No. 7

A BRIEF OUTLINE OF WELDING WITH PARTICULAR REFERENCE TO THE METALLIC ARC PROCESS

Object.—To join together previously shaped sections or pieces of metals such that in similar metals the resultant joint has the same physical and chemical properties as the parent metal.

This cannot be fully realized, but the physical properties obtainable by modern methods approach those of the parent metal, and joint efficiencies up to 90 per cent. are allowable where the design of joint, the material used, and the workmanship put into the weld are up to standard.

Methods of Welding.

Forge Welding.—The metal parts are heated to the plastic state and united by hammer blows. Given that the operator has sufficient skill—and considerable personal skill is required—sound welds can be, and are, produced, but the field of such welding is extremely limited. Larger jobs may be tackled with a power hammer, but again the applications are very limited by reason of the heating facilities offered by a forge or furnace and the restrictions imposed by the hammer itself.

Water Gas Welding.—In this process the required heat is obtained by the combustion of water gas in suitable burners. This gas is of a reducing nature and therefore an improvement on forge heating from an oxidizing point of view and lends itself to machine work in which forge heating would be difficult. As with forge work the metal is heated to the plastic state and the weld completed by application of pressure—either by mechanical hammer or rollers. This form of welding is still limited in its application, is essentially a shop process, and the results obtained are not too good. The ductility is usually low.

Pressure or Resistance Welding.—Although water gas welding when carried out by rollers is a form of pressure welding, the much more widely used form of pressure welding is that often spoken of as resistance welding. This is a branch of electric welding, but as with the former processes, no added metal is used in the formation of the weld, the electrical energy being used purely to heat the parts to be welded to a plastic state, the weld being completed by the application of pressure. This form of welding is subdivided into three types—butt, spot, and seam, all of which are machine processes. Whilst in the case of resistance butt welding it is possible to unite areas as large as 60 sq. in., spot welding (used in lieu of rivets to make lap joints) is limited to an added thickness of 1 in. and seam welding (a continuous lap joint) to an added thickness of ¼ in. The limits are due to practical considerations in the construction of the machines and the supply of power. The principle is the same in all types. The surfaces to be welded are placed in contact and an electric current of high amperage and low voltage derived from a transformer is passed across the junction (about 30 K.W. per sq. in. of area for 10 seconds). The resistance of the junction causes a rapid rise in temperature. When the metals are hot enough the current is switched off and the weld consolidated by pressure applied either by hand leverage, spring, pneumatic or hydraulic power. About 5,000 lbs. per sq. in. of area is required.

Such machines have a great many applications and are used extensively in industry, particularly for repetition work.

The work is very rapid and the output great.

Fusion Welding.—In this type of welding additional metal is used to make the joint, and no external pressure is applied. As the name suggests, the resultant joint is a fusion of the added metal with the two parts to be welded together. Electric arc welding comes into this category which is divided into three methods—gas, electric arc, and aluminothermic (Thermit).

The last method, in which the heat is generated by the chemical reaction between a mixture of finely divided aluminium and iron oxide, is beyond the scope of this paper, and will not be dealt with further.

Gas Welding. — The heat necessary to melt both the parent metal and the filler rod is supplied by the reaction of a combustible gas with oxygen. The filler rod is usually an uncovered wire of material suitable for fusion with the parent metal. The most usual gas in use in this country is acetylene which produces a flame temperature of about 3,100° C.

Correct regulation of the gas mixture is of great importance—an excess of acetylene will give a carbonizing flame, which causes hardness and loss of ductility in the weld, whilst an excess of oxygen will cause oxidation of the metal. A neutral flame is invariably necessary and requires a certain amount of skill to maintain, as adjustments are required according to the heat of the torch as welding proceeds and these must be foreseen.

Coal gas is also used but gives a much lower flame temperature, and hence is particularly useful in cast iron welding where it is very necessary to limit the amount of heat put into the job. A much wider use of coal gas occurs in oxy-coal gas cutting machines. Such machines are frequently employed for cutting out the metal shapes which are to be welded together and for preparing the edges of plates for butt welding by the electric arc process. Plates cut by oxy-coal gas cutting machines are in most cases ready for arc welding without further preparation and such machines are to be found in the preparing bays of practically all large welding shops.

Gas welding is very suitable for thin gauge materials, as an absence of local concentration of heat can be obtained by spreading the flame and the risk of burning through the parent metal can be avoided. With thin materials there is little volume of parent metal to conduct the heat away and if the heat becomes intensely localized, as with the electric arc method, burning may occur. In steels, however, this spreading of the heat zone has the objection that the area of thermal disturbance is extended considerably, with ill-effects both from the point of view of ultimate structure and that of distortion—the bugbear of all welding.

Gas welding is also the most suitable for the majority of non-ferrous metals such as copper, brass, aluminium—in fact, even to-day it is the only fusion process which is satisfactory for non-ferrous work except the atomic-hydrogen method. It is not suitable for heavy sections as sufficient local concentration of heat cannot be obtained, and it is not sufficiently flexible in its application as is arc welding.

Electric Arc Welding.

(*a*) **Atomic-Hydrogen.**—This may be described as a combination of electric arc and gas welding, although strictly speaking it is a form of electric welding, the gas being used as a medium which makes the process possible and as an envelope in which the welding takes place. If an arc is struck between tungsten electrodes and a stream of hydrogen passed through the arc, the hydrogen molecules are broken up.

On reuniting a short distance away from the arc, a large amount of energy is given out which appears in the form of intense heat. It is this heat which is used to fuse the parent metal and a suitable filler rod to form the desired weld. In practice a pair of tungsten electrodes of about $\frac{1}{16}$ in. diameter are held in a special form of holder at an angle of about 30° to each other and so arranged that a hand grip enables the tips of the electrodes to touch when striking the arc, and then to open about $\frac{1}{8}$ in. to maintain the arc. A stream of hydrogen is directed into the arc, part of which becomes atomized and reunites about $\frac{1}{2}$ in. from the arc and gives a fan-shaped flame which forms the heat source, whilst the remainder of the hydrogen which is not atomized, burns in the normal way as an envelope round the heat flame and protects the weld from oxidation. The heat is not derived from the burning hydrogen but directly from the arc energy. The temperature at the hottest part of the flame is computed at 3,700° C. and in consequence there is a slow burning away of the tungsten electrodes, some of the tungsten so dissipated appearing in the weld metal. The heat is intensely local and hence it is claimed that distortion troubles are reduced to a minimum. Again, due to the intense heat, the metal under the arc is very fluid and therefore the process is only suitable for horizontal work.

This fluidity gives the weld a very smooth-finished appearance, but this is a little deceptive as molten steel has an affinity for hydrogen, with the result that there is some hydrogen absorption and the weld is inclined to be porous due to the hydrogen being given out on solidification.

There is no protective slag coating, hence cooling is rapid and ductility may suffer.

Briefly, the advantages are :—

Speed of welding. The intense heat and bare filler rod make for high speed.
Lack of distortion.
Very suitable for high melting point alloy steels.
Can be used for cast iron and non-ferrous metals.
Freedom from oxides and slag inclusions.

The disadvantages are :—

Porosity and lack of ductility.
Only suitable for horizontal work.
Not very portable as, in addition to the apparatus for supply of a suitable electric current (an A.C. supply giving 300 volts on open circuit is necessary), a supply of hydrogen is required.
High cost of outfit.

There may well be further developments in this process for special cases. The writer has seen it used successfully for building up heavy nickel cast iron dies, used in the pressed steel industry.

(*b*) **Carbon Arc.**—In this case again the arc is the heat source and a filler rod is used. The electrode is either hard carbon or graphite and an arc is struck between the parent metal and the electrode which melts both parent metal and filler rod. It is a semi-casting process, in which the filler rod is puddled into the molten parent metal, and is used in steel foundries for repairs to defective castings. The arc temperature is about 3,600° C. and the intense local heat gives it an advantage over the oxy-acetylene torch. Having struck the arc, it is very essential that the arc shall not be restruck in the pool of molten metal, as a heavy carbon pick up will take place, resulting in an unmachinable spot in the weld. This method is only satisfactory for horizontal work.

(*c*) **Metallic Arc.**—Again the electric arc is the heat source, but in this case the filler rod of all fusion welding becomes the electrode. This is by far the most universal form of all welding processes, and is the form of welding to which the remainder of this paper will be devoted.

Whilst it is true that metallic arc welding can be used successfully on all forms of steel, and with varying degrees of success on cast iron and many non-ferrous metals, its prime application is in joining together or building up mild or low carbon steels, and the following remarks refer in the main to that application.

There are three essentials for a satisfactory metallic arc weld :—

Suitable electrodes.
A suitable supply of electrical energy.
The correct technique in application.

Dealing with these in this order :—

Electrodes.—As was to be expected in the early days of metallic arc welding the filler rod of gas welding—a length of low carbon mild steel, or iron wire—was connected to a source of electrical supply and an arc struck between the end of the wire and the work to be welded. The comparative ease and simple equipment with which such work could be carried out made an immense appeal, and in America, where metallic arc welding appears to have made the first early strides, bare wire electrodes were used universally. From simple tensile tests, this appeared to give quite sound results for it is easily possible to obtain tensile figures of up to 30 tons per sq. in. from bare wire welds. Further, in the early stages, metallic arc welding was not used for highly stressed parts.

It was soon found, however, that all the other physical properties associated with mild steel were only of a very low order in bare wire welds. The elongation and " reduction of area " were low and izod value practically nil. This result is due to oxide and nitride inclusion and rapid cooling. The oxides appear as such between the grain boundaries and tend to weaken the metal, whilst the nitrides go into solid solution and have a hardening effect resulting in loss of toughness and embrittlement.

This led to the development of the coated electrode, whereby a gas shield, flux and additional elements could be introduced. Such electrodes may be divided into three classes—lightly, medium and heavily coated.

Lightly coated electrodes are dipped into a suitable solution and dried, and, as the name implies, the coating is only of a thin nature. They are cheap to produce, give better weldability than bare wire—(steadier arc and easier flowing)—are comparatively fast, leave little slag to remove after welding and can be used on an A.C. supply, but on the whole they do not give greatly increased physical properties over bare wire. Some forms of lightly coated electrodes have a coating which volatilizes to form a gas shield and leaves no slag.

Medium coated electrodes are likewise usually dipped, but the medium into which they are dipped is more heavily bodied, or alternatively repeated dipping is carried out, thereby giving a thicker coating. Naturally such electrodes are slightly more expensive, but in return the physical results are an improvement on those obtained with the lightly coated type. In either case care must be taken not to bend such electrodes, as bending will in most cases cause the coating to break. This will give discontinuity in the coating and difficulties with the weld when such a place is reached in the electrode. If bending is necessary for accessibility, the bend should be made close up to the holder in the discard portion.

Heavily coated electrodes are prepared by winding or braiding with asbestos fibre, cotton twine, or other similar materials followed by dipping several times in baths of various compositions, or by mechanical pressing in of the material in a pasty condition by the extrusion process.

The latter is the more usual method of producing the modern heavily coated electrode. The wire is reeled at one end of a machine, straightened, cleaned, braided, paste extruded, dried and cut to length in a continuous operation.

The physical properties obtained from welds made with heavily coated electrodes are without question superior to those obtainable with bare wire, or light or medium coated electrodes, and for this reason, although more expensive to produce, are used more than any other type, particularly for work subject to high stresses.

The composition of the coating is, somewhat naturally, seldom given by the electrode makers, but silica, manganese and various metallic oxides play their part in most coatings. In general electrode manufacturers will not allow visitors to see either their laboratories or their electrode manufacturing shops. Many varied elements are introduced into the coating for a number of purposes and in this connection it may be said that, for the majority of electrodes on the market for dealing with steels other than special alloy steels, the core is a plain low carbon mild steel—about 0·15 per cent. C. All the other elements required in the weld are added in the coating.

In the case of electrodes for alloy steels such as the austenitic heat-resisting steels, or the nickel-chromium stainless steels, the core must be of the same composition as the parent metal.

The duties of the coating are as follows :—

(i) To provide a slag, which (*a*) prevents oxidation of the weld metal by protecting it against atmospheric contamination ; (*b*) allows slower cooling, and therefore greater time for any absorbed gases in the weld metal to come out of solution, and a more ductile weld metal results.

(ii) To flush away oxides and dirt on the joint surfaces of the parent metal (plate edges prepared in the oxy-coal gas cutting machine can be welded without further preparation, which is not strictly true of hand cutting or machine cutting for very special work such as boiler drums).

(iii) To prevent the arc from wandering.

(iv) To give a hotter weld metal, and therefore greater heating of the parent metal with better penetration.

(v) To provide a gas stream in which the arc voltage is higher, and therefore for constant current value allows of a greater heat input (Murex " Fastex "—liberates hydrogen).

(vi) To provide a vehicle for elements required in the weld metal.

(vii) To increase electrical conductivity of the rod with rise of temperature and so balance the opposite effect in the metal core, thus giving more stable current conditions for the arc, which is an essential for good work.

There is one important disadvantage, however, which must be dealt with by suitable technique in the use of the coated rod, *i.e.*, the danger of trapping slag in the deposited metal with resultant weakness. Provided sufficient care is used this danger can be avoided.

Another disadvantage is that the protective slag coating must be removed completely if another run of weld metal is to be deposited on top of the previous run. Although every effort is made to make the coating flake away from the weld metal on cooling, the degree of adhesion varies with different coatings, and even in the most easily removed coatings, there is usually some adhesion at the edges of the run which necessitates the use of a light chipping hammer and wire brush. This takes time and adds to the cost, but where high physical properties are required in the weld, the use of the heavily coated electrode is recognized as being essential.

The number of electrodes on the market is legion, each claiming some particular virtue, and whilst it is highly desirable to reduce the number of types in use, a diversity of work naturally calls for a diversity of types. Efforts have been made by electrode manufacturers to reduce their types of electrode by combining the properties of two electrodes in one, but the usual result is that although the new electrode sells well, there is still a demand for the two originals, so that three have to be made instead of one, as was hoped. Extensive testing and use will determine those which are most suitable for any particular work, and having established that a certain electrode is suitable for the work in hand, it is inadvisable to change that electrode without good reason, as there is little doubt that if an operator has become accustomed to a certain electrode, a change will immediately lower his standard of work until he becomes accustomed to the new type.

The human element enters largely into all hand welding and although suitable precautions will do much to reduce this factor to small proportions, it is always present and must always be borne in mind.

A list of approved electrodes is published in A.F.Os. from time to time, giving the type of work for which each electrode is approved to be used. This list is intended primarily for constructional work, but there is a note stating that for machinery purposes the use of electrodes, other than for welding mild steel, should be confined for the present to those obtainable from Murex or Quasi-Arc.

Electrical Supply.—The supply of electrical energy to the arc—(as distinct from the primary power required)—may be either D.C. or A.C. There is very divided opinion as to which is the better, if either.

A.C. is not suitable for bare wire nor for some alloy steels requiring special cored electrodes.

On the other hand it is contended by some authorities that the thermally disturbed area in the parent metal is less with A.C.

A.C. supply forces the operator to use a short arc—an essential for good work.

A.C. supply gives freedom from arc blow—a wandering of the arc due to magnetic circuits set up in the parent metal—and this is very important in mechanical arc welding. It only becomes apparent as the heavier gauge electrodes, and hence heavy currents are used.

There is little doubt that equally good physical results can be obtained from either D.C. or A.C.

When an A.C. primary supply is available, the choice of welding supply is influenced largely by the low initial cost and the freedom from maintenance offered by the static A.C. welding set.

The requirements of the arc supply are that it shall give :—

(i) An open circuit voltage of at least 50 for D.C. and 70 to 90 for A.C.

(ii) Sufficient current per welder, capable of regulation in small steps from the minimum to the maximum required, and that once set, the current value shall be free from fluctuations (the minimum and maximum values will depend on the gauges of electrodes and the work it is desired to undertake, but for most normal work a range of from 30 to 200 amperes is sufficient).

(iii) Freedom from interference between operators, where more than one operator is working off a set.

Welding Plant.—In the case of a D.C. supply, this will consist of a generator driven by the form of power most readily obtainable, which may be an electric motor, a petrol or heavy oil engine or even belt drive from shafting.

The more usual form where an electrical supply is available is a motor generator, the motor being either A.C. or D.C. according to the power supply. The generator may be arranged to supply from one operator up to possibly thirty in a large shipyard set, although a more usual upper limit is twelve. In the case of a multi-operator plant, the generator must have a level or preferably a slightly rising characteristic so as to avoid voltage drop to operators already at work when an additional operator comes into circuit.

The arc requires 50–60 volts D.C. to establish it, but having been struck only 20–30 volts (dependent on the type of electrode) are required to maintain it, so that there must be some external method of voltage reduction. This is accomplished by the use of variable resistances in the circuit, which serve to effect the required reduction of voltage and regulate the current to that desired within the limits of the generator.

Such resistances are wasteful as at least half the power output from the generator is dissipated by the resistance, but they provide a simple control and are in general use in multi-operator D.C. plants.

In addition reactances are necessary in each welding circuit to prevent heavy current surges when the arc is struck and to smooth out the supply as much as possible.

For single-operator sets a generator having a falling characteristic is used. The windings are so arranged that whilst an open circuit voltage of 60 is available, as soon as any appreciable load comes on to the machine the voltage falls to that required for the arc only. By this means a wasteful external resistance is avoided. The current output is controlled by a small rheostat in the field windings or by armature reaction, in which case the brushes are moved for control.

There is another form of D.C. generator which makes use of what is known as the A.D.C. system developed by Mawdsley's, in which D.C. current at arc voltage is generated, and a separate A.C. supply is also generated which is superimposed on the D.C. supply by means of a separate winding on the normal reactance winding, making the reactance into a form of transformer. The addition of the two voltages provides sufficient pressure to strike the arc. Immediately the arc is struck the heavy current flow through the reactance-transformer causes a contactor to break the superimposed A.C. circuit and welding is carried out by the normal D.C. supply at the correct voltage without heavy waste in control. As soon as the arc is broken the A.C. circuit is re-made and a sufficient voltage for restriking the arc is at once available.

This type of generator may be used for either single-operator or multi-operator sets, but each welding circuit must be equipped with a transformer—reactance having the A.C. supply taken to it and fitted with contactor gear.

Arc welding sets are now being supplied to all capital ships and cruisers and the latest sets to be supplied are single-operator sets by Mawdsley's working on the above system. These sets are motor-driven from the normal ship's 220-volt D.C. supply and give an open circuit voltage of 55 to 60 and a maximum current output of 175 amps. for arc welding which will allow of electrodes up to 6 gauge being worked fairly comfortably, and should meet all requirements for single-operator ship work.

In addition, these machines are arranged to give a momentary current of 270 amperes at 60 volts for stud welding.

Where an A.C. primary supply is available, an A.C. welding supply can be obtained readily by means of a transformer and suitable choke regulators.

It is advisable to have at least 90 volts available on open circuit as there are some types of electrodes which, whilst working well on an A.C. supply, will not permit of the arc being struck below this voltage.

The alternating characteristic of the supply naturally has some effect on the maintenance of the arc once it has been struck, so that it is necessary for the transformer to be so arranged that the normal sine wave form of current and voltage be deformed to approach a rectangular peak so that the period of low and no voltage be reduced to a minimum, and the peak voltage be maintained for a maximum.

In a single-operator set it is usual to use only one phase of the primary supply, but for multi-operator sets all three phases are used and the number of operators the set provides for rises in groups of three, one operator from each group being supplied by each phase. This is very desirable in order to keep the phase loading even.

Current regulation is carried out by an iron-cored or other form of choke which, whilst regulating efficiently, does not waste current as do the resistance regulators used in multi-operator D.C. sets.

An advantage of static transformer sets previously referred to is the absence of maintenance due to freedom from moving and wearing parts, particularly brush gear. It is most important with all forms of motor generator sets that the bush gear shall receive frequent periodic attention, if uniformity of supply—an essential for good work—is to be maintained.

The remaining items of plant required are the welding supply cable, the electrode holder, a face shield with suitable glass, and a plain glass for use when chipping off slag.

The main cable should be of ample section to carry the maximum current, whilst the last 6 ft. at the electrode holder end should be as light and flexible as possible, or the operator will suffer from fatigue and poor welding will result. The electrode holder should be as simple as possible and free from parts which will be adversely affected by heat, and should be well insulated and preferably have a safety disc above the hand grip. The glass in the face screen must cut out all rays from the arc which are dangerous to the eye and yet allow a clear view of the work. Arc eye is a very real danger and even at some distance it is inadvisable to look directly at the arc without some form of screen. The coloured glass in the screen should be protected by a piece of plain glass which can be readily changed when it becomes fouled from the arc, and the screen should be as light as possible and made entirely of insulating material.

A fairly accurate ammeter registering the welding current is of advantage, although not essential to a skilled operator.

One further item is the earth return. The job is earthed and if welding on a steel bench, the bench is often used as the return.

Practice.—The current value to be used must be that suitable to the type of rod, gauge of rod, and the section and position of the material on which the weld is being made.

The limiting value for any one rod occurs when the rod becomes so hot that the coating flakes off, but limitations imposed by the work ensure that this limiting value is never reached. The practical value is determined by the necessity for ensuring complete fusion or penetration without undercutting or burning away of the edges of the parent metal, and in the case of vertical and overhead work, without the weld metal becoming so fluid as to run away from the work.

With the majority of the makes of rod in general use, the current value is approximately the same, when doing similar work and as a rough guide may be taken to be 100 amps. for 10 gauge, rising or falling 30 amps. for each two gauges above and below 10. This embraces the sizes of rod in general use, *i.e.*, 14 gauge, 40 amps.; 12 gauge, 70 amps.; 10 gauge, 100 amps.; 8 gauge, 130 amps.; 6 gauge, 170 amps. Certain rods, however, require a higher current value generally due to a type of coating which requires greater heat to melt, and it is well in the first place to be guided by the current value recommended by the makers.

This value must be modified to suit the work in hand; *e.g.* the first run of a butt weld in which the prepared V edges of the plates must not be burnt through. For normal 10 gauge electrodes the first run of such a weld would be made at 90 amps. instead of the usual 100. The next run, assuming the work to be horizontal, would be made at 110 amps., as the natural V trough will readily hold a more fluid metal. The additional heat will give better penetration and undercutting is not greatly to be feared. The current for the final run will probably have to be reduced, for not only is the job hot but also undercutting of the edges must be avoided.

Again, for vertical work, the current value may have to be reduced if the weld metal becomes too fluid to control.

Penetration.—It is essential to ensure complete fusion between the deposit and the parent metal, and between successive deposits. This is known as penetration and is accomplished by maintaining a short arc and using a current value high enough to ensure sufficient melting of the parent metal. Efficient penetration is essential for good work, and it must be remembered that lack of penetration cannot be detected in the finished weld. The term " penetration " is also used with reference to the first run of a butt weld in which it is essential that the weld metal shall penetrate through to the reverse side of the joint. This form of penetration can usually be seen. It is likewise essential that root fusion—or penetration—shall occur at the butting edges of all welded seams, or a reduction of strength will result with ugly stress concentrations in service. In fact, lack of root penetration may be a very definite source of failure, for the contraction stresses set up as the first run cools may be large enough to start a crack in the root of the run due to heavy stress concentration. This crack is hidden as it does not penetrate right through the run, other runs are added, and all appears well till the job goes into service when failure occurs. It is always advisable to use as high a current value as the job will carry without impairing the work in any way.

Undercutting.—One of the principle limitations to current value is undercutting. This is apparent at the junction of the weld metal with the parent metal and may be a slight or a very pronounced veeing of the parent metal. It is a running or forcing away of the parent metal due to too high a current value or wrong angle of the electrode. It may be seen on either side of the last run of a butt weld, but is more generally to be found at the junction of the weld metal with the vertical surface in a T fillet weld. In either case a more or less severe reduction of strength of the parent metal or joint results. Not only is there a direct loss of strength as expressed by a simple tensile test, but the "notch effect" of undercutting is infinitely more if the job is subject to alternating or shock stresses. Even in the best work, a hair line undercut is usually to be found which causes a slight reduction of fatigue strength in work subject to alternating stresses. Undercutting therefore must be avoided, and in horizontal work is inexcusable, whilst in vertical work correct technique will overcome it.

Splashing.—Another ill-effect of too high a current is splashing, as evidenced by a number of small globules of weld metal on either side of the weld which have little attachment to the parent metal. The arc is too fierce and small globules of weld metal are thrown into the air and fall back on the plate. All these globules do not fall back on to the plate—a few fall into the still molten weld metal, and as during their passage through the atmosphere outside the arc, the surface of these globules have become oxidized, we have small particles of metal in the weld metal completely covered with an oxide skin. There is no metallic adhesion between the globules and the weld metal and the trapped oxidized particles might just as well be holes. Too long an arc, or poor quality electrodes may also be responsible for splashing.

Short Arc.—The necessity for a short arc has been referred to. A proportion of the heat generated in the parent metal which is necessary to cause the formation of the molten pool without which efficient penetration cannot be attained, is derived from transference of the highly superheated metal from the electrode and from radiation from the electrode. If the arc is too long, both these sources of heat are reduced and poor penetration will result, but an even worse effect of a long arc is that during the passage of the molten metal from the electrode to the job, a gas pick-up occurs, and since with all arc welding the solidification period is very short, some of the gas remains trapped in the weld metal. The result is a porous spongy mass of low strength. A coated electrode enables a longer arc to be maintained without ill-effect than does a bare wire electrode.

It should be appreciated that the longer the arc the higher the voltage across the arc, and hence for the same current value, a long arc will enable more heat energy to be put into the job. This will result in faster work and if the operator is in a hurry, there is a tendency to use a long arc, but the resultant deposit will be subject to gas inclusions and lack efficient penetration.

A short arc is essential for good work and a strict observance of this point cannot be emphasized too strongly.

Slag Inclusions.—It has been pointed out that one of the objections to a heavily coated rod is that slag may be trapped in the weld metal. Such slag inclusions are equally as bad as gas inclusions. Slag inclusions can be overcome by correct technique. When viewing a weld through the coloured screen the bright red part is the slag and the dull red is the fluid metal. The rod must be held at the correct angle and the slag " played " as necessary to keep it behind the rod in the direction of travel. It is essential not to allow the slag to run in front of the rod. If there is any tendency for the slag to pile up and run in front of the rod, a pause at the bead of slag sufficient to melt the slag and make it very fluid will allow the arc to force the slag back over the metal deposited. Slag control is a matter of practice, for too long a pause may cause a hole to be burnt through the plate if it is thin, or cause undercutting on top runs through forcing the metal away as well as the slag.

To summarize the foregoing, for a sound weld capable of developing the theoretical strength of the joint, there must be complete penetration, with lack of undercut, gas inclusions or slag inclusions. In this connection it may be observed that, with efficient supervision, it is reasonable to allow a joint efficiency of 80 to 90 per cent. and figures of this order are allowed by such bodies as Lloyds and the Board of Trade for work carried out under the conditions imposed by these Authorities.

Types of Joints.—There are two fundamental types of welds—the butt and the fillet.

In the case of the butt weld, as the name implies, the edges of material to be joined are butted against each other in the same plane. Except in the case of thin plates, $\frac{3}{16}$ in. thick and under, it is necessary to prepare the abutting edges for welding. Up to about $\frac{3}{4}$ in. plate it is usual to prepare the edges by chamfering at an angle of 30° so that on butting a 60° V is formed.

To reduce the tendency to burn through the thin edge during the first run the chamfer is only carried to within $\frac{1}{16}$ in. of the lower face of the plate, and in order to ensure efficient penetration the plates are separated at the abutting edges by $\frac{1}{16}$ to $\frac{1}{8}$ in. according to the thickness of the plates and the gauge of electrode employed. In this connection a small gauge electrode (usually 10 gauge) must always be used for the first run, as a larger electrode cannot be brought near enough to ensure the desirable short arc and full penetration. The preparation of the plate edge may be carried out by an oxy-coal gas cutting flame or in a plate edge planing machine—the later method being preferred for very important work, such as pressure vessels.

For thicker work, the V gap becomes uneconomical as the volume of weld metal to be deposited increases as the square of the plate thickness. For thick plates, say up to an inch or $1\frac{1}{2}$ ins. an X or double V gap may be used which halves the volume of weld metal required, but the X gap has objections in highly stressed work which will be referred to later.

For still thicker work, or where it is essential to plane the edge, the U gap is used. This type of gap is invariably used for heavy pressure vessels, such as boiler drums. The plate edges are planed to the shape of half a U, the thickness at the bottom of the U being $\frac{1}{8}$ in. and the total width of the U, $\frac{3}{4}$ in. Such a gap may be used for any thickness of plate within reason.

As with the V, in both the X and the U welds, initial gaps must be left to ensure penetration. If the two pieces of plate are placed in position with the desired gap and welding begun, it will soon be found that the gap has closed in to nothing and even the edges may start overlapping due to contraction effect of the cooling weld metal.

To prevent this, tacking is used in the first place, such tacks being about 4 ins. apart for thin material up to 18 ins. or 2 ft. for very thick material. The stresses set up are of a high order and it is as well to use full block tacks even though these may have to be cut out after the first run is completed.

In all V or U butt welds, although complete penetration is aimed at it is never perfect, and for all stressed work it is necessary (if possible) to put a sealing run down on the reverse side of the work.

Further, the first run in a butt weld is always the most difficult to make, due to the close quarters in which it has to be made, and for this reason is most suspect. For all highly stressed work, therefore, it is advisable wherever possible to reverse the joint and cut out the first run in the form of a shallow U and then fill up from the reverse side. In boiler drum work the metal is cut out to a depth of $\frac{3}{8}$ in. and refilled.

Herein lies the objection to the X or double V joint, *i.e.*, the first run cannot be cut out.

Fillet Welds.—The fillet weld occurs in lap joints and T junctions and consists of filling an angle of 90°. This is much easier than the close quarters imposed by the 60° V butt joint, and provided correct current values and technique are employed, good penetration can be ensured.

The most important requirement of a fillet weld is that the full throat thickness shall be maintained. It is better to aim for a slightly convex surface, for the strength of the fillet is in direct proportion to the throat thickness. Further, in a lap joint, for the highest efficiency the shear leg of the fillet should be made $\frac{1}{16}$ in. longer than the tension leg. Good fillet joints cannot be made with large gauge electrodes unless the 90° V is arranged with the apex at the bottom so as to form a natural trough for the molten metal, as the fluid weld metal tends to run down to the horizontal level and full throat thickness will not be attained. Even so, the first run must be made with a small gauge electrode to ensure adequate root penetration.

Multi- versus Single-Run Welds.—In highly stressed work, and in cases where the capacity of the plant is limited, it is usual to make small gauge multi-run welds, due to :—

(i) The annealing effect of each subsequent run on the previous run. Despite the use of coated electrodes producing a heavy slag with resultant comparatively slow cooling, the deposited metal is still somewhat in the "as cast" condition and "locked up stresses" may be high. Provided the run is not too big, any subsequent run will tend to anneal the previous run, thus relieving the locked up stresses and refining the grain so that better shock resisting qualities will result—the elongation and izod value will increase.

In this connection it may be pointed out that, if very large gauge electrodes are used for multi-run work, such as $\frac{3}{8}$ in. diameter, annealing will not be carried out right through the previous run and an unsatisfactory "layer" effect results ;

(ii) Reduction of the disturbed area in the parent metal due to the lower rate of heat energy put into the job ;

(iii) Inability to control large quantities of molten metal produced with large electrodes in cases where the work is other than horizontal.

From the point of view of cost, it is desirable to be able to make the required weld with such a size electrode that one run is sufficient. The welding time is much reduced and there is no necessity for careful removal of several layers of slag, but the above-mentioned disadvantages are such that 10, 8 and 6 gauge are used more than any other size, and the majority of welds are built up from sufficient runs of these sizes of electrodes to form the desired depth or throat thickness.

In certain horizontal work $\frac{1}{2}$ in. electrodes at 400 to 500 amps. have been used in this country and in America experiments are being carried out with as much as 1,000 amps. When it becomes necessary to make a butt weld in 3-in. plate or say, a fillet 2 ins. deep, there is a big incentive to use the biggest electrode one can get, particularly when it is remembered that a butt weld in 1-in. plate requires 39 runs of a 10-gauge or 22 runs of a 6-gauge electrode, and that the time taken will be at least 3 minutes and more, probably 6 to 8 minutes per foot for *each* run.

If stress-relief annealing is possible after welding, large single run work may be quite saitsfactory, but it must be remembered that annealing is not a cheap process, and the saving effected by single-run work may be lost.

Concerning annealing, there is no doubt that heat treatment will improve the weld, and it is now usual practice for all dynamically stressed welds to be stress-relief annealed. Boiler drums which probably represent the highest class of static work are also so treated. It should be emphasized that such annealing is a stress-relief anneal and not normalizing. Annealing is not essential however, for the large majority of welded work, and in a number of cases, the work would not lend itself to annealing treatment.

Distortion.—Not only are high contraction stresses set up by welding, but a large amount of the material used for fabrication by welding, such as rolled sheets and sections, has locked up internal stresses in it due to the various manufacturing processes which the material has undergone. These stresses are partially relieved or their distribution altered by the welding heat, and the combined effect of contraction and initial residual stress invariably causes distortion of the welded product to a greater or lesser degree. It may be said with a fair degree of truth that if there is considerable distortion in a welded job it is probable that the residual stresses will be very low, whilst if there is no distortion the reverse holds good.

As distortion is generally objectionable, means must be taken to overcome it, such as clamping by simple means or by complicated jigs in complicated repetition work.

A great deal of welded work is built up in jigs to limits as close as 0·010 in. or even closer, but clamping and all forms of restraint are liable to introduce some form of residual stress. Much can be done to avoid distortion by initial setting of the work in the opposite direction, and by the scheme of welding—that is, the order in which the various welding runs are carried out.

For example, if an area of any size is to be reinforced, after putting down two or three runs on one patch, transferring the welding to another patch remote from the first will keep down the concentration of heat input into the job and tend to reduce distortion.

Again, if a shaft is to be built up, the runs should be disposed first one on one side, and then one on the other, by which means the shaft can be kept straight. A double V or X butt weld can be made free from distortion by putting the runs down on alternate sides. A long seam should preferably be started in the centre and alternate short lengths welded from either side. In jobs with several joints or seams, experience will dictate the sequence of making each joint so as to produce the minimum amount of distortion with a minimum amount of locked up stresses. Endeavour should be made to arrange the sequence so that no member of the structure is tied completely till the last of the welding on that member is to be carried out. The use of small electrodes and multi-run work will help to keep down distortion. Each job must be treated on its merits and practical experience is necessary, for whilst the gauge of electrode, number of runs, and length of run per electrode is usually indicated on a welding drawing, the sequence of operations is left to the welder or supervisor.

Examination and Inspection.—Surface examination of a welded joint or seam will enable helpful opinions to be formed as to the soundness or otherwise of the weld. The hair line of an undercut will indicate good penetration, whilst heavy undercutting will be evidence of too high a current value, as will likewise heavy splashing at the sides. This latter may also be indicative of poor quality electrodes. A rolling over of the weld metal on the surface of the plate will indicate lack of complete fusion, as will crevices between the weld and parent metals. The size and shape of the weld should be according to the requirements. The surface should be regular, although in this respect the ripple marks will vary in size according to the type of electrode used. If cracks are revealed in the surface, embrittlement may be suspected. If irregular lumps are present on the surface, light chipping of the lumps may reveal slag inclusions or porosity.

Even so, a weld which appears sound from visual external examination may still be bad if nothing is known of the ability of the operator, electrodes and plant used.

Tests of the plant are simple, the electrodes being best tested by making all weld metal test specimens and subjecting them to tensile, bend and izod tests, whilst periodical tests of the operator by means of test welds which are pulled and bent will indicate whether his work is up to standard.

If it is possible to cut a cross section of a weld so much the better, for then root fusion may be examined and freedom or otherwise from slag and gas inclusions easily observed, but in general it is not possible to cut such sections and so for important work X-ray analysis is used. A good deal of experience is necessary to interpretate the X-ray photographs, but there is little doubt than when correctly interpretated, all defects in the weld metal itself can be not only revealed but their extent and depth closely gauged, so that cutting out the defect becomes a straightforward matter. It is obvious that X-ray examination is costly both from the point of view of capital cost and the time required for it, and therefore only warranted in work of first importance.

The Applications of Metallic Arc Welding.—Metallic arc welding is of assistance, great or small, in every conceivable branch of engineering both for fabrication and repair. In fabrication from the simple " sticking on " of a piece of metal to the construction of buildings, bridges, ships, or machinery, it enables the desired section of material to be placed just where that material is wanted.

Steel and iron castings can often be replaced by welded structures which are lighter yet stronger, and cost less, and without the fear of a failure and the consequent loss of time. Heavy machinery bedplates, diesel engine frames, boiler drums, condenser shells, even turbine casings including the bearing housings, and a multitude of other parts are fabricated from mild steel plates and sections.

In a ship equipped with oxy-acetylene cutting pipe and a single-operator set of small capacity, numerous small parts may be readily made, irrepairable broken castings may often be replaced in mild steel, reinforcement of worn parts can be carried out, and broken parts repaired or strengthened.

There are one or two hints which may be of help.

The operator should be as comfortable as possible—fatigue is a great enemy to sound welds.

Keep the brush gear of the generator in first-class order—a smooth steady current supply under all conditions is an essential for good work.

Use mild steel wherever possible, unless a sufficient experience of high carbon or alloy steels and the right electrodes are available.

Always bend in lieu of welding where possible, *i.e.*, reduce the welding to a minimum.

Do not overweld in an effort to make the job as strong as possible—this is often as bad as too little attachment between the parts to be joined.

Do not necessarily follow blindly the previous design when replacing cast or riveted parts if full advantage is to be taken of welding—the original design has probably been influenced by the necessity to cast or rivet.

Make the job portable so that as much as possible of the welding can be carried out in the horizontal plane, *i.e.*, downhand.

In conclusion, the writer would refer all those whose interest has been aroused to the " Welding Handbooks " published by electrode manufacturers, to the various periodicals on metallic arc welding, and to the papers included in the " Symposium on the welding of iron and steel " prepared by the Iron and Steel Institute in co-operation with the majority of Engineering Institutes and Associations throughout the country. These papers, published in two volumes, of which Vol. 2 is of greater interest to practical students, are international in character, are fully illustrated, and cover every phase of welding as applied to the ferrous metals.