WELDING

1. Historical Perspectives and Process Description

1.1 Introduction

'Welding' is a term used to describe a wide range of processes for joining any materials by fusion or coalescence of the interface. It involves bringing two surfaces together under conditions of pressure or temperature which allow bonding to occur at the atomic level. Usually, this is accompanied by diffusion or mixing across the boundary, so that in the region of the weld an alloy is formed between the two pieces that have been joined. Welding and other methods of joining, such as soldering or brazing, can be distinguished clearly (Lancaster, 1980). In the latter, a low-melting alloy is heated until it flows and fills the gap between the two pieces of metal to be joined; the workpieces do not melt, and there is negligible diffusion or mixing of the metal across the boundaries. Metal can be welded by the application of energy in many forms: mechanical energy is utilized in forge, friction, ultrasonic and explosive welding; chemical energy in oxy-gas and thermit welding; electrical energy in arc welding, various forms of resistance welding and electron beam welding; and optical energy in laser welding. The term 'welding' is applicable equally to metals, thermoplastics and various other materials.

Many of the techniques used in welding can also be used for other purposes. Oxy-gas flames and electric arcs are used for cutting. Various processes, including flame spraying, plasma spraying and manual metal arc and metal inert gas hard surfacing, are used for depositing hard metal surface coatings and for building up worn machine components.

1.2 Development of welding in the twentieth century

Welding of metals has its origins in pre-history: at least 5000 years ago, metal was welded by heating and hammering overlapping pieces. The same principles are employed to this day in forge welding and other modern forms of 'solid state welding' (Lancaster, 1980; Lindberg & Braton, 1985). The development of modern welding technology began in the late nineteenth century with the application of oxy-fuel flames, electric arcs and electrical resistance welding. The industrial application of oxy-fuel combustion for cutting and welding was facilitated by the availability of calcium carbide, from which acetylene gas could be generated as required, and by the commercial availability from about 1895 of bottled oxygen produced by the liquefaction of air (Skriniar, 1986). Oxy-fuel welding underwent rapid development in the early years of the twentieth century, and by the middle of the First World War good quality welds could be made in steel plate, aluminium and other metals.

The phenomenon of the electric arc was first discovered in 1802 by Petrov; its first recorded use for welding was in 1882 by Bernardos (Skriniar, 1986), who used an electric arc struck between carbon electrodes to melt ferrous metals to effect repairs and make joints. The results were often brittle and unsatisfactory because of oxidation and nitrogen absorption from the surrounding air, and consequently arc welding developed only slowly at first. To fill larger gaps, metal wire had to be fed by hand into the molten metal of the weld pool. Early attempts to use the filler metal itself as a 'consumable' electrode, and to strike the arc onto the workpiece, produced poor results, largely because of nitrogen embrittlement (Lancaster, 1980). Electrodes consisting of wire wrapped in paper or asbestos string were found to produce better results (Brillié, 1990), and a range of materials was experimented with as 'flux' coatings. Flux compositions gradually evolved, and the resulting weld quality was improved as minerals were added to act as gas and slag formers, deoxidants and scavengers. A variety of binding agents was used to attach the flux coating to the electrode, but water-glass (sodium and potassium silicates) was quickly discovered to be most effective. By about 1930, the modern welding rod had been developed and weld quality was adequate for many structural and manufacturing purposes. The process came to be known as manual metal arc (MMA) (Morgan, 1989) or shielded metal arc welding (Lancaster, 1980). Throughout the 1930s, asbestos continued to be added to a small proportion of electrodes in the form of powder in the flux mixture, or as asbestos string wrapped around the electrodes. This practice declined after the Second World War and ceased in the 1950s.

Electrical resistance welding was also developed before the turn of the century. This process was found to be relatively immune to the embrittlement problems that usually accompanied early arc welding. Spot welding was developed for fastening thin sheet, and butt welding for joining bars and making chains. These and the related process of seam welding, used for making unbroken joints in sheet metal, were well developed by about 1920 (Lancaster, 1980).

Before 1914, welding was not a common industrial process and was often restricted to repair applications. It received a spur during the First World War in armament manufacture. Later, the car industry, particularly in the USA, adopted resistance welding techniques, and these were taken up for other production line manufacture; however, riveting remained the principal method of joining metal plates in buildings, bridges, ships, tanks and armaments until the late 1930s.

The Second World War provided a major impetus to the heavy manufacturing industry and heralded the widespread adoption of welding technology. Tanks and heavy armaments were built in large numbers using MMA welding, and this method of assembly was also applied to shipbuilding. Early welded ships were prone to catastrophic fractures due to hydrogen embrittlement, but this was overcome in the early 1940s when basic low-hydrogen MMA electrodes were developed (Lancaster, 1980). Other, newer welding processes also found applications in the war years. In 1936, submerged arc welding was patented in the USA (Skriniar, 1986). This differs from the MMA process in that the electrode is in the form of a continuous wire which is driven mechanically into the arc as it melts. A granulated flux is poured from a hopper so that it surrounds the arc region and melts to form a slag layer over the weld metal. This process was used extensively for the manufacture of tanks in the final years of the war. Tungsten inert gas (TIG) welding (gas tungsten arc welding; Lindberg & Braton, 1985), the first successful gas-shielded welding process, was introduced in 1943 (Lancaster, 1980). In this technique, a non-consumable tungsten electrode is used, and the arc is shielded with argon gas delivered by a nozzle which surrounds the electrode. The process was used initially instead of rivets for the assembly of aluminium and magnesium alloy aircraft frames (Skriniar, 1986). When filler metal was required, wire was fed by hand into the weld pool. A variant of TIG welding, developed in the late 1960s, is the plasma arc process, in which some of the shield gas is forced through the arc and ejected as a high velocity jet of ionized gas (plasma). Plasma arcs can be used either for cutting or welding, and higher welding speeds can be achieved than with TIG welding (Lindberg & Braton, 1985).

After the Second World War, welding became the principal means of joining metal throughout the manufacturing, shipbuilding and construction industries, and welding technology research and development accelerated. Metal inert gas (MIG) welding, the first gas-shielded welding process to involve a consumable metal electrode, was put into use in 1948 (Skriniar, 1986). As in submerged arc welding, the wire electrode is driven mechanically into the arc region at the same rate as it is consumed. The arc region is bathed in an inert gas mixture based on argon or helium to protect the molten weld metal from atmospheric gases. Attempts to use cheaper shield gases such a carbon dioxide were not very successful at first because of weld porosities; however, the development of special welding wires containing antioxidants in the early 1950s overcame this problem. As carbon dioxide cannot be described as an inert gas, the new process was referred to as metal active gas (MAG) welding. The terms MIG and MAG are loosely interchangeable, but, as argon- and helium-based shield gases usually contain some oxygen or carbon dioxide, MAG is the more accurate description. In the USA, both MIG and MAG welding are usually referred to as gas metal arc welding (Lindberg & Braton, 1985).

In the late 1950s, tubular electrodes were introduced for semi-automatic welding. Hand-held tubular electrodes had first appeared in the 1920s and were used to a limited extent after the Second World War for oxy-fuel welding. The new 'flux-cored' tubular electrodes were incorporated into MIG-type welding torches with a carbon dioxide shield gas. Their adoption was gradual, but by the mid 1960s the advantage of flux-cored wires over the solid-wire carbon dioxide process was generally appreciated. The flux contents of tubular wires can be used to control oxidation and alloying of the weld metal and gives it more effective protection during cooling. Tubular electrodes that contained gas-forming compounds and could be used without an external shield gas were introduced in the late 1950s. In the 1960s, such 'self-shielded' flux-cored welding wires rapidly gained popularity in the USA, the USSR and Japan but saw only limited use in Europe until the 1970s and 1980s (Widgery, 1988).

Recent developments in welding technology have involved refinements of the existing welding processes and the introduction of new, often more automated processes. Welding power supplies, once little more than heavy transformers and rectifiers, are increasingly sophisticated (Wilkinson, 1988): since the late 1970s, development of transistorized 'solid state' power sources has been dramatic; voltage and current profiles can be computer-programmed to give precise drop-by-drop delivery of weld metal to the weld pool. This can improve weld quality and productivity in MIG welding and related processes. The 1970s and 1980s have witnessed increasing use of electron beam and laser welding and in particular a marked increase in automated and robot welding. The automotive industry has for many years been highly automated, and few welds on motor vehicles are made by human welders. This type of automation is very inflexible and car production lines are usually built for a single product. Robot automation, in contrast, can be highly flexible and can be used for a variety of products. Computer-aided design and manufacture is now increasing, and this will gradually reduce the number of human welders employed in manufacturing industries in countries with advanced economies.

1.3 Description of major welding processes

(*a*) *Introduction*

Despite the many different types of welding process that have been developed, the large majority of welding still involves MMA, MAG, TIG, flux-cored and submerged arc processes (Stern, 1983; Lindberg & Braton, 1985). MMA has been the dominant welding process since the 1930s but is now declining in importance (Wilkinson, 1988). Since the late 1970s, the market for MMA electrodes in Europe has fallen markedly, partly due to the recession in heavy industry and the reduction in shipbuilding and off-shore construction, but also because of increasing use of other welding processes, particularly MIG. Cored wires have been important in the USA since the 1960s and are of rapidly increasing importance in Japan and the newly industrialized nations of the far east (Widgery, 1988).

Although welding is a recognized profession, many other workers, not employed specifically as welders, also carry out some welding. Most welders are familiar with the majority of the common industrial welding processes but usually have extensive work experience with only a few. Most welders have experience with MMA and many are also experienced with MIG. Fewer have much experience with TIG, submerged arc and the many other forms of welding. Some welders use a wide range of processes routinely, while others are employed to specialize in certain welding processes, such as TIG, and many specialize in welding certain types of metal such as stainless-steel and aluminium.

The fabrication of large structures, such as ships and heavy bridge girders, can involve long periods of continuous welding. Small, intricate assemblies require more manipulation of the workpieces and shorter, more intermittent periods of welding. Before a workpiece is welded, it usually requires some preparation including cutting, shaping and grinding of the edges to be joined. Such preparation is not usually carried out by welders; however, they might have to spend time positioning the parts to be joined and tacking them at intervals along the seam prior to welding, again reducing the overall arcing time. The proportion of the working day involved in arcing is sometimes referred to as the 'duty cycle'. Duty cycles rarely exceed 70% of the day and can be very much less. For MMA welding, the average duty cycle rarely exceeds 50% on average, and a figure of 20% is reported to be typical (Widgery, 1986).

The speed with which a weld can be made is determined by many factors, including the rate at which weld metal can be deposited. Metal deposition rates depend upon the type of welding process being used, the welding current, electrode diameter and characteristics, and upon the position of the weld being made. For all welding processes, the highest rates of deposition are achieved when horizontal welds are made from above (downhand welding). Vertical, overhead and other 'positional' welding require lower welding speeds to avoid sagging of the weld metal (Widgery, 1986). It is often necessary to finish the weld by chipping away residual flux or grinding away excess weld metal. Sometimes it is necessary to cut out areas of weld metal that contain flaws such as cracks and flux inclusions. This can be done by grinding, but often an electric arc gouging process is used. The most common of these is arc-air gouging which involves a carbon arc and a compressed air jet to blow away the molten metal.

Welding can be carried out in almost any setting, including under water and in hyperbaric conditions. It is often carried out on benches in engineering workshops, but much structural welding is done outdoors; some assemblies, such as ships, boilers, tanks and pipes, often require welding in confined spaces.

(*b*) *Manual metal arc welding*

MMA (or shielded metal arc) welding equipment is relatively simple, consisting of a heavy source of electric current, such as a transformer, transformer-rectifier or generator, and a simple spring-loaded holder for the electrode (welding rod). A heavy cable carries the current to the electrode holder, and a similar cable provides a return or earth connection which is clamped to the workpiece or to a heavy metal bench on which the workpiece is placed. The welder strikes an electric arc between the tip of the electrode and the workpiece by brief contact and then withdraws the electrode tip several millimetres to maintain an arc gap, which must be adjusted continually as the electrode is consumed. Each electrode must be replaced after only a few minutes. The weld that is produced by the MMA process is covered by a layer of slag resulting from the flux coating on the electrode. This must be removed before the work is completed or before another layer of weld metal can be laid to build up a large joint, usually by use of a chipping hammer. Some types of slag systems are designed to peel off the weld easily, while other types adhere strongly and must be chipped vigorously. This cleaning task further slows the welding operation. The metal deposition rates achieved by MMA welding during continuous arcing are usually in the range 1-3 kg/h, although higher rates can be achieved with some electrodes. MMA electrodes in a wide range dimensions and compositions are available for welding different types of metal and for obtaining different mechanical and corrosion resistant properties. Most metals are welded with electrodes of similar composition; for example, stainless-steel electrodes are used to weld stainless-steel components. A notable exception to this general rule is the use of nickel consumables to weld cast iron. Three types of MMA flux system are commonly used: cellulosic — containing mostly cellulose, rutile (titanium dioxide) sand and magnesium silicate; rutile — containing mostly rutile sand and calcium carbonate plus a small amount of cellulose; and basic — containing mostly calcium carbonate. Many other ingredients are added to fluxes, including calcium fluoride (Brillié, 1990), sodium and potassium silicates and iron powder (Lancaster, 1980).

(*c*) *Metal inert gas welding*

MIG/MAG (or gas metal arc) welding equipment is considerably more complicated than MMA equipment and consists of a special power source, an automatic wire feed unit and a gas-shielded welding torch. The welding wire is stored coiled on a drum and is fed automatically to the welding torch by a 'wire feed unit'. The power source is usually a 'constant potential' transformer-rectifier designed to provide a welding current proportional to the rate of consumption of the welding wire. A heavy cable carries the current to the torch, where it is delivered to the welding wire by a tubular copper 'contact tip' through which the wire passes. A heavy return cable is used, as in the MMA process. The power supply is activated by a trigger-like switch on the torch, and the arc is struck between the wire tip and the workpiece after a brief contact. At the same time, the shield gas flow and the wire feed unit are activated. Shield gases may be based on carbon dioxide, argon or helium; pure inert gases are rarely used as they do not result in a stable arc, and shield gases usually contain small amounts of carbon dioxide or oxygen. Because the welding wire must be replaced only occasionally and there is no slag to remove from the weld, duty cycles for MIG welding may be considerably longer than for MMA. Metal deposition rates may also be higher — from about 1 to 10 kg/h or more (Widgery, 1988). Some welding torches are water cooled to permit continuous operation at high power.

(*d*) *Flux-cored wire welding*

Flux-cored wire welding involves almost the same type of equipment as MIG welding, and the processes are technically similar. Self-shielded tubular electrodes do not need a shield gas, but a shield gas must be used for those flux-cored wires that do not contain gas-forming agents. In Japan, carbon dioxide is the gas most commonly used for this purpose, whereas in Europe argon-rich gas mixtures are preferred. The slag layer that is left on the weld is usually self-detaching or is relatively easy to detach mechanically. Flux-cored wires are easier to use in vertical welds because the slag can help to support the molten weld metal. Duty cycles are comparable with those of MIG welding, but weld metal deposition rates can be higher, particularly in positional welding. Deposition rates considerably in excess of 10 kg/h are possible in downhand welding (Widgery, 1988). A variety of fluxes is used in tubular electrodes including many (such as rutile sand) that are used in MMA electrodes. Self-shielded tubular electrodes frequently contain barium carbonate or barium fluoride (Dare *et al.*, 1984), but these are not usually found in gas-shielded flux-cored welding wires.

(*e*) *Tungsten inert gas welding*

TIG (or gas tungsten arc) welding involves use of a gas-shielded welding torch with a tungsten electrode. As the melting-point of tungsten is nearly 3500 °C, the electrode does not melt during welding, provided that a high frequency alternating current is used or that a negative electrode is used in direct current welding. The arc region is shielded by argon, helium or a mixture of the two. The TIG process can be used for spot welding, or a filler wire can be used to produce larger welds. In simple TIG welding, a filler wire can be fed by hand into the molten weld pool. To obtain higher rates of metal deposition, mechanical wire feed units are used similar to those used in the MIG process. Higher heat inputs can be obtained by attaching a second power supply to deliver current to the filler wire. This process, sometimes referred to as 'hot wire TIG' is in fact a combination of the TIG and MIG processes (Lindberg & Braton, 1985). TIG welding gives high quality welds and is suitable for a wide range of metals including stainless-steel, aluminium, magnesium alloys and titanium.

(*f*) *Submerged arc welding*

In the submerged arc process, the welding arc and the still molten weld metal are entirely buried in granulated flux. The welding wire is delivered mechanically by a wire feed unit mounted directly above the welding torch, and the flux is fed continuously from a hopper ahead of the advancing arc. Loose flux granules are usually recovered by a vacuum attachment which follows the torch and recycled to the flux hopper. The welding torch, wire feed unit, flux hopper and vacuum unit are all mounted on a carriage which travels on wheels along the length of the weld. Metal deposition rates of several tens of kilograms per hour can be attained with a single torch and wire feed unit. Sometimes, several wires are used in line to give multiple weld layers at one pass. Submerged arc welding is almost automatic, and the welders' task is to set up the equipment to make each joint and to ensure weld quality with minimal intervention. Because the equipment must be repositioned to make each weld, the overall duty cycle is reduced; however, metal deposition rates can be very high, particularly if multiple wires are used.

1.4 Number and distribution of welders

A comparison of the industrial economies of the world suggests that there might be of the order of 3 million workers worldwide who perform some welding. In the USA, more than 185 000 workers are employed as welders, brazers or thermal cutters, and it is estimated that up to 700 000 US workers carry out some welding during their work (National Institute for Occupational Safety and Health, 1988).

The balance of different welding processes is difficult to estimate, partly because manufacturers do not publish figures of sales of welding equipment and materials. Such figures are available for Sweden in 1974 (Ulfvarson, 1981), and these are summarized in Table 1. Approximately 22% of Swedish welders were reported to be stainless-steel welders. This is a higher proportion than in countries of the European Economic Community, as the average for France, the Federal Republic of Germany, Spain and the UK was about 10% prior to 1979; and the proportion is even lower in less developed countries (Stern, 1980a).

In western Europe, MIG welding has a greater market share than in the USA because it usually allows greater productivity than MMA welding, since fewer welders are needed to lay the same amount of weld metal. This affects estimates not only

Table 1. Distribution of Swedish welders by process and material in 1974[a]

Process[b]	Material				
	Total	Mild-steel	Stainless-steel	Aluminium	Other
MMA	25 585	16 854	5 896	1 496	1 339
MIG + MAG	9 143	6 232	1 594	1 141	176
TIG	4 216	1 547	1 529	913	233
Gas	3 823	2 762	479	325	257
Submerged arc	783	540	210	32	1
Total	43 550	27 935	9 708	3 907	2 006

[a]From Ulfvarson (1981)

[b]MMA, manual metal arc; MIG, metal inert gas; TIG, tungsten inert gas

of total numbers of welders but also of the relative importance of different welding processes. Sales of MMA electrodes in the major economies represent about 46% by weight of the total for all consumables. In terms of weld metal sales, i.e. excluding the weight of flux, MMA represents about 41% of the total. Assuming weld metal deposition rates of 3 kg/h for MMA and 7 kg/h for MIG welding, MMA must represent about two-thirds of welding in terms of arcing time. Furthermore, as the duty cycle for MMA might be only about half that for semi-automatic processes, MMA welding might represent about 80% of welders' payroll time (Jefferson, 1988).

Many types of metal are welded, including stainless-steel, high chromium armour plate, aluminium, copper and nickel; however, the large majority of welding is on mild and low alloy steels. Stainless-steel represents only about 4-5% of MMA electrode sales and about 3% of MAG and TIG wire sales in western Europe. Similarly, about 2-3% of MAG and TIG wire sales are aluminium.