Welding Engineering

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Welding

Gas metal arc welding

Welding is a fabrication or sculptural process that joins materials, usually metals or thermoplastics, by causing coalescence. This is often done by melting the workpieces and adding a filler material to form a pool of molten material (the *weld pool*) that cools to become a strong joint, with pressure sometimes used in conjunction with heat, or by itself, to produce the weld. This is in contrast with soldering and brazing, which involve melting a lower-melting-point material between the workpieces to form a bond between them, without melting the workpieces.

Many different energy sources can be used for welding, including a gas flame, an electric arc, a laser, an electron beam, friction, and ultrasound. While often an industrial process, welding can be done in many different environments, including open air, under water and in outer space. Regardless of location, welding remains dangerous, and precautions are taken to avoid burns, electric shock, eye damage, poisonous fumes, and overexposure to ultraviolet light.

Until the end of the 19th century, the only welding process was forge welding, which blacksmiths had used for centuries to join iron and steel by heating and hammering them. Arc welding and oxyfuel welding were among the first processes to develop late in the century, and resistance welding followed soon after. Welding technology advanced quickly during the early 20th century as World War I and World War II drove the demand for reliable and inexpensive joining methods. Following the wars, several modern welding techniques were developed, including manual methods like shielded metal arc welding, now one of the most popular welding methods, as well as semi-automatic and automatic processes such as gas metal arc welding, submerged arc welding, flux-cored arc welding and electroslag welding. Developments continued with the invention of laser beam welding and electron beam welding in the latter half of the century. Today, the science continues to advance. Robot welding is becoming more commonplace in industrial settings, and researchers continue to develop new welding methods and gain greater understanding of weld quality and properties.

History

The iron pillar of Delhi

The history of joining metals goes back several millennia, with the earliest examples of welding from the Bronze Age and the Iron Age in Europe and the Middle East. Welding was used in the construction of the iron pillar in Delhi, India, erected about 310 AD and weighing 5.4 metric tons.

The Middle Ages brought advances in forge welding, in which blacksmiths pounded heated metal repeatedly until bonding occurred. In 1540, Vannoccio Biringuccio published *De la pirotechnia*, which includes descriptions of the forging operation. Renaissance craftsmen were skilled in the process, and the industry continued to grow during the following centuries.

In 1802, Russian scientist Vasily Petrov discovered the electric arc and subsequently proposed its possible practical applications, including welding. In 1881–82 a Russian inventor Nikolai Benardos created the first electric arc welding method known as carbon arc welding, using carbon electrodes. The advances in arc welding continued with the invention of metal electrodes in the late 1800s by a Russian, Nikolai Slavyanov (1888), and an American, C. L. Coffin (1890). Around 1900, A. P. Strohmenger released a coated metal electrode in Britain, which gave a more stable arc. In 1905 Russian scientist Vladimir Mitkevich proposed the usage of three-phase electric arc for welding. In 1919, alternating current welding was invented by C. J. Holslag but did not become popular for another decade.

Resistance welding was also developed during the final decades of the 19th century, with the first patents going to Elihu Thomson in 1885, who produced further advances over the next 15 years. Thermite welding was invented in 1893, and around that time another process, oxyfuel welding, became well established. Acetylene was discovered in 1836 by Edmund Davy, but its use was not practical in welding until about 1900, when a suitable blowtorch was developed. At first, oxyfuel welding was one of the more popular welding methods due to its portability and relatively low cost. As the 20th century progressed, however, it fell out of favor for industrial applications. It was largely replaced with arc welding, as metal coverings (known as flux) for the electrode that stabilize the arc and shield the base material from impurities continued to be developed.

World War I caused a major surge in the use of welding processes, with the various military powers attempting to determine which of the several new welding processes would be best. The British primarily used arc welding, even constructing a ship, the *Fulagar*, with an entirely welded hull. Arc welding was first applied to aircraft during the war as well, as some German airplane fuselages were constructed using the process. Also noteworthy is the first welded road bridge in the world, designed by Stefan Bryła of the Warsaw University of Technology in 1927, and built across the river Słudwia Maurzyce near Łowicz, Poland in 1929.

During the 1920s, major advances were made in welding technology, including the introduction of automatic welding in 1920, in which electrode wire was fed continuously. Shielding gas became a subject receiving much attention, as scientists attempted to protect welds from the effects of oxygen and nitrogen in the atmosphere. Porosity and brittleness were the primary problems, and the solutions that developed included the use of hydrogen, argon, and helium as welding atmospheres. During the following decade, further advances allowed for the welding of reactive metals like aluminum and magnesium. This in conjunction with developments in automatic welding, alternating current, and fluxes fed a major expansion of arc welding during the 1930s and then during World War II.

During the middle of the century, many new welding methods were invented. 1930 saw the release of stud welding, which soon became popular in shipbuilding and construction. Submerged arc welding was invented the same year and continues to be popular today. In 1932 a Russian, Konstantin Khrenov successfully implemented the first underwater electric arc welding. Gas tungsten arc welding, after decades of development, was finally perfected in 1941, and gas metal arc welding followed in 1948, allowing for fast welding of non-ferrous materials but requiring expensive shielding gases. Shielded metal arc welding was developed during the 1950s, using a flux-coated consumable electrode, and it quickly became the most popular metal arc welding process. In 1957, the flux-cored arc welding process debuted, in which the self-shielded wire electrode could be used with automatic equipment, resulting in greatly increased welding speeds, and that same year, plasma arc welding was invented. Electroslag welding was introduced in 1958, and it was followed by its cousin, electrogas welding, in 1961. In 1953 the Soviet scientist N. F. Kazakov proposed the diffusion bonding method.

Other recent developments in welding include the 1958 breakthrough of electron beam welding, making deep and narrow welding possible through the concentrated heat source. Following the invention of the laser in 1960, laser beam welding debuted several decades later, and has proved to be especially useful in high-speed, automated welding. In 1991 friction stir welding was invented in the UK and found high-quality applications all over the world. All of these three new processes continue to be quite expensive due the high cost of the necessary equipment, and this has limited their applications.

Processes

Arc

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.

Power supplies

To supply the electrical energy necessary for arc welding processes, a number of different power supplies can be used. The most common welding power supplies are constant current power supplies and constant voltage power supplies. In arc welding, the length of the arc is directly related to the voltage, and the amount of heat input is related to the current. 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.

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, the base metal will be hotter, increasing weld penetration and welding speed. Alternatively, a negatively charged electrode results in more shallow welds. 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.

Processes

One of the most common types of arc welding is shielded metal arc welding (SMAW); it 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 carbon dioxide (CO_2) gas during the welding process. The electrode core itself acts as filler material, making a separate filler unnecessary.

Shielded metal arc welding

The process is versatile and can be performed with relatively inexpensive equipment, making it well suited to shop jobs and field work. 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 special electrodes have made possible the welding of cast iron, nickel, aluminum, copper, and other metals.

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. Since the electrode is continuous, welding speeds are greater for GMAW than for SMAW.

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, 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 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, electroslag welding, electrogas welding, and stud arc welding.

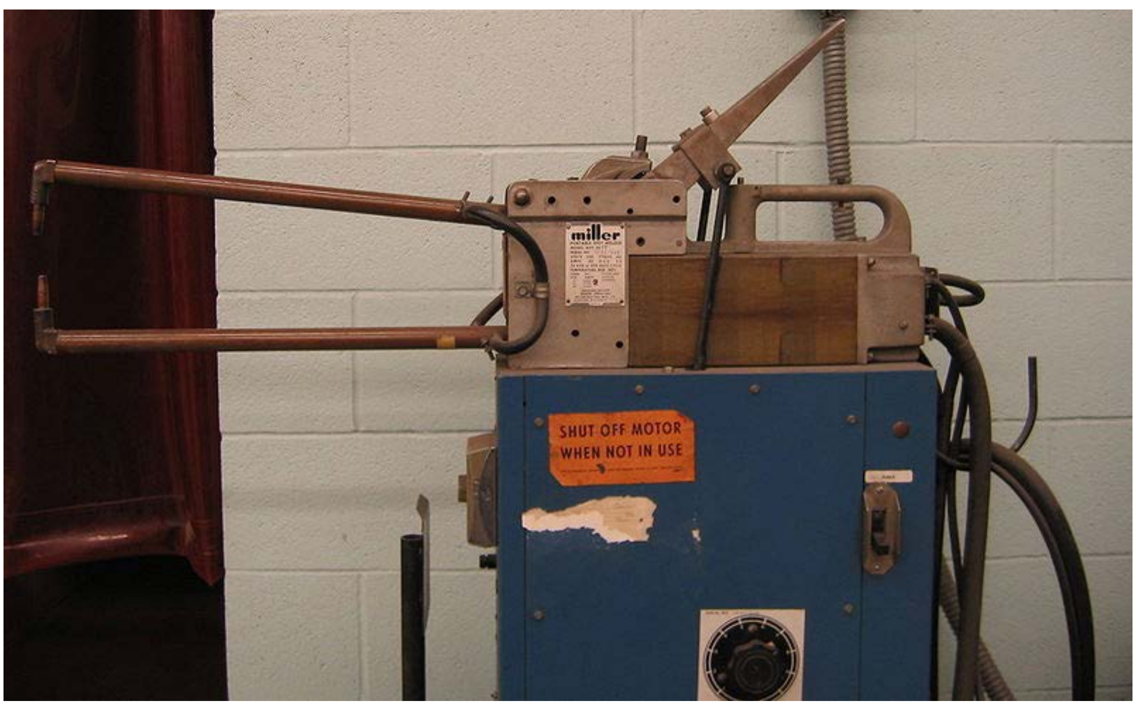
Gas

The most common gas welding process is oxyfuel welding, also known as oxyacetylene welding. It is one of the oldest and most versatile welding processes, but in recent years it has become less popular in industrial applications. It is still widely used for welding pipes and tubes, as well as repair work.

The equipment is relatively inexpensive and simple, generally employing the combustion of acetylene in oxygen to produce a welding flame temperature of about 3100 °C. The flame, since it is less concentrated than an electric arc, causes slower weld cooling, which can lead to greater residual stresses and weld distortion, though it eases the welding of high alloy steels. A similar process, generally called oxyfuel cutting, is used to cut metals.

Resistance

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.



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 butt welding, flash welding, projection welding, and upset welding.

Energy beam

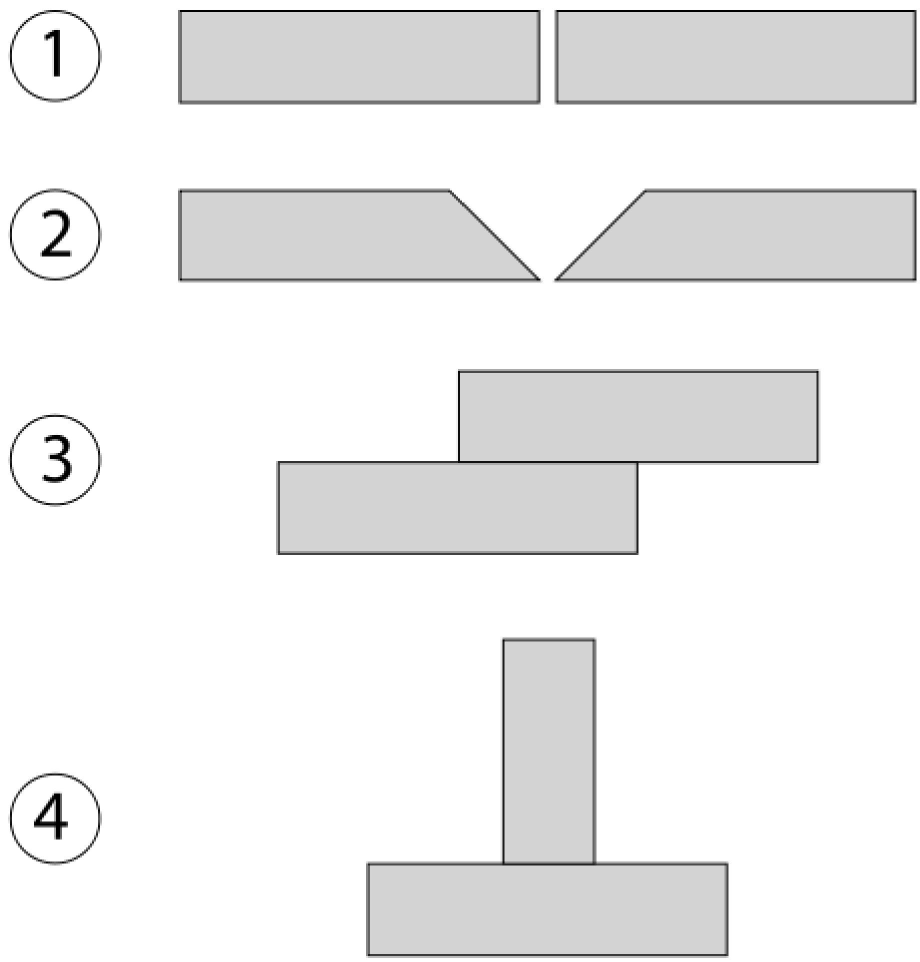
Energy beam welding methods, namely laser beam welding and electron beam welding, are relatively new processes that have become quite popular in high production applications. The two processes are quite similar, differing most notably in their source of power. Laser beam welding employs a highly focused 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, and X-ray welding.

Solid-state

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 friction welding (including friction stir welding), electromagnetic pulse welding, co-extrusion welding, cold welding, diffusion welding, exothermic welding, high frequency welding, hot pressure welding, induction welding, and roll welding.

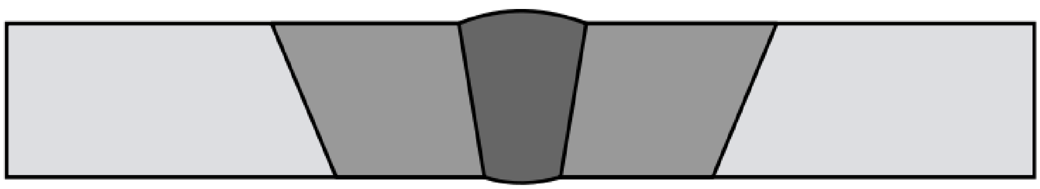
Geometry



Common welding joint types – (1) Square butt joint, (2) V butt 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 (a variant of this last is the cruciform 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.

Many welding processes require the use of a particular joint designs; for example, resistance spot welding, laser beam welding, and electron beam welding are most frequently performed on lap joints. Other welding methods, like shielded metal arc welding, are extremely versatile and can weld virtually any type of joint. Some processes can also 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.



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.

Quality

The blue area results from oxidation at a corresponding temperature of 600 °F (316 °C). This is an accurate way to identify temperature, but does not represent the HAZ width. The HAZ is the narrow area that immediately surrounds the welded base metal.

Many distinct factors influence the strength of welds and the material around them, including the welding method, the amount and concentration of energy input, the weldability of the base material, filler material, and 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 free of defects, have acceptable levels of residual stresses and distortion, and have acceptable heat-affected zone (HAZ) properties. Types of welding defects include cracks, distortion, gas inclusions (porosity), non-metallic inclusions, lack of fusion, incomplete penetration, lamellar tearing, and undercutting. Welding codes and specifications exist to guide welders in proper welding technique and in how to judge the quality of welds.

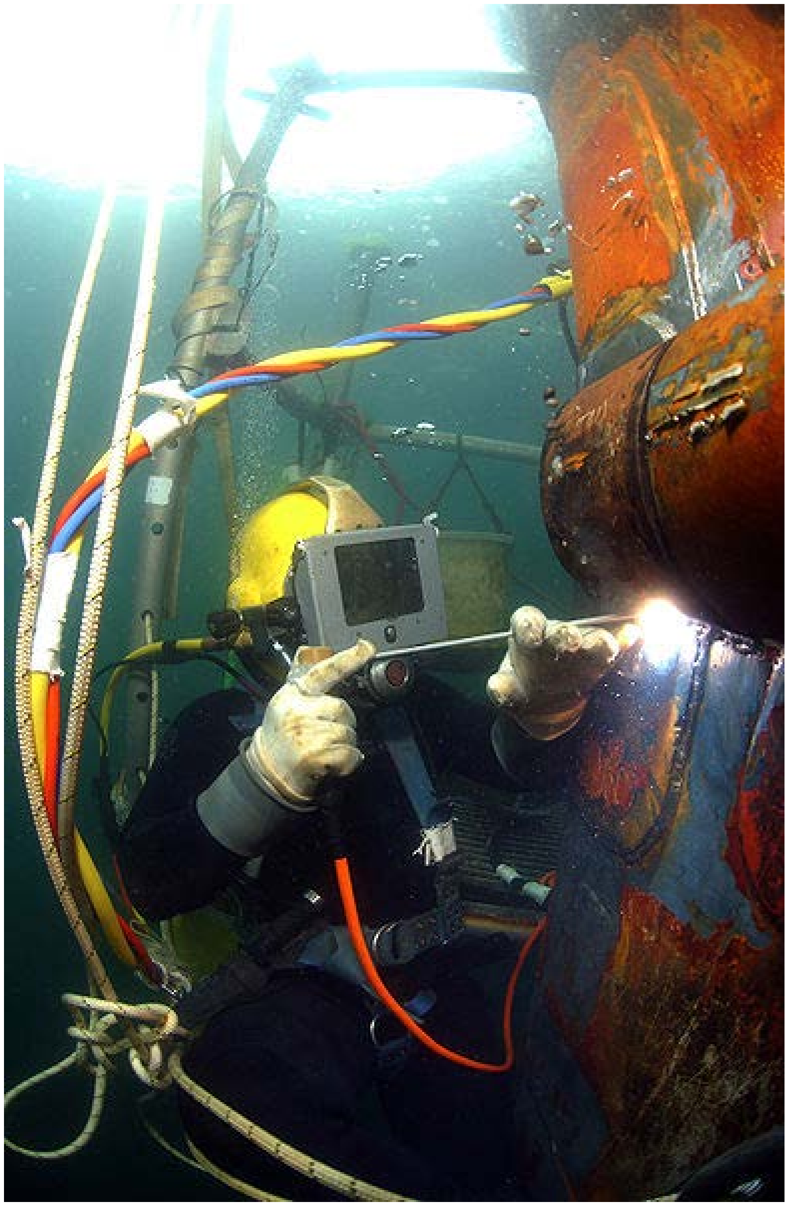
Heat-affected zone

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. To calculate the heat input for arc welding procedures, the following formula can be used:

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

where Q = heat input (kJ/mm), V = voltage (V), I = current (A), and S = 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.

Unusual conditions



Underwater welding

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 may be useful for future endeavours similar to the construction of the International Space Station, which could rely on welding for joining in space the parts that were manufactured on Earth.

Safety issues

Arc welding with a welding helmet, gloves, and other protective clothing

Welding, without the proper precautions, can be a dangerous and unhealthy practice. However, with the use of new technology and proper protection, 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 and fire is significant; this is why it is classified as a hot work process. 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 or flash burns in which ultraviolet light causes 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. The size of the particles in question tends to influence the toxicity of the fumes, with smaller particles presenting a greater danger. This is due to the fact that smaller particles have the ability to cross the blood brain barrier. 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. Exposure to manganese welding fumes, for example, even at low levels (<0.2 mg/m^3), may lead to neurological problems or to damage to the lungs, liver, kidneys, or central nervous system. Furthermore, because the use of compressed gases and flames in many welding processes poses 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.

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-saving measures are focused on minimizing 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 automation 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.

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 and at first, spot welding was its most common application, but robotic arc welding increases in popularity as technology advances. 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.

Chapter 2

Fabrication (Metal)

A typical steel fabrication shop

A set of six-axis welding robots.

Fabrication as an industrial term refers to building metal structures by cutting, bending, and assembling. The cutting part of fabrication is via sawing, shearing, or chiseling (all with manual and powered variants); torching with handheld torches (such as oxy-fuel torches or plasma torches); and via CNC cutters (using a laser, torch, or water jet). The bending is via hammering (manual or powered) or via press brakes and similar tools. The assembling (joining of the pieces) is via welding, binding with adhesives, riveting, threaded fasteners, or even yet more bending in the form of a crimped seam. Structural steel and sheet metal are the usual starting materials for fabrication, along with the welding wire, flux, and fasteners that will join the cut pieces. As with other manufacturing processes, both human labor and automation are commonly used. The product resulting from (the process of) fabrication may be called a fabrication. Shops that specialize in this type of metal work are called *fab shops*. The end products of other common types of metalworking, such as machining, metal stamping, forging, and casting, may be similar in shape and function, but those processes are not classified as fabrication.

Fabrication comprises or overlaps with various metalworking specialties:

- Fabrication shops and machine shops have overlapping capabilities, but fabrication shops generally concentrate on metal preparation and assembly as described above. By comparison, machine shops also cut metal, but they are more concerned with the machining of parts on machine tools. Firms that encompass both fab work and machining are also common.

- Blacksmithing has always involved fabrication, although it was not always called by that name.
- The products produced by welders, which are often referred to as weldments, are an example of fabrication.
- Boilermakers originally specialized in boilers, leading to their trade's name, but the term as used today has a broader meaning.
- Similarly, millwrights originally specialized in setting up grain mills and saw mills, but today they may be called upon for a broad range of fabrication work.
- Ironworkers, also known as steel erectors, also engage in fabrication. Often the fabrications for structural work begin as prefabricated segments in a fab shop, then are moved to the site by truck, rail, or barge, and finally are installed by erectors.

Metal fabrication

Metal fabrication is a value added process that involves the construction of machines and structures from various raw materials. A fab shop will bid on a job, usually based on the engineering drawings, and if awarded the contract will build the product.

Fabrication shops are employed by contractors, OEM's and VAR's. Typical projects include; loose parts, structural frames for buildings and heavy equipment, and hand railings and stairs for buildings.

Engineering

The fabricator may employ or contract out steel detailers to prepare shop drawings, if not provided by the customer, which the fabricating shop will use for manufacturing. Manufacturing engineers will program CNC machines as needed.

Raw materials

Standard raw materials used by metal fabricators are;

- plate metal
- formed and expanded metal
    - tube stock, CDSM
    - square stock
    - sectional metals (I beams, W beams, C-channel...)
- welding wire
- hardware
- castings
- fittings

Cutting and burning

The raw material has to be cut to size. This is done with a variety of tools.

The most common way to cut material is by Shearing (metalworking);

Special band saws designed for cutting metal have hardened blades and a feed mechanism for even cutting. Abrasive cut-off saws, also known as chop saws, are similar to miter saws but with a steel cutting abrasive disk. Cutting torches can cut very large sections of steel *with little effort*.

Burn tables are CNC cutting torches, usually natural gas powered. Plasma and laser cutting tables, and Water jet cutters, are also common. Plate steel is loaded on a table and the parts are cut out as programmed. The support table is made of a grid of bars that can be replaced. Some very expensive burn tables also include CNC punch capability, with a carousel of different punches and taps. Fabrication of structural steel by plasma and laser cutting introduces robots to move the cutting head in three dimensions around the material to be cut.

Forming

Hydraulic brake presses with v-dies are the most common method of forming metal. The cut plate is placed in the press and a v-shaped die is pressed a predetermined distance to bend the plate to the desired angle. Wing brakes and hand powered brakes are sometimes used.

Tube bending machines have specially shaped dies and mandrels to bend tubular sections without kinking them.

Rolling machines are used to form plate steel into a round section.

English Wheel or Wheeling Machines are used to form complex double curvature shapes using sheet metal.

Machining

Fab shops will generally have a limited machining capability including; metal lathes, mills, magnetic based drills along with other portable metal working tools.

Welding

Welding is the main focus of steel fabrication. The formed and machined parts will be assembled and tack welded into place then re-checked for accuracy. A fixture may be used to locate parts for welding if multiple weldments have been ordered.

The welder then completes welding per the engineering drawings, if welding is detailed, or per his own judgment if no welding details are provided.

Special precautions may be needed to prevent warping of the weldment due to heat. These may include re-designing the weldment to use less weld, welding in a staggered fashion, using a stout fixture, covering the weldment in sand during cooling, and straightening operations after welding.

Straightening of warped steel weldments is done with an Oxy-acetylene torch and is somewhat of an art. Heat is selectively applied to the steel in a slow, linear sweep. The steel will have a net contraction, upon cooling, in the direction of the sweep. A highly skilled welder can remove significant warpage using this technique.

Steel weldments are occasionally annealed in a low temperature oven to relieve residual stresses.

Final assembly

After the weldment has cooled it is generally sand blasted, primed and painted. Any additional manufacturing specified by the customer is then completed. The finished product is then inspected and shipped.

Specialities

Many fabrication shops have speciality processes which they develop or invest in, based on their customers needs and their expertise:

- brazing
- casting
- chipping
- drawing
- extrusion
- forging
- heat treatment
- hydroforming
- oven soldering
- plastic fabrication
- powder coating
- powder metallurgy
- punching
- shearing
- spinning
- English wheeling
- welding

And higher-level specializations such as:

- electrical
- hydraulics
- prototyping/machine design/technical drawing
- sub-contract manufacturing

Chapter 3

Electron Beam Welding and Friction Welding

Electron beam welding

Electron beam welding (EBW) is a fusion welding process in which a beam of high-velocity electrons is applied to the materials being joined. The workpieces melt as the kinetic energy of the electrons is transformed into heat upon impact, and the filler metal, if used, also melts to form part of the weld. The welding is often done in conditions of a vacuum to prevent dispersion of the electron beam. The process was developed by German physicist Karl-Heinz Steigerwald, who was at the time working on various electron beam applications, perceived and developed the first practical electron beam welding machine which began operation in 1958.

Operation

The three primary methods of EBW are each applied in different welding environments.

Vacuum welding

The method first developed requires that the welding chamber be at a hard vacuum. Material as thick as 15 cm (6 in) can be welded, and the distance between the welding gun and workpiece (the *stand-off distance*) can be as great as 0.7 m (30 in). While the most efficient of the three modes, disadvantages include the amount of time required to properly evacuate the chamber and the cost of the entire machine.

Low pressure welding

As electron beam gun technology advanced, it became possible to perform EBW in a soft vacuum, under pressure of 0.1 torr. This allows for larger welding chambers and reduces the time and equipment required to attain evacuate the chamber, but reduces the maximum stand-off distance by half and decreases the maximum material thickness to 5 cm (2 in).

In-air welding

The third EBW mode is called nonvacuum or out-of-vacuum EBW, since it is performed at atmospheric pressure. The stand-off distance must be diminished to 4 cm (1.5 in), and the maximum material thickness is about 5 cm (2 in). However, it allows for workpieces of any size to be welded, since the size of the welding chamber is no longer a factor. A schematic drawing may be helpful.

Equipment

The electron beam gun used in EBW both produces the electrons and accelerates them, using a hot cathode emitter made of tungsten that emits electrons when heated. (Steigerwald also experimented with tantalum filaments because of the lower work function). The electrons are then accelerated to a hollow anode inside the gun column by means of a high voltage differential. They pass through the anode at high speed (approx 1/2 the speed of light) and are then directed to the workpiece with magnetic forces resulting from focusing and deflection coils. These components are all housed in an electron beam gun column, in which a hard vacuum (about 0.00001 torr) is maintained.

The EBW power supply pulls a low current (usually less than 1 A), but provides a voltage as high as 60 kV in low-voltage machines, or 200 kV in high-voltage machines. High-voltage machines supply a current as low as 40 mA, and can provide a weld depth-to-width ratio of 25:1, whereas the ratio with a low-voltage machine is around 12:1. The beam power of a power supply is an indicator of its ability to do work, and determines the power density (generally 40-4000 kW/cm^2 or 100-10,000 kW/in^2).

The welding chamber walls and doors must be thick enough to act as X-ray shielding.

For the hard vacuum and soft vacuum EBW methods, the welding chamber used must be airtight and strong enough to prevent it from being crushed by atmospheric pressure. It must have openings so that the workpieces can be inserted and removed, and its size must be sufficient to hold the workpieces but not significantly larger, as larger chambers require more time to evacuate. The chamber must also be equipped with pumps capable of evacuating it to the desired pressure. For a hard vacuum, a diffusion pump is necessary, while soft vacuums can often be obtained by less costly equipment.

Electron beams can also be sent from their vacuum column through membrane or plasma window for a short distance into the air and this is used for production welding, for example welding the hard teeth of hacksaw blades onto a tougher backing steel. The plasma window is a relatively recent advance which has turned this kind of EBW into a far more practical tool. Previously the vacuum containment membranes were expensive and degraded quickly by the constant stream of high energy electrons.

Friction welding

Friction welding (**FW**) is a class of solid-state welding processes that generates heat through mechanical friction between a moving workpiece and a stationary component, with the addition of a lateral force called "upset" to plastically displace and fuse the materials. Technically, because no melt occurs, friction welding is not actually a welding process in the traditional sense, but a forging technique. However, due to the similarities between these techniques and traditional welding, the term has become common. Friction welding is used with metals and thermoplastics in a wide variety of aviation and automotive applications.

Benefits

The combination of fast joining times of the order of a few seconds, and the direct heat input at the weld interface, gives rise to relatively small heat affected zones. Friction welding techniques are generally melt-free, which offers the advantage of avoiding grain growth in engineered materials such as high-strength heat-treated steels. Another advantage is that the motion tends to "clean" the surface between the materials being welded, which means they can be joined without as much prior preparation. During the welding process, depending on the method being used, small pieces of the "plastic" metal will be forced out of the working mass in rippled sheets of metal known as "flash". It is believed that the flash carries away debris and dirt.

Another advantage of friction welding is that it allows dissimilar materials to be joined. This is particularly useful in the aerospace field, where it is used to join lightweight aluminum stock to high-strength steels. Normally the wide difference in melting points of the two materials would make it impossible to weld using traditional techniques, and would require some sort of mechanical connection instead (bolts, etc.). Friction welding provides a "full strength" bond with no additional weight. Other common uses for these sorts of bi-metal joins is in the nuclear industry, where copper-steel joints are common in the reactor cooling systems; and in the transport of cryogenic fluids, where friction welding has been used to join aluminum alloys to stainless steels and high-nickel-alloy materials for cryogenic-fluids piping and containment vessels.

Friction welding is also used with thermoplastics, which act in a fashion analogous to metals under heat and pressure. The heats and pressures used on these materials are much lower than on metals, but the technique can be used to join metals to plastics with the metal interface being machined. For instance, the technique can be used to join eyeglass frames to the pins in their hinges. The lower energies and pressures used allows for a wider variety of techniques to be used.

History

Further patents were issued throughout Europe and the former Soviet Union. The US companies Caterpillar, Rockwell International, and American Manufacturing Foundry all developed machines for this process. The most extensive historical records are kept with the American Welding Society.

Metal techniques

Spin welding

Spin welding systems consist of two chucks for holding the materials to be welded, one of which is fixed and the other rotating. Before welding one of the work pieces is attached to the rotating chuck along with a flywheel of a given weight. The piece is then spun up to a high rate of rotation to store the required energy in the flywheel. Once spinning at the proper speed, the motor is removed and the pieces forced together under pressure. The force is kept on the pieces after the spinning stops to allow the weld to "set". This technique is also known as **inertia welding**, **rotational welding** or **inertial friction welding**.

Linear friction welding

Linear friction welding (*LFW*) is similar to spin welding except that the moving chuck oscillates laterally instead of spinning. The speeds are much lower in general, which requires the pieces to be kept under pressure at all times. This also requires the parts to have a high shear strength. Linear friction welding requires more complex machinery than spin welding, but has the advantage that parts of any shape can be joined, as opposed to parts with a circular meeting point.

Friction surfacing

Friction surfacing is a process derived from friction welding whereby a coating material is applied to a substrate. A rod composed of the coating material (called a mechtrode) is rotated under pressure, generating a plasticised layer in the rod at the interface with the substrate. By moving a substrate across the face of the rotating rod a plasticised layer is deposited between 0.2–2.5 millimetres (0.0079–0.098 in) thick depending on mechtrode diameter and coating material.

Thermoplastic techniques

Linear vibration welding

In *linear vibration welding* the materials are placed in contact and put under pressure. An external vibration force is then applied to slip the pieces relative to each other, perpendicular to the pressure being applied. The parts are vibrated through a relatively small displacement known as the amplitude, typically between 1.0 and 1.8 mm, for a frequency of vibration of 200 Hz (high frequency), or 2–4 mm at 100 Hz (low frequency), in the plane of the joint. This technique is widely used in the automotive industry, among others. A minor modification is *angular friction welding*, which vibrates the materials by torquing them through a small angle.

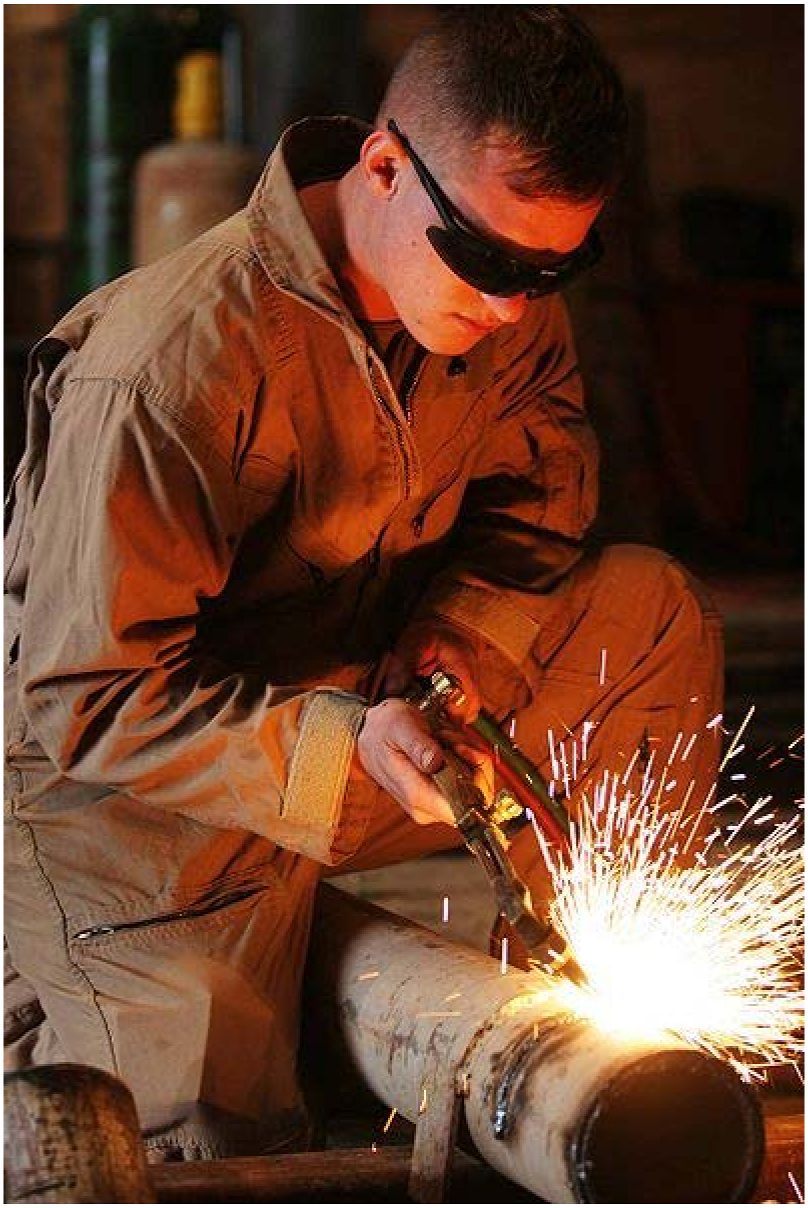
Orbital friction welding

Orbital friction welding is similar to spin welding, but uses a more complex machine to produce an orbital motion in which the moving part rotates in a small circle, much smaller than the size of the joint as a whole.

Chapter 4

Oxy-Fuel Welding and Cutting

Side of metal, cut by oxygen - propane cutting torch



A cutting torch is used to cut a steel pipe.

Oxy-fuel welding (commonly called **oxyacetylene welding**, **oxy welding**, or **gas welding** in the U.S.) and **oxy-fuel cutting** are processes that use fuel gases and oxygen to weld and cut metals, respectively. French engineers Edmond Fouché and Charles Picard became the first to develop oxygen-acetylene welding in 1903. Pure oxygen, instead of air (20% oxygen/80% nitrogen), is used to increase the flame temperature to allow localized melting of the workpiece material (e.g. steel) in a room environment. A common propane/air flame burns at about 3,630 °F (2,000 °C), a propane/oxygen flame burns at about 4,530 °F (2,500 °C), and an acetylene/oxygen flame burns at about 6,330 °F (3,500 °C).

Oxy-fuel is one of the oldest welding processes, though in recent years it has become less popular in industrial applications. However, it is still widely used for welding pipes and tubes, as well as repair work. It is also frequently well-suited, and favored, for fabricating some types of metal-based artwork.

In **oxy-fuel welding**, a welding torch is used to weld metals. Welding metal results when two pieces are heated to a temperature that produces a shared pool of molten metal. The molten pool is generally supplied with additional metal called filler. Filler material depends upon the metals to be welded.

In **oxy-fuel cutting**, a cutting torch is used to heat metal to kindling temperature. A stream of oxygen is then trained on the metal, and metal burns in that oxygen and then flows out of the cut (kerf) as an oxide slag.

Torches that do not mix fuel with oxygen (combining, instead, atmospheric air) are not considered oxy-fuel torches and can typically be identified by a single tank (Oxy-fuel welding/cutting generally requires two tanks, fuel and oxygen). Most metals cannot be melted with a single-tank torch. As such, single-tank torches are typically used only for soldering and brazing, rather than welding.

Uses

Oxy-gas torches are used for or have been used for:

- Welding metal
- Cutting metal
- Also, oxy-hydrogen flames are used:
    - In Stone Work for "flaming" where the stone is heated and a top layer crackles and breaks. A steel circular brush is attached to an angle grinder and used to remove the first layer leaving behind a bumpy surface similar to hammered bronze.
    - In the glass industry for "fire polishing".
    - In jewelry production for "water welding" using a *water torch*.
    - Formerly, to heat lumps of quicklime to obtain a bright white light called limelight, in theatres or optical ("magic") lanterns.
    - Formerly, in platinum works, as platinum is only fusible in the oxy-hydrogen flame and in an electric furnace.

In short, oxy-fuel equipment is quite versatile – not only because it is preferred for some sorts of iron or steel welding but also because it lends itself to brazing, braze-welding, metal heating (for annealing or tempering, bending or forming), the loosening of corroded nuts and bolts, and also is the ubiquitous means for oxy-fuel cutting of ferrous metals.

Apparatus

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

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

There are also examples of pressurized liquid fuel cutting torches, usually using gasoline. These are used for their increased portability.

Regulator

The regulator is used to control pressure from the tanks to the required pressure in the hose. The flow rate is then adjusted by the operator using needle valves on the torch. Accurate flow control with a needle valve relies on a constant inlet pressure to it.

Most regulators have two stages: the first stage of the regulator is a fixed-pressure regulator whose function is to release the gas from the cylinder at a constant intermediate pressure, despite the pressure in the cylinder falling as the gas in the cylinder is used. This is similar to the first stage of a scuba-diving regulator. The adjustable second stage of the regulator controls the pressure reduction from the intermediate pressure to the low outlet pressure. The regulator has two pressure gauges, one indicating cylinder pressure, the other indicating hose pressure. The adjustment knob of the regulator is sometimes roughly calibrated for pressure, but an accurate setting requires observation of the gauge.

Some simpler or cheaper oxygen-fuel regulators have only a single stage regulator, or only a single gauge. A single-stage regulator will tend to reduce its outlet pressure as the cylinder is emptied, requiring manual readjustment. For low-volume users, this is an acceptable simplification. Welding regulators, unlike simpler LPG heating regulators, retain their outlet (hose) pressure gauge and do not rely on the calibration of the adjustment knob. The cheaper single-stage regulators may sometimes omit the cylinder contents gauge, or replace the accurate dial gauge with a cheaper and less precise "rising button" gauge.

Gas hoses

The hoses are specifically designed for welding and cutting. The hose is usually a double-hose design, meaning that there are two hoses joined together. These hoses are colour-coded for visual identification and their threaded connectors are handed to avoid accidental mis-connection: oxygen is right-handed as normal, fuel gases use a left-handed thread. These left-handed threads also have an identifying groove cut into their nuts.

Colour coding of hoses varies between countries. In the USA, oxygen is green, and the fuel hose is red. In the UK, the oxygen hose is blue (black hoses may still be found on old equipment), and the acetylene fuel hose is red. Where LPG fuel, such as propane, is used, the fuel hose should be orange, indicating that it is compatible with LPG. LPG will damage an incompatible hose, including most acetylene hoses.

Connections between flexible hoses and rigid fittings are made by a crimped hose clip over a barbed spigot. The use of worm-drive or Jubilee clips is specifically forbidden in the UK. The hoses should also be clipped together at intervals approximately 3 feet apart.

Non-return valve

Between the regulator and hose, and ideally between hose and torch on both oxygen and fuel lines, a flashback arrestor and/or non-return valve (check valve) should be installed to prevent flame or oxygen-fuel mixture being pushed back into either cylinder and damaging the equipment or making a cylinder explode.

European practice is to fit flashback arrestors at the regulator and check valves at the torch. US practice is to fit both at the regulator.

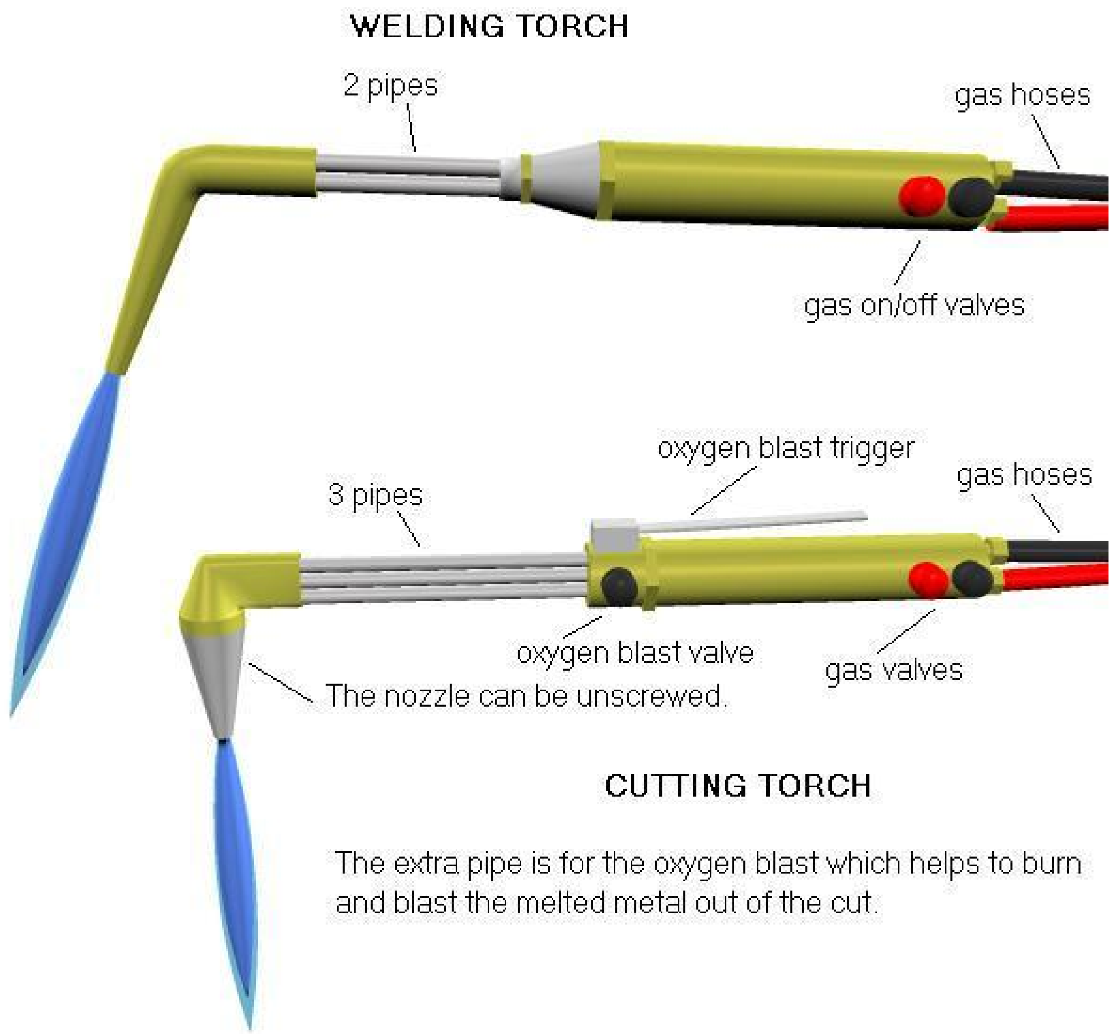
The flashback arrestor (not to be confused with a check valve) prevents the shock waves from downstream coming back up the hoses and entering the cylinder (possibly rupturing it), as there are quantities of fuel/oxygen mixtures inside parts of the equipment (specifically within the mixer and blowpipe/nozzle) that may explode if the equipment is incorrectly shut down; and acetylene decomposes at excessive pressures or temperatures. The flashback arrestor will remain switched off until someone resets it, in case the pressure wave created a leak downstream of the arrestor.

Check valve

A check valve lets gas flow in one direction only. Not to be confused with a flashback arrestor, a check valve is not designed to block a shock wave. The pressure wave could occur while the ball is so far from the inlet that the pressure wave gets past before the ball reaches its off position. A check valve is usually a chamber containing a ball that is pressed against one end by a spring: gas flow one way pushes the ball out of the way, and no flow or flow the other way lets the spring push the ball into the inlet, blocking it.

Torches

The torch is the part that the welder holds and manipulates to make the weld. It has a connection and valve for the fuel gas and a connection and valve for the oxygen, a handle for the welder to grasp, a mixing chamber (set at an angle) where the fuel gas and oxygen mix, with a tip where the flame forms.



The top torch is a welding torch and the bottom is a cutting torch

Welding torch

A welding torch head is used to weld metals. It can be identified by having only one or two pipes running to the nozzle and no oxygen-blast trigger and two valve knobs at the bottom of the handle letting the operator adjust the oxygen flow and fuel flow.

Cutting torch

A cutting torch head is used to cut materials. It is similar to a welding torch, but can be identified by the oxygen blow out trigger or lever.

The metal is first heated by the flame until it is cherry red. Once this temperature is attained, oxygen is supplied to the heated parts by pressing the "oxygen-blast trigger". This oxygen reacts with the metal, forming iron oxide and producing heat. It is this heat which continues the cutting process. The cutting torch only heats the metal to start the process; further heat is provided by the burning metal.

The melting point of the iron oxide is around half of that of the metal; as the metal burns, it immediately turns to liquid iron oxide and flows away from the cutting zone. However, some of the iron oxide remains on the work piece, forming a hard "slag" which can be removed by gentle tapping, and/or a grinder.

Rose-bud torch

A rose-bud torch is used to heat metals for bending, straightening, etc. where a large area needs to be heated. It is called as such because the flame at the end looks like a rose-bud. A welding torch can also be used to heat small area such as rusted nuts and bolts.

Injector torch

A typical oxy-fuel torch, called an equal-pressure torch, merely mixes the two gases. In an injector torch, high pressure oxygen comes out of a small nozzle inside the torch head so that it drags the fuel gas along with it, via venturi effect.

Fuels

Oxy-fuel processes may use a variety of fuel gases, the most common being acetylene. Other gases that may be used are propylene, liquified petroleum gas (LPG), propane, natural gas, hydrogen, and MAPP gas. Many brands use different kinds of gases in their mixes.

Acetylene

Acetylene generator as used in Bali by a reaction of calcium carbide with water. This is used where acetylene cylinders are not available. The term 'Las Karbit' means acetylene (carbide) welding in Indonesian.

Acetylene is the primary fuel for oxy-fuel welding and is the fuel of choice for repair work and general cutting and welding. Acetylene gas is shipped in special cylinders designed to keep the gas dissolved. The cylinders are packed with porous materials (e.g. kapok fibre, diatomaceous earth, or (formerly) asbestos), then filled to around 50% capacity with acetone, as acetylene is acetone soluble. This method is necessary because above 207 kPa (30 lbf/in²) (absolute pressure) acetylene is unstable and may explode.

There is about 1700 kPa (250 psi) pressure in the tank when full. Acetylene when combined with oxygen burns at a temperature of 3200 °C to 3500 °C (5800 °F to 6300 °F), highest among commonly used gaseous fuels. As a fuel acetylene's primary disadvantage, in comparison to other fuels, is high cost.

As acetylene is unstable at a pressure roughly equivalent to 33 feet/10 meters underwater, water submerged cutting and welding is reserved for hydrogen rather than acetylene.

Compressed gas cylinders containing oxygen and MAPP gas.

Gasoline

Oxy-gasoline, also known as oxy-petrol, torches have been found to perform very well, especially where bottled gas fuel is not available or difficult to transport to the worksite. Tests showed that an oxy-gasoline torch cut steel plate up to 0.5 in (13 mm) thick at the same rate as oxy-acetylene. In plate thicknesses greater than 0.5 inch the cutting rate was better than oxy-acetylene; at 4.5 in (110 mm) it was three times faster.

The gasoline is fed from a pressure tank whose pressure can be hand-pumped or fed from a gas cylinder. Another low cost approach commonly used by jewelry makers in Asia is using air bubbled through a gasoline container by a foot-operated air pump, and burning the fuel-air mixture in a specialized welding torch.

Hydrogen

Hydrogen has a clean flame and is good for use on aluminium. It can be used at a higher pressure than acetylene and is therefore useful for underwater welding and cutting. It is a good type of flame to use when heating large amounts of material. The flame temperature is high, about 2,000 °C for hydrogen gas in air at atmospheric pressure, and up to 2800 °C when pre-mixed in a 2:1 ratio with pure oxygen (oxyhydrogen).

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

- The oxygen and the hydrogen are led off the electrolysis cell separately and are fed into the two gas connections of an ordinary oxy-gas torch. This happens in the water torch, which is sometimes used in small torches used in making jewelry and electronics.
- The mixed oxygen and hydrogen are drawn from the electrolysis cell and are led into a special torch designed to prevent flashback.

MPS and MAPP gas

Methylacetylene-propadiene (MPS) *gas* and *MAPP gas* are similar fuels, because MAPP gas is liquefied petroleum gas mixed with MPS. It has the storage and shipping characteristics of LPG and has a heat value a little less than acetylene. Because it can be shipped in small containers for sale at retail stores, it is used by hobbyists and large industrial companies and shipyards because it does not polymerize at high pressures - above 15 psi or so (as acetylene does) and is therefore much less dangerous than acetylene. Further, more of it can be stored in a single place at one time, as the increased compressibility allows for more gas to be put into a tank. MAPP gas can be used at much higher pressures than acetylene, sometimes up to 40 or 50 psi in high-volume oxy-fuel cutting torches which can cut up to 12-inch-thick (300 mm) steel. Other welding gases that develop comparable temperatures need special procedures for safe shipping and handling. MPS and MAPP are recommended for cutting applications in particular, rather than welding applications.

Butane, propane and butane/propane mixes

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

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

Propane is cheaper than acetylene and easier to transport.

Like propylene, most propane tips are of a two-piece design. Propane often gets unfair criticism because it really needs changing the torch (from an equal pressure torch to an injector torch) and not just changing the tip to get the best performance. Most torches are equal pressure and designed for gases, such as acetylene, which are lighter than oxygen. Propane is a great deal heavier and runs much better through a low-pressure injector torch with a setting from a few ounces to about two pounds per square inch when cutting.

Propylene

Propylene is used in production welding and cutting. It cuts similarly to propane. When propylene is used, the torch rarely needs tip cleaning. There is often a substantial advantage to cutting with an injector torch rather than an equal-pressure torch when using propylene.

The role of oxygen

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

The word "oxygen" is often shortened to 'oxy', as in the term 'oxy-acetylene torch'.

Oxygen is usually produced elsewhere by distillation of liquified air and shipped to the welding site in high pressure vessels (commonly called "tanks" or "cylinders") at a pressure of about 21,000 kPa (3,000 lbf/in^2 = 200 atmospheres). It is also shipped as a liquid in Dewar type vessels (like a large Thermos jar) to places that use large amounts of oxygen.

It is also possible to separate oxygen from air by passing the air, while under pressure, through a zeolite sieve which selectively absorbs the nitrogen and lets the oxygen (and argon) pass. This gives a purity of oxygen of about 93%. This works well for brazing.

Types of flame

The welder can adjust the oxy-acetylene flame to be carbonizing (aka reducing), neutral, or oxidizing. Adjustment is made by adding more or less oxygen to the acetylene flame. The neutral flame is the flame most generally used when welding or cutting. The welder uses the neutral flame as the starting point for all other flame adjustments because it is so easily defined. This flame is attained when welders, as they slowly open the oxygen valve on the torch body, first see only two flame zones. At that point, the acetylene is being completely burned in the welding oxygen and surrounding air . The flame is chemically neutral. The two parts of this flame are the light blue inner cone and the darker blue to colorless outer cone. The inner cone is where the acetylene and the oxygen combine. The tip of this inner cone is the hottest part of the flame. It is approximately 6,000 °F (3,300 °C) and provides enough heat to easily melt steel . In the inner cone the acetylene breaks down and partly burns to hydrogen and carbon monoxide, which in the outer cone combine with more oxygen from the surrounding air and burn.

An excess of acetylene creates a carbonizing flame. This flame is characterized by three flame zones; the hot inner cone, a white-hot "acetylene feather", and the blue-colored outer cone. This is the type of flame observed when oxygen is first added to the burning acetylene. The feather is adjusted and made ever smaller by adding increasing amounts of oxygen to the flame. A welding feather is measured as 2X or 3X, with X being the length of the inner flame cone. The unburned carbon insulates the flame and drops the temperature to approximately 5,000 °F (2,800 °C). The reducing flame is typically used for hardfacing operations or backhand pipe welding techniques. The feather is caused by incomplete combustion of the acetylene to cause an excess of carbon in the flame. Some of this carbon is dissolved by the molten metal to carbonize it. The carbonizing flame will tend to remove the oxygen from iron oxides which may be present, a fact which has caused the flame to be known as a "reducing flame".

The oxidizing flame is the third possible flame adjustment. It occurs when the ratio of oxygen to acetylene required for a neutral flame has been changed to give an excess of oxygen. This flame type is observed when welders add more oxygen to the neutral flame. This flame is hotter than the other two flames because the combustible gases will not have to search so far to find the necessary amount of oxygen, nor heat up as much thermally inert carbon. It is called an oxidizing flame because of its effect on metal. This flame adjustment is generally not preferred. The oxidizing flame creates undesirable oxides to the structural and mechanical detriment of most metals. In an oxidizing flame, the inner cone acquires a purplish tinge, gets pinched and smaller at the tip, and the sound of the flame gets harsh. A slightly oxidizing flame is used in braze-welding and bronze-surfacing while a more strongly oxidizing flame is used in fusion welding certain brasses and bronzes

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

Welding

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

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

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

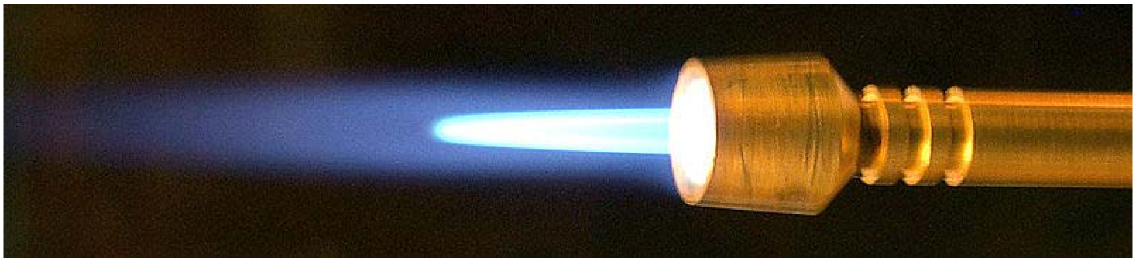
The welder must add the filler rod to the molten puddle. The welder must also keep the filler metal in the hot outer flame zone when not adding it to the puddle to protect filler metal from oxidation. Do not let the welding flame burn off the filler metal. The metal will not wet into the base metal and will look like a series of cold dots on the base metal. There is very little strength in a cold weld. When the filler metal is properly added to the molten puddle, the resulting weld will be stronger than the original base metal.

Cutting

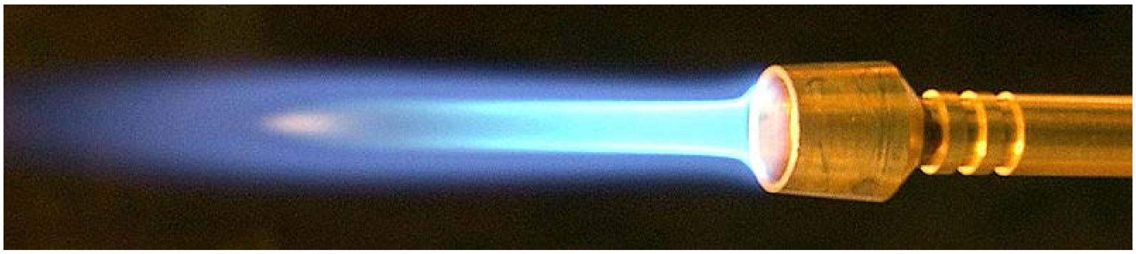
For cutting, the set-up is a little different. A cutting torch has a 60- or 90-degree angled head with orifices placed around a central jet. The outer jets are for preheat flames of oxygen and acetylene. The central jet carries only oxygen for cutting. The use of a number of preheating flames, rather than a single flame makes it possible to change the direction of the cut as desired without changing the position of the nozzle or the angle which the torch makes with the direction of the cut, as well as giving a better preheat balance . Manufacturers have developed custom tips for Mapp, propane, and polypropylene gases to optimize the flames from these alternate fuel gases.

The flame is not intended to melt the metal, but to bring it to its ignition temperature.

The torch's trigger blows extra oxygen at higher pressures down the torch's third tube out of the central jet into the workpiece, causing the metal to burn and blowing the resulting molten oxide through to the other side. The ideal kerf is a narrow gap with a sharp edge on either side of the workpiece; overheating the workpiece and thus melting through it causes a rounded edge.



Oxygen Rich Butane Torch Flame



Fuel Rich Butane Torch Flame

Cutting a rail just before renewing the rails and the ballast.

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

It is worth noting several things at this point:

- The oxygen flowrate is critical — too little will make a slow ragged cut; too much will waste oxygen and produce a wide concave cut. Oxygen Lances and other custom made torches do not have a separate pressure control for the cutting oxygen, so the cutting oxygen pressure must be controlled using the oxygen regulator. The oxygen cutting pressure should match the cutting tip oxygen orifice. Consult the tip manufacturer's equipment data for the proper cutting oxygen pressures for the specific cutting tip .
- The oxidation of iron by this method is highly exothermic. Once started, steel can be cut at a surprising rate, far faster than if it was merely melted through. At this point, the pre-heat jets are there purely for assistance. The rise in temperature will be obvious by the intense glare from the ejected material, even through proper goggles. (*A thermic lance is a tool which also uses rapid oxidation of iron to cut through almost any material.*)
- Since the melted metal flows out of the workpiece, there must be room on the opposite side of the workpiece for the spray to exit. When possible, pieces of metal are cut on a grate that lets the melted metal fall freely to the ground. The same equipment can be used for oxyacetylene blowtorches and welding torches, by exchanging the part of the torch in front of the torch valves.

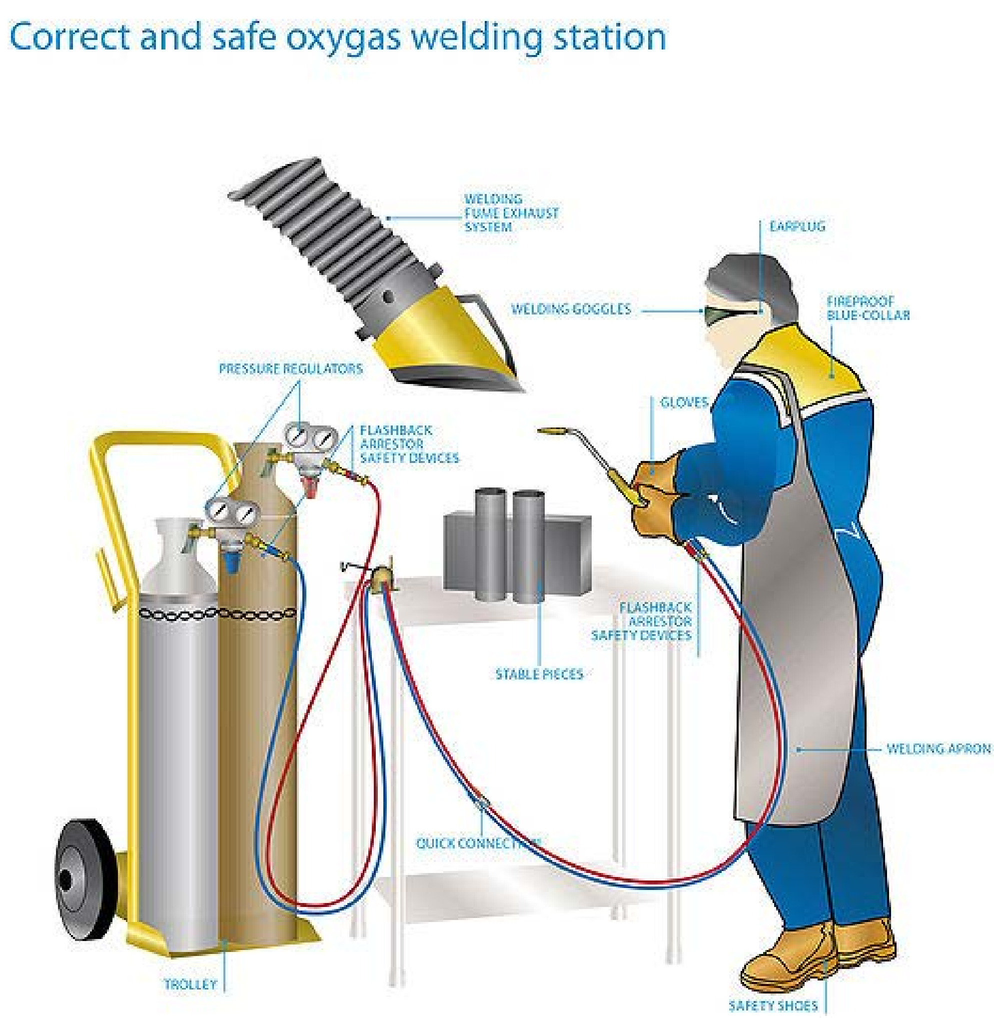
For a basic oxy-acetylene rig, the cutting speed in light steel section will usually be nearly twice as fast as a petrol-driven cut-off grinder. The advantages when cutting large sections are obvious - an oxy-fuel torch is light, small and quiet and needs very little effort to use, whereas a cut-off grinder is heavy and noisy and needs considerable operator exertion and may vibrate severely, leading to stiff hands and possible long-term repetitive strain injury. Oxy-acetylene torches can easily cut through ferrous materials in excess of 50 mm (2 inches). Oxygen Lances are used in scrapping operations and cut sections thicker than 200 mm (8 inches). Cut-off grinders are useless for these kinds of application.

Robotic oxy-fuel cutters sometimes use a high-speed divergent nozzle. This uses an oxygen jet that opens slightly along its passage. This allows the compressed oxygen to expand as it leaves, forming a high-velocity jet that spreads less than a parallel-bore nozzle, allowing a cleaner cut. These are not used for cutting by hand since they need very accurate positioning above the work. Their ability to produce almost any shape from large steel plates gives them a secure future in shipbuilding and in many other industries.

Oxy-propane torches are usually used for cutting up scrap to save money, as LPG is far cheaper joule-for-joule than acetylene, although propane does not produce acetylene's very neat cut profile. Propane also finds a place in production, for cutting very large sections.

Oxy-acetylene can only cut low to medium carbon steels and wrought iron. High carbon steels cannot be cut because the melting point is very close to the temperature of the flame, and so the slag from the cutting action does not eject as sparks, but rather mixes with the clean melt near the cut. This keeps the oxygen from reaching the clean metal and burning it. In the case of cast iron, graphite between the grains and the shape of the grains themselves interfere with cutting action of torch.

Safety



Oxygas welding station (keep cylinders and hoses away from the flame)

Gas welding/cutting goggles and safety helmet

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

- More than 1/7 the capacity of the cylinder should not be used per hour. This causes the acetone inside the acetylene cylinder to come out of the cylinder and contaminate the hose and possibly the torch.
- Acetylene is dangerous above 15 psi pressure. It is unstable and explosively decomposes.
- Proper ventilation when welding will help to avoid large chemical exposure.

The importance of eye protection

Proper protection such as welding goggles should be worn at all times, including to protect the eyes against glare and flying sparks. Special safety eyewear must be used—both to protect the welder and to provide a clear view through the yellow-orange flare given off by the incandescing flux. In the 1940s cobalt melters' glasses were borrowed from steel foundries and were still available until the 1980s. However, the lack of protection from impact, ultra-violet, infrared and blue light caused severe eyestrain and eye damage. Didymium eyewear, developed for glassblowers in the 1960s, was also borrowed—until many complained of eye problems from excessive infrared, blue light, and insufficient shading. Today very good eye protection can be found designed especially for gas-welding aluminum that cuts the sodium orange flare completely and provides the necessary protection from ultraviolet, infrared, blue light and impact, according to ANSI Z87-1989 safety standards for a Special Purpose Lens.

Fuel leakage

Fuel gases that are denser than air (Propane, Propylene, MAPP, Butane, etc...), may collect in low areas if allowed to escape. To avoid an ignition hazard, special care should be taken when using these gases over areas such as basements, sinks, storm drains, etc. In addition, leaking fittings may catch fire during use and pose a risk to personnel as well as property.

Safety with cylinders

When using fuel and oxygen tanks they should be fastened securely upright to a wall or a post or a portable cart. An oxygen tank is especially dangerous for the reason that the oxygen is at a pressure of 21 MPa (3000 lbf/in² = 200 atmospheres) when full, and if the tank falls over and its valve strikes something and is knocked off, the tank will effectively become an extremely deadly flying missile propelled by the compressed oxygen, capable of even breaking through a brick wall. For this reason, never move an oxygen tank around without its valve cap screwed in place.

On an oxyacetylene torch system there will be three types of valves, the tank valve, the regulator valve, and the torch valve. There will be a set of these three valves for each gas. The gas in the tanks or cylinders is at high pressure. Oxygen cylinders are generally filled to approximately 2200 psi. The regulator converts the high pressure gas to a low pressure stream suitable for welding. Never attempt to directly use high-pressure gas.

Chemical exposure

A less obvious hazard of welding is exposure to harmful chemicals. Exposure to certain metals, metal oxides, or carbon monoxide can often lead to severe medical conditions. Damaging chemicals can be produced from the fuel, from the work-piece, or from a protective coating on the work-piece. By increasing ventilation around the welding environment, the welders will have much less exposure to harmful chemicals from any source.

The most common fuel used in welding is acetylene, which has a two-stage reaction. The primary chemical reaction involves the acetylene disassociating in the presence of oxygen to produce heat, carbon monoxide, and hydrogen gas: $C_2H_2 + O_2 \rightarrow 2CO + H_2$. A secondary reaction follows where the carbon monoxide and hydrogen combine with more oxygen to produce carbon dioxide and water vapor. When the secondary reaction does not burn all of the reactants from the primary reaction, the welding processes produces large amounts of carbon monoxide, and it often does. Carbon monoxide is also the byproduct of many other incomplete fuel reactions.

Almost every piece of metal is an alloy of one type or another. Copper, aluminium, and other base metals are occasionally alloyed with beryllium, which is a highly toxic metal. When a metal like this is welded or cut, high concentrations of toxic beryllium fumes are released. Long-term exposure to beryllium may result in shortness of breath, chronic cough, and significant weight loss, accompanied by fatigue and general weakness. Other alloying elements such as arsenic, manganese, silver, and aluminium can cause sickness to those who are exposed.

More common are the anti-rust coatings on many manufactured metal components. Zinc, cadmium, and fluorides are often used to protect irons and steels from oxidizing. Galvanized metals have a very heavy zinc coating. Exposure to zinc oxide fumes can lead to a sickness named "metal fume fever". This condition rarely lasts longer than 24 hours, but is still unpleasant. Not unlike common influenza, fevers, chills, nausea, cough, and fatigue are common effects of high zinc oxide exposure.

Flashback

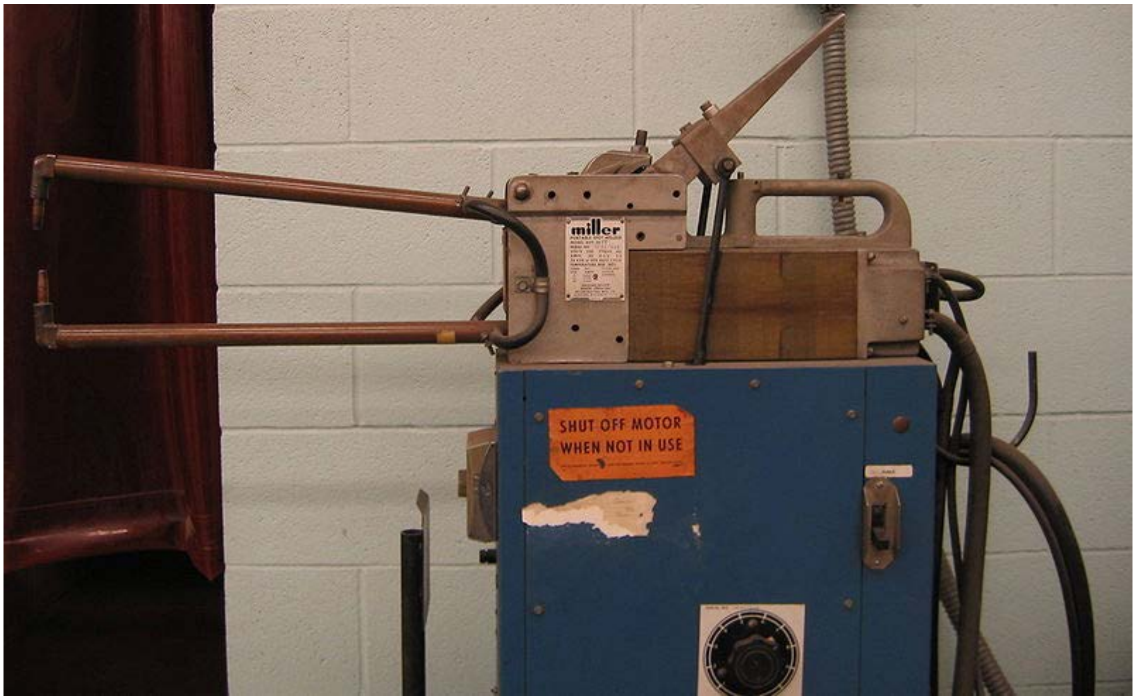
Flashback is the condition of the flame propagating down the hoses of an oxy-fuel welding and cutting system. To prevent such a situation a flashback arrestor is usually employed. The flame burns backwards into the hose, causing a popping or squealing noise. It can cause an explosion in the hose with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

Chapter 5

Electric Resistance Welding

Electric resistance welding (**ERW**) refers to a group of welding processes such as spot and seam welding that produce coalescence of faying surfaces where heat to form the weld is generated by the electical reistance of material vs the time and the force used to hold the materials together during welding. Some factors influencing heat or welding temperatures are the proportions of the workpieces, the coating or the lack of coating, the electrode materials, electrode geometry, electrode pressing force, weld current and weld time. Small pools of molten metal are formed at the point of most electrical resistance (the connecting surfaces) as a high current (100–100,000 A) is passed through the metal. In general, resistance welding methods are efficient and cause little pollution, but their applications are limited to relatively thin materials and the equipment cost can be high (although in production situations the cost per weld may be as low as $0.04 USD per weld depending on application and manufacturing rate).

Spot welding



Spot welder

Spot welding is a resistance welding method used to join two to three overlapping metal sheets, studs, projections, electrical wiring hangers, some heat exchanger fins, and some tubing. Usually power sources and welding equipment are sized, to the specific thickness and material being welded together. Thickness are limited to the output of the welding power source and equipment range due to the high current required for the application . Care is taken to eliminate, contaminates between the faying surfaces. Usually, Two copper electrodes are simultaneously used to clamp the metal sheets together and to pass current through the sheets. When the current is passed through the electrodes to the sheets, heat is generated due to the higher electrical resistance where the surfaces contact each other. As the electrical resistance of the material causes an heat buildup in the work between the copper electrodes, the rising temperature causes a rising resistance, and results in a molten pool contained most of the time between the electrodes. The water cooled copper electrodes remove the surface heat quickly, speeding solidification of the weld, since copper is an excellent conductor. As the heat dissipates throughout the workpiece in less than a second(controls are based in AC cycles, or microseconds) the molten, or at least plastic, state grows to meet the welding tips. When the current is stopped the copper tips cool the spot weld, causing the metal to solidify under pressure. Some of the different currents used are Direct Current, Alternating Current, and Medium Frequency Half wave Direct Current, as well as high frequency half wave Direct current.

If excessive heat is applied, or applied too quickly,or the force between the base materials is too low, or the coating too thick, or too conductive, the molten area may extend to the outside, and with its high pressure (typically 30,000 psi) will escape the containment force of the tips with a burst of molten metal called expulsion. When this occurs, the metal will be thinner and have less strength than a weld with no expulsion. The common method of checking a weld is a peel test. A alternative test is the restrained tensile test, which is much more difficult to perform, and requires calibrated equipment. Ultrasonic Evaluation has been tried and is still in a "unapproved" state for many OEMs.

The advantages of the method include efficient energy use, limited workpiece deformation, high production rates, easy automation, and no required filler materials. When high strength in shear is needed, spot welding is used in preference to more costly mechanical fastening, such as riveting. While the shear strength of each weld is high, the fact that the weld spots do not form a continuous seam means that the overall strength is often significantly lower than with other welding methods, limiting the usefulness of the process. It is used extensively in the automotive industry— cars can have several thousand spot welds. A specialized process, called shot welding, can be used to spot weld stainless steel.

There are three basic types of resistance welding bonds: solid state, fusion, and reflow braze. In a *solid state bond*, also called a thermo-compression bond, dissimilar materials with dissimilar grain structure, e.g. molybdenum to tungsten, are joined using a very short heating time, high weld energy, and high force. There is little melting and minimum grain growth, but a definite bond and grain interface. Thus the materials actually bond while still in the solid state. The bonded materials typically exhibit excellent shear and tensile strength, but poor peel strength. In a *fusion bond*, either similar or dissimilar materials with similar grain structures are heated to the melting point (liquid state) of both. The subsequent cooling and combination of the materials forms a “nugget” alloy of the two materials with larger grain growth. Typically, high weld energies at either short or long weld times, depending on physical characteristics, are used to produce fusion bonds. The bonded materials usually exhibit excellent tensile, peel and shear strengths. In a *reflow braze bond*, a resistance heating of a low temperature brazing material, such as gold or solder, is used to join either dissimilar materials or widely varied thick/thin material combinations. The brazing material must “wet” to each part and possess a lower melting point than the two workpieces. The resultant bond has definite interfaces with minimum grain growth. Typically the process requires a longer (2 to 100 ms) heating time at low weld energy. The resultant bond exhibits excellent tensile strength, but poor peel and shear strength.

Seam welding

Resistance seam welding is a process that produces a weld at the faying surfaces of two similar metals. The seam may be a butt joint or an overlap joint and is usually an automated process. It differs from butt welding in that butt welding typically welds the entire joint at once and seam welding forms the weld progressively, starting at one end. Like spot welding, seam welding relies on two electrodes, usually made from copper, to apply pressure and current. The electrodes are disc shaped and rotate as the material passes between them. This allows the electrodes to stay in constant contact with the material to make long continuous welds. The electrodes may also move or assist the movement of the material.

A transformer supplies energy to the weld joint in the form of low voltage, high current AC power. The joint of the work piece has high electrical resistance relative to the rest of the circuit and is heated to its melting point by the current. The semi-molten surfaces are pressed together by the welding pressure that creates a fusion bond, resulting in a uniformly welded structure. Most seam welders use water cooling through the electrode, transformer and controller assemblies due to the heat generated. Seam welding produces an extremely durable weld because the joint is forged due to the heat and pressure applied. A properly welded joint formed by resistance welding is typically stronger than the material from which it is formed.

A common use of seam welding is during the manufacture of round or rectangular steel tubing. Seam welding has been used to manufacture steel beverage cans but is no longer used for this as modern beverage cans are seamless aluminum.

Other methods

Other ERW methods include flash welding, resistance projection welding, and upset welding.

Chapter 6

Arc Welding

Gas metal arc welding

Arc welding is a type of welding that uses a welding power supply to create an electric arc between an electrode and the base material to melt the 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/or an evaporating filler material. The process of arc welding is widely used because of its low capital and running costs. Getting the arc started is called striking the arc. An arc may be struck by either lightly tapping the electrode against the metal or scratching the electrode against the metal at high speed.

Development

While examples of forge welding go back to the Bronze Age and the Iron Age, arc welding did not come into practice until much later. In 1802, Vasily Petrov discovered the continuous electric arc and subsequently proposed its possible practical applications, including welding. The French electrical inventor Auguste de Méritens produced the first carbon arc torch, patented in 1881, which was successfully used for welding lead in the manufacture of lead-acid batteries. In 1881-1882 a Russian inventor Nikolai Bernardos created the an electric arc welding method for steel known as carbon arc welding, using carbon electrodes. The advances in arc welding continued with the invention of metal electrodes in the late 19th century by a Russian, Nikolai Slavyanov (1888), and an American, C. L. Coffin. Around 1900, A. P. Strohmenger released in Britain a coated metal electrode which gave a more stable arc. In 1905 Russian scientist Vladimir Mitkevich proposed the usage of three-phase electric arc for welding. In 1919, alternating current welding was invented by C.J. Holslag but did not become popular for another decade.

Competing welding processes such as resistance welding and oxyfuel welding were developed during this time as well; but both, especially the latter, faced stiff competition from arc welding especially after metal coverings (known as flux) for the electrode, to stabilize the arc and shield the base material from impurities, continued to be developed.

During World War I welding started to be used in shipbuilding in Great Britain in place of riveted steel plates. The Americans also became more accepting of the new technology when the process allowed them to repair their ships quickly after a German attack in the New York Harbor at the beginning of the war. Arc welding was first applied to aircraft during the war as well, and some German airplane fuselages were constructed using this process. In 1919, the British shipbuilder Cammell Laird started construction of merchant ship, the *Fullagar*, with an entirely welded hull; she was launched in 1921.

During the 1920s, major advances were made in welding technology, including the 1920 introduction of automatic welding in which electrode wire was continuously fed. Shielding gas became a subject receiving much attention as scientists attempted to protect welds from the effects of oxygen and nitrogen in the atmosphere. Porosity and brittleness were the primary problems and the solutions that developed included the use of hydrogen, argon, and helium as welding atmospheres. During the following decade, further advances allowed for the welding of reactive metals such as aluminum and magnesium. This, in conjunction with developments in automatic welding, alternating current, and fluxes fed a major expansion of arc welding during the 1930s and then during World War II.

During the middle of the century, many new welding methods were invented. Submerged arc welding was invented in 1930 and continues to be popular today. In 1932 a Russian, Konstantin Khrenov successfully implemented the first underwater electric arc welding. Gas tungsten arc welding, after decades of development, was finally perfected in 1941 and gas metal arc welding followed in 1948, allowing for fast welding of non-ferrous materials but requiring expensive shielding gases. Using a consumable electrode and a carbon dioxide atmosphere as a shielding gas, it quickly became the most popular metal arc welding process. In 1957, the flux-cored arc welding process debuted in which the self-shielded wire electrode could be used with automatic equipment, resulting in greatly increased welding speeds. In that same year, plasma arc welding was invented. Electroslag welding was released in 1958 and was followed by its cousin, electrogas welding, in 1961.

Power supplies

Engine driven welder capable of AC/DC welding

A diesel powered welding generator (the electric generator is on the left) as used in Indonesia.

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. Typical currents are 50 to 500 amps, depending on the size of weld required; 100 amps is typical for manual welders. Voltage output is typically 20 to 50 volts during welding, though some power supplies also include a small high voltage source to aid in initially striking the arc. 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.

The direction 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. Non-consumable electrode processes, such as gas tungsten arc welding, can use either type of direct current (DC), as well as alternating current (AC). With direct current however, 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, eliminating low-voltage time after the zero crossings and minimizing the effects of the problem.

Consumable electrode methods

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. An electric current is used to strike an arc between the base material and a consumable electrode rod or 'stick'. The electrode rod is made of a material that is compatible with the base material being welded and is covered with a flux that protects the weld area from oxidation and contamination by producing CO_2 gas during the welding process. The electrode core itself acts as filler material, making a separate filler unnecessary. The process is very versatile, requiring little operator training and inexpensive equipment. However, 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 specialty electrodes have made possible the welding of cast iron, nickel, aluminium, copper and other metals. The versatility of the method makes it popular in a number of applications including repair work and construction.

Gas metal arc welding (GMAW), commonly called MIG (Metal Inert Gas), is a semi-automatic or automatic welding process with a continuously fed consumable wire acting as both electrode and filler metal, along with an inert or semi-inert shielding gas flowed around the wire to prevent the weld site from contamination. Constant voltage, direct current power source is most commonly used with GMAW, but constant current alternating current are used as well. With continuously fed filler electrodes, GMAW offers relatively high welding speeds, however the more complicated equipment reduces convenience and versatility in comparison to the SMAW process. Originally developed for welding aluminium and other non-ferrous materials in the 1940s, GMAW was soon economically applied to steels. Today, GMAW is commonly used in industries such as the automobile industry for its quality, versatility and speed. Because of the need to maintain a stable shroud of shielding gas around the weld site, it can be problematic to use the GMAW process in areas of high air movement such as outdoors.

Flux-cored arc welding (FCAW) is a variation of the GMAW technique. FCAW wire is actually a fine metal tube filled with powdered flux materials. Flux cored wire generates an effective gas shield precisely at the weld site, permitting application involving more windy conditions or contaminated materials, however the flux cored wire leaves a slag residue and is more expensive than solid wire.

Submerged arc welding (SAW) is a high-productivity automatic 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 no smoke is produced. The process is commonly used in industry, especially for large products. As the arc is not visible, it requires full automatization. In-position welding is not possible with SAW.

Non-consumable electrode methods

Gas tungsten arc welding (GTAW), or tungsten inert gas (TIG) welding, is a manual welding process that uses a non-consumable electrode made of tungsten, 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. It 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 is much faster. It can be applied to all of the same materials as GTAW except magnesium; 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.

Other arc welding processes include atomic hydrogen welding, carbon arc welding, electroslag welding, electrogas welding, and stud arc welding.

Corrosion issues

Some materials, notably high-strength steels, aluminium, and titanium alloys, are susceptible to hydrogen embrittlement. If the electrodes used for welding contain traces of moisture, the water decomposes in the heat of the arc and the liberated hydrogen enters the lattice of the material, causing its brittleness. Electrodes for such materials, with special low-hydrogen coating, are delivered in sealed moisture-proof packaging. New electrodes can be used straight from the can, but when moisture absorption may be suspected, they have to be dried by baking (usually at 800 to 1000 °F (425 to 550 °C)) in a drying oven. Flux used has to be kept dry as well.

Some austenitic stainless steels and nickel-based alloys are prone to intergranular corrosion. When subjected to temperatures around 700 °C (1,300 °F) for too long time, chromium reacts with carbon in the material, forming chromium carbide and depleting the crystal edges of chromium, impairing their corrosion resistance in a process called sensitization. Such sensitized steel undergoes corrosion in the areas near the welds where the temperature-time was favorable for forming the carbide. This kind of corrosion is often termed weld decay.

Knifeline attack (KLA) is another kind of corrosion affecting welds, impacting steels stabilized by niobium. Niobium and niobium carbide dissolves in steel at very high temperatures. At some cooling regimes, niobium carbide does not precipitate, and the steel then behaves like unstabilized steel, forming chromium carbide instead. This affects only a thin zone several millimeters wide in the very vicinity of the weld, making it difficult to spot and increasing the corrosion speed. Structures made of such steels have to be heated in a whole to about 1,950 °F (1,070 °C), when the chromium carbide dissolves and niobium carbide forms. The cooling rate after this treatment is not important.

Filler metal (electrode material) improperly chosen for the environmental conditions can make them corrosion-sensitive as well. There are also issues of galvanic corrosion if the electrode composition is sufficiently dissimilar to the materials welded, or the materials are dissimilar themselves. Even between different grades of nickel-based stainless steels, corrosion of welded joints can be severe, despite that they rarely undergo galvanic corrosion when mechanically joined.

Safety issues

WELDING SAFETY CHECKLIST		
HAZARD	**FACTORS TO CONSIDER**	**PRECAUTION SUMMARY**
Electric shock can kill	• Wetness • Welder in or on workpiece • Confined space • Electrode holder and cable insulation	• Insulate welder from workpiece and ground using *dry* insulation. Rubber mat or dry wood. • Wear *dry, hole-free* gloves. (Change as necessary to keep dry.) • Do not touch electrically "hot" parts or electrode with bare skin or wet clothing. • If wet area and welder cannot be insulated from workpiece with dry insulation, use a semiautomatic, constant-voltage welder or stick welder with voltage reducing device. • Keep electrode holder and cable insulation in good condition. Do not use if insulation damaged or missing.
Fumes and gases can be dangerous	• Confined area • Positioning of welder's head • Lack of general ventilation • Electrode types, i.e., manganese, chromium, etc. See MSDS • Base metal coatings, galvanize, paint	• Use ventilation or exhaust to keep air breathing zone clear, comfortable. • Use helmet and positioning of head to minimize fume in breathing zone. • Read warnings on electrode container and material safety data sheet (MSDS) for electrode. • Provide additional ventilation/exhaust where special ventilation requirements exist. • Use special care when welding in a confined area. • Do not weld unless ventilation is adequate.
Welding sparks can cause fire or explosion	• Containers which have held combustibles • Flammable materials	• Do not weld on containers which have held combustible materials (unless strict AWS F4.1 procedures are followed). Check before welding. • Remove flammable materials from welding area or shield from sparks, heat. • Keep a fire watch in area during and after welding. • Keep a fire extinguisher in the welding area. • Wear fire retardant clothing and hat. Use earplugs when welding overhead.
Arc rays can burn eyes and skin	• Process: gas-shielded arc most severe	• Select a filter lens which is comfortable for you while welding. • Always use helmet when welding. • Provide non-flammable shielding to protect others. • Wear clothing which protects skin while welding.
Confined space	• Metal enclosure • Wetness • Restricted entry • Heavier than air gas • Welder inside or on workpiece	• Carefully evaluate adequacy of ventilation especially where electrode requires special ventilation or where gas may displace breathing air. • If basic electric shock precautions cannot be followed to insulate welder from work and electrode, use semiautomatic, constant-voltage equipment with cold electrode or stick welder with voltage reducing device. • Provide welder helper and method of welder retrieval from outside enclosure.
General work area hazards	• Cluttered area	• Keep cables, materials, tools neatly organized.
	• Indirect work (welding ground) connection	• Connect work cable as close as possible to area where welding is being performed. Do *not* allow alternate circuits through scaffold cables, hoist chains, ground leads.
	• Electrical equipment	• Use only double insulated or properly grounded equipment. • Always disconnect power to equipment before servicing.
	• Engine-driven equipment	• Use in only open, well ventilated areas. • Keep enclosure complete and guards in place. • See Lincoln service shop if guards are missing. • Refuel with engine off. • If using auxiliary power, OSHA may require GFI protection or assured grounding program (or isolated windings if less than 5KW).
	• Gas cylinders	• Never touch cylinder with the electrode. • Never lift a machine with cylinder attached. • Keep cylinder upright and chained to support.

Welding Safety Checklist

Welding can be a dangerous and unhealthy practice without the proper precautions; however, with the use of new technology and proper protection the risks of injury or death associated with welding can be greatly reduced.

Heat and sparks

Because many common welding procedures involve an open electric arc or flame, the risk of burns from heat and sparks is significant. To prevent them, welders wear protective clothing in the form of heavy leather gloves and protective long sleeve jackets to avoid exposure to extreme heat, flames, and sparks.

Eye damage

Auto Darkening Welding hood with 90x110 mm cartridge and 3.78 in. x 1.85 in. viewing area

The brightness of the weld area leads to a condition called arc eye in which ultraviolet light causes inflammation of the cornea and can burn the retinas of the eyes. Welding goggles and helmets with dark face plates are worn to prevent this exposure and, in recent years, new helmet models have been produced featuring a face plate that self-darkens upon exposure to high amounts of UV light. To protect bystanders, transparent 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.

Those dark face plates must be much darker than those in sunglasses or blowtorching goggles. Sunglasses and blowtorching goggles are ***not*** adequate for arc welding protection.

In 1970, a Swedish doctor, Åke Sandén, developed a new type of welding goggles that used a multilayer interference filter to block most of the light from the arc. He had observed that most welders could not see well enough, with the mask on, to strike the arc, so they would flip the mask up, then flip it down again once the arc was going: this exposed their naked eyes to the intense light for a while. By coincidence, the spectrum of an electric arc has a notch in it, which coincides with the yellow sodium line. Thus, a welding shop could be lit by sodium vapor lamps or daylight, and the welder could see well to strike the arc. The Swedish government required these masks to be used for arc welding, but they were not used in the United States. They may have disappeared.

Inhaled matter

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. 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 various gases (most commonly carbon dioxide and ozone, but others as well) that can prove dangerous if ventilation is inadequate. Furthermore, 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.

Interference with pacemakers

Certain welding machines which use a high frequency AC current component have been found to affect pacemaker operation when within 2 meters of the power unit and 1 meter of the weld site.

Chapter 7

Plastic Welding

Plastic welding or **heat sealing** is the process of welding plastic workpieces together. It is one of the primary processes of joining or welding plastics.

There are several techniques with which this can be accomplished:

Hot gas welding

Hot gas welding, also known as *hot air welding*, is a plastic welding technique which is analogous to gas welding metals, though the specific techniques are different. A specially designed heat gun, called a *hot air welder*, produces a jet of hot air that softens both the parts to be joined and a plastic filler rod, all of which must be of the same or a very similar plastic. Welding PVC to acrylic is an exception to this rule.

Hot air/gas welding is a common fabrication technique for manufacturing smaller items such as chemical tanks, water tanks, heat exchangers, and plumbing fittings.

In the case of webs and films a filler rod may not be used. Two sheets of plastic are heated via a hot gas (or a heating element) and then rolled together. This is a quick welding process and can be performed continuously.

Freehand welding

With freehand welding, the jet of hot air (or inert gas) from the welder is played on the weld area and the tip of the weld rod at the same time. As the rod softens, it is pushed into the joint and fuses to the parts. This process is slower than most others, but it can be used in almost any situation.

Speed tip welding

With speed welding, the plastic welder, similar to a soldering iron in appearance and wattage, is fitted with a feed tube for the plastic weld rod. The speed tip heats the rod and the substrate, while at the same time it presses the molten weld rod into position. A bead of softened plastic is laid into the joint, and the parts and weld rod fuse. With some types of plastic such as polypropylene, the melted welding rod must be "mixed" with the semi-melted base material being fabricated or repaired. These welding techniques have been perfected over time and have been utilised for over 50 years by professional plastic fabricators and repairers internationally. Speed tip welding method is a much faster welding technique and with practice can be used in tight corners.

Extrusion welding

Extrusion welding allows the application of bigger welds in a single weld pass. It is the preferred technique for joining material over 6 mm thick. Welding rod is drawn into a miniature hand held plastic extruder, plasticized, and forced out of the extruder against the parts being joined, which are softened with a jet of hot air to allow bonding to take place.

Contact welding

This is the same as spot welding except that heat is supplied with conduction of the pincher tips instead of electrical conduction. Two plastic parts are brought together where heated tips pinch them, melting and joining the parts in the process.

Hot plate welding

Related to contact welding, this technique is used to weld larger parts, or parts that have a complex weld joint geometry. The two parts to be welded are placed in the tooling attached to the two opposing platens of a press. A hot plate, with a shape that matches the weld joint geometry of the parts to be welded, is moved in position between the two parts. The two opposing platens move the parts into contact with the hot plate until the heat softens the interfaces to the melting point of the plastic. When this condition is achieved the hot plate is removed, and the parts are pressed together and held until the weld joint cools and re-solidifies to create a permanent bond.

The most common form of this welding is butt heat fusion welding which welds two circular tubes end to end.

High frequency welding

Certain plastics with chemical dipoles, such as PVC, polyamides (PA) and acetates can be heated with high frequency electromagnetic waves. High frequency welding uses this property to soften the plastics for joining. The heating can be localized, and the process can be continuous. Also known as Dielectric Sealing, R.F. (Radio Frequency) Heat Sealing.

In a ferromagnetic work piece, plastics can be induction-welded by formulating them with metallic or ferromagnetic compounds, called susceptors. These susceptors absorb electromagnetic energy from an induction coil, become hot, and lose their heat energy to the surrounding material by thermal conduction.

Radio frequency welding is a very mature technology that has been around since the 1940s. Two pieces of material are placed on a table press that applies pressure to both surface areas. Dies are used to direct the welding process. When the press comes together, high frequency waves (usually 27.12 MHz) are passed through the small area between the die and the table where the weld takes place. This high frequency (radio frequency) field causes the molecules in certain materials to move and get hot, and the combination of this heat under pressure causes the weld to take the shape of the die. RF welding is fast. This type of welding is used to connect polymer films used in a variety of industries where a strong consistent leak-proof seal is required. In the fabrics industry, RF is most often used to weld PVC and polyurethane (PU) coated fabrics. This is a very consistent method of welding.

The most common materials used in RF welding are PVC and polyurethane. It is also possible to weld other polymers such as nylon, PET, EVA and some ABS plastics.

Ultrasonic welding

In ultrasonic welding, high frequency (15 kHz to 40 kHz) low amplitude vibration is used to create heat by way of friction between the materials to be joined. The interface of the two parts is specially designed to concentrate the energy for the maximum weld strength. Ultrasonic can be used on almost all plastic material. It is the fastest heat sealing technology available.

Friction welding

In friction welding, the two parts to be assembled are rubbed together at a lower frequency (typically 100–300 Hz) and higher amplitude (typically 1 to 2 mm (0.039 to 0.079 in)) than ultrasonic welding. The friction caused by the motion combined with the clamping pressure between the two parts creates the heat which begins to melt the contact areas between the two parts. At this point, the plasticized materials begin to form layers that intertwine with one another, which therefore results in a strong weld. At the completion of the vibration motion, the parts remain held together until the weld joint cools and the melted plastic re-solidifies. The friction movement can be linear or orbital, and the joint design of the two parts has to allow this movement.

Spin welding

Spin welding is another form of frictional welding. With this process, one part is held stationary, while the other one is rotated at high velocity. The rotating part is then pressed against the fixed part with significant force.

Laser welding

This technique requires one part to be transmissive to a laser beam and either the other part absorptive or a coating at the interface to be absorptive to the beam. The two parts are put under pressure while the laser beam moves along the joining line. The beam passes through the first part and is absorbed by the other one or the coating to generate enough heat to soften the interface creating a permanent weld.

Semiconductor diode lasers are typically used in plastic welding. Wavelengths in the range of 808 nm to 980 nm can be used to join various plastic material combinations. Power levels from less than 1W to 100W are needed depending on the materials, thickness and desired process speed.

Diode laser systems have the following advantages in joining of plastic materials:

- Cleaner than adhesive bonding
- No micro-nozzles to get clogged
- No liquid or fumes to affect surface finish
- No consumables
- Higher throughput
- Can access work-piece in challenging geometry
- High level of process control

Requirements for high strength joints include:

- Adequate transmission through upper layer
- Absorption by lower layer
- Material compatibility – wetting
- Good joint design – clamping pressure, joint area
- Lower power density

Materials that can be joined include:

- Polypropylene
- Polycarbonate
- Acrylic
- Nylon
- ABS

Specific applications include sealing / welding / joining of: catheter bags, medical containers, automobile remote control keys, heart pacemaker casings, syringe tamper evident joints, headlight or tail-light assemblies, pump housings, and cellular phone parts.

Solvent welding

In solvent welding, a solvent is applied which can temporarily dissolve the polymer at room temperature. When this occurs, the polymer chains are free to move in the liquid and can mingle with other similarly dissolved chains in the other component. Given sufficient time, the solvent will permeate through the polymer and out into the environment, so that the chains lose their mobility. This leaves a solid mass of entangled polymer chains which constitutes a solvent weld.

This technique is commonly used for connecting PVC and ABS pipe, as in household plumbing. The "gluing" together of plastic (polycarbonate, polystyrene or ABS) models is also a solvent welding process.

Dichloromethane (methylene chloride), which is obtainable in paint stripper, can solvent weld polycarbonate and polymethylmethacrylate. Dichloromethane chemically welds certain plastics; for example, it is used to seal the casing of electric meters. It is also a component - along with tetrahydrofuran - of the solvent used to weld plumbing.

Welding rod

A plastic welding rod, also known as a *thermoplastic welding rod*, is a rod with circular or triangular cross-section used to bind two pieces of plastic together. They are available in a wide range of colors to match the base material's color.

An important aspect of plastic welding rod design and manufacture is the porosity of the material. A high porosity will lead to air bubbles (known as *voids*) in the rods, which decrease the quality of the welding. The highest quality of plastic welding rods are therefore those with zero porosity, which are called *voidless*.

Chapter 8

Nondestructive Testing

Nondestructive testing or **Non-destructive testing** (**NDT**) is a wide group of analysis techniques used in science and industry to evaluate the properties of a material, component or system without causing damage. The terms **Nondestructive examination** (**NDE**), **Nondestructive inspection** (**NDI**), and **Nondestructive evaluation** (**NDE**) are also commonly used to describe this technology. Because NDT does not permanently alter the article being inspected, it is a highly-valuable technique that can save both money and time in product evaluation, troubleshooting, and research. Common NDT methods include ultrasonic, magnetic-particle, liquid penetrant, radiographic, remote visual inspection (RVI), eddy-current testing, and low coherence interferometry . NDT is a commonly-used tool in forensic engineering, mechanical engineering, electrical engineering, civil engineering, systems engineering, aeronautical engineering, medicine, and art.

Methods

NDT methods may rely upon use of electromagnetic radiation, sound, and inherent properties of materials to examine samples. This includes some kinds of microscopy to examine external surfaces in detail, although sample preparation techniques for metallography, optical microscopy and electron microscopy are generally destructive as the surfaces must be made smooth through polishing or the sample must be electron transparent in thickness. The inside of a sample can be examined with penetrating electromagnetic radiation, such as X-rays or 3D X-rays for volumetric inspection. Sound waves are utilized in the case of ultrasonic testing. Contrast between a defect and the bulk of the sample may be enhanced for visual examination by the unaided eye by using liquids to penetrate fatigue cracks. One method (liquid penetrant testing) involves using dyes, fluorescent or non-fluorescing, in fluids for non-magnetic materials, usually metals. Another commonly used method for magnetic materials involves using a liquid suspension of fine iron particles applied to a part while it is in an externally applied magnetic field (magnetic-particle testing). Thermoelectric effect (or use of the Seebeck effect) uses thermal properties of an alloy to quickly and easily characterize many alloys.

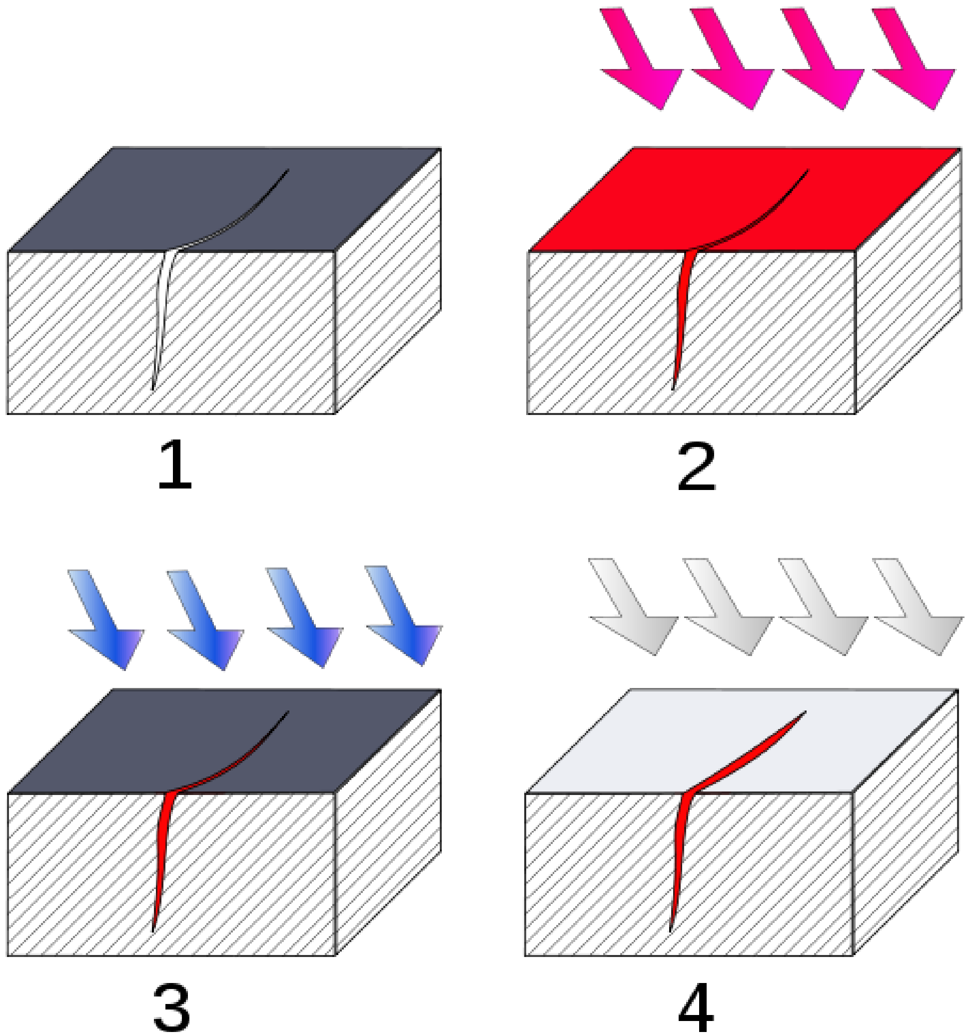
The chemical test, or chemical spot test method, utilizes application of sensitive chemicals that can indicate the presence of individual alloying elements.

Training

Non-Destructive Testing (NDT) training is provided for people working in many industries. It is generally necessary that the student successfully completes a theoretical training program (usually 40 hours of classroom training), as well as have performed several hundred hours of practical application of the particular method they wish to be trained in. At this point, they can apply to write a certifying exam with one of the few governing bodies. Getting certified to inspect steels is quite a complex, and difficult process. Further, NDT Training has recently become available online. WorldSpec.org is one of the innovative companies that helped pioneer this new "era" in NDT Training.

Examples

Weld verification



1. Section of material with a surface-breaking crack that is not visible to the naked eye.
2. Penetrant is applied to the surface.
3. Excess penetrant is removed.
4. Developer is applied, rendering the crack visible.

In manufacturing, welds are commonly used to join two or more metal surfaces. Because these connections may encounter loads and fatigue during product lifetime, there is a chance that they may fail if not created to proper specification. For example, the base metal must reach a certain temperature during the welding process, must cool at a specific rate, and must be welded with compatible materials or the joint may not be strong enough to hold the surfaces together, or cracks may form in the weld causing it to fail. The typical welding defects, lack of fusion of the weld to the base metal, cracks or porosity inside the weld, and variations in weld density, could cause a structure to break or a pipeline to rupture.

Welds may be tested using NDT techniques such as industrial radiography using X-rays or gamma rays, ultrasonic testing, liquid penetrant testing or via eddy current. In a proper weld, these tests would indicate a lack of cracks in the radiograph, show clear passage of sound through the weld and back, or indicate a clear surface without penetrant captured in cracks.

Welding techniques may also be actively monitored with acoustic emission techniques before production to design the best set of parameters to use to properly join two materials.

Structural mechanics

Structures can be complex systems that undergo different loads during their lifetime. Some complex structures, such as the turbomachinery in a liquid-fuel rocket, can also cost millions of dollars. Engineers will commonly model these structures as coupled second-order systems, approximating dynamic structure components with springs, masses, and dampers. These sets of differential equations can be used to derive a transfer function that models the behavior of the system.

In NDT, the structure undergoes a dynamic input, such as the tap of a hammer or a controlled impulse. Key properties, such as displacement or acceleration at different points of the structure, are measured as the corresponding output. This output is recorded and compared to the corresponding output given by the transfer function and the known input. Differences may indicate an inappropriate model (which may alert engineers to unpredicted instabilities or performance outside of tolerances), failed components, or an inadequate control system.

Notable events in early industrial NDT

- 1854 Hartford, Connecticut: a boiler at the Fales and Gray Car works explodes, killing 21 people and seriously injuring 50. Within a decade, the State of Connecticut passes a law requiring annual inspection (in this case visual) of boilers.
- 1895 Wilhelm Conrad Röntgen discovers what are now known as X-rays. In his first paper he discusses the possibility of flaw detection.
- 1880 - 1920 The "Oil and Whiting" method of crack detection is used in the railroad industry to find cracks in heavy steel parts. (A part is soaked in thinned oil, then painted with a white coating that dries to a powder. Oil seeping out from cracks turns the white powder brown, allowing the cracks to be detected.) This was the precursor to modern liquid penetrant tests.
- 1920 Dr. H. H. Lester begins development of industrial radiography for metals.
- 1924 — Lester uses radiography to examine castings to be installed in a Boston Edison Company steam pressure power plant .
- 1926 The first electromagnetic eddy current instrument is available to measure material thicknesses.

- 1927 - 1928 Magnetic induction system to detect flaws in railroad track developed by Dr. Elmer Sperry and H.C. Drake.
- 1929 Magnetic particle methods and equipment pioneered (A.V. DeForest and F.B. Doane.)
- 1930s Robert F. Mehl demonstrates radiographic imaging using gamma radiation from Radium, which can examine thicker components than the low-energy X-ray machines available at the time.
- 1935 - 1940 Liquid penetrant tests developed (Betz, Doane, and DeForest)
- 1935 - 1940s Eddy current instruments developed (H.C. Knerr, C. Farrow, Theo Zuschlag, and Fr. F. Foerster).
- 1940 - 1944 Ultrasonic test method developed in USA by Dr. Floyd Firestone.
- 1950 The Schmidt Hammer (also known as "Swiss Hammer") is invented. The instrument uses the world's first patented non-destructive testing method for concrete.
- 1950 J. Kaiser introduces acoustic emission as an NDT method.

Applications

NDT is used in a variety of settings that covers a wide range of industrial activity.

- Automotive
    - Engine parts
    - Frame
- Aviation / Aerospace
    - Airframes
        - Spaceframes
    - Powerplants
        - Propellers
        - Reciprocating Engines
        - Gas turbine engines
    - Rocketry
- Construction
    - Structures
    - Bridges
    - Cover Meter
- Maintenance, repair and operations
    - Bridges
- Manufacturing
    - Machine parts
    - Castings and Forgings
- Industrial plants such as Nuclear, Petrochemical, Power, Refineries, Pulp and Paper, Fabrication shops, Mine processing and their Risk Based Inspection programmes.
    - Pressure vessels
    - Storage tanks
    - Welds
    - Boilers
    - Heat exchangers

    - Turbine bores
    - In-plant Piping
- Miscellaneous
    - Pipelines
        - In-line Inspection using "pigs"
        - Pipeline integrity management
        - Leak Detection
    - Railways
        - Rail Inspection
        - Wheel Inspection
    - Tubular NDT, for Tubing material
    - Corrosion Under Insulation (CUI)
    - Amusement park rides
    - Submarines and other Naval warships
    - Medical imaging applications

Methods and techniques

An example of a 3D replicating technique. The flexible high-resolution replicas allow surfaces to be examined and measured under laboratory conditions. A replica can be taken from all solid materials.

NDT is divided into various *methods* of nondestructive testing, each based on a particular scientific principle. These methods may be further subdivided into various *techniques*. The various methods and techniques, due to their particular natures, may lend themselves especially well to certain applications and be of little or no value at all in other applications. Therefore choosing the right method and technique is an important part of the performance of NDT.

- Acoustic emission testing (AE or AT)
- Blue Etch Anodize (BEA)
- Dye penetrant inspection Liquid penetrant testing (PT or LPI)

- Electromagnetic testing (ET)
    - Alternating current field measurement (ACFM)
    - Alternating current potential drop measurement (ACPD)
    - Barkhausen testing
    - Direct current potential drop measurement (DCPD)
    - Eddy-current testing (ECT)
    - Magnetic flux leakage testing (MFL) for pipelines, tank floors, and wire rope
    - Magnetic-particle inspection (MT or MPI)
    - Remote field testing (RFT)
- Ellipsometry
- Guided wave testing (GWT)
- Hardness testing
- Impulse excitation technique (IET)
- Infrared and thermal testing (IR)
    - Thermographic inspection
- Laser testing
    - Electronic speckle pattern interferometry
    - Holographic interferometry
    - Low coherence interferometry
    - Profilometry
    - Shearography
- Leak testing (LT) or Leak detection
    - Absolute pressure leak testing (pressure change)
    - Bubble testing
    - Halogen diode leak testing
    - Hydrogen leak testing
    - Mass spectrometer leak testing
    - Tracer-gas leak testing method Helium, Hydrogen and refrigerant gases
- Magnetic resonance imaging (MRI) and NMR spectroscopy
- Optical microscopy
- Positive Material Identification (PMI)
- Radiographic testing (RT)
    - Computed radiography
    - Digital radiography (real-time)
    - Neutron radiographic testing (NR)
    - SCAR (Small Controlled Area Radiography)
    - X-ray computed tomography (CT)
- Scanning electron microscopy
- Surface Temper Etch (Nital Etch)
- Ultrasonic testing (UT)
    - ART (Acoustic Resonance Technology)
    - Electro Magnetic Acoustic Transducer (EMAT) (non-contact)
    - Laser ultrasonics (LUT)
    - Internal rotary inspection system (IRIS) ultrasonics for tubes
    - Phased array ultrasonics
    - Time of flight diffraction ultrasonics (TOFD)
    - Time of Flight Ultrasonic Determination of 3D Elastic Constants (TOF)

- Visual inspection (VT)
    - Pipeline video inspection
- Corroscan/C-scan
- IRIS - Internal Rotary Inspection System
- 3D Tomography
- Heat Exchanger Life Assessment System
- RTJ Flange Special Ultrasonic Testing

Personnel qualification and certification

Succeful and consistent application of nondestructive testing techniques depends heavily on personnel training and experience. Personnel involved in application of industrial NDT methods and interpretation of results should be certified, and in some idustrial sectors certification is enforced by law or by the applied codes and standards.

Definitions

The following definitions for *qualification* and *certification* are given in ISO 9712 and EN 473:

- **Certification:** "Procedure, used by the certification body to confirm that the qualification requirements for a method, level and sector have been fulfilled, leading to the issuing of a certificate".

- **Qualification:** "Demonstration of physical attributes, knowledge, skill, training and experience required to properly perform NDT tasks".

In US standards and codes, while a very similar definition of qualification is included in ASNT SNT-TC-1A, certification is simply defined as: "Written testimony of qualification".

Certification schemes

There are two approaches in personnel certification:

1. **Employer Based Certification**: Under this system the employer compiles their own *Written Practice*. The written practice defines the responsibilities of each level of certification, as implemented by the company, and describes the training, experience and examination requirements for each level of certification. In industrial sectors the written practices are usually based on recommended practice SNT-TC-1A of the American Society for Nondestructive Testing. ANSI standard CP-189 outlines requirements for any written practice that conforms to the standard.
2. **Personal Central Certification**: The concept of central certification is that an NDT operator can obtain certification from a central certification authority, that is recognised by most employers, third parties and/or government authorities. Industrial standards for central certification schemes are ISO 9712 and EN 473. Certification under these standards involves training, work experience under

supervision and passing a written and practical examination set up by the independent certification authority.

In the United States employer based schemes are the norm, however central certification schemes exist as well. The most notable is *ASNT Level III* (established in 1976-1977), which is organized by the American Society for Nondestructive Testing for Level 3 NDT personnel.

NAVSEA 250-1500 is another US central certification scheme, specifically developed for use in the naval nuclear program.

Central certification is more widely used in the European Union, where certifications are issued by accredited bodies (independent organizations conforming to ISO 17024 and accredited by a national accreditation authority like UKAS). The Pressure Equipment Directive (97/23/EEC) actually enforces personnel certification to EN 473 for the initial testing of steam boilers and some categories of pressure vessels and piping. Certifications issued by a national NDT society which is a member of the European Federation of NDT (EFNDT) are mutually acceptable by the other member societies under a multilateral recognition agreement.

Canada also implements an ISO 9712 central certification scheme, which is administered by Natural Resources Canada, a government department.

The aerospace sector worldwide sticks to employer based schemes. In America it is based mostly on AIA-NAS-410 and in the European Union on the equivalent and very similar standard EN 4179

Levels of certification

Most NDT personnel certification schemes listed above specify three "levels" of qualification and/or certification, usually designated as *Level 1*, *Level 2* and *Level 3* (although some codes specify roman numerals, like *Level II*). The roles and responsibilities of personnel in each level are generally as follows (there are slight differences or variations between different codes and standards):

- **Level 1** are technicians qualified to perform only specific calibrations and tests under close supervision and direction by higher level personnel. They can only report test results. Normally they work following specific work instructions for testing procedures and rejection criteria.

- **Level 2** are engineers or experienced technicians who are able to set up and calibrate testing equipment, conduct the inspection according to codes and standards (instead of following work instructions) and compile work instructions for Level 1 technicians. They are also authorized to report, interpret, evaluate and document testing results. They can also supervise and train Level 1 technicians. In addition to testing methods, they must be familiar with applicable codes and standards and have some knowledge of the manufacture and service of tested products.

- **Level 3** are usually specialized engineers or very experienced technicians. They can establish NDT techniques and procedures and interpret codes and standards. They also direct NDT laboratories and have central role in personnel certification. They are expected to have wider knowledge covering materials, fabrication and product technology.

Terminology

Indication
: The response or evidence from an examination, such as a blip on the screen of an instrument. Indications are classified as *true* or *false*. *False indications* are those caused by factors not related to the principles of the testing method or by improper implementation of the method, like film damage in radiography, electrical interference in ultrasonic testing etc. *True indications* are further classified as *relevant* and *non relevant*. *Relevant indications* are those caused by flaws. *Non relevant indications* are those caused by known features of the tested object, like gaps, threads, case hardening etc.

Interpretation
: Determining if an indication is of a type to be investigated. For example, in electromagnetic testing, indications from metal loss are considered flaws because they should usually be investigated, but indications due to variations in the material properties may be harmless and nonrelevant.

Flaw
: A type of discontinuity that must be investigated to see if it is rejectable. For example, porosity in a weld or metal loss.

Evaluation
: Determining if a flaw is rejectable. For example, is porosity in a weld larger than acceptable by code?

Defect
: A flaw that is rejectable — i.e. does not meet acceptance criteria. Defects are generally removed or repaired.

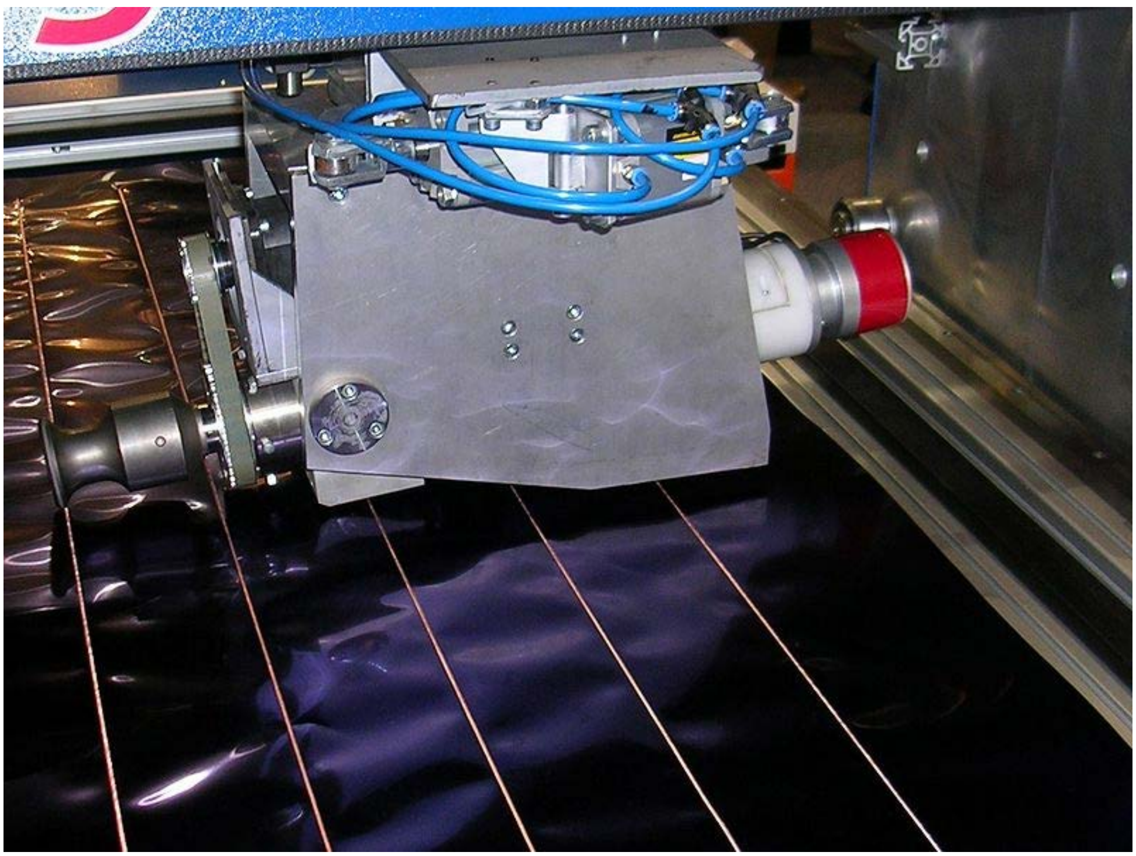
Penetrant testing
: Non-destructive test typically comprising a penetrant, a method of excess removal and a developer to produce a visible indication of surface-breaking discontinuities.

Reliability and statistics

Defect detection tests are among the more commonly employed of non-destructive tests. The evaluation of NDT reliability commonly contains two statistical errors. First, most tests fail to define the objects that are called "sampling units" in statistics; it follows that the reliability of the tests cannot be established. Second, the literature usually misuses statistical terms in such a way as to make it sound as though sampling units *are* defined. These two errors may lead to incorrect estimates of probability of detection. .

Chapter 9

Ultrasonic Welding



Ultrasonic welding of thin metallic foils. The sonotrode is rotated along the weld seam.

Ultrasonic welding is an industrial technique whereby high-frequency ultrasonic acoustic vibrations are locally applied to workpieces being held together under pressure to create a solid-state weld. It is commonly used for plastics, and especially for joining dissimilar materials. In ultrasonic welding, there are no connective bolts, nails, soldering materials, or adhesives necessary to bind the materials together.

History

In 1960 Sonobond Ultrasonics, originally known as Aeroprojects, Incorporated, developed the first metal ultrasonic welding machine to be awarded a United States Patent.

Process

For joining complex injection molded thermoplastic parts, ultrasonic welding equipment can be easily customized to fit the exact specifications of the parts being welded. The parts are sandwiched between a fixed shaped nest (anvil) and a sonotrode (horn) connected to a transducer, and a ~20 kHz low-amplitude acoustic vibration is emitted. (Note: Common frequencies used in ultrasonic welding of thermoplastics are 15 kHz, 20 kHz, 30 kHz, 35 kHz, 40 kHz and 70 kHz). When welding plastics, the interface of the two parts is specially designed to concentrate the melting process. One of the materials usually has a spiked energy director which contacts the second plastic part. The ultrasonic energy melts the point contact between the parts, creating a joint. This process is a good automated alternative to glue, screws or snap-fit designs. It is typically used with small parts (e.g. cell phones, consumer electronics, disposable medical tools, toys, etc.) but it can be used on parts as large as a small automotive instrument cluster. Ultrasonics can also be used to weld metals, but are typically limited to small welds of thin, malleable metals, e.g. aluminum, copper, nickel. Ultrasonics would not be used in welding the chassis of an automobile or in welding pieces of a bicycle together, due to the power levels required.

Ultrasonic welding of thermoplastics causes local melting of the plastic due to absorption of vibration energy. The vibrations are introduced across the joint to be welded. In metals, Ultrasonic welding occurs due to high-pressure dispersion of surface oxides and local motion of the materials. Although there is heating, it is not enough to melt the base materials. Vibrations are introduced along the joint being welded.

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

The first car made entirely out of plastic was assembled using ultrasonic welding in 1969. Even though plastic cars did not catch on ultrasonic welding did. The automotive industry has used it regularly since the 1980s. It is now used for a multitude of applications.

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

Benefits of Ultrasonic welding are that it is much faster than conventional adhesives or solvents. Drying time is very quick, the pieces do not need to remain in a jig for long periods of time waiting for the joint to dry or cure. The welding can easily be automated also, making clean and precise joints. Site of the weld is also very clean not needing any touch up to material and bond.

Components

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

- A press to put the 2 parts to be assembled under pressure
- A nest or anvil where the parts are placed and allowing the high frequency vibration to be directed to the interfaces
- An ultrasonic stack composed of a converter or piezoelectric transducer, an optional booster and a sonotrode (US: Horn). All three elements of the stack are specifically tuned to resonate at the same exact ultrasonic frequency (Typically 20, 30, 35 or 40 kHz)
    - Converter: Converts the electrical signal into a mechanical vibration
    - Booster: Modifies the amplitude of the vibration. It is also used in standard systems to clamp the stack in the press.
    - Sonotrode: Applies the mechanical vibration to the parts to be welded.
- An electronic ultrasonic generator (US: Power supply) delivering a high power AC signal with frequency matching the resonance frequency of the stack.
- A controller controlling the movement of the press and the delivery of the ultrasonic energy.

Applications

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

Computer and electrical industries

In the electrical and computer industry ultrasonic welding is often used to join wired connections and to create connections in small, delicate circuits. Junctions of wire harnesses are often joined using ultrasonic welding. Wire harnesses are large groupings of wires used to distribute electrical signals and power. Electric motors, field coils, transformers and capacitors may also be assembled with ultrasonic welding. It is also often preferred in the assembly of storage media such as flash drives and computer disks because of the high volumes required. Ultrasonic welding of computer disks has been found to have cycle times of less than 300 ms.

One of the areas in which ultrasonic welding is most used and where new research and experimentation is centered is microcircuits. This process is ideal for microcircuits since it creates reliable bonds without introducing impurities or thermal distortion into components. Semiconductor devices, transistors and diodes are often connected by thin aluminum and gold wires using ultrasonic welding. It is also used for bonding wiring and ribbons as well as entire chips to microcircuits. An example of where microcircuits are used is in medical sensors used to monitor the human heart in bypass patients.

One difference between ultrasonic welding and traditional welding is the ability of ultrasonic welding to join dissimilar materials. The assembly of battery components is a good example of where this ability is utilized. When creating battery and fuel cell components, thin gauge copper, nickel and aluminum connections, foil layers and metal meshes are often ultrasonically welded together. Multiple layers of foil or mesh can often be applied in a single weld eliminating steps and cost.

Aerospace and automotive industries

For automobiles, ultrasonic welding tends to be utilized in the assembly of large plastic components and electrical components such as instrument panels, door panels, lamps, air ducts, steering wheels, upholstery and engine components. As plastics have continued to replace other materials in the design and manufacture of automobiles, the assembly and joining of plastic components has increasingly become a critical issue. Some of the advantages for ultrasonic welding are low cycle times, automation, low capital costs, and flexibility. Also, ultrasonic welding does not damage surface finish, which is a crucial consideration for many car manufacturers, because the high-frequency vibrations prevent marks from being generated.

Ultrasonic welding is generally utilized in the aerospace industry when joining thin sheet gauge metals and other lightweight materials. Aluminum is a difficult metal to weld using traditional techniques because of its high thermal conductivity. However, it is one of the easier materials to weld using ultrasonic welding because it is a softer alloy metal and thus a solid-state weld is simple to achieve. Since aluminum is so widely used in the aerospace industry, it follows that ultrasonic welding is an important manufacturing process. Also, with the advent of new composite materials, ultrasonic welding is becoming even more prevalent. It has been used in the bonding of the popular composite material carbon fiber. Numerous studies have been done to find the optimum parameters that will produce quality welds for this material.

Medical industry

In the medical industry ultrasonic welding is often used because it does not introduce contaminants or degradation into the weld and the machines can be specialized for use in clean rooms. The process can also be highly automated, provides strict control over dimensional tolerances and does not interfere with the biocompatibility of parts. Therefore, it increases part quality and decreases production costs. Items such as arterial filters, anesthesia filters, blood filters, IV catheters, dialysis tubes, pipettes, cardiometry reservoirs, blood/gas filters, face masks and IV spike/filters can all be made using ultrasonic welding. Another important application in the medical industry for ultrasonic welding is textiles. Items like hospital gowns, sterile garments, masks, transdermal patches and textiles for clean rooms can be sealed and sewn using ultrasonic welding. This prevents contamination and dust production and reduces the risk of infection.

Packaging industry

Butane lighter

Packaging is perhaps the application in which ultrasonic welding is most often used. Many everyday items are either created or packaged using ultrasonic welding techniques. Sealing containers, tubes and blister packs are some common applications.

Ultrasonic welding is also applied in the packaging of dangerous materials such as explosives, fireworks and other reactive chemicals. These items tend to require hermetic sealing but cannot be subjected to high temperatures. One simple example of this application is the container for a butane lighter. This container weld must be able to withstand high pressure and stress and must be airtight to contain the butane. Another example is the packaging of ammunition and propellants. These packages must be able to withstand high pressure and stresses in order to protect the consumer from the contents. When sealing hazardous materials, safety is a primary concern.

The food industry finds ultrasonic welding preferable to traditional joining techniques because it is fast, sanitary and can produce hermetic seals. Milk and juice containers are examples of some products that are often sealed using ultrasonic welding. The paper parts to be sealed are coated with plastic, generally polypropylene or polyethylene, and then welded together to create an airtight seal. The main obstacle to overcome in this process is the setting of the parameters. For example, if over-welding occurs then the concentration of plastic in the weld zone may be too low and cause the seal to break. If it is under-welded the seal is incomplete. Variations in the thicknesses of materials can cause variations in weld quality. Some other food items that are sealed using ultrasonic welding include candy bar wrappers, frozen food packages and beverage containers.

The electrical and computer, automotive, aerospace, medical, and packaging industries are some of the industries which utilize ultrasonic welding. This process is used to assemble everything from microcircuits to milk cartons. It is increasing in popularity throughout many of these industries because of low cycle times, automation, low capital costs, flexibility, cleanliness, dimensional reliability and the bonding of dissimilar materials. Some of the drawbacks of ultrasonic welding are that its use is limited by the thickness of the materials, it may require expensive specialized tooling and it may generate noise.

Safety

Ultrasonic welding machines, like most industrial equipment, pose the risk of some hazards. These include exposure to high heat levels and voltages. This equipment should always be operated using the safety guidelines provided by the manufacturer in order to avoid injury. For instance, operators must never place hands or arms near the welding tip when the machine is activated. Also, operators should be provided with hearing protection and safety glasses. Operators should be informed of the OSHA regulations for the ultrasonic welding equipment and these regulations should be enforced.

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

Since this is an ultrasonic process it would seem that sound would not be an issue. However, sub-harmonic vibrations, which can create annoying audible noise, may be caused in larger parts near the machine due to the ultrasonic welding frequency. This noise can be dampened by clamping these large parts at one or more locations. Also, high-powered welders with frequencies of 15 kHz and 20 kHz typically emit a potentially damaging high-pitched squeal in the range of human hearing. Shielding this radiating sound can be done using an acoustic enclosure. In short, there are hearing and safety concerns with ultrasonic welding that are important to consider, but generally they are comparable to those of other welding techniques.

Chapter 10

Welding Defect

A **welding defect** is any flaw that compromises the usefulness of the finished weldment.

According to the American Society of Mechanical Engineers (ASME) welding defect causes are broken down into the following percentages: 41% poor process conditions, 32% operator error, 12% wrong technique, 10% incorrect consumables, and 5% bad weld grooves.

Major causes

Residual stresses

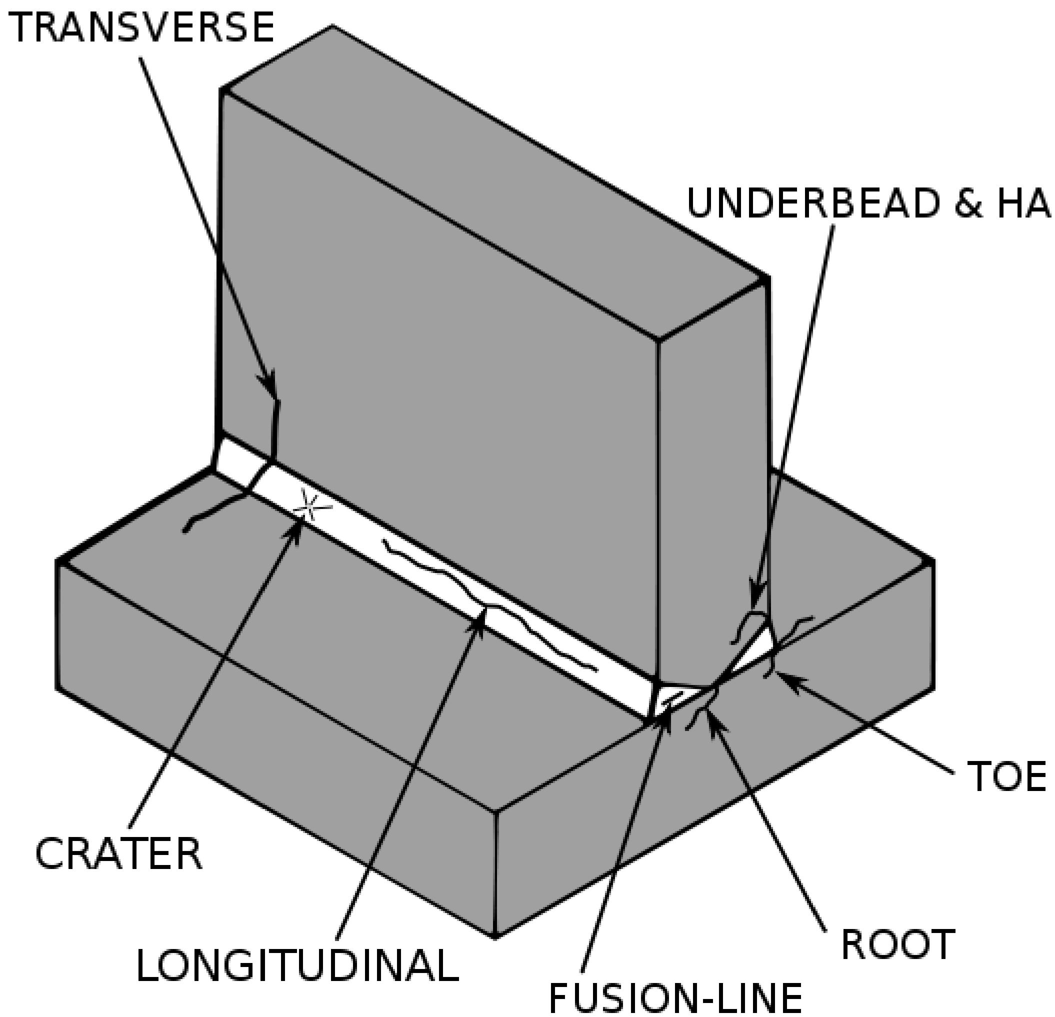
The magnitude of stress that can be formed from welding can be roughly calculated using:

$$E\alpha\Delta T$$

Where E is Young's modulus, α is the coefficient of thermal expansion, and ΔT is the temperature change. For steel this calculates out to be approximately 3.5 GPa (510,000 psi).

Types

Cracks



Defects related to fracture.

Arc strike cracking

Arc strike cracking occurs when the arc is struck but the spot is not welded. This occurs because the spot is heated above the materials upper critical temperature and then essentially quenched. This forms martensite, which is brittle, and micro-cracks. Usually the arc is struck in the weld groove so this type of crack does not occur, but if the arc is struck outside of the weld groove then it must be welded over to prevent the cracking. If this is not an option then the arc spot can be postheated, *i.e.*, the area is heated with an oxy-acetylene torch, and then allowed to cool slowly.

Cold cracking

Residual 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.

Cold cracking only occurs when all the following preconditions are met:

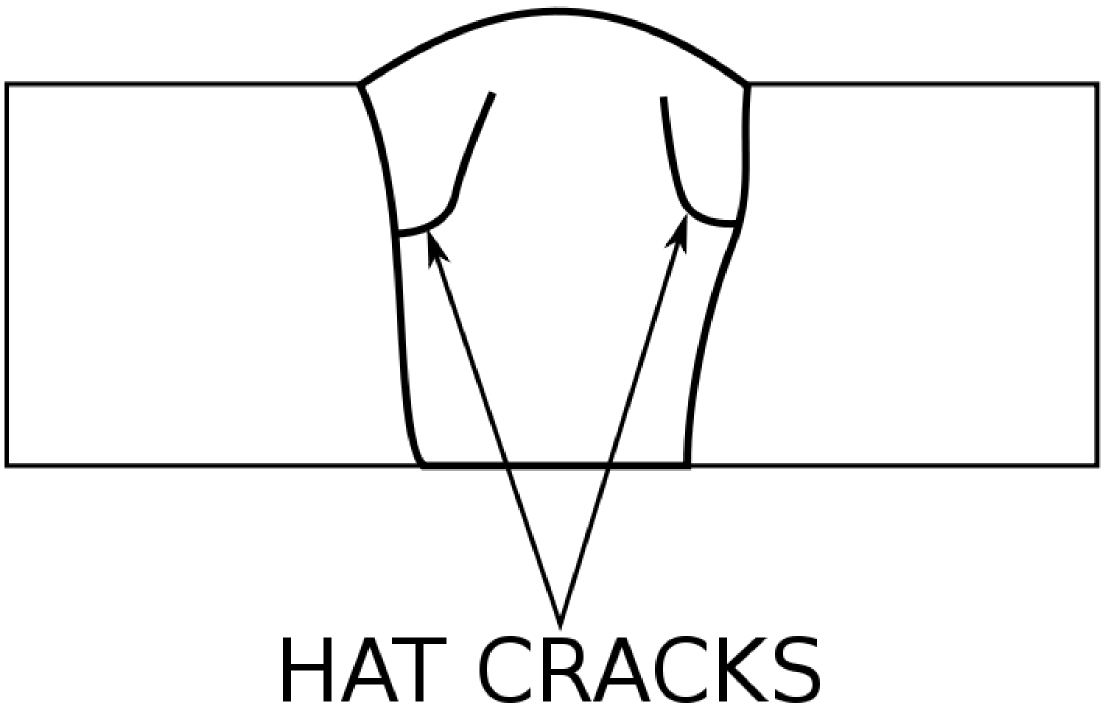
- susceptible microstructure (*e.g.* martensite)
- hydrogen present in the microstructure (hydrogen embrittlement)
- service temperature environment (normal atmospheric pressure): -100 to +100 °F
- high restraint

Eliminating any one of these will eliminate this condition.

Crater crack

Crater cracks occur when a crater is not filled before the arc is broken. This causes the outer edges of the crater to cool more quickly than the crater, which creates sufficient stresses to form a crack. It may form a longitudinal or transverse crack or form multiple radial cracks.

Hat crack



Hat cracks get their name from the shape of the cross-section of the weld, because the weld flares out at the face of the weld. The crack starts at the fusion line and extends up through the weld. They are usually caused by too much voltage or not enough speed.

Hot cracking

Hot cracking, also known as solidification cracking, can occur with 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. Other causes include too high welding current, poor joint design that does not diffuse heat, impurities (such as sulfur and phosphorus), preheating, speed is too fast, and long arcs.

Underbead crack

An underbead crack, also known as a heat-affected zone (HAZ) crack, is a crack that forms a short distance away from the fusion line; it occurs in low alloy and high alloy steel. The exact causes of this type of crack are not completely understood, but it is known that dissolved hydrogen must be present. The other factor that affects this type of crack is internal stresses resulting from: unequal contraction between the base metal and the weld metal, restraint of the base metal, stresses from the formation of martensite, and stresses from the precipitation of hydrogen out of the metal.

Longitudinal crack

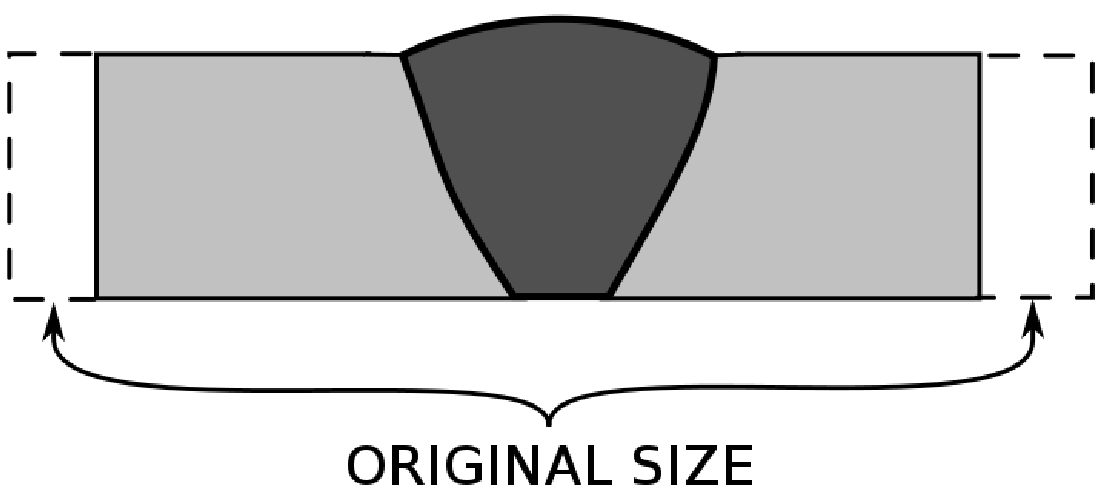
Longitudinal cracks run along the length of a weld bead. There are three types: *check cracks*, *root cracks*, and *full centerline cracks*. Check cracks are visible from the surface and extend partially into weld. They are usually caused by high shrinkage stresses, especially on final passes, or by a hot cracking mechanism. Root cracks start at the root and extent part way into the weld. They are the most common type of longitudinal crack because of the small size of the first weld bead. If this type of crack is not addresses then it will usually propagate into subsequent weld passes, which is how full centerline cracks (a crack from the root to the surface) usually form.

Reheat cracking

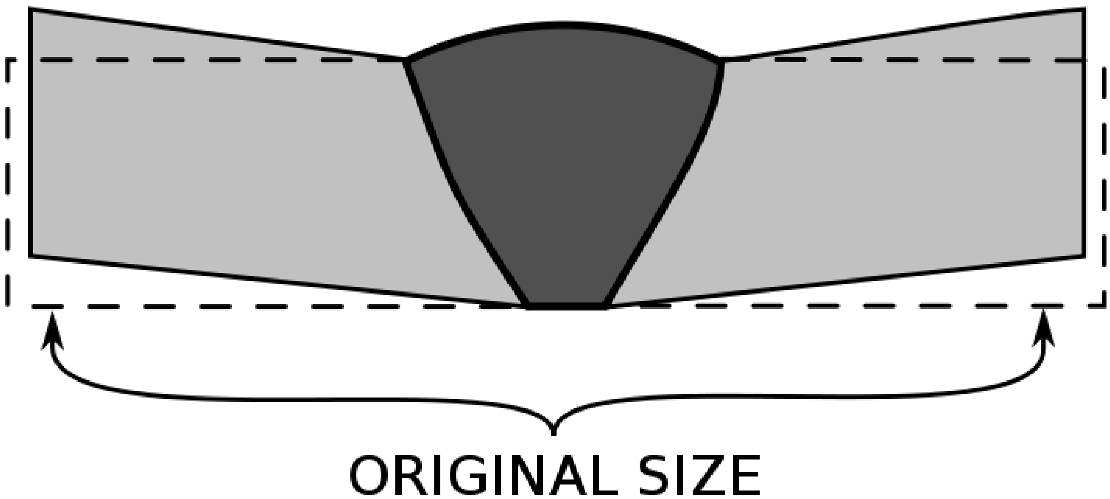
Reheat cracking is a type of cracking that occurs in HSLA steels, particularly chromium, molybdenum and vanadium steels, during postheating. It is caused by the poor creep ductility of the heat affected zone. Any existing defects or notches aggravate crack formation. Things that help prevent reheat cracking include heat treating first with a low temperature soak and then with a rapid heating to high temperatures, grinding or peening the weld toes, and using a two layer welding technique to refine the HAZ grain structure.

Distortion

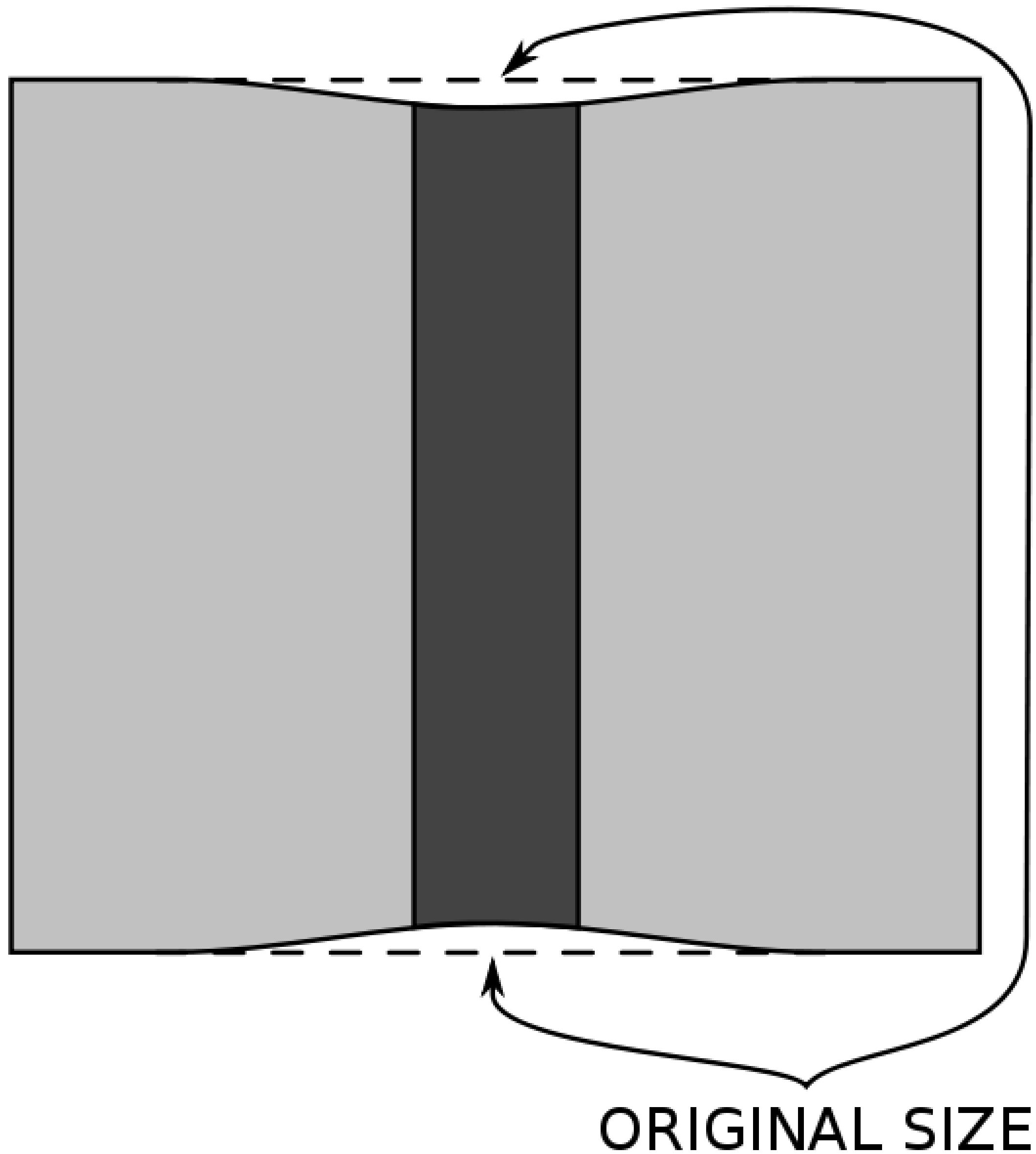
Welding methods that involve the melting of metal at the site of the joint necessarily are prone to shrinkage as the heated metal cools. Shrinkage then introduces residual stresses and distortion. Distortion can pose a major problem, since the final product is not the desired shape. To alleviate certain types of distortion the workpieces can be offset so that after welding the product is the correct shape. The following pictures describe various types of welding distortion:



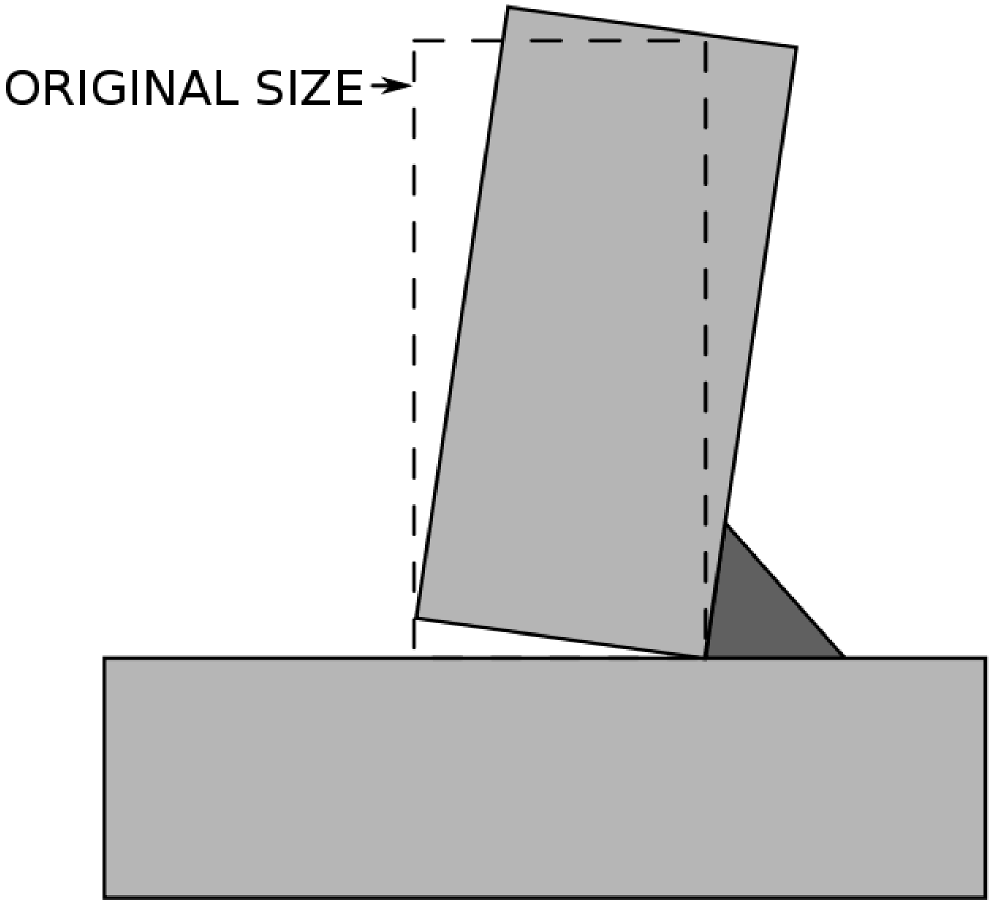
Transverse shrinkage



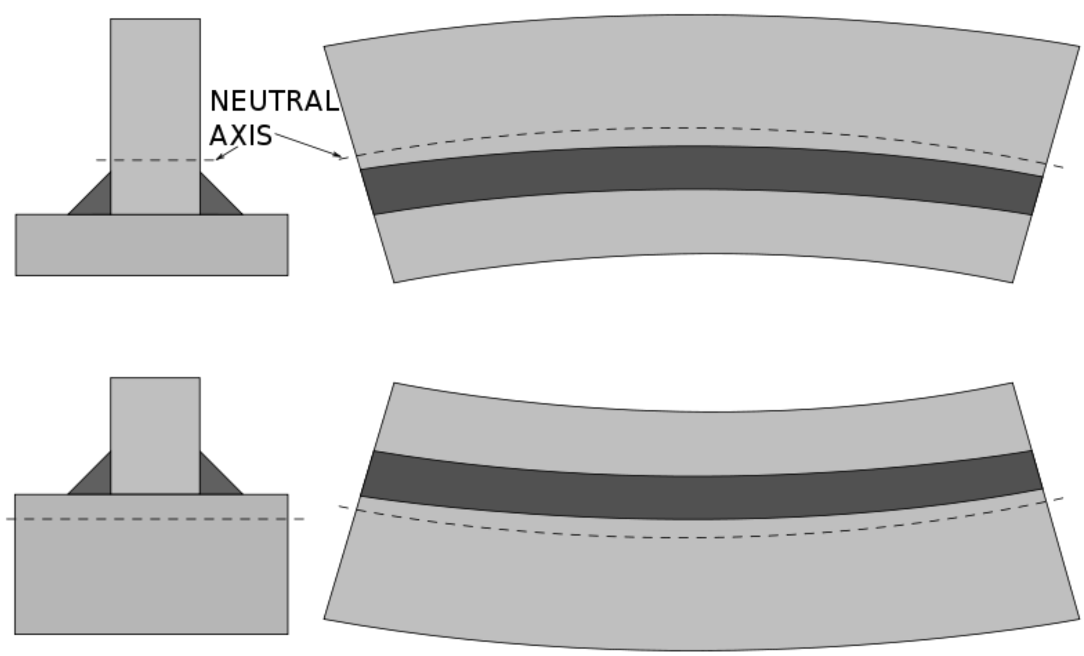
Angular distortion



Longitudinal shrinkage



Fillet distortion



Neutral axis distortion

Gas inclusion

Gas inclusions is a wide variety of defects that includes *porosity*, *blow holes*, and *pipes* (or *wormholes*). The underlying cause for gas inclusions is the entrapment of gas within the solidified weld. Gas formation can be from any of the following causes: high sulfur content in the workpiece or electrode, excessive moisture from the electrode or workpiece, too short of an arc, or wrong welding current or polarity.

Inclusions

There are two types of inclusions: *linear inclusions* and *isolated inclusions*. Linear inclusions occur when there is slag or flux in the weld. Slag forms from the use of a flux, which is why this type of defect usually occurs in welding processes that use flux, such as shielded metal arc welding, flux-cored arc welding, and submerged arc welding, but it can also occur in gas metal arc welding. This defect usually occurs in welds that require multiple passes and there is poor overlap between the welds. The poor overlap does not allow the slag from the previous weld to melt out and rise to the top of the new weld bead. It can also occur if the previous weld left and undercut or an uneven surface profile. To prevent slag inclusions the slag should be cleaned from the weld bead between passes via grinding, wire brushing, or chipping.

Isolated inclusions occur when rust or mill scale is present on the base metal.

Lack of fusion and incomplete penetration

Lack of fusion is the poor adhesion of the weld bead to the base metal; incomplete penetration is a weld bead that does not start at the root of the weld groove. Incomplete penetration forms channels and crevices in the root of the weld which can cause serious issues in pipes because corrosive substances can settle in these areas. These types of defects occur when the welding procedures are not adhered to; possible causes include the current setting, arc length, electrode angle, and electrode manipulation.

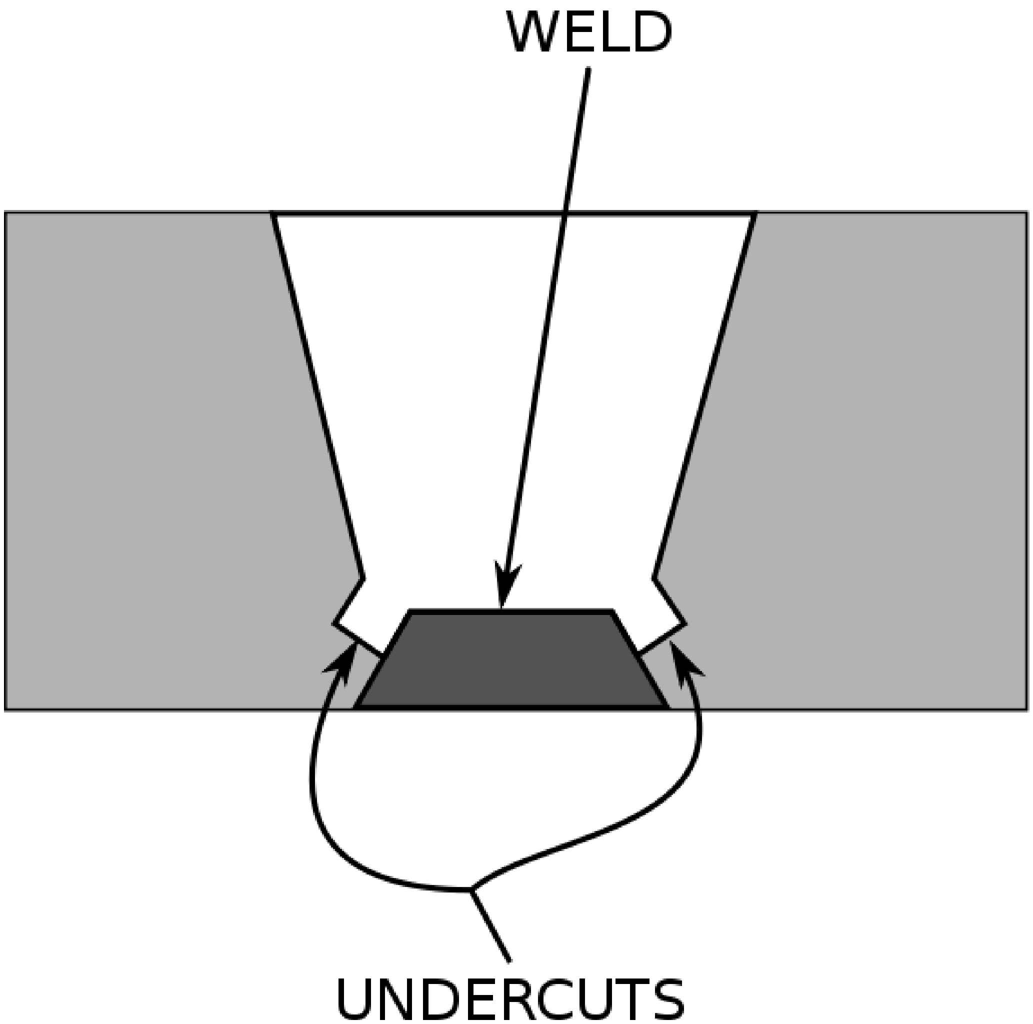
Lamellar tearing

Lamellar tearing is a type of welding defect that occurs in rolled steel plates. It has rarely been an issue since the 1970s because steel produced since then has less sulfur.

There is a combination of causes: non-metallic inclusions, too much hydrogen in the material, and shrinkage forces perpendicular to the face of the plates. The main factor among these reasons is the non-metal inclusions, of which the sulfur is the main problem. Lamellar tearing is no longer a problem anymore because sulfur levels are typical kept below 0.005%.

Some things that are done to overcome lamellar tearing are: reducing amount of sulfur in the material or adding alloying elements that control the shape of sulfide inclusions, such as rare earth elements, zirconium, or calcium. A more drastic option is change the workpieces to castings or forgings because this type of defect does not occur in those workpieces.

Undercut

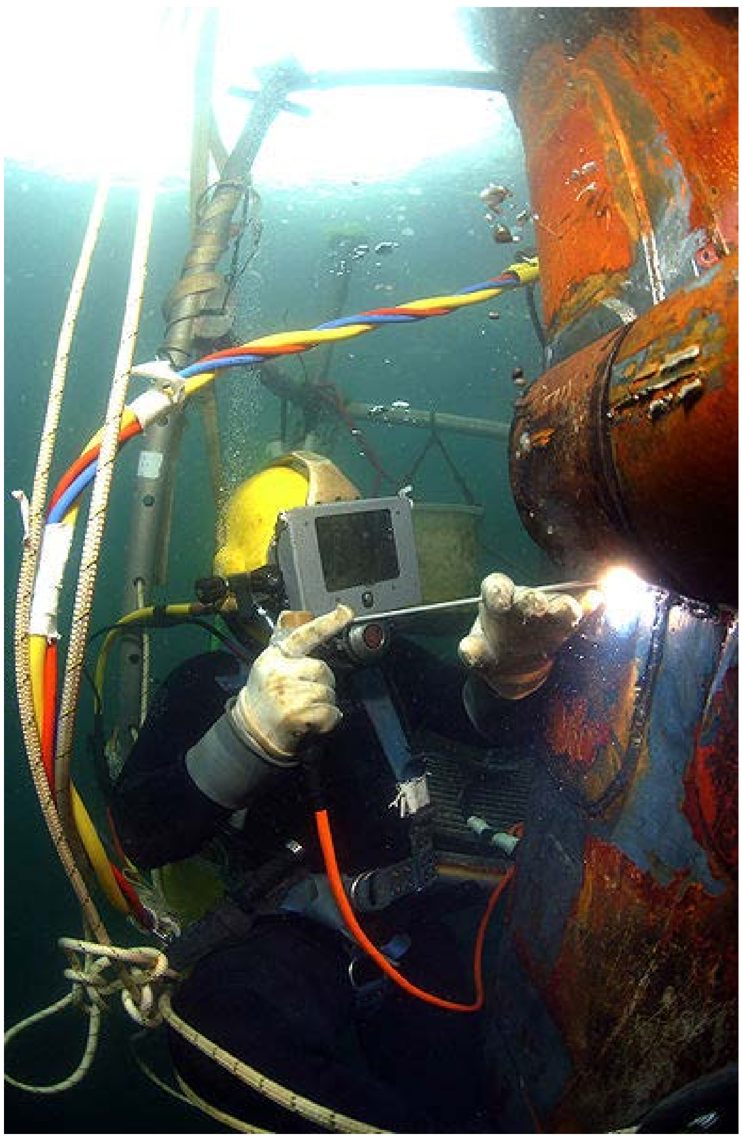


Undercutting is when the weld reduces the cross-sectional thickness of the base metal, which reduces the strength of the weld and workpieces. One reason for this type of defect is excessive current, causing the edges of the joint to melt and drain into the weld; this leaves a drain-like impression along the length of the weld. Another reason is if a poor technique is used that does not deposit enough filler metal along the edges of the weld. A third reason is using an incorrect filler metal, because it will create greater temperature gradients between the center of the weld and the edges. Other causes include too small of an electrode angle, a dampened electrode, excessive arc length, and slow speed.

Chapter 11

Hyperbaric Welding and Orbital Welding

Hyperbaric welding



A US Navy diver at work.

Underwater welding

Hyperbaric welding is the process of welding at elevated pressures, normally underwater. Hyperbaric welding can either take place *wet* in the water itself or *dry* inside a specially constructed positive pressure enclosure and hence a dry environment. It is predominantly referred to as "hyperbaric welding" when used in a dry environment, and "**underwater welding**" when in a wet environment. The applications of hyperbaric welding are diverse—it is often used to repair ships, offshore oil platforms, and pipelines. Steel is the most common material welded.

Dry hyperbaric welding is used in preference to wet underwater welding when high quality welds are required because of the increased control over conditions which can be exerted, such as through application of prior and post weld heat treatments. This improved environmental control leads directly to improved process performance and a generally much higher quality weld than a comparative wet weld. Thus, when a very high quality weld is required, dry hyperbaric welding is normally utilized. Research into using dry hyperbaric welding at depths of up to 1,000 metres (3,300 ft) is ongoing. In general, assuring the integrity of underwater welds can be difficult (but is possible using various nondestructive testing applications), especially for wet underwater welds, because defects are difficult to detect if the defects are beneath the surface of the weld.

Underwater hyperbaric welding was invented by the Russian metallurgist Konstantin Khrenov in 1932.

Dry

Dry hyperbaric welding involves the weld being performed at the prevailing pressure in a chamber filled with a gas mixture sealed around the structure being welded.

Most welding processes SMAW, FCAW, GTAW, GMAW, PAW could be operated at hyperbaric pressures, but all suffer as the pressure increases. Gas tungsten arc welding is most commonly used. The degradation is associated with physical changes of the arc behaviour as the gas flow regime around the arc changes and the arc roots contract and become more mobile. Of note is a dramatic increase in arc voltage which is associated with the increase in pressure. Overall a degradation in capability and efficiency results as the pressure increases.

Special control techniques have been applied which have allowed welding down to 2500m simulated water depth in the laboratory, but dry hyperbaric welding has thus far been limited operationally to less than 400m water depth by the physiological capability of divers to operate the welding equipment at high pressures and practical considerations concerning construction of an automated pressure / welding chamber at depth.

Wet

Wet underwater welding commonly uses a variation of shielded metal arc welding, employing a waterproof electrode. Other processes that are used include flux-cored arc welding and friction welding. In each of these cases, the welding power supply is connected to the welding equipment through cables and hoses. The process is generally limited to low carbon equivalent steels, especially at greater depths, because of hydrogen-caused cracking.

Risks

The risks of underwater welding include the risk of electric shock to the welder. To prevent this, the welding equipment must be adaptable to a marine environment, properly insulated and the welding current must be controlled. Commercial divers must also consider the safety issues that normal divers face; most notably, the risk of decompression sickness following saturation diving due to the increased pressure of inhaled breathing gases. Another risk, generally limited to wet underwater welding, is the buildup of hydrogen and oxygen pockets, because these are potentially explosive. Many divers have reported a metallic taste that is related to the breakdown of dental amalgam. There may also be long term cognitive and possibly musculoskeletal effects associated with underwater welding.

Orbital welding

Orbital welding is a particularly specialised area of welding whereby the arc is rotated mechanically through 360° around a static workpiece, (around an object such as a pipe), in a continuous process.

Equipment

The main components of every orbital welding system are the power source and controller, the welding head and, where required, a wire feed mechanism. There are a large number of factors that can have an influence on the welding result. Significant parameters are arc length, magnitude and pulse frequency of the welding current, welding speed, inert shielding gas, parent material, filler material, weld preparation, and thermal conductivity. Ultimately, a high quality weld is achieved through detailed knowledge of how to precisely adjust all these parameters for the individual welding task.

Application

The welding process

It is very difficult to achieve the highest standards of quality and safety using manual welding, because certain welding positions, overhead and down-hand welds for example, often lead to faulty welds due to restricted access and freedom of movement. In order to have complete control over the weld pool, a perfect balance must be maintained between gravitational force and surface tension at every position of the torch. With mechanised variants of the technique, certain parts of the welding process are handled by mechanical components, with a welder monitoring and controlling the process. In an ideal situation, all welding parameters would be fully programmed before welding is started. In practice, however, the presence of variable constraints means that it is often necessary for the welder to make corrective interventions. With automated welding, the computer-controlled welding process runs completely independently, without the need for any intervention from the operator.

Materials

Welding of tubes in the food and pharmaceutical industry complying with "high purity" standards

Since its beginnings, orbital welding has been carried out almost exclusively by the Tungsten Inert Gas (TIG) technique using non-consumable electrodes, with additional cold-wire feed where necessary. Many different types of metal can be welded; high-strength, high-temperature and corrosion-resistant steels, unalloyed and low-alloyed carbon steels, nickel alloys, titanium, copper, aluminium and associated alloys. Carried out in an inert atmosphere, this controlled technique produces results that are extremely clean, have low particle counts and are free from unwanted spatter. Meeting the highest demands when it comes to the mechanical and optical properties of a weld seam.

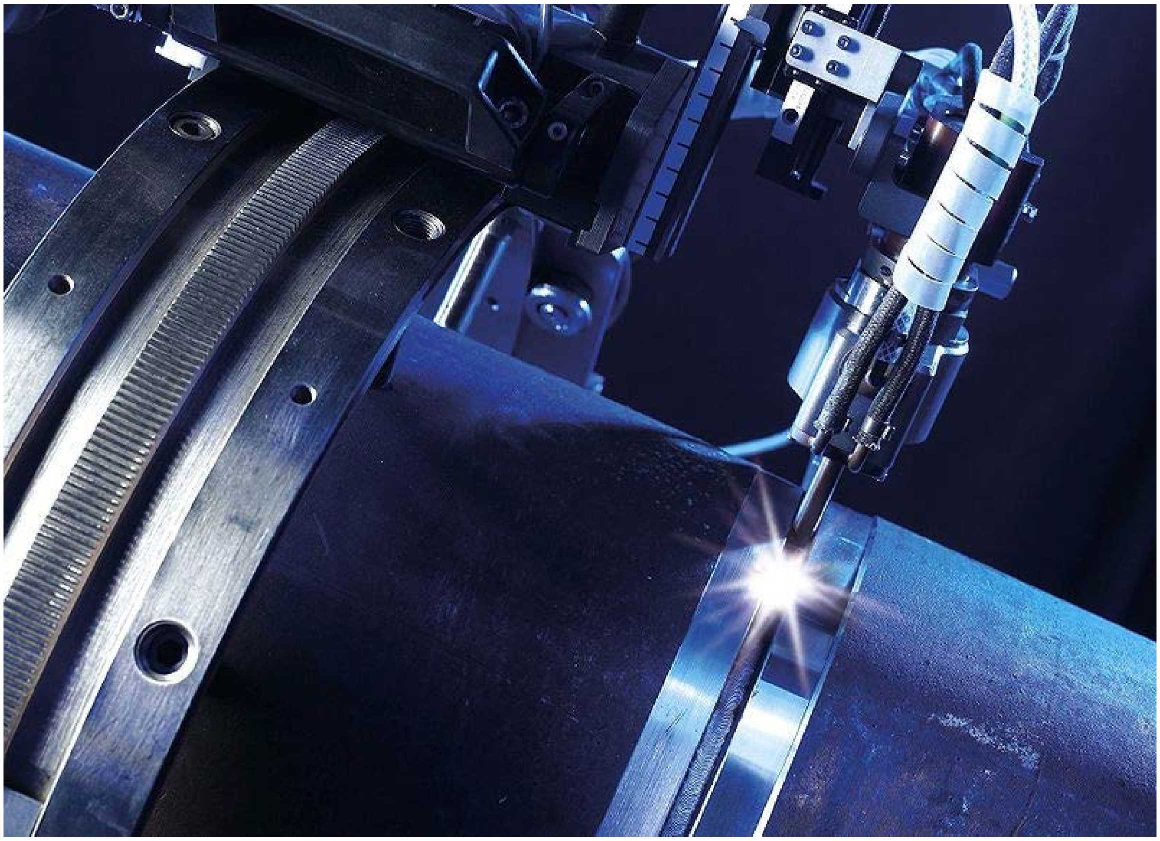
Tube diameters

MU IV- Open welding head type - Welding of steel tubes and elbows in the boiles production

Due to the precision of orbital TIG welding, even the smallest standard tube diameters from 1.6 millimetres can be processed. At the other end of the scale, pipes with diameters up to 170mm and walls up to 3.5mm thick can be joined using closed chamber weld heads. These weld heads allow the torch to be positioned very precisely and ensure that the pipe is held securely. The inert gas atmosphere in the closed chamber prevents heat from tinting, even with the most sensitive of materials. For tube diameters between 8 and 275mm, it is possible to use more easily manageable open welding heads. A flexible hose system is used to supply the welding head with power, inert gas, cooling water and filler wire, if required. The need for filler wire during the welding process depends on the type of welding task; thicker tube walls and difficult-to-control parent materials require the use of additional material, whereas thin-walled tubes can be welded without extra wire.

In order to create high quality weld seams it is essential that tube ends are carefully prepared with the edges of the workpieces being free of scale and impurities. For thinner-walled tubes up to medium diameters, a simple right-angled saw cut is often sufficient. For thicker tube walls it is necessary to prepare the edges more carefully, for example using a U-groove cross-section.

Business sectors and markets



Hot wire narrow gap welding in the production of power stations

Thanks to its ability to realise high purity results, orbital welding found its place in the production of clean-room components for the semiconductor industry. Its application has now expanded to the construction of pipework and equipment for diverse industries like food processing, pharmaceuticals, chemical engineering, automotive engineering, biotechnology, shipbuilding and aerospace. Automated orbital TIG welding is also used in the construction of power stations, (thermal power plants). The construction materials used must be able to withstand the enormous mechanical loads produced by the high pressures and temperatures created by the media carried in the tubes. Notches, pores and inclusions in the weld seams must be avoided at all costs, as these create weak points that can lead to subsequent formation of cracks, which in turn can have serious consequences in terms of component failure. This means that tubes are often made from nickel-based materials with walls up to 200mm thick. One manufacturer has developed an orbital narrow gap welding system with hot-wire feed specifically for this purpose, which uses running gear that moves on a guide ring fixed around the tube. This new variant has excited a lot of interest in the sector, with the worldwide boom in power station construction fueling the never-ending search for increasingly productive manufacturing methods using new types of high-temperature steels.

Perspectives

Next to the current method using TIG cold and hot wire welding there is a steady progress in the development of MIG/MAG welding which allows a whole range of new applications. Whether the job involves the thickest of walls or the smallest of tube diameters, exotic materials or inhospitable environmental conditions, whenever the need exists for a reliable weld of reproducible quality, there is a place for orbital welding with its wide-ranging applications and different types of techniques.

Chapter 12

Friction Stud Welding

Friction stud welding is a solid phase welding technique involving a stud, appurtenance or small pipe fitting being rotated at high speed while being forced against a substrate, generating heat by friction. The metal surfaces reach a temperature at which they flow plastically under pressure, surface impurities are expelled and a forged weld is formed.

A friction stud weld.

This technique is rather more costly than arc stud welding and is therefore used for special applications where arc welding may present problems, such as:

- welding underwater
- welding on live subsea pipelines to attach anodes
- welding in explosive environments and zoned areas
- welding materials that are difficult to join by fusion welding processes
- friction plug welding
- welding pipe fittings onto flat or curved surfaces

Portable equipment for friction stud welding is available for use on construction work sites, offshore, underwater and in workshops. These portable units are much lighter and smaller than the large static friction welding machines which are used, for example, in factories to weld engine components such as drive shafts.

Principle of operation

A portable friction stud welding tool consists of a motor to rotate the stud at high speed and a piston to apply the necessary force to the stud. The equipment may be air or hydraulically powered. A clamping system is also required to hold the tool onto the work piece and to provide reaction to the force on the stud. The clamps used are typically magnetic or vacuum clamps for flat surfaces, chain or claw clamps for pipes and various mechanical clamps for welding onto I beams or other shapes.

The weld is made by rotating the stud at high speed and forcing it onto the substrate causing friction which heats the stud tip and substrate surface. Metal at the interface between the stud and the substrate flows plastically under pressure, removing impurities from the metal surfaces, and a solid phase weld is formed. The rotation of the stud is then stopped but the force on the stud is maintained for a few seconds. The maximum temperatures reached during welding are much lower than the melting point of the metals.

Advantages and disadvantages

Some notable advantages of the process are:

- The relatively low temperature at which the weld is formed means that the process can be adapted for applications such as welding on live pipelines and in explosive environments.
- The absence of an electric arc and a liquid phase in the metal avoids some of the potential problems encountered with arc welding such as contamination of the weld with hydrogen, nitrogen and oxygen.
- The rapid weld cycle time (typically 5 to 10 seconds) and the method of weld formation result in a fine grain structure.

In the “as welded” condition the residual stresses are compressive which tend to result in good fatigue life. Studs can also be welded through epoxy paint coatings up to approximately 3 mm thickness.

The main disadvantages of this process are:

- The process can only be used to weld relatively small components (such as studs, pipe nipples or plugs) which can be rotated at high speed, onto a work piece. The systems used are limited to studs up to typically 25 mm diameter, pipe nipples and appurtenances up to typically 60 mm diameter and plugs for filling holes up to typically 25 mm diameter (plug welding).
- The system requires a rigid clamp to hold the welding tool on the work piece and withstand the force applied to the stud during welding. Although these clamps can be moved from one weld location to the next quite rapidly they are generally larger and more cumbersome than is the case with arc stud welding systems.

Applications

For the type of applications listed here it is especially important that the welding and operating procedures are fully tested and certified for both weld integrity and operational safety prior to use in production. Operators must be thoroughly trained and systems must be in place to ensure that the procedures are properly applied and risks properly assessed.

Welding underwater

When this process is used underwater, a shroud is fitted around the stud which prevents the weld from being cooled too rapidly by the surrounding water. The air powered systems can operate underwater to a depth of approximately 20m and are relatively simple for divers to use. The hydraulically powered systems can also be used by divers and have welded to depths in excess of 300m from a Remotely Operated Vehicle (ROV). Current friction stud welding systems are designed to operate to a depth of approximately 1000m.

Welding on live subsea pipelines to attach anodes

Friction stud welding has been used to retrofit sacrificial anodes to subsea pipelines while the pipeline is “live” (that is, it continues to transport hydrocarbons at pressure). In some cases the anodes are placed on the sea bed next to the pipeline and a lug on a cable from the anode is connected to the stud welded on the pipeline. Another option is a *tripartite weld* where the lug on the anode cable is made of steel with a tapered hole in it. The tapered end of the stud welds through the hole onto the pipeline, welding to both the lug and the pipe and providing a fully welded connection between the anode cable and pipeline. The advantage of this method is that there is no significant increase in the electrical resistance of the connection due to corrosion during the lifetime of the pipeline. Many subsea pipelines have concrete weight coating on them and a small area of this can be removed with a water jet to permit welding.

Welding in explosive environments and zoned areas

Friction stud welding has been used to attach *grating* to offshore oil platforms in areas where arc welding is not permitted because of the risk of causing a fire or explosion. A shroud similar to the one used for welding underwater acts as a barrier between the weld and the surrounding atmosphere. A water screen can also be used as an additional barrier.

An M16 stud weld being performed with a shroud inside a vacuum clamp. In this example the central part of the clamp is flooded with water during welding.

Welding materials that are difficult to join by fusion welding processes

Friction stud welding is a solid phase welding process where the metals do not liquefy. This permits metal combinations such as welding aluminium studs to steel which would be problematic with arc welding because of the formation of brittle inter-metallic compounds.

Friction plug welding

In *friction plug welding* a tapered shaped plug is friction welded into a tapered hole in the substrate. This welding method can be used to repair defects in castings. It has also been used to fill the holes that occur on completion of a friction stir welding pass when the stirring probe is withdrawn from the weld.

Welding pipe fittings onto flat or curved surfaces

On the larger portable friction welding tools the stud can be replaced by a small diameter pipe nipple which can be friction welded directly to a flat or curved surface such as a storage tank or pressure vessel. A suitable valve can then be fitted to the nipple and a hot tapping drill used to cut a hole through the wall of the tank. The drill is then removed and a pipe or hose fitted to the valve and used to pass fluid to or from the tank.

Chapter 13

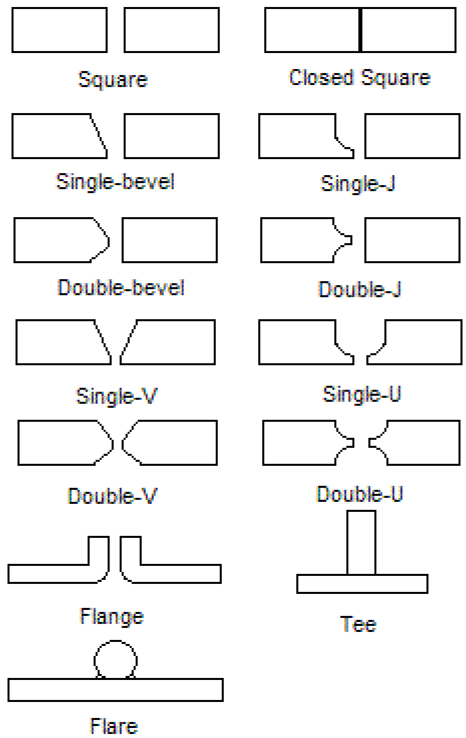
Welding Joints

Welding joints are formed by welding two or more workpieces, made of metals or plastics, according to a particular geometry. The most common types are butt and lap joints; there are various lesser used welding joints including flange and corner joints.

Butt welds

Butt welds are welds where two pieces of metal are joined at surfaces that are at 90 degree angles to the surface of at least one of the other pieces. These types of welds require only some preparation and are used with thin sheet metals that can be welded with a single pass . Common issues that can weaken a butt weld are the entrapment of slag, excessive porosity, or cracking. For strong welds, the goal is to use the least amount of welding material possible. Butt welds are prevalent in automated welding processes, such as submerged-arc welding, due to their relative ease of preparation. When metals are welded without human guidance, there is no operator to make adjustments for non-ideal joint preparation. Because of this necessity, butt welds can be utilized for their simplistic design to be fed through automated welding machines efficiently.

Types



Butt joint geometries

There are many types of butt welds, but all fall within one of these categories: single welded butt joints, double welded butt joint, and open or closed butt joints. A single welded butt joint is the name for a joint that has only been welded from one side. A double welded butt joint is created when the weld has been welded from both sides. With double welding, the depths of each weld can vary slightly. A closed weld is a type of joint in which the two pieces that will be joined are touching during the welding process. An open weld is the joint type where the two pieces have a small gap in between them during welding.

Square butt joints

The square-groove is a butt welding joint with the two pieces being flat and parallel to each other. This joint is simple to prepare, economical to use, and provides satisfactory strength, but is limited by joint thickness. The closed square butt weld is a type of square-groove joint with no spacing in between the pieces. This joint type is common with gas and arc welding.

For thicker joints, the edge of each member of the joint must be prepared to a particular geometry to provide accessibility for welding and to ensure the desired weld soundness and strength. The opening or gap at the root of the joint and the included angle of the groove should be selected to require the least weld metal necessary to give needed access and meet strength requirements.

Bevel butt joints

Single-bevel butt welds are welds where one piece in the joint is beveled and the other surface is perpendicular to the plane of the surface. These types of joints are used where adequate penetration cannot be achieved with a square-groove and the metals are to be welded in the horizontal position . Double-bevel butt welds are common in arc and gas welding processes. In this type both sides of one of the edges in the joint are beveled.

V-joints

Single-V butt welds are similar to a bevel joint, but instead of only one side having the beveled edge, both sides of the weld joint are beveled. In thick metals, and when welding can be performed from both sides of the work piece, a double-V joint is used. When welding thicker metals, a double-V joint requires less filler material because there are two narrower V-joints compared to a wider single-V joint. Also the double-V joint helps compensate for warping forces. With a single-V joint, stress tends to warp the piece in one direction when the V-joint is filled, but with a double-V-joint, there are welds on both sides of the material, having opposing stresses, straightening the material.

J-joints

Single-J butt welds are when one piece of the weld is in the shape of a *J* that easily accepts filler material and the other piece is square. A J-groove is formed either with special cutting machinery or by grinding the joint edge into the form of a J. Although a J-groove is more difficult and costly to prepare than a V-groove, a single J-groove on metal between a half an inch and three quarters of an inch thick provides a stronger weld that requires less filler material. Double-J butt welds have one piece that has a *J* shape from both directions and the other piece is square.

U-joints

Single-U butt welds are welds that have both edges of the weld surface shaped like a J, but once they come together, they form a U. Double-U joints have a U formation on both the top and bottom of the prepared joint. U-joints are the most expensive edge to prepare and weld. They are usually used on thick base metals where a V-groove would be at such a extreme angle, that it would cost too much to fill.

Others

Thin sheet metals are often flanged to produce edge-flange or corner-flange welds. These welds are typically made without the addition of filler metal because the flange melts and provides all the filler needed. Pipes and tubing can be made from rolling and welding together strips, sheets, or plates of material.

Flare-groove joints are used for welding metals that, because of their shape, form a convenient groove for welding, such as a pipe against a flat surface.

The Tee Butt Weld is formed when two bars or sheets are joined perpendicular to each other in the form of a *T* shape. This weld is made from the resistance butt welding process.

Selection of the right weld joint depends on the thickness and process used. The square welds are the most economical for pieces thinner than 3/8", because they don't require the edge to be prepared. Double-groove welds are the most economical for thicker pieces because they require less weld material and time. The use of fusion welding is common for closed single-bevel, closed single J, open single J, and closed double J butt joints. The use of gas and arc welding is ideal for double-bevel, closed double-bevel, open double-bevel, single-bevel, and open single-bevel butt welds.

Below are listed ideal joint thicknesses for the various types of butt welding joints. When the thickness of a butt weld is defined it is measured at the thinner part and does not compensate for the weld reinforcement.

Workpiece thickness limits per joint type

Joint type	Thickness
Square joint	Up to ¼ in (0.64 cm)
Single-bevel joint	3⁄16–⅜ in (0.48–0.95 cm)
Double-bevel joint	Over ⅜ in (0.95 cm)
Single-V joint	Up to ¾ in (1.9 cm)
Double-V joint	Over ¾ in (1.9 cm)
Single-J joint	½–¾ in (1.3–1.9 cm)
Double-J joint	Over ¾ in (1.9 cm)
Single-U joint	Up to ¾ in (1.9 cm)
Double-U joint	Over ¾ in (1.9 cm)
Flange (edge of corner)	Sheet metals less than 12 gauge
Flare groove	All thickness

Cruciform

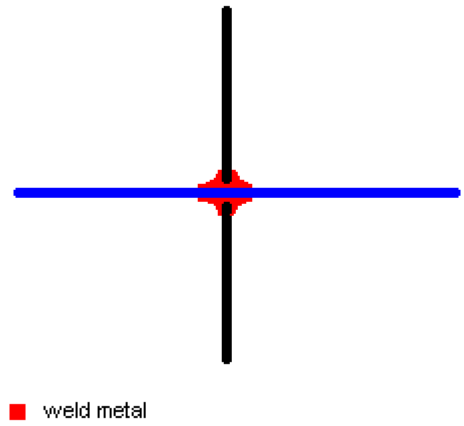


Diagram of a cruciform joint between 3 plates of metal

A *cruciform joint* is a specific joint in which four spaces are created by the welding of three plates of metal at right angles. In the American Bureau of Shipping Rules for Steel Vessels, cruciform joints may be considered a double barrier if the two substances requiring a double barrier are in opposite corners diagonally. Double barriers are often required to separate oil and seawater, chemicals and potable water, etc.

Plate edge preparation

In common welding practices, the welding surface needs to be prepared to ensure the strongest weld possible. Preparation is needed for all forms of welding and all types of joints. Generally, butt welds require very little preparation, but some is still needed for the best results. Plate edges can be prepared for butt joints in various ways, but the five most common techniques are oxyacetylene cutting (oxy-fuel welding and cutting), machining, chipping, grinding, and air carbon-arc cutting or gouging. Each technique has unique advantages to their use.

For steel materials, oxyacetylene cutting is the most common form of preparation. This technique is advantageous because of its speed, low cost, and adaptability. Machining is the most effective for reproducibility and mass production of parts. Preparation of J or U joints is common prepared by machining due to the need for high accuracy. The chipping method is used to prepare parts that were produced by casting. The use of grinding to prepare pieces is reserved for small sections that cannot be prepared by other methods. Air carbon arc welding is common in industries that work with stainless steels, cast iron, or ordinary carbon steel.

Prior to welding dissimilar materials, one or both faces of the groove can be buttered. The buttered layer can be the same alloy as the filler metal or a different filler metal that will act as a buffer between the two metals to be joined.