment

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

### 2.2.2. Welding gun and wire feed unit

![GMAW torch nozzle cutaway image](image1.png)

Fig. GMAW torch nozzle cutaway image. (1) Torch handle, (2) Molded phenolic dielectric (shown in white) and threaded metal nut insert (yellow), (3) Shielding gas nozzle, (4) Contact tip, (5) Nozzle output face

![GMAW wire feed unit](image2.png)

Fig. A GMAW wire feed unit
The typical GMAW welding gun has a number of 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 the 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 passage of the electrode while maintaining an electrical contact. Before arriving at 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 is used to evenly direct the shielding gas into the welding zone—if the flow is inconsistent, it may not provide adequate protection of the weld area. Larger nozzles provide greater shielding gas flow, which is useful for high current welding operations, in which the size of the molten weld pool is increased. The gas is supplied to the nozzle through a gas hose, which is connected to the tanks of shielding gas. 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 30.5 m/min (1200 in/min), but feed rates for semiautomatic GMAW typically range from 2 to 10 m/min (75–400 in/min).

### 2.2.3. Power supply

Most applications of gas metal arc welding use a constant voltage power supply. As a result, any change in arc length (which is directly related to voltage) results in a large change in heat input and current. A shorter arc length will cause a much greater heat input, which will make the wire electrode melt more quickly and thereby restore the original arc length. This helps operators keep the arc length consistent even when manually welding with hand-held welding guns. To achieve a similar effect, sometimes a constant current power source is used in combination with an arc voltage-controlled wire feed unit. In this case, a change in arc length makes the wire feed rate adjust in order to maintain a relatively constant arc length. In rare circumstances, a constant current power source and a constant wire feed rate unit might be coupled, especially for the welding of metals with high thermal conductivities, such as aluminum. This grants the operator additional control over the heat input into the weld, but requires significant skill to perform successfully.

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 not popular, a negatively charged electrode is rarely employed.

### 2.2.4. Electrode
The selection of an electrode to be used in GMAW is a complicated decision, as it depends on the process variation being used, the composition of the metal being welded, the joint design, and the material surface conditions. The choice of an electrode strongly influences the mechanical properties of the weld area, making it a key factor in weld quality. In general, it is desirable that the welded metal have mechanical properties similar to those of the base material, and that there be no discontinuities, such as porosity, within the weld. To achieve these goals in different materials using different GMAW variations, a wide variety of electrodes exist. All contain deoxidizing metals such as silicon, manganese, titanium, and aluminum in small percentages to help prevent oxygen porosity, and some contain denitrizing metals such as titanium and zirconium to avoid nitrogen porosity. Depending on the process variation and base material being used, the diameters of the electrodes used in GMAW 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 are associated with short-circuiting metal transfer, while the pulsed spray mode generally uses electrodes of at least 1.6 mm (0.06 in).

Fig. GMAW Circuit diagram. (1) Welding torch, (2) Workpiece, (3) Power source, (4) Wire feed unit, (5) Electrode source, (6) Shielding gas supply.

2.2.5. Shielding gas

Shielding gases are necessary for gas metal arc welding to protect the welding area from atmospheric gases such as nitrogen and oxygen, which can cause fusion defects, porosity, and weld metal embrittlement if they come in contact with the electrode, the arc, or the welding metal. This problem is common to all arc welding processes, but instead of a shielding gas, many arc welding methods utilize a flux material which disintegrates into a protective gas when heated to welding temperatures. In GMAW, however, the electrode wire does not have a flux coating, and a separate shielding gas is employed to protect the weld. This eliminates slag, the hard residue from the flux that builds up after welding and must be chipped off to reveal the completed weld.

The choice of a shielding gas depends on several factors, most importantly the type of material being welded and the process variation being used. Pure inert gases such as argon and helium are only used for nonferrous welding; with steel they cause an erratic arc and encourage spatter (with helium) or do not provide adequate weld penetration (argon). Pure carbon dioxide, on the other hand, allows for deep penetration welds but encourages oxide formation, which adversely affect the mechanical properties of the weld. Its low cost makes it an attractive choice, but because of the violence of the arc, spatter is unavoidable and welding thin materials is difficult. As a result, argon and carbon dioxide are frequently mixed in a 75%/25%
or 80%/20% mixture, which reduces spatter and makes it possible to weld thin steel workpieces.

Argon is also commonly mixed with other gases, such as oxygen, helium, hydrogen, and nitrogen. The addition of up to 5% oxygen encourages spray transfer, which is critical for spray-arc and pulsed spray-arc GMAW. However, more oxygen makes the shielding gas oxidize the electrode, which can lead to porosity in the deposit if the electrode does not contain sufficient deoxidizers. An argon-helium mixture is completely inert, and is used on nonferrous materials. A helium concentration of 50%–75% raises the voltage and increases the heat in the arc, making it helpful for welding thicker workpieces. Higher percentages of helium also improve the weld quality and speed of using alternating current for the welding of aluminum. Hydrogen is added to argon in small concentrations (up to about 5%) for welding nickel and thick stainless steel workpieces. In higher concentrations (up to 25% hydrogen), it is useful for welding conductive materials such as copper. However, it should not be used on steel, aluminum or magnesium because of the risk of hydrogen porosity. Additionally, nitrogen is sometimes added to argon to a concentration of 25%–50% for welding copper, but the use of nitrogen, especially in North America, is limited. Mixtures of carbon dioxide and oxygen are similarly rarely used in North America, but are more common in Europe and Japan.

Recent advances in shielding gas mixtures use three or more gases to gain improved weld quality. A mixture of 70% argon, 28% carbon dioxide and 2% oxygen is gaining in popularity for welding steels, while other mixtures add a small amount of helium to the argon-oxygen combination, resulting in higher arc voltage and welding speed. Helium is also sometimes used as the base gas, to which smaller amounts of argon and carbon dioxide are added. Additionally, other specialized and often proprietary gas mixtures claim to offer even greater benefits for specific applications.[6]

The desirable rate of gas flow depends primarily on weld geometry, speed, current, the type of gas, and the metal transfer mode being utilized. Welding flat surfaces requires higher flow than welding grooved materials, since the gas is dispersed more quickly. Faster welding speeds mean that more gas must be supplied to provide adequate coverage. Additionally, higher current requires greater flow, and generally, more helium is required to provide adequate coverage than argon. Perhaps most importantly, the four primary variations of GMAW have differing shielding gas flow requirements—for the small weld pools of the short circuiting and pulsed spray modes, about 10 L/min (20 ft³/h) is generally suitable, while for globular transfer, around 15 L/min (30 ft³/h) is preferred. The spray transfer variation normally requires more because of its higher heat input and thus larger weld pool; along the lines of 20–25 L/min (40–50 ft³/h).[9]

2.2.6. Operation
In most of its applications, gas metal arc welding is a fairly simple welding process to learn, requiring no more than several days to master basic welding technique. Even when welding is performed by well-trained operators, however, weld quality can fluctuate, since it depends on a number of external factors. And all GMAW is dangerous, though perhaps less so than some other welding methods, such as shielded metal arc welding.\cite{9}

### 2.2.7. Technique

The basic technique for GMAW is quite simple, since the electrode is fed automatically through the torch. In gas tungsten arc welding, the welder must handle a welding torch in one hand and a separate filler wire in the other, and in shielded metal arc welding, the operator must frequently chip off slag and change welding electrodes. GMAW, on the other hand, requires only that the operator guide the welding gun with proper position and orientation along the area being welded. Keeping a consistent contact tip-to-work distance (the *stickout* distance) is important, because a long stickout distance can cause the electrode to overheat and will also waste shielding gas. The orientation of the gun is also important—it should be held so as to bisect the angle between the workpieces; that is, at 45 degrees for a fillet weld and 90 degrees for welding a flat surface. The travel angle or lead angle is the angle of the torch with respect to the direction of travel, and it should generally remain approximately vertical. However, the desirable angle changes somewhat depending on the type of shielding gas used—with pure inert gases, the bottom of the torch is out often slightly in front of the upper section, while the opposite is true when the welding atmosphere is carbon dioxide.\cite{1}

### 2.2.8. Quality

Two of the most prevalent quality problems in GMAW are dross and porosity. If not controlled, they can lead to weaker, less ductile welds. Dross is an especially common problem in aluminum GMAW welds, normally coming from particles of aluminum oxide or aluminum nitride present in the electrode or base materials. Electrodes and workpieces must be brushed with a wire brush or chemically treated...
to remove oxides on the surface. Any oxygen in contact with the weld pool, whether from the atmosphere or the shielding gas, causes dross as well. As a result, sufficient flow of inert shielding gases is necessary, and welding in volatile air should be avoided.[2]

In GMAW the primary cause of porosity is gas entrapment in the weld pool, which occurs when the metal solidifies before the gas escapes. The gas can come from impurities in the shielding gas or on the workpiece, as well as from an excessively long or violent arc. Generally, the amount of gas entrapped is directly related to the cooling rate of the weld pool. Because of its higher thermal conductivity, aluminum welds are especially susceptible to greater cooling rates and thus additional porosity. To reduce it, the workpiece and electrode should be clean, the welding speed diminished and the current set high enough to provide sufficient heat input and stable metal transfer but low enough that the arc remains steady. Preheating can also help reduce the cooling rate in some cases by reducing the temperature gradient between the weld area and the base material.[3]

### 2.2.9. Safety

Gas metal arc welding can be dangerous if proper precautions are not taken. Since GMAW employs an electric arc, welders wear protective clothing, including heavy leather gloves and protective long sleeve jackets, to avoid exposure to extreme heat and flames. In addition, the brightness of the electric arc can cause arc eye, in which ultraviolet light causes the inflammation of the cornea and can burn the retinas of the eyes. Helmets with dark face plates are worn to prevent this exposure, and in recent years, new helmet models have been produced that feature a liquid crystal-type face plate that self-darkens upon exposure to high amounts of UV light. Transparent welding curtains, made of a polyvinyl chloride plastic film, are often used to shield nearby workers and bystanders from exposure to the UV light from the electric arc.[8,10]

Welders are also often exposed to dangerous gases and particulate matter. GMAW produces smoke containing particles of various types of oxides, and the size of the particles in question tends to influence the toxicity of the fumes, with smaller particles presenting a greater danger. Additionally, carbon dioxide and ozone gases can prove dangerous if ventilation is inadequate. Furthermore, because the use of compressed gases in GMAW pose an explosion and fire risk, some common precautions include limiting the amount of oxygen in the air and keeping combustible materials away from the workplace.[10]

### 2.3. Resistance welding

Resistance welding involves the generation of heat by passing current through the resistance caused by the contact between two or more metal surfaces. Small pools of molten metal are formed at the weld area as high current (1000–100,000 A) is passed through the metal. In general, resistance welding methods are efficient and
cause little pollution, but their applications are somewhat limited and the equipment cost can be high.

Fig. Spot welder

Spot welding is a popular resistance welding method used to join overlapping metal sheets of up to 3 mm thick. Two electrodes are simultaneously used to clamp the metal sheets together and to pass current through the sheets. The advantages of the method include efficient energy use, limited workpiece deformation, high production rates, easy automation, and no required filler materials. Weld strength is significantly lower than with other welding methods, making the process suitable for only certain applications. It is used extensively in the automotive industry—ordinary cars can have several thousand spot welds made by industrial robots. A specialized process, called shot welding, can be used to spot weld stainless steel.

Like spot welding, seam welding relies on two electrodes to apply pressure and current to join metal sheets. However, instead of pointed electrodes, wheel-shaped electrodes roll along and often feed the workpiece, making it possible to make long continuous welds. In the past, this process was used in the manufacture of beverage cans, but now its uses are more limited. Other resistance welding methods include flash welding, projection welding, and upset welding.

2.4. Energy beam welding

Energy beam welding methods, namely laser beam welding and electron beam welding, are relatively new processes that have become quite popular in high production applications. The two processes are quite similar, differing most notably in their source of power. Laser beam welding employs a highly focused laser beam, while electron beam welding is done in a vacuum and uses an electron beam. Both have a very high energy density, making deep weld penetration possible and minimizing the size of the weld area. Both processes are extremely fast, and are easily automated, making them highly productive. The primary disadvantages are their very high equipment costs (though these are decreasing) and a susceptibility to thermal cracking. Developments in this area include laser-hybrid welding, which uses principles from both laser beam welding and arc welding for even better weld properties.

2.5. Solid-state welding
Like the first welding process, forge welding, some modern welding methods do not involve the melting of the materials being joined. One of the most popular, ultrasonic welding, is used to connect thin sheets or wires made of metal or thermoplastic by vibrating them at high frequency and under high pressure. The equipment and methods involved are similar to that of resistance welding, but instead of electric current, vibration provides energy input. Welding metals with this process does not involve melting the materials; instead, the weld is formed by introducing mechanical vibrations horizontally under pressure. When welding plastics, the materials should have similar melting temperatures, and the vibrations are introduced vertically. Ultrasonic welding is commonly used for making electrical connections out of aluminum or copper, and it is also a very common polymer welding process.

Another common process, explosion welding, involves the joining of materials by pushing them together under extremely high pressure. The energy from the impact plasticizes the materials, forming a weld, even though only a limited amount of heat is generated. The process is commonly used for welding dissimilar materials, such as the welding of aluminum with steel in ship hulls or compound plates. Other solid-state welding processes include co-extrusion welding, cold welding, diffusion welding, friction welding (including friction stir welding), high frequency welding, hot pressure welding, induction welding, and roll welding.

3. Geometry

![Common welding joint types](image)

Fig. Common welding joint types – (1) Square butt joint, (2) Single-V preparation joint, (3) Lap joint, (4) T-joint.

Welds can be geometrically prepared in many different ways. The five basic types of weld joints are the butt joint, lap joint, corner joint, edge joint, and T-joint. Other variations exist as well—for example, double-V preparation joints are characterized by the two pieces of material each tapering to a single center point at one-half their height. Single-U and double-U preparation joints are also fairly common—instead of having straight edges like the single-V and double-V preparation joints, they are curved, forming the shape of a U. Lap joints are also commonly more than two pieces thick—depending on the process used and the thickness of the material, many pieces can be welded together in a lap joint geometry.
Often, particular joint designs are used exclusively or almost exclusively by certain welding processes. For example, resistance spot welding, laser beam welding, and electron beam welding are most frequently performed on lap joints. However, some welding methods, like shielded metal arc welding, are extremely versatile and can weld virtually any type of joint. Additionally, some processes can be used to make multipass welds, in which one weld is allowed to cool, and then another weld is performed on top of it. This allows for the welding of thick sections arranged in a single-V preparation joint, for example.

![Image of welded butt joint](image)

Fig. The cross-section of a welded butt joint, with the darkest gray representing the weld or fusion zone, the medium gray the heat-affected zone, and the lightest gray the base material.

After welding, a number of distinct regions can be identified in the weld area. The weld itself is called the fusion zone—more specifically, it is where the filler metal was laid during the welding process. The properties of the fusion zone depend primarily on the filler metal used, and its compatibility with the base materials. It is surrounded by the heat-affected zone, the area that had its microstructure and properties altered by the weld. These properties depend on the base material's behavior when subjected to heat. The metal in this area is often weaker than both the base material and the fusion zone, and is also where residual stresses are found.

### 4. Quality

Most often, the major metric used for judging the quality of a weld is its strength and the strength of the material around it. Many distinct factors influence this, including the welding method, the amount and concentration of heat input, the base material, the filler material, the flux material, the design of the joint, and the interactions between all these factors. To test the quality of a weld, either destructive or nondestructive testing methods are commonly used to verify that welds are defect-free, have acceptable levels of residual stresses and distortion, and have acceptable heat-affected zone (HAZ) properties. Welding codes and specifications exist to guide welders in proper welding technique and in how to judge the quality of welds.

#### 4.1. Heat-affected zone

![Image of pipe weld HAZ](image)

Fig. The HAZ of a pipe weld, with the blue area being the metal most affected by the heat.
The effects of welding on the material surrounding the weld can be detrimental—depending on the materials used and the heat input of the welding process used, the HAZ can be of varying size and strength. The thermal diffusivity of the base material plays a large role—if the diffusivity is high, the material cooling rate is high and the HAZ is relatively small. Conversely, a low diffusivity leads to slower cooling and a larger HAZ. The amount of heat injected by the welding process plays an important role as well, as processes like oxyacetylene welding have an unconcentrated heat input and increase the size of the HAZ. Processes like laser beam welding give a highly concentrated, limited amount of heat, resulting in a small HAZ. Arc welding falls between these two extremes, with the individual processes varying somewhat in heat input.\textsuperscript{[29][30]} To calculate the heat input for arc welding procedures, the following formula can be used:

$$Q = \left( \frac{V \times I \times 60}{S \times 1000} \right) \times \text{Efficiency}$$

where $Q = \text{heat input (kJ/mm)}$, $V = \text{voltage (V)}$, $I = \text{current (A)}$, and $S = \text{welding speed (mm/min)}$. The efficiency is dependent on the welding process used, with shielded metal arc welding having a value of 0.75, gas metal arc welding and submerged arc welding, 0.9, and gas tungsten arc welding, 0.8.

\subsection*{4.2. Distortion and cracking}

Welding methods that involve the melting of metal at the site of the joint necessarily are prone to shrinkage as the heated metal cools. Shrinkage, in turn, can introduce residual stresses and both longitudinal and rotational distortion. Distortion can pose a major problem, since the final product is not the desired shape. To alleviate rotational distortion, the workpieces can be offset, so that the welding results in a correctly shaped piece.\textsuperscript{[32]} Other methods of limiting distortion, such as clamping the workpieces in place, cause the buildup of residual stress in the heat-affected zone of the base material. These stresses can reduce the strength of the base material, and can lead to catastrophic failure through cold cracking, as in the case of several of the Liberty ships. Cold cracking is limited to steels, and is associated with the formation of martensite as the weld cools. The cracking occurs in the heat-affected zone of the base material. To reduce the amount of distortion and residual stresses, the amount of heat input should be limited, and the welding sequence used should not be from one end directly to the other, but rather in segments. The other type of cracking, hot cracking or solidification cracking, can occur in all metals, and happens in the fusion zone of a weld. To diminish the probability of this type of cracking, excess material restraint should be avoided, and a proper filler material should be utilized.\textsuperscript{[1,8]}

\subsection*{4.3. Weldability}

The quality of a weld is also dependent on the combination of materials used for the base material and the filler material. Not all metals are suitable for welding, and not all filler metals work well with acceptable base materials.
4.3.1. Steels

The weldability of steels is inversely proportional to a property known as the hardenability of the steel, which measures the ease of forming martensite during heat treatment. The hardenability of steel depends on its chemical composition, with greater quantities of carbon and other alloying elements resulting in a higher hardenability and thus a lower weldability. In order to be able to judge alloys made up of many distinct materials, a measure known as the equivalent carbon content is used to compare the relative weldabilities of different alloys by comparing their properties to a plain carbon steel. The effect on weldability of elements like chromium and vanadium, while not as great as carbon, is more significant than that of copper and nickel, for example. As the equivalent carbon content rises, the weldability of the alloy decreases. The disadvantage to using plain carbon and low-alloy steels is their lower strength—there is a trade-off between material strength and weldability. High strength, low-alloy steels were developed especially for welding applications during the 1970s, and these generally easy to weld materials have good strength, making them ideal for many welding applications.

Stainless steels, because of their high chromium content, tend to behave differently with respect to weldability than other steels. Austenitic grades of stainless steels tend to be the most weldable, but they are especially susceptible to distortion due to their high coefficient of thermal expansion. Some alloys of this type are prone to cracking and reduced corrosion resistance as well. Hot cracking is possible if the amount of ferrite in the weld is not controlled—to alleviate the problem, an electrode is used that deposits a weld metal containing a small amount of ferrite. Other types of stainless steels, such as ferritic and martensitic stainless steels, are not as easily welded, and must often be preheated and welded with special electrodes.

4.3.2. Aluminum

The weldability of aluminum alloys varies significantly, depending on the chemical composition of the alloy used. Aluminum alloys are susceptible to hot cracking, and to combat the problem, welders increase the welding speed to lower the heat input. Preheating reduces the temperature gradient across the weld zone and thus helps reduce hot cracking, but it can reduce the mechanical properties of the base material and should not be used when the base material is restrained. The design of the joint can be changed as well, and a more compatible filler alloy can be selected to decrease the likelihood of hot cracking. Aluminum alloys should also be cleaned prior to welding, with the goal of removing all oxides, oils, and loose particles from the surface to be welded. This is especially important because of an aluminum weld's susceptibility to porosity due to hydrogen and dross due to oxygen.

5. Unusual conditions

While many welding applications are done in controlled environments such as factories and repair shops, some welding processes are commonly used in a wide variety of conditions, such as open air, underwater, and vacuums (such as space). In open-air applications, such as construction and outdoors repair, shielded metal arc welding is the most common process. Processes that employ inert gases to protect the weld cannot be readily used in such situations, because unpredictable atmospheric movements can result in a faulty weld. Shielded metal arc welding is
also often used in underwater welding in the construction and repair of ships, offshore platforms, and pipelines, but others, such as flux cored arc welding and gas tungsten arc welding, are also common. Welding in space is also possible—it was first attempted in 1969 by Russian cosmonauts, when they performed experiments to test shielded metal arc welding, plasma arc welding, and electron beam welding in a depressurized environment. Further testing of these methods was done in the following decades, and today researchers continue to develop methods for using other welding processes in space, such as laser beam welding, resistance welding, and friction welding. Advances in these areas could prove indispensable for projects like the construction of the International Space Station, which will likely rely heavily on welding for joining in space the parts that were manufactured on Earth.\[5\]

6. Safety

Welding, without the proper precautions, can be a dangerous and unhealthy practice. However, with the use of new technology and proper protection, the risks of injury and death associated with welding can be greatly reduced. Because many common welding procedures involve an open electric arc or flame, the risk of burns is significant. To prevent them, welders wear personal protective equipment in the form of heavy leather gloves and protective long sleeve jackets to avoid exposure to extreme heat and flames. Additionally, the brightness of the weld area leads to a condition called arc eye in which ultraviolet light causes the inflammation of the cornea and can burn the retinas of the eyes. Goggles and welding helmets with dark face plates are worn to prevent this exposure, and in recent years, new helmet models have been produced that feature a face plate that self-darkens upon exposure to high amounts of UV light. To protect bystanders, translucent welding curtains often surround the welding area. These curtains, made of a polyvinyl chloride plastic film, shield nearby workers from exposure to the UV light from the electric arc, but should not be used to replace the filter glass used in helmets.

Welders are also often exposed to dangerous gases and particulate matter. Processes like flux-cored arc welding and shielded metal arc welding produce smoke containing particles of various types of oxides, which in some cases can lead to medical conditions like metal fume fever. The size of the particles in question tends to influence the toxicity of the fumes, with smaller particles presenting a greater danger. Additionally, many processes produce fumes and various gases, most commonly carbon dioxide, ozone and heavy metals, that can prove dangerous without proper ventilation and training. Furthermore, because the use of compressed gases and flames in many welding processes pose an explosion and fire risk, some common precautions include limiting the amount of oxygen in the air and keeping combustible materials away from the workplace.\[10\]

7. Costs and trends
As an industrial process, the cost of welding plays a crucial role in manufacturing decisions. Many different variables affect the total cost, including equipment cost, labor cost, material cost, and energy cost. Depending on the process, equipment cost can vary, from inexpensive for methods like shielded metal arc welding and oxyfuel welding, to extremely expensive for methods like laser beam welding and electron beam welding. Because of their high cost, they are only used in high production operations. Similarly, because automation and robots increase equipment costs, they are only implemented when high production is necessary. Labor cost depends on the deposition rate (the rate of welding), the hourly wage, and the total operation time, including both time welding and handling the part. The cost of materials includes the cost of the base and filler material, and the cost of shielding gases. Finally, energy cost depends on arc time and welding power demand.

For manual welding methods, labor costs generally make up the vast majority of the total cost. As a result, many cost-savings measures are focused on minimizing the operation time. To do this, welding procedures with high deposition rates can be selected, and weld parameters can be fine-tuned to increase welding speed. Mechanization and automatization are often implemented to reduce labor costs, but this frequently increases the cost of equipment and creates additional setup time. Material costs tend to increase when special properties are necessary, and energy costs normally do not amount to more than several percent of the total welding cost.[7]

In recent years, in order to minimize labor costs in high production manufacturing, industrial welding has become increasingly more automated, most notably with the use of robots in resistance spot welding (especially in the automotive industry) and in arc welding. In robot welding, mechanized devices both hold the material and perform the weld,[42] and at first, spot welding was its most common application. But robotic arc welding has been increasing in popularity as technology has advanced. Other key areas of research and development include the welding of dissimilar materials (such as steel and aluminum, for example) and new welding processes, such as friction stir, magnetic pulse, conductive heat seam, and laser-hybrid welding. Furthermore, progress is desired in making more specialized methods like laser beam welding practical for more applications, such as in the aerospace and automotive industries. Researchers also hope to better understand the often unpredictable properties of welds, especially microstructure, residual stresses, and a weld's tendency to crack or deform.[8]

8. Welding Glossary

Actual throat thickness The perpendicular distance between two lines each parallel to a line joining the outer toes one being tangent at the weld face and the other being through the furthermost point of fusion penetration.

Air-arc cutting Thermal cutting using an arc for melting the metal and a stream of air to remove the molten metal to enable a cut to be made.

All-position A gas welding technique in which the flame rightward welding

All-weld test A block of metal consisting of one or more beads or runs fused
piece together for test purposes. It may or may not include portions of parent metal.

All-weld test A test specimen that is composed wholly of weld metal over the portion to be tested.

Arc blow A lengthening or deflection of a DC welding arc caused by the interaction of magnetic fields set up in the work and arc or cables.

Arc fan The fan-shaped flame associated with the atomic-hydrogen arc.

Arc voltage The voltage between electrodes or between an electrode and the work, measured at a point as near as practical to the work.

Atomic-hydrogen welding Arc welding in which molecular hydrogen, passing through an arc between two tungsten or other suitable electrodes, is changed to its atomic form and then re-combines to supply the heat for welding.

Back-step sequence A welding sequence in which short lengths of run are (Back-step sequence)

Backfire Retrogression of the flame into the blowpipe neck or body with rapid self extinction.

Backing bar A piece of metal or other material placed at a root (Temporary backing)(These terms are applied only to the welding of pipes or tubes.)

Backing strip A piece of metal placed at a root and penetrated by (Permanent backing)

Block sequence A welding sequence in which short lengths of the (Block welding)

Blowhole A cavity generally over 1.6 mm in diameter, formed by entrapped gas during solidification of molten metal.

Blowpipe A device for mixing and burning gases to produce a flame for welding, brazing, bronze welding, cutting, heating and similar operations.

Burn back Fusing of the electrode wire to the current contact tube by sudden lengthening of the arc in any form of automatic or semi-automatic metal-arc welding using a bare electrode.

Burn off rate The linear rate of consumption of a consumable electrode.

Burn through A localised collapse of the molten pool due to (Melt through)

Carbon-arc welding Arc welding using a carbon electrode or electrodes.

Chain intermittent weld An intermittent weld on each side of a joint (usually fillet welds in T and lap joints) arranged so that the welds lie opposite to one another along the joint.

CO2 flux Metal-arc welding in which a flux-coated or flux containing electrode is deposited under a shield of carbon dioxide.

CO2 welding Metal-arc welding in which a bare wire electrode is used the arc and molten pool being shielded with carbon dioxide.

Concave fillet weld A fillet weld in which the weld face is concave (curved inwards).

Cone The more luminous part of a flame, which is adjacent to the nozzle orifice.

Continuous A weld extending along the entire length of a joint.
weld
Convex fillet weld A fillet weld in which the weld face is convex (bulbous).

Coupon plate A test piece made by adding plates to the end of a joint to give an extension of the weld for test purposes. (Note: this term is usually used in the shipbuilding industry.)

Crack A longitudinal discontinuity produced by fracture. Cracks may be longitudinal, transverse, edge, crater, centre line, fusion zone underhead, weld metal or parent metal.

Crater pipe A depression due to shrinkage at the end of a run where the source of heat was removed.

Cruciform testpiece A flat plate to which two other flat plates or two bars are welded at right angles and on the same axis.

Cutting electrode An electrode with a covering that aids the production of such an arc that molten metal is blown away to produce a groove or cut in the work.

Cutting oxygen Oxygen used at a pressure suitable for cutting.

De-seaming The removal of the surface defects from ingots, blooms, billets and slabs by means of a manual thermal cutting.

Dip transfer A method of metal-arc welding in which fused particles of the electrode wire in contact with the molten pool are detached from the electrode in rapid succession by the short circuit current, which develops every time the wire touches the molten pool.

Drag The projected distance between the two ends of a drag line.

Drag lines Serrations left on the face of a cut made by thermal cutting.

Electron-beam cutting Thermal cutting in vacuum by melting and vaporising a narrow section of the metal by the impact of a focused beam of electrons.

Excess penetration bead Excessive metal protruding through the root of a fusion weld made from one side only.

Face bend test A bend test in which a specified side of the weld is bent. (The side opposite that containing the root or )

Feather The carbon-rich zone, visible in a flame, extending around and beyond the cone when there is an excess of carbonaceous gas.

Fillet weld A fusion weld, other than a butt, edge or fusion spot weld, which is approximately triangular in transverse cross-section.

Flame cutting Oxygen cutting in which the appropriate part of the material to be cut is raised to ignition temperature by an oxy-fuel gas flame.

Flame snap-out Retrogression of the flame beyond the blowpipe body into the hose, with possible subsequent explosion.

Flame washing A method of surface shaping and dressing of metal by flamecutting using a nozzle designed to produce a suitably shaped cutting oxygen stream.

Flashback arrestor A safety device fitted in the oxygen and fuel gas system to prevent any flashback reaching the gas supplies.

Floating head A blowpipe holder on a flame cutting machine which, through a
suitable linkage, is designed to follow the contour of the surface of
the plate, thereby enabling the correct nozzle-to-workpiece distance
to be maintained.

**Free bend test**  A bend test made without using a former.

**Fusion penetration**  In fusion welding. The depth to which the parent metal has been
fused.

**Fusion zone**  The part of the parent metal which is melted into the weld metal.

**Gas economiser**  An auxiliary device designed for temporarily cutting off the supply of
gas to the welding equipment except the supply to a pilot jet where
fitted.

**Gas envelope**  The gas surrounding the inner cone of an oxy-gas flame.

**Gas pore**  A cavity generally under 1.6 mm in diameter, formed by entrapped
molten metal.

**Gas regulator**  A device for attachment to a gas cylinder or pipeline for reducing
and regulating the gas pressure to the working pressure required.

**Guided bend test**  A bend test made by bending the specimen round a specified
former.

**Heat affected zone**  The part of the parent metal which is metallurgically affected by the
heat of welding or thermal cutting but not melted. (Also known as the
zone of thermal disturbance).

**Hose protector**  A small non-return valve fitted to the blow-pipe end of a hose to
resist the retrogressive force of a flashback.

**Included angle**  The angle between the planes of the fusion faces of parts to be
welded.

**Inclusion**  Slag or other foreign matter entrapped during welding. The defect is
usually more irregular in shape than a gas pore.

**Incomplete root penetration**  Failure of weld metal to extend into the root of a joint.

**Incompletely filled groove**  A continuous or intermittent channel in the surface of a weld,
running along its length, due to insufficient weld metal. The channel
may be along the centre or along one or both edges of the weld.

**Intermittent weld**  A series of welds at intervals along a joint.

**Kerf**  The void left after metal has been removed by thermal cutting.

**Lack of fusion**  Lack of union in a weld.(Between weld metal and parent metal,
parent metal and parent metal or between weld metal and weld
metal.)

**Leftward welding**  A gas welding technique in which the flame is (Forward welding)

**Leg**  The width of a fusion face in a fillet weld.

**Metal-arc cutting**  Thermal cutting by melting using the heat of an arc between a metal
electrode and the metal to be cut.

**Metal-arc welding**  Arc welding using a consumable electrode.

**Metal transfer**  The transfer of metal across the arc from a consumable electrode to
the molten pool.
**MIG - welding**  Inert-gas welding using a consumable electrode (inert-gas metal-arc welding)

**Multi-stage regulator**  A gas regulator in which the gas pressure is reduced to the working pressure in more than one stage.

**Nick-break test**  A fracture test in which a specimen is broken from a notch cut at a predetermined position where the interior of the weld is to be examined.

**Open arc welding**  Arc welding in which the arc is visible.

**Open circuit voltage**  In a welding plant ready for welding, the voltage between two output terminals which are carrying no current.

**Overlap**  An imperfection at a toe or a root of a weld caused by metal flowing on to the surface of the parent metal without fusing it.

**Oxygen-arc cutting**  Thermal cutting in which the ignition temperature is produced by an electric arc, and cutting oxygen is conveyed through the centre of an electrode, which is consumed in the process.

**Oxygen lance**  A steel tube, consumed during cutting, through which cutting oxygen passes, for the cutting or boring of holes.

**Oxygen lancing**  Thermal cutting in which an oxygen lance is used.

**Packed lance**  An oxygen lance with steel rods or wires.

**Penetration bead**  Weld metal protruding through the root of a fusion weld made from one side only.

**Plug weld**  A weld made by filling a hole in one component of a workpiece so as to join it to the surface of an overlapping component exposed through the hole.

**Porosity**  A group of gas pores.

**Powder cutting**  Oxygen cutting in which powder is injected into the cutting oxygen stream to assist the cutting action.

**Powder lance**  An oxygen lance in which powder is mixed with the oxygen stream.

**Preheating oxygen**  Oxygen used at a suitable pressure in conjunction with fuel gas for raising to ignition temperature the metal to be cut.

**Residual welding stress**  Stress remaining in a metal part or structure as a result of welding.

**Reverse bend test**  A bend test in which the other than that specified for a face bend test is in tension.

**Rightward welding**  A gas welding technique in which the flame is (Backward welding)

**Root (of weld)**  The zone on the side of the first run farthest from the welder.

**Root face**  The portion of a fusion face at the root which is not bevelled or grooved.

**Run-off-plate(s)**  A piece, or pieces, of metal so placed as to enable the full section of of weld to be obtained at the end of the joint.

**Run-on-plate(s)**  A piece, or pieces, of metal so placed as to enable the full section of weld metal to be obtained at the beginning of a joint.

**Scarfing**  The removal of the surface defects from ingots, blooms, billets and slabs by means of a flame cutting machine.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td><strong>Seal weld</strong></td>
<td>A weld, not being a strength weld, used to make a (sealing weld)</td>
</tr>
<tr>
<td><strong>Sealing run</strong></td>
<td>The final run deposited on the root side of a fusion (backing run)</td>
</tr>
<tr>
<td><strong>Shrinkage groove</strong></td>
<td>A shallow groove caused by contraction of the metal along each side of a penetration bead.</td>
</tr>
<tr>
<td><strong>Side bend test</strong></td>
<td>A bend test in which the face of a transverse section of the weld is in tension</td>
</tr>
<tr>
<td><strong>Skip sequence</strong></td>
<td>A welding sequence in which short lengths of run are (skip welding)</td>
</tr>
<tr>
<td><strong>Slag-trap</strong></td>
<td>A configuration in a joint or joint preparation which may lead to the entrapment of slag.</td>
</tr>
<tr>
<td><strong>Slot lap joint</strong></td>
<td>A joint between two overlapping components made by depositing a fillet weld round the periphery of a hole in one component so as to join it to the other component exposed through the hole.</td>
</tr>
<tr>
<td><strong>Spray transfer</strong></td>
<td>Metal transfer which takes place as globules of diameter substantially larger than that of the consumable electrode from which they are transferred.</td>
</tr>
<tr>
<td><strong>Stack cutting</strong></td>
<td>The thermal cutting of a stack of plates usually clamped together.</td>
</tr>
<tr>
<td><strong>Staggered intermittent weld</strong></td>
<td>An intermittent weld on each side of a joint (usually fillet welds in T and lap joints) arranged so that the welds on one side lie opposite the spaces on the other side along the joint.</td>
</tr>
<tr>
<td><strong>Striking voltage</strong></td>
<td>The minimum voltage at which any specified arc may be initiated.</td>
</tr>
<tr>
<td><strong>Submerged-arc welding</strong></td>
<td>Metal-arc welding in which a bare wire electrode or electrodes are used; the arc or arcs are enveloped in a flux, some of which fuses to form a removable covering of slag on the weld.</td>
</tr>
<tr>
<td><strong>Surface-fusion welding</strong></td>
<td>Gas welding in which a carburizing flame is used to melt the surface of the parent metal which then unites with the metal from a suitable filler rod.</td>
</tr>
<tr>
<td><strong>Sustained backfire</strong></td>
<td>Retrogression of the flame into the blowpipe neck or body the flame remaining alight. Note: This manifests itself either as &quot;popping&quot; or &quot;squealing&quot; with a small pointed flame issuing from the nozzle orifice or as a rapid series of minor explosions inside.</td>
</tr>
<tr>
<td><strong>Test piece</strong></td>
<td>Components welded together in accordance with a specified welding procedure, or a portion of a welded joint detached from a structure for test.</td>
</tr>
<tr>
<td><strong>Test specimen</strong></td>
<td>A portion detached for a test piece and prepared as (Test coupon)</td>
</tr>
<tr>
<td><strong>Thermal cutting</strong></td>
<td>The parting or shaping of materials by the application of heat with or without a stream of cutting oxygen.</td>
</tr>
<tr>
<td><strong>TIG - welding</strong></td>
<td>Inert-gas welding using a non-consumable electrode (inert-gas tungsten-arc welding)</td>
</tr>
<tr>
<td><strong>Toe</strong></td>
<td>The boundary between a weld face and the parent metal or between weld faces.</td>
</tr>
<tr>
<td><strong>Tongue-bend test specimen</strong></td>
<td>A potion so cut in two straight lengths of pipe joined by a butt weld as to produce a tongue containing a portion of the weld. The cuts are made so that the tongue is parallel to the axis of the pipes and the weld is tested by bending the tongue round a</td>
</tr>
<tr>
<td><strong>Touch welding</strong></td>
<td>Metal-arc welding using a covered electrode, the covering of which is kept in contact with the parent metal during welding.</td>
</tr>
</tbody>
</table>
**Tungsten inclusion**  
An inclusion of tungsten from the electrode in TIG-welding.

**Two-stage regulator**  
A gas regulator in which the gas pressure is reduced to the working pressure in two stages.

**Undercut**  
An irregular groove at a toe of a run in the parent metal, or in previously deposited weld metal, due to welding.

**Weld junction**  
The boundary between the fusion zone and the heat affected zone.

**Welding procedure**  
A specified course of action followed in welding including the list of materials and, where necessary, tools to be used.

**Welding sequence**  
The order and direction in which joints, welds or runs are made.

**Welding technique**  
The manner in which the operator manipulates an electrode, a blowpipe or a similar appliance.

**Worm-hole**  
An elongated or tubular cavity formed entrapped gas during the solidification of molten metal.

## 9. Bending

**Bending** is a common manufacturing method to process sheet metal. It is usually done on a bend press (or break press), but also swing-bending-machines are used. Typical products that are made like this are electrical enclosures.

In engineering mechanics, **bending** (also known as **flexure**) characterizes the behavior of a structural element subjected to a lateral load. A structural element subjected to bending is known as a beam. A closet rod sagging under the weight of clothes on clothes hangers is an example of a beam experiencing bending.

Bending produces reactive forces inside a beam as the beam attempts to accommodate the flexural load: in the case of the beam in Figure 1, the material at the top of the beam is being compressed while the material at the bottom is being stretched. There are three notable internal forces caused by lateral loads (shown in Figure 2): shear parallel to the lateral loading, compression along the top of the beam, and tension along the bottom of the beam. These last two forces form a couple or moment as they are equal in magnitude and opposite in direction. This bending moment produces the sagging deformation characteristic of compression members experiencing bending.

The compressive and tensile forces shown in Figure 2 induce stresses on the beam. The maximum compressive stress is found at the uppermost edge of the beam while the maximum tensile stress is located at the lower edge of the beam. Since the stresses between these two opposing maxima vary linearly, there therefore exists a point on the linear path between them where there is no bending stress. The locus of these points is the neutral axis. Because of this area with no stress and the adjacent areas with low stress, using uniform cross section beams in bending is not a particularly efficient means of supporting a load as it does not use the full capacity of the beam until it is on the brink of collapse. Wide-flange beams (I-Beams) and truss girders effectively address this inefficiency as they minimize the amount of material in this under-stressed region.
9.1. Simple or Symmetrical Bending

Beam bending is analyzed with the Euler-Bernoulli beam equation. The classic formula for determining the bending stress in a member is:

\[ \sigma = \frac{M y}{I_x} \]

simplified for a beam of rectangular cross-section to:

\[ \sigma = \frac{6M}{bh^2} \]

- \( \sigma \) is the bending stress
- \( M \) - the moment at the neutral axis
- \( y \) - the perpendicular distance to the neutral axis
- \( I_x \) - the area moment of inertia about the neutral axis
- \( b \) - the width of the section being analyzed
- \( h \) - the depth of the section being analyzed

This equation is valid only when the stress at the extreme fiber (i.e. the portion of the beam furthest from the neutral axis) is below the yield stress of the material it is constructed from. At higher loadings the stress distribution becomes non-linear, and ductile materials will eventually enter a plastic hinge state where the magnitude of the stress is equal to the yield stress everywhere in the beam, with a discontinuity at the neutral axis where the stress changes from tensile to compressive. This plastic hinge state is typically used as a limit state in the design of steel structures.

9.2. Complex or Unsymmetrical Bending

The equation above is, also, only valid if the cross-section is symmetrical. For unsymmetrical sections, the full form of the equation must be used (presented below):

\[ \sigma_z = -\frac{(MyI_x - M_xI_{xy})}{I_xI_y - I_{xy}^2}x - \frac{(M_xI_y - MyI_{xy})}{I_xI_y - I_{xy}^2}y \]

Complex Bending of Homogeneous Beams

The complex bending stress equation for elastic, homogeneous beams is given as where \( M_x \) and \( M_y \) are the bending moments about the \( x \) and \( y \) centroid axes, respectively. \( I_x \) and \( I_y \) are the second moments of area (also known as moments of inertia) about the \( x \) and \( y \) axes, respectively, and \( I_{xy} \) is the product of inertia. Using this equation it would be possible to calculate the bending stress at any point on the beam cross section regardless of moment orientation or cross-sectional shape. Note that \( M_x \), \( M_y \), \( I_x \), \( I_y \), and \( I_{xy} \) are all unique for a given section along the length of the beam. In other words, they will not change from one point to another on the cross section. However, the \( x \) and \( y \) variables shown in the equation correspond to the coordinates of a point on the cross section at which the stress is to be determined.
10. Sheet metal

Sheet metal is simply metal formed into thin and flat pieces. It is one of the fundamental forms used in metalworking, and can be cut and bent into a variety of different shapes. Countless everyday objects are constructed of the material. Thicknesses can vary significantly, although extremely thin pieces of sheet metal would be considered to be foil or leaf, and pieces thicker than 1/4 inch or a centimeter can be considered plate.

10.1. Introduction

Sheet metal is generally produced in sheets less than 6 mm. by reducing the thickness of a long work piece by compressive forces applied through a set of rolls. This process is known as rolling and began around 1500 AD. Sheet metals are available as flat pieces or as strip in coils. It is characterized by its thickness or gauge of the metal. The gauge of sheet metal ranges from 30 gauge to about 8 gauge. The higher the gauge, the thinner the metal is. There are many different metals that can be made into sheet metal. Aluminum, brass, copper, cold rolled steel, mild steel, tin, nickel and titanium are just a few examples of metal that can be made into sheet metal. Sheet metal has applications in car bodies, airplane wings, medical tables, roofs for building and many other things.

10.2. Processes

Fig. Forming metal on a pressbrake

A main feature of sheet metal is its ability to be formed and shaped by a variety of processes. Each process does something different from the metal giving it a different shape or size.

10.3. Stretching
Stretching is a process where sheet metal is clamped around its edges and stretched over a die or form block. This process is mainly used for the manufacture of aircraft wings, automotive door and window panels.

10.4. Drawing

Drawing forms sheet metal into cylindrical or box shaped parts by using a punch which presses the blank into a die cavity. Drawing process can also be utilised to create arbitrary shapes with the help of soft punch.

10.5. Deep Drawing

Deep Drawing is a type of Drawing process where the depth of the part is greater than its diameter. Deep drawing is used for making automotive fuel tanks, kitchen sinks, 2 piece aluminum cans, etc.

10.6. Cutting

Cutting sheet metal can be done in various ways from hand tools called tin snips up to very large powered shears. With the advances in technology, sheet metal cutting has turned to computers for precise cutting.

Most modern sheet metal cutting operations are now based either on CNC Lasers cutting or multi-tool CNC punch press.

CNC laser involves moving a lens assembly carrying a beam of laser light over the surface of the metal. Oxygen or nitrogen is fed through the same nozzle through which the laser beam exits. The metal is heated and then burnt by the laser beam, cutting the metal sheet. The quality of the edge can be mirror smooth, and with a precision of around 0.1mm can be obtained. Cutting speeds on thin (1.2mm) sheet can be as high as 25m a minute. Most of the laser cutting systems use a CO2 based laser source with a wavelength of around 10um, some more recent systems use a YAG based laser with a wavelength of around 1um.

Punching is performed by moving the sheet of metal between the top and bottom tools of a punch. The top tool (punch) mates with the bottom tool (die), cutting a simple shape (e.g. a square, circle, or hexagon) from the sheet. An area can be cut out by making several hundred small square cuts around the perimeter. A punch is less flexible than a laser for cutting compound shapes, but faster for repetitive shapes (for example, the grille of an air-conditioning unit). A typical CNC punch has a choice of up to 60 tools in a "turret" that can be rotated to bring any tool to the active punching position. A modern CNC punch can take 600 blows per minute.

A typical component (such as the side of a computer case) can be cut to high precision from a blank sheet in under 30 seconds by either punch or laser.
10.7. Bending and Flanging

Bending and flanging imparts stiffness to a sheet metal part or to form various shapes, such as 3 piece aluminum cans[1]. See Bending (metalworking).

10.8. Punching and Shearing

During punching or shearing, the sheet metal is cut by using a punch and die.

10.9. Spinning

Spinning is used to make axis-symmetric parts by applying a work piece to a rotating mandrel with the help of rollers or rigid tools. Spinning is used to make rocket motor casings and missile nose cones and satellite dishes for example.

10.10. Press Forming

This is a form of bending, used for long and thin sheet metal parts. The machine that bends the metal is called a pressbrake. The lower part of the press contains a V shaped groove. This is called the die. The upper part of the press contains a blade that will press the sheet metal down into the v shaped die, causing it to bend. There are several techniques used here, but the most common modern method is "air bending". Here, the die has a sharper angle than the required bend (typically 85 degrees for a 90 degree bend) and the upper tool is precisely controlled in its stroke to push the metal down the required amount to bend it through 90 degrees. Typically, a general purpose machine has a bending force available of around 25 tonnes per metre of length. The opening width of the lower die is typically 8 to 10 times the thickness of the metal to be bent (for example, 5mm material could be bent in a 40mm die) the inner radius of the bend formed in the metal is determined not by the radius of the upper tool, but by the lower die width. Typically, the inner radius is equal to 1/6th of the V width used in the forming process. The press usually has some sort of backstop to position the material in the jaws of the machine. The backstop can be computer controlled to allow the operator to make a series of bends in a component to a high degree of accuracy. Simple machines control only the backstop, more advanced machines control the position and angle of the stop, its height and the position of the two reference pegs used to locate the material. The machine can also record the exact position and pressure required for each bending operation to allow the operator to achieve a perfect 90 degree bend across a variety of operations on the part.

10.11. Roll Forming

A continuous bending operation for producing open profiles or welded tubes with long lengths or in large quantities, see Roll forming.
Roll forming is a continuous bending operation in which a long strip of metal is passed through consecutive sets of rolls, or stands, each performing only an incremental part of the bend, until the desired cross-section profile is obtained. Roll forming is ideal for producing parts with long lengths or in large quantities.

A variety of cross-section profiles can be produced, but each profile requires a carefully crafted set of roll tools. Design of the rolls starts with a flower pattern, which is the sequence of profile cross-sections, one for each stand of rolls. The roll contours are then derived from the profile contours. Because of the high cost of the roll sets, simulation is often used to validate the designed rolls and optimize the forming process to minimize the number of stands and material stresses in the final product.

10.11.1. Rolling

Rolling is a fabricating process in which the metal, plastic, paper, glass, etc. is passed through a pair of rolls. There are two types of rolling process, flat and profile rolling. In flat rolling the final shape of the product is either classed as sheet (typically thickness less than 3 mm, also called "strip") or plate (typically thickness more than 3 mm). In profile rolling, the final product may be a round rod or other shaped bar such as a structural section (beam, channel, joist etc). Rolling is also classified according to the temperature of the metal rolled. If the temperature of the metal is above its recrystallization temperature then the process is termed as hot rolling, If the temperature of metal is below its recrystallization temperature the process is termed as cold rolling.
Other processes also termed as 'hot bending' are induction bending, whereby the section is heated in small sections, and dragged into a required radius (see 'steel bending services'[1] for examples of all bending processes).

Heavy plate tends to be formed using a press process, and is termed forming, rather than rolling.

11. Molding Process

11.1. Introduction

A **press**, or a **machine press** is a tool used to work metal (typically steel) by changing its shape and internal structure.

A forge press reforms the workpiece into a three dimensional object—not only changing its visible shape but also the internal structure of the material. A stronger part results from this process than if the object was machined.

Bending is a typical operation performed and occurs by a machine pressing, or applying direct pressure, to the material and forcing it to change shape. A press brake is a typical machine for this operation.

An easy to understand type of machine press is a set of rollers. Metal is fed into the rollers, which are turning to pull the material through. The space between the rollers is smaller than the unfinished metal, and thus the metal is made thinner and/or wider.

Another kind of press is a set of plates with a relief, or depth-based design, in them. The metal is placed between the plates, and the plates are pressed up against each other, deforming the metal in the desired fashion. This may be coining or embossing or forming. A punch press is used for forming holes.

Progressive stamping is a manufacturing method that can encompass punching, coining, bending and several ways of modifying the metal, combined with an automatic feeding system. The feeding system pushes a coil of metal through all of the stations of a progressive stamping die. Each station performs one or more operations until a finished part is made per the requirements on the print. The final operation is a cutoff operation, which separates the finished part from the carrying web. The carrying web, along with metal that is punched away in previous operations, is considered scrap metal.

A **Press Brake** is a special type of machine press that bends sheetmetal into shape.
A good example of the type of work a press brake can do is the backplate of a computer case. Other examples include brackets, frame pieces and electronic enclosures just to name a few. Some press breaks have CNC controls and can form parts with accuracy to a fraction of a millimeter. These machines can be dangerous considering the knife-edge bending dies and powerful 100+ ton bending force. However in the hands of a skilled operator the machine presents minimum hazard.

Machine presses are used extensively around the world for shaping all kinds of metals to a desired shape. A typical toaster (for bread) has a metal case that has been bent and pressed into shape by a machine press.

Also remember that machine presses have a high hazardous level, so safety measures must always be taken. Injuries in a press may be permanent, since there are over 100s tons on top of a limb. Bimanual controls (both hands need to be on the buttons to make the press work) are a very good way to prevent accidents. Also light sensors that keep the machine from working if the operator is in range of the die (tool that goes inside the press to shape metal), or any limbs is in range.

11.2. Types of Presses

- Mechanical Press
- Pneumatic Press
- Knuckle-joint Press
- Hydraulic Press
- Fine blanking Press
- Forging Press (Hammers)

9. References

