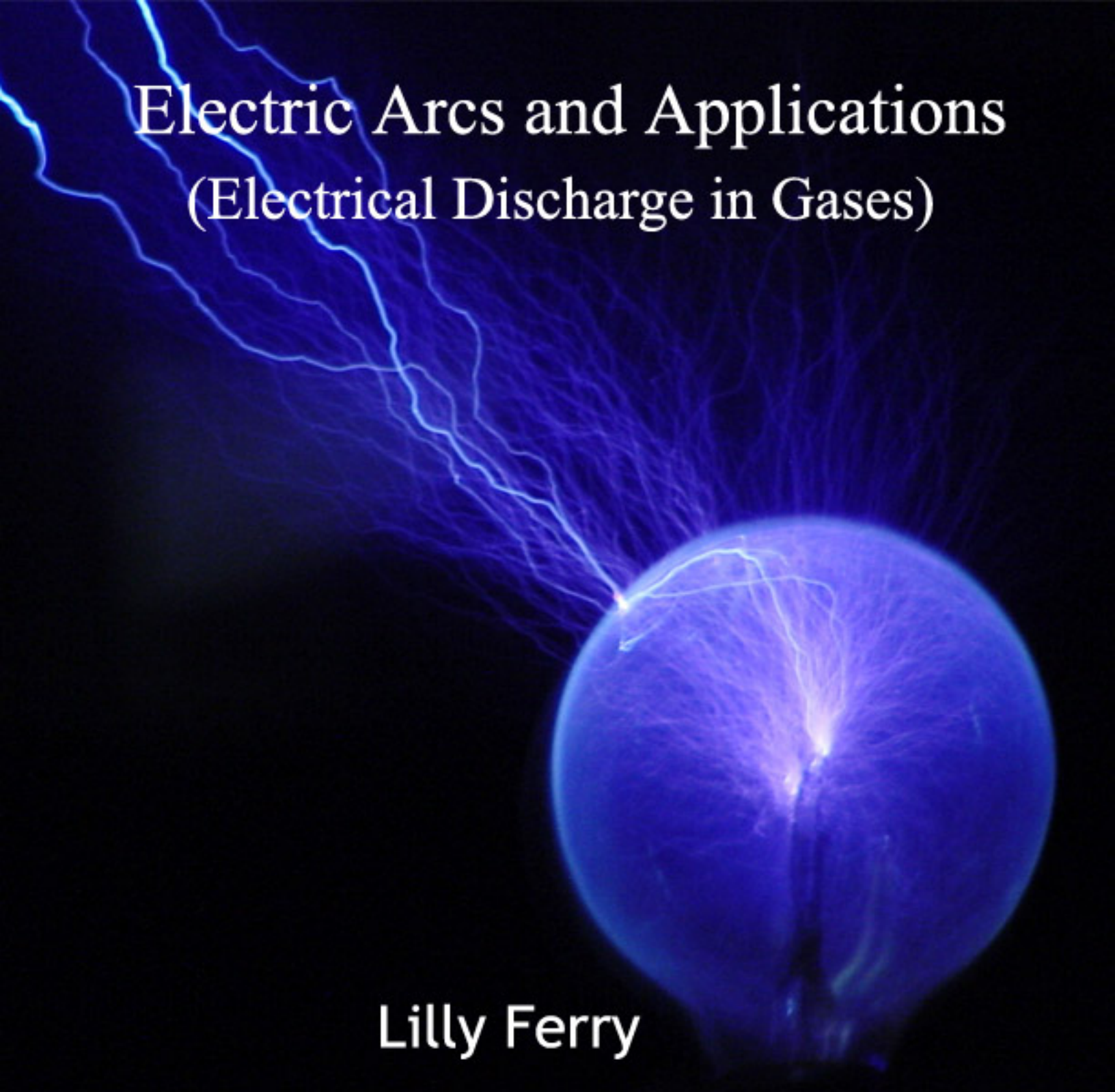
Electric Arcs and Applications

(Electrical Discharge in Gases)



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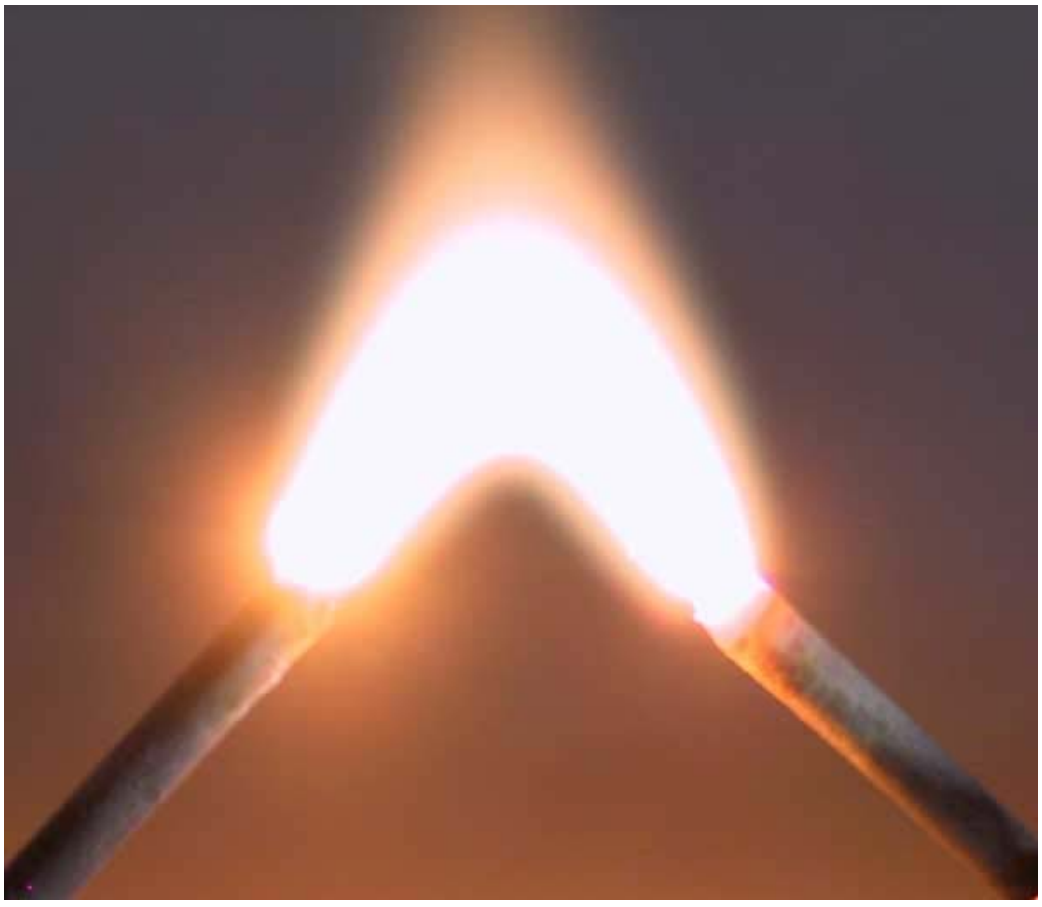
Electric Arc



An electric arc between two nails

An **electric arc** is an electrical breakdown of a gas which produces an ongoing plasma discharge, resulting from a current flowing through normally nonconductive media such as air. A synonym is **arc discharge**. An arc discharge is characterized by a lower voltage

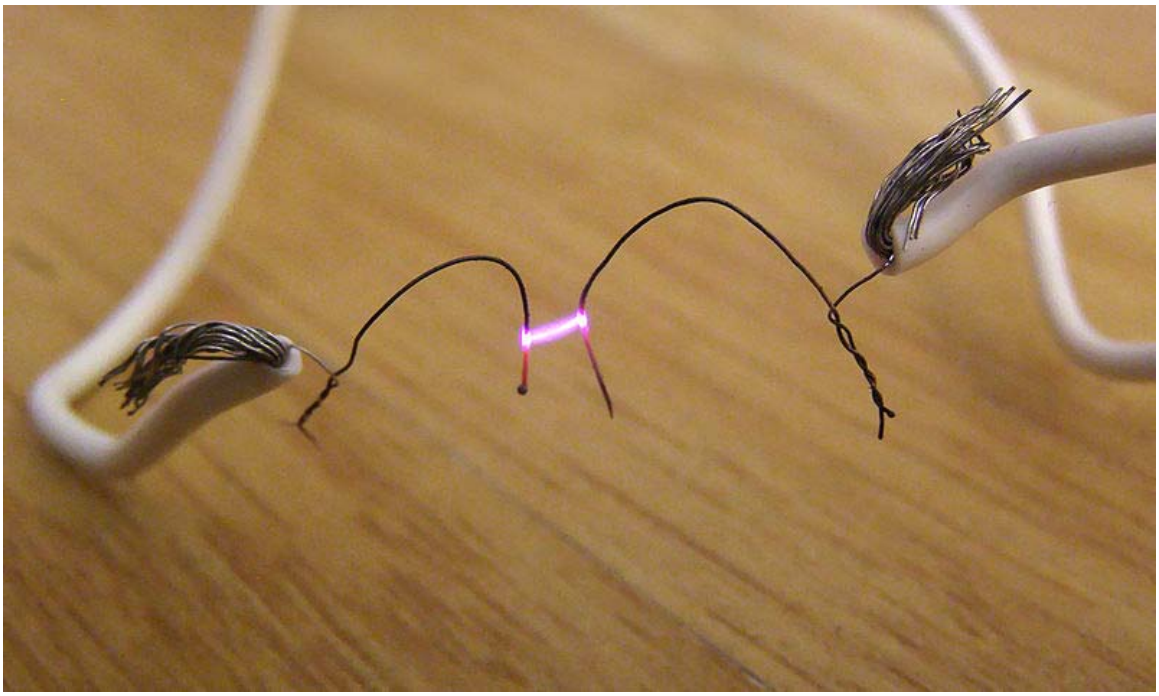
than a glow discharge, and relies on thermionic emission of electrons from the electrodes supporting the arc. An archaic term is **voltaic arc** as used in the phrase "voltaic arc lamp".

History

The phenomenon was first described by Vasily V. Petrov, a Russian scientist who discovered it in 1802. Sir Humphry Davy first demonstrated the arc early in the nineteenth century (1802, 1805, 1807 and 1809 are all mentioned) by transmitting an electric current through two touching carbon rods and then pulling them a short distance apart. He is also credited with naming the arc.

Overview

Electricity arcs between the power rail and electrical pickup "shoe" on a London Underground train

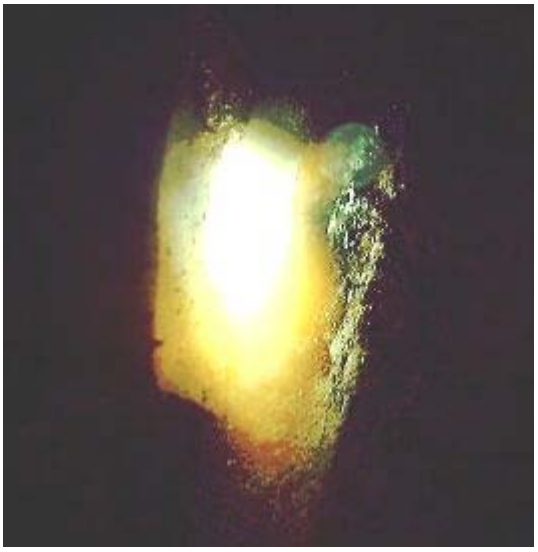


Electric arc between strands of wire.

The various shapes of electric arc are emergent properties of nonlinear patterns of current and electric field. The arc occurs in the gas-filled space between two conductive electrodes (often made of tungsten or carbon) and it results in a very high temperature, capable of melting or vaporizing most materials. An electric arc is a continuous discharge, while a similar electric spark discharge is momentary. An electric arc may occur either in Direct current circuits or in alternating current circuits. In the latter case, the arc may re-strike on each half cycle of the current. An electric arc differs from a glow discharge in that the current density is quite high, and the voltage drop within the arc is low; at the cathode the current density may be as high as one megaampere per square centimeter.

An electric arc has a non-linear relationship between current and voltage. Once the arc is established (either by progression from a glow discharge or by momentarily touching the electrodes then separating them), increased current results in a lower voltage between the arc terminals. This negative resistance effect requires that some positive form of impedance to be placed in the circuit, if it is desired to maintain a stable arc. This property is the reason uncontrolled electrical arcs in apparatus become so destructive, since once initiated an arc will draw more and more current from a fixed-voltage supply until the apparatus is destroyed.

Uses



An electric arc can melt calcium oxide

Industrially, electric arcs are used for welding, plasma cutting, for electrical discharge machining, as an arc lamp in movie projectors and followspots in stage lighting. Electric arc furnaces are used to produce steel and other substances. Calcium carbide is made in this way as it requires a large amount of energy to promote an endothermic reaction (at temperatures of 2500 °C).

Low-pressure electric arcs are used for lighting, e.g., fluorescent tubes, mercury and sodium street lamps, and camera flash lamps.

Formation of an intense electric arc, similar to a small-scale arc flash, is the foundation of exploding-bridgewire detonators.

Electric arcs have been studied for electric propulsion of spacecraft.

Undesired arcing

Arc damage to a CEE 7/7 plug. The discharge path was formed by a conductive liquid seeping into the plug-socket assembly.

Undesired or unintended electric arcing can have detrimental effects on electric power transmission, distribution systems and electronic equipment. Devices which may cause arcing include switches, circuit breakers, relay contacts, fuses and poor cable terminations. When an inductive circuit is switched off the current cannot instantaneously jump to zero; a transient arc will be formed across the separating contacts. Switching devices susceptible to arcing are normally designed to contain and extinguish an arc, and snubber circuits can supply a path for transient currents, preventing arcing. If a circuit has enough current and voltage to sustain an arc formed outside of a switching device, the arc can cause damage to equipment such as melting of conductors, destruction of insulation, and fire. An arc flash describes an explosive electrical event that presents a hazard to people and equipment.

Undesired arcing in electrical contactors can be suppressed by various devices, including:

- immersion in transformer oil, dielectric gas or vacuum
- arc chutes
- magnetic blowouts

Arcing can also occur when a low resistance channel (foreign object, conductive dust, moisture...) forms between places with different potential. The conductive channel then can facilitate formation of an electric arc. The ionized air has high electrical conductivity approaching that of metals, and can conduct extremely high currents, causing a short circuit and tripping protective devices (fuses, circuit breakers). Similar situation may occur when a lightbulb burns out and the fragments of the filament pull an electric arc between the leads inside the bulb, leading to overcurrent that trips the breakers.

Electric arc over the surface of plastics causes their degradation. A conductive carbon-rich track tends to form in the arc path, negatively influencing their insulation properties. The arc susceptibility is tested according to ASTM D495, by point electrodes and continuous and intermittent arcs; it is measured in seconds to form a track that is conductive under high-voltage low-current conditions. Some materials are less susceptible to degradation than others; e.g. polytetrafluoroethylene has arc resistance of about 200 seconds. From thermosetting plastics, alkyds and melamine resins are better than phenolic resins. Polyethylenes have arc resistance of about 150 seconds, polystyrenes and polyvinyl chlorides have relatively low resistance of about 70 seconds. Plastics can be formulated to emit gases with arc-extinguishing properties; these are known as *arc-extinguishing plastics*.

Arcing over some types of printed circuit boards, possibly due to cracks of the traces or the failure of a solder, renders the affected insulating layer conductive as the dielectric is combusted due to the high temperatures involved. This conductivity prolongs the arcing due to cascading failure of the surface.

Chapter-2

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.

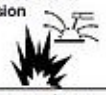
Knifeline attack (KLA) is another kind of corrosion affecting welds, impacting steels stabilized by niobium. Niobium and niobium carbide dissolves in steel at very high temperatures. At some cooling regimes, niobium carbide does not precipitate, and the steel then behaves like unstabilized steel, forming 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

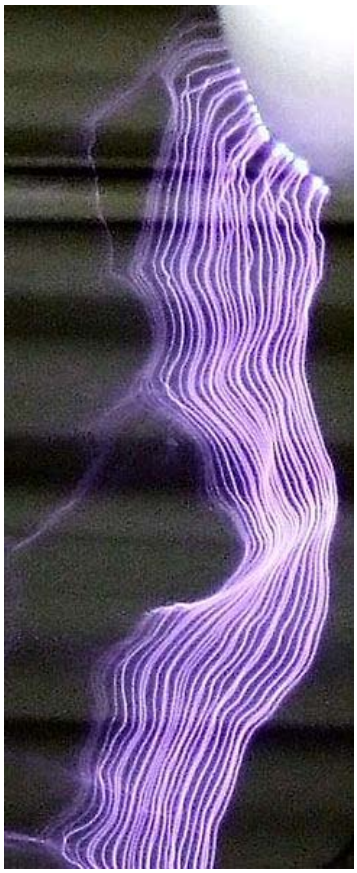
Welders are also often exposed to dangerous gases and particulate matter. Processes like flux-cored arc welding and shielded metal arc welding produce smoke containing particles of various types of oxides. The size of the particles in question tends to influence the toxicity of the fumes, with smaller 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-3

Electrical Breakdown



Electrical breakdown in an electric discharge showing the ribbon-like plasma filaments from a Tesla coil.

The term **electrical breakdown** or **electric breakdown** has several similar but distinctly different meanings. For example, the term can apply to the failure of an electric circuit. Alternatively, it may refer to a rapid reduction in the resistance of an electrical insulator

that can lead to a spark jumping around or through the insulator. This may be a momentary event (as in an electrostatic discharge), or may lead to a continuous arc discharge if protective devices fail to interrupt the current in a high power circuit.

Electrical system failure

The most common meaning is related to automobiles and is the failure of an electric circuit or associated device resulting in a loss of vehicle function (a breakdown). Common problems include battery discharge, alternator failure, broken wires, blown fuses, etc.

Failure of electrical insulation

The second meaning of the term is more specifically a reference to the breakdown of the insulation of an electrical wire or other electrical component. Such breakdown usually results in a short circuit or a blown fuse. This occurs at the breakdown voltage. Actual insulation breakdown is more generally found in high-voltage applications, where it sometimes causes the opening of a protective circuit breaker. Electrical breakdown is often associated with the failure of solid or liquid insulating materials used inside high voltage transformers or capacitors in the electricity distribution grid. Electrical breakdown can also occur across the insulators that suspend overhead power lines, within underground power cables, or lines arcing to nearby branches of trees. Under sufficient electrical stress, electrical breakdown can occur within solids, liquids, gases or vacuum. However, the specific breakdown mechanisms are significantly different for each, particularly in different kinds of dielectric medium. All this leads to catastrophic failure of the instruments.

Disruptive devices

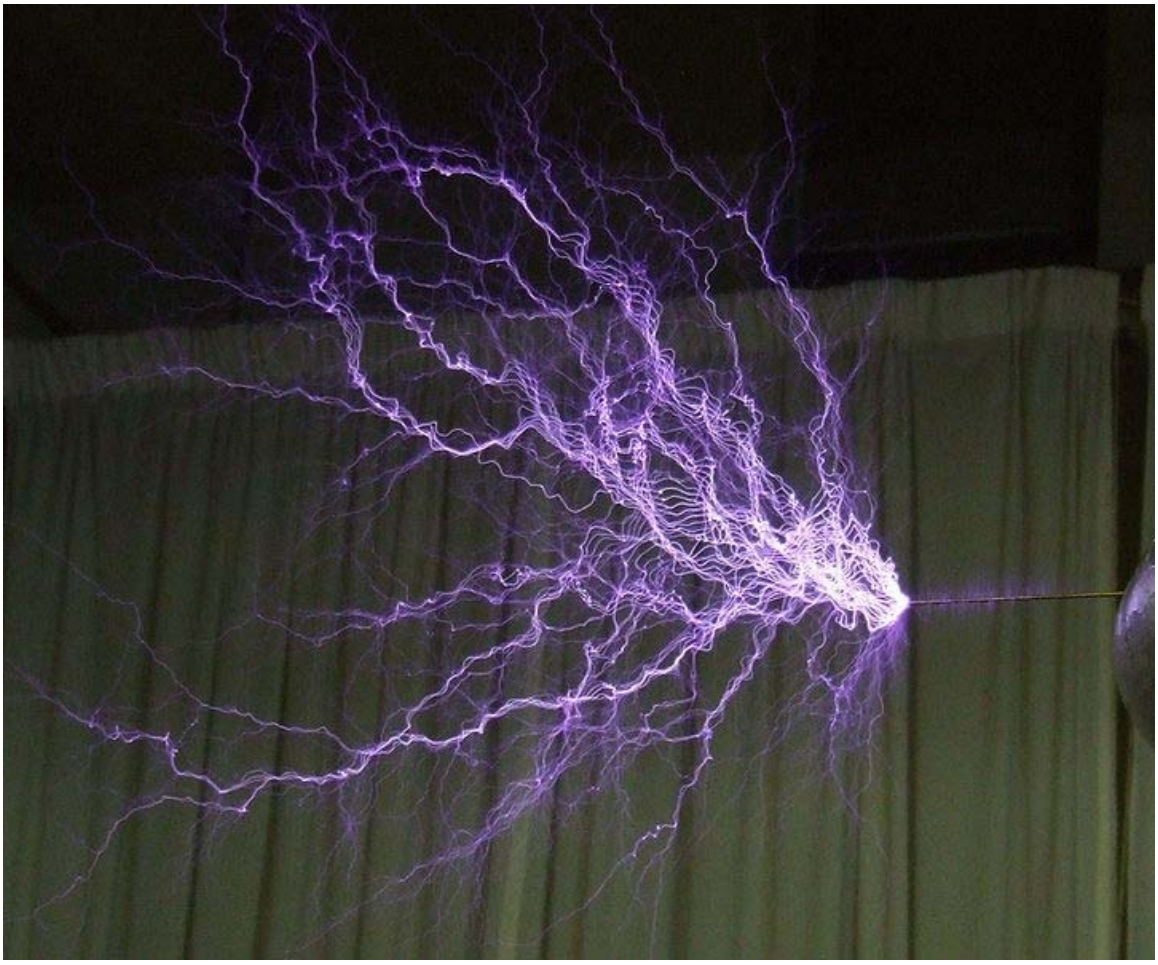
A **disruptive device** is a device that has a dielectric, whereupon being stressed beyond its dielectric strength, has an electrical breakdown. This results in the sudden transition of part of the dielectric material from an insulating state to a highly conductive state. This transition is characterized by the formation of an electric spark, and possibly an electric arc through the material. If this occurs within a solid dielectric, physical and chemical changes along the path of the discharge will cause permanent degradation and significant reduction in the material's dielectric strength. A spark gap is a type of disruptive discharge device that uses a gas or fluid dielectric between spaced electrodes. It may be used to discharge the primary capacitor of a resonance transformer into the primary inductor. Unlike solid dielectrics, liquid or gaseous dielectrics can usually recover their full dielectric strength once current flow (through the plasma in the gap) has been externally interrupted.

Mechanism

Electrical breakdown occurs within a gas (or mixture of gases, such as air) when the dielectric strength of the gas(es) is exceeded. Regions of high electrical stress can cause

nearby gas to partially ionize and begin conducting. This is done deliberately in low pressure discharges such as in fluorescent lights or in an electrostatic precipitator.

Partial electrical breakdown of the air causes the "fresh air" smell of ozone during thunderstorms or around high-voltage equipment. Although air is normally an excellent insulator, when stressed by a sufficiently high voltage (an electric field strength of about 3×10^6V/m), air can begin to break down, becoming partially conductive. If the voltage is sufficiently high, complete electrical breakdown of the air will culminate in an electrical spark or arc that bridges the entire gap. While the small sparks generated by static electricity may barely be audible, larger sparks are often accompanied by a loud snap or bang. Lightning is an example of an immense spark that can be many miles long. The color of the spark depends upon the gases that make up the gaseous media.

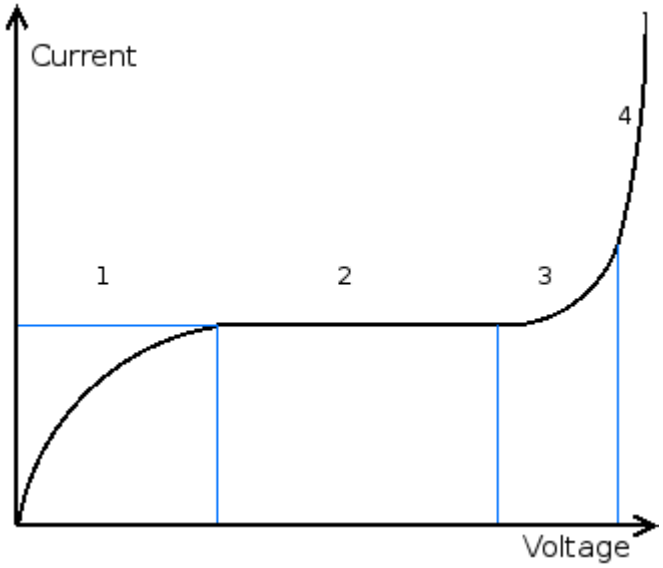


Electric discharge showing the lightning-like plasma filaments from a Tesla coil.

If a fuse or circuit breaker fails to interrupt the current through a spark in a power circuit, current may continue, forming a very hot electric arc. The color of an arc depends primarily upon the conductor materials (as they are vaporized and mix within the hot

plasma in the arc). Although sparks and arcs are usually undesirable, they can be useful in everyday applications such as spark plugs for gasoline engines, electrical welding of metals, or for metal melting in an electric arc furnace.

Voltage-current relation



Voltage-current relation before breakdown

Before breakdown, there is a non-linear relation between voltage and current as shown in the figure. In region 1, there are free ions that can be accelerated by the field and induce a current. These will be saturated after a certain voltage and give a constant current, region 2. Region 3 and 4 are caused by ion avalanche as explained by the Townsend discharge mechanism.

Corona breakdown

Partial breakdown of the air occurs as a corona discharge on high voltage conductors at points with the highest electrical stress. As the dielectric strength of the material surrounding the conductor determines the maximum strength of the electric field the surrounding material can tolerate before becoming conductive, conductors that consist of sharp points, or balls with small radii, are more prone to causing dielectric breakdown. Corona is sometimes seen as a bluish glow around high voltage wires and heard as a sizzling sound along high voltage power lines. Corona also generates radio frequency noise that can also be heard as 'static' or buzzing on radio receivers. Corona can also occur naturally at high points (such as church spires, treetops, or ship masts) during thunderstorms as St. Elmo's Fire. Although corona discharge is usually undesirable, until recently it was essential in the operation of photocopiers (Xerography) and laser printers. Many modern copiers and laser printers now charge the photoconductor drum with an electrically conductive roller, reducing undesirable indoor ozone pollution. Additionally, lightning rods use corona discharge to create conductive paths in the air that point

towards the rod, deflecting potentially-damaging lightning away from buildings and other structures.

Corona discharge ozone generators have been used for more than 30 years in the water purification process. Ozone is a toxic gas, even more potent than chlorine. In a typical drinking water treatment plant, the ozone gas is dissolved into the filtered water to kill bacteria and viruses. Ozone also removes the bad odours and taste from the water. The main advantage of ozone is that the overdose (residual) decomposes to gaseous oxygen well before the water reaches the consumer. This is in contrast with chlorine which stays in the water and can be tasted by the consumer.

Corona discharges are also used to modify the surface properties of many polymers. An example is the corona treatment of plastic materials which allows paint or ink to adhere properly.

Dielectric breakdown within a solid insulator can permanently change its appearance and properties.

Chapter-4

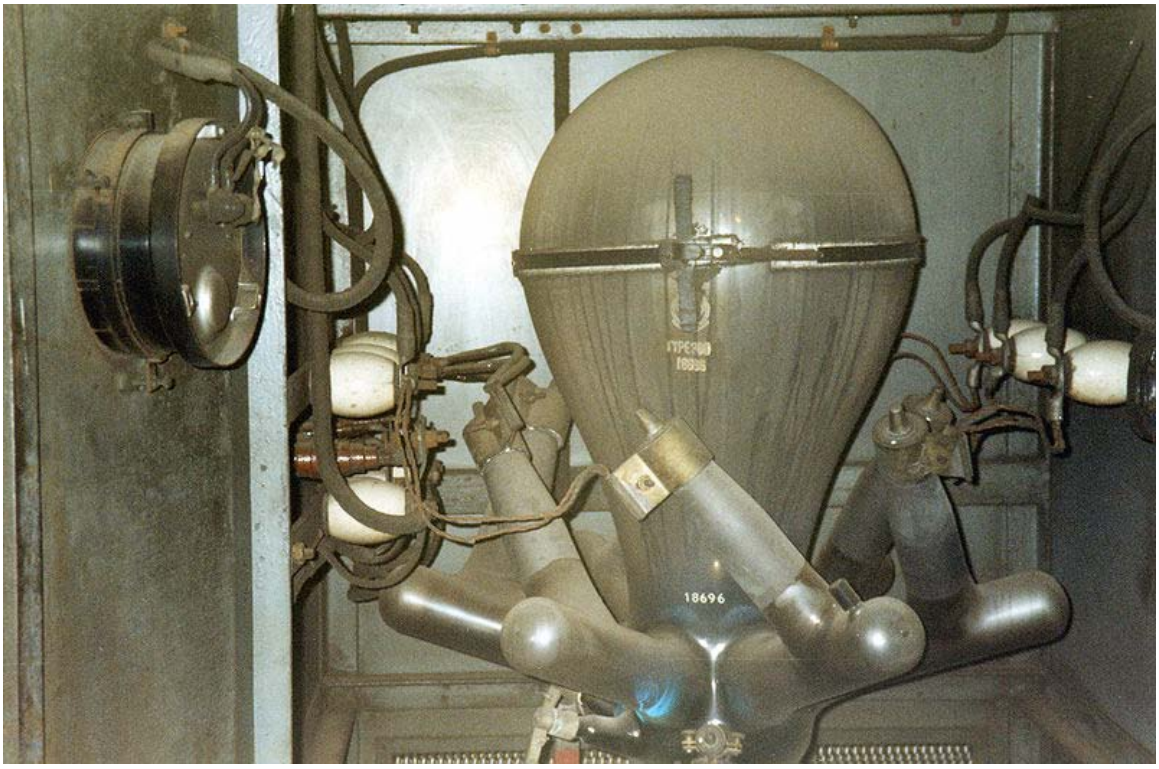
Mercury Arc Valve

Mercury rectifier on display in Beromünster, Switzerland before being decommissioned

A **mercury arc valve** (**mercury vapor rectifier**) is a type of electrical rectifier used for converting high-voltage or high-current alternating current (AC) into direct current (DC).

Rectifiers of this type were used to provide power for industrial motors, electric railways, streetcars, and electric locomotives, as well as for high-voltage direct current power transmission. They were the primary method of rectification before the advent of semiconductor rectifiers such as diodes and gate turn-off thyristor (GTOs).

History



Glass bulb mercury arc rectifier from the 1940s

The mercury arc rectifier was invented by Peter Cooper Hewitt in 1902 and further developed throughout the 1920s and 1930s by researchers in both Europe and North America. Before the advent of solid-state devices, mercury arc rectifiers were one of the most efficient rectifiers. Mercury arc rectifiers or "converters" were used for charging storage batteries and in arc lighting systems where they were found to be more efficient than rotary converters.

Since about 1975, high-voltage solid state devices such as the silicon diode and thyristor have made mercury arc rectifiers largely obsolete, even in some high-voltage DC applications.

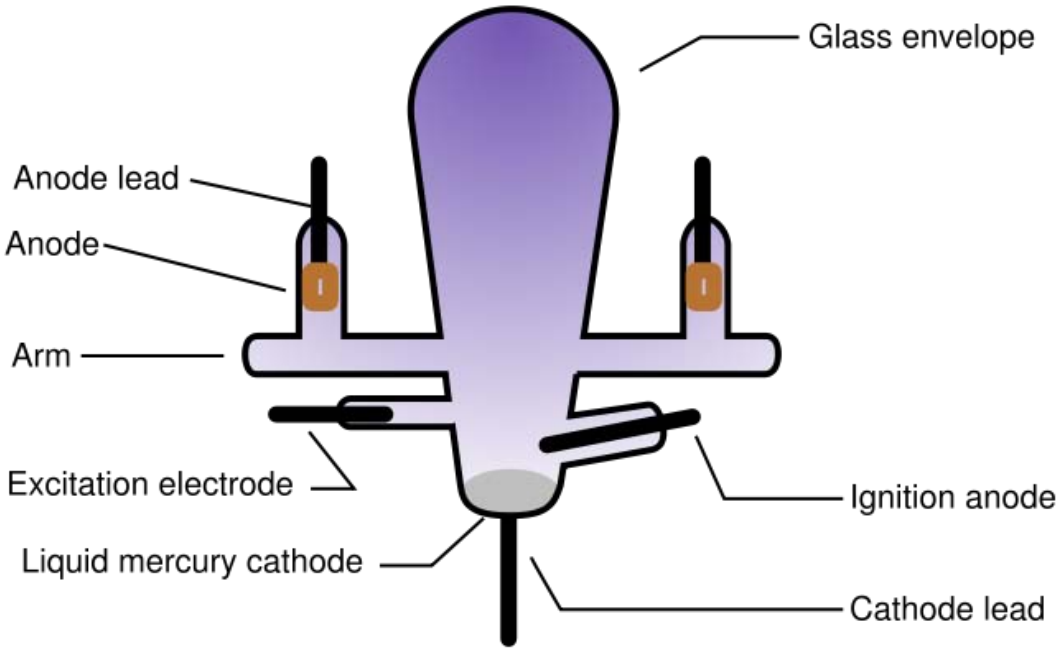
Applications

Mercury arc valves were widely used until the 1960s for the conversion of alternating current into direct current. Applications included power supply for streetcars, electric

railways, and variable-voltage power supplies for large radio transmitters. Mercury arc stations were used to provide DC power to legacy Edison-style DC power grids in urban centers until the 1950s.

They remain in use, for example, in some South African mines, on the Manx Electric Railway on the Isle of Man, the Inter-Island HVDC (high voltage direct current) link between the North and South Islands of New Zealand, and the HVDC Vancouver Island link between Vancouver Island and the Canadian mainland.

Design



A glass envelope mercury arc rectifier valve

One type of mercury vapor electric rectifier consists of an evacuated glass bulb, with a pool of liquid mercury sitting in the bottom as the cathode. Over it curves the glass bulb, which condenses mercury evaporated in the course of operation of the device. The glass envelope has one or more arms with graphite rods as anodes. Their number depends on the application. If direct current is to be produced from single-phase alternating current, then two anodes are used, each connected to the outer ends of a centre-tapped transformer secondary winding. With three-phase alternating current three or six anodes are used, to provide a smoother direct current. Six-phase operation can improve the efficiency of the transformer as well as providing smoother DC, by enabling two anodes to conduct simultaneously. During operation, the arc transfers to the anodes at the highest positive potential (with respect to the cathode). Design of the arms and envelope is intended to prevent an arc from forming between the anodes; such a condition is called "backfire" and is a critical factor in the design of mercury arc rectifiers.

Glass envelope rectifiers can produce hundreds of kilowatts of direct-current power in a single unit. A 6-phase rectifier rated 150 amperes has a glass envelope approximately 600 mm (24 inches) high by 300 mm (12 inches) outside diameter. These rectifiers will contain several pounds of liquid mercury. The large size of the envelope is required due to the low thermal conductivity of glass. Mercury vapor in the upper part of the envelope must give up heat through the glass envelope to condense and return to the cathode pool.

The current-carrying capacity of a rectifier is limited in part by the size of the wires fused into the glass envelope for connection of the anodes and cathode. Development of high-current rectifiers required leadwire materials and glass with very similar coefficients of thermal expansion in order to prevent leakage of air into the envelope.

For larger valves, a metal tank with ceramic insulators for the electrodes is used, with a vacuum pump system to counteract slight leakage of air into the tank around imperfect seals. The design patented by Uno Lamm of ASEA is one example of this type which includes grading electrodes between the anode and cathode to prevent backfire. Metal-tank rectifiers were built with ratings of 2000 A and 125 kV per unit.

Both glass and metal envelope rectifiers may have control grids inserted between the anode and cathode. This allows the conduction of the rectifier to be controlled, for example to delay the instant at which the arc transfers to the anode on the alternating current waveform, thereby giving control of the mean output voltage produced by the rectifier. Such grid-controlled valves are an essential part of a static inverter.

The temperature of the envelope must be carefully controlled, since the working pressure within the envelope is set by the coolest spot on the enclosure wall. A typical design maintains temperature at 40 degrees Celsius and a mercury vapor pressure of 7 millipascals.

Function

Principle

Operation of the rectifier relies on an electrical arc discharge between electrodes in a sealed envelope containing mercury vapor. A pool of liquid mercury acts as a self-renewing cathode that does not deteriorate with time. The mercury emits electrons freely, whereas the carbon anodes emit very few electrons even when heated, thus rectifying action occurs.

Once an arc is formed, electrons are emitted from the surface of the pool, causing ionization of mercury vapor along the path towards the anodes. The mercury ions are attracted towards the cathode, and the resulting ionic bombardment of the pool maintains the temperature of the 'emission spot', so long as a current of a few amperes continues.

The mercury ions emit light at characteristic wavelengths, the relative intensities of which are determined by the pressure of the vapor. At the low pressure within a rectifier, the light appears pale blue-violet and contains much ultraviolet light.

The cathode is connected to the DC load, which in turn is connected to the center tap of an AC transformer, which always remains at zero potential. For each AC phase, a wire from each of the two end taps is connected to an anode "arm" on the mercury arc rectifier. As the voltage on each anode goes positive, it will begin to conduct through the mercury vapor to the cathode. As the anodes of each AC phase are fed from opposite ends of the transformer winding, one will be positive, and the other negative, and thus a current will always be maintained from one or more positive anodes to the cathode.

Single-phase mercury arc rectifiers were infrequently used because every time the AC voltage dropped to zero the arc would be extinguished. The direct current produced by a single-phase rectifier contains a varying component (ripple) at twice the power supply frequency, which was undesirable in many applications for DC. The solution was to use 2, 3 or even 6 phase AC power supplies so that the rectified current would maintain a more constant voltage level. Polyphase rectifiers also balanced the load on the phases of a polyphase supply system, which is desirable for reasons of system performance and economy.

Starting

A conventional mercury arc rectifier is started by a brief high-voltage arc within the rectifier, between the cathode pool and a starting electrode. By one of a number of means, the starting electrode is brought into contact with the pool and allowed to pass current through an inductive circuit. The contact with the pool is then broken, resulting in a high emf.

The momentary contact between the starting electrode and the pool may be achieved by allowing an external electromagnet to pull the electrode into contact with the pool; the electromagnet can also serve as the starting inductance. Alternatively, the electromagnet may be arranged to tip the bulb of a small rectifier, just enough to allow mercury from the pool to reach the starting electrode. An alternative system provides a narrow neck of mercury between two pools, and by passing a very high current at negligible voltage through the neck, displaces it by magnetostriction, thus opening the circuit.

Excitation

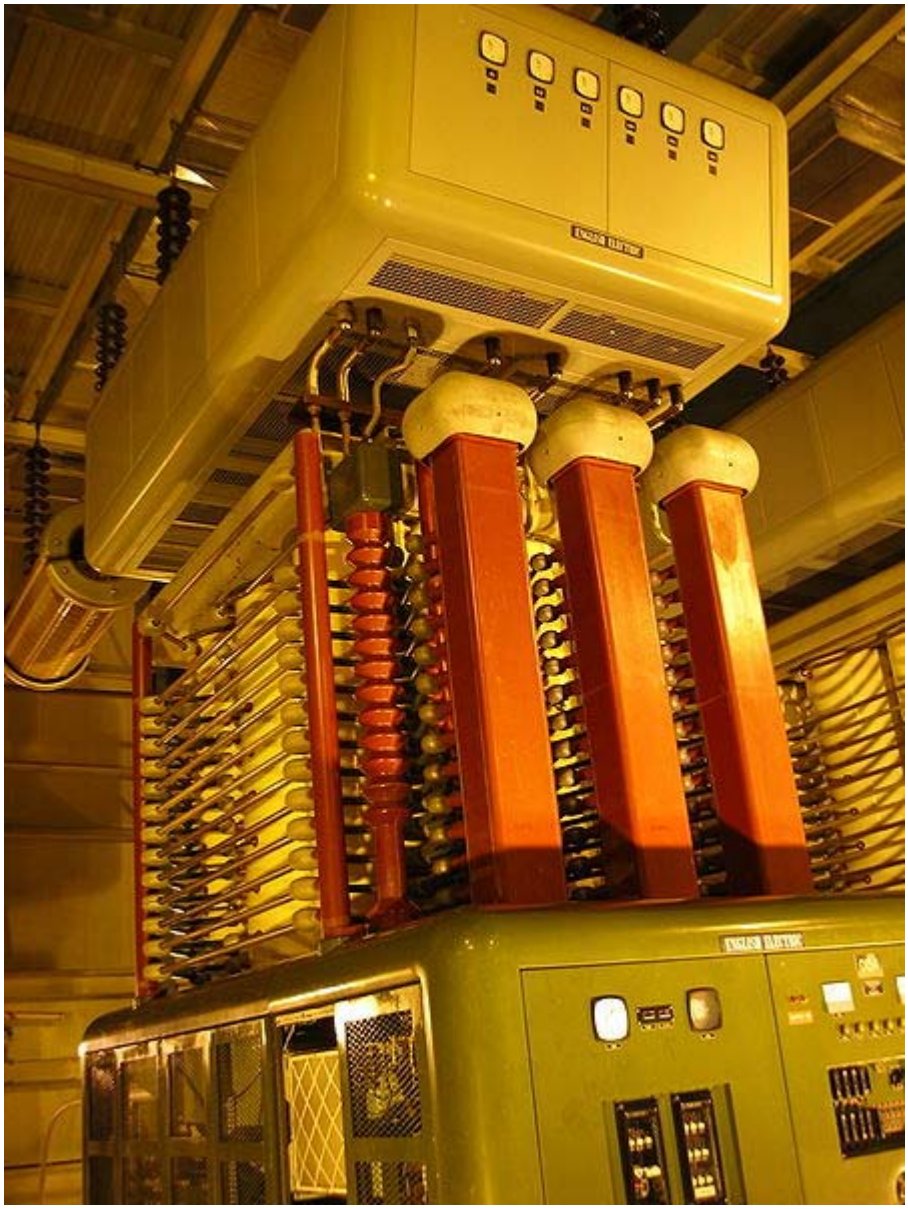
Since momentary interruptions or reductions of output current may cause the cathode spot to extinguish, many rectifiers incorporate an additional electrode to maintain an arc whenever the plant is in use. Typically, a two or three phase supply of a few amperes passes through small 'excitation' anodes. A magnetically shunted transformer of a few hundred VA rating is commonly used to provide this supply.

This excitation or *keep-alive* circuit was absolutely necessary for mercury arc rectifiers used in the high voltage supply of radiotelegraphy transmitters, as current flow was regularly interrupted every time the morse key was released.

Control

Installation of a control grid between the anode and the pool cathode allows control of the conduction of the valve. Start of the current flow can be delayed past the point at which the arc would form in an uncontrolled valve. This allows the output voltage of a valve group to be adjusted by delaying the firing point, and allows controlled mercury arc valves to form the active switching elements in an inverter converting direct current into alternating current.

Others



A 150 kV mercury arc valve at Manitoba Hydro's Radisson converter station, August 2003

The largest ever mercury arc rectifiers were used until 2004 at the Nelson River Bipole high-voltage DC power transmission project.

Special types of mercury arc rectifiers are the Ignitron and the Excitron.

In 1919 the book "Cyclopedia of Telephony & Telegraphy Vol. 1" described an amplifier for telephone signals that used a magnetic field to modulate an arc in a mercury rectifier

tube. This pre-dated the application of the vacuum tube to amplification of audio signals but was never commercially important.

Environmental hazard

Mercury compounds are toxic, highly persistent in the environment, and present a danger to humans and the environment. The use of large quantities of mercury in fragile glass envelopes presents a hazard of potential release of mercury to the environment should the glass bulb be broken. Some HVDC static inverter stations have required expensive clean-up to eliminate traces of mercury emitted from the station over its service life. Steel tank rectifiers frequently required vacuum pumps which continually emitted small amounts of mercury vapor.

Chapter-5

Electric Arc Furnace

Steel mill with two arc furnaces

An **electric arc furnace** (**EAF**) is a furnace that heats charged material by means of an electric arc.

Arc furnaces range in size from small units of approximately one ton capacity (used in foundries for producing cast iron products) up to about 400 ton units used for secondary steelmaking. Arc furnaces used in research laboratories and by dentists may have a capacity of only a few dozen grams. Industrial electric arc furnace temperatures can be up to 1,800 degrees Celsius, while laboratory units can exceed 3,000 °C. Arc furnaces differ from induction furnaces in that the charge material is directly exposed to an electric arc, and the current in the furnace terminals passes through the charged material.

History

In the 19th century, a number of men had employed an electric arc to melt iron. Sir Humphry Davy conducted an experimental demonstration in 1810; welding was investigated by Pepys in 1815; Pinchon attempted to create an electrothermic furnace in 1853; and, in 1878–79, Sir William Siemens took out patents for electric furnaces of the arc type.

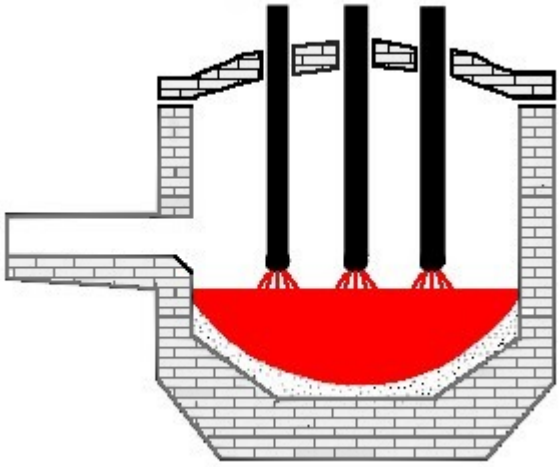
The first electric arc furnaces were developed by Paul Héroult, of France, with a commercial plant established in the United States in 1907. The Sanderson brothers formed The Sanderson Brothers steel Co. in Syracuse, New York, installing the first **electric arc furnace** in the U.S. This furnace is now on display at Station Square, Pittsburgh, Pennsylvania.

Initially "electric steel" was a specialty product for such uses as machine tools and spring steel. Arc furnaces were also used to prepare calcium carbide for use in carbide lamps. The *Stessano electric furnace* is an arc type furnace that usually rotates to mix the bath. The *Girod furnace* is similar to the *Héroult furnace*.

While EAFs were widely used in World War II for production of alloy steels, it was only later that electric steelmaking began to expand. The low capital cost for a mini-mill—around US$140–200 per ton of annual installed capacity, compared with US$1,000 per ton of annual installed capacity for an integrated steel mill—allowed mills to be quickly established in war-ravaged Europe, and also allowed them to successfully compete with the big United States steelmakers, such as Bethlehem Steel and U.S. Steel, for low-cost, carbon steel "long products" (structural steel, rod and bar, wire, and fasteners) in the U.S. market.

When Nucor—now one of the largest steel producers in the U.S.—decided to enter the long products market in 1969, they chose to start up a mini-mill, with an EAF as its steelmaking furnace, soon followed by other manufacturers. Whilst Nucor expanded rapidly in the Eastern US, the companies that followed them into mini-mill operations concentrated on local markets for long products, where the use of an EAF allowed the plants to vary production according to local demand. This pattern was also followed globally, with EAF steel production primarily used for long products, while integrated mills, using blast furnaces and basic oxygen furnaces, cornered the markets for "flat products"—sheet steel and heavier steel plate. In 1987, Nucor made the decision to expand into the flat products market, still using the EAF production method.

Construction



A schematic cross-section through an EAF. Three electrodes (black), molten bath (red), tapping spout at left, refractory brick movable roof, brick shell, and a refractory-lined bowl-shaped hearth.

An electric arc furnace used for steelmaking consists of a refractory-lined vessel, usually water-cooled in larger sizes, covered with a retractable roof, and through which one or more graphite electrodes enter the furnace. The furnace is primarily split into three sections:

- the *shell*, which consists of the sidewalls and lower steel "bowl";
- the *hearth*, which consists of the refractory that lines the lower bowl;
- the *roof*, which may be refractory-lined or water-cooled, and can be shaped as a section of a sphere, or as a frustum (conical section). The roof also supports the refractory delta in its centre, through which one or more graphite electrodes enter.

The hearth may be hemispherical in shape, or in an eccentric bottom tapping furnace, the hearth has the shape of a halved egg. In modern meltshops, the furnace is often raised off the ground floor, so that ladles and slag pots can easily be maneuvered under either end of the furnace. Separate from the furnace structure is the electrode support and electrical system, and the tilting platform on which the furnace rests. Two configurations are possible: the electrode supports and the roof tilt with the furnace, or are fixed to the raised platform.

A typical alternating current furnace has three electrodes. Electrodes are round in section, and typically in segments with threaded couplings, so that as the electrodes wear, new segments can be added. The arc forms between the charged material and the electrode, the charge is heated both by current passing through the charge and by the radiant energy evolved by the arc. The electrodes are automatically raised and lowered by a positioning system, which may use either electric winch hoists or hydraulic cylinders. The regulating system maintains approximately constant current and power input during the melting of

the charge, even though scrap may move under the electrodes as it melts. The mast arms holding the electrodes carry heavy busbars, which may be hollow water-cooled copper pipes carrying current to the electrode holders. Modern systems use "hot arms", where the whole arm carries the current, increasing efficiency. These can be made from copper-clad steel or aluminium. Since the electrodes move up and down automatically for regulation of the arc, and are raised to allow removal of the furnace roof, heavy water-cooled cables connect the bus tubes/arms with the transformer located adjacent to the furnace. To protect the transformer from heat, it is installed in a vault.

The furnace is built on a tilting platform so that the liquid steel can be poured into another vessel for transport. The operation of tilting the furnace to pour molten steel is called "tapping". Originally, all steelmaking furnaces had a tapping spout closed with refractory that washed out when the furnace was tilted, but often modern furnaces have an eccentric bottom tap-hole (EBT) to reduce inclusion of nitrogen and slag in the liquid steel. These furnaces have a taphole that passes vertically through the hearth and shell, and is set off-centre in the narrow "nose" of the egg-shaped hearth. It is filled with refractory sand, such as olivine, when it is closed off. Modern plants may have two shells with a single set of electrodes that can be transferred between the two; one shell preheats scrap while the other shell is utilised for meltdown. Other DC-based furnaces have a similar arrangement, but have electrodes for each shell and one set of electronics.

AC furnaces usually exhibit a pattern of hot and cold-spots around the hearth perimeter, with the cold-spots located between the electrodes. Modern furnaces mount oxygen-fuel burners in the sidewall and use them to provide chemical energy to the cold-spots, making the heating of the steel more uniform. Additional chemical energy is provided by injecting oxygen and carbon into the furnace; historically this was done through lances in the slag door, now this is mainly done through multiple wall-mounted injection units.

A mid-sized modern steelmaking furnace would have a transformer rated about 60,000,000 volt-amperes (60 MVA), with a secondary voltage between 400 and 900 volts and a secondary current in excess of 44,000 amperes. In a modern shop such a furnace would be expected to produce a quantity of 80 metric tonnes of liquid steel in approximately 60 minutes from charging with cold scrap to tapping the furnace. In comparison, basic oxygen furnaces can have a capacity of 150–300 tonnes per batch, or "heat", and can produce a heat in 30–40 minutes. Enormous variations exist in furnace design details and operation, depending on the end product and local conditions, as well as ongoing research to improve furnace efficiency—the largest scrap-only furnace (in terms of tapping weight and transformer rating) is in Turkey, with a tap weight of 300 metric tonnes and a transformer of 300 MVA.

To produce a ton of steel in an electric arc furnace requires approximately 400 kilowatt-hours per short ton of electricity, or about 440 kWh per metric tonne; the theoretical minimum amount of energy required to melt a tonne of scrap steel is 300 kWh (melting point 1520°C/2768°F). Therefore, the 300-tonne, 300 MVA EAF mentioned above will require approximately 132 MWh of energy to melt the steel, and a "power-on time" (the time that steel is being melted with an arc) of approximately 37 minutes, allowing for the

power factor. Electric arc steelmaking is only economical where there is plentiful electricity, with a well-developed electrical grid. In many locations, mills operate during off-peak hours when utilities have surplus power generating capacity.

Operation

An arc furnace pouring out steel into a small ladle car. The transformer vault can be seen at the right side of the picture. For scale, note the operator standing on the platform at upper left. This is a 1941-era photograph and so does not have the extensive dust collection system that a modern installation would have, nor is the operator wearing a hard hat or dust mask.

- Scrap metal is delivered to a scrap bay, located next to the melt shop. Scrap generally comes in two main grades: shred (whitegoods, cars and other objects made of similar light-gauge steel) and heavy melt (large slabs and beams), along with some direct reduced iron (DRI) or pig iron for chemical balance. Some furnaces melt almost 100% DRI.
- The scrap is loaded into large buckets called baskets, with "clamshell" doors for a base. Care is taken to layer the scrap in the basket to ensure good furnace operation; heavy melt is placed on top of a light layer of protective shred, on top of which is placed more shred. These layers should be present in the furnace after

charging. After loading, the basket may pass to a scrap pre-heater, which uses hot furnace off-gases to heat the scrap and recover energy, increasing plant efficiency.

- The scrap basket is then taken to the melt shop, the roof is swung off the furnace, and the furnace is charged with scrap from the basket. Charging is one of the more dangerous operations for the EAF operators. There is a lot of energy generated by multiple tonnes of falling metal; any liquid metal in the furnace is often displaced upwards and outwards by the solid scrap, and the grease and dust on the scrap is ignited if the furnace is hot, resulting in a fireball erupting. In some twin-shell furnaces, the scrap is charged into the second shell while the first is being melted down, and pre-heated with off-gas from the active shell. Other operations are continuous charging—pre-heating scrap on a conveyor belt, which then discharges the scrap into the furnace proper, or charging the scrap from a shaft set above the furnace, with off-gases directed through the shaft. Other furnaces can be charged with hot (molten) metal from other operations.
- After charging, the roof is swung back over the furnace and meltdown commences. The electrodes are lowered onto the scrap, an arc is struck and the electrodes are then set to bore into the layer of shred at the top of the furnace. Lower voltages are selected for this first part of the operation to protect the roof and walls from excessive heat and damage from the arcs. Once the electrodes have reached the heavy melt at the base of the furnace and the arcs are shielded by the scrap, the voltage can be increased and the electrodes raised slightly, lengthening the arcs and increasing power to the melt. This enables a molten pool to form more rapidly, reducing tap-to-tap times. Oxygen is also supersonically blown into the scrap, combusting or cutting the steel, and extra chemical heat is provided by wall-mounted oxygen-fuel burners. Both processes accelerate scrap meltdown.
- An important part of steelmaking is the formation of slag, which floats on the surface of the molten steel. Slag usually consists of metal oxides, and acts as a destination for oxidised impurities, as a thermal blanket (stopping excessive heat loss) and helping to reduce erosion of the refractory lining. For a furnace with basic refractories, which includes most carbon steel-producing furnaces, the usual slag formers are calcium oxide (CaO, in the form of burnt lime) and magnesium oxide (MgO, in the form of dolomite and magnesite). These slag formers are either charged with the scrap, or blown into the furnace during meltdown. Another major component of EAF slag is iron oxide from steel combusting with the injected oxygen. Later in the heat, carbon (in the form of coke or coal) is injected into this slag layer, reacting with the iron oxide to form metallic iron and carbon monoxide gas, which then causes the slag to foam, allowing greater thermal efficiency, and better arc stability and electrical efficiency. The slag blanket also covers the arcs, preventing damage to the furnace roof and sidewalls from radiant heat.
- Once flat bath conditions are reached, i.e. the scrap has been completely melted down, another bucket of scrap can be charged into the furnace and melted down, although EAF development is moving towards single-charge designs. After the second charge is completely melted, refining operations take place to check and correct the steel chemistry and superheat the melt above its freezing temperature

in preparation for tapping. More slag formers are introduced and more oxygen is blown into the bath, burning out impurities such as silicon, sulfur, phosphorus, aluminium, manganese, and calcium, and removing their oxides to the slag. Removal of carbon takes place after these elements have burnt out first, as they have a greater affinity for oxygen. Metals that have a poorer affinity for oxygen than iron, such as nickel and copper, cannot be removed through oxidation and must be controlled through scrap chemistry alone, such as introducing the direct reduced iron and pig iron mentioned earlier. A foaming slag is maintained throughout, and often overflows the furnace to pour out of the slag door into the slag pit. Temperature sampling and chemical sampling take place via automatic lances. Oxygen and carbon can be automatically measured via special probes that dip into the steel, but for all other elements, a "chill" sample—a small, solidified sample of the steel—is analysed on an arc-emission spectrometer.

- Once the temperature and chemistry are correct, the steel is tapped out into a preheated ladle through tilting the furnace. For plain-carbon steel furnaces, as soon as slag is detected during tapping the furnace is rapidly tilted back towards the deslagging side, minimising slag carryover into the ladle. For some special steel grades, including stainless steel, the slag is poured into the ladle as well, to be treated at the ladle furnace to recover valuable alloying elements. During tapping some alloy additions are introduced into the metal stream, and some more lime is added on top of the ladle to begin building a new slag layer. Often, a few tonnes of liquid steel and slag is left in the furnace in order to form a "hot heel", which helps preheat the next charge of scrap and accelerate its meltdown. During and after tapping, the furnace is "turned around": the slag door is cleaned of solidified slag, repairs may take place, and electrodes are inspected for damage or lengthened through the addition of new segments; the taphole is filled with sand at the completion of tapping. For a 90-tonne, medium-power furnace, the whole process will usually take about 60–70 minutes from the tapping of one heat to the tapping of the next (the tap-to-tap time).

Advantages of electric arc furnace for steelmaking

The use of EAFs allows steel to be made from a 100% scrap metal feedstock, commonly known as "cold ferrous feed" to emphasise the fact that for an EAF, scrap is a regulated feed material. The primary benefit of this is the large reduction in specific energy (energy per unit weight) required to produce the steel. Another benefit is flexibility: while blast furnaces cannot vary their production by much and are never stopped, EAFs can be rapidly started and stopped, allowing the steel mill to vary production according to demand. Although steelmaking arc furnaces generally use scrap steel as their primary feedstock, if hot metal from a blast furnace or direct-reduced iron is available economically, these can also be used as furnace feed.

A typical steelmaking arc furnace is the source of steel for a mini-mill, which may make bars or strip product. Mini-mills can be sited relatively near to the markets for steel products, and the transport requirements are less than for an integrated mill, which would commonly be sited near a harbour for access to shipping.

Environmental issues

Although the modern electric arc furnace is a highly efficient recycler of steel scrap, operation of an arc furnace shop can have adverse environmental effects. Much of the capital cost of a new installation will be devoted to systems intended to reduce these effects, which include:

- enclosures to reduce high sound levels
- Dust collector for furnace off-gas
- Slag production
- Cooling water demand
- Heavy truck traffic for scrap, materials handling, and products
- Environmental effects of electricity generation

Because of the very dynamic quality of the arc furnace load, power systems may require technical measures to maintain the quality of power for other customers; flicker and harmonic distortion are common side-effects of arc furnace operation on a power system.

Other electric arc furnaces

For steelmaking, direct current (DC) arc furnaces are used, with a single electrode in the roof and the current return through a conductive bottom lining or conductive pins in the base. The advantage of DC is lower electrode consumption per ton of steel produced, since only one electrode is used, as well as less electrical harmonics and other similar problems. However, the size of DC arc furnaces is limited by the available electrodes and maximum allowable voltage. Maintenance of the conductive furnace hearth is a bottleneck in extended operation of a DC arc furnace. However, Danieli—makers of steel plant equipment—are preparing to install a 420-tonne DC furnace, powered by two 160 MVA transformers, in a Japanese steel mill. Instead of an upper graphite electrode and a lower conductive hearth, this EAF would have two upper graphite electrodes.

In a steel plant, a ladle furnace (LF) is used to maintain the temperature of liquid steel during processing after tapping from EAF or to change the alloy composition. The ladle is used for the first purpose when there is a delay later in the steelmaking process. The ladle furnace consists of a refractory roof, a heating system, and, when applicable, a provision for injecting argon gas into the bottom of the melt for stirring. Unlike a scrap melting furnace, a ladle furnace does not have a tilting or scrap charging mechanism.

Electric arc furnaces are also used for production of ferroalloys and other non-ferrous alloys, and for production of phosphorus. Furnaces for these services are physically different from steel-making furnaces and may operate on a continuous, rather than batch, basis. Continuous process furnaces may also use paste-type, Søderberg electrodes to prevent interruptions due to electrode changes. Such a furnace is known as a submerged arc furnace because the electrode tips are buried in the slag/charge, and arcing occurs through the slag, between the matte and the electrode. A steelmaking arc furnace, by comparison, arcs in the open. The key is the electrical resistance, which is what generates

the heat required: the resistance in a steelmaking furnace is the atmosphere, while in a submerged-arc furnace the slag or charge forms the resistance. The liquid metal formed in either furnace is too conductive to form an effective heat-generating resistance.

Amateurs have constructed a variety of arc furnaces, often based on electric arc welding kits contained by silical blocks or flower pots. Though crude, these simple furnaces are capable of melting a wide range of materials and creating calcium carbide etc. An example is shown here.

Plasma arc furnace

A plasma arc furnace (PAF) uses plasma torches instead of graphite electrodes. Each of these torches consists of a casing provided with a nozzle and an axial tubing for feeding a plasma-forming gas (either nitrogen or argon), and a burnable cylindrical graphite electrode located within the tubing. Such furnaces can be referred to as "PAM" (Plasma Arc Melt) furnaces. They are used extensively in the titanium melt industry and similar specialty metals industries.

Vacuum arc remelting

Vacuum arc remelting (VAR) is a secondary remelting process for vacuum refining and manufacturing of ingots with improved chemical and mechanical homogeneity.

In critical military and commercial aerospace applications, material engineers commonly specify VIM-VAR steels. VIM means Vacuum Induction Melted and VAR means Vacuum Arc Remelted. VIM-VAR steels become bearings for jet engines, rotor shafts for military helicopters, flap actuators for fighter jets, gears in jet or helicopter transmissions, mounts or fasteners for jet engines, jet tail hooks and other demanding applications.

Most grades of steel are melted once and are then cast or teemed into a solid form prior to extensive forging or rolling to a metallurgically sound form. In contrast, VIM-VAR steels go through two more highly purifying melts under vacuum. After melting in an electric arc furnace and alloying in an argon oxygen decarburization vessel, steels destined for vacuum remelting are cast into ingot molds. The solidified ingots then head for a vacuum induction melting furnace. This vacuum remelting process rids the steel of inclusions and unwanted gases while optimizing the chemical composition. The VIM operation returns these solid ingots to the molten state in the contaminant-free void of a vacuum. This tightly controlled melt often requires up to 24 hours. Still enveloped by the vacuum, the hot metal flows from the VIM furnace crucible into giant electrode molds. A typical electrode stands about 15 feet (5 m) tall and will be in various diameters. The electrodes solidify under vacuum.

For VIM-VAR steels, the surface of the cooled electrodes must be ground to remove surface irregularities and impurities before the next vacuum remelt. Then the ground electrode is placed in a VAR furnace. In a VAR furnace the steel gradually melts drop-by-drop in the vacuum-sealed chamber. Vacuum arc remelting further removes lingering

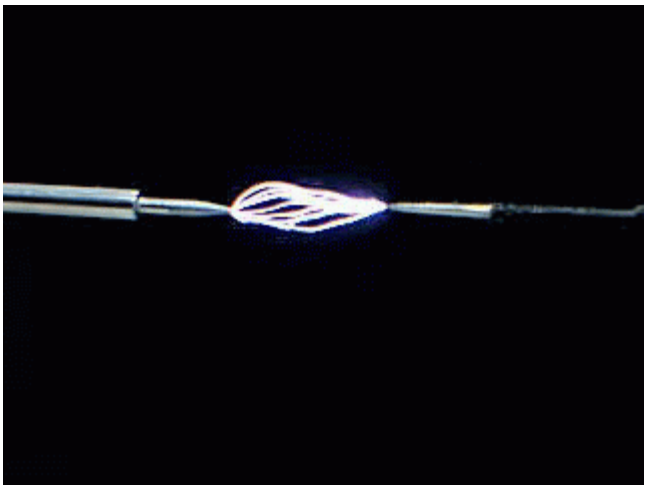
inclusions to provide superior steel cleanliness and further remove gases such as oxygen, nitrogen and hydrogen. Controlling the rate at which these droplets form and solidify ensures a consistency of chemistry and microstructure throughout the entire VIM-VAR ingot. This in turn makes the steel more resistant to fracture and/or fatigue. This refinement process is essential to meet the performance characteristics of parts like a helicopter rotor shaft, a flap actuator on a military jet or a bearing in a jet engine.

For some commercial or military applications, steel alloys may go through only one vacuum remelt, namely the VAR. For example, steels for solid rocket cases, landing gears or torsion bars for fighting vehicles typically involve the one vacuum remelt.

Vacuum arc remelting is also used in production of titanium and other metals which are reactive or in which high purity is required.

Chapter-6

Spark Gap



A spark gap

A **spark gap** consists of an arrangement of two conducting electrodes separated by a gap usually filled with a gas such as air, designed to allow an electric spark to pass between the conductors. When the voltage difference between the conductors exceeds the gap's breakdown voltage, a spark forms, ionizing the gas and drastically reducing its electrical resistance. An electric current then flows until the path of ionized gas is broken or the current reduces below a minimum value called the 'holding current'. This usually happens when the voltage drops, but in some cases occurs when the heated gas rises, stretching out and then breaking the filament of ionized gas. Usually the action of ionizing the gas is violent and disruptive, often leading to sound (ranging from a *snap* for a spark plug to thunder for a lightning discharge), light and heat. Spark gaps were used historically in early electrical equipment, such as spark gap radio transmitters, electrostatic machines, and x-ray machines. Their most widespread use today is in spark plugs to ignite the fuel in internal combustion engines, but they are also used in lightning arrestors and other devices to protect electrical equipment from high voltage transients.

Spark visibility

The light emitted by a spark does not come from the current of electrons itself, but from the material medium fluorescing in response to collisions from the electrons. When electrons collide with molecules of air in the gap, they excite their orbital electrons to higher energy levels. When they fall back to their original energy levels, they emit the energy as light. It is impossible for a visible spark to form in a vacuum. Without intervening matter capable of electromagnetic transitions, the spark will be invisible.

Applications

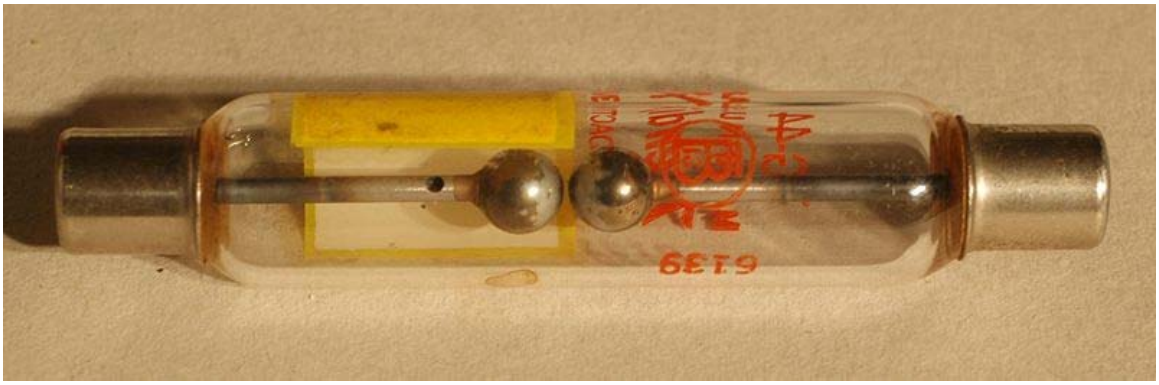
Spark gaps are essential to the functioning of a number of electronic devices.

Ignition devices

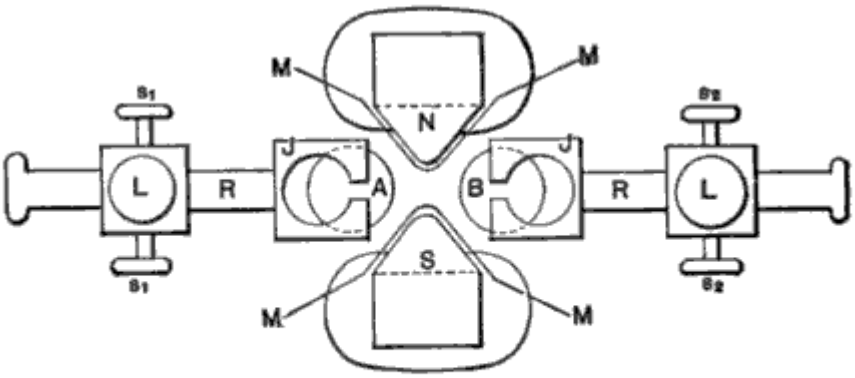
A spark plug. The spark gap is at the bottom.

A spark plug uses a spark gap to initiate combustion. The heat of the ionization trail ignites a fuel-air mixture inside an internal combustion engine, or a burner in a furnace, oven, or stove.

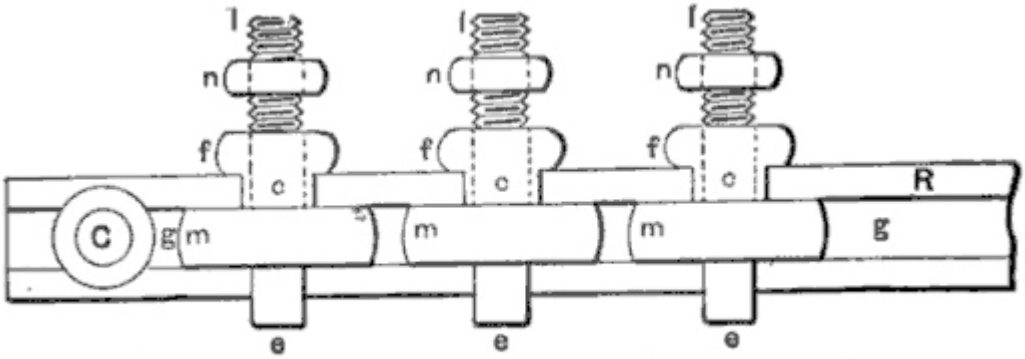
Radio transmitters



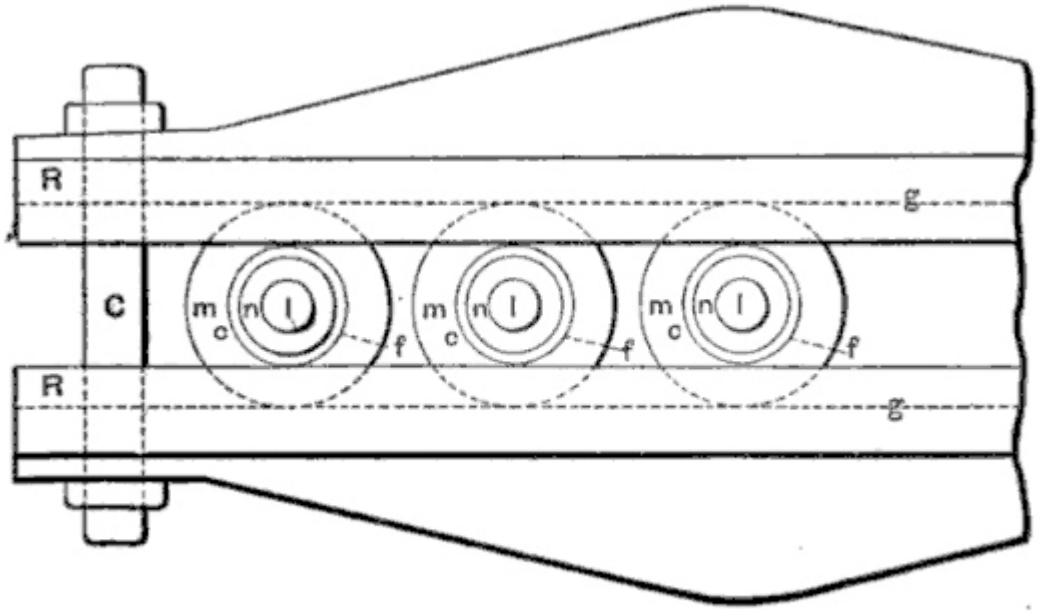
Spark gap tube



ARRANGEMENT OF IMPROVED DISCHARGER AND MAGNET.



DISCHARGER WITH MULTIPLE GAPS.



DISCHARGER WITH MULTIPLE GAPS.

A spark radiates energy throughout the electromagnetic spectrum. Nowadays, this is usually regarded as illegal radio frequency interference and is suppressed, but in the early days of radio communications (1900-1920), this was the means by which radio signals were transmitted, in the unmodulated spark-gap transmitter. Many radio spark gaps include cooling devices such as the rotary gap and heat sinks, since the spark gap becomes quite hot under continuous use at high power.

Spark gaps as protective devices

Spark gaps are frequently used to prevent voltage surges from damaging equipment. Spark gaps are used in high-voltage switches, for example, in power plants and electrical substations. Such switches are constructed with a large, remote-operated switching blade with a hinge as one contact and two leaf springs holding the other end as second contact. If the blade is opened, a spark may keep the connection between blade and spring conducting. (The spark ionizes the air, which becomes conductive, allowing an arc to form, which sustains ionization and hence conduction.) Here, a **Jacob's ladder** on top of the switch will pull the arc apart and so extinguish it. You might also find small Jacob's ladders mounted on top of ceramic insulators of high-voltage pylons. These are sometimes called horn gaps. If a spark should ever manage to jump over the insulator and give rise to an arc, it will be extinguished.

Smaller spark gaps are often used to protect sensitive electrical or electronic equipment from high voltage surges. In sophisticated versions of these devices (called gas tube arresters), a small spark gap breaks down during an abnormal voltage surge, safely shunting the surge to ground and thereby protecting the equipment. These devices are commonly used for telephone lines as they enter a building; the spark gaps help protect the building and internal telephone circuits from the effects of lightning strikes. Less

sophisticated (and much less expensive) spark gaps are made using modified ceramic capacitors; in these devices, the spark gap is simply an air gap sawn between the two lead wires that connect the capacitor to the circuit. A voltage surge causes a spark which jumps from lead wire to lead wire across the gap left by the sawing process. These low-cost devices are often used to prevent damaging arcs between the elements of the electron gun(s) within a cathode ray tube (CRT).

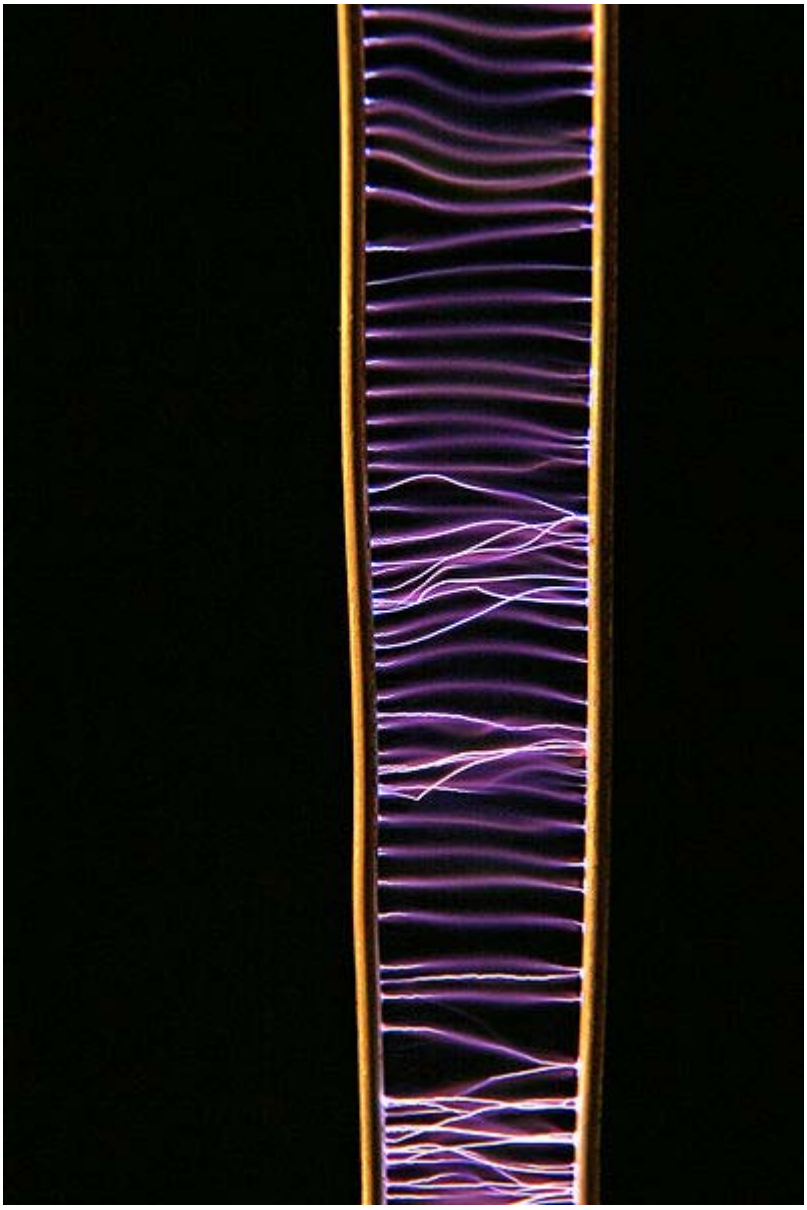
Small spark gaps are very common in telephone switchboards, as the long phone cables are very susceptible to induced surges from lightning strikes. Larger spark gaps are used to protect power lines.

Transils and trisils are the solid-state alternatives to spark gaps for lower-power applications. Neon bulbs are also used for this purpose.

Power-switching devices

Special purpose, high-energy triggerable spark gaps can be used to rapidly switch high voltages and very high currents for certain pulsed power applications, such as pulsed lasers, railguns, fusion, ultrastrong pulsed magnetic field research, and in the triggering of nuclear bombs. Commercially available devices can be divided into two classes: positive pressure and triggered vacuum gaps. Positive pressure triggered gaps have a limited operating voltage range (for instance, from 1/3 to 2/3 of the self breakdown voltage). Triggered vacuum gaps offer a wide operating voltage range (400 V to 90 kV is achievable). Both classes can switch higher energy levels than any thyristor, thyratron, krytron, or sprytron. Triggered gaps are popular for single shot and low repetition rate applications. One such switch is known as a trigatron. The Ignitron and Crossatron could be considered a triggered gaps. The latter is unique in that it can be turned back off by the control electrode after conduction begins. The xenon flash tube is another common triggered gap. Various schemes have also been devised to trigger open air gaps on command. A set of spark gaps are a key element of a Marx generator, used to generate high-voltage impulses; the spark gaps allow a chain of capacitors to be slowly charged in parallel and then rapidly discharged in series.

Visual entertainment



A time exposure of a Jacob's Ladder

A **Jacob's ladder** (more formally, a **high voltage traveling arc**) is a device for producing a continuous train of large sparks which rise upwards. The spark gap is formed by two wires, approximately vertical but gradually diverging away from each other towards the top in a narrow "V" shape. It was named for the "ladder to heaven" described in the Bible.

When high voltage is applied to the gap, a spark forms across the bottom of the wires where they are nearest each other, rapidly changing to an electric arc. Air breaks down at about 30 kV/cm, depending on humidity, temperature, etc. Apart from the anode and

cathode voltage drops, the arc behaves almost as a short circuit, drawing as much current as the electrical power supply can deliver, and the heavy load dramatically reduces the voltage across the gap.

The heated, ionized air rises, carrying the current path with it. As the trail of ionization gets longer, it becomes more and more unstable, finally breaking. The voltage across the electrodes then rises and the spark re-forms at the bottom of the device.

This cycle leads to an exotic-looking display of electric white, yellow, blue or purple arcs which is often seen in films about mad scientists. The device was a staple in schools and science fairs of the 1950s and 1960s, typically constructed out of a Model T spark coil, or any other source of high voltage in the 10,000–30,000 volt range, like a neon sign transformer (5–15 kV) or a television picture tube circuit (flyback transformer) (10–28 kV), and two coat hangers or rods built into a "V" shape. For larger ladders, microwave oven transformers connected in series or utility pole transformers (pole pigs) run in reverse (step-up) are used.

Traveling-arc devices are dangerous. The sparks can burn through thin paper and plastic and start fires, and contact with the exposed high-voltage conductors can be lethal.

Health hazards

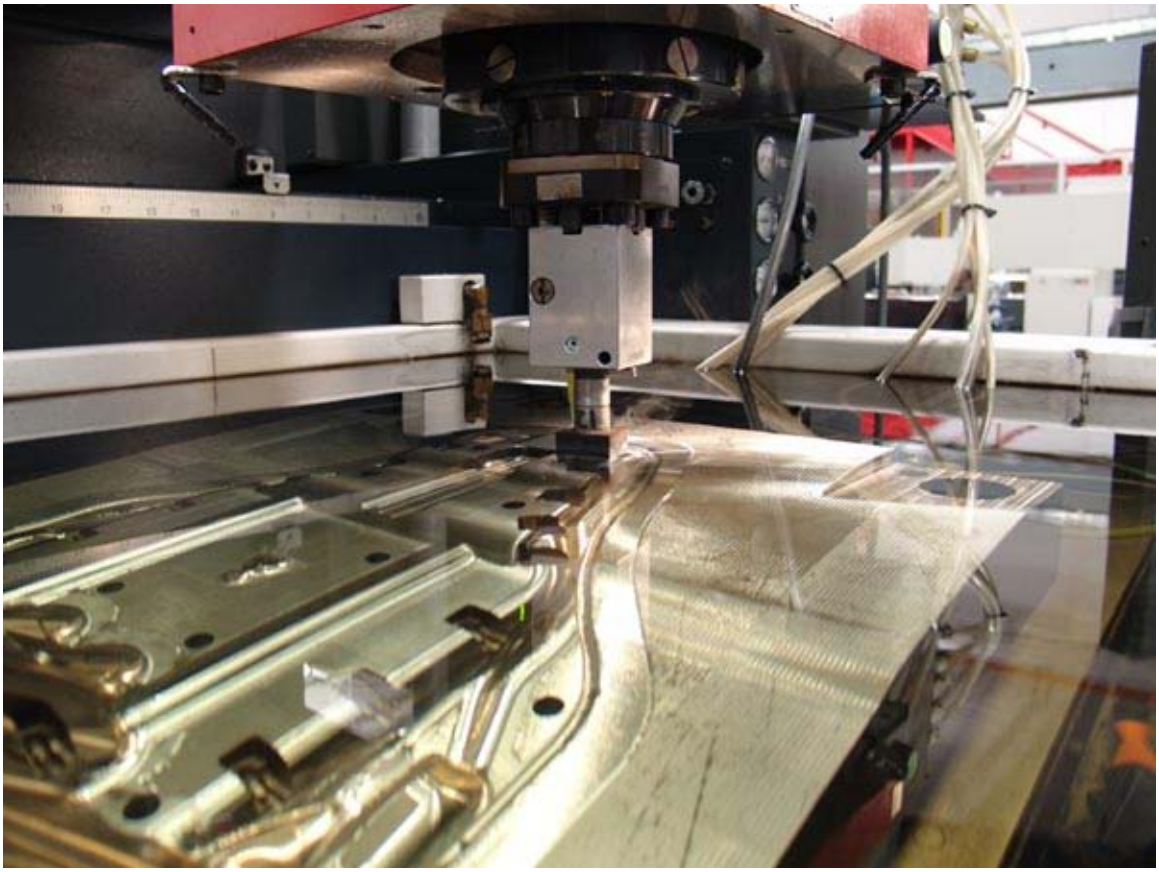
Exposure to an arc-producing device can pose health hazards. In a closed space such as a classroom or home, the continuous arc formation of an open-air Jacob's Ladder will ionize oxygen and nitrogen, which then re-form into reactive molecules such as ozone and nitric oxide. These free radicals can be damaging to the mucous membranes of people near the spark gap. Plants are also susceptible to ozone poisoning.

These hazards are not present when the arc is formed outdoors since the heated ionized gases will rise up into the air and dissipate into the atmosphere. Spark gaps which only intermittently produce short spark bursts are also minimally hazardous because the volume of ions generated is very small.

Arcs can also produce a broad spectrum of wavelengths spanning the visible light and the invisible ultraviolet and infrared spectrum. Very intense arcs generated by means such as arc welding can produce significant amounts of ultraviolet which is damaging to the retina of the observer. These arcs should only be observed through special dark filters which reduce the arc intensity and shield the observer's eyes from the ultraviolet rays.

Chapter-7

Electrical Discharge Machining



An electrical discharge machine

Electric discharge machining (**EDM**), sometimes colloquially also referred to as **spark machining**, **spark eroding**, **burning**, **die sinking** or **wire erosion**, is a manufacturing process whereby a desired shape is obtained using electrical discharges (sparks). Material is removed from the workpiece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric liquid and subject to an electric voltage.

One of the electrodes is called the tool-electrode, or simply the ‘tool’ or ‘electrode’, while the other is called the workpiece-electrode, or ‘workpiece’.

When the distance between the two electrodes is reduced, the intensity of the electric field in the volume between the electrodes becomes greater than the strength of the dielectric (at least in some point(s)), which breaks, allowing current to flow between the two electrodes. This phenomenon is the same as the breakdown of a capacitor (condenser). As a result, material is removed from both the electrodes. Once the current flow stops (or it is stopped - depending on the type of generator), new liquid dielectric is usually conveyed into the inter-electrode volume enabling the solid particles (debris) to be carried away and the insulating proprieties of the dielectric to be restored. Adding new liquid dielectric in the inter-electrode volume is commonly referred to as flushing. Also, after a current flow, a difference of potential between the two electrodes is restored to what it was before the breakdown, so that a new liquid dielectric breakdown can occur.

History

In 1770, English Physicist Joseph Priestley studied the erosive effect of electrical discharges. Furthering Priestley's research, the EDM process was invented by two Russian scientists, Dr. B.R. Lazarenko and Dr. N.I. Lazarenko in 1943. In their efforts to exploit the destructive effects of an electrical discharge, they developed a controlled process for machining of metals. Their initial process used a spark machining process, named after the succession of sparks (electrical discharges) that took place between two electrical conductors immersed in a dielectric fluid. The discharge generator effect used by this machine, known as the Lazarenko Circuit, was used for many years in the construction of generators for electrical discharge.

Additional researchers entered the field and contributed many fundamental characteristics of the machining method we know today. In 1952, the manufacturer Charmilles created the first machine using the spark machining process and was presented for the first time at the European Machine Tool Exhibition in 1955.

In 1969 Agie launched the world's first numerically controlled wire-cut EDM machine. Seibu developed the first CNC wire EDM machine 1972 and the first system manufactured in Japan.

Generalities

Electrical discharge machining is a machining method primarily used for hard metals or those that would be very difficult to machine with traditional techniques. EDM typically works with materials that are electrically conductive, although methods for machining insulating ceramics with EDM have also been proposed. EDM can cut intricate contours or cavities in pre-hardened steel without the need for heat treatment to soften and re-harden them. This method can be used with any other metal or metal alloy such as titanium, hastelloy, kovar, and inconel. Also, applications of this process to shape polycrystalline diamond tools have been reported.

EDM is often included in the 'non-traditional' or 'non-conventional' group of machining methods together with processes such as electrochemical machining (ECM), water jet cutting (WJ, AWJ), laser cutting and opposite to the 'conventional' group (turning, milling, grinding, drilling and any other process whose material removal mechanism is essentially based on mechanical forces).

Ideally, EDM can be seen as a series of breakdown and restoration of the liquid dielectric in-between the electrodes. However, caution should be exerted in considering such a statement because it is an idealized model of the process, introduced to describe the fundamental ideas underlying the process. Yet, any practical application involves many aspects that may also need to be considered. For instance, the removal of the debris from the inter-electrode volume is likely to be always partial. Thus the electrical proprieties of the dielectric in the inter-electrodes volume can be different from their nominal values and can even vary with time. The inter-electrode distance, often also referred to as spark-gap, is the end result of the control algorithms of the specific machine used. The control of such a distance appears logically to be central to this process. Also, not all of the current flow between the dielectric is of the ideal type described above: the spark-gap can be short-circuited by the debris. The control system of the electrode may fail to react quickly enough to prevent the two electrodes (tool and workpiece) to get in contact, with a consequent short circuit. This is unwanted because a short circuit contributes to the removal differently from the ideal case. The flushing action can be inadequate to restore the insulating properties of the dielectric so that the flow of current always happens in the point of the inter-electrode volume (this is referred to as arcing), with a consequent unwanted change of shape (damage) of the tool-electrode and workpiece. Ultimately, a description of this process in a suitable way for the specific purpose at hand is what makes the EDM area such a rich field for further investigation and research.

To obtain a specific geometry, the EDM tool is guided along the desired path very close to the work, ideally it should not touch the workpiece, although in reality this may happen due to the performance of the specific motion control in use. In this way a large number of current discharges (colloquially also called sparks) happen, each contributing to the removal of material from both tool and workpiece, where small craters are formed. The size of the craters is a function of the technological parameters set for the specific job at hand. They can be with typical dimensions ranging from the nanoscale (in micro-EDM operations) to some hundreds of micrometers in roughing conditions.

The presence of these small craters on the tool results in the gradual erosion of the electrode. This erosion of the tool-electrode is also referred to as wear. Strategies are needed to counteract the detrimental effect of the wear on the geometry of the workpiece. One possibility is that of continuously replacing the tool-electrode during a machining operation. This is what happens if a continuously replaced wire is used as electrode. In this case, the correspondent EDM process is also called wire EDM. The tool-electrode can also be used in such a way that only a small portion of it is actually engaged in the machining process and this portion is changed on a regular basis. This is, for instance, the case when using a rotating disk as a tool-electrode. The corresponding process is often also referred to as EDM grinding.

A further strategy consists in using a set of electrodes with different sizes and shapes during the same EDM operation. This is often referred to as multiple electrode strategy, and is most common when the tool electrode replicates in negative the wanted shape and is advanced towards the blank along a single direction, usually the vertical direction (i.e. z-axis). This resembles the sink of the tool into the dielectric liquid in which the workpiece is immersed, so, not surprisingly, it is often referred to as die-sinking EDM (also called conventional EDM and ram EDM). The corresponding machines are often called sinker EDM. Usually, the electrodes of this type have quite complex forms. If the final geometry is obtained using a usually simple shaped electrode which is moved along several directions and is possibly also subject to rotations often the term EDM milling is used.

In any case, the severity of the wear is strictly dependent on the technological parameters used in the operation (for instance: polarity, maximum current, open circuit voltage). For example, in micro-EDM, also known as μ-EDM, these parameters are usually set at values which generates severe wear. Therefore, wear is a major problem in that area.

The problem of wear to graphite electrodes is being addressed. In one approach a digital generator, controllable within milliseconds, reverses polarity as electro-erosion takes place. That produces an effect similar to electroplating that continuously deposits the eroded graphite back on the electrode. In another method, a so-called "Zero Wear" circuit reduces how often the discharge starts and stops, keeping it on for as long a time as possible.

Definition of the technological parameters

Difficulties have been encountered in the definition of the technological parameters that drive the process.

Two broad categories of generators, also known as power supplies, are in use on EDM machines commercially available: the group based on RC circuits and the group based on transistor controlled pulses.

In the first category, the main parameters to choose from at setup time are the resistance(s) of the resistor(s) and the capacitance(s) of the capacitor(s). In an ideal condition these quantities would affect the maximum current delivered in a discharge which is expected to be associated with the charge accumulated on the capacitors at a certain moment in time. Little control, however, is expected over the time duration of the discharge, which is likely to depend on the actual spark-gap conditions (size and pollution) at the moment of the discharge. The RC circuit generator can allow the user to obtain short time durations of the discharges more easily than the pulse-controlled generator, although this advantage is diminishing with the development of new electronic components. Also, the open circuit voltage (i.e. the voltage between the electrodes when the dielectric is not yet broken) can be identified as steady state voltage of the RC circuit.

In generators based on transistor control, the user is usually able to deliver a train of pulses of voltage to the electrodes. Each pulse can be controlled in shape, for instance, quasi-rectangular. In particular, the time between two consecutive pulses and the duration of each pulse can be set. The amplitude of each pulse constitutes the open circuit voltage. Thus, the maximum duration of discharge is equal to the duration of a pulse of voltage in the train. Two pulses of current are then expected not to occur for a duration equal or larger than the time interval between two consecutive pulses of voltage.

The maximum current during a discharge that the generator delivers can also be controlled. Because other sorts of generators may also be used by different machine builders, the parameters that may actually be set on a particular machine will depend on the generator manufacturer. The details of the generators and control systems on their machines are not always easily available to their user. This is a barrier to describing unequivocally the technological parameters of the EDM process. Moreover, the parameters affecting the phenomena occurring between tool and electrode are also related to the controller of the motion of the electrodes.

A framework to define and measure the electrical parameters during an EDM operation directly on inter-electrode volume with an oscilloscope external to the machine has been recently proposed by Ferri *et al.* These authors conducted their research in the field of μ-EDM, but the same approach can be used in any EDM operation. This would enable the user to estimate directly the electrical parameter that affect their operations without relying upon machine manufacturer's claims. Finally, it is worth mentioning that when machining different materials in the same setup conditions, the actual electrical parameters of the process are significantly different.

Material removal mechanism

The first serious attempt of providing a physical explanation of the material removal during electric discharge machining is perhaps that of Van Dijk. Van Dijk presented a thermal model together with a computational simulation to explain the phenomena between the electrodes during electric discharge machining. However, as Van Dijk himself admitted in his study, the number of assumptions made to overcome the lack of experimental data at that time was quite significant.

Further models of what occurs during electric discharge machining in terms of heat transfer were developed in the late eighties and early nineties, including an investigation at Texas A&M University with the support of AGIE, now Agiecharmilles. It resulted in three scholarly papers: the first presenting a thermal model of material removal on the cathode, the second presenting a thermal model for the erosion occurring on the anode and the third introducing a model describing the plasma channel formed during the passage of the discharge current through the dielectric liquid. Validation of these models is supported by experimental data provided by AGIE.

These models give the most authoritative support for the claim that EDM is a thermal process, removing material from the two electrodes because of melting and/or

vaporization, along with pressure dynamics established in the spark-gap by the collapsing of the plasma channel. However, for small discharge energies the models are inadequate to explain the experimental data. All these models hinge on a number of assumptions from such disparate research areas as submarine explosions, discharges in gases, and failure of transformers, so it is not surprising that alternative models have been proposed more recently in the literature trying to explain the EDM process.

Among these, the model from Singh and Ghosh reconnects the removal of material from the electrode to the presence of an electrical force on the surface of the electrode that could mechanically remove material and create the craters. This would be possible because the material on the surface has altered mechanical properties due to an increased temperature caused by the passage of electric current. The authors' simulations showed how they might explain EDM better than a thermal model (melting and/or evaporation), especially for small discharge energies, which are typically used in μ-EDM and in finishing operations.

Given the many available models, it appears that the material removal mechanism in EDM is not yet well understood and that further investigation is necessary to clarify it, especially considering the lack of experimental scientific evidence to build and validate the current EDM models. This explains an increased current research effort in related experimental techniques.

Types

Sinker EDM

Sinker EDM allowed quick production of 614 uniform injectors for the J-2 rocket engine, six of which were needed for each trip to the moon.

Sinker EDM, also called cavity type EDM or volume EDM, consists of an electrode and workpiece submerged in an insulating liquid such as, more typically, oil or, less frequently, other dielectric fluids. The electrode and workpiece are connected to a suitable power supply. The power supply generates an electrical potential between the two parts. As the electrode approaches the workpiece, dielectric breakdown occurs in the fluid, forming a plasma channel, and a small spark jumps.

These sparks usually strike one at a time because it is very unlikely that different locations in the inter-electrode space have the identical local electrical characteristics which would enable a spark to occur simultaneously in all such locations. These sparks happen in huge numbers at seemingly random locations between the electrode and the workpiece. As the base metal is eroded, and the spark gap subsequently increased, the electrode is lowered automatically by the machine so that the process can continue uninterrupted. Several hundred thousand sparks occur per second, with the actual duty

cycle carefully controlled by the setup parameters. These controlling cycles are sometimes known as "on time" and "off time", which are more formally defined in the literature.

The on time setting determines the length or duration of the spark. Hence, a longer on time produces a deeper cavity for that spark and all subsequent sparks for that cycle, creating a rougher finish on the workpiece. The reverse is true for a shorter on time. Off time is the period of time that one spark is replaced by another. A longer off time, for example, allows the flushing of dielectric fluid through a nozzle to clean out the eroded debris, thereby avoiding a short circuit. These settings can be maintained in micro seconds. The typical part geometry is a complex 3D shape, often with small or odd shaped angles. Vertical, orbital, vectorial, directional, helical, conical, rotational, spin and indexing machining cycles are also used.

Wire EDM

CNC Wire-cut EDM machine

In *wire electrical discharge machining* (WEDM), also known as *wire-cut EDM* and *wire cutting*, a thin single-strand metal wire, usually brass, is fed through the workpiece, submerged in a tank of dielectric fluid, typically deionized water. Wire-cut EDM is typically used to cut plates as thick as 300mm and to make punches, tools, and dies from hard metals that are difficult to machine with other methods.

The wire, which is constantly fed from a spool, is held between upper and lower diamond guides. The guides, usually CNC-controlled, move in the *x*–*y* plane. On most machines, the upper guide can also move independently in the *z*–*u*–*v* axis, giving rise to the ability

to cut tapered and transitioning shapes (circle on the bottom square at the top for example). The upper guide can control axis movements in *x–y–u–v–i–j–k–l–*. This allows the wire-cut EDM to be programmed to cut very intricate and delicate shapes.

The upper and lower diamond guides are usually accurate to 0.004 mm, and can have a cutting path or *kerf* as small as 0.12 mm using Ø 0.1 mm wire, though the average cutting kerf that achieves the best economic cost and machining time is 0.335 mm using Ø 0.25 brass wire. The reason that the cutting width is greater than the width of the wire is because sparking occurs from the sides of the wire to the work piece, causing erosion. This "overcut" is necessary, for many applications it is adequately predictable and therefore can be compensated for (for instance in micro-EDM this is not often the case). Spools of wire are long—an 8 kg spool of 0.25 mm wire is just over 19 kilometers in length. Wire diameter can be as small as 20 micrometres and the geometry precision is not far from +/- 1 micrometre.

The wire-cut process uses water as its dielectric fluid, controlling its resistivity and other electrical properties with filters and de-ionizer units. The water flushes the cut debris away from the cutting zone. Flushing is an important factor in determining the maximum feed rate for a given material thickness.

Along with tighter tolerances, multiaxis EDM wire-cutting machining center have added features such as multiheads for cutting two parts at the same time, controls for preventing wire breakage, automatic self-threading features in case of wire breakage, and programmable machining strategies to optimize the operation.

Wire-cutting EDM is commonly used when low residual stresses are desired, because it does not require high cutting forces for removal of material. If the energy/power per pulse is relatively low (as in finishing operations), little change in the mechanical properties of a material is expected due to these low residual stresses, although material that hasn't been stress-relieved can distort in the machining process.

The workpiece may undergo a significant thermal cycle, its severity depending on the technological parameters used. Such thermal cycles may cause formation of a recast layer on the part and residual tensile stresses on the workpiece.

Applications

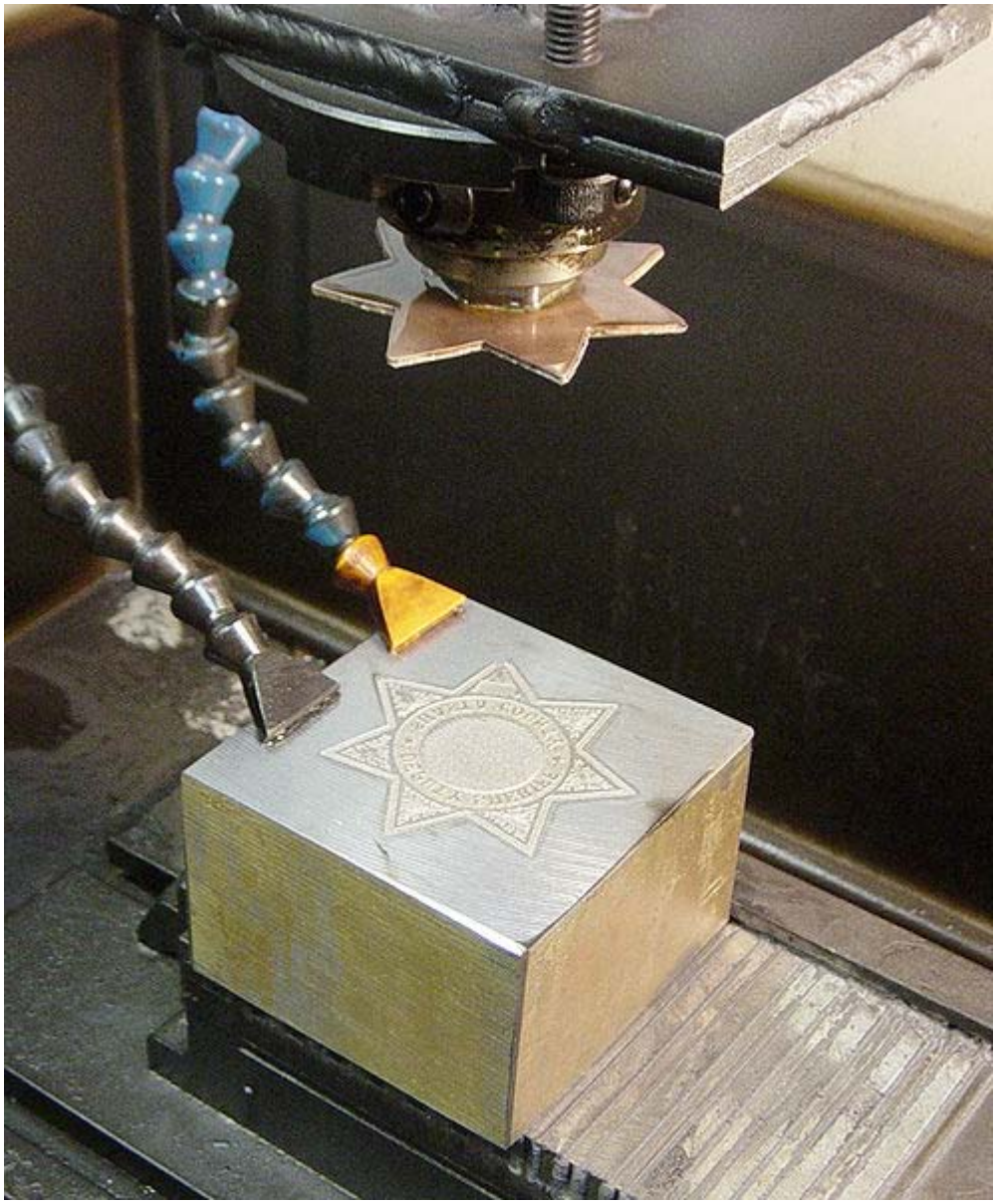
Prototype production

The EDM process is most widely used by the mould-making tool and die industries, but is becoming a common method of making prototype and production parts, especially in the aerospace, automobile and electronics industries in which production quantities are relatively low. In Sinker EDM, a graphite, copper tungsten or pure copper electrode is machined into the desired (negative) shape and fed into the workpiece on the end of a vertical ram.

Coinage die making

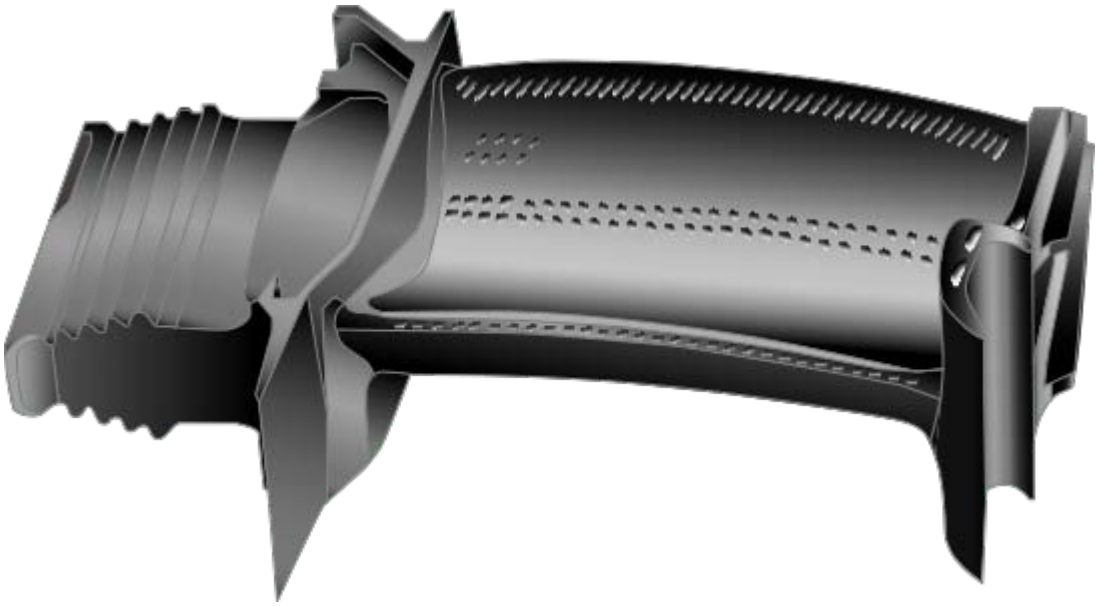
For the creation of dies for producing jewelry and badges by the coinage (stamping) process, the positive master may be made from sterling silver, since (with appropriate machine settings) the master is significantly eroded and is used only once. The resultant negative die is then hardened and used in a drop hammer to produce stamped flats from cutout sheet blanks of bronze, silver, or low proof gold alloy. For badges these flats may be further shaped to a curved surface by another die. This type of EDM is usually performed submerged in an oil-based dielectric. The finished object may be further refined by hard (glass) or soft (paint) enameling and/or electroplated with pure gold or nickel. Softer materials such as silver may be hand engraved as a refinement.

EDM control panel (Hansvedt machine). Machine may be adjusted for a refined surface (electropolish) at end of process.



Master at top, badge die workpiece at bottom, oil jets at left (oil has been drained). Initial flat stamping will be "dapped" to give a curved surface.

Small hole drilling



A turbine blade with internal cooling as applied in the high-pressure turbine.

Small hole drilling EDM is used in a variety of applications.

On wire-cut EDM machines, small hole drilling EDM is used to make a through hole in a workpiece in through which to thread the wire for the wire-cut EDM operation. A separate EDM head specifically for small hole drilling is mounted on a wire-cut machine and allows large hardened plates to have finished parts eroded from them as needed and without pre-drilling.

Small hole EDM is used to drill rows of holes into the leading and trailing edges of turbine blades used in jet engines. Gas flow through these small holes allows the engines to use higher temperatures than otherwise possible. The high-temperature, very hard, single crystal alloys employed in these blades makes conventional machining of these holes with high aspect ratio extremely difficult, if not impossible.

Small hole EDM is also used to create microscopic orifices for fuel system components, spinnerets for synthetic fibers such as rayon, and other applications.

There are also stand-alone small hole drilling EDM machines with an *x*–*y* axis also known as a super drill or *hole popper* that can machine blind or through holes. EDM drills bore holes with a long brass or copper tube electrode that rotates in a chuck with a constant flow of distilled or deionized water flowing through the electrode as a flushing agent and dielectric. The electrode tubes operate like the wire in wire-cut EDM machines, having a spark gap and wear rate. Some small-hole drilling EDMs are able to drill through 100 mm of soft or through hardened steel in less than 10 seconds, averaging 50%

to 80% wear rate. Holes of 0.3 mm to 6.1 mm can be achieved in this drilling operation. Brass electrodes are easier to machine but are not recommended for wire-cut operations due to eroded brass particles causing "brass on brass" wire breakage, therefore copper is recommended.

Metal disintegration machining

Several manufacturers produce EDM machines for the specific purpose of removing broken tools (drill bits or taps) from work pieces. In this application, the process is termed "metal disintegration machining".

Advantages and disadvantages

Some of the advantages of EDM include machining of:

- Complex shapes that would otherwise be difficult to produce with conventional cutting tools
- Extremely hard material to very close tolerances
- Very small work pieces where conventional cutting tools may damage the part from excess cutting tool pressure.
- There is no direct contact between tool and work piece. Therefore delicate sections and weak materials can be machined without any distortion.
- A good surface finish can be obtained.
- Very fine holes can be easily drilled.

Some of the disadvantages of EDM include:

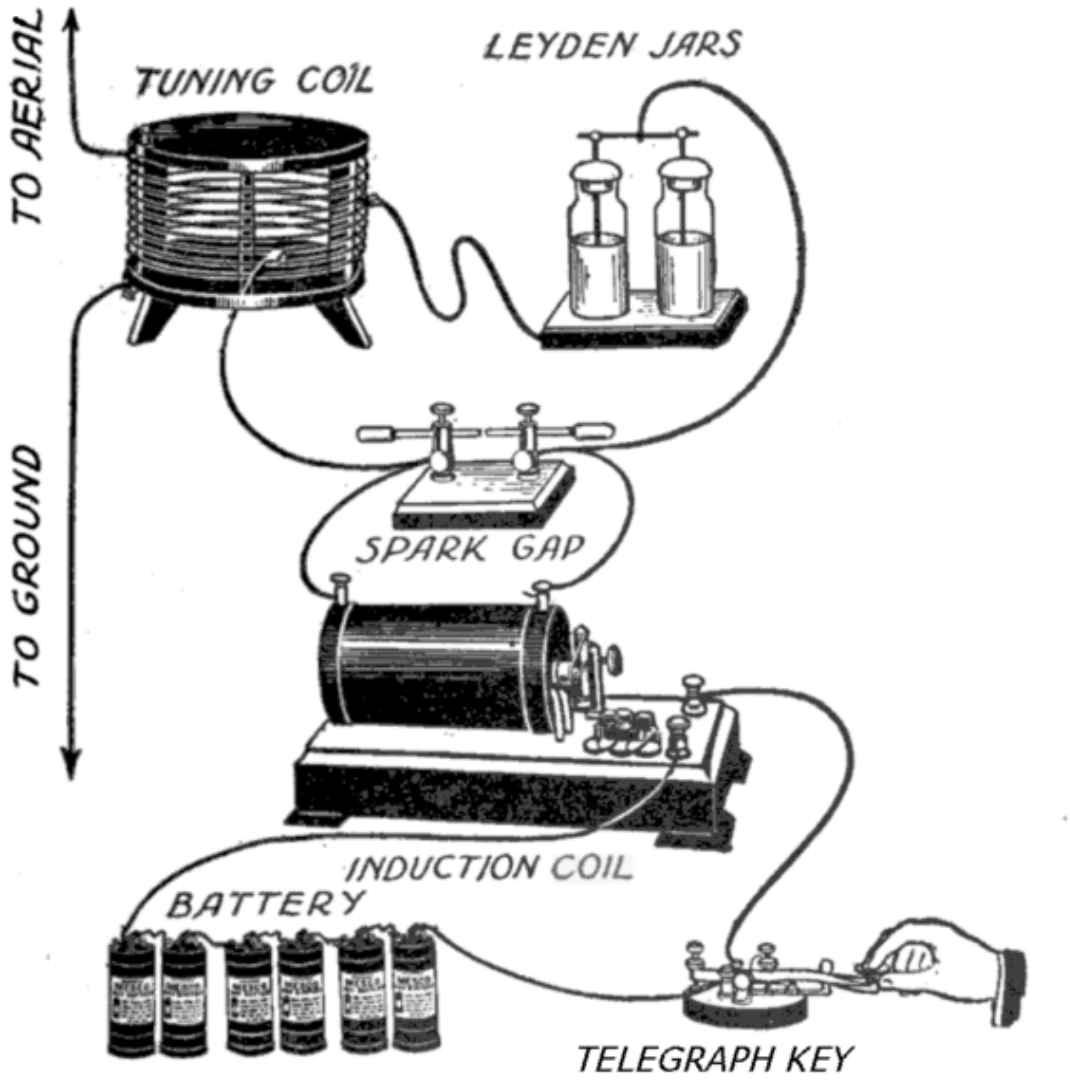
- The slow rate of material removal.
- The additional time and cost used for creating electrodes for ram/sinker EDM.
- Reproducing sharp corners on the workpiece is difficult due to electrode wear.
- Specific power consumption is very high.
- Power consumption is high.
- "Overcut" is formed.
- Excessive tool wear occurs during machining.
- Electrically non-conductive materials can be machined only with specific set-up of the process.

Chapter-8

Spark-gap Transmitter

A **spark-gap transmitter** is a device for generating radio frequency electromagnetic waves using a spark gap.

These devices served as the transmitters for most wireless telegraphy systems for the first three decades of radio (1887–1916) and the first demonstrations of practical radio were carried out using them. In later years (prior to the development of practical vacuum tube systems) somewhat more efficient transmitters were developed based on high-speed Alexanderson alternators and Poulsen Arc generators, but spark transmitters were still preferred by most operators. This was both because of their uncomplicated design and the fact that the transmitter stopped generating a carrier as soon as the Morse Code key was released, allowing the operator to "listen through" for a reply. With the other types of transmitter, the carrier wave could not be controlled so easily, and elaborate measures were required both to modulate the carrier and to separate the receiving antenna from the transmitting antenna, to keep transmitter leakage from de-sensitizing the receiver. After WWI, greatly improved transmitters based on vacuum tubes became available, which overcame these problems, and by the late 1920s the only spark transmitters still in regular operation were "legacy" installations on Naval vessels. Even when vacuum tube based transmitters had been installed, many vessels retained their crude but reliable spark transmitters as an emergency backup. However, by 1940, the technology was no longer used for communication. Use of the spark-gap transmitter led to many radio operators being nicknamed "Sparks" long after spark transmitters ceased to be used. Even today, the German verb "funken", literally, "to spark", also means "to send a radio message/signal".



Pictorial diagram of a simple spark-gap transmitter showing examples of the early electronic components used. From a 1917 boy's book, it is typical of the low power transmitters homebuilt by thousands of amateurs to explore the exciting new technology of radio.

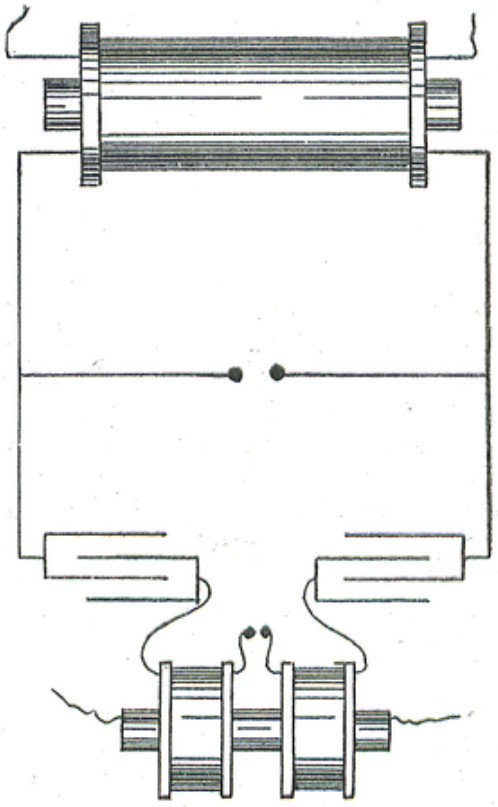
History

The history of radio shows that the spark gap transmitter was the product of many people, often working in competition. In 1862 James Clerk Maxwell predicted the propagation of electromagnetic waves through a vacuum.

In 1887, David E. Hughes used a spark gap to generate radio signals, achieving a detectable range of approximately 500 metres.

In 1888 physicist Heinrich Hertz set out to scientifically verify Maxwell's predictions. Hertz used a tuned spark gap transmitter and a tuned spark gap detector (consisting of a loop of wire connected to a small spark gap) located a few meters away. In a series of UHF experiments, Hertz verified that electromagnetic waves were being produced by the transmitter. When the transmitter sparked, small sparks also appeared across the receiver's spark gap, which could be seen under a microscope.

Nikola Tesla introduced his radio system in 1893 and later developed the so-called "loose coupler" system which was a major technological breakthrough. It produced a far more coherent carrier wave, generated far less interference, worked with much greater efficiency, required much lower operating voltages and could be operated in any weather conditions.



One form of Nikola Tesla's Spark-gap transmitter

Tesla pursued the application of his high voltage high frequency technology to radio. By tuning a receiving coil to the specific frequency used in the transmitting coil, he showed that the radio receiver's output could be greatly magnified through resonant action. Tesla was one of the first to patent a means to reliably produce radio frequencies (e.g., U.S. Patent 447,920, "Method of Operating Arc-Lamps" (March 10, 1891)). Tesla also invented a variety of rotary, cooled, and quenched spark gaps capable of handling high power.

Marconi began experimenting with wireless telegraphy in the early 1890s. In 1895 he succeeded in transmitting over a distance of 1 1/4 miles. His first transmitter consisted of an induction coil connected between a wire antenna and ground, with a spark gap across it. Every time the induction coil pulsed, the antenna would be momentarily charged up to tens (sometimes hundreds) of thousands of volts until the spark gap started to arc over. This acted as a switch, essentially connecting the charged antenna to ground, producing a very brief burst of electromagnetic radiation.

While the various early systems of spark transmitters worked well enough to prove the concept of wireless telegraphy, the primitive spark gap assemblies used had some severe shortcomings. The biggest problem was that the maximum power that could be transmitted was directly determined by how much electrical charge the antenna could hold. Because the capacitance of practical antennas is quite small, the only way to get a reasonable power output was to charge it up to very high voltages. However, this made transmission impossible in rainy or even damp conditions. Also, it necessitated a quite wide spark gap, with a very high electrical resistance, with the result that most of the electrical energy was used simply to heat up the air in the spark gap.

The other problem was that, due to the very brief duration of each burst of electromagnetic radiation, the system radiated an extremely "dirty" signal sideband-wise, which was almost impossible to tune out if the listener wanted to monitor a different station. This signal-bleed played a role in the inability of the *RMS Titanic* and the *SS Californian* to communicate with each other in 1912.

Despite these flaws, Marconi was able to generate sufficient interest from the British Admiralty in these originally crude systems to eventually finance the development of a commercial wireless telegraph service between United States and Europe using vastly improved equipment.

Reginald Fessenden's first attempts to transmit voice employed a spark transmitter operating at approximately 10,000 sparks/second. To modulate this transmitter he inserted a carbon microphone in series with the supply lead. He experienced great difficulty in achieving intelligible sound. At least one high-powered audio transmitter used water cooling for the microphone.

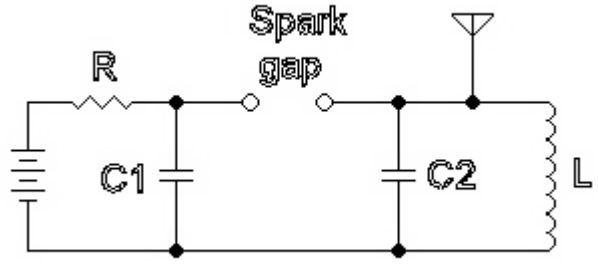
In 1905 a "state of the art" spark gap transmitter generated a signal having a wavelength between 250 meters (1.2 MHz) and 550 meters (545 kHz). 600 meters (500 kHz) became the International distress frequency. The receivers were simple unamplified Magnetic

Detectors or electrolytic detectors. This later gave way to the famous and more sensitive galena crystal sets. Tuners were primitive or nonexistent. Early amateur radio operators built low power spark gap transmitters using the spark coil from Ford Model T automobiles. But a typical commercial station in 1916 might include a 1/2 kW transformer that supplied 14,000 volts, an eight section capacitor, and a rotary gap capable of handling a peak current of several hundred amperes.

Shipboard installations usually used a DC motor (usually run off the ship's DC lighting supply) to drive an alternator whose AC output was then stepped up to 10,000–14,000 volts by a transformer. This was a very convenient arrangement, since the signal could be easily modulated by simply connecting a relay between the relatively low voltage alternator output and the transformer's primary winding, and activating it with the morse key. (Lower-powered units sometimes used the morse key to directly switch the AC, but this required a heavier key making it more difficult to operate).

Spark gap transmitters generate fairly broad-band signals. As the more efficient transmission mode of continuous waves (CW) became easier to produce and band crowding and interference worsened, spark-gap transmitters and damped waves were legislated off the new shorter wavelengths by international treaty, and replaced by Poulsen arc converters and high frequency alternators which developed a sharply defined transmitter frequency. These approaches later yielded to vacuum tube technology and the 'electric age' of radio would end. Long after they stopped being used for communications, spark gap transmitters were employed for radio jamming. As late as 1955, a Japanese radio-controlled toy bus used a spark transmitter and coherer receiver; the spark was visible behind a sheet of blue transparent plastic. Spark gap oscillators are still used to generate high frequency high voltage to initiate welding arcs in gas tungsten arc welding. Powerful spark gap pulse generators are still used to simulate EMPs. Most high power gas-discharge street lamps (mercury and sodium vapor) still use modified spark transmitters as switch-on ignitors.

Operation



A typical spark transmitter circuit.
Legend:
capacitor - C_1 and C_2;
resistor - R;
inductor - L.

The spark transmitter is very simple in operation, but it presented significant technical problems mostly due to very large induced EMF when the spark struck, which caused breakdown of the insulation in the primary transformer. To overcome this the construction of even low-power sets was very solid. The damped wave output was very wasteful of bandwidth, and this limited the number of stations that could communicate effectively without interfering with each other.

In its simplest form, a spark-gap transmitter consists of a spark gap connected across an oscillatory circuit consisting of a capacitor and an inductor in series or parallel. In a typical transmitter circuit, a high voltage source (shown in the schematic as a battery, but usually a high voltage transformer) charges a capacitor (C1 in figure) through a resistor until the spark gap discharges, then a pulse of current passes through the capacitor (C2 in figure). The inductor and capacitor after the gap form a resonant circuit. After being excited by the current pulse, the oscillation rapidly decays because energy is radiated from the antenna. Because of the rapid onset and decay of the oscillation, the RF pulse occupies a large band of frequencies.

The function of the spark gap is to present initially a high resistance to the circuit to allow the capacitor to charge. When the breakdown voltage of the gap is reached, it then presents a low resistance to the circuit causing the capacitor to discharge. The discharge through the conducting spark takes the form of a damped oscillation, at a frequency determined by the resonant frequency of the LC circuit.

Spark gaps

A simple **spark gap** consists of two conducting electrodes separated by a gap immersed within a gas (typically air). When a sufficiently high voltage is applied, a spark will bridge the gap, ionizing the gas and drastically reducing its electrical resistance. An electric current then flows until the path of ionized gas is broken or the current is reduced below a minimum value called the 'holding current'. This usually occurs when the voltage across the gap drops sufficiently, but the process may also be assisted by cooling the spark channel or by physically separating the electrodes. This breaks the conductive filament of ionized gas, allowing the capacitor to recharge, and permitting the recharging/discharging cycle to repeat. The action of ionizing the gas is quite sudden and violent (*disruptive*), and it creates a sharp sound (ranging from a *snap* for a spark plug, to a loud *bang* for a wider gap). The spark gap also liberates light and heat.

Quenching the arc

Quenching refers to the act of extinguishing the previously established arc within the spark gap. This is considerably more difficult than initiating spark breakdown in the gap. As transmitter power was increased, the problem of quenching arose.

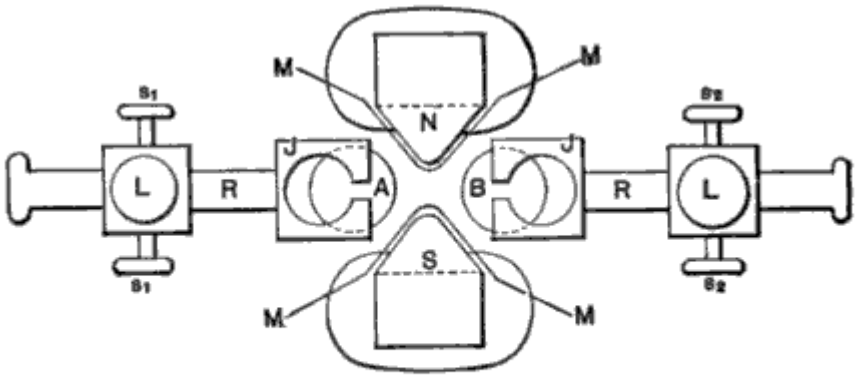
A cold, non-firing spark gap contains no ionized gases. Once the voltage across the gap reaches its breakdown voltage, gas molecules in the gap are very quickly ionized along a path, creating a hot electric arc, or plasma, that consists of large numbers of ions and free

electrons between the electrodes. The arc also heats part of the electrodes to incandescence. The incandescent regions contribute free electrons via thermionic emission, and (easily ionized) metal vapor. The mixture of ions and free electrons in the plasma is highly conductive, resulting in a sharp drop in the gap's electrical resistance. This highly conductive arc supports efficient tank circuit oscillations. However, the oscillating current also sustains the arc and, until it can be extinguished, the tank capacitor cannot be recharged for the next pulse.

Several methods were applied to quench the arc.

- Jets of air that cool, stretch, and literally 'blow out' the plasma,
- multi-plate discharger of Max Wien to cool the arcs in medium power spark sets, known as the "whistling spark" for its distinctive signal,
- using a different gas, such as hydrogen, that quenches more efficiently by providing more effective electrode cooling,
- a magnetic field (from a pair of permanent magnets or poles of an electromagnets) oriented at right angles to the gap to stretch and cool the arc.

Magnetic



ARRANGEMENT OF IMPROVED DISCHARGER AND MAGNET.

A magnetic blowout

Spark gaps used in early radio transmitters varied in construction, depending on the power to be handled. Some were fairly simple, consisting of one or more fixed (*static*) gaps connected in series, while others were significantly more complex. Because sparks were quite hot and erosive, electrode wear and cooling were constant problems.

Rotary gaps

The need to extinguish arcs in increasingly higher power transmitters led to the development of the rotating spark gap. These devices were used with an alternating current power supply, produced a more regular spark, and could handle more power than

conventional static spark gaps. The inner rotating metal disc typically had a number of studs on its outer edge. A discharge would take place when two of the studs lined up with the two outer contacts which carried the high voltage. The resulting arcs were rapidly stretched, cooled, and broken as the disk rotated.

Rotary gaps were operated in two modes, synchronous and asynchronous. A synchronous gap was driven by a synchronous AC motor so that it ran at a fixed speed, and the gap fired in direct relation to the waveform of the A.C. supply that recharged the tank capacitor. The point in the waveform where the gaps were closest was changed by adjusting the rotor position on the motor shaft relative to the stator's studs. By properly adjusting the synchronous gap, it was possible to have the gap fire only at the voltage peaks of the input current. This technique allowed the tank circuit to fire only at successive voltage peaks, thereby delivering maximum energy from the fully charged tank capacitor each time the gap fired. The *break rate* was thus fixed at twice the incoming power frequency (typically, 100 to 120 breaks/second). When properly engineered and adjusted, synchronous spark gap systems delivered the largest amount of power to the antenna. However, electrode wear would progressively change the gap's *firing point*, so synchronous gaps were somewhat temperamental and difficult to maintain.

Asynchronous gaps were considerably more common. In an asynchronous gap, the rotation of the motor had no fixed relationship relative to the incoming AC waveform. Asynchronous gaps worked quite well and were much easier to maintain. By using a larger number of rotating studs or a higher rotational speed, many asynchronous gaps operated at break rates in excess of 400 breaks/second. Since the gap could be fired more often than the input waveform switched polarity, the tank capacitor was charged and discharged more rapidly than a synchronous gap. However, each discharge would occur at a varying voltage that was almost always lower than the consistent peak voltage obtained from a synchronous gap.

Rotary gaps also served to alter the tone of the transmitter, since changing either the number of studs or the rotational speed changed the spark discharge frequency which was audible in receivers with detectors that could detect the modulation on the spark signal. This enabled listeners to distinguish between different transmitters that were nominally tuned to the same frequency. A typical high-power multiple spark system (as it was also called) used a 9-to-24-inch-diameter (230 to 610 mm) rotating commutator with six to twelve studs per wheel, typically switching several thousand volts.

The output of a rotary spark gap transmitter was turned on and off by the operator using a special kind of telegraph key that switched power going to the high voltage power supply. The key was designed with large contacts to carry the heavy current that flowed into the low voltage (primary) side of the high voltage transformer (often in excess of 20 amps). Alternatively a relay was used to do the actual switching.

Chapter-9

Gas-discharge Lamp

Germicidal lamps are simple low pressure mercury vapor discharges in a fused quartz envelope.

Gas-discharge lamps are a family of artificial light sources that generate light by sending an electrical discharge through an ionized gas, i.e. a plasma. The character of the

gas discharge critically depends on the frequency or modulation of the current. Typically, such lamps use a noble gas (argon, neon, krypton and xenon) or a mixture of these gases. Most lamps are filled with additional materials, like mercury, sodium, and/or metal halides. In operation the gas is ionized, and free electrons, accelerated by the electrical field in the tube, collide with gas and metal atoms. Some electrons in the atomic orbitals of these atoms are excited by these collisions to a higher energy state. When the excited atom falls back to a lower energy state, it emits a photon of a characteristic energy, resulting in infrared, visible light, or ultraviolet radiation. Some lamps will convert the ultraviolet radiation to visible light with a fluorescent coating on the inside of the lamp's glass surface. The fluorescent lamp is perhaps the best known gas-discharge lamp.

Gas-discharge lamps offer long life and high efficiency, but are more complicated to manufacture, and they require electronics to provide the correct current flow through the gas.

History

The history of gas-discharge lamps began in 1675 when French astronomer Jean-Felix Picard observed that the empty space in his mercury barometer glowed as the mercury jiggled while he was carrying the barometer. Investigators, including Francis Hauksbee, tried to determine the cause of the phenomenon. Hauksbee first demonstrated a gas-discharge lamp in 1705. He showed that an evacuated or partially evacuated glass globe, while charged by static electricity could produce a light bright enough to read by. The phenomenon of electric arc was first described by Vasily V. Petrov, a Russian scientist, in 1802; Sir Humphry Davy demonstrated in the same year the electric arc at the Royal Institution of Great Britain. Since then, discharge light sources have been researched because they create light from electricity considerably more efficiently than incandescent light bulbs.

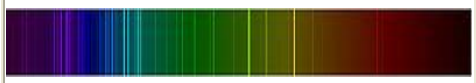
Later it was discovered that the arc discharge could be optimized by using an inert gas instead of air as a medium. Therefore noble gases neon, argon, krypton or xenon were used, as well as carbon dioxide historically.

The introduction of the metal vapor lamp, including various metals within the discharge tube, was a later advance. The heat of the gas discharge vaporized some of the metal and the discharge is then produced almost exclusively by the metal vapor. The usual metals are sodium and mercury owing to their high vapor pressures that increase efficiency of visible spectrum emission.

One hundred years of research later led to lamps without electrodes which are instead energized by microwave or radio frequency sources. In addition, light sources of much lower output have been created, extending the applications of discharge lighting to home or indoor use.

Color

Each gas, depending on its atomic structure emits certain wavelengths which translates in different colors of the lamp. As a way of evaluating the ability of a light source to reproduce the colors of various objects being lit by the source, the International Commission on Illumination (CIE) introduced the color rendering index. Some gas-discharge lamps have a relatively low CRI, which means colors they illuminate appear substantially different than they do under sunlight or other high-CRI illumination.

Gas	Color	Spectrum	Notes	Image
Helium	White to orange; under some conditions may be gray, blue, or green-blue.		Used by artists for special purpose lighting.	
Neon	Red-orange		Intense light. Used frequently in neon signs and neon lamps.	
Argon	Violet to pale lavender blue		Often used together with mercury vapor.	
Krypton	Gray off-white to green. At high peak currents, bright blue-white.		Used by artists for special purpose lighting.	

Xenon	Gray or blue-gray dim white. At high peak currents, very bright green-blue.		Used in flashbulbs, xenon HID headlamps, and xenon arc lamps.	
Nitrogen	Similar to argon but duller, more pink; at high peak currents bright blue-white.			
Oxygen	Violet to lavender, dimmer than argon			
Hydrogen	Lavender at low currents, pink to magenta over 10 mA			
Water vapor	Similar to hydrogen, dimmer			
Carbon dioxide	Blue-white to pink, in lower currents brighter than xenon		Used in Carbon Dioxide Lasers.	

Mercury vapor	Light blue, intense ultraviolet	 Ultraviolet not shown	In combination with phosphors used to generate many colors of light. Widely used in mercury-vapor lamps.	
Sodium vapor (low pressure)	Bright orange-yellow		Widely used in sodium vapor lamps.	

Most common gas-discharge lamps

Low pressure discharge lamps

A Compact fluorescent lamp

Low-pressure lamps have working pressure much less than atmospheric pressure.

- Fluorescent lamps, the most common lamp in office lighting and many other applications, produces up to 100 lumens per watt
- Low pressure sodium lamps, the most efficient gas-discharge lamp type, producing up to 200 lumens per watt, but at the expense of very poor color

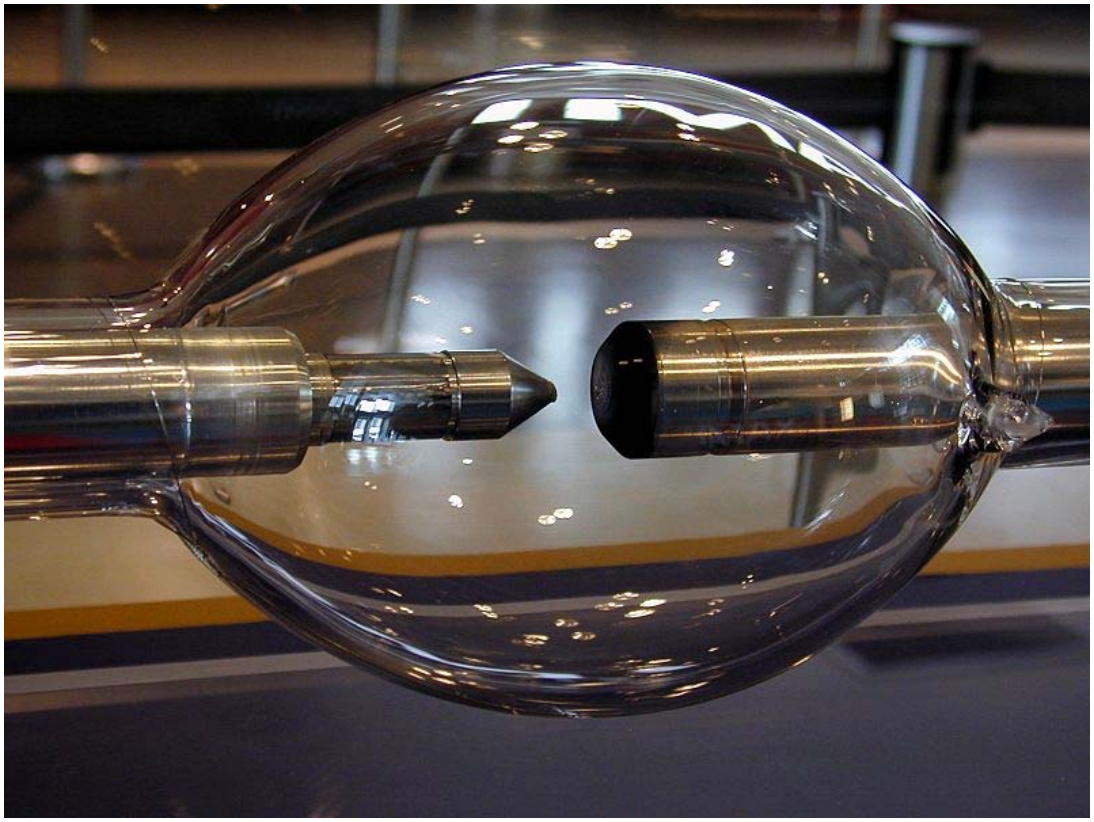
rendering. The almost monochromatic yellow light is only acceptable for street lighting and similar applications.

High pressure discharge lamps

High-pressure lamps have a discharge that takes place in gas under slightly less to greater than atmospheric pressure. For example, a high pressure sodium lamp has an arc tube under 100 to 200 torr pressure, about 14% to 28% of atmospheric pressure; some automotive HID headlamps have up to 50 bar or fifty times atmospheric prssure.

- Metal halide lamps. These lamps produce almost white light, and attain 100 lumen per watt light output. Applications include indoor lighting of high buildings, parking lots, shops, sport terrains.
- High pressure sodium lamps, producing up to 150 lumens per watt. These lamps produce a broader light spectrum than the low pressure sodium lamps. Also used for street lighting, and for artificial photoassimilation for growing plants
- High pressure mercury-vapor lamps. This lamp type is the oldest high pressure lamp type, being replaced in most applications by the metal halide lamp and the high pressure sodium lamp.

High-intensity discharge lamps



15 kW xenon short-arc lamp used in IMAX projectors

A high-intensity discharge (HID) lamp is a type of electrical lamp which produces light by means of an electric arc between tungsten electrodes housed inside a translucent or transparent fused quartz or fused alumina arc tube. Compared to other lamp types, relatively high arc power exists for the arc length. Examples of HID lamps include:

- Mercury-vapor lamps
- Metal halide lamps
- Ceramic discharge metal halide lamps
- Sodium vapor lamps
- Xenon arc lamps
- Ultra-High Performance (UHP)

HID lamps are typically used when high levels of light over large areas are required, and when energy efficiency and/or light intensity are desired.

Other examples

- Neon signs may use either direct illumination or, to obtain certain colors, indirect phosphor excitation.

- Xenon flash lamp. This lamp is commonly found in film and digital cameras, even in single-use cameras. These lamps have produced interesting illumination effects in theatre and dancing. More robust versions of this lamps, known as strobe lights, can produce short intense flashes repeatedly, allowing the stroboscopic examination of repetitive motion (useful in certain balancing applications). These were at one time popular, "freezing" the motion of the actors or dancers. This type of lamp was also used to demonstrate persistence of vision, where an entire room would be illuminated by multiple lamps behind diffusing wall panels. In this otherwise darkened room a periodic flash would cause every detail of the occupants to be imaged on the observer's retina, completely frozen in motion.

Chapter-10

Spark Plug

Spark plug with single-ground electrode.

A **spark plug** (very rarely in British English: a **sparking plug**) is an electrical device that fits into the cylinder head of some internal combustion engines and ignites compressed fuels such as aerosol, gasoline, ethanol, and liquefied petroleum gas by means of an electric spark.

Spark plugs have an insulated central electrode which is connected by a heavily insulated wire to an ignition coil or magneto circuit on the outside, forming, with a grounded terminal on the base of the plug, a spark gap inside the cylinder.

Reciprocating internal combustion engines can be divided into *spark-ignition engines*, which require spark plugs to initiate combustion, and *compression-ignition engines* (diesel engines), which compress the air and then inject diesel fuel into the heated compressed air mixture where it autoignites. Compression-ignition engines may use glow plugs to improve cold start characteristics.

Spark plugs may also be used in other applications such as furnaces where a combustible mixture should be ignited. In this case, they are sometimes referred to as **flame igniters**.

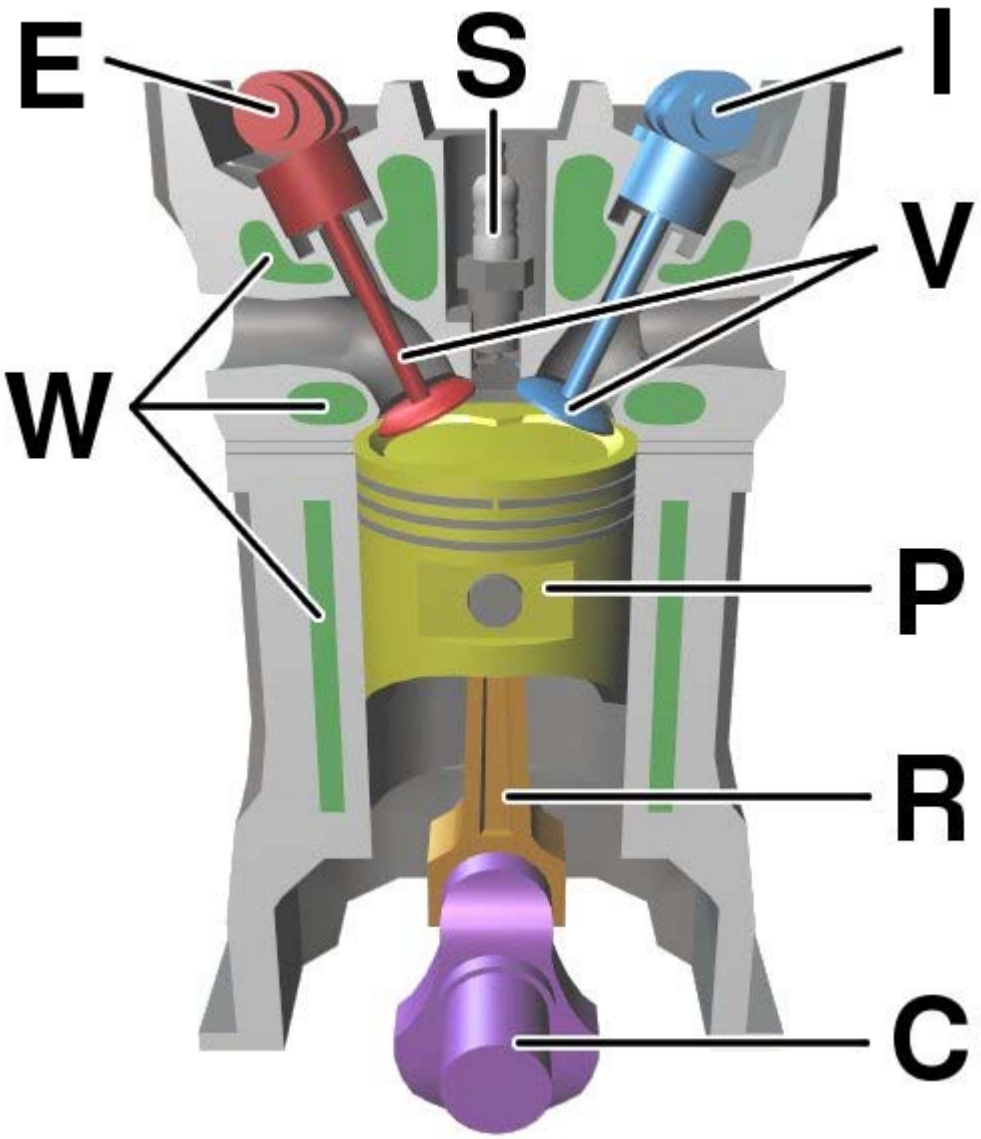
History

In about 1807 François Isaac de Rivaz invented a hydrogen and oxygen powered internal combustion engine with electric ignition, and in 1808 he fitted it into a working vehicle.

In 1860 Étienne Lenoir used an electric spark plug in his first internal combustion engine and is generally credited with the invention of the spark plug.

Early patents for spark plugs included those by Nikola Tesla (in U.S. Patent 609,250 for an ignition timing system, 1898), Frederick Richard Simms (GB 24859/1898, 1898) and Robert Bosch (GB 26907/1898). But only the invention of the first commercially viable high-voltage spark plug as part of a magneto-based ignition system by Robert Bosch's engineer Gottlob Honold in 1902 made possible the development of the internal combustion engine. Subsequent manufacturing improvements can also be credited to Albert Champion, the Lodge brothers, sons of Sir Oliver Joseph Lodge, who developed and manufactured their father's idea and also Kenelm Lee Guinness, of the Guinness brewing family, who developed the KLG brand.

Operation



Components of a typical, four stroke cycle, DOHC piston engine. (E) Exhaust camshaft, (I) Intake camshaft, **(S) Spark plug**, (V) Valves, (P) Piston, (R) Connecting rod, (C) Crankshaft, (W) Water jacket for coolant flow.

The plug is connected to the high voltage generated by an ignition coil or magneto. As the electrons flow from the coil, a voltage difference develops between the central electrode and side electrode. No current can flow because the fuel and air in the gap is an insulator, but as the voltage rises further, it begins to change the structure of the gases between the electrodes. Once the voltage exceeds the dielectric strength of the gases, the gases become ionized. The ionized gas becomes a conductor and allows electrons to flow across the gap. Spark plugs usually require voltage of 12,000–25,000 volts or more to

'fire' properly, although it can go up to 45,000 volts. They supply higher current during the discharge process resulting in a hotter and longer-duration spark.

As the current of electrons surges across the gap, it raises the temperature of the spark channel to 60,000 K. The intense heat in the spark channel causes the ionized gas to expand very quickly, like a small explosion. This is the "click" heard when observing a spark, similar to lightning and thunder.

The heat and pressure force the gases to react with each other, and at the end of the spark event there should be a small ball of fire in the spark gap as the gases burn on their own. The size of this fireball or kernel depends on the exact composition of the mixture between the electrodes and the level of combustion chamber turbulence at the time of the spark. A small kernel will make the engine run as though the ignition timing was retarded, and a large one as though the timing was advanced.

Spark plug construction

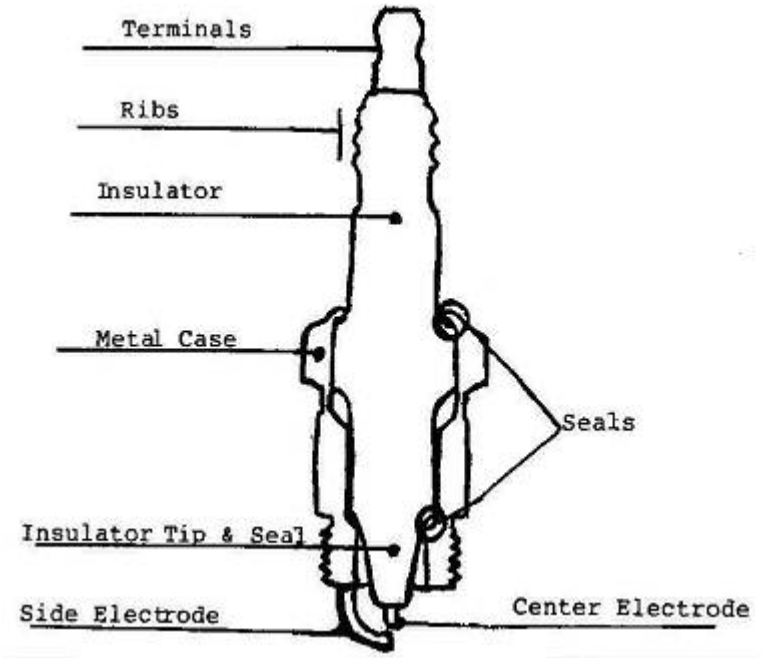


Diagram of single-ground spark plug (the bottom hook "side electrode" is the single ground electrode).

A spark plug is composed of a shell, insulator and the central conductor. It pierces the wall of the combustion chamber and therefore must also seal the combustion chamber against high pressures and temperatures without deteriorating, over long periods of time and extended use.

Parts of the plug

Terminal

The top of the spark plug contains a terminal to connect to the ignition system. The exact terminal construction varies depending on the use of the spark plug. Most passenger car spark plug wires snap onto the terminal of the plug, but some wires have spade connectors which are fastened onto the plug under a nut. Plugs which are used for these applications often have the end of the terminal serve a double purpose as the nut on a thin threaded shaft so that they can be used for either type of connection. These are a necessary part of the spark plug.

Insulator

The main part of the insulator is made from porcelain. Its major function is to provide mechanical support for the central electrode, whilst insulating the high voltage. It has a secondary role, particularly in modern engines with deeply recessed plugs, in extending the terminal above the cylinder head so as to make it more readily accessible.

Ribs

By lengthening the surface between the high voltage terminal and the grounded metal case of the spark plug, the physical shape of the ribs functions to improve the electrical insulation and prevent electrical energy from leaking along the insulator surface from the terminal to the metal case. The disrupted and longer path makes the electricity encounter more resistance along the surface of the spark plug even in the presence of dirt and moisture. Some modern sparking plugs are not manufactured with ribs. Improvements in the dielectric strength of the insulator make them less important.

Insulator tip

The tip of the insulator, the part from the metal body of the plug to the electrode protruding into the combustion chamber, must resist high temperatures while retaining electrical insulation. To avoid over-heating the electrode, it must also provide good thermal conductivity. The porcelain of the main insulator is inadequate and so a sintered aluminium oxide ceramic is used, designed to withstand 650 °C and 60,000 V.

The exact composition and length of the insulator determines the heat range of the plug. Short insulators are "cooler" plugs. "Hotter" plugs are made with a lengthened path to the metal body, by isolating the insulator over much of its length with an annular groove.

Older spark plugs, particularly in aircraft, used an insulator made of stacked layers of mica, compressed by tension in the centre electrode. With the development of leaded petrol in the 1930s, lead deposits on the mica became a problem and reduced the interval between needing to clean the spark plug. Sintered aluminium oxide was developed by Siemens in Germany to counteract this.

Seals

Because the spark plug also seals the combustion chamber or the engine when installed, the seals ensure there is no leakage from the combustion chamber. The seal is typically made by the use of a multi-layer braze because there are no braze compositions that will wet both the ceramic and metal case and therefore intermediary alloys are required.

Metal case

The metal case (or the "jacket" as many people call it) of the spark plug withstands the torque of tightening the plug, serves to remove heat from the insulator and pass it on to the cylinder head, and acts as the ground for the sparks passing through the central electrode to the side electrode. Marine engine spark plug threads are cold rolled to prevent seizing in aluminium cylinder heads, due to corrosion. Also, a marine spark plug's shell is double-dipped, zinc-chromate coated metal.

Central electrode

Central and lateral electrodes

The central electrode is connected to the terminal through an internal wire and commonly a ceramic series resistance to reduce emission of RF noise from the sparking. The tip can be made of a combination of copper, nickel-iron, chromium, or precious metals. In the late seventies, the development of engines reached a stage where the ‘heat range’ of conventional spark plugs with solid nickel alloy centre electrodes was unable to cope with their demands. A plug that was ‘cold’ enough to cope with the demands of high speed driving would not be able to burn off the carbon deposits caused by stop-start urban conditions, and would foul in these conditions, making the engine misfire. Similarly, a plug that was ‘hot’ enough to run smoothly in town, could actually melt when called upon to cope with extended high speed running on motorways. The answer

to this problem, devised by the spark plug manufacturers, was a centre electrode that carried the heat of combustion away from the tip more effectively than was possible with a solid nickel alloy. Copper was the material chosen for the task and a method for manufacturing the copper-cored centre electrode was created by Floform.

The central electrode is usually the one designed to eject the electrons (the cathode) because it is the hottest (normally) part of the plug; it is easier to emit electrons from a hot surface, because of the same physical laws that increase emissions of vapor from hot surfaces. In addition, electrons are emitted where the electrical field strength is greatest; this is from wherever the radius of curvature of the surface is smallest, *i.e.* from a sharp point or edge rather than a flat surface. It would be easiest to pull electrons from a pointed electrode but a pointed electrode would erode after only a few seconds. Instead, the electrons emit from the sharp edges of the end of the electrode; as these edges erode, the spark becomes weaker and less reliable.

At one time it was common to remove the spark plugs, clean deposits off the ends either manually or with specialized sandblasting equipment and file the end of the electrode to restore the sharp edges, but this practice has become less frequent as spark plugs are now merely replaced, at much longer intervals. The development of precious metal high temperature electrodes (using metals such as yttrium, iridium, platinum, tungsten, or palladium, as well as the relatively prosaic silver or gold) allows the use of a smaller centre wire, which has sharper edges but will not melt or corrode away. The smaller electrode also absorbs less heat from the spark and initial flame energy. At one point, Firestone marketed plugs with polonium in the tip, under the questionable theory that the radioactivity would ionize the air in the gap, easing spark formation.

Side electrode, or ground electrode

The side electrode is made from high nickel steel and is welded (or hot forged) to the side of the metal case. The side electrode also runs very hot, especially on projected nose plugs. Some designs have provided a copper core to this electrode, so as to increase heat conduction. Multiple side electrodes may also be used, so that they don't overlap the central electrode.

Spark plug gap

Gap gauge: A disk with sloping edge; the edge is thicker going counter-clockwise, and a spark plug will be hooked along the edge to check the gap.

Spark plugs are typically designed to have a spark gap which can be adjusted by the technician installing the spark plug, by the simple method of bending the ground electrode slightly to bring it closer to or further from the central electrode. The belief that plugs are properly gapped as delivered in their box from the factory is only partially true, as proven by the fact that the same plug may be specified for several different engines, requiring a different gap for each. Spark plugs in automobiles generally have a gap between 0.035"–0.070" (0.9–1.8 mm). But it can depend on the engine: new spark plugs might be pre-gapped for a V-8 engine, installing all 8 plugs unchanged; however if installed in a 6-cylinder engine, all (6) plugs would require re-gapping.

A *spark plug gap gauge* is a disc with a sloping edge, or with round wires of precise diameters, and is used to measure the gap; use of a feeler gauge with flat blades instead of round wires, as is used on distributor points or valve lash, will give erroneous results, due to the shape of spark plug electrodes. The simplest gauges are a collection of keys of various thicknesses which match the desired gaps and the gap is adjusted until the key fits snugly. With current engine technology, universally incorporating solid state ignition systems and computerized fuel injection, the gaps used are much larger than in the era of carburetors and breaker point distributors, to the extent that spark plug gauges from that era are much too small for measuring the gaps of current cars.

The gap adjustment can be fairly critical, and if it is maladjusted the engine may run badly, or not at all. A narrow gap may give too small and weak a spark to effectively ignite the fuel-air mixture, while a gap that is too wide might prevent a spark from firing at all. Either way, a spark which only intermittently fails to ignite the fuel-air mixture may not be noticeable directly, but will show up as a reduction in the engine's power and fuel efficiency. The main issues with spark plug gaps are:

- **narrow-gap** *risk*: spark might be too weak/small to ignite fuel;
- **narrow-gap** *benefit*: plug always fires on each cycle;

- **wide-gap** *risk*: plug might not fire, or miss at high speeds;
- **wide-gap** *benefit*: spark is strong for a clean burn.

A properly gapped plug will be wide enough to burn hot, but not so wide that it skips or misses at high speeds, causing that cylinder to drag, or the engine to begin to rattle.

As a plug ages, and the metal of both the tip and hook erode, the gap will tend to widen; therefore experienced mechanics often set the gap on new plugs at the engine manufacturer's minimum recommended gap, rather than in the middle of the specified acceptable range, to ensure longer life between plug changes. On the other hand, since a larger gap gives a "hotter" or "fatter" spark and more reliable ignition of the fuel-air mixture, and since a new plug with sharp edges on the central electrode will spark more reliably than an older, eroded plug, experienced mechanics also realize that the maximum gap specified by the engine manufacturer is the largest which will spark reliably even with old plugs and will in fact be a bit narrower than necessary to ensure sparking with new plugs; therefore, it is possible to set the plugs to an extremely wide gap for more reliable ignition in high performance applications, at the cost of having to replace or re-gap the plugs more frequently, as soon as the tip begins to erode.

Variations on the basic design

Over the years variations on the basic spark plug design have attempted to provide either better ignition, longer life, or both. Such variations include the use of two, three, or four equally spaced ground electrodes surrounding the central electrode. Other variations include using a recessed central electrode surrounded by the sparkplug thread, which effectively becomes the ground electrode. Also there is the use of a V-shaped notch in the tip of the ground electrode. Multiple ground electrodes generally provide longer life, as when the spark gap widens due to electric distcharge wear, the spark moves to another closer ground electrode. The disadvantage of multiple ground electrodes is that a shielding effect can occur in the engine combustion chamber inhibiting the flame face as the fuel air mixture burns. This can result in a less efficient burn and increased fuel consumption.

Surface-discharge spark plug

A piston engine has a part of the combustion chamber that is always out of reach of the piston; and this zone is where the conventional spark plug is located. A Wankel engine has a permanently varying combustion area; and the spark plug is inevitably swept by the tip seals. Clearly, if a spark plug were to protrude into the Wankel's combustion chamber it would foul the rotating tip; and if the plug were recessed to avoid this, the sunken spark might lead to poor combustion. So a new type of "surface discharge" plug was developed for the Wankel. Such a plug presents an almost flat face to the combustion chamber. A stubby centre electrode projects only very slightly; and the entire earthed body of the plug acts as the side electrode. The advantage is that the plug sits just beneath the tip-seal that sweeps over it, keeping the spark accessible to the fuel/air mixture. The "plug gap" remains constant throughout its life; and the spark path will continually vary (instead of

darting from the centre to the side electrode as in a conventional plug). Whereas a conventional side electrode will (admittedly, rarely) come adrift in use and potentially cause engine damage, this is impossible with a surface discharge plug, as there is nothing to break off. Surface-discharge spark plugs have been produced by, inter alia, Champion and Bosch.

Sealing to the cylinder head

Old spark plug removed from a car, new one ready to install.

Most spark plugs seal to the cylinder head with a hollow metal washer which is crushed slightly between the flat surface of the head and that of the plug, just above the threads. If the torque used to install the plugs is not excessive, the washer can be reused when the plug is removed and reinserted, although this practice is, strictly speaking, not recommended and replacement washers are available.

Ford engines, however, were once distinct in using a tapered hole and a matching taper on the bottom of the plug above the threads, in order to seal the plug. The torque for installing and removing these plugs was higher and it was easier to break them if the wrench was applied partially off axis.

More recently, some types of Ford Fiesta, and Ka also had a similar sealing system. The torque required to install these plugs is less than with the above type, and it is extremely critical that they not be overtightened, since overtightening can result in it being difficult

or impossible to remove them. In addition, they have been known to corrode into the cylinder head, particularly if left in too long between removals. In such a situation, it is not unknown for a plug to snap below the hexagonal nut, leaving just the threaded portion (and the outer electrode) in the cylinder head. Ford has on occasion issued TSB reminding technicians to use the correct methods of installation.

Tip protrusion

Different sizes of spark plug. The left and right plug are identical in threading, electrodes, tip protrusion, and heat range. The centre plug is a compact variant, with smaller hex and porcelain portions outside the head, to be used where space is limited. The rightmost plug has a longer threaded portion, to be used in a thicker cylinder head.

The length of the threaded portion of the plug should be closely matched to the thickness of the head. If a plug extends too far into the combustion chamber, it may be struck by the piston, damaging the engine internally. Less dramatically, if the threads of the plug extend into the combustion chamber, the sharp edges of the threads act as point sources of heat which may cause preignition; in addition, deposits which form between the exposed threads may make it difficult to remove the plugs, even damaging the threads on aluminium heads in the process of removal. The protrusion of the tip into the chamber also affects plug performance, however; the more centrally located the spark gap is, generally the better the ignition of the air-fuel mixture will be, although experts believe the process is actually much more complex and dependent on combustion chamber shape. On the other hand, if an engine is "burning oil", the excess oil leaking into the combustion chamber tends to foul the plug tip and inhibit the spark; in such cases, a plug with less protrusion than the engine would normally call for often collects less fouling

and performs better, for a longer period. In fact, special "antifouling" adapters are sold which fit between the plug and the head to reduce the protrusion of the plug for just this reason, on older engines with severe oil burning problems; this will cause the ignition of the fuel-air mixture to be less effective, but in such cases, this is of lesser significance.

Heat range

The operating temperature of a spark plug is the actual physical temperature at the tip of the spark plug within the running engine. This is determined by a number of factors, but primarily the actual temperature within the combustion chamber. There is no direct relationship between the actual operating temperature of the spark plug and spark voltage. However, the level of torque currently being produced by the engine will strongly influence spark plug operating temperature because the maximum temperature and pressure occurs when the engine is operating near peak torque output (torque and RPM directly determine the power output). The temperature of the insulator responds to the thermal conditions it is exposed to in the combustion chamber but not vice versa. If the tip of the spark plug is too hot it can cause pre-ignition or sometimes detonation/knocking and damage may occur. If it is too cold, electrically conductive deposits may form on the insulator causing a loss of spark energy or the actual shorting-out of the spark current.

A spark plug is said to be "hot" if it is a better heat insulator, keeping more heat in the tip of the spark plug. A spark plug is said to be "cold" if it can conduct more heat out of the spark plug tip and lower the tip's temperature. Whether a spark plug is "hot" or "cold" is known as the heat range of the spark plug. The heat range of a spark plug is typically specified as a number, with some manufacturers using ascending numbers for hotter plugs and others doing the opposite, using ascending numbers for colder plugs.

The heat range of a spark plug (i.e. in scientific terms its thermal conductivity characteristics) is affected by the construction of the spark plug: the types of materials used, the length of insulator and the surface area of the plug exposed within the combustion chamber. For normal use, the selection of a spark plug heat range is a balance between keeping the tip hot enough at idle to prevent fouling and cold enough at maximum power to prevent pre-ignition or engine knocking. By examining "hotter" and "cooler" spark plugs of the same manufacturer side by side, the principle involved can be very clearly seen; the cooler plugs have a less substantial ceramic insulator filling the gap between the center electrode and the shell, effectively allowing more heat to be carryed off by the shell, while the hotter plugs have more ceramic material, so that the tip is more isolated from the body of the plug and retains heat better.

Heat from the combustion chamber escapes through the exhaust gases, the side walls of the cylinder and the spark plug itself. The heat range of a spark plug has only a minute effect on combustion chamber and overall engine temperature. A cold plug will not materially cool down an engine's running temperature. (Too hot of a plug may, however, indirectly lead to a runaway pre-ignition condition that *can* increase engine temperature.)

Rather, the main effect of a "hot" or "cold" plug is to affect the temperature of the tip of the spark plug.

It was common before the modern era of computerized fuel injection to specify at least a couple of different heat ranges for plugs for an automobile engine; a hotter plug for cars which were mostly driven slowly around the city, and a colder plug for sustained high speed highway use. This practice has, however, largely become obsolete now that cars' fuel/air mixtures and cylinder temperatures are maintained within a narrow range, for purposes of limiting emissions. Racing engines, however, still benefit from picking a proper plug heat range. Very old racing engines will sometimes have two sets of plugs, one just for starting and another to be installed once the engine is warmed up, for actually driving the car.

Spark plug manufacturers use different numbers to denote heat range of their spark plugs.

Reading spark plugs

The spark plug's firing end will be affected by the internal environment of the combustion chamber. As the spark plug can be removed for inspection, the effects of combustion on the plug can be examined. An examination, or "reading" of the characteristic markings on the firing end of the spark plug can indicate conditions within the running engine. The spark plug tip will bear the marks as evidence of what is happening inside the engine. Usually there is no other way to know what is going on inside an engine running at peak power. Engine and spark plug manufacturers will publish information about the characteristic markings in spark plug reading charts. Such charts are useful for general use but are of almost no use in reading racing engine spark plugs, which is an entirely different matter.

A light brownish discoloration of the tip of the block indicates proper operation; other conditions may indicate malfunction. For example, a sandblasted look to the tip of the spark plug means persistent, light detonation is occurring, often unheard. The damage that is occurring to the tip of the spark plug is also occurring on the inside of the cylinder. Heavy detonation can cause outright breakage of the spark plug insulator and internal engine parts before appearing as sandblasted erosion but is easily heard. As another example, if the plug is too cold, there will be deposits on the nose of the plug. Conversely if the plug is too hot, the porcelain will be porous looking, almost like sugar. The material which seals the central electrode to the insulator will boil out. Sometimes the end of the plug will appear glazed, as the deposits have melted.

An idling engine will have a different impact on the spark plugs than one running at full throttle. Spark plug readings are only valid for the most recent engine operating conditions and running the engine under different conditions may erase or obscure characteristic marks previously left on the spark plugs. Thus, the most valuable information is gathered by running the engine at high speed and full load, immediately cutting the ignition off and stopping without idling or low speed operation and removing the plugs for reading.

Spark plug reading viewers, which are simply combined flashlight/magnifiers, are available to improve the reading of the spark plugs.

Two spark plug viewers

Indexing spark plugs

A matter of some debate is the "indexing" of plugs upon installation, usually only for high performance or racing applications; this involves installing them so that the open area of the spark gap, not shrouded by the ground electrode, faces the centre of the combustion chamber, towards the intake valve, rather than the wall. Some engine tuners believe that this will maximize the exposure of the fuel-air mixture to the spark, also ensuring that every combustion chamber is an even in layout and therefore result in better ignition ; others, however, believe that this is useful only to keep the ground electrode out of the way of the piston in ultra-high-compression engines if clearance is insufficient. In any event, this is accomplished by marking the location of the gap on the outside of the plug, installing it, and noting the direction in which the mark faces; then the plug is removed and additional washers are added so as to change the orientation of the tightened plug. This must be done individually for each plug, as the orientation of the gap with respect to the threads of the shell is random. Some plugs are made with a non-random orientation of the gap and are usually marked as such by a suffix to the model number; typically these are specified by manufacturers of very small engines where the spark plug tip and electrodes form a significantly large part of the shape of the combustion chamber.

Chapter-11

Flux-cored Arc Welding and Electroslag Welding

Flux-cored arc welding

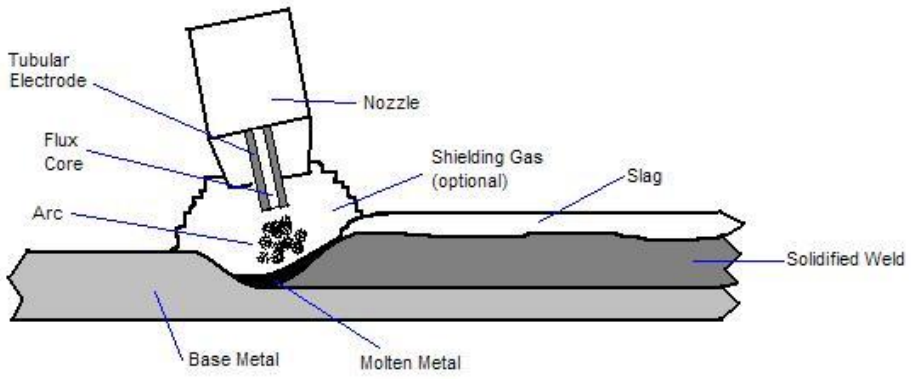
FCAW wire feeder

Flux-cored arc welding (**FCAW** or **FCA**) is a semi-automatic or automatic arc welding process. FCAW requires a continuously-fed consumable tubular electrode containing a flux and a constant-voltage or, less commonly, a constant-current welding power supply. An externally supplied shielding gas is sometimes used, but often the flux itself is relied upon to generate the necessary protection from the atmosphere. The process is widely used in construction because of its high welding speed and portability.

FCAW was first developed in the early 1950s as an alternative to shielded metal arc welding (SMAW). The advantage of FCAW over SMAW is that the use of the stick electrodes used in SMAW is unnecessary. This helped FCAW to overcome many of the restrictions associated with SMAW.

Types

One type of FCAW requires no shielding gas. This is made possible by the flux core in the tubular consumable electrode. However, this core contains more than just flux, it also contains various ingredients that when exposed to the high temperatures of welding generate a shielding gas for protecting the arc. This type of FCAW is attractive because it is portable and generally has good penetration into the base metal. Also, windy conditions need not be considered. Some disadvantages are that this process can produce excessive, noxious smoke; under some conditions it can produce welds with inferior mechanical properties; the slag is often difficult and time-consuming to remove; and operator skill can be a major factor.



A drawing of FCAW at the weld point

Another type of FCAW uses a shielding gas that must be supplied by an external supply. This is known informally as "dual shield" welding. This type of FCAW was developed primarily for welding structural steels. In fact, since it uses both a flux-cored electrode and an external shielding gas, one might say that it is a combination of gas metal (GMAW) and flux-cored arc welding (FCAW). This particular style of FCAW is preferable for welding thicker and out-of-position metals. The slag created by the flux is also easy to remove. The main advantages of this process is that in a closed shop

environment, it generally produces welds of better and more consistent mechanical properties, with fewer weld defects than either the SMAW or GMAW processes. In practice it also allows a higher production rate, since the operator does not need to stop periodically to fetch a new electrode, as is the case in SMAW. However, like GMAW, it cannot be used in a windy environment as the loss of the shielding gas from air flow will produce visible porosity (small craters) on the surface of the weld.

Process variables

- Wire feed speed (and current)
- Arc voltage
- Electrode extension
- Travel speed and angle
- Electrode angles
- Electrode wire type
- Shielding gas composition (if required) Note: FCAW wires that don't require a shielding gas commonly emit fumes that are **extremely** toxic; these require adequate ventilation or the use of a sealed mask that will provide the welder with fresh air.

Advantages and applications

- FCAW may be an "all-position" process with the right filler metals (the consumable electrode)
- No shielding gas needed making it suitable for outdoor welding and/or windy conditions
- A high-deposition rate process (speed at which the filler metal is applied) in the 1G/1F/2F
- Some "high-speed" (e.g., automotive applications)
- Less precleaning of metal required
- Metallurgical benefits from the flux such as the weld metal being protected initially from external factors until the flux is chipped away

Used on the following alloys:

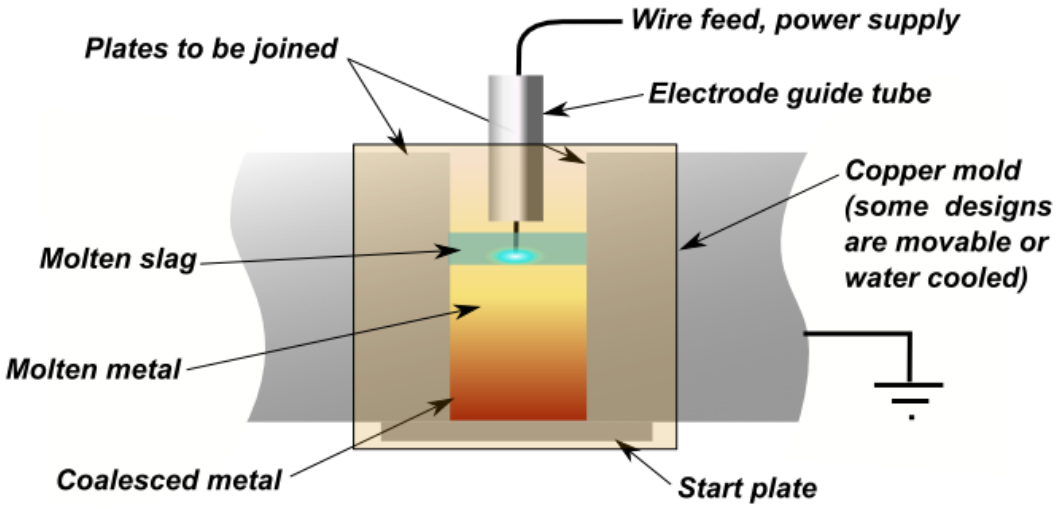
- Mild and low alloy steels
- Stainless steels
- Some high nickel alloys
- Some wearfacing/surfacing alloys

Disadvantages

Of course, all of the usual issues that occur in welding can occur in FCAW such as incomplete fusion between base metals, slag inclusion (non-metallic inclusions), and cracks in the welds. But there are a few concerns that come up with FCAW that are worth taking special note of:

- Melted Contact Tip – happens when the electrode actually contacts the base metal, thereby fusing the two
- Irregular wire feed – typically a mechanical problem
- Porosity – the gases (specifically those from the flux-core) don't escape the welded area before the metal hardens, leaving holes in the welded metal
- More costly filler material/wire as compared to GMAW

Electroslag welding



Electroslag welding (ESW) is a highly productive, single pass welding process for thick (greater than 25mm up to about 300mm) materials in a vertical or close to vertical position. (ESW) is similar to electrogas welding, but the main difference is the arc starts in a different location. An electric arc is initially struck by wire that is fed into the desired weld location and then flux is added. Additional flux is added until the molten slag, reaching the tip of the electrode, extinguishes the arc. The wire is then continually fed through a consumable guide tube (can oscillate if desired) into the surfaces of the metal workpieces and the filler metal are then melted using the electrical resistance of the molten slag to cause coalescence. The wire and tube then move up along the workpiece while a copper retaining shoe that was put into place before starting (can be water cooled if desired) is used to keep the weld between the plates that are being welded. Electroslag welding is used mainly to join low carbon steel plates and/or sections that are very thick. It can also be used on structural steel if certain precautions are observed. This process uses a direct current (DC) voltage usually ranging from about 600A and 40-50V, higher currents are needed for thicker materials. Because the arc is extinguished, this is not an arc process.

History

The process was patented by Robert K Hopkins in the United States in February 1940 (patent 2191481) and developed and refined at the Paton Institute, Kiev, USSR during the 1940s. The Paton method was released to the west at the Bruxelles Trade Fair of 1950. The first widespread use in the U.S. was in 1959, by General Motors Electromotive Division, Chicago, for the fabrication of engine blocks. In 1968 Hobart Brothers of Troy, Ohio, released a range of machines for use in the shipbuilding, bridge construction and large structural fabrication industries. Between the late 1960s and late 1980s, it is estimated that only in California was welded over a million stiffeners with the electroslag welding process. Two of the tallest buildings in California were welded, using the electroslag welding process - The Bank of America building in San Francisco, and the twin tower Security Pacific buildings in Los Angeles. The Northridge Earthquake and the Loma Prieta Earthquakes provided a "real world" test to compare all of the welding processes. The Structural Steel welding industry is well aware that, over one billion dollars in crack repairs were needed, after the Northridge earthquake, to repair weld cracks propagated in welds made with the gasless flux cored wire process. Not one failure or one crack propagation was initiated in any of the hundreds-of-thousands of welds made on continuity plates welded with the Electroslag welding process. The History Of Electroslag Welding For High Rise Building And Bridges

However the Federal Highway Administration (FHWA) monitored the new process and found that electroslag welding, because of the very large amounts of confined heat used, produced a coarse-grained and brittle weld and in 1977 banned the use of the process for many applications. The FHWA commissioned research from universities and industry and **Narrow Gap Improved Electro Slag Welding (NGI-ESW)** was developed as a replacement. The FHWA moratorium was rescinded in 2000.

Benefits

Benefits of the process include its high metal deposition rates—it can lay metal at a rate between 15 and 20 kg per hour (35 and 45 lb/h) per electrode—and its ability to weld thick materials. Many welding processes require more than one pass for welding thick workpieces, but often a single pass is sufficient for electroslag welding. The process is also very efficient, since joint preparation and materials handling are minimized while filler metal utilization is high. The process is also safe and clean, with no arc flash and low weld splatter or distortion. Electroslag welding easily lends itself to mechanization, thus reducing the requirement for skilled manual welders.

One electrode is commonly used to make welds on materials with a thickness of 25 to 75 mm (1 to 3 in), and thicker pieces generally require more electrodes. The maximum workpiece thickness that has ever been successfully welded was a 0.91 m (36 in) piece that required the simultaneous use of six electrodes to complete.

Chapter-12

Gas Metal Arc Welding

Gas metal arc welding

Gas metal arc welding (GMAW), sometimes referred to by its subtypes **metal inert gas (MIG) welding** or **metal active gas (MAG) welding**, is a semi-automatic or automatic

arc welding process in which a continuous and consumable wire electrode and a shielding gas are fed through a welding gun. A constant voltage, direct current power source is most commonly used with GMAW, but constant current systems, as well as alternating current, can be used. There are four primary methods of metal transfer in GMAW, called globular, short-circuiting, spray, and pulsed-spray, each of which has distinct properties and corresponding advantages and limitations.

Originally developed for welding aluminum and other non-ferrous materials in the 1940s, GMAW was soon applied to steels because it allowed for lower welding time compared to other welding processes. The cost of inert gas limited its use in steels until several years later, when the use of semi-inert gases such as carbon dioxide became common. Further developments during the 1950s and 1960s gave the process more versatility and as a result, it became a highly used industrial process. Today, GMAW is the most common industrial welding process, preferred for its versatility, speed and the relative ease of adapting the process to robotic automation. The automobile industry in particular uses GMAW welding almost exclusively. Unlike welding processes that do not employ a shielding gas, such as shielded metal arc welding, it is rarely used outdoors or in other areas of air volatility. A related process, flux cored arc welding, often does not utilize a shielding gas, instead employing a hollow electrode wire that is filled with flux on the inside.

Development

The principles of gas metal arc welding began to be understood in the early 19th century, after Humphry Davy discovered the short pulsed electric arcs in 1800 and then Vasily Petrov independently produced the continuous electric arc in 1802 (soon followed by Davy). In his work published in 1803 Petrov proposed the usage of electric arc in welding, having managed to perform a simple experimental welding. But it was not until the 1880s that the technology became developed with the aim of industrial usage. At first, the practical method of carbon arc welding invented by Nikolay Benardos was used, utilising carbon electrodes known from the time of Davy and Petrov. By the late 1880s, metal electrodes had been invented by Nikolay Slavyanov (1888) and C. L. Coffin (1890). In 1920, an early predecessor of GMAW was invented by P. O. Nobel of General Electric. It used a bare electrode wire and direct current, and used arc voltage to regulate the feed rate. It did not use a shielding gas to protect the weld, as developments in welding atmospheres did not take place until later that decade. In 1926 another forerunner of GMAW was released, but it was not suitable for practical use.

It was not until 1948 that GMAW was finally developed by the Battelle Memorial Institute. It used a smaller diameter electrode and a constant voltage power source, which had been developed by H. E. Kennedy. It offered a high deposition rate, but the high cost of inert gases limited its use to non-ferrous materials and cost savings were not obtained. In 1953, the use of carbon dioxide as a welding atmosphere was developed, and it quickly gained popularity in GMAW, since it made welding steel more economical. In 1958 and 1959, the short-arc variation of GMAW was released, which increased welding versatility and made the welding of thin materials possible while relying on smaller electrode wires

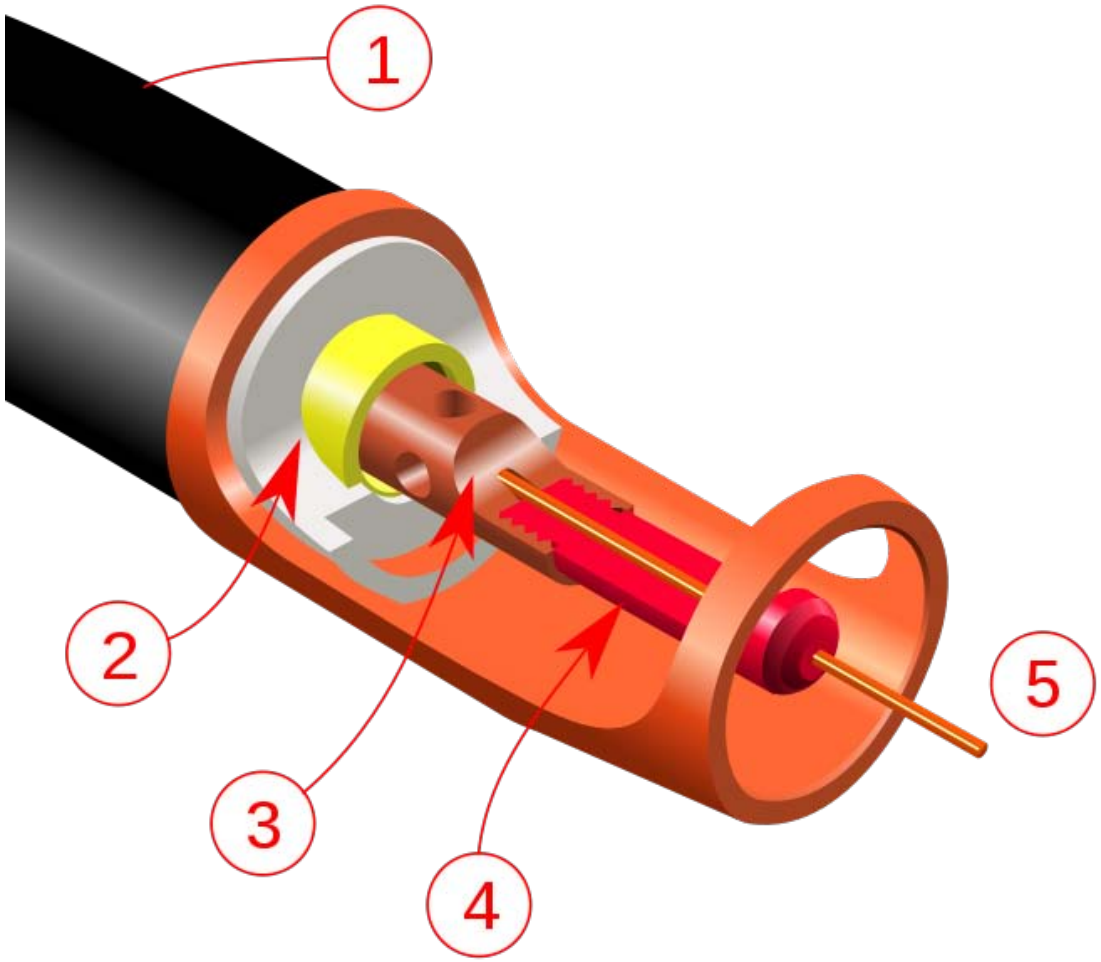
and more advanced power supplies. It quickly became the most popular GMAW variation. The spray-arc transfer variation was developed in the early 1960s, when experimenters added small amounts of oxygen to inert gases. More recently, pulsed current has been applied, giving rise to a new method called the pulsed spray-arc variation.

As noted, GMAW is currently one of the most popular welding methods, especially in industrial environments. It is used extensively by the sheet metal industry and, by extension, the automobile industry. There, the method is often used for arc spot welding, thereby replacing riveting or resistance spot welding. It is also popular for automated welding, in which robots handle the workpieces and the welding gun to speed up the manufacturing process. Generally, it is unsuitable for welding outdoors, because the movement of the surrounding air can dissipate the shielding gas and thus make welding more difficult, while also decreasing the quality of the weld. The problem can be alleviated to some extent by increasing the shielding gas output, but this can be expensive and may also affect the quality of the weld. In general, processes such as shielded metal arc welding and flux cored arc welding are preferred for welding outdoors, making the use of GMAW in the construction industry rather limited. Furthermore, the use of a shielding gas makes GMAW an unpopular underwater welding process, but can be used in space since there is no oxygen to oxidize the weld.

Equipment

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

Welding gun and wire feed unit



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

GMAW on stainless steel

The typical GMAW welding gun has a number of key parts—a control switch, a contact tip, a power cable, a gas nozzle, an electrode conduit and liner, and a gas hose. The control switch, or trigger, when pressed by the operator, initiates the wire feed, electric power, and the shielding gas flow, causing an electric arc to be struck. The contact tip, normally made of copper and sometimes chemically treated to reduce spatter, is connected to the welding power source through the power cable and transmits the electrical energy to the electrode while directing it to the weld area. It must be firmly secured and properly sized, since it must allow the passage of the electrode while maintaining an electrical contact. Before arriving at the contact tip, the wire is protected and guided by the electrode conduit and liner, which help prevent buckling and maintain an uninterrupted wire feed. The gas nozzle is used to evenly direct the shielding gas into the welding zone—if the flow is inconsistent, it may not provide adequate protection of the weld area. Larger nozzles provide greater shielding gas flow, which is useful for high current welding operations, in which the size of the molten weld pool is increased. The gas is supplied to the nozzle through a gas hose, which is connected to the tanks of shielding gas. Sometimes, a water hose is also built into the welding gun, cooling the gun in high heat operations.

The wire feed unit supplies the electrode to the work, driving it through the conduit and on to the contact tip. Most models provide the wire at a constant feed rate, but more advanced machines can vary the feed rate in response to the arc length and voltage. Some wire feeders can reach feed rates as high as 30.5 m/min (1200 in/min), but feed rates for semiautomatic GMAW typically range from 2 to 10 m/min (75–400 in/min).

Welding Gun Types

The most common welding gun is a hand held air-cooled gun, it is used for general welding. The second most common type of welding torch is water-cooled, it uses higher current levels for heavier sections and larger wire diameters. The third typical holder type is an automatic gun that is water cooled; this gun is used typically with automated equipment.

Power supply

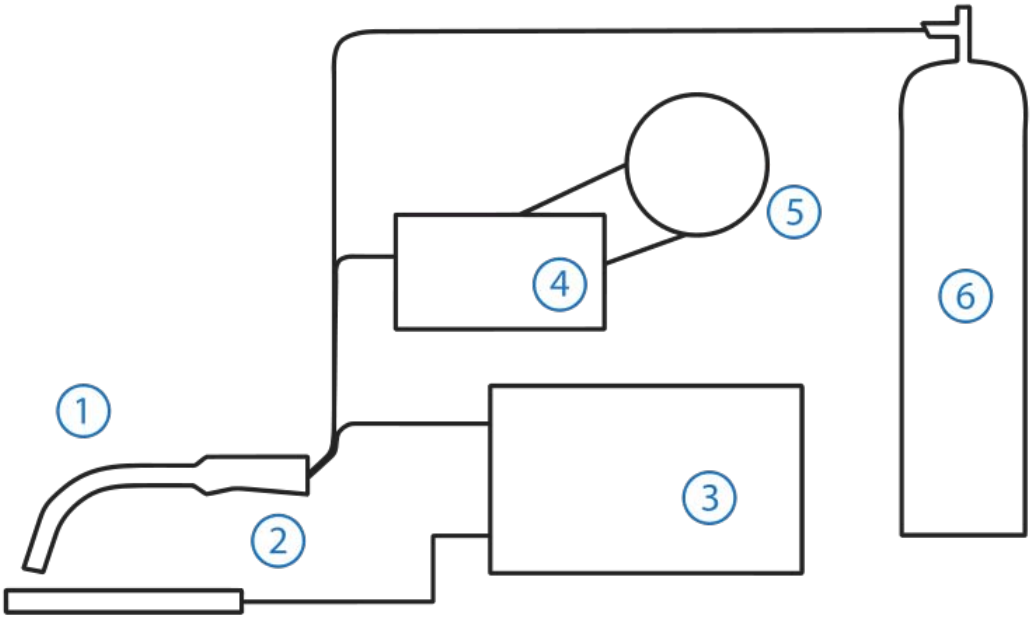
Most applications of gas metal arc welding use a constant voltage power supply. As a result, any change in arc length (which is directly related to voltage) results in a large change in heat input and current. A shorter arc length will cause a much greater heat input, which will make the wire electrode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

Alternating current is rarely used with GMAW; instead, direct current is employed and the electrode is generally positively charged. Since the anode tends to have a greater heat concentration, this results in faster melting of the feed wire, which increases weld penetration and welding speed. The polarity can be reversed only when special emissive-coated electrode wires are used, but since these are not popular, a negatively charged electrode is rarely employed.

Electrode

Electrode selection is based primarily on the composition of the metal being welded, the process variation being used, joint design and the material surface conditions. Electrode selection greatly influences the mechanical properties of the weld and is a key factor of weld quality. In general the finished weld metal should have mechanical properties similar to those of the base material with no defects such as discontinuities, entrained contaminants or porosity within the weld. To achieve these goals a wide variety of electrodes exist. All commercially available electrodes contain deoxidizing metals such

as silicon, manganese, titanium and aluminum in small percentages to help prevent oxygen porosity. Some contain denitriding metals such as titanium and zirconium to avoid nitrogen porosity. Depending on the process variation and base material being welded the diameters of the electrodes used in GMAW typically range from 0.7 to 2.4 mm (0.028–0.095 in) but can be as large as 4 mm (0.16 in). The smallest electrodes, generally up to 1.14 mm (0.045 in) are associated with the short-circuiting metal transfer process, while the most common spray-transfer process mode electrodes are usually at least 0.9 mm (0.035 in).



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

Shielding gas

Shielding gases are necessary for gas metal arc welding to protect the welding area from atmospheric gases such as nitrogen and oxygen, which can cause fusion defects, porosity, and weld metal embrittlement if they come in contact with the electrode, the arc, or the welding metal. This problem is common to all arc welding processes; for example, in the older Shielded-Metal Arc Welding process (SMAW), the electrode is coated with a solid flux which evolves a protective cloud of carbon dioxide when melted by the arc. In GMAW, however, the electrode wire does not have a flux coating, and a separate shielding gas is employed to protect the weld. This eliminates slag, the hard residue from the flux that builds up after welding and must be chipped off to reveal the completed weld.

The choice of a shielding gas depends on several factors, most importantly the type of material being welded and the process variation being used. Pure inert gases such as

argon and helium are only used for nonferrous welding; with steel they do not provide adequate weld penetration (argon) or cause an erratic arc and encourage spatter (with helium). Pure carbon dioxide, on the other hand, allows for deep penetration welds but encourages oxide formation, which adversely affect the mechanical properties of the weld. Its low cost makes it an attractive choice, but because of the reactivity of the arc plasma, spatter is unavoidable and welding thin materials is difficult. As a result, argon and carbon dioxide are frequently mixed in a 75%/25% to 90%/10% mixture. Generally, in short circuit GMAW, higher carbon dioxide content increases the weld heat and energy when all other weld parameters (volts, current, electrode type and diameter) are held the same. As the carbon dioxide content increases over 20%, spray transfer GMAW becomes increasingly problematic, especially with smaller electrode diameters.

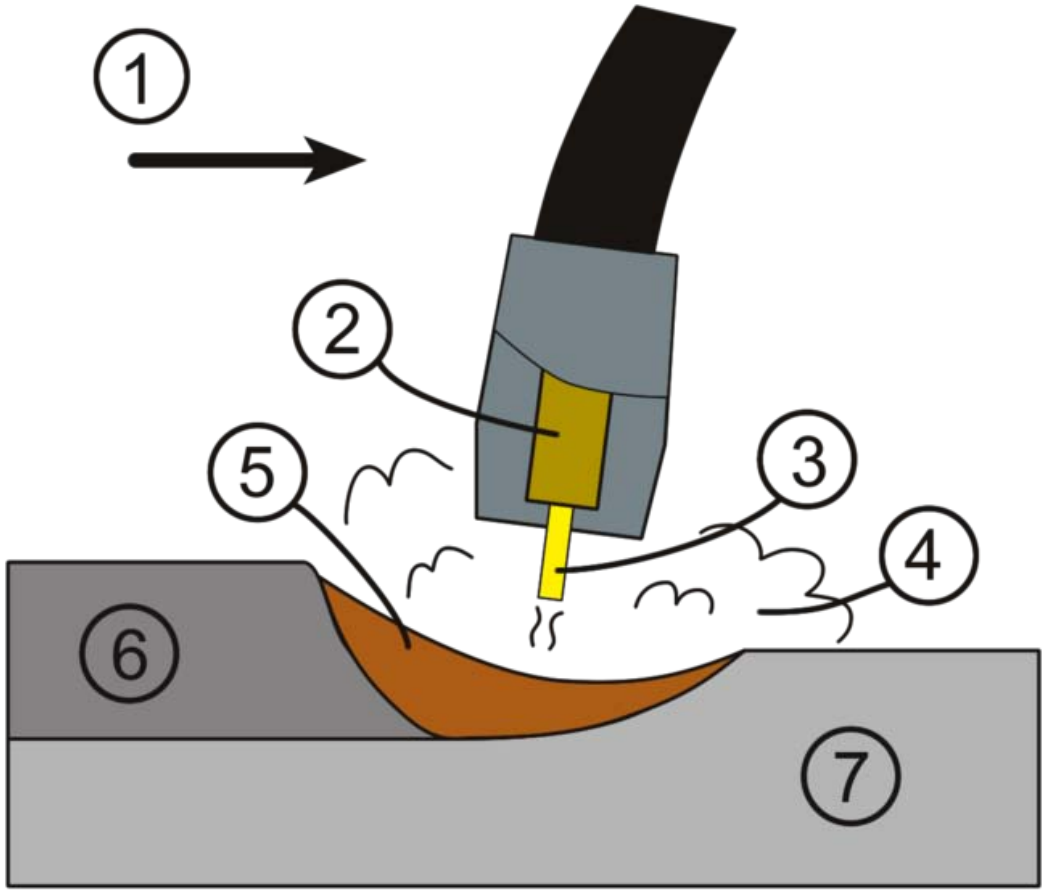
Argon is also commonly mixed with other gases, oxygen, helium, hydrogen, and nitrogen. The addition of up to 5% oxygen (like the higher concentrations of carbon dioxide mentioned above) can be helpful in welding stainless steel, however, in most applications carbon dioxide is preferred. Increased oxygen makes the shielding gas oxidize the electrode, which can lead to porosity in the deposit if the electrode does not contain sufficient deoxidizers. Excessive oxygen, especially when used in application for which it is not prescribed, can lead to brittleness in the heat affected zone. Argon-helium mixtures are extremely inert, and can be used on nonferrous materials. A helium concentration of 50%–75% raises the required voltage and increases the heat in the arc, due to helium's higher ionization temperature. Hydrogen is sometimes added to argon in small concentrations (up to about 5%) for welding nickel and thick stainless steel workpieces. In higher concentrations (up to 25% hydrogen), it may be used for welding conductive materials such as copper. However, it should not be used on steel, aluminum or magnesium because it can cause porosity and hydrogen embrittlement. Additionally, nitrogen is sometimes added to argon to a concentration of 25%–50% for welding copper, but the use of nitrogen, especially in North America, is limited.

Shielding gas mixtures of three or more gases are also available. Mixtures of argon, carbon dioxide and oxygen are marketed for welding steels. Other mixtures add a small amount of helium to argon-oxygen combinations, these mixtures are claimed to allow higher arc voltages and welding speed. Helium is also sometimes used as the base gas, with small amounts of argon and carbon dioxide added. However, because it is less dense than air, helium is less effective in shielding the weld than argon– which is denser than air. It also can lead to arc stability and penetration issues, and increased spatter, due to its much more energetic arc plasma. Helium is also substantially more expensive than other shielding gases. Other specialized and often proprietary gas mixtures claim even greater benefits for specific applications.

The desirable rate of shielding-gas flow depends primarily on weld geometry, speed, current, the type of gas, and the metal transfer mode being utilized. Welding flat surfaces requires higher flow than welding grooved materials, since the gas is dispersed more quickly. Faster welding speeds, in general, mean that more gas needs to be supplied to provide adequate coverage. Additionally, higher current requires greater flow, and generally, more helium is required to provide adequate coverage than if argon is used.

Perhaps most importantly, the four primary variations of GMAW have differing shielding gas flow requirements—for the small weld pools of the short circuiting and pulsed spray modes, about 10 L/min (20 ft³/h) is generally suitable, whereas for globular transfer, around 15 L/min (30 ft³/h) is preferred. The spray transfer variation normally requires more shielding-gas flow because of its higher heat input and thus larger weld pool. Typical gas-flow amounts are approximately 20–25 L/min (40–50 ft³/h).

Operation



GMAW weld area. **(1)** Direction of travel, **(2)** Contact tube, **(3)** Electrode, **(4)** Shielding gas, **(5)** Molten weld metal, **(6)** Solidified weld metal, **(7)** Workpiece.

For most of its applications gas metal arc welding is a fairly simple welding process to learn requiring no more than a week or two to master basic welding technique. Even when welding is performed by well-trained operators weld quality can fluctuate since it depends on a number of external factors. All GMAW is dangerous, though perhaps less so than some other welding methods, such as shielded metal arc welding.

Technique

The basic technique for GMAW is quite simple, since the electrode is fed automatically through the torch. By contrast, in gas tungsten arc welding, the welder must handle a welding torch in one hand and a separate filler wire in the other, and in shielded metal arc welding, the operator must frequently chip off slag and change welding electrodes. GMAW requires only that the operator guide the welding gun with proper position and orientation along the area being welded. Keeping a consistent contact tip-to-work distance (the *stick out* distance) is important, because a long stickout distance can cause the electrode to overheat and will also waste shielding gas. Stickout distance varies for different GMAW weld processes and applications. For short-circuit transfer, the stickout is generally 1/4 inch to 1/2 inch, for spray transfer the stickout is generally 1/2 inch. The position of the end of the contact tip to the gas nozzle are related to the stickout distance and also varies with transfer type and application. The orientation of the gun is also important—it should be held so as to bisect the angle between the workpieces; that is, at 45 degrees for a fillet weld and 90 degrees for welding a flat surface. The travel angle, or lead angle, is the angle of the torch with respect to the direction of travel, and it should generally remain approximately vertical. However, the desirable angle changes somewhat depending on the type of shielding gas used—with pure inert gases, the bottom of the torch is often slightly in front of the upper section, while the opposite is true when the welding atmosphere is carbon dioxide.

Quality

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

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

Safety

Gas metal arc welding can be dangerous if proper precautions are not taken. Since GMAW employs an electric arc, welders wear protective clothing, including heavy leather gloves and protective long sleeve jackets, to avoid exposure to extreme heat and flames. In addition, the brightness of the electric arc is a source of the condition known as arc eye, an inflammation of the cornea caused by ultraviolet light and, in prolonged exposure, possible burning of the retina in the eye. Conventional welding helmets contain dark face plates to prevent this exposure. Newer helmet designs feature a liquid crystal-type face plate that self-darken upon exposure to high amounts of UV light. Transparent welding curtains, made of a polyvinyl chloride plastic film, are often used to shield nearby workers and bystanders from exposure to the UV light from the electric arc.

Welders are also often exposed to dangerous gases and particulate matter. GMAW produces smoke containing particles of various types of oxides, and the size of the particles in question tends to influence the toxicity of the fumes, with smaller particles presenting a greater danger. Additionally, carbon dioxide and ozone gases can prove dangerous if ventilation is inadequate. Furthermore, because the use of compressed gases in GMAW pose an explosion and fire risk, some common precautions include limiting the amount of oxygen in the air and keeping combustible materials away from the workplace. While porosity usually results from atmospheric contamination, too much shielding gas has a similar effect; if the flow rate is too high it may create a vortex that draws in the surrounding air, thereby contaminating the weld pool as it cools. The gas output should be felt (as a cool breeze) on a dry hand but not enough to create any noticeable pressure, this equates to between 20–25 psi (mild and stainless steel). Above 26 volts the gas debit should be augmented slightly since the weld pool takes longer to cool. As a factor that is often ignored, many flow meters are never adjusted and typically run between 35–45 psi. A healthy reduction of gas will not affect the quality of the weld, will save money on shielding gas and reduce the rate at which the tank must be replaced.

Metal transfer modes

The three transfer modes in GMAW are globular, short-circuiting, and spray. There are a few recognized variations of these three transfer modes including modified short-circuiting and pulsed-spray.

Globular

GMAW with globular metal transfer is often considered the most undesirable of the three major GMAW variations, because of its tendency to produce high heat, a poor weld surface, and spatter. The method was originally developed as a cost efficient way to weld steel using GMAW, because this variation uses carbon dioxide, a less expensive shielding gas than argon. Adding to its economic advantage was its high deposition rate, allowing welding speeds of up to 110 mm/s (250 in/min). As the weld is made, a ball of molten metal from the electrode tends to build up on the end of the electrode, often in irregular shapes with a larger diameter than the electrode itself. When the droplet finally detaches

either by gravity or short circuiting, it falls to the workpiece, leaving an uneven surface and often causing spatter. As a result of the large molten droplet, the process is generally limited to flat and horizontal welding positions. The high amount of heat generated also is a downside, because it forces the welder to use a larger electrode wire, increases the size of the weld pool, and causes greater residual stresses and distortion in the weld area.

Short-circuiting

Further developments in welding steel with GMAW led to a variation known as short-circuiting or short-arc GMAW, in which the current is lower than for the globular method. As a result of the lower current, the heat input for the short-arc variation is considerably reduced, making it possible to weld thinner materials while decreasing the amount of distortion and residual stress in the weld area. As in globular welding, molten droplets form on the tip of the electrode, but instead of dropping to the weld pool, they bridge the gap between the electrode and the weld pool as a result of the lower wire feed rate. This causes a short circuit and extinguishes the arc, but it is quickly reignited after the surface tension of the weld pool pulls the molten metal bead off the electrode tip. This process is repeated about 100 times per second, making the arc appear constant to the human eye. This type of metal transfer provides better weld quality and less spatter than the globular variation, and allows for welding in all positions, albeit with slower deposition of weld material. Setting the weld process parameters (volts, amps and wire feed rate) within a relatively narrow band is critical to maintaining a stable arc: generally between 100 to 200 amps at 17 to 22 volts for most applications. Also, using short-arc transfer can result in lack of fusion and insufficient penetration when welding thicker materials, due to the lower arc energy and rapidly freezing weld pool. Like the globular variation, it can only be used on ferrous metals.

Modified short-circuiting

There are proprietary derivatives of the short-circuiting transfer mode which use a modified waveform to reduce some of the problems found with short-circuiting, mainly spatter and a turbulent weld pool. Typically these systems sense the progression of the short circuit as it happens and modulate the current to limit the amount of force behind spatter and turbulence-producing events. Several manufacturers now sell welding power supplies which employ technology to this end: Miller Electric has a process called Regulated Metal Deposition (RMD), while Lincoln Electric sells their process called Surface Tension Transfer (STT). Other companies take a different approach to making short circuit transfer usable: Fronius has a technique called Cold Metal Transfer (CMT) which physically withdraws the electrode from the welding puddle at a certain rate and pattern.

RMD and STT achieve the modified short circuiting via software that controls the current. The RMD process breaks the process into seven steps:

1. **Wet**: Let the ball on the end of the wire wet-out to the puddle.
2. **Pinch**: Increase the current to a level high enough to initiate a pinch effect.

3. **Clear**: Maintain and slightly increase the pinch current to clear the short circuit while simultaneously watching for pinch detection.
4. **Blink**: Upon pinch detection, rapidly decrease the current. Pinch detection occurs before the short clears. The inverter "shuts off" and current decays to a low level before the short circuit breaks.
5. **Ball**: Increase current to form a ball for the next short circuit.
6. **Background**: Drop the current to a low enough level to allow a short circuit to occur.
7. **Pre-short**: If the background current exists for a relatively long time, the pre-short period drops current to an even lower level to make sure arc force does not produce excessive puddle agitation.

Spray

Spray transfer GMAW was the first metal transfer method used in GMAW, and well-suited to welding aluminum and stainless steel while employing an inert shielding gas. In this GMAW process, the weld electrode metal is rapidly passed along the stable electric arc from the electrode to the workpiece, essentially eliminating spatter and resulting in a high-quality weld finish. As the current and voltage increases beyond the range of short circuit transfer the weld electrode metal transfer transitions from larger globules through small droplets to a vaporized stream at the highest energies. Since this vaporized spray transfer variation of the GMAW weld process requires higher voltage and current than short circuit transfer, and as a result of the higher heat input and larger weld pool area (for a given weld electrode diameter), it is generally used only on workpieces of thicknesses above about 6.4 mm (0.25 in). Also, because of the large weld pool, it is often limited to flat and horizontal welding positions and sometimes also used for vertical-down welds. It is generally not practical for root pass welds. When a smaller electrode is used in conjunction with lower heat input, its versatility increases. The maximum deposition rate for spray arc GMAW is relatively high; about 60 mm/s (150 in/min).

Pulsed-spray

A variation of the spray transfer mode, pulse-spray is based on the principles of spray transfer but uses a pulsing current to melt the filler wire and allow one small molten droplet to fall with each pulse. The pulses allow the average current to be lower, decreasing the overall heat input and thereby decreasing the size of the weld pool and heat-affected zone while making it possible to weld thin workpieces. The pulse provides a stable arc and no spatter, since no short-circuiting takes place. This also makes the process suitable for nearly all metals, and thicker electrode wire can be used as well. The smaller weld pool gives the variation greater versatility, making it possible to weld in all positions. In comparison with short arc GMAW, this method has a somewhat slower maximum speed (85 mm/s or 200 in/min) and the process also requires that the shielding gas be primarily argon with a low carbon dioxide concentration. Additionally, it requires a special power source capable of providing current pulses with a frequency between 30 and 400 pulses per second. However, the method has gained popularity, since it requires

lower heat input and can be used to weld thin workpieces, as well as nonferrous materials.

Chapter-13

Gas Tungsten Arc Welding

TIG welding of a bronze sculpture

Gas tungsten arc welding (**GTAW**), also known as **tungsten inert gas** (**TIG**) **welding**, is an arc welding process that uses a nonconsumable tungsten electrode to produce the weld. The weld area is protected from atmospheric contamination by a shielding gas (usually an inert gas such as argon), and a filler metal is normally used, though some

welds, known as autogenous welds, do not require it. A constant-current welding power supply produces energy which is conducted across the arc through a column of highly ionized gas and metal vapors known as a plasma.

GTAW is most commonly used to weld thin sections of stainless steel and non-ferrous metals such as aluminum, magnesium, and copper alloys. The process grants the operator greater control over the weld than competing processes such as shielded metal arc welding and gas metal arc welding, allowing for stronger, higher quality welds. However, GTAW is comparatively more complex and difficult to master, and furthermore, it is significantly slower than most other welding techniques. A related process, plasma arc welding, uses a slightly different welding torch to create a more focused welding arc and as a result is often automated.

Development

After the discovery of the electric arc in 1800 by Humphry Davy, arc welding developed slowly. C. L. Coffin had the idea of welding in an inert gas atmosphere in 1890, but even in the early 20th century, welding non-ferrous materials like aluminum and magnesium remained difficult, because these metals reacted rapidly with the air, resulting in porous and dross-filled welds. Processes using flux-covered electrodes did not satisfactorily protect the weld area from contamination. To solve the problem, bottled inert gases were used in the beginning of the 1930s. A few years later, a direct current, gas-shielded welding process emerged in the aircraft industry for welding magnesium.

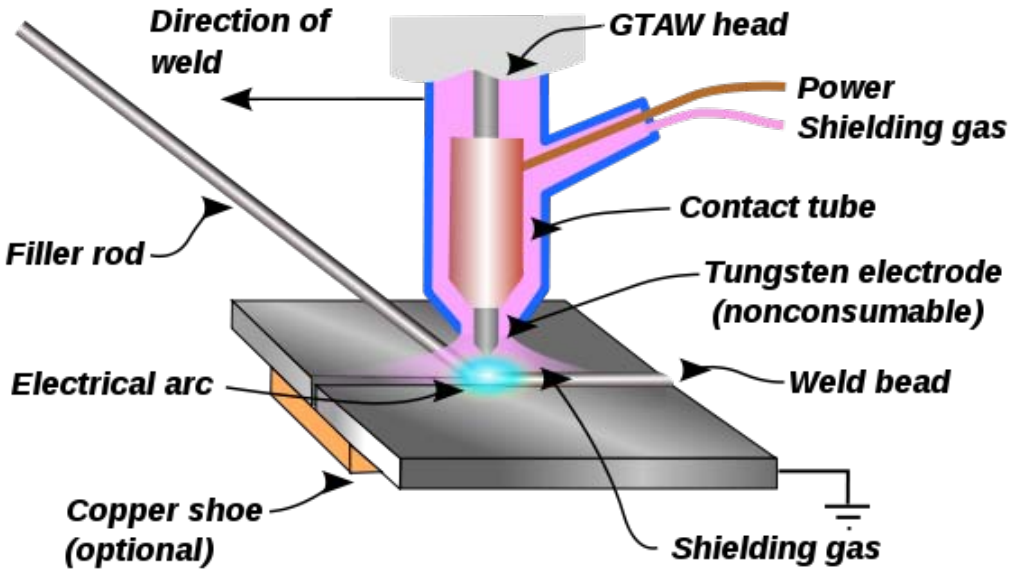
This process was perfected in 1941, and became known as heliarc or tungsten inert gas welding, because it utilized a tungsten electrode and helium as a shielding gas. Initially, the electrode overheated quickly, and in spite of tungsten's high melting temperature, particles of tungsten were transferred to the weld. To address this problem, the polarity of the electrode was changed from positive to negative, but this made it unsuitable for welding many non-ferrous materials. Finally, the development of alternating current units made it possible to stabilize the arc and produce high quality aluminum and magnesium welds.

Developments continued during the following decades. Linde Air Products developed water-cooled torches that helped to prevent overheating when welding with high currents. Additionally, during the 1950s, as the process continued to gain popularity, some users turned to carbon dioxide as an alternative to the more expensive welding atmospheres consisting of argon and helium. However, this proved unacceptable for welding aluminum and magnesium because it reduced weld quality, and as a result, it is rarely used with GTAW today.

In 1953, a new process based on GTAW was developed, called plasma arc welding. It affords greater control and improves weld quality by using a nozzle to focus the electric arc, but is largely limited to automated systems, whereas GTAW remains primarily a manual, hand-held method. Development within the GTAW process has continued as well, and today a number of variations exist. Among the most popular are the pulsed-

current, manual programmed, hot-wire, dabber, and increased penetration GTAW methods.

Operation



GTAW weld area

Manual gas tungsten arc welding is often considered the most difficult of all the welding processes commonly used in industry. Because the welder must maintain a short arc length, great care and skill are required to prevent contact between the electrode and the workpiece. Similar to torch welding, GTAW normally requires two hands, since most applications require that the welder manually feed a filler metal into the weld area with one hand while manipulating the welding torch in the other. However, some welds combining thin materials (known as autogenous or fusion welds) can be accomplished without filler metal; most notably edge, corner, and butt joints.

To strike the welding arc, a high frequency generator (similar to a Tesla coil) provides an electric spark; this spark is a conductive path for the welding current through the shielding gas and allows the arc to be initiated while the electrode and the workpiece are separated, typically about 1.5–3 mm (0.06–0.12 in) apart. This high voltage, high frequency burst can be damaging to some vehicle electrical systems and electronics, because induced voltages on vehicle wiring can also cause small conductive sparks in the vehicle wiring or within semiconductor packaging. Vehicle 12V power may conduct across these ionized paths, driven by the high-current 12V vehicle battery. These currents can be sufficiently destructive as to disable the vehicle; thus the warning to disconnect the vehicle battery power from both +12 and ground before using welding equipment on vehicles.

An alternate way to initiate the arc is the "scratch start". Scratching the electrode against the work with the power on also serve to strike an arc, in the same way as SMAW ("stick") arc welding. However, scratch starting can cause contamination of the weld and electrode. Some GTAW equipment is capable of a mode called "touch start" or "lift arc"; here the equipment reduces the voltage on the electrode to only a few volts, with a current limit of one or two amps (well below the limit that causes metal to transfer and contamination of the weld or electrode). When the GTAW equipment detects that the electrode has left the surface and a spark is present, it immediately (within microseconds) increases power, converting the spark to a full arc.

Once the arc is struck, the welder moves the torch in a small circle to create a welding pool, the size of which depends on the size of the electrode and the amount of current. While maintaining a constant separation between the electrode and the workpiece, the operator then moves the torch back slightly and tilts it backward about 10–15 degrees from vertical. Filler metal is added manually to the front end of the weld pool as it is needed.

Welders often develop a technique of rapidly alternating between moving the torch forward (to advance the weld pool) and adding filler metal. The filler rod is withdrawn from the weld pool each time the electrode advances, but it is never removed from the gas shield to prevent oxidation of its surface and contamination of the weld. Filler rods composed of metals with low melting temperature, such as aluminum, require that the operator maintain some distance from the arc while staying inside the gas shield. If held too close to the arc, the filler rod can melt before it makes contact with the weld puddle. As the weld nears completion, the arc current is often gradually reduced to allow the weld crater to solidify and prevent the formation of crater cracks at the end of the weld.

Operation modes

GTAW can use a positive direct current, negative direct current or an alternating current, depending on the power supply set up. A negative direct current from the electrode causes a stream of electrons to collide with the surface, generating large amounts of heat at the weld region. This creates a deep, narrow weld. In the opposite process where the electrode is connected to the positive power supply terminal, electrons flow from the part being welded to the tip of the electrode instead, so the heating action of the electrons is mostly on the electrode. This mode also helps to remove oxide layers from the surface of the region to be welded, which is good for metals such as aluminum or magnesium. A shallow, wide weld is produced from this mode, with minimum heat input. Alternating current gives a combination of negative and positive modes, giving a cleaning effect and imparts a lot of heat as well.

Safety

Like other arc welding processes, GTAW can be dangerous if proper precautions are not taken. The process produces intense ultraviolet radiation, which can cause a form of sunburn and, in a few cases, trigger the development of skin cancer. Flying sparks and

droplets of molten metal can cause severe burns and start a fire if flammable material is nearby, though GTAW generally produces very few sparks or metal droplets when performed properly.

It is essential that the welder wear suitable protective clothing, including leather gloves, a closed shirt collar to protect the neck (especially the throat), a protective long sleeve jacket and a suitable welding helmet to prevent retinal damage or ultraviolet burns to the cornea, often called arc eye. The shade of welding lens will depend upon the amperage of the welding current. Due to the absence of smoke in GTAW, the arc appears brighter than shielded metal arc welding and more ultraviolet radiation is produced. Exposure of bare skin near a GTAW arc for even a few seconds may cause a painful sunburn. Additionally, the tungsten electrode is heated to a white hot state like the filament of a light bulb, adding greatly to the total radiated light and heat energy. Transparent welding curtains, made of a polyvinyl chloride plastic film, dyed in order to block UV radiation, are often used to shield nearby personnel from exposure.

Welders are also often exposed to dangerous gases and particulate matter. Shielding gases can displace oxygen and lead to asphyxiation, and while smoke is not produced, the arc in GTAW produces very short wavelength ultraviolet light, which causes surrounding air to break down and form ozone. Metals will volatilize and heavy metals can be taken into the lungs. Similarly, the heat can cause poisonous fumes to form from cleaning and degreasing materials. For example, chlorinated products such as brake cleaner on a weld surface generate the toxic gas phosgene when heated. Cleaning operations using these agents should not be performed near the site of welding, and proper ventilation is necessary to protect the welder.

Applications

While the aerospace industry is one of the primary users of gas tungsten arc welding, the process is used in a number of other areas. Many industries use GTAW for welding thin workpieces, especially nonferrous metals. It is used extensively in the manufacture of space vehicles, and is also frequently employed to weld small-diameter, thin-wall tubing such as those used in the bicycle industry. In addition, GTAW is often used to make root or first pass welds for piping of various sizes. In maintenance and repair work, the process is commonly used to repair tools and dies, especially components made of aluminum and magnesium. Because the weld metal is not transferred directly across the electric arc like most open arc welding processes, a vast assortment of welding filler metal is available to the welding engineer. In fact, no other welding process permits the welding of so many alloys in so many product configurations. Filler metal alloys, such as elemental aluminum and chromium, can be lost through the electric arc from volatilization. This loss does not occur with the GTAW process. Because the resulting welds have the same chemical integrity as the original base metal or match the base metals more closely, GTAW welds are highly resistant to corrosion and cracking over long time periods, GTAW is the welding procedure of choice for critical welding operations like sealing spent nuclear fuel canisters before burial.

Quality

GTAW fillet weld

Engineers prefer GTAW welds because of its low-hydrogen properties and the match of mechanical and chemical properties with the base material. Maximum weld quality is assured by maintaining the cleanliness of the operation—all equipment and materials used must be free from oil, moisture, dirt and other impurities, as these cause weld porosity and consequently a decrease in weld strength and quality. To remove oil and

grease, alcohol or similar commercial solvents may be used, while a stainless steel wire brush or chemical process can remove oxides from the surfaces of metals like aluminum. Rust on steels can be removed by first grit blasting the surface and then using a wire brush to remove any embedded grit. These steps are especially important when negative polarity direct current is used, because such a power supply provides no cleaning during the welding process, unlike positive polarity direct current or alternating current. To maintain a clean weld pool during welding, the shielding gas flow should be sufficient and consistent so that the gas covers the weld and blocks impurities in the atmosphere. GTA welding in windy or drafty environments increases the amount of shielding gas necessary to protect the weld, increasing the cost and making the process unpopular outdoors.

Because of GTAW's relative difficulty and the importance of proper technique, skilled operators are employed for important applications. Welders in the U.S. should be qualified following the requirements of the American Welding Society or American Society of Mechanical Engineers. Low heat input, caused by low welding current or high welding speed, can limit penetration and cause the weld bead to lift away from the surface being welded. If there is too much heat input, however, the weld bead grows in width while the likelihood of excessive penetration and spatter increase. Additionally, if the welding torch is too far from the workpiece the shielding gas becomes ineffective causing porosity within the weld. This results in a weld with pinholes, which is weaker than a typical weld.

If the amount of current used exceeds the capability of the electrode, tungsten inclusions in the weld may result. Known as tungsten spitting, it can be identified with radiography and prevented by changing the type of electrode or increasing the electrode diameter. In addition, if the electrode is not well protected by the gas shield or the operator accidentally allows it to contact the molten metal, it can become dirty or contaminated. This often causes the welding arc to become unstable, requiring that electrode be ground with a diamond abrasive to remove the impurity.

Equipment

GTAW torch with various electrodes, cups, collets and gas diffusers

GTAW torch, disassembled

The equipment required for the gas tungsten arc welding operation includes a welding torch utilizing a nonconsumable tungsten electrode, a constant-current welding power supply, and a shielding gas source.

Welding torch

GTAW welding torches are designed for either automatic or manual operation and are equipped with cooling systems using air or water. The automatic and manual torches are similar in construction, but the manual torch has a handle while the automatic torch normally comes with a mounting rack. The angle between the centerline of the handle and the centerline of the tungsten electrode, known as the head angle, can be varied on some manual torches according to the preference of the operator. Air cooling systems are most often used for low-current operations (up to about 200 A), while water cooling is required for high-current welding (up to about 600 A). The torches are connected with cables to the power supply and with hoses to the shielding gas source and where used, the water supply.

The internal metal parts of a torch are made of hard alloys of copper or brass in order to transmit current and heat effectively. The tungsten electrode must be held firmly in the

center of the torch with an appropriately sized collet, and ports around the electrode provide a constant flow of shielding gas. Collets are sized according to the diameter of the tungsten electrode they hold. The body of the torch is made of heat-resistant, insulating plastics covering the metal components, providing insulation from heat and electricity to protect the welder.

The size of the welding torch nozzle depends on the amount of shielded area desired. The size of the gas nozzle will depend upon the diameter of the electrode, the joint configuration, and the availability of access to the joint by the welder. The inside diameter of the nozzle is preferably at least three times the diameter of the electrode, but there are no hard rules. The welder will judge the effectiveness of the shielding and increase the nozzle size to increase the area protected by the external gas shield as needed. The nozzle must be heat resistant and thus is normally made of alumina or a ceramic material, but fused quartz, a glass-like substance, offers greater visibility. Devices can be inserted into the nozzle for special applications, such as gas lenses or valves to improve the control shielding gas flow to reduce turbulence and introduction of contaminated atmosphere into the shielded area. Hand switches to control welding current can be added to the manual GTAW torches.

Power supply

Gas tungsten arc welding uses a constant current power source, meaning that the current (and thus the heat) remains relatively constant, even if the arc distance and voltage change. This is important because most applications of GTAW are manual or semiautomatic, requiring that an operator hold the torch. Maintaining a suitably steady arc distance is difficult if a constant voltage power source is used instead, since it can cause dramatic heat variations and make welding more difficult.

GTAW power supply

The preferred polarity of the GTAW system depends largely on the type of metal being welded. Direct current with a negatively charged electrode (DCEN) is often employed when welding steels, nickel, titanium, and other metals. It can also be used in automatic GTA welding of aluminum or magnesium when helium is used as a shielding gas. The negatively charged electrode generates heat by emitting electrons which travel across the arc, causing thermal ionization of the shielding gas and increasing the temperature of the base material. The ionized shielding gas flows toward the electrode, not the base material. Direct current with a positively charged electrode (DCEP) is less common, and is used primarily for shallow welds since less heat is generated in the base material. Instead of flowing from the electrode to the base material, as in DCEN, electrons go the other direction, causing the electrode to reach very high temperatures. To help it maintain its shape and prevent softening, a larger electrode is often used. As the electrons flow toward the electrode, ionized shielding gas flows back toward the base material, cleaning the weld by removing oxides and other impurities and thereby improving its quality and appearance.

Alternating current, commonly used when welding aluminum and magnesium manually or semi-automatically, combines the two direct currents by making the electrode and base material alternate between positive and negative charge. This causes the electron flow to

switch directions constantly, preventing the tungsten electrode from overheating while maintaining the heat in the base material. Surface oxides are still removed during the electrode-positive portion of the cycle and the base metal is heated more deeply during the electrode-negative portion of the cycle. Some power supplies enable operators to use an unbalanced alternating current wave by modifying the exact percentage of time that the current spends in each state of polarity, giving them more control over the amount of heat and cleaning action supplied by the power source. In addition, operators must be wary of rectification, in which the arc fails to reignite as it passes from straight polarity (negative electrode) to reverse polarity (positive electrode). To remedy the problem, a square wave power supply can be used, as can high-frequency voltage to encourage ignition.

Electrode

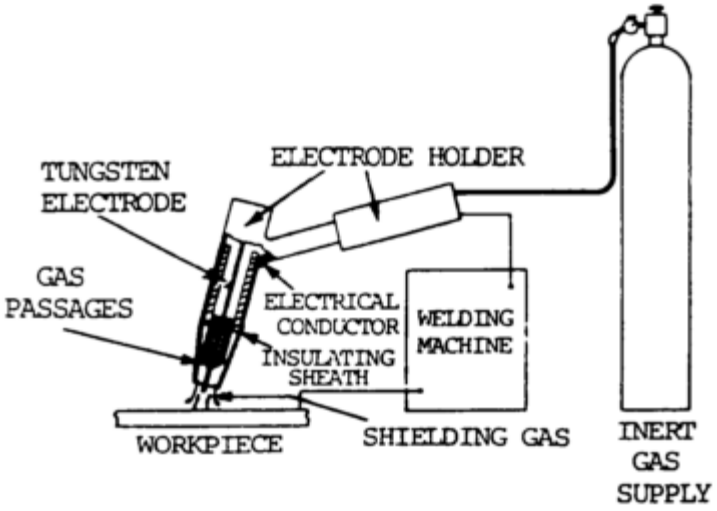
ISO Class	ISO Color	AWS Class	AWS Color	Alloy
WP	Green	EWP	Green	None
WC20	Gray	EWCe-2	Orange	~2% CeO_2
WL10	Black	EWLa-1	Black	~1% La_2O_3
WL15	Gold	EWLa-1.5	Gold	~1.5% La_2O_3
WL20	Sky-blue	EWLa-2	Blue	~2% La_2O_3
WT10	Yellow	EWTh-1	Yellow	~1% ThO_2
WT20	Red	EWTh-2	Red	~2% ThO_2
WT30	Violet			~3% ThO_2
WT40	Orange			~4% ThO_2
WY20	Blue			~2% Y_2O_3
WZ3	Brown	EWZr-1	Brown	~0.3% ZrO_2
WZ8	White			~0.8% ZrO_2

The electrode used in GTAW is made of tungsten or a tungsten alloy, because tungsten has the highest melting temperature among pure metals, at 3,422 °C (6,192 °F). As a result, the electrode is not consumed during welding, though some erosion (called burn-off) can occur. Electrodes can have either a clean finish or a ground finish—clean finish electrodes have been chemically cleaned, while ground finish electrodes have been ground to a uniform size and have a polished surface, making them optimal for heat conduction. The diameter of the electrode can vary between 0.5 and 6.4 millimetres (0.02 and 0.25 in), and their length can range from 75 to 610 millimetres (3.0 to 24 in).

A number of tungsten alloys have been standardized by the International Organization for Standardization and the American Welding Society in ISO 6848 and AWS A5.12, respectively, for use in GTAW electrodes, and are summarized in the adjacent table. Pure tungsten electrodes (classified as WP or EWP) are general purpose and low cost electrodes. Cerium oxide (or ceria) as an alloying element improves arc stability and ease of starting while decreasing burn-off. Using an alloy of lanthanum oxide (or lanthana) has a similar effect. Thorium oxide (or thoria) alloy electrodes were designed for DC applications and can withstand somewhat higher temperatures while providing many of the benefits of other alloys. However, it is somewhat radioactive. Inhalation of the thorium grinding dust during preparation of the electrode is hazardous to one's health. As a replacement to thoriated electrodes, electrodes with larger concentrations of lanthanum oxide can be used. Electrodes containing zirconium oxide (or zirconia) increase the current capacity while improving arc stability and starting and increasing electrode life. In addition, electrode manufacturers may create alternative tungsten alloys with specified metal additions, and these are designated with the classification EWG under the AWS system.

Filler metals are also used in nearly all applications of GTAW, the major exception being the welding of thin materials. Filler metals are available with different diameters and are made of a variety of materials. In most cases, the filler metal in the form of a rod is added to the weld pool manually, but some applications call for an automatically fed filler metal, which often is stored on spools or coils.

Shielding gas



GTAW system setup

As with other welding processes such as gas metal arc welding, shielding gases are necessary in GTAW to protect the welding area from atmospheric gases such as nitrogen and oxygen, which can cause fusion defects, porosity, and weld metal embrittlement if

they come in contact with the electrode, the arc, or the welding metal. The gas also transfers heat from the tungsten electrode to the metal, and it helps start and maintain a stable arc.

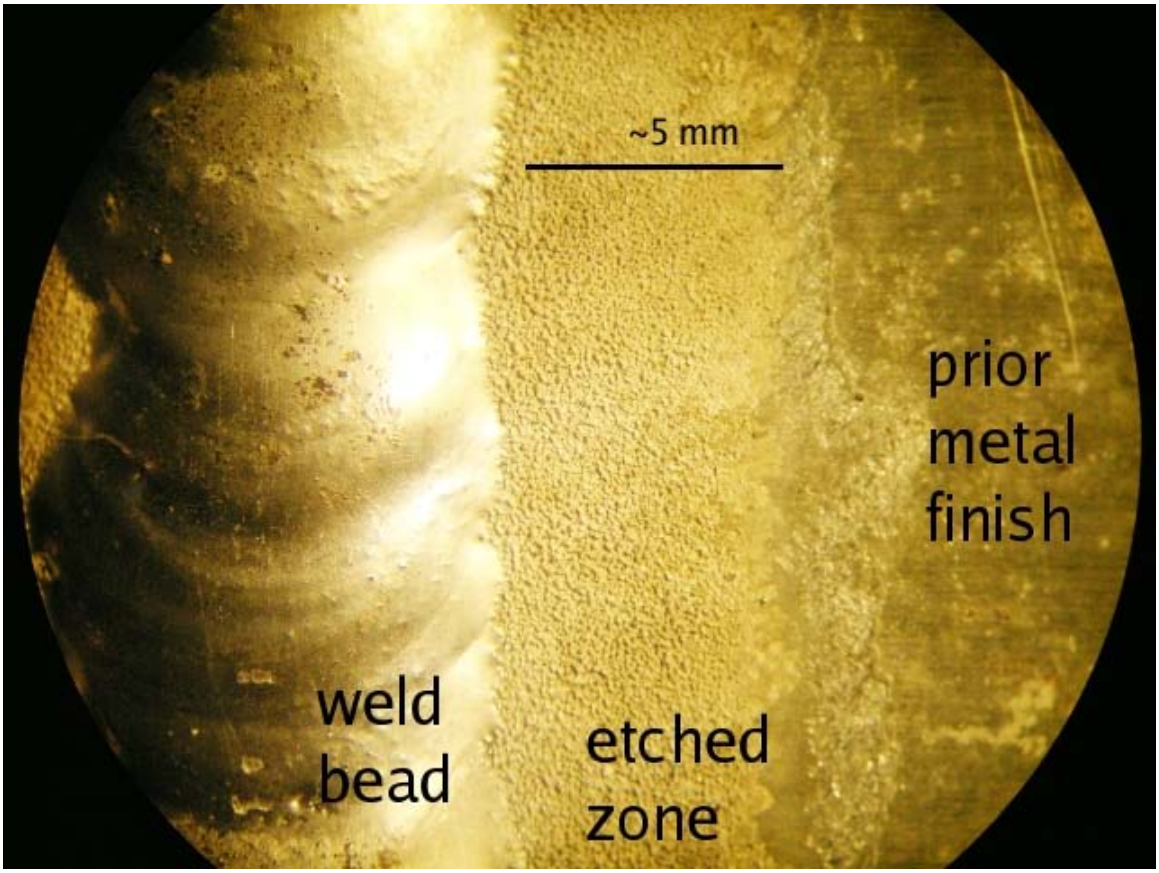
The selection of a shielding gas depends on several factors, including the type of material being welded, joint design, and desired final weld appearance. Argon is the most commonly used shielding gas for GTAW, since it helps prevent defects due to a varying arc length. When used with alternating current, the use of argon results in high weld quality and good appearance. Another common shielding gas, helium, is most often used to increase the weld penetration in a joint, to increase the welding speed, and to weld metals with high heat conductivity, such as copper and aluminum. A significant disadvantage is the difficulty of striking an arc with helium gas, and the decreased weld quality associated with a varying arc length.

Argon-helium mixtures are also frequently utilized in GTAW, since they can increase control of the heat input while maintaining the benefits of using argon. Normally, the mixtures are made with primarily helium (often about 75% or higher) and a balance of argon. These mixtures increase the speed and quality of the AC welding of aluminum, and also make it easier to strike an arc. Another shielding gas mixture, argon-hydrogen, is used in the mechanized welding of light gauge stainless steel, but because hydrogen can cause porosity, its uses are limited. Similarly, nitrogen can sometimes be added to argon to help stabilize the austenite in austentitic stainless steels and increase penetration when welding copper. Due to porosity problems in ferritic steels and limited benefits, however, it is not a popular shielding gas additive.

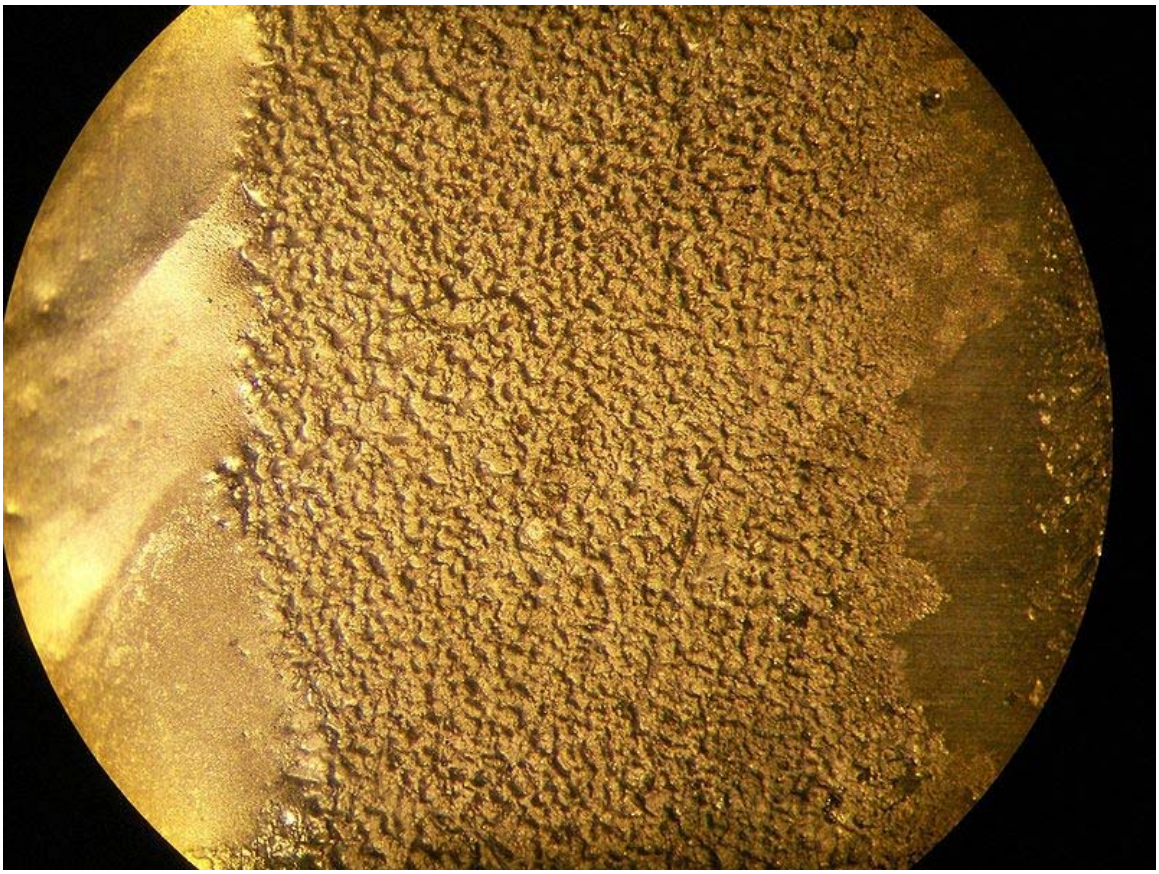
Materials

Gas tungsten arc welding is most commonly used to weld stainless steel and nonferrous materials, such as aluminum and magnesium, but it can be applied to nearly all metals, with notable exceptions being lead and zinc. Its applications involving carbon steels are limited not because of process restrictions, but because of the existence of more economical steel welding techniques, such as gas metal arc welding and shielded metal arc welding. Furthermore, GTAW can be performed in a variety of other-than-flat positions, depending on the skill of the welder and the materials being welded.

Aluminum and magnesium



A TIG weld showing an accentuated AC etched zone



Closeup view of an aluminium TIG weld AC etch zone

Aluminum and magnesium are most often welded using alternating current, but the use of direct current is also possible, depending on the properties desired. Before welding, the work area should be cleaned and may be preheated to 175 to 200 °C (347 to 392 °F) for aluminum or to a maximum of 150 °C (302 °F) for thick magnesium workpieces to improve penetration and increase travel speed. AC current can provide a self-cleaning effect, removing the thin, refractory aluminium oxide (sapphire) layer that forms on aluminium metal within minutes of exposure to air. This oxide layer must be removed for welding to occur. When alternating current is used, pure tungsten electrodes or zirconiated tungsten electrodes are preferred over thoriated electrodes, as the latter are more likely to "spit" electrode particles across the welding arc into the weld. Blunt electrode tips are preferred, and pure argon shielding gas should be employed for thin workpieces. Introducing helium allows for greater penetration in thicker workpieces, but can make arc starting difficult.

Direct current of either polarity, positive or negative, can be used to weld aluminum and magnesium as well. Direct current with a negatively charged electrode (DCEN) allows for high penetration. Argon is commonly used as a shielding gas for DCEN welding of aluminum. Shielding gases with high helium contents are often used for higher penetration in thicker materials. Thoriated electrodes are suitable for use in DCEN

welding of aluminum. Direct current with a positively charged electrode (DCEP) is used primarily for shallow welds, especially those with a joint thickness of less than 1.6 mm (0.063 in). A thoriated tungsten electrode is commonly used, along with a pure argon shielding gas.

Steels

For GTA welding of carbon and stainless steels, the selection of a filler material is important to prevent excessive porosity. Oxides on the filler material and workpieces must be removed before welding to prevent contamination, and immediately prior to welding, alcohol or acetone should be used to clean the surface. Preheating is generally not necessary for mild steels less than one inch thick, but low alloy steels may require preheating to slow the cooling process and prevent the formation of martensite in the heat-affected zone. Tool steels should also be preheated to prevent cracking in the heat-affected zone. Austenitic stainless steels do not require preheating, but martensitic and ferritic chromium stainless steels do. A DCEN power source is normally used, and thoriated electrodes, tapered to a sharp point, are recommended. Pure argon is used for thin workpieces, but helium can be introduced as thickness increases.

Copper alloys

TIG welding of copper and some of its alloys is possible, but in order to get a seam free of oxidation and porosities, shielding gas needs to be provided on the root side of the weld. Alternatively, a special "backing tape", consisting of a fiberglass weave on heat-resistant aluminum tape can be used, to prevent air reaching the molten metal.

Dissimilar metals

Welding dissimilar metals often introduces new difficulties to GTAW welding, because most materials do not easily fuse to form a strong bond. However, welds of dissimilar materials have numerous applications in manufacturing, repair work, and the prevention of corrosion and oxidation. In some joints, a compatible filler metal is chosen to help form the bond, and this filler metal can be the same as one of the base materials (for example, using a stainless steel filler metal with stainless steel and carbon steel as base materials), or a different metal (such as the use of a nickel filler metal for joining steel and cast iron). Very different materials may be coated or "buttered" with a material compatible with a particular filler metal, and then welded. In addition, GTAW can be used in cladding or overlaying dissimilar materials.

When welding dissimilar metals, the joint must have an accurate fit, with proper gap dimensions and bevel angles. Care should be taken to avoid melting excessive base material. Pulsed current is particularly useful for these applications, as it helps limit the heat input. The filler metal should be added quickly, and a large weld pool should be avoided to prevent dilution of the base materials.

Process variations

Pulsed-current

In the pulsed-current mode, the welding current rapidly alternates between two levels. The higher current state is known as the pulse current, while the lower current level is called the background current. During the period of pulse current, the weld area is heated and fusion occurs. Upon dropping to the background current, the weld area is allowed to cool and solidify. Pulsed-current GTAW has a number of advantages, including lower heat input and consequently a reduction in distortion and warpage in thin workpieces. In addition, it allows for greater control of the weld pool, and can increase weld penetration, welding speed, and quality. A similar method, manual programmed GTAW, allows the operator to program a specific rate and magnitude of current variations, making it useful for specialized applications.

Dabber

The dabber variation is used to precisely place weld metal on thin edges. The automatic process replicates the motions of manual welding by feeding a cold filler wire into the weld area and dabbing (or oscillating) it into the welding arc. It can be used in conjunction with pulsed current, and is used to weld a variety of alloys, including titanium, nickel, and tool steels. Common applications include rebuilding seals in jet engines and building up saw blades, milling cutters, drill bits, and mower blades.

Hot wire

Welding filler metal can be resistance heated to a temperature near its melting point before being introduced into the weld pool. This increases the deposition rate of machine and automatic GTAW welding processes. More pounds per hour of filler metal is introduced into the weld joint than when filler metal is added cold and the heat of the electric arc introduces all of the heat. This process is used extensively in base material build up before machining, clad metal overlays, and hardfacing operations.

Chapter-14

Shielded Metal Arc Welding

Shielded metal arc welding

Shielded metal arc welding (SMAW), also known as **manual metal arc (MMA) welding**, **flux-shielded arc welding** or informally as **stick welding**, is a manual arc welding process that uses a consumable electrode coated in flux to lay the weld. An electric current, in the form of either alternating current or direct current from a welding power supply, is used to form an electric arc between the electrode and the metals to be

joined. As the weld is laid, the flux coating of the electrode disintegrates, giving off vapors that serve as a shielding gas and providing a layer of slag, both of which protect the weld area from atmospheric contamination.

Because of the versatility of the process and the simplicity of its equipment and operation, shielded metal arc welding is one of the world's most popular welding processes. It dominates other welding processes in the maintenance and repair industry, and though flux-cored arc welding is growing in popularity, SMAW continues to be used extensively in the construction of steel structures and in industrial fabrication. The process is used primarily to weld iron and steels (including stainless steel) but aluminium, nickel and copper alloys can also be welded with this method.

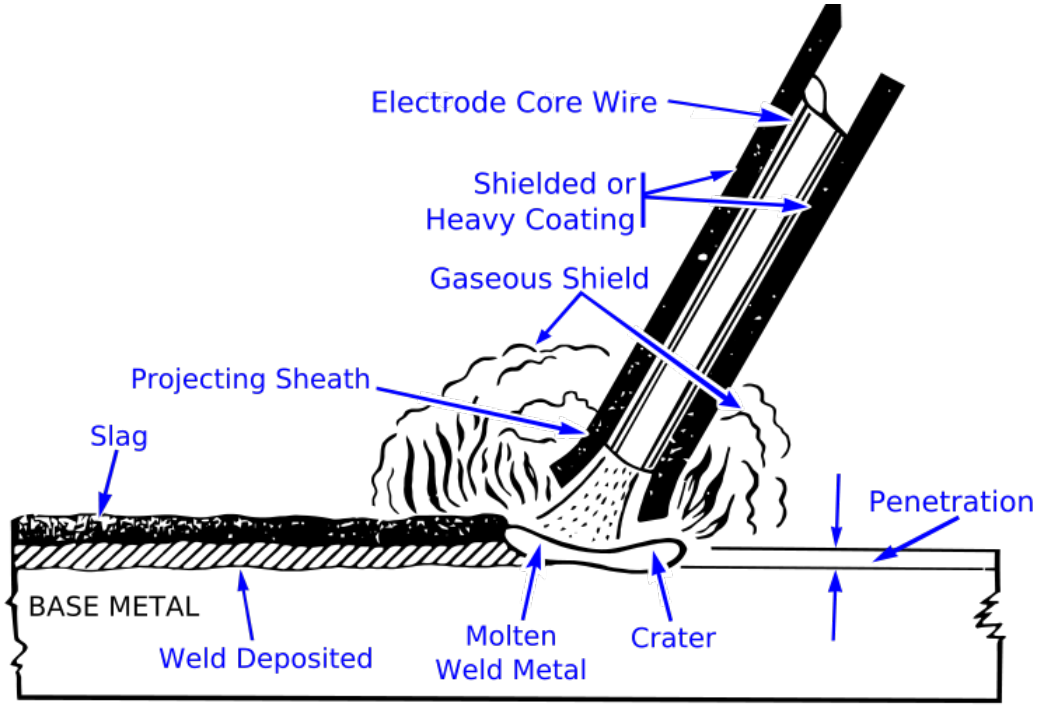
Development

After the discovery of the electric arc in 1800 by Humphry Davy there was little development in electrical welding until Auguste de Méritens developed a carbon arc torch, patented in 1881. Nikolay Benardos developed carbon arc welding, obtaining patents from 1887 showing a rudimentary electrode holder. In 1888 consumable metal electrode was invented by Nikolay Slavyanov. Later in 1890 C. L. Coffin received U.S. Patent 428,459 for his arc welding method that utilized a metal electrode. The process, like SMAW, deposited melted electrode metal into the weld as filler.

Around 1900 A. P. Strohmenger and Oscar Kjellberg released the first coated electrodes. Strohmenger used Clay and lime coating to stabilize the arc, while Kjellberg dipped iron wire into mixtures of carbonates and silicates to coat the electrode. In 1912 Strohmenger released a heavily coated electrode but high cost and complex production methods prevented these early electrodes from gaining popularity. In 1927 the development of an extrusion process reduced the cost of coating electrodes while allowing manufacturers to produce more complex coating mixtures designed for specific applications. In the 1950s manufacturers introduced iron powder into the flux coating, making it possible to increase the welding speed.

In 1938 K. K. Madsen described an automated variation of SMAW, now known as gravity welding. It briefly gained popularity in the 1960s after receiving publicity for its use in Japanese shipyards though today its applications are limited. Another little used variation of the process, known as firecracker welding, was developed around the same time by George Hafergut in Austria.

Operation



SMAW weld area

To strike the electric arc, the electrode is brought into contact with the workpiece by a very light touch with the electrode to the base metal then is pulled back slightly. This initiates the arc and thus the melting of the workpiece and the consumable electrode, and causes droplets of the electrode to be passed from the electrode to the weld pool. As the electrode melts, the flux covering disintegrates, giving off shielding gases that protect the weld area from oxygen and other atmospheric gases. In addition, the flux provides molten slag which covers the filler metal as it travels from the electrode to the weld pool. Once part of the weld pool, the slag floats to the surface and protects the weld from contamination as it solidifies. Once hardened, it must be chipped away to reveal the finished weld. As welding progresses and the electrode melts, the welder must periodically stop welding to remove the remaining electrode stub and insert a new electrode into the electrode holder. This activity, combined with chipping away the slag, reduce the amount of time that the welder can spend laying the weld, making SMAW one of the least efficient welding processes. In general, the operator factor, or the percentage of operator's time spent laying weld, is approximately 25%.

The actual welding technique utilized depends on the electrode, the composition of the workpiece, and the position of the joint being welded. The choice of electrode and welding position also determine the welding speed. Flat welds require the least operator skill, and can be done with electrodes that melt quickly but solidify slowly. This permits

higher welding speeds. Sloped, vertical or upside-down welding requires more operator skill, and often necessitates the use of an electrode that solidifies quickly to prevent the molten metal from flowing out of the weld pool. However, this generally means that the electrode melts less quickly, thus increasing the time required to lay the weld.

Quality

The most common quality problems associated with SMAW include weld spatter, porosity, poor fusion, shallow penetration, and cracking. Weld spatter, while not affecting the integrity of the weld, damages its appearance and increases cleaning costs. It can be caused by excessively high current, a long arc, or arc blow, a condition associated with direct current characterized by the electric arc being deflected away from the weld pool by magnetic forces. Arc blow can also cause porosity in the weld, as can joint contamination, high welding speed, and a long welding arc, especially when low-hydrogen electrodes are used. Porosity, often not visible without the use of advanced nondestructive testing methods, is a serious concern because it can potentially weaken the weld. Another defect affecting the strength of the weld is poor fusion, though it is often easily visible. It is caused by low current, contaminated joint surfaces, or the use of an improper electrode. Shallow penetration, another detriment to weld strength, can be addressed by decreasing welding speed, increasing the current or using a smaller electrode. Any of these weld-strength-related defects can make the weld prone to cracking, but other factors are involved as well. High carbon, alloy or sulfur content in the base material can lead to cracking, especially if low-hydrogen electrodes and preheating are not employed. Furthermore, the workpieces should not be excessively restrained, as this introduces residual stresses into the weld and can cause cracking as the weld cools and contracts.

Safety

SMAW welding, like other welding methods, can be a dangerous and unhealthy practice if proper precautions are not taken. The process uses an open electric arc, which presents a risk of burns which are prevented by personal protective equipment in the form of heavy leather gloves and long sleeve jackets. Additionally, the brightness of the weld area can lead to a condition called arc eye, in which ultraviolet light causes inflammation of the cornea and can burn the retinas of the eyes. 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, especially in industrial environments, 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.

In addition, the vaporizing metal and flux materials expose welders to dangerous gases and particulate matter. The smoke produced contains 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, gases like carbon dioxide and

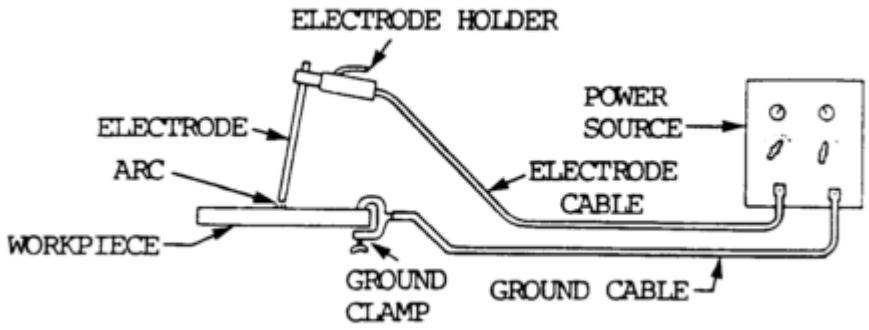
ozone can form, which can prove dangerous if ventilation is inadequate. Some of the latest welding masks are fitted with an electric powered fan to help disperse harmful fumes.

Application and materials

Shielded metal arc welding is one of the world's most popular welding processes, accounting for over half of all welding in some countries. Because of its versatility and simplicity, it is particularly dominant in the maintenance and repair industry, and is heavily used in the construction of steel structures and in industrial fabrication. In recent years its use has declined as flux-cored arc welding has expanded in the construction industry and gas metal arc welding has become more popular in industrial environments. However, because of the low equipment cost and wide applicability, the process will likely remain popular, especially among amateurs and small businesses where specialized welding processes are uneconomical and unnecessary.

SMAW is often used to weld carbon steel, low and high alloy steel, stainless steel, cast iron, and ductile iron. While less popular for nonferrous materials, it can be used on nickel and copper and their alloys and, in rare cases, on aluminium. The thickness of the material being welded is bounded on the low end primarily by the skill of the welder, but rarely does it drop below 0.05 in (1.5 mm). No upper bound exists: with proper joint preparation and use of multiple passes, materials of virtually unlimited thicknesses can be joined. Furthermore, depending on the electrode used and the skill of the welder, SMAW can be used in any position.

Equipment



SMAW system setup

Shielded metal arc welding equipment typically consists of a constant current welding power supply and an electrode, with an electrode holder, a **ground** clamp, and welding cables (also known as welding leads) connecting the two.

Power supply

The power supply used in SMAW has constant current output, ensuring that the current (and thus the heat) remains relatively constant, even if the arc distance and voltage change. This is important because most applications of SMAW are manual, requiring that an operator hold the torch. Maintaining a suitably steady arc distance is difficult if a constant voltage power source is used instead, since it can cause dramatic heat variations and make welding more difficult. However, because the current is not maintained absolutely constant, skilled welders performing complicated welds can vary the arc length to cause minor fluctuations in the current.

A high output welding power supply for Stick, GTAW, MIG, Flux-Cored, & Gouging

The preferred polarity of the SMAW system depends primarily upon the electrode being used and the desired properties of the weld. Direct current with a negatively charged electrode (DCEN) causes heat to build up on the electrode, increasing the electrode melting rate and decreasing the depth of the weld. Reversing the polarity so that the electrode is positively charged (DCEP) and the workpiece is negatively charged increases the weld penetration. With alternating current the polarity changes over 100 times per second, creating an even heat distribution and providing a balance between electrode melting rate and penetration.

Typically, the equipment used for SMAW consists of a step-down transformer and for direct current models a rectifier, which converts alternating current into direct current. Because the power normally supplied to the welding machine is high-voltage alternating current, the welding transformer is used to reduce the voltage and increase the current. As a result, instead of 220 V at 50 A, for example, the power supplied by the transformer is around 17–45 V at currents up to 600 A. A number of different types of transformers can be used to produce this effect, including multiple coil and inverter machines, with each using a different method to manipulate the welding current. The multiple coil type adjusts the current by either varying the number of turns in the coil (in tap-type transformers) or by varying the distance between the primary and secondary coils (in movable coil or movable core transformers). Inverters, which are smaller and thus more portable, use electronic components to change the current characteristics.

Electrical generators and alternators are frequently used as portable welding power supplies, but because of lower efficiency and greater costs, they are less frequently used in industry. Maintenance also tends to be more difficult, because of the complexities of using a combustion engine as a power source. However, in one sense they are simpler: the use of a separate rectifier is unnecessary because they can provide either AC or DC. However, the engine driven units are most practical in field work where the welding often must be done out of doors and in locations where transformer type welders are not usable because there is no power source available to be transformed.

In some units the alternator is essentially the same as that used in portable generating sets used to supply mains power, modified to produce a higher current at a lower voltage but still at the 50 or 60 Hz grid frequency. In higher-quality units an alternator with more poles is used and supplies current at a higher frequency, such as 400 Hz. The smaller amount of time the high-frequency waveform spends near zero makes it much easier to strike and maintain a stable arc than with the cheaper grid-frequency sets or grid-frequency mains-powered units.

Electrode

Various accessories for SMAW

The choice of electrode for SMAW depends on a number of factors, including the weld material, welding position and the desired weld properties. The electrode is coated in a metal mixture called flux, which gives off gases as it decomposes to prevent weld contamination, introduces deoxidizers to purify the weld, causes weld-protecting slag to form, improves the arc stability, and provides alloying elements to improve the weld quality. Electrodes can be divided into three groups—those designed to melt quickly are called "fast-fill" electrodes, those designed to solidify quickly are called "fast-freeze" electrodes, and intermediate electrodes go by the name "fill-freeze" or "fast-follow" electrodes. Fast-fill electrodes are designed to melt quickly so that the welding speed can be maximized, while fast-freeze electrodes supply filler metal that solidifies quickly, making welding in a variety of positions possible by preventing the weld pool from shifting significantly before solidifying.

The composition of the electrode core is generally similar and sometimes identical to that of the base material. But even though a number of feasible options exist, a slight difference in alloy composition can strongly impact the properties of the resulting weld. This is especially true of alloy steels such as HSLA steels. Likewise, electrodes of compositions similar to those of the base materials are often used for welding nonferrous materials like aluminium and copper. However, sometimes it is desirable to use electrodes with core materials significantly different from the base material. For example,

stainless steel electrodes are sometimes used to weld two pieces of carbon steel, and are often utilized to weld stainless steel workpieces with carbon steel workpieces.

Electrode coatings can consist of a number of different compounds, including rutile, calcium fluoride, cellulose, and iron powder. Rutile electrodes, coated with 25%–45% TiO_2, are characterized by ease of use and good appearance of the resulting weld. However, they create welds with high hydrogen content, encouraging embrittlement and cracking. Electrodes containing calcium fluoride (CaF_2), sometimes known as basic or low-hydrogen electrodes, are hygroscopic and must be stored in dry conditions. They produce strong welds, but with a coarse and convex-shaped joint surface. Electrodes coated with cellulose, especially when combined with rutile, provide deep weld penetration, but because of their high moisture content, special procedures must be used to prevent excessive risk of cracking. Finally, iron powder is a common coating additive, as it improves the productivity of the electrode, sometimes as much as doubling the yield.

To identify different electrodes, the American Welding Society established a system that assigns electrodes with a four- or five-digit number. Covered electrodes made of mild or low alloy steel carry the prefix *E*, followed by their number. The first two or three digits of the number specify the tensile strength of the weld metal, in thousand pounds per square inch (ksi). The penultimate digit generally identifies the welding positions permissible with the electrode, typically using the values 1 (normally fast-freeze electrodes, implying all position welding) and 2 (normally fast-fill electrodes, implying horizontal welding only). The welding current and type of electrode covering are specified by the last two digits together. When applicable, a suffix is used to denote the alloying element being contributed by the electrode.

Common electrodes include the E6010, a fast-freeze, all-position electrode with a minimum tensile strength of 60 ksi (410 MPa) which is operated using DCEP. Its cousin E6011 is similar except that it is used with alternating current. E7024 is a fast-fill electrode, used primarily to make flat or horizontal welds using AC, DCEN, or DCEP. Examples of fill-freeze electrodes are the E6012, E6013, and E7014, all of which provide a compromise between fast welding speeds and all-position welding.

Process variations

Though SMAW is almost exclusively a manual arc welding process, one notable process variation exists, known as gravity welding or gravity arc welding. It serves as an automated version of the traditional shielded metal arc welding process, employing an electrode holder attached to an inclined bar along the length of the weld. Once started, the process continues until the electrode is spent, allowing the operator to manage multiple gravity welding systems. The electrodes employed (often E6027 or E7024) are coated heavily in flux, and are typically 28 in (0.8 m) in length and about 0.25 in (6 mm) thick. As in manual SMAW, a constant current welding power supply is used, with either negative polarity direct current or alternating current. Due to a rise in the use of semiautomatic welding processes such as flux-cored arc welding, the popularity of gravity welding has fallen as its economic advantage over such methods is often minimal.

Other SMAW-related methods that are even less frequently used include firecracker welding, an automatic method for making butt and fillet welds, and massive electrode welding, a process for welding large components or structures that can deposit up to 60 lb (27 kg) of weld metal per hour.