= Welding =

Welding is a fabrication or sculptural process that joins materials , usually metals or thermoplastics , by causing fusion , which is distinct from lower temperature metal @-@ joining techniques such as brazing and soldering , which do not melt the base metal . In addition to melting the base metal , a filler material is often added to the joint to form a pool of molten material (the weld pool) that cools to form a joint that can be as strong , or even stronger , than the base material . Pressure may also be used in conjunction with heat , or by itself , to produce a weld .

Although less common , there are also solid state welding processes such as friction welding or shielded active gas welding in which metal does not melt .

Some of the best known welding methods include :

Shielded metal arc welding (SMAW) ? also known as " stick welding or electric welding " , uses an electrode that has flux around it to protect the weld puddle . The electrode holder holds the electrode as it slowly melts away . Slag protects the weld puddle from atmospheric contamination .

Gas tungsten arc welding (GTAW) ? also known as TIG (tungsten , inert gas) , uses a non @-@ consumable tungsten electrode to produce the weld . The weld area is protected from atmospheric contamination by an inert shielding gas such as argon or helium .

Gas metal arc welding (GMAW) ? commonly termed MIG (metal , inert gas) , uses a wire feeding gun that feeds wire at an adjustable speed and flows an argon @-@ based shielding gas or a mix of argon and carbon dioxide (CO2) over the weld puddle to protect it from atmospheric contamination .

Flux @-@ cored arc welding (FCAW) ? almost identical to MIG welding except it uses a special tubular wire filled with flux ; it can be used with or without shielding gas , depending on the filler .

Submerged arc welding (SAW) ? uses an automatically fed consumable electrode and a blanket of granular fusible flux . The molten weld and the arc zone are protected from atmospheric contamination by being " submerged " under the flux blanket .

Electroslag welding (ESW) ? a highly productive , single pass welding process for thicker materials between 1 inch (25 mm) and 12 inches (300 mm) in a vertical or close to vertical position .

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 may be performed in many different environments , including in open air , under water , and in outer space . Welding is a hazardous undertaking and precautions are required to avoid burns , electric shock , vision damage , inhalation of poisonous gases and fumes , and exposure to intense ultraviolet radiation .

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 . Arc welding and oxyfuel welding were among the first processes to develop late in the century , and electric resistance welding followed soon after . Welding technology advanced quickly during the early 20th century as the world wars drove the demand for reliable and inexpensive joining methods . Following the wars , several modern welding techniques were developed , including manual methods like SMAW , now one of the most popular welding methods , as well as semi @-@ automatic and automatic processes such as GMAW , SAW , FCAW and ESW . Developments continued with the invention of laser beam welding , electron beam welding , magnetic pulse welding (MPW) , and friction stir welding in the latter half of the century . Today , the science continues to advance . Robot welding is commonplace in industrial settings , and researchers continue to develop new welding methods and gain greater understanding of weld quality .

= = History = =

The history of joining metals goes back several millennia . Called forge welding , the earliest examples come from the Bronze and Iron Ages in Europe and the Middle East . The ancient Greek historian Herodotus states in The Histories of the 5th century BC that Glaucus of Chios " was the man who single @-@ handedly invented iron welding " . Welding was used in the construction of the

Iron pillar of Delhi , erected in Delhi , India 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 1800 , Sir Humphry Davy discovered the short @-@ pulse electrical arc and presented his results in 1801 . In 1802 , Russian scientist Vasily Petrov created the continuous electric arc , and subsequently published " News of Galvanic @-@ Voltaic Experiments " in 1803 , in which he described experiments carried out in 1802 . Of great importance in this work was the description of a stable arc discharge and the indication of its possible use for many applications , one being melting metals . In 1808 , Davy , who was unaware of Petrov 's work , rediscovered the continuous electric arc . In 1881 ? 82 inventors Nikolai Benardos (Russian) and Stanis?aw Olszewski (Polish) 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 using a 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 torch 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 " Fullagar " 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 , the Maurzyce Bridge designed by Stefan Bry?a of the Lwów University of Technology in 1927 , and built across the river S?udwia near ?owicz , Poland in 1928 .

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 . In 1930 , the first all @-@ welded merchant vessel , M / S Carolinian , was launched .

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 . Magnetic pulse welding (MPW) is industrially used since 1967 . Friction stir welding was invented in 1991 by Wayne Thomas at The Welding Institute (TWI , UK) and found high @-@ quality applications all over the world . All of these four 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 power necessary for arc welding processes , a variety 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 plays an important role in arc 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 affects 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 filler material (typically steel) and is covered with a flux that protects the weld area from oxidation and contamination by producing carbon dioxide (CO2) gas during the welding process . The electrode core itself acts as filler material , making a separate filler unnecessary .

The process is versatile and can be performed with relatively inexpensive equipment , making it well suited to shop jobs and field work . 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 welding = = =

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 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 , laser cladding , 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) , magnetic pulse welding , co @-@ extrusion welding , cold welding , diffusion bonding , exothermic welding , high frequency welding , hot pressure welding , induction welding , and roll welding .

= = Geometry = =

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 design ; 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 .

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 = =

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 .

The metalworking industry has instituted specifications and codes to guide welders , weld inspectors , engineers , managers , and property owners in proper welding technique , design of welds , how to judge the quality of Welding Procedure Specification , how to judge the skill of the person performing the weld , and how to ensure the quality of a welding job . Methods such as

visual inspection , radiography , ultrasonic testing , phased @-@ array ultrasonics , dye penetrant inspection , magnetic particle inspection , or industrial computed tomography can help with detection and analysis of certain defects .

= = = 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 :
<formula>