10 Welding and Soldering

W Lucas PhD, DSc, CEng, FIM, FWeldI, EWE
The Welding Institute, Cambridge

S Westgate BSc(Hons)
The Welding Institute, Cambridge

Contents

10.1 Arc welding

The arc is an ideal means of generating intense heat of sufficient power to melt most materials, especially metals. The arc is formed between an electrode and the workpiece. The electrode can be of a refractory metal rod, such as tungsten, or a metal rod or wire, as shown in *Figure 10.1*. In the tungsten arc process, the arc is formed between the pointed tip of the electrode and the abutting faces of the two components being welded. The faces are melted and the bridge or weld is formed between the components. In the case of a metal electrode, the electrode fulfils the same function as the tungsten electrode in forming a point heat source, but in this case, the electrode is consumed in the course of welding and the molten metal from the electrode helps to bridge the gap between the components being welded.

The welding current can be either d.c. or a.c., but in either case the voltage, in particular, must be sufficient so that the arc discharge or plasma can be sustained. With the tungsten electrode, the arc formed is in a gas flow of argon or helium gas, whilst in the metal arc processes, the plasma is formed either from CO_2 or an argon based gas with a small amount of oxygen or CO_2. The plasma reaches a temperature of the order of 15 000 K, at least in the core, but it is noteworthy that most of the heat is associated with the arc root mechanisms. The voltage distribution across the arc shows three distinct regions, the anode drop, plasma column drop and the cathode drop, *Figure 10.2*. The anode and cathode voltage drops are determined by the electrode material and the ionised gas compositions, but for welding applications the plasma drop is a function of the arc length.

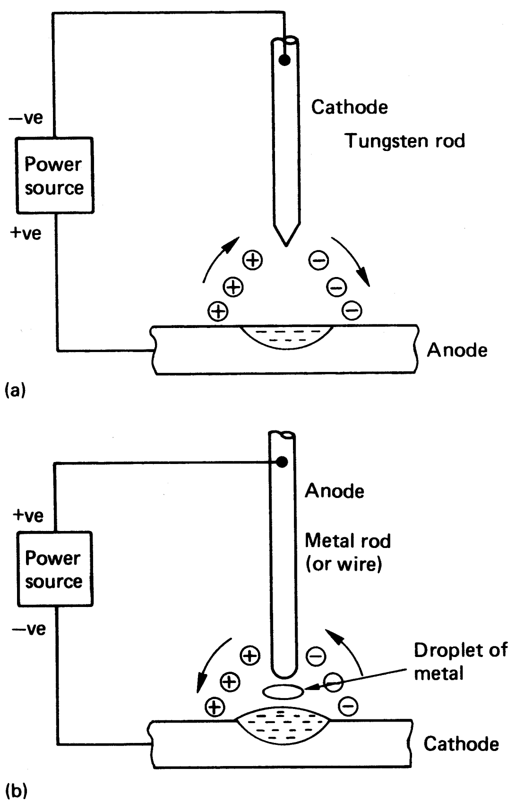


Figure 10.1 Principles of operation for the tungsten electrode and metal electrode welding processes. (a) Tungsten electrode; (b) metal rod (or wire) electrode

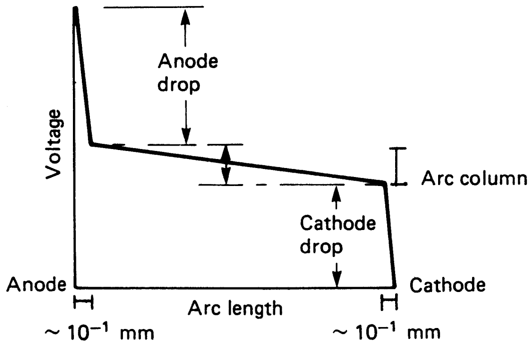


Figure 10.2 Voltage distribution across a tungsten arc

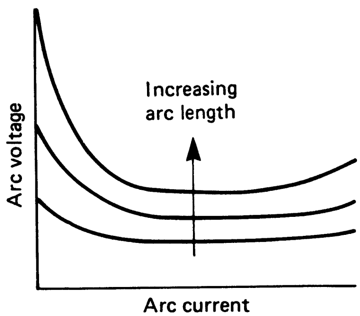


Figure 10.3 Typical voltage–current arc characteristics

The arc voltage–current characteristics are shown in *Figure 10.3*. There are three regions, depending on the current level. At low currents, the voltage–current relationship has a negative slope (as the current increases, the voltage decreases), the flat portion at intermediate current levels is essentially a constant voltage irrespective of current, and at high currents the slope of the voltage–current relationship is positive.

10.1.1 Power sources for arc welding

The basic function of the arc welding power supply is to provide sufficient power to melt the joint between the parts and, if required, the additional weld metal provided by a filler wire. As most arc welding processes require a high current, (50–500 A) but at relatively low arc voltages (10–50 V), the high-voltage mains supply (240 or 440 V) must be reduced. Thus, in its basic form the arc welding power source comprises a transformer to reduce the mains voltage and increase the current. For d.c. a rectifier is placed on the secondary side of the transformer (*Figure 10.4*).

The conventional d.c. power source operates on either a single-phase or a three-phase a.c. supply. The disadvantage of the former is that, even with full wave rectification, the output waveform contains a high degree of ripple, as shown schematically in *Figure 10.5*; a high level of ripple can result in poor arc stability at low current levels. A much smoother d.c. output is provided by a three-phase input and a bridge rectifier which produces full rectification, as shown schematically in *Figure 10.6*. Nevertheless, even with the three-phase output, the final current waveform will contain a

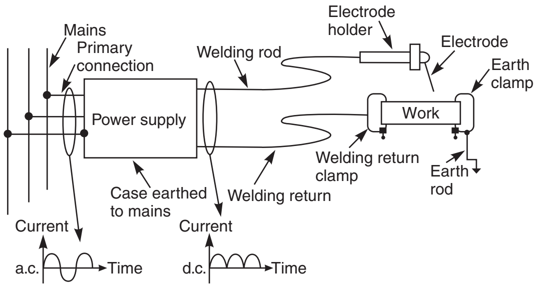


Figure 10.4 Reducing high voltage using a transformer

significant amount of 300 cycle ripple (as shown in *Figure 10.6*), which can noticeably affect the shape of the arc and its stability. The more advanced, so-called 'electronic', control systems have been designed to provide an accurate d.c. output, with high response and sophisticated control of the output.

10.1.1.1 D.c. power-source control

Traditional power-source control uses a variable reactor, moving coil or moving iron transformer, or a magnetic amplifier to control the welding current. Such equipment has the highly desirable features of simple operation, reliability and robustness, making it ideally suited for application in aggressive industrial environments. The disadvantages are relatively high material cost, large size, and limited accuracy with slow response. The latter feature, in particular, can limit the performance of the power source, especially when sophisticated control of the output is required.

In recent years, electronic power sources employing high power semiconductors, have become available which do not suffer from these disadvantages. The various types of electronic power source are:

(1) thyristor phase control;
(2) transistor, series regulator;
(3) transistor, secondary switched (chopper); and
(4) a.c. line, or primary, rectifier plus inverter (SCR or transistor).

The advantages and disadvantages of these types of power source compared with conventional variable reactor or magnetic amplifier power sources are listed in *Table 10.1*. The main features of the different power sources are described below.

Thyristor-phase control Of the power source designs listed in *Table 10.1*, thyristor control represents an excellent compromise in terms of performance and cost. In this power-source design, the output is controlled by the phase angle of the a.c. voltage, at which the thyristors (SCRs) are switched on. Whilst high current sources have a three-phase input, low current sources normally have a single-phase input with current control on the primary side of the

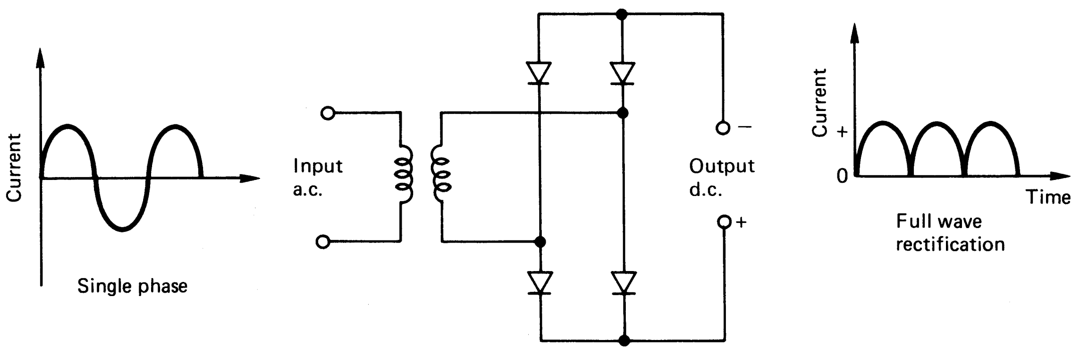


Figure 10.5 D.c. power source with single-phase supply

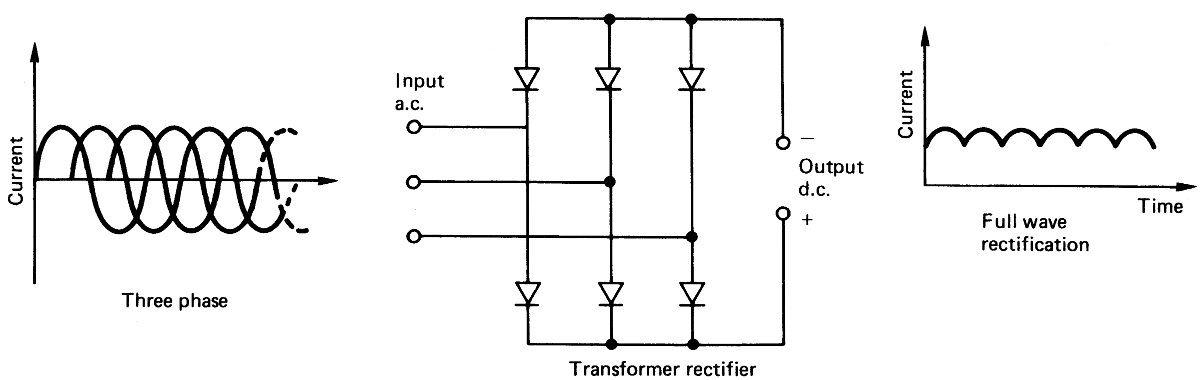


Figure 10.6 D.c. power source with three-phase a.c. supply

Table 10.1 Major operational features of electronic power sources compared with conventional variable reactor or magnetic amplifier power sources

Control type	*Method of control*	*Advantages*	*Disadvantages*
Thyristor, phase	Thyristors replace diodes on secondary output of the transformer. Alternatively, triacs or inverse parallel thyristors are used in the primary of the transformer	Better accuracy of current and time settings. Can be used to produce square-wave a.c. waveform. Can be used for pulsed operation	High ripple unless large amount of inductance is placed in series with output. Pulsed response normally limited to 100 Hz
Transistor, series regulator	Power transistors in parallel; analogue control from low current input signal	Very stable and accurate control of current level—better than 1% of set level. Pulsing over wide range of frequencies (up to 10 kHz), and pulse shape can be varied	Poor electrical efficiency. D.c. supply only
Transistor, switched	Transistor, high frequency switching (20 kHz) of d.c. supply	Accuracy and control similar to series controller. Less wasteful of energy compared with series regulator. Greater arc stiffness can be exploited for low current operation	Although the output is similar to that of a series regulator, pulse frequency and wave shaping is less flexible
A.c. line rectifier, plus inverter	Mains supply rectified to high voltage d.c. and then converted by transistors or thyristors to a.c. operating at 2–50 kHz. Final output produced by small mains transformer and rectified to d.c.	Because the transformer operates at high frequency, the size and weight of the mains transformer can be greatly reduced. Because of its small size, the cost of raw materials is significantly reduced. Accuracy of control is better than with a magnetic amplifier	Rapid switching can cause an unpleasant whining noise from the arc

transformer. The output waveform suffers from inherent ripple, the frequency being a simple multiple of the mains supply, i.e. 100, 150 or 300 Hz. Whilst the ripple is not normally a problem at medium or high welding currents, excessive ripple can cause problems in arc starting and in operating at currents below 20 A.

Transistor-series regulator The transistor based control systems offer highly desirable features for precision welding, namely accuracy and reproducibility of the welding parameters. The analogue type control (*Figure 10.7*(*a*)) where the current flowing through all the transistors is regulated, provides a ripple-free and easily controlled output. The output, under feedback control, can be pulsed at a frequency within the kilohertz range and the pulse waveform and the overall operating sequence can be precisely shaped. However, the regulator stage tends to be wasteful of electrical energy as the excess power in the transistors must be dissipated by water cooling; as the difference in the voltage between the arc and the open circuit appears across the transistors, this excess power (voltage difference times the current) is dissipated by the transistors which are usually cooled by mounting on water-cooled copper heat sinks.

Transistor-switched Switching transistor control, in which each transistor operates in either an 'on' and 'off' state, (*Figure 10.7*(*b*)) is an attractive alternative to analogue control. The output is determined by the ratio of the 'on' time to the 'off' time. As power is dissipated at the moment of switching, this design is more efficient which obviates the

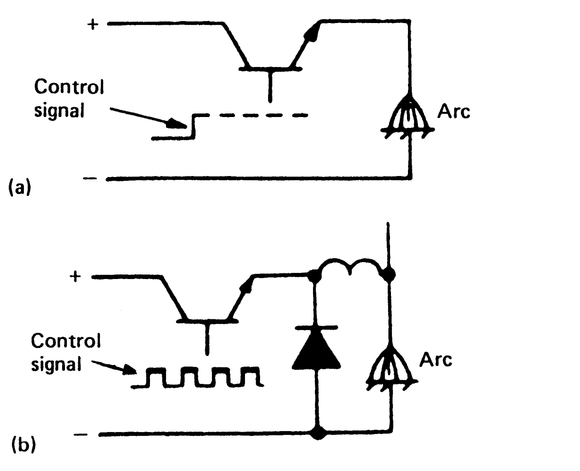


Figure 10.7 Transistor controlled power sources. (a) Series regulator transistor control; (b) Switching on/off transistor controlled power source

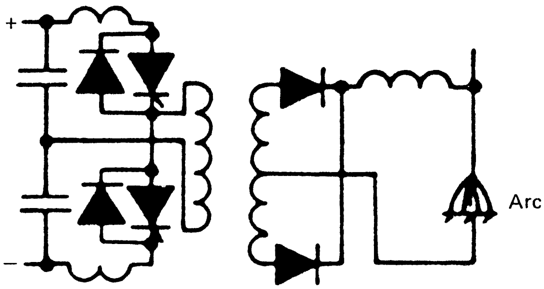


Figure 10.8 High frequency inverter power source

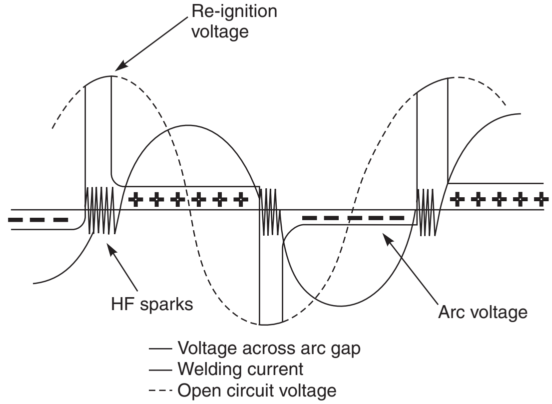


Figure 10.9 AC waveform showing voltage required to re-ignite the arc

need for water cooling. The output is 'chopped' at a frequency usually in excess of 10 kHz, which has the beneficial effect of constricting the arc shape, thereby making it more directional. Thus, switching transistors have enabled the advantageous features of transistor control (high accuracy and reproducibility) to be exploited without the limitations of the analogue control system, particularly its high energy consumption. Various models of this type of power source have also been designed for specific welding operations, e.g. for welding thin sheets at low current levels, or for high-speed welding at higher current levels.

A.c. line rectifier plus inverter The a.c. line rectifier, plus inverter, type of control (*Figure 10.8*) represents a basically different approach to power source design. Compared with the normal mains frequency transformer/rectifier, the mains supply is first rectified and stored by a capacitor. The medium-voltage d.c. is then converted to a.c. at a frequency in excess of 500 Hz by means of switching transistors or thyristors. The high-frequency a.c. is finally transformed down to a voltage suitable for welding and then rectified to d.c. to provide the normal range of welding current levels. As the transformer operating within the range 20–100 kHz can be substantially reduced in size, compared with conventional transformers for use at mains frequency, higher electrical efficiency and power factor and small size have been achieved. The main limitation at this stage of development concerns the performance of the switching devices which must withstand a high hold-off potential in excess of approximately 1.5 kV. With regard to the operation of the power source itself, the relatively high level of arc noise can be an annoying factor; the noise is related to the switching frequency and power sources operating at frequencies above 20 kHz do not suffer from this problem.

10.1.1.2 A.c. power source control

The simplest a.c. power source is the single-phase type, with moving core control. *A.c./d.c.* power sources have moving core or thyristor control with the thyristors (phase angle control) acting on either the primary or the secondary side. The problem of operating an a.c. welding arc is that a high open-circuit voltage is required to ensure that the arc re-ignites on polarity reversal. For example, when welding with a metal electrode, a covering which contains easily ionised elements is required to sustain the arc, and sine wave power sources are normally operated with an open-circuit voltage of 80 V. When using a tungsten electrode which does not have a flux coating, high voltage or high-frequency oscillation is also applied continuously to ensure arc re-ignition (*Figure 10.9*).

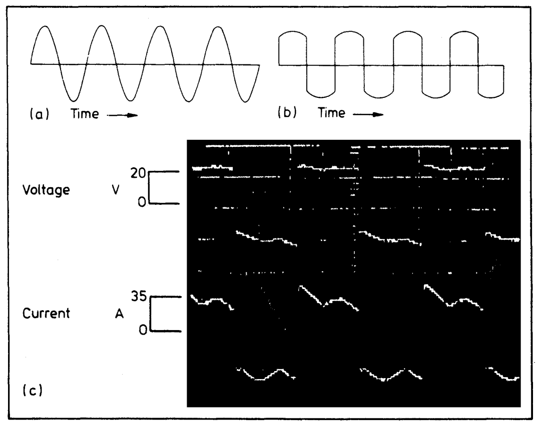


Figure 10.10 Characteristic re-ignition waveforms for: (a) sine wave supply at an open-circuit voltage of 100 V; (b) switched d.c. supply at an open-circuit voltage of 75 V; (c) output waveform of a square wave a.c. power source

In an alternative form of power source the output current assumes a more square waveform as compared with the conventional sine wave (*Figure 10.10*). Two types of power source are available: the squared sine wave a.c., and the switched d.c. power source. The squared a.c. wave is generated by using inverted a.c. (*Figure 10.11*(*a*)), whilst the more truly square waveform is produced by directly inverting a d.c. supply (*Figure 10.11*(*b*)). The rates of circuit current rise for the two types of power source on polarity reversal are typically 110 A in 0.1 ms and 160 A in 0.02 ms for the square wave a.c. and the switched d.c. power source, respectively. In comparison, the rate of change of current for conventional sine wave a.c. can be as much as two orders of magnitude less than the switched d.c. power source; a time of approximately 3 ms is required to achieve a circuit current of 110 A from zero with 50 V across the arc gap.

The advantages of rapid current build up on polarity reversal are:

(1) a reduction in the open-circuit voltage;
(2) easier arc re-ignition; and
(3) reduction in electrode heating.

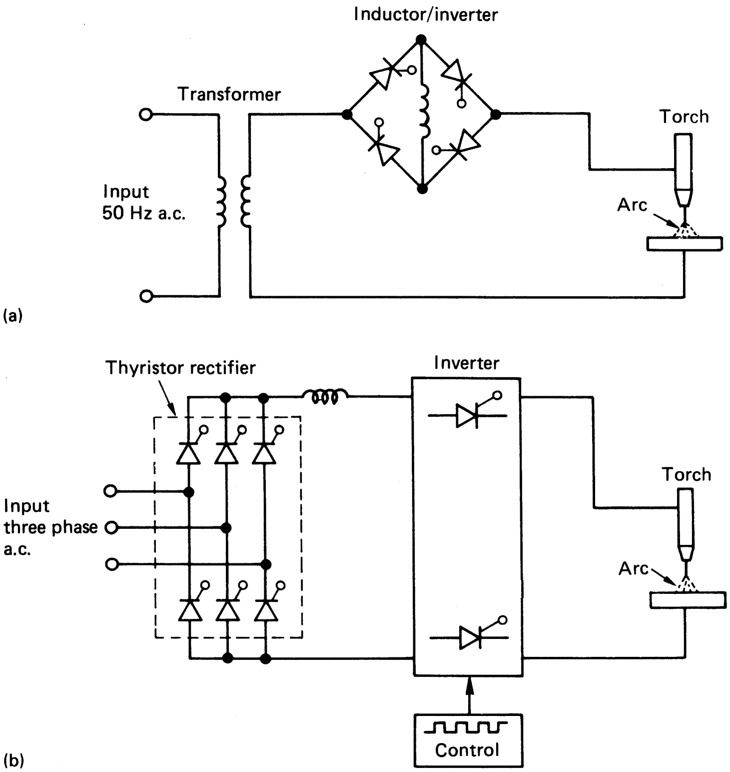


Figure 10.11 Square wave d.c. power source designs: (a) 'squared' a.c.; (b) switched d.c.

These advantageous features of square wave power sources are discussed when considering specific arc welding processes (see Sections 10.1.3 to 10.1.8).

10.1.1.3 Intelligent control

Whilst the earliest welding power systems implemented control using electronic analogue feedback, today a number of power sources on the market employ digital control concepts. Digital control systems have the advantage of being cheaper to develop, less susceptible to the degradation of the electronic components, and easier to update and modify.

Employing software to control the power source output enables intelligence to be included in the control system. For example, power sources have the capacity to store welding parameters and welding programmes tailored to the application i.e. type of welding process, material etc. As an indication of the increase in the intelligence of power sources, the memory requirements have increased typically from 50 kb for the early inverter power sources to 500 kb for the latest designs.

Power sources are also available which implement the control strategy using fuzzy logic. This approach makes it easier to develop sophisticated and intuitive control strategies than would otherwise be possible using traditional coding techniques. Fuzzy logic is being applied in the dynamic control of the welding arc.

10.1.1.4 Rating plate/power source specification

In selecting a suitable power source design for a welding process, it is important to check that the specification of

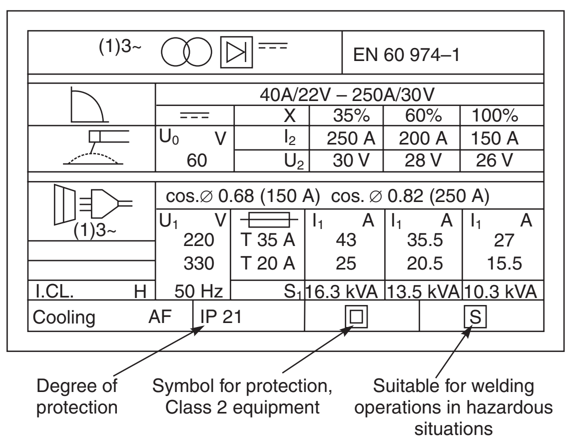


Figure 10.12 Rating plate for arc welding power sources

the power source will be suitable for the intended job. Information about a new power source can be obtained direct from the manufacturer or from the product literature. For an existing power source, the handbook can be consulted but often the rating plate information is all that is available. Any power source controlling the welding parameters made to a National, European or International standard should have a rating plate similar to the one shown in *Figure 10.12*. This plate provides information about the manufacturer, supply requirements, performance and suitability for use. For equipment built in the last few years the rating plate should conform to IEC 60974-1 (EN 60974-1).

The following symbols are used on the manufacturer's rating plate to indicate the type of protection:

- ⧈ Insulation protection, class 2 equipment.
- S Power source suitable for supplying power to welding operations carried out in an environment with increased hazard of electric shock.
- IP XX Degree of protection of the enclosure.

The symbol S refers to the suitability of the power source for operating in environments with increased hazard of electric shock. The rated no-load voltage of such power sources shall not exceed:

D.c. 113 V peak
A.c. 68 V peak and 48 V r.m.s.

The symbol S is also often displayed on the front of the power source. The code for the degree of protection which refers to risk of electric shock in normal service from direct contact is as follows:

- IP2X The 2 refers to protection to solid objects larger than 12 mm. e.g. fingers.
- IPX1 The 1 refers to protection from vertically falling drops of water.
- IPX3 The 3 refers to protection from drops of rain water up to 60° from the vertical.

The minimum degree of protection for welding power sources is IP 21. However, power sources specifically designed for outdoor use shall have a minimum degree of protection of IP 23.

10.1.1.5 Welding installations

Typical arc welding installations for both single and multi-welder operations are described in National guidelines e.g. the UK HSE Guideline No 118, 'Electrical Safety in Arc Welding'. In connecting the welding circuit, the following best practice should be adopted:

- the connection between the welding power source and the workpiece should be as direct as practicable;
- use insulated cables and connection devices of adequate current carrying capacity;
- extraneous conductive parts should not be used as part of the welding return circuit unless part of the workpiece itself;
- the current return clamp should be as near to the welding arc as possible.

When attaching the welding current and current return cables, it is essential that an efficient electrical contact is achieved between the connection device and the workpiece to prevent overheating and arcing. For example, the current and return clamps must be securely attached to 'bright' metal i.e. any rust or primer coatings should be locally removed.

Power source and earthing The normal practice in the UK has been to provide a separate earth connection to the workpiece. The reason is that, in the unlikely event of an insulation breakdown between the primary and the secondary circuit, the fuses will blow. However, the separate earth connection increases the risk of stray currents which may cause damage to other equipment and conductors.

As modern power sources have been designed to have a much higher level of insulation (termed double or reinforced insulation), a separate earth connection is not recommended.

There is a potential problem in that both power source designs can often be found in the same welding shop. The newer (double or reinforced insulation) power source can be identified by reference to the power source's rating plate (*Figure 10.12*) which will indicate that it has been manufactured to current standards e.g. EN 60974-1 or IEC 60974-1.

In older power source designs, the welding circuit was sometimes connected internally to the power source enclosure. However, the danger is that even with the welding return lead disconnected, and a separate earth connection, welding is possible with the current flowing through the earth. Because of the risk of damaging protective earth and other connectors, this type of power source is considered to be obsolete and should not be used.

Supply requirements Power sources will require either a single- or three-phase supply at 230 V a.c. or 400 V a.c. In many parts of Europe the 230 V supply is 16 A, but in the UK the standard ring main is 13 A. Therefore, the relatively low power output of the 230 V system is further reduced if a 13 A plug is fitted and a dedicated circuit may be required.

Three-phase supplies may be limited to 30 A, but higher power welding equipment may require a 45 A or even 60 A supply. The effective current is displayed on the rating plate. This value should be used to determine the cable size and fusing requirements.

Apart from the obvious hazards associated with overloading a supply, e.g. overheating and blowing fuses, problems with other equipment may be caused. If the supply has a high impedance (commonly known as soft) as may be the case in rural areas supplied by overhead cables, a high current draw may cause the voltage of the supply to fall below levels which may cause problems with other equipment.

Engines and motor drives For equipment not supplied from the mains, such as generators, information is provided about the characteristics of the motor, load and idle speed and power consumption. While this type of equipment may be ideal for welding outside in remote locations, it tends to generate a high level of acoustic noise. The noise levels are limited by an EU directive but can be as high as 97 dBA.

Environment All power sources should be marked with an IP rating which provides information about the degree to which the equipment is protected against water. Normally equipment will be IP 21 or IP 23. The first number means that it should not be possible to touch live parts and the second number describes protection against water ingress. A power source marked IP 21 is protected from vertical drops of water, as for example may occur if the roof leaks. If the equipment is marked IP 23, this means that the equipment is protected from water at up to 60° from the vertical and is thus suitable for outdoor use. Additional letters to the IP number indicate tests with or without the fan running and increased mechanical protection from electrical hazards.

Areas of increased risk are in wet or humid conditions, confined spaces or when the welder is exposed to large areas of bare metal. For use in this type of environment, it is important to use a power source with an S mark which means that the no-load voltage is below 48 V r.m.s. a.c. or 113 V peak d.c. If the power source has a higher no-load voltage, a voltage reduction device should be used which will limit the voltage at the holder to approximately 25 V.

10.1.1.6 Relevant standards

The relevant standards for arc welding power sources, equipment and accessories are:

EN 60974-1:1998, IEC 60974-1:1998, 'Arc welding equipment—Part 1: Welding power sources'
EN 60974-7:2000, 'Arc welding equipment, Part 7, Torches'
EN 60974-11:1995, 'Arc welding power equipment, Part 11, Electrode holders'
EN 60974-12:1995, 'Arc welding equipment, Part 12, Coupling devices for welding cables'
EN 169:1992, 'Specification for filters for personal eye protection equipment used in welding and similar operations'
EN 60529:1992, 'Specification for degree of protection provided by enclosures' (IP codes)
EN 470-1:1995, 'Protective clothing for use in welding and allied processes—general requirements'
EN 50199:1996, 'Electromagnetic compatibility (EMC)—Product standard for arc welding equipment'
EN 50060:1989 'Power sources for manual metal arc welding with limited duty'

10.1.2 Manual metal arc welding

10.1.2.1 Principles of operation

The manual metal arc (MMA) process is the most versatile welding method. It can be used to weld most materials in a wide range of thicknesses and in all welding positions. The basic principles of the process are shown in *Figure 10.13* and the essential features are a central metal rod surrounded by a flux covering. The function of the flux is as follows:

(1) The vaporised flux contains easily ionisable elements which help to stabilise the arc.
(2) The molten flux surrounds the molten droplets to prevent oxidation.
(3) The presence of slag on the weld pool and the gas shroud of mainly carbon dioxide, prevent oxidation of the weld pool.
(4) The composition of the flux also influences the chemical composition of the weld metal and hence its mechanical properties.
(5) The properties of the molten flux and the flux residue or slag, particularly its fluidity and rate of freezing, determine the so-called 'handleability' of the electrodes and their ability to weld in positions other than flat; a viscous fast-freezing slag is preferred for welding in vertical and overhead positions.
(6) The slag also has an influence on the final shape of the weld bead—for example, a fluid slag/weld pool will 'wet' more smoothly into the parent metal producing a flat weld bead, whilst a less fluid slag will produce a more convex weld bead profile.

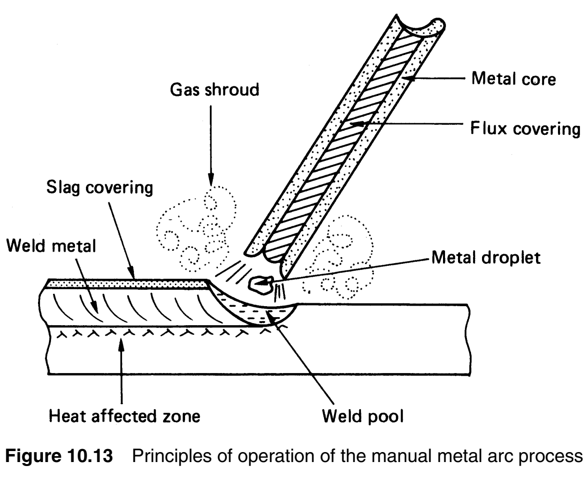


Figure 10.13 Principles of operation of the manual metal arc process

10.1.2.2 Electrode

The MMA electrode which has a diameter of typically 3.25, 4.0 or 5.0 mm, is classified into one of three main types according to the flux covering (cellulosic, rutile or basic). Iron powder may also be added to the covering to increase the deposition rate and to improve the arc stability and smoothness of operation.

Cellulosic electrodes contain a high proportion of cellulose in the covering and are characterised by a deeply penetrating arc with a thin slag covering on the weld pool and weld bead. The low slag volume makes these electrodes highly suitable for vertical down and pipe welding and the resulting mechanical properties of the weld metal are reasonably good. The main disadvantage is the high level of hydrogen generated which increases the risk of hydrogen induced cracking in the heat affected zone. Cracking in this zone is preventable by preheating the material prior to welding which allows the hydrogen to diffuse away from the hard crack susceptible heat affected zone. The preheat temperature is determined by the thickness of material, the carbon equivalent (as determined by the chemical composition), the amount of hydrogen generated in the weld metal and the heat input.

Rutile electrode coverings contain a high proportion of titanium oxide (rutile). The presence of titanium oxide promotes easy arc ignition and smooth arc operation and low spatter. Iron powder can be added to improve metal deposition, and recovery rates above 150% can be achieved without deterioration of the arcing characteristics. The lower weld metal mechanical properties and high hydrogen levels (ca. 20 ml/100 g) make these electrodes less suitable for welding the higher strength steels or thicker materials.

Basic electrodes contain a high proportion of calcium carbonate and calcium fluoride in the form of limestone and fluorspar in their coverings. The electrodes are used for high quality (high strength/good toughness) and low hydrogen weld metal. Low hydrogen electrodes can produce deposits with less than 5 ml/100 g hydrogen. The slag from the covering melts at a lower temperature than that from rutile electrodes and has a higher surface tension. The welding characteristics are termed 'fast freezing', which promotes welding in the vertical position and permits higher welding currents and faster welding speeds. The main disadvantages are the convex weld bead surface profile, and the slag can be more difficult to remove from the weld surface.

10.1.2.3 Power source

As the metal rod electrode is consumed under the action of the arc with the droplets forming the weld bead, the function of the power source can be viewed as simply providing a current for melting. However, the power supply must be capable of providing sufficient voltage to sustain the arc, a rapid rate of rise to a high current level to initiate the arc and to clear the periodic short circuiting of the electrode to the workpiece, and constant current during the welding operation itself. With regard to accommodating short circuits, it must be noted that small diameter molten droplets of metal are not projected across the arc from the end of the rod, i.e. in free flight; large droplets form on the tip of the electrode which then transfer as large globules or during short-circuit bridging of the arc gap. The power supply must provide sufficient current to clear the short circuit, but at a controlled rate of rise to prevent explosive rupturing of the metal bridge.

The operation of the power source can be described in terms of the arc characteristics and the static and dynamic characteristics of the power source. The arc characteristic is nominally flat or slightly rising over the range of current levels (as shown in *Figure 10.3*). The power source static characteristic (*Figure 10.14*) is drooping so that there are well-defined current levels according to the arc length, and the current is essentially constant for a given current setting. Also shown in *Figure 10.14* is the open-circuit voltage which is available both to strike the arc and to ensure arc resignation in the operation. The short-circuit current is the maximum current available for clearing short circuits. Because of the steeply drooping characteristic, the current will only vary by approximately ±10% for changes in the arc length.

The welding current can be adjusted by varying the secondary connections of the transformer which produces a series of voltage–current characteristics. In the more usual design of power sources, the inductance can be adjusted which has the advantage of maintaining a high open-circuit voltage (*Figure 10.14*).

The dynamic characteristics of the power source relate to the way in which the power source reacts to variation in the load, e.g. during arc ignition, a short circuit, a momentary arc outage, or fluctuations in the arc length.

In the UK, the specification for the design and construction of welding power sources is EN60974 *Arc welding equipment Part 1 Welding power sources*; hobby transformers are covered by EN 50060: 1989. The load voltages for air-cooled power sources can be calculated using the equation

$U_2 = (20 + 0.04\,I_2)\ V$ (up to 44 V at 600 A and above)

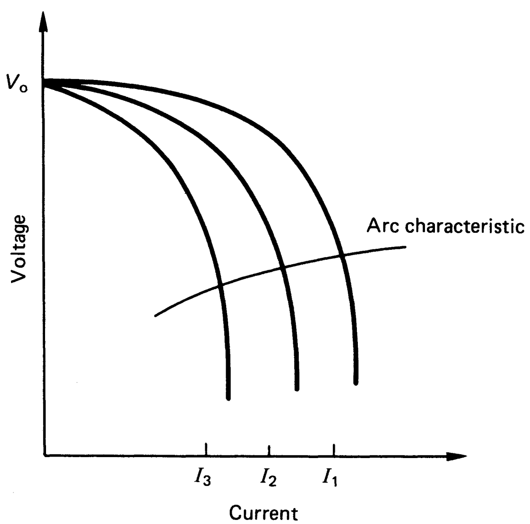


Figure 10.14 Variation in static output characteristics of the power source to adjust the welding current. V_o, open-circuit voltage

where U_2 is the conventional load voltage, and I_2 is the conventional welding current.

The standard also specifies the following maximum open-circuit voltage for oil- and air-cooled power supplies:

a.c. equipment	80 V (r.m.s.)
d.c. > 10% ripple	80 V (r.m.s.)
d.c. < 10% ripple	100 V (r.m.s.)

EN 609774-1:1998 does not specify a ripple level, but the maximum no-load voltage is 113 V peak for d.c. and 68 V peak and 48 V r.m.s. for a.c.

The maximum permissible no-load voltage (open-circuit voltage) for normal a.c. welding has been agreed by the European Committee for Electrotechnical Standardisation (CENELEC) to be 80 V. However, in confined spaces or wet conditions, the open-circuit voltage can be further restricted to 42 V, and 12 V in certain European countries. As 12 V, in particular, is insufficient to operate the process, a voltage-reduction device is incorporated in the equipment which allows the full open-circuit voltage to be obtained when the electrode is short circuited to the workpiece.

The minimum open-circuit voltage and electrode polarity requirements for the various types of electrode are given in BS EN 499:1995—*Welding Consumables—Covered Electrodes for Manual Metal Arc Welding of Non Alloy and Fine Grain Steels—Classification*. The requirements can be related to the various electrode types. For example, most cellulosic electrodes require an open-circuit voltage of > 50 V, but some electrodes can be used with either d.c. electrode-positive (DCEP) or d.c. electrode-negative (DCEN) and require a low open-circuit voltage of only 50 V for a.c. operation. Basic electrodes are the more demanding for a.c. operation and require a higher open-circuit voltage (>60 V). D.c. operation is the more normal electrode polarity.

10.1.2.4 Single operator transformer equipment

The most common form of single-operator equipment comprises a transformer wound on the primary side for normal low-voltage (1 V) mains and on the secondary side for 60–100 V, together with a tapped inductor (*Figure 10.15*) or moving-core inductor. It is preferable to connect the primary across the two lines of a three-phase supply rather than between line and neutral. Sets are produced with T or open-delta connection to three-phase supplies, but as the single-phase load cannot actually be balanced over three phases no great advantage is obtained. The voltage-reduction device is placed in the secondary circuit of the transformer, i.e. between the output side of the welding equipment and the electrode holder.

10.1.2.5 Two-operator equipment

Transformer welding sets are also available for two welders who can work simultaneously. These may consist of two single-phase units included in a single tank (*Figure 10.16*) or comprise a single transformer to which two variable inductors are connected in parallel on the secondary side. Sets of both types have the advantage that the two secondary circuits can be connected together to a single arc to give a high current for large electrodes or heavy work.

10.1.2.6 Power-factor correction

Because the load taken by a welding transformer is highly inductive, the power-factor will necessarily be

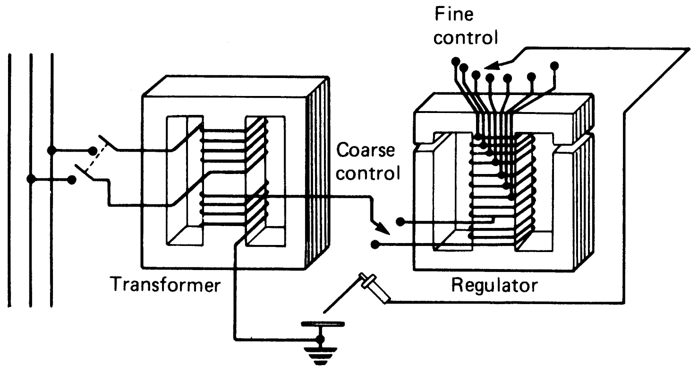


Figure 10.15 Single-phase transformer and tapped inductor

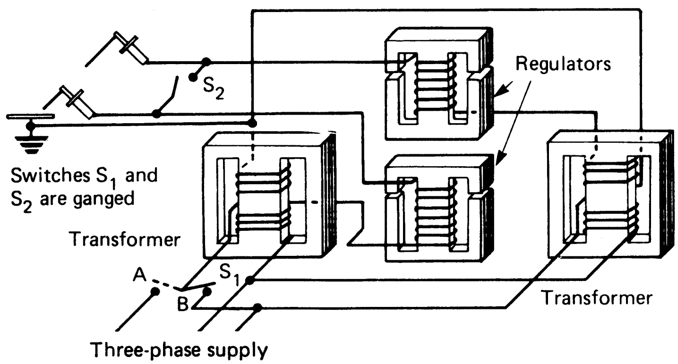


Figure 10.16 Double-operator welding equipment

low. For single-operator equipment it is of the order of 0.3–0.5 lagging, depending on the design of the set and the type of electrode used, arc length, etc. It is well known that the greater the inductance of the welding circuit, the better the conditions. A welding set which is not provided with a capacitor or other means of power-factor correction cannot; therefore, operate at a high power-factor.

The simple, single-phase transformer welding source lends itself readily to power-factor correction by the connection of a capacitor on the primary side. Power sources are available in which the capacitor is incorporated in or attached to the welding transformer.

Where many single-operator sets are connected, care must be taken not be overcorrect the power-factor. It must be borne in mind that a welding load is intermittent, and probably for 50% of the time for which the set is connected no welding will be in progress. If, therefore, each welding equipment is provided with a separate capacitor, there is the danger of a leading load being taken if the diversity factor of the welding load is small. This difficulty may be overcome by:

(1) automatic switching on of the capacitors when the load is applied;
(2) a central bank of capacitors to correct the load of the whole work based on an average observed load; and
(3) careful instructions to operatives to switch off capacitors as soon as they stop welding.

10.1.2.7 Multi-operator transformer equipment

Multi-operator transformer equipment consists of a single transformer to the secondary windings of which a number of arcs can be connected. Each welding circuit must be provided with a current regulator which can be a variable resistor or inductor. The latter gives higher efficiency and improved arc stability.

The most common form of installation is a three-phase transformer having a delta-connected primary winding and an interconnected-star secondary (*Figure 10.17*). It will be noted that the inductive current regulators are connected to the line terminals and the material to be welded is connected to the star or neutral which should be connected to earth.

The number of reactors and welders' circuits on the three-phase system must be a multiple of 3, so that they can be distributed evenly on the three secondary windings.

This type of plant is economical for installations where work is concentrated in one shop, and also for outside construction work where it is desirable to safeguard welders from possible shock from the primary voltage of the supply. This precaution is particularly necessary in the case of shipbuilding and bridge and storage-tank construction.

EN 60974-1:1998 IEC 60974-1:1998 indicates a method of connecting the welding equipment and specifies special plug and socket connections and distribution boxes. The leading dimensions of these are laid down, so components from different manufacturers are interchangeable.

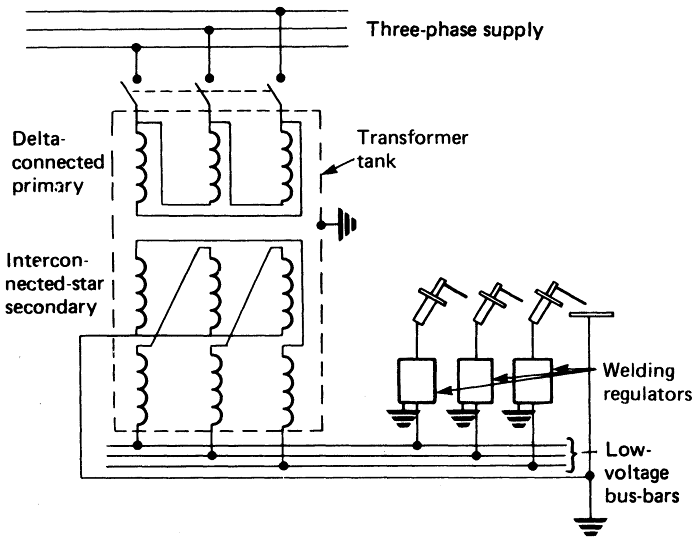


Figure 10.17 Three-phase multi-operator welding equipment

The sizes of transformers are limited to four (57, 95, 128 and 160 kV-A continuous rating) which are capable of providing one, two, three or four welding operators per phase, each at a maximum continuous hand-welding current of 350 A, or a lesser number at a higher current. The three standard sizes of current regulators are designed to give a maximum welding current of 350, 450 or 600 A, at 90 V.

10.1.2.8 Application

There are no special power source requirements for any of the particular group of electrodes (cellulosic, rutile and basic) although some power source manufacturers claim superior running characteristics with cellulosic electrodes. If recommended by the manufacturer, particular brands of electrodes can be operated with a.c. or d.c. power sources. Note, not all d.c. electrodes can be operated on a.c. but a.c. electrodes can usually be used on d.c. For a.c. operation, the no-load voltage is important and some electrodes, particularly the basic types, may require 70 to 80 V (a.c.).

A.c. electrodes are frequently operated with the simple, single-phase transformer whilst for d.c. electrodes, thyristor and transistor controlled power sources are used. The small size and weight of the inverter type power source offers the advantage of being easily transported and, therefore, ideal for moving around the workshop or site work.

The welding current level is determined by the size of the electrode and typical operating ranges for a range of electrode sizes are 50 to 400 A. As a rule of thumb, when choosing a suitable power source of adequate capacity, an electrode will require approximately 40 A per millimetre (diameter). As an example, for a commonly used electrode size of 4 mm, with an operating range of 140 to 180 A, the power source should have a current capacity of at least 200 A at an appropriate duty cycle i.e. 20%, 60% or 100%, depending on the type of work.

With small hobby type MMA transformers a duty cycle figure is not given. Instead, the rating is based on the number of electrodes that can be burnt in one hour, both when welding from cold and when the equipment has warmed up.

10.1.3 Metal inert gas welding

10.1.3.1 Principles of operation

The generic name ‘metal inert gas (MIG) welding’ has been given to those welding processes which use a continuously fed small-diameter, solid-wire electrode and a gas shroud. The principal operating features are shown schematically in *Figure 10.18*. The wire diameter is normally 0.8, 1.0, 1.2 or 1.6 mm and the shielding gas is usually CO_2 or argon with 2–5% O_2, or 5–25% CO_2. Argon–helium mixtures (with O_2 or CO_2 additions) can be used for special applications, e.g. for welding stainless steel.

MIG welding is slowly replacing MMA for manual welding, especially in the welding of thin section ferrous and non-ferrous materials, and when continuous operation or high deposition rates are required. Because of the continuous feeding of the wire electrode, MIG welding has found special application in mechanised and robotic welding. The process can also be used at high current levels, almost

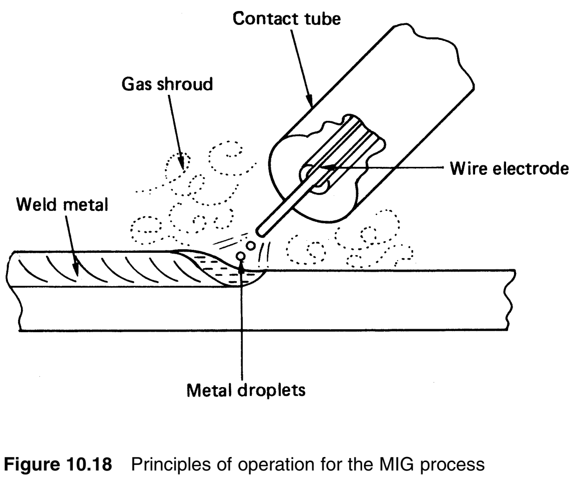


Figure 10.18 Principles of operation for the MIG process

twice that of MMA which can be exploited for welding thicker materials at higher speeds, but only in a mechanised operation.

Because the process is often used to increase the deposition rate/welding speed, care must be taken to avoid introducing weld defects such as lack of fusion. For this reason the process requires careful tuning of the power source, and welder training, when high quality is required.

10.1.3.2 D.c. metal transfer modes

There are three main metal transfer modes:

(1) short circuiting or dip;
(2) spray; and
(3) pulsed.

Short circuiting is a low-current mode of metal transfer, whilst the spray mode only occurs at high current levels. The pulsed mode is a technique used to obtain spray-type metal transfer at low current levels.

Short circuiting metal transfer The short-circuiting mode is used at low current levels, typically less than 250 A with a 1.2 mm diameter wire at which levels it is impossible to operate with an open arc to give free flight (spray) metal transfer. The transition from the short-circuiting mode to the spray-mode is shown schematically in *Figure 10.19*. The mode is established by setting a low open-circuit voltage so that the molten metal forming at the tip of the electrode wire transfers by short circuiting with the weld pool as shown in *Figure 10.20*.

If a free-flight technique, i.e. a spray-type mode of metal transfer, were to be attempted below the threshold current level, the low arc forces would be insufficient to prevent large globules forming at the tip of the wire which would then transfer erratically across the arc under normal gravitational forces. Thus, in operating the short circuiting transfer mode, the initial selection of the welding parameters (open-circuit voltage, inductance and wire feed speed) and the dynamic characteristics of the power source are crucial in stabilising the arc and metal transfer.

Spray metal transfer The spray metal transfer mode operates above the threshold current level (see *Figure 10.19*) and in this mode the droplets transfer to the workpiece in free flight. The voltage must be set at a higher current than for the short-circuiting mode in order to ensure that the tip of the wire does not bridge the arc gap which is typically set at 6 mm. The droplet diameter at current levels slightly above the threshold level approximates to the wire diameter.

The threshold current level is determined by the wire diameter and the shielding gas composition. Typical values for 1.6 mm diameter, low carbon steel wire in a range of argon–helium gas mixtures are shown in *Figure 10.21*. It can be seen that the threshold value increases significantly in high helium gas mixtures, indicating that the spray transfer is more difficult to obtain.

The droplets are detached by a combination of an electromagnetic effect, a plasma jet and the formation of gas bubbles in the molten droplet. The droplets have velocity when they are detached from the tip of wire but then accelerate across the arc gap.

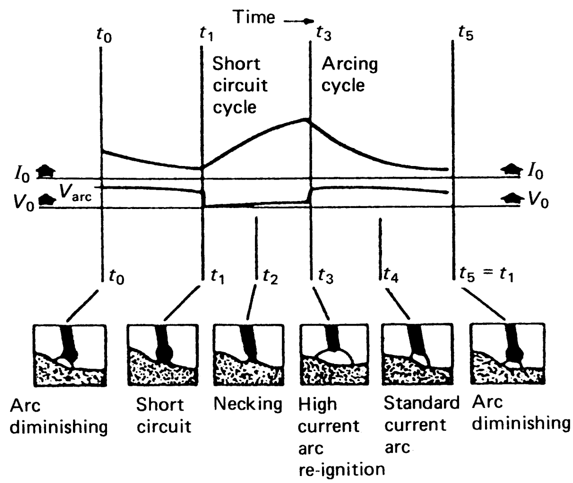


Figure 10.20 Short circuiting metal transfer in MIG welding. Note that a fluctuation in the welding current waveform occurs whenever the electrode short circuits to the workpiece

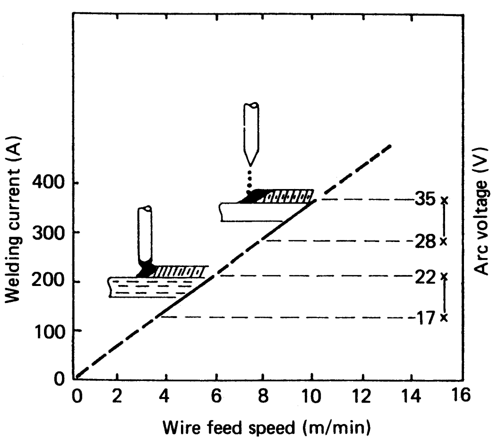


Figure 10.19 Normal operating ranges in MIG welding. Note that the voltage must be reduced at low current levels to induce short circuiting metal transfer

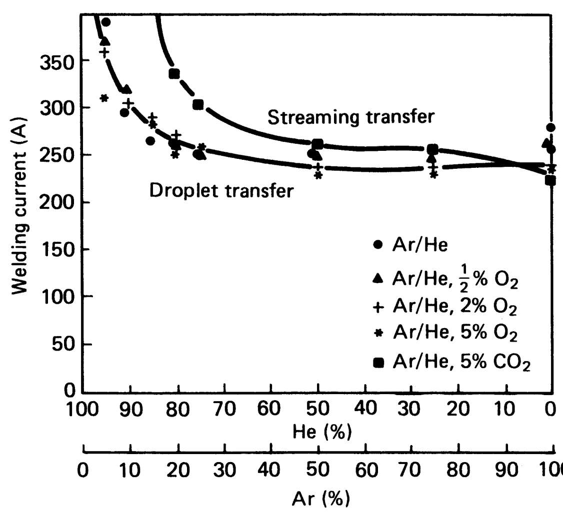


Figure 10.21 Threshold values for spray metal transfer

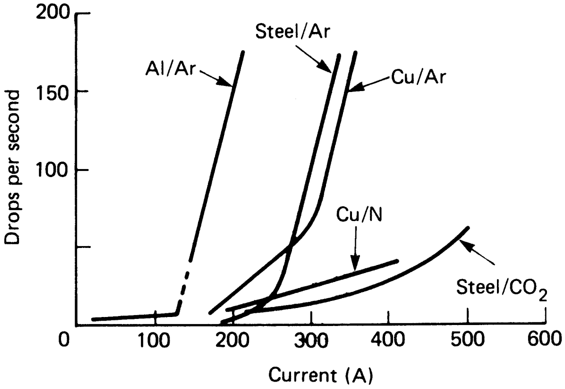


Figure 10.22 Droplet frequency for various material–gas compositions of 1.6 mm diameter wire

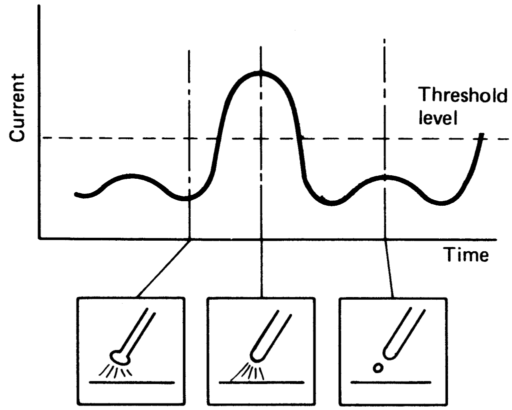


Figure 10.23 Pulsed metal transfer in MIG welding

The frequency at which the droplets transfer increases as the current level increases; the relationship between droplet frequency and the current for various material combinations is shown in *Figure 10.22*. The droplet size is about the same as the wire diameter at the threshold level, but decreases significantly as the welding current increases. At current levels well above the threshold level the droplets transfer in a stream of fine droplets and the wire tip assumes a pencil-point shape.

At very high current levels, e.g. above 450 A for 1.0 mm diameter, low carbon steel wire, the end of the wire which is softened by resistive heating can rotate. Rotation of the wire is promoted by extending the electrode stick-out, i.e. the distance the wires extend from the contact tip to the arc. The principal benefits of extended stick-out are increased deposition rate and an improved weld bead penetration profile (bowl shaped).

Conventional pulsed metal transfer The pulsed transfer mode is a free-flight technique, i.e. non-short-circuiting, which can be operated at welding currents below the threshold level. For this technique, high current pulses at a frequency of typically 50 Hz and 100 Hz are applied. The magnitude of the pulses must be sufficient to detach the droplets and project them across the arc. Droplet transfer to the weld pool is often completed during the background period; the process of metal transfer is shown schematically in *Figure 10.23* where it can be seen that, although significant melting occurs during the background period, the high current pulse is required for droplet detachment.

The pulsed MIG technique is an attractive alternative to the short-circuiting mode at low current levels because the open arc/free flight metal transfer greatly reduces spatter and provides greater tolerance to variations in the gun-to-workpiece distance. Until recently, the technique was not widely practised because of the difficulty in setting up and maintaining suitable welding parameters at a fixed pulse frequency. For example, as the mean current level demanded by the wire feed speed is set by adjusting the pulse and background current levels, the welding parameters are likewise a compromise for arc and metal transfer stability and weld bead penetration. The effect of the compromise can be seen in the metal transfer where the droplet size and frequency of transfer can vary depending on the number of pulses used to detach each droplet. Thus, power sources which can generate pulses over a range of frequencies are significantly more flexible, as the pulse frequency can be better matched to the wire feed speed.

Synergic pulsed MIG In the synergic process, the pulse parameters are varied according to the operating conditions. The basic concept is that a 'unit' pulse can be derived which, when applied, will detach one droplet of metal. A typical unit pulse is shown in *Figure 10.24*. There is range of unit pulses which will detach droplets of specific volume; to a first approximation the droplet volume increases proportionally with pulse duration.

Process stability can be readily achieved by relating the pulse-repeat frequency to the wire feed speed, i.e. the number of droplets (or increments of wire feed) to be detached from the wire. Under open-loop control; the pulse current and pulse time are set to detach one droplet of the desired volume and the background time and level are then adjusted to generate the required number of pulses to maintain the current burn-off rate. In synergic control, the unit-pulse principle has been used to produce a fully automated control system. The unit pulse (pulse current level and time) is uniquely determined by the material composition and the wire diameter. However, once the unit pulses have been determined for the desired range of materials, the power source is preprogrammed and the operator is merely required to select the appropriate programme for the wire being used. On setting the desired wire feed speed, the

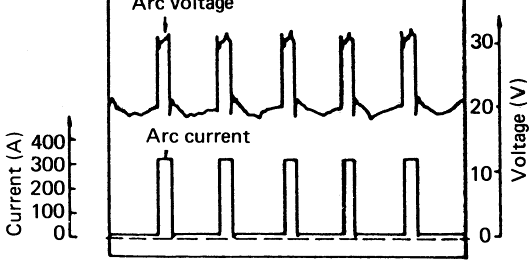


Figure 10.24 Typical oscillogram of arc current and voltage for 2 m/min wire feed speed, 50 Hz pulse frequency and 4 ms pulse duration

power source delivers the correct number of pulses to maintain arc stability.

10.1.3.3 D.c. power source

Short circuiting and spray metal transfer The basic power source for MIG welding has a nominally flat or constant voltage output characteristic as shown in *Figure 10.25*. The welding current is principally determined by the wire feed speed and the arc length by the power source voltage level (open-circuit voltage). Automatic adjustment of the wire burn-off rate is used to compensate for minor variations in the torch-to-workpiece distance, wire feed speed or current pick-up in the contact tip. For example, if the torch is moved away from the workpiece the arc length is momentarily increased, but this results in an increase in the voltage and a reduction in the level. Consequently, as the wire speed is constant, the reduction in the burn-off rate forces the arc length to return to the set arc length. If the torch is moved closer to the workpiece, the converse occurs, i.e. the burn-off rate is momentarily increased to maintain a constant arc length. Alternatively, a low inductance produces a rapid rise in current which assists arc starting.

In setting the power source for the two main operating modes (spray and short-circuiting metal transfer), the open-circuit voltage must be set to produce the required arc length for a given wire feed speed. For the short-circuiting mode, the inductance must also be selected by the operator to give a smooth rupturing of the metal bridge formed between the wire tip and the weld pool during the short circuit. Failure to set these parameters gives an erratic arc, as indicated by momentary arc outages and wire stubbing which results in excessive ejection of molten droplets from the weld pool (termed 'spatter') and a poor weld-bead profile. For the spray metal transfer mode, circuit inductance is not essential, but it helps to smooth the process, especially when operating with a short arc length.

The modern electronic, high response power sources have been designed to overcome some of the inherent limitations of operating the MIG process with more conventional power sources, namely the sensitivity to variations in gun-to-workpiece distance, wire-feed fluctuations, and long-term variations in the main supply voltage or through 'warm-up' drift in the control system. These limitations can make it difficult to sustain a high level of weld quality under low spatter conditions, particularly in mechanised or robotic applications. Transistor controlled power sources, in particular, can have sophisticated control systems such as:

(1) programmable parameter selection—the optimum welding parameters can be generated from the input of information on the wire being used (composition, diameter), shielding gas composition and the wire feed speed; or
(2) arc voltage as the setting up parameter—the operator is only required to set the desired voltage level and the wire feed speed is automatically adjusted by the system control.
(3) automatic setting of circuit inductance.

The trend in electronic power sources is towards 'one-knob' control with the wire feed speed level, which is under feedback control, being held within much closer limits.

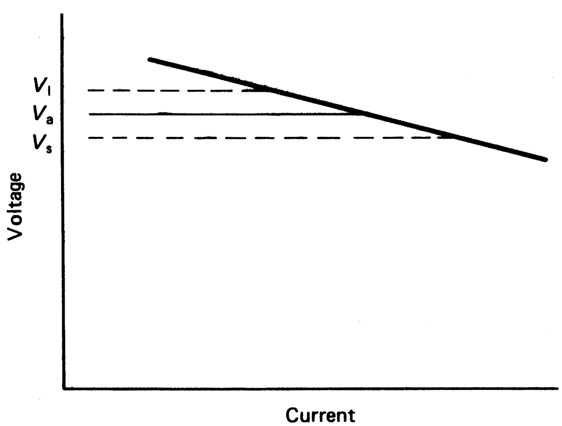


Figure 10.25 Nominally constant voltage output characteristic of the power source for MIG welding and self-adjustment of the arc length. V_a, set arc length; V_s, momentary shortening of the arc length; V_l, momentary lengthening of the arc length

Pulsed MIG In conventional pulsed MIG power sources, current pulses are generated through half-wave rectification of the mains supply to give sinusoidal pulses at a frequency of 50 Hz. The background current is usually supplied by a separate and independent supply. Full-wave and three-phase half-wave rectification are used for 100 and 50 Hz, respectively, whilst submultiples of these frequencies give sinusoidal pulses at repeat frequencies of 75, 37½, 33⅓ and 225 Hz.

In synergic control, high response, electronic (transistor or inverter) power sources are required in order to generate the 'unit' pulses; typical pulse durations are 2–5 ms and the pulse frequency lies within 25–500 Hz for current levels up to 300 A. The first type of synergic control modified the output of the power source (pulse frequency) by monitoring the wire feed speed. More recently, commercial power sources began to employ a range of synergic control systems to set the pulse frequency and the wire feed speed. The arc length is controlled by monitoring the arc voltage, and the wire feed speed or the pulse frequency may be adjusted to compensate for changes in the gun-to-workpiece distance.

Unlike conventional (constant current) MIG power sources, the first synergic power sources employed a constant-current characteristic with adaptive control of the arc length; the output of a technogenerator mounted on the wire feed was used to vary the pulse frequency to maintain arc stability. However, the more modern power sources use a combination of constant-current and constant-voltage characteristics. A common technique is to employ constant-current characteristics during the background period but constant-voltage characteristics during the pulse period for self-adjustment of the arc length. A limitation of this technique, however, is the very high peak current that can be produced. An alternative design is to use a constant-current supply with instantaneous voltage feedback acting on each pulse.

10.1.3.4 Control of short circuiting

In the conventional short circuiting process, metal transfers from the tip of the wire by periodically dipping into the weld pool (*Figure 10.20*). The process is controlled by setting the arc voltage to control the arc length and the circuit inductance to control the rate of rise of the current during the short circuit and the peak short circuit current.

The short circuiting process is characterised by spatter and low heat input to the material. The spatter originates from the explosion of the wire tip as it ruptures under the high short circuit current in a similar manner to the breaking of a fuse. The intermittent periods of arcing and arc outages during the short circuits increase the risk of cold laps.

As power sources have become more intelligent (see Section 10.1.1.3), control strategies can be used to improve process performance. For example, the Surface Tension Transfer (STT) process aims to control spatter and increase the heat input by improving the control of the current waveform and the sequence of events is as follows:

(1) At the onset of the short circuit, the current is reduced immediately and the molten metal on the tip of the wire is allowed to transfer under surface tension forces.
(2) A high 'pinch' current level is applied to speed up transfer of the molten metal.
(3) When the wire tip approaches 'necking', the current is quickly reduced to produce a smooth rupture of the wire.
(4) As the arc will form at a low current level, the risk of eject molten metal from the weld pool is greatly reduced.
(5) During the arcing period a pulse of current is applied to broaden the arc and reduce the risk of weld laps.

The advantages claimed for the STT process over conventional short circuiting metal transfer MIG are a reduction in parent metal dilution and lower labour costs through the higher travel speeds, reduction in repairs and less clean-up work.

10.1.3.5 A.c pulsed MIG

The a.c. arc has been recently stabilised for MIG welding by using a special power source with two inverters. The primary inverter controls the output current whilst the secondary inverter produces rapid switching between electrode positive and electrode negative polarities. A high voltage pulse is applied at current reversal to ensure that the arc is re-ignited. A pulse of current is also applied during the electrode positive half-cycle to ensure that the molten metal droplets are smoothly detached from the end of the wire. The pulse parameters (pulse current level and duration) are set to give one droplet per pulse.

Compared with conventional d.c. MIG, in the a.c. MIG process the wire burn-off rate is increased for a given current level which produces a 'colder' arc and a shallower weld pool penetration. These process features provide greater tolerance to joint gap as demonstrated for lap joints in thin sheet.

10.1.3.6 Twin wire MIG

As a means of increasing the deposition rate, two in-line wires, i.e. one behind each other, are fed simultaneously into the weld pool, *Figure 10.26*. The wires are powered by two separate power sources and as the contact tips are electrically isolated, they can be operated independently i.e. with different wire diameters, current levels or operating modes (continuous or pulsing). In practice, current pulsing is normally used but synchronisation of the power source outputs is necessary to minimise arc interaction. The current pulses are out of phase to avoid arc instability which would be caused by the interaction of the strong magnetic fields generated by the high current pulses. Metal transfers from one wire during the pulse period whilst the other wire has a low background current to avoid droplets being ejected from the arc. To control the process, the power source supplying current to the lead wire is designated as the lead (master). The current from trailing power source

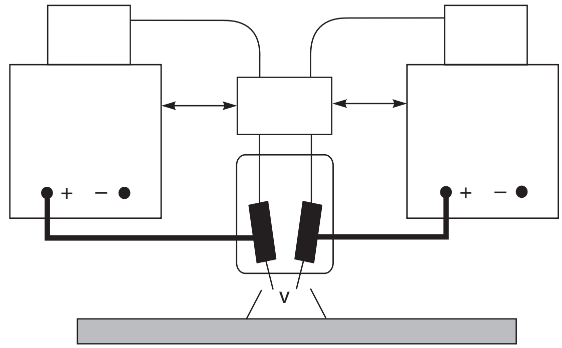


Figure 10.26 Electrical connections for twin wire with separate contact tips

(slave) is then synchronised to the current supplied to the lead wire.

The process requires a special torch but is sufficiently compact for welding the root in a V joint. In a fully automatic operation, very high welding speeds and high deposition rates can be achieved. Welding speeds are up to 3–4 times faster than those achieved using a single wire. For example, for 6 mm leg length fillet welds, the welding speed using the tandem wire process was 1.1 m/min compared with 300 mm/min for the single wire MIG process. Deposition rates can be as high as 20 Kg/hr which is about three times greater than is normally possible with a single wire.

Typical welding parameters for welding thin sheets components are:

Wire feed speed:	1st wire	12 m/min
	2nd wire	10 m/min
Pulse parameters:	pulse current	380 A
	pulse voltage	38 V
	background current	70 A
	frequency	280 Hz

The process uses the pulsed mode on each wire with a deposition rate of 10 kg/hr and a travel speed of 5 m/min.

10.1.4 Flux cored arc welding

10.1.4.1 Principles of operation

Flux cored arc (FCA) welding is an alternative to MIG and MMA welding. The wire consists of a hollow tube which is filled with flux and metal powder. The flux filling is similar in nature to the MMA covering, e.g. basic or rutile. The wire can be used without a separate gas shield (self-shielded welding), and the gas which is required to protect the weld pool is generated from the burning of the flux. In gas-shielded (FCA) welding, a gas shield of CO_2 or an argon–CO_2 mixture is used in the same manner as in solid-wire MIG welding.

10.1.4.2 Wire electrodes

As the first generation of wires were of large diameter (3.2 mm and above), the FCA process was initially used for welding at high deposition rates: the welding current levels were greater than 400 A, which gave deposition rates in excess of 24 kg/h. The availability of smaller diameter wires gives a wide range of deposition rates and the capacity to

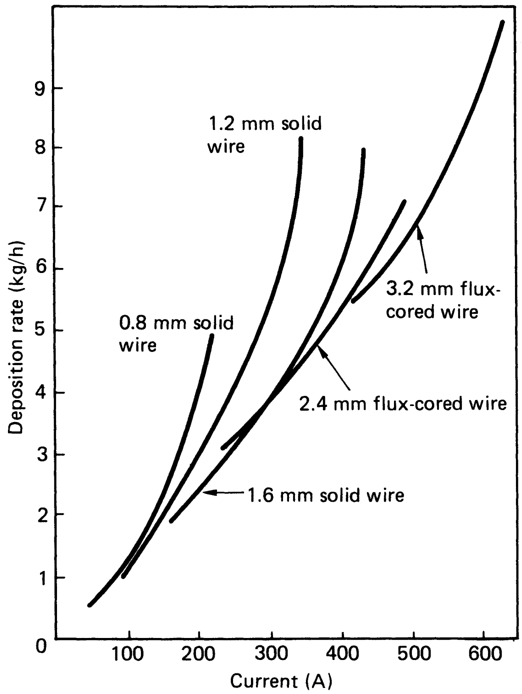


Figure 10.27 Deposition rates for various steel wires and welding processes

weld in the vertical and overhead positions; a comparison of deposition rates for the MIG solid wire, and is given in *Figure 10.27*. However, the past disadvantages of the quality of the wire (e.g. consistency of the core filling) and the cost compared with solid wire, have restricted widespread application of FCA welding. Advances in flux formulations and manufacturing technology to produce an attractive range of smaller diameter wires (down to 0.9 mm) with all-position welding capability and good mechanical properties will make the FCA process more competitive than the alternative MIG and MMA processes.

Cored wires are normally classified according to the American Welding Society Standard AWS-A5.20 which defines the type of wire in terms of the core composition, the performance and the mechanical properties of the weld metal. The more commonly used wires are listed below.

Type T1 These wires are usually rutile based with a CO_2 or argon–CO_2 shielding gas. As the wires have a spray transfer mode with a fast freezing slag, they can be used in all welding positions.

Type T5 These wires have a basic flux core and use a CO_2 or argon–CO_2 gas shield. The transfer mode is globular which produces a convex bead shape, generates more spatter and is not suited to positional welding operations.

Type T7 These wires are self-shielded and have a globular type metal transfer. The slag is designed for high current/high deposition rates. However, the resulting welds have good mechanical (impact) properties.

Type T8 These are self-shielded wires which can be used in all welding positions and with good low-temperature impact properties. Small diameter wires, typically 1.2 mm, have all-position welding capability.

Recent developments in cored wires include barium free E71T-8 wires and E7OT-1 all-position rutile wires.

10.1.4.3 Power source

The power source designed for normal MIG welding is suitable for operating with cored wires. However, as the wire diameter can be significantly larger, and because higher deposition rates are possible in the flat position, the capacity of the power source is greater than is normally specified for MIG welding. For example, a 2.4 mm diameter wire can be used at current levels up to 500 A and a 3.2 mm diameter wire can require a power source with over 600 A capacity.

The wires are normally operated with d.c., but both electrode-positive and electrode-negative polarities are used. The usual practice is to use electrode-positive for a rutile wire and electrode-negative for basic and metal cored wires. As both the short circuiting and spray transfer modes are used, the power sources require voltage range and inductance settings to control the process. The pulsed mode of transfer is not normally used, but claims have been made that the technique can improve metal transfer, especially for larger diameter wires at low current levels.

10.1.5 Submerged arc welding

10.1.5.1 Principles of operation

The submerged arc process is a high current, bare wire electrode process in which the arc operates below a bed of powdered flux. The principles of the process are shown in *Figure 10.28*. The flux has a similar function as in MMA and FCA welding in generating gases to protect the arc and the weld pool from the atmosphere, and providing alloying elements to achieve the desired mechanical properties in the weld metal. However, unlike the MMA and FCA processes, excess flux is laid down which must be recycled via a hopper. The slag, as is formed in MMA, must be removed after welding and discarded.

The electrode is normally wire (1.6–6.0 mm diameter), but for cladding large surface areas a strip electrode of up to 130 mm in width, 0.5 mm thickness can be used. The normal welding current range is 200–2000 A and the corresponding arc voltage level is 25–45 V.

The weld metal recovery rate is almost 100%, as very little metal is lost through spatter. The flux consumed in forming the slag, is approximately equal to the weight of wire deposited. As heat losses from the arc are exceptionally low, due to the insulating effect of the flux bed, the thermal

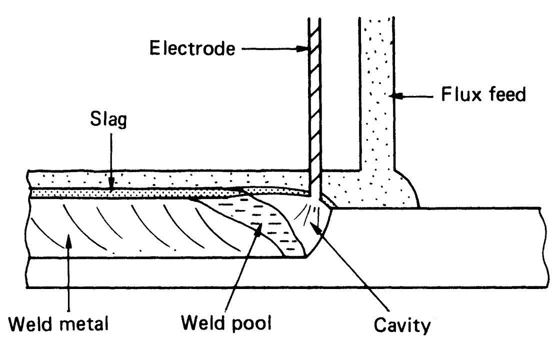


Figure 10.28 The principles of the submerged arc process

efficiency of the process can be as high as 60%, compared with about 25% for MMA welding.

10.1.5.2 Power source

The power sources can be a.c. or d.c. but, because the process is used for large diameter wire or strip electrodes giving high deposition rates, the capacity can be high as 2000 A.

Single wire For a.c. operation, the power source has a constant-current characteristic (drooping V/I output) or the open-circuit voltage should be at least 80 V to ensure reliable arc reignition on reversed polarity. The d.c. power sources have either constant-current (drooping output) or constant-voltage (flat) characteristics. With the constant-current power source, the arc length must be set by balancing the wire feed for the given current setting, i.e. to match the burn-off rate. The arc length can be adjusted automatically by using the arc voltage to vary the wire feed speed. In the constant-voltage power source, the normal self-adjustment of the arc length is obtained using the arc voltage as the control parameter for a given wire feed speed/welding current setting.

The constant-voltage power source is normally used for thin sheet welding, but the constant-current power source is preferred for welding thicker plates. The constant-current arc is more stable for deep penetration applications where the self-adjustment effect of the constant-voltage power source can lead to arc instability.

10.1.5.3 Electrode polarity

The electrode polarity can be either d.c. (electrode-positive or negative) or a.c. D.c. electrode-positive gives the deepest penetration, d.c. electrode-negative has the greater deposition rate, and a.c. has an intermediate characteristic. The effect of electrode polarity on deposition rate is shown in *Figure 10.29*. The d.c. electrode-positive polarity will produce approximately 20–25% increase in penetration compared with d.c. electrode-negative. For this reason, d.c. electrode-positive polarity is normally used for the root run in welds to ensure that adequate penetration is achieved. However, for surfacing applications where low penetration and parent metal dilution is required, d.c. electrode-negative is preferred.

The wire burn-off rate can be increased significantly by increasing the electrode extension (the distance between the contact tip and the arc). The effect is to preheat the wire according to the relationship

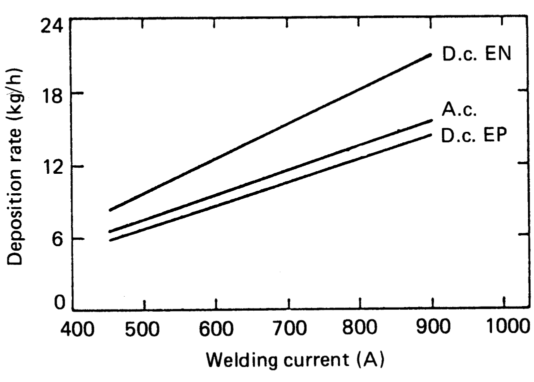


Figure 10.29 Effect of electrode polarity on deposition rate (standard electrode extension 32 mm; 4 mm diameter wire; 32 V). EP, electrode-positive; EN, electrode-negative

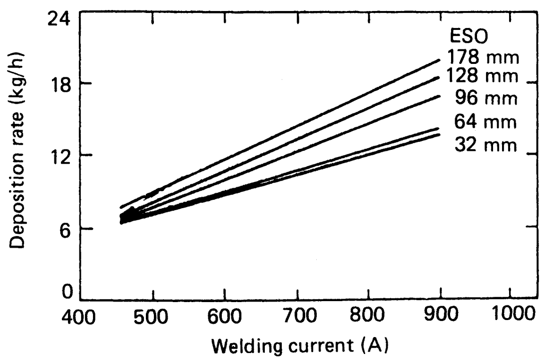


Figure 10.30 Effect of stick-out on deposition rate (d.c. electrode-positive; 4.75 mm diameter wire). ESO, extended stick-out

$$\text{Heat generated} \Leftarrow \frac{I^2LR}{d}$$

where I is the current, L is the electrode stick-out, R is the resistivity of the wire, and d is the diameter of the wire.

Preheating of the wire can be used to increase significantly the deposition rate (see *Figure 10.30*). As the wire will soften through resistance heating, the stick-out must be limited or supported to avoid arc wander under the high electromagnetic forces. It is usual practice to support the wire with an insulated guide tube to a distance of 25 mm above the workpiece surface. Even with a guide tube, it is normally recommended that the maximum stick-out be limited to, typically, 76 mm for 3.2 mm diameter wire, but this can be increased to, typically, 130 mm for a 4 mm diameter wire.

10.1.5.4 Hot wire welding

The resistance heating of a wire can be used to increase the weld metal deposition rate by feeding a separate (I^2R heated) wire into the weld pool. The wire is heated using a low voltage of typically 8–15 V from a separate a.c. power source. The wire, which is typically 1.6 mm in diameter, enters the weld pool at a temperature just below its melting point and no arcing occurs. Deposition rates are in excess of those achieved with single-wire d.c. electrode-negative polarity, even with an extended electrode stick-out.

10.1.5.5 Series arc welding—single power source

As series arc welding is used for high deposition rate welding applications, specialised techniques have been designed specifically to increase the deposition rate and the welding speed. As the maximum welding current on a single wire is limited by a deterioration in weld quality through excessive arc forces, the techniques are based on the use of multi-arcs.

The simplest arrangement is two wires connected to the same power source to give d.c. electrode-positive and d.c. electrode-negative arcs or, alternatively, two a.c. arcs (*Figure 10.31*). When used in tandem (d.c. electrode-positive leading), a substantial increase in welding speed, typically 1.5 times the single-wire process, can be achieved with no deterioration in the weld-bead shape.

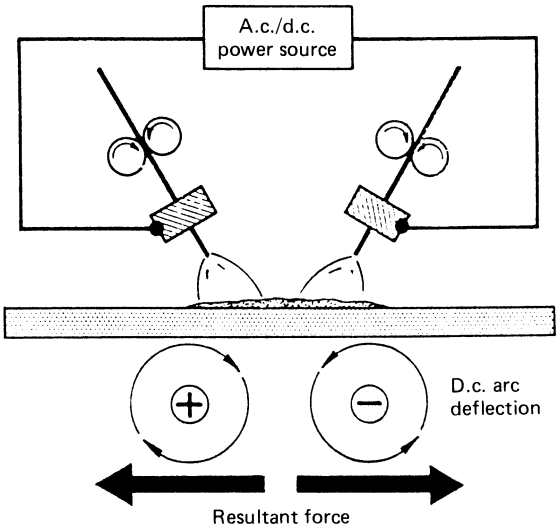


Figure 10.31 Series arc welding

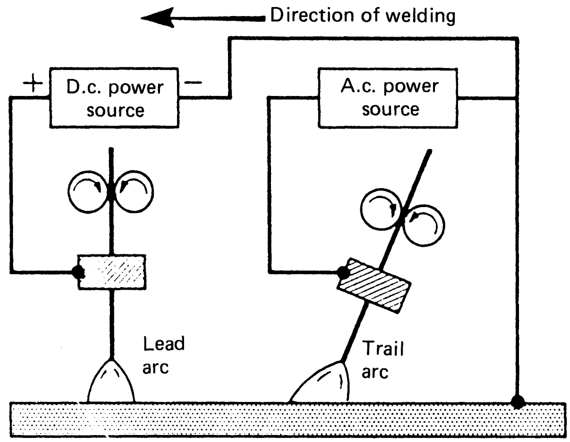


Figure 10.32 Two-wire welding

The two arcs operate into a single weld pool and, because of this close proximity, there is significant arc interaction. With d.c., the arcs will diverge, i.e. be repelled by each other, whilst two a.c. arcs will be largely unaffected.

10.1.5.6 Series arc—multipower

Multipower systems use separate wire feed systems and power sources. The increased flexibility of electrode polarity and number of arcs permits a substantial increase in the deposition rate and welding speed and an improvement in the weld-bead shape. Of the possible combinations, multiple d.c. arcs are normally avoided to reduce the risk of arc blow which is caused by the large magnetic fields associated with the high current levels. High current, multipower systems are, therefore, normally a combination of d.c. and a.c. arcs.

The most commonly used arrangement is a twin-wire system with a d.c. electrode-positive leading arc and an a.c. trailing arc (*Figure 10.32*). When operated at high current and low voltage, the d.c. electrode-positive arc will give deep penetration, whilst the lower power (lower current/higher voltage) a.c. arc will provide joint filling with minimum weld pool disturbance and a smooth final weld bead surface profile. The normal spacing between the arcs is 30–50 mm. The power sources are normally a d.c. thyristor controlled rectifier and a single-phase transformer for the a.c. arc.

For three-wire systems, the leading arc is d.c. electrode-positive, but the middle and trailing arcs are normally a.c. as shown schematically in *Figure 10.33*. The phasing of the two a.c. arc voltages is important to minimise arc interaction. In order to produce a phase difference, separate a.c. power sources are preferable, but a Scott-type transformer will give a 90° difference in phase shift between the two outputs. As the deposition rates can be substantially increased with multi-wire welding processes, the techniques are used in industries such as shipbuilding, where large flat plates must be welded. Typical welding speeds for various plate thicknesses are given in *Figure 10.34*, where it can be seen that the joint completion rate for a 20 mm thick plate

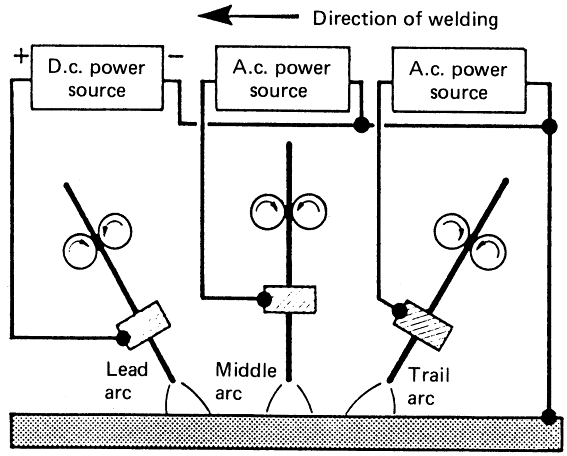


Figure 10.33 Three-wire multiple-electrode welding

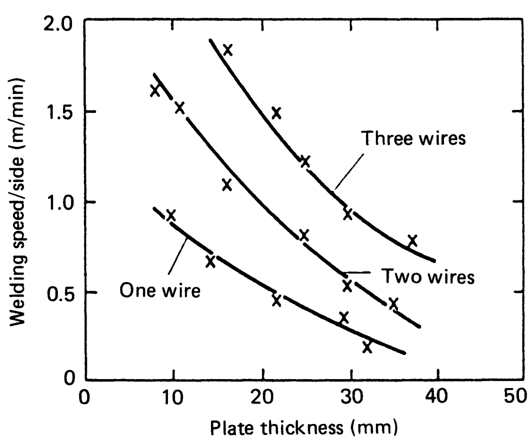


Figure 10.34 The effect of the number of electrodes on joint completion rate (speed/side)

is doubled for a twin-wire system and trebled for the three-wire system.

10.1.6 Tungsten inert gas welding

10.1.6.1 Principles of operation

In the tungsten inert gas (TIG) welding process, the arc is formed between a pointed tungsten electrode and the workpiece in an atmosphere of argon or helium (see *Figure 10.35*). The small intense arc provided by the pointed electrode is ideally suited to precision and controlled melting of the workpiece. Since the electrode is not consumed during welding as with the MMA and MIG processes, autogenous welding can be practised without the continual compromise between the heat input from the arc and the deposition of filler metal. When filler metal is required, this must be fed separately into the weld pool using a wire or rod feed system.

The process can be operated with d.c or a.c. In d.c welding the electrode polarity is always negative so that its electron thermionic emission properties reduce the risk of overheating which would occur with electrode-positive polarity. The arc heat is distributed approximately one-third into the electrode and two-thirds into the workpiece. However, the alternative of d.c. electrode-positive would have advantages in that the cathodic action on the workpiece surface would clean the surface of the oxide coatings. For this reason, a.c. is the preferred polarity for welding materials such as aluminium which have a tenacious oxide film.

10.1.6.2 Electrode

The electrode for d.c. welding is pure tungsten with 1, 2 or 4% thoria, the thoria being added to improve electron emission which facilitates arc ignition. Alternative additives to lower the electron work function are lanthanum oxide or cerium oxide, which it is claimed have improved starting characteristics, lower electrode consumption and, compared with thoria, are non-radioactive. When using thoriated electrodes it is recommended that precautions are taken to avoid contact with the grinding dust and smoke.

The electrode tip angle for the d.c. arc must be tapered to a fine point to concentrate and stabilise the arc. The general rule is that the lower the welding current, the smaller the electrode diameter and the tip angle. Recommended electrode diameters and tip angles for d.c. and a.c. arcs are given in *Table 10.2*.

In a.c. welding, the electrode must operate at a much higher temperature due to the heat generated during the positive half-cycle. As the rate of tungsten loss is somewhat less than with thoriated electrodes, pure tungsten or tungsten with zirconia electrode is preferred. Furthermore, because of the greater heating of the electrode, it is difficult to maintain a pointed tip, and the end of the electrode assumes a spherical or 'balled' profile.

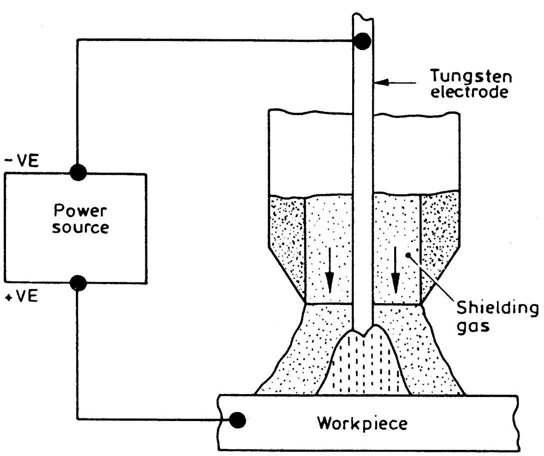


Figure 10.35 Principles and features of the plasma arc process

10.1.6.3 Shielding gas

The shielding gas must be inert or slightly reducing and the composition is normally selected according to the material being used.

(1) *Argon*—This is the most common gas employed because of its low cost compared with the other inert gases, and it can be used for most materials.
(2) *Argon–H_2*—Hydrogen can be added (up to 5%) to produce a slightly reducing atmosphere. The gas is hotter and, being slightly more constricted, produces deeper penetration and higher welding speeds.
(3) *Helium and helium/argon*—A typical gas mixture is 75/25, helium/argon mixture which produces a higher heat input and higher welding speeds; the greater heat input is produced by the higher ionisation potential which is 25 eV for helium compared with 16 eV for argon. Besides the higher cost (approximately three times the cost of argon), the arc may be more difficult to ignite, especially in pure helium.
(4) *Nitrogen*—As nitrogen is diatomic, on reassociation at the workpiece surface it is capable of transferring more energy than the monatomic argon or helium. The gas is used to weld high-conductivity metals, e.g. copper, but because of nitrogen pick-up in the weld pool, it cannot be used with steels due to the reduction in the toughness.

10.1.6.4 Power source

The power source necessary to maintain the TIG arc has a drooping voltage-current characteristic which provides an essentially constant-current output even when the arc length is varied over several millimetres. Hence, the natural variations in arc length which occur in manual welding have

Table 10.2 Recommended electrode diameter and vertex angle for TIG welding at various current levels

	D.c. electrode-negative		*A.c.*
Welding current (A)	*Electrode diameter** (mm)	*Vertex angle* (°)	*Electrode diameter†* (mm)
< 20	1.0	30	1.0–1.6
20–100	1.6	30–60	1.6–2.4
100–200	2.4	60–90	2.4–4.0
200–300‡⇐	3.2	90–120	4.0–4.8
300–400‡⇐	3.2	120	4.8–6.4

* Thoriated tungsten.
† Zirconiated tungsten, balled tip, electrode diameter depends on degree of balance on a.c. waveform.
‡ Use current slope-in to minimise thermal shock which may cause splitting of the electrode.

little effect on the welding current. The capacity to limit the current to the set value is equally crucial when the electrode is inadvertently short circuited onto the workpiece. Otherwise, excessively high currents would be drawn, damaging the electrode and even fusing the electrode to the workpiece.

In practice, the power source is required to reduce the high-voltage mains supply (240 or 440 V and a.c.) to a relatively low voltage (60–80 V, a.c. or d.c.) supply. In its basic form, the power source comprises a transformer to reduce the mains voltage and to increase the current and the rectifier, placed on the secondary side of the transformer, to provide the d.c. supply. Traditional power-source designs employ a variable reactor, moving coil or moving iron transformers, or a magnetic amplifier to control the welding current. Such equipment has the highly desirable features of simple operation and robustness, making it ideally suited to application in aggressive industrial environments. The disadvantages are relatively high material costs, large size, limited accuracy and slow response. Electronic power sources (described earlier) have become available which do not suffer from these disadvantages:

(1) thyristor (SCR) phase control;
(2) transistor, series regulator;
(3) transistor, switched; and
(4) a.c. line rectifier plus inverter.

The major operating features of these systems are described in Section 10.1.1 and the advantages/disadvantages compared with conventional power sources are given in *Table 10.1*. Of the above power sources, the transistor based control systems offer greater accuracy and reproducibility of welding parameters, but tend to be wasteful of electrical energy. The a.c. line rectifier, plus inverter type offers a combination of high electrical efficiency and small size.

Because of the constant-current output characteristics, the arc can be ignited by either touching the electrode to the workpiece or in a contact system by a series of high-frequency high/voltage sparks. The effect of the high-frequency is to ionise the gas between the electrode and the workpiece. As the voltage and frequency are approximately 10–20 kV at 100 MHz, care must be taken to prevent insulation breakdown of the welding control system. Line and air-borne high frequencies can cause problems in instrumentation and electrical equipment in the vicinity of the arc and the power lines of the welding system. High-frequency feedback to the power source can be eliminated by placing an air-cored inductor between the high-frequency generator and the transformer rectifier; the isolator may be built into the high-frequency transformer, as shown in *Figure 10.36*. Care must be taken to ensure that all equipment is properly earthed and that all welding leads are kept as short as possible.

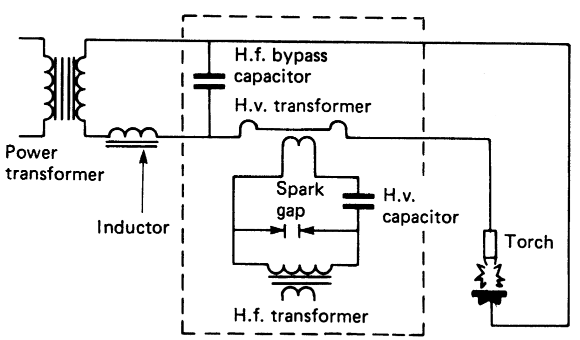


Figure 10.36 High-frequency arc-starting unit for TIG welding. H.f., high frequency; h.v., high voltage

Sine wave a.c. The cyclical nature of the current introduces certain difficulties. When the tungsten electrode changes from positive to negative polarity, a smooth transition takes place because the tungsten electrode (being a thermionic emitter) has an electron cloud available for re-ignition as an arc cathode. When the change in electrode polarity is from negative to positive, a cathode root or a group of multiple cathode roots have to form on the plate. This function requires a high restriking voltage to re-ignite the arc, which is over 150 V when welding aluminium.

For the usual inductive supply, the arc voltage and current waveforms (*Figure 10.37*) both lag considerably on the open-circuit voltage. As a result, a high restriking voltage is available (*Figure 10.37*(*a*)). If the arc fails to re-ignite because of insufficient restrike voltage, a rectifying arc can occur, with the current flowing predominantly in the negative half-periods. Under low-voltage conditions, it is possible to secure positive half-period current by use of auxiliary equipment to give, for example, spark re-ignition. The sparks must be properly timed, as otherwise some degree of rectification will occur.

A more precise method of obtaining the electrode-positive half cycle is the use of the surge injection technique. With a surge injector added to a welding transformer, the open-circuit voltage can be reduced to 50 V. The basic circuit of the

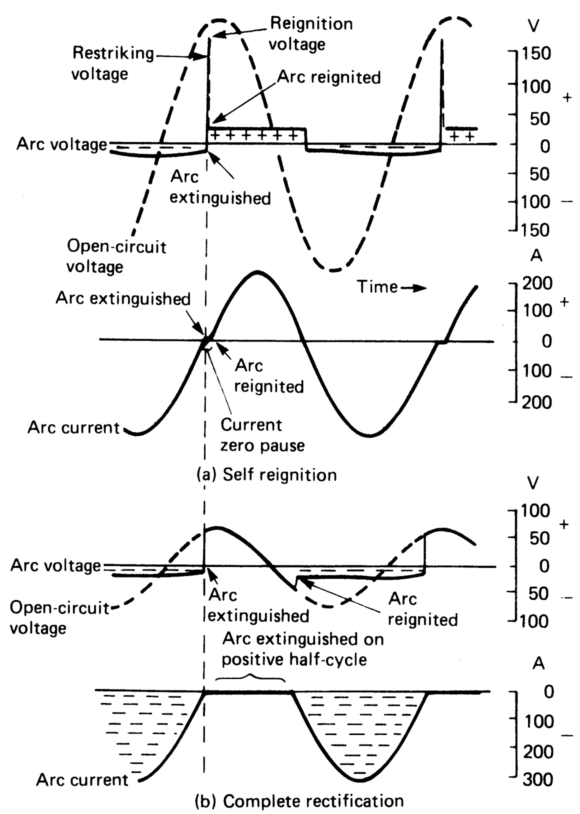


Figure 10.37 Waveforms of voltage and current for TIG a.c. welding

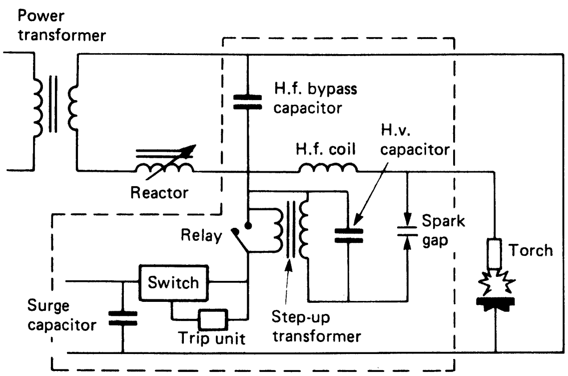


Figure 10.38 Surge injector unit and welding circuit. H.f., high frequency; h.v., high voltage

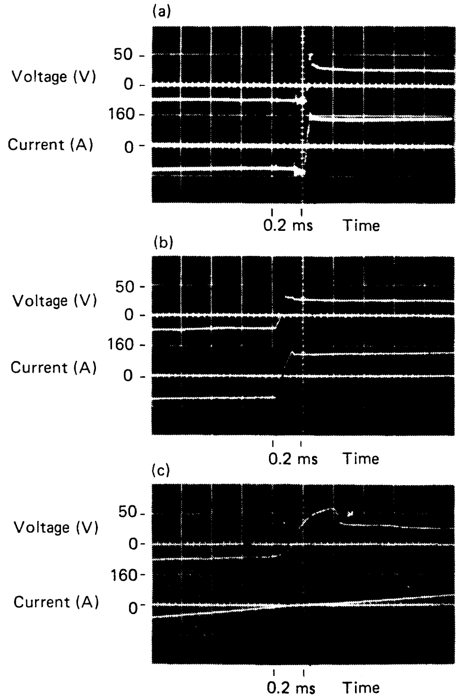


Figure 10.39 Typical positive re-ignition waveforms of voltage and current when welding at 160 A r.m.s. (a) Square wave supply at 75 V open-circuit voltage. (b) Square sine wave at 79 V open-circuit voltage. (c) Sine wave supply at 75 V open-circuit voltage

surge injector together with the high-frequency arc starter is shown in relationship to the welding circuit in *Figure 10.38*.

The operation of the circuit for starting is as follows. When full open-circuit voltage is applied to the system, the relay contact is opened, and the trip unit operates the switch to discharge the surge capacitor into the primary of the step-up transformer. The voltage induced in the secondary builds up until the breakdown voltage of the spark gap into the torch is reached. When the arc has been established, the voltage applied to the relay falls to the arc voltage level and the relay contact closes, the surge capacitor then being discharged directly into the arc. The instant of discharge is governed by the trip unit and is so timed as to occur at arc extinction when the polarity is changing to the electrode-positive half-cycle. The surge capacitor, which is charged to a voltage of sufficient amplitude, is then used to provide an artificial restrike voltage.

Square wave a.c. An alternative design of power source which is becoming more popular is the square wave power source. The principal feature of such designs is that the output current assumes a more square waveform, compared with the conventional sine wave (*Figure 10.10*). Two types of power source are available, differing in the manner in which the square waveform is produced. Whilst a 'squared' sine wave-form is generated by using inverted a.c., a more truly square waveform is produced by a switched d.c. supply (see *Figure 10.11*). In either case the importance for TIG welding is that the current is held at a relatively high level prior to zero and then transfers rapidly to the opposite polarity. In comparison, the current developed by sine wave power sources decreases more slowly to current zero, and likewise the current built up after re-ignition is at a much lower rate.

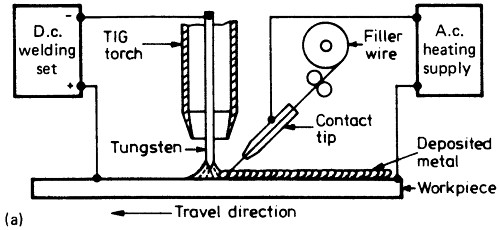
As shown in *Figure 10.39(a)*, if a square wave a.c. derived from a switched d.c. supply is used at 75 V open circuit and 160 A r.m.s. welding current, a voltage of 50 V and a circuit current of some 160 A are both obtained within 0.02 ms from zero. With a squared sine wave, a voltage across the gap of above 50 V is achieved in 0.02 ms and a circuit current of 110 A is attained in 0.1 ms from zero (*Figure 10.39(b)*). In comparison, the equivalent rise time for a conventional sine wave supply is 0.15 ms to achieve 5 V across the arc gap, and a relatively long time of approximately 3 ms to achieve 110 A from zero.

The benefit of square wave a.c. is that, aided by the inherent high surge voltage associated with the rapid current reversal, a.c. TIG can in some instances be practised at 75 V r.m.s. without the need for high-frequency spark injection to be superimposed for arc re-ignition.

An additional feature of square wave a.c. power sources is the capacity to imbalance the current waveform, i.e. to vary the proportion of electrode-positive to electrode-negative polarity. In practice, the percentage of electrode-positive polarity can be varied from 30 to 70% at a fixed repeat frequency of 50 Hz. By operating with a greater proportion of electrode-negative, heating of the electrode can be substantially reduced compared to that experienced with a balanced waveform. Although cleaning of the oxide on the surface of the material is normally sufficient with 30% electrode-positive, the degree of arc cleaning may be increased by operating with a higher proportion of electrode-positive polarity (up to a limit of approximately 70%).

10.1.6.5 TIG hot wire

The TIG hot wire variant was developed as a means of achieving very high deposition rates without reducing the high weld quality normally associated with TIG welding. The essential feature is that filler wire is fed directly into the back of the weld pool and resistance heated using a separate power source (see *Figure 10.40(a)*). This second power source is usually a.c., to minimise any interference with the welding arc through the magnetic field generated by the current flowing in the wire. In a low current manual system, a single power source can be used to provide both the arc and resistance heating currents, but in this case the hot wire current is d.c. (*Figure 10.40(b)*).



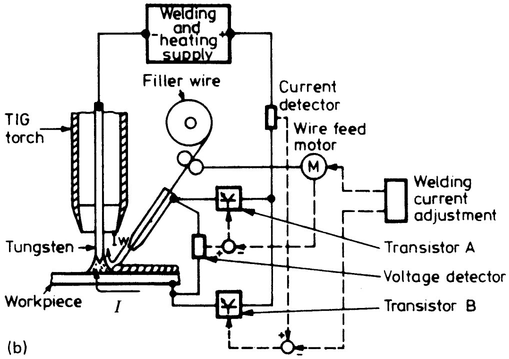


Figure 10.40 Electrical system and torch arrangement for the TIG-hot wire process. (a) Separate hot wire a.c. power source; (b) Single d.c. power source for arc and wire currents: I, arc current; I_w, wire heating current; $I + I_w$, welding current

In operation, the arc melts the base metal to form the weld pool. The filler wire, heated to its melting point by its own power source, enters the weld pool behind the arc to form the weld bead (*Figure 10.41*). Smooth feeding of the wire, control of the angle of entry into the weld pool, and a stable power source are all essential for stable operation, otherwise random arcing from the filler wire will occur with the resulting pool disturbances, causing porosity.

The main advantage of the process is that deposition rates can be achieved which approach those obtainable with MIG welding, i.e. 5–20 kg/h. Hence, TIG hot wire is used for welding, thicker section material, where the significantly higher depletion rates compared with those of the TIG cold wire process, can be fully exploited without any reduction in weld quality. In a specific example—welding steel tube of approximately 20 mm wall thickness- the deposition rate could be increased by a factor of 4. As the number of passes was reduced from approximately nine to five, the overall joint completion rate was reduced by a factor of almost 3.

TIG hot wire is also used for high deposition rate cladding, and here deposition rates of 10 kg/h are readily obtained. Even higher deposition rates of the order of 14 kg/h can be achieved, but only through the use of oscillation of the torch.

10.1.6.6 Pulsed current

Pulsing the welding current at a frequency of 0.1–10 Hz is used to improve control over the arc stability and weld pool behaviour. The essential feature is that a high current pulse is applied, causing rapid penetration of the workpiece.

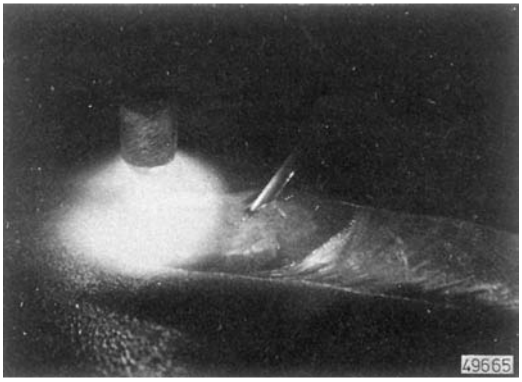


Figure 10.41 Photograph showing the TIG arc and the (hot) wire entering the weld pool behind the arc

If this high current is maintained, excessive penetration and ultimately burn-through occur. Therefore, the pulse is terminated after a pre-set time and the weld pool is allowed to solidify under a low background or pilot arc. Thus, the weld progresses in a series of discrete steps with the pulse frequency balanced to the welding speed to give approximately 60% overlap of the weld spots. The surface appearance of a typical pulsed current TIG weld is shown in *Figure 10.42*.

The pulsed technique has been found to be particularly beneficial in controlling the penetration of the weld bead, even with extreme variation in heat sink. Such variations are experienced either through component design, e.g. thick to thin sections, or from normal production variations in component dimensions, fit-up, clamping and heat build up. In conventional continuous-current welding, where a balance must always be achieved between the heat input from the arc, the melting to form the weld pool, and the heat sink represented by the material of the component being welded, the degree of penetration is greatly influenced by these variations. However, in pulsed operation, the rapidly penetrating weld pool during the high current pulse and the solidification of the weld pool between pulses, markedly reduce the sensitivity to process variation through the effects of heat build up and/or disparity in heat sink.

Despite the obvious advantages of the pulsed process to production, the technique may appear to be a further complication of the process in that a greater number of welding parameters must be considered, i.e.

(1) pulse time;
(2) pulse level;
(3) background time; and
(4) background level.

The technique can be simplified in the first instance from the knowledge that, for a given material, there is a preferred pulse level which is based on its diffusivity and, to a lesser extent, on its thickness. The preferred currents are approximately 400 A for copper, 150 A for stainless steel, and 50 A for lead. Thus, for a given component, the operator need only set the pulse time to achieve penetration which, as shown in the nomograph in (*Figure 10.43*(*a*)), is determined solely by thickness. For example, for welding 2 mm stainless steel at 150 A, a 0.5 s pulse would be demanded, whilst for a 1 mm thick material, the pulse time would be reduced to 0.1 s at the same current level. The background parameters are considerably less critical in the pulsing operation. The background level is normally set at approximately 15 A

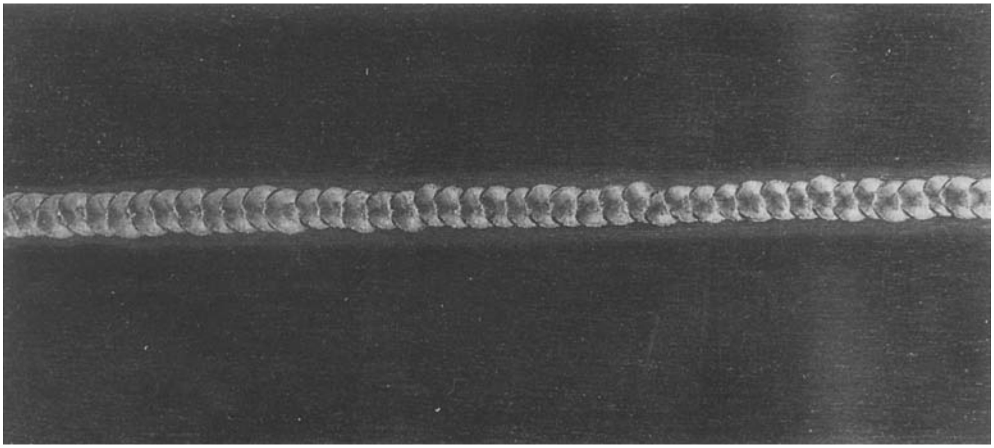


Figure 10.42 Photograph of a pulsed TIG weld

which provides the greatest possible heat dissipation during this period, whilst being high enough to maintain a stable arc. The background period is normally equal to the pulse period, but may be some two to three times greater when welding thicker sections.

The nomograph is presented only as a guideline for the initial selection of welding parameters and must be treated with caution, particularly when welding at the extremes of the thickness range, i.e. sections of > 0.3 mm and < 1.0 mm. In both instances, the preferred pulse current level will be outside the above theoretical operating ranges. For example, in the welding of stainless steel, practical trials have established that for a thickness of 4 mm the preferred pulse parameters are 200 A and 0.75 s, whilst for 0.5 mm thick material the preferred pulse parameters are 50 A and 0.1 s (*Figure 10.43*(*b*)).

Welding thick sections at too low a pulsed current can result in the loss of most of the advantages of pulsing, controlled depth of penetration and tolerance to variation in heat sink, as the weld pool takes a long time to penetrate the material and thermal diffusion occurs ahead of the fusion front. In welding thinner sections with too high a pulsed current, the excessive arc forces may cause cutting and splashing of the weld pool, resulting in a poor bead profile and electrode contamination.

The capacity to use lower pulsed currents and longer pulse time (see *Figure 10.43*(*b*)) is also of particular importance when using power sources which have a limited response, a low rate of rise and fall of the current between the background and the pulsed current levels. For instance, power sources in which the current is controlled by a magnetic amplifier are generally limited to pulses of 0.2 s duration, whilst in thyristor controlled types the response is markedly improved and pulses as short as 0.03 s can be generated. However, for complete flexibility, transistor controlled or inverter power sources are used which can generate pulses within an almost unlimited frequency range up to 10 kHz. An added advantage of these power sources is the capacity to reproduce accurately complex pulse waveshapes which can be of benefit in controlling the weld pool and solidification structure.

10.1.7 Plasma welding

10.1.7.1 Principles of operation

In plasma welding, the arc is formed between a non-consumable tungsten electrode and the workpiece as in TIG welding. However, the electrode is positioned within the body of the torch and the plasma forming gas is separated from the shielding gas (*Figure 10.44*). Thus, the emanating plasma is constricted by a fine bore copper nozzle which produces a columnar, deeply penetrating arc, compared to the more conical TIG arc.

The penetration capacity of the arc is determined by the degree of constriction of the plasma (diameter of the bore of the nozzle) and the plasma gas flow rate. The electrode angle has no effect on penetration and is usually maintained at 30°. However, as in TIG welding, the gas composition has a secondary influence on penetration. In this instance hydrogen, which increases the temperature of the arc (as shown by the increase in arc voltage), is particularly effective. Helium is also used to increase the temperature of the plasma but, because of its lower mass, penetration can decrease in certain operating modes.

The properties of the constricted plasma with variable arc force, which results from varying the plasma gas flow rate, have led to three distinct welding process variants:

(1) microplasma welding, 0.1–1.5 A;
(2) medium current plasma welding, 15–100 A; and
(3) 'keyhole' plasma welding, >100 A.

10.1.7.2 Microplasma

Microplasma welding has been so termed because a very stable arc can be maintained, even at welding current as low as 0.1 A. It is possible to vary the arc length over a comparatively wide range, up to 20 mm, without adversely affecting arc stability and because of the columnar nature of the plasma, without causing excessive spreading of the arc. With TIG welding, the arc is more sensitive to variation in torch distance, both with regard to stability and to spreading of the arc, due to its conical shape.

10.1.7.3 Medium current

At higher currents, that is up to 100 A, the plasma arc is similar to the TIG arc, although it is slightly 'stiffer' and more tolerant to variation in arc length. The plasma gas flow rate can also be increased to give a slightly deeper penetrating weld pool, but with high flow rates there is a risk of shielding gas and air entrapment in the weld pool

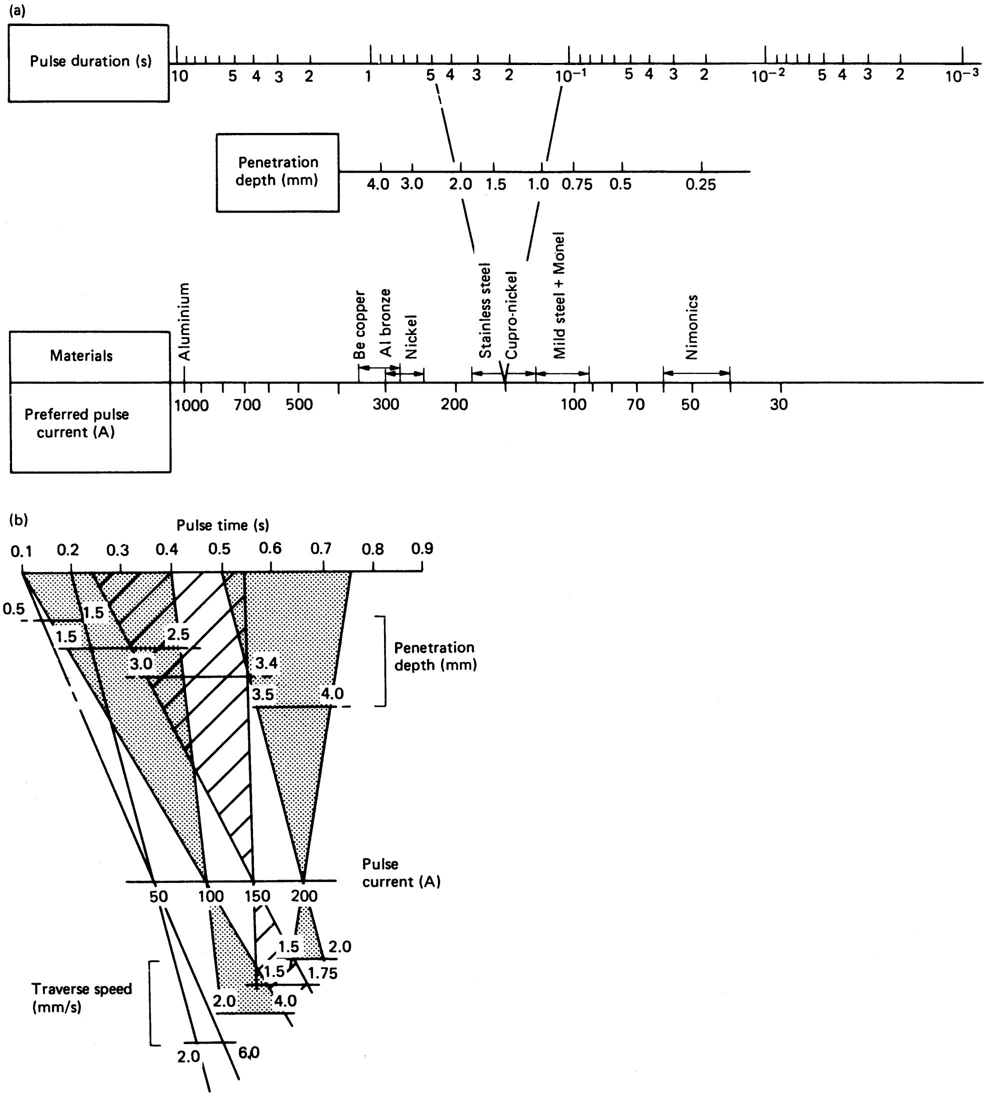


Figure 10.43 Nomographs as an aid to the selection of pulse parameters in pulsed TIG welding. (a) Theoretical pulse parameters according to material type; pulse duration determined by thicknes of material. (b) Selection of pulse parameters in 304 stainless steel based on practical welding trials. Note that the pulse current level is selected according to the material-thickness range

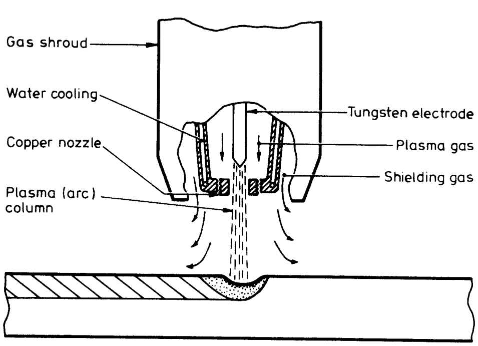


Figure 10.44 The plasma process showing constriction of the arc by a copper nozzle

through excessive turbulence in the gas shield and agitation of the weld pool.

10.1.7.4 Keyhole

The most significant difference between the no and plasma welding arcs lies in the keyhole technique. A combination of high welding current and plasma gas flow rates forces the plasma jet to penetrate completely the material, forming a hole as in laser or electron beam welding (*Figure 10.45*). During welding, this hole progressively cuts through the metal with the molten metal flowing behind to form the weld bead under surface-tension forces. The deeply penetrating plasma is capable of welding, in a single pass, relatively thick sections up to approximately 10 mm. However, despite the tolerance of the plasma process to variation in

Figure 10.45 Formation of the keyhole and efflux plasma in plasma keyhole welding of 5.0 mm stainless steel. The efflux plasma is inclined backwards as the arc cuts through the plate

torch-to-workpiece distance, this technique is more suitable to mechanised welding, as the welding parameters, i.e. welding current, plasma gas flow rate and welding speed, must be carefully balanced to maintain the stability of the keyhole and the weld pool. Instabilities can easily result in the loss of the keyhole, giving only partial penetration of the weld bead and increasing the risk of porosity.

10.1.7.5 A.c. arc

Sine wave a.c. The plasma arc is not readily stabilised with sine wave a.c. for two reasons: arc re-ignition is difficult when operating with a constricted plasma, and a long arc length and the progressive balling of the electrode tip (during the electrode positive half-cycle) severely disturbs arc root stability. Thus, plasma welding of aluminium is not widely practised, although successful welding has been reported using d.c. (negative polarity) and helium shielding gas.

Square wave a.c. The recent advent of the square wave power supplies described in Section 10.1.6.3 has made it possible to stabilise the a.c. plasma arc without the need for continuously applied high frequency for arc re-ignition. In addition, by operating with only 30% electrode-positive, the electrode is kept so cool that a pointed electrode tip, and hence arc stability, can be sustained. It is particularly important, however, that to limit electrode/nozzle erosion, the maximum current is reduced to less than that which can be operated with a d.c. plasma arc. For example, using 30% electrode-positive, the current rating of a 4.8 mm diameter tungsten electrode with a 40° tip angle would be reduced from 175 A (d.c.) to approximately 100 A (a.c.). Furthermore, any increase in the proportion of electrode positive polarity, so as to improve arc cleaning, would significantly reduce the maximum operating current.

Despite the reduction in the maximum current at which the various electrode sizes can operate, stabilisation of the a.c. arc represents a significant advance in plasma welding. Until now, in the welding of aluminium, no advantage could be taken of the deep penetration capability of the plasma arc—because of the need to use a blunt electrode, the alternative a.c. TIG process produces shallow penetration.

10.1.7.6 Electrode and nozzle

The electrode in the plasma system is normally tungsten–2% thoria. Typical electrode diameters, vertex angles and plasma nozzle bore diameters for the various current ranges are given in *Table 10.3*. At low and medium currents, the electrode is sharpened to a point whilst at high currents, it is blunted to approximately 1 mm diameter tip.

The plasma nozzle bore diameter, in particular, must be selected carefully and it is prudent to employ a nozzle the current rating of which is well in excess of the operating current level. The plasma gas flow rate can also have a pronounced effect on the nozzle life with too low a flow rate possibly leading to excessive erosion. Multi-port nozzles, which contain two additional small orifices on each side of the main orifice, can be used at high current to improve control of the arc shape. Use of an oval or elongated plasma arc has been found to be beneficial in high current welding, particularly when operating in the keyhole mode.

10.1.7.7 Plasma and shielding gas

Argon is the preferred plasma gas as it gives the lowest rate of electrode and nozzle erosion. Helium can be used for

Table 10.3 Maximum current for plasma welding for selected electrode diameter, vertex angle and nozzle bore diameter. (Levels are for guidance only, it is important to refer to manufacturer's recommended operating conditions for specific torch and plasma nozzle designs)

Maximum current (A)						*Plasma**		*Shielding*†⇐	
Torch rating (A)				*Electrode diameter* (mm)	*Vertex angle* (°)	*Nozzle bore diameter* (mm)	*Flow rate* (1/min)	*Shroud diameter* (mm)	*Flow rate* (1/min)
20	*100*	*200*	*400*						
Microplasma									
5				1.0	15	0.8	0.2	8	4–7
10						0.8	0.3		
20						1.0	0.5		
Medium current									
	30			2.4	30	0.79	0.47	12	4–7
	50					1.17	0.71		
	75					1.57	0.94		
	100					2.06	1.18		
		50		4.8	30	1.17	0.71	17	4–12
		100				1.57	0.94		
		160				2.36	1.42		
		200				3.20	1.65		
			180	3.2	60‡⇐	2.82	2.4	18	20–35
			200			2.82§	2.5		
High current									
			250	4.8	60‡⇐	3.45§	3.0		20–35
			300			3.45§	3.5		
			350			3.96§	4.1		

* Argon plasma gas.
† Argon and argon–5% H_2 shielding gas.
‡ Electrode tip blunted to 1 mm diameter.
§ Multi-port nozzle.

medium and high current operations to increase the temperature of the plasma which, in the melt (non-keyhole) mode, will often promote higher welding speeds. However, the use of helium as the plasma gas can reduce the current-carrying capacity of the nozzle. Furthermore, because of its lower mass, weld-pool penetration will be reduced which, in certain materials, will make the formation of a keyhole difficult. For this reason, helium is seldom used for the plasma gas when operating with the keyhole mode. Hydrogen is often added to the shielding gas, argon plus 2.5%H_2 being the most common mixture, but up to a maximum of 15%H_2 can be used to produce a hotter arc and a more reducing atmosphere. Hydrogen also constricts the arc, which can increase the depth of the weld pool penetration and promote higher welding speeds.

Helium or a helium–argon mixture, typically 75% helium–25% argon, can also be used as the shielding gas. Whilst a hotter arc will be generated, it is less constricted, which can result in a wider weld bead compared with argon or argon–hydrogen shielding.

10.1.7.8 *Pulsed current*

Similar benefits of improved arc stability and better control over the behaviour of the weld pool can be derived from pulsing the welding current. However, pulsing has special advantages for improving the keyhole mode of operation which, with continuous current, requires careful setting of the welding parameters.

The same principle applies in that a high current pulse causes rapid penetration of the material and establishes a stable keyhole and weld pool. If this high current were maintained, the keyhole would continue to grow, causing excessive penetration and, ultimately, cutting would occur. Therefore, the pulse is terminated after a pre-set time and the weld pool allowed to solidify under a low background or pilot arc. It is equally important that the plasma gas flow be maintained during this period so that the keyhole does not close and, on re-applying the pulse current, the plasma can quickly penetrate the plate, re-establishing a stable keyhole and weld pool. Thus, welding progresses in a series of discrete steps with the pulse frequency balanced to the traverse rate to produce overlapping weld spots (see *Figure 10.46*). In pulsing, the important variables are:

Welding current	*Plasma gas*
Pulse time	Pulse level
Pulse level	Background level
Background time	
Background level	

Selection of welding parameters can be simplified, first with the knowledge that the pulse time is determined more by the physical requirements of forming the keyhole and weld pool at a given traverse rate, than by the plate thickness or material composition. For most materials, within a plate thickness of 3–5 mm, a minimum pulse time of 0.1 s is required to re-establish the keyhole and weld pool. At longer pulse times, the excess energy is largely dissipated in the efflux plasma. The background time is usually set equal

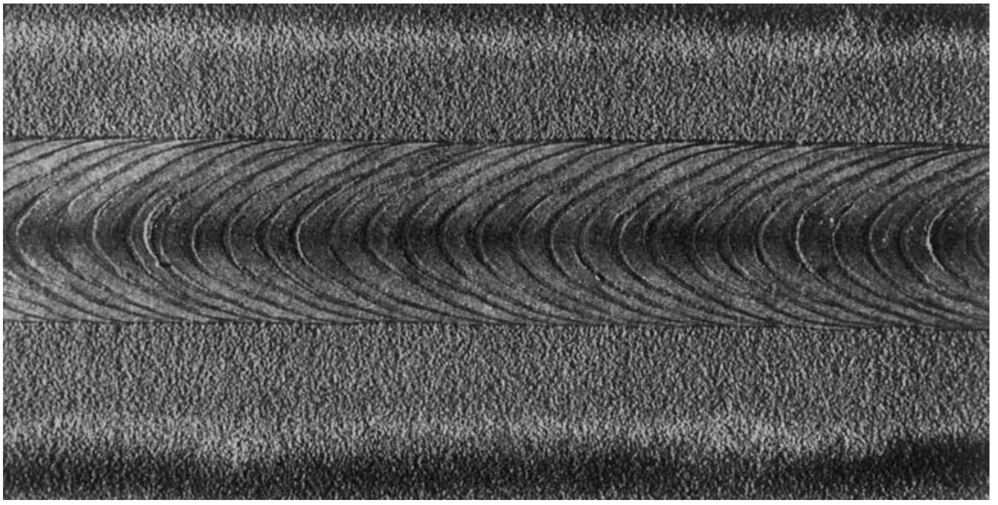


Figure 10.46 Appearance of the pulsed (keyhole) plasma arc weld

to the pulse time, which is sufficient for solidification between pulses. Thus, the pulse frequency is determined by the welding speed and the need for at least 60% overlap of the pulses to provide a continuous seam. For instance, when welding 4.4 mm stainless steel at a speed of 0.15 m/min, a suitable frequency is 2 Hz.

It follows that the pulsed current level and plasma gas flow rate are the major welding parameters which must be set to give an over penetrating plasma for a particular material composition and plate thickness combination. The background current is held low to give rapid cooling between pulses, while the plasma flow rate is held constant to maintain the keyhole. For instance, when welding 4.4 mm austenitic stainless steel, the pulsed current and plasma gas flow rate are typically 140 A and 2 l/min, respectively. However, when welding the same steel in 5.0 mm thickness, the pulsed current and plasma gas flow rate are increased to 190 A and 2.3 l/min and all other parameters are held constant.

10.1.8 Electroslag and electrogas welding

10.1.8.1 Principles of operation

Electroslag welding, originally developed for the welding of thick mild and low-alloy steels, is restricted to welding in the vertical or near-vertical position. *Figure 10.47* shows the basic arrangement.

Once established, the electroslag process is basically arcless, the heat required to melt the wire and fuse the parent material being supplied by resistive heating of the molten slag bath. To ensure uniform fusion of the joint faces, it is necessary with thick material either to use more than one electrode or to oscillate the electrode(s) across the joint. As the weld progresses, the level of the weld pool rises and the welding head and water-cooled shoes are moved slowly up the joint. A typical speed for electroslag welding of 76 mm thick mild steel would be 1 m/h at 550 A and 44 V. Since the process is only stable once a slag of appropriate depth has been established, it is essential that a run-on plate is provided so that the defective start position of the weld can be removed on completion of the joint.

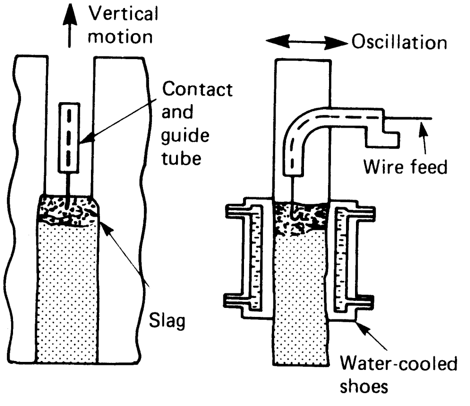


Figure 10.47 Electroslag process

As the electroslag process is virtually a continuous casting process, the resulting welds have large grain size and a tendency towards columnar growth. Because of this, the weld metal and heat-affected zone generally have extremely poor (mechanical) properties. While this can be mitigated by a post-weld, normalising heat treatment, such treatment may cancel out the economic advantages that the process otherwise offers.

Although electroslag welding is mainly used for the joining of mild and low-alloy steels, satisfactory welds have been made in high-alloy steels, titanium and aluminium.

10.1.8.2 Consumable-guide welding

Consumable-guide welding is a much simplified version of electroslag welding. This simplification stems mainly from the use of a wire guide which is progressively melted into the weld. The consumable guide (or guides) eliminates the need for a moving welding head and also results in faster welding speeds. The two moving water-cooled copper shoes used for electroslag welding are generally replaced by two pairs of shoes which are leap-frogged up each side of the joint as welding progresses.

10.1.8.3 Electrogas welding

Electrogas welding is very similar in principle to electroslag welding in that it is used for welding thick section material in a single pass and in the vertical position. The main difference being that the heat for welding is generated by an arc which is formed between a flux-cored electrode and the molten weld pool. The flux from the electrode forms a protective layer over the weld pool, but additional protection in the form of a gaseous shield (usually CO_2) is used. The electrogas process is generally faster than electroslag welding when used on relatively thin sections. The resulting weld metallurgy is similar to a high-current submerged-arc weld.

10.1.9 Metal cutting and gouging

Metal can be removed from workpieces by use of coated electrode, plasma-arc and carbon arc processes.

10.1.9.1 Coated-electrode process

Flux-coated electrodes are available in two types. The first has a specially formulated coating that gives a deeply penetrating and forceful arc, tending to create a weld pool and to blow out the molten metal: a hole or recess is left, which can be carried along the material. When thick material is being cut, a sawing action is employed. The second type of electrode is a hollow electrode through which a high-pressure stream of oxygen is passed. The cutting action is akin to that with oxyacetylene.

Electrode techniques are, in the main, limited to ferrous materials.

10.1.9.2 Plasma-arc process

The plasma-arc process can give neat and accurate cutting. The principles are basically the same as in plasma-arc welding, but the force of the plasma column is increased by higher gas flow through the nozzle and a higher power output. Virtually any conducting material can be cut, at speeds faster than those of other methods, e.g. 8 m/min for 6 mm thick aluminium.

The most common gases are argon–H_2, nitrogen, oxygen and air. The use of air has increased in recent years especially for cutting thin sheet steel, e.g. automotive and 'do-it-yourself' users. The torch which is suitable for air and oxygen employs a water-cooled, copper–hafnium tipped electrode.

The power source is similar to the ones used for plasma welding, but the output (cutting) voltage can be as high as 200 V. Safety precautions in the use of these power sources are essential (see appropriate standards e.g. IEC 60974-8)

10.1.9.3 Carbon arc process

In this process an arc between a carbon electrode and the workpiece is used to create a molten pool of metal which is blown away by a jet of compressed air. The method is useful for all grades of ferritic steels.

10.2 Resistance welding

Resistance welding processes involve the welding of two or more metal parts together in a localised area by the application of heat and pressure. The heat is generated by the resistance to the passage of a high current through the metal parts held under a preset pressure. Copper or copper alloy electrodes are normally used to apply pressure and convey the electrical current through the workpieces. In the case of spot and seam welding, the electrodes or wheels are shaped to concentrate the force and current. In projection welding and butt welding the shape of the components dictates the weld area. No consumable materials such as welding wire, fluxes or gases are required.

The heat generated depends on the current (I), the time of application (t) and the resistance (R) and is proportional to I^2Rt. The heat generated is governed largely by the bulk resistance of the materials being joined and the interface resistance at the contact between the materials. In some cases, a fused zone is produced, as in the spot or seam welding of sheet materials. However, in many cases of projection welding, and particularly resistance butt and flash welding, a forge weld is produced without melting. The plastic deformation of the heated parts in contact produces a bond in the solid state analogous to the blacksmith's weld.

Resistance welding can be used to join a wide range of materials and the ease of welding depends on the metallurgical compatibility of the materials and their electrical resistivity. Mild steel is readily weldable, having a resistivity some six times that of the copper alloy electrode. Surfaces should be free from rust, scale, dirt and other materials likely to hinder current flow but light oils or lubricants do not normally interfere with the welding. Aluminium alloys, with their higher conductivity, require up to three times the current required for steel to develop the heat for welding. In addition, the surface resistance of aluminium alloys is strongly influenced by the oxide film and this needs to be closely controlled for high quality welds. Anodised or heavily passivated surfaces can be insulating and therefore impossible to weld.

10.2.1 Welding equipment

Figure 10.48 shows the essential features of a spot welding machine. The three basic units are a structural frame, a force application system and the electrical system. The frame provides strength and rigidity to react the electrode force without undue flexure of the machine. The electrical circuit on the low voltage secondary side of the transformer may constitute part of the frame or, in the case of the welding gun, provide most of the structural strength. The force application system is normally pneumatic. Regulated air pressure is fed to a cylinder to provide the electrode force. Servomotors are increasingly being used to provide programmable control of electrode position, approach speed and force. Hydraulic systems are used occasionally for compact, high force applications, and springs are used for very small hand or foot operated machines. The electrical system comprises a welding transformer and a timer/controller unit.

10.2.1.1 Machine types

Pedestal or bench mounted machines are fixed types and the workpieces are fed into the machines manually or mechanically using a carousel or pick and place device. Gun welders are used for welding fixed, often larger structures and the gun is manipulated either manually, being suspended from a counterbalance system, or using a robot. The transformer may either be remote from the gun, connected by a heavy water cooled kickless cable, or integral with the gun itself. In the latter case, the transformer can be of a substantially smaller size because of the reduced secondary impedance, and current is supplied at mains voltage through smaller

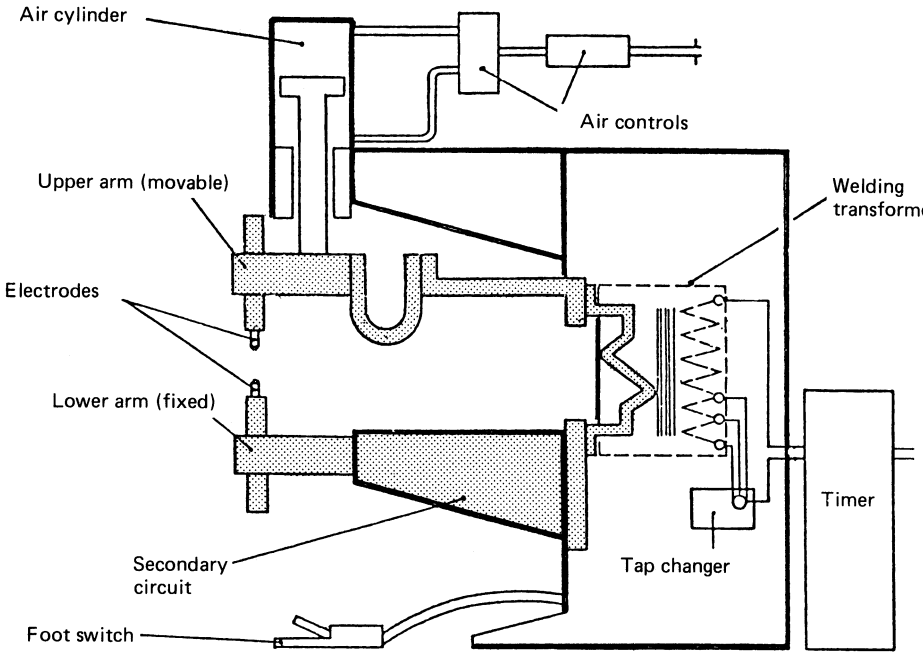


Figure 10.48 A pedestal spot welding machine

cables. This allows the gun to be more manoeuvrable despite its greater weight, often in the region of 60 to 100 kg. Modern residual current circuit breakers provide the necessary safety protection for manual operation of integral transformer guns.

Multiwelders can be used to weld components in a dedicated machine where each spot is welded with a separate pair of electrodes. One electrode is operated with its own cylinder and the opposing electrode is fixed. A frame provides the structural support and reacts the electrode force. A number of transformers may be used, each usually serving two or more electrode pairs from a two turn secondary with separate outputs. If more than one electrode pair is supplied from one transformer connection, the machine is sequenced so that only one weld is made at a time, the other electrodes remaining open. In order also to prevent too high a mains current demand from simultaneous firing of the transformers, the weld times are sequenced or cascaded. Where two electrode pairs are connected to one transformer, it is important that the circuits are similar so that the impedance, and thus the current drawn, is the same in each circuit.

10.2.1.2 Resistance welding power supplies

The most common power supply comprises a single-phase a.c. transformer, see *Figure 10.49*. This converts the mains supply primary voltage to a low (2–20 V) secondary welding voltage. The turns ratio of the transformer is the number of turns of the primary conductor, divided by the number of turns of the heavy secondary conductor (usually 1 or 2). This is the ratio by which the voltage is reduced and the mains current magnified. The open circuit secondary voltage may be considered nominally constant, so the current drawn on the welding circuit depends on the circuit impedance according to Ohm's law. This circuit is virtually a dead short with a resistance in the region of $10^{-3}\,\Omega$. Thus, several thousand amperes of welding current can be developed at the low secondary voltage.

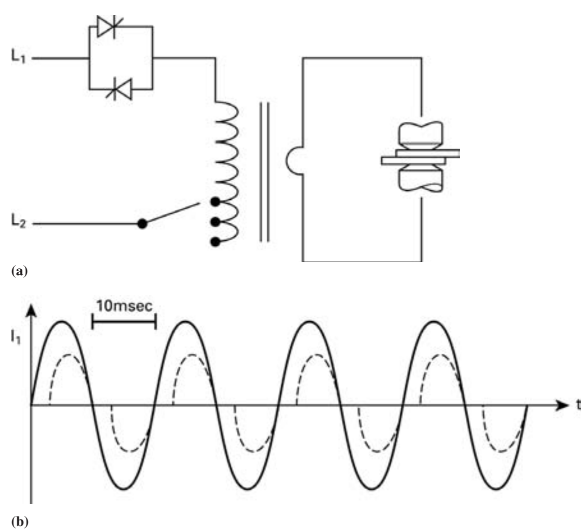


Figure 10.49 Single-phase a.c. power supply. (a) Welding circuit; (b) Current waveform, broken line illustrates phase shift control of current level

The power capacity of a machine is normally quoted in kVA at 50% duty cycle. This refers to the power that may be drawn by the transformer over a long period of time, with current flowing for 50% of that time, without causing the transformer to overheat.

The maximum allowed current on the primary side of the transformer at 50% duty cycle is then the kVA rating divided by the mains voltage. In practice, much higher primary current levels can be drawn by resistance welding machines for short times, and this is acceptable, provided account is taken of the actual duty cycle (current on time/ total time) expressed as a percentage.

The allowable power at duty cycle $x\%$ may be calculated as follows:

$$\mathrm{kVA}_{x\%} = \mathrm{kVA}_{50\%}\sqrt{\frac{50}{x}}$$

The single-phase a.c. transformers are of the shell/core type of a compact design and the insulation is cured to provide a robust unit capable of the mechanical and electrical loading typical of resistance welding equipment. Water cooling may be provided on the low voltage secondary conductors, thus improving its thermal rating. A number of standards cover the specific requirements of transformers such as ISO5826 (BS7125) and BS EN ISO 7284. Many transformers have tap switches so that the secondary voltage can be changed to provide step changes in the welding current range. Fine control of current is by phase shift control using the timer/ controller.

It is the available welding current rather than kVA rating that determines the suitability of a machine to weld a particular component. While the maximum short circuit current may be known for a particular machine, the welding current available will be much lower. This is because of the added resistance of the component being welded and the associated electrode or tooling. The secondary circuit impedance is also influenced by an inductive component, which is related to the area within the machine throat. Current is reduced if this area is increased, and even more so if there is steel within the throat. Thus, the arm spacing and routing of jumpers or flexible connections is important in order to minimise the losses.

A number of alternative power supply types are available, as follows:

Secondary rectified d.c. This type is used for high power applications as it uses a balanced three-phase supply and the rectified d.c. welding current is not subject to the inductive power losses suffered by a.c. current, see *Figure 10.50*. Single-phase d.c. machines are available but are much less common.

Frequency converter d.c. Primary rectification of a three-phase supply avoids the need to rectify high welding currents. A short duration d.c. pulse (less than 0.2 sec) is then delivered to the welding transformer. The d.c. polarity is changed for each pulse to avoid transformer saturation. This type of equipment has been widely used for high power applications, such as high quality welding of aluminium alloys.

Inverter welders Medium frequency inverter welders are used to enable more efficient, lighter weight welding transformers to be used, typically for robot guns. A three-phase supply is first rectified then chopped with a transistor unit to give medium frequency, typically up to 1000 Hz ac. This a.c. at about 600 V is then converted in the welding transformer to low voltage/high current at the same frequency. This is immediately rectified to give a d.c. welding current. These supplies are finding increasing use in robotic spot welding in the automotive industry and also for miniature applications, where fine control of the current pulse shape can be achieved.

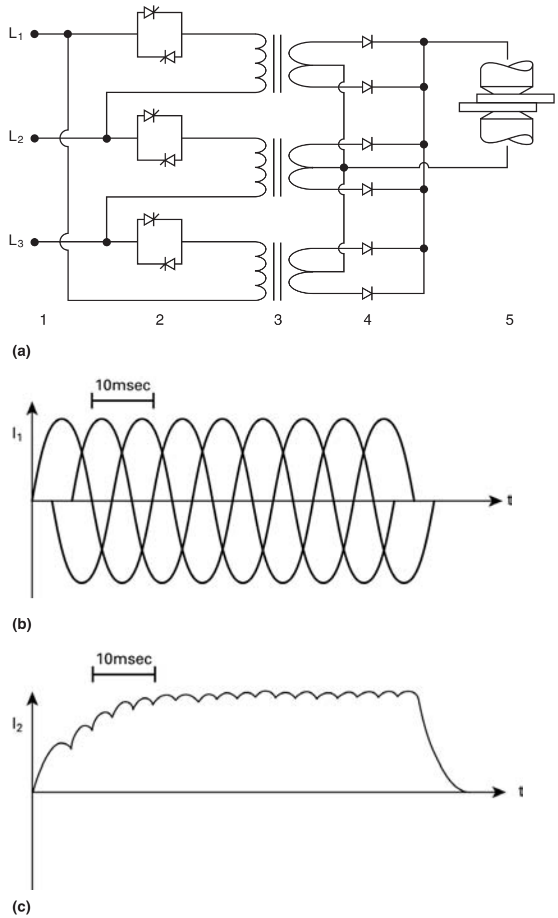


Figure 10.50 Three-phase secondary rectified d.c. power supply (a) Welding circuit. 1—mains supply, 2—thyristor current control, 3—welding transformer, 4—secondary rectification, 5—welding electrodes (b) Primary current waveform. (c) Welding current waveform.

Capacitor discharge A short duration d.c. pulse, typically less than 10 msec, is achieved by discharging a bank of capacitors through a welding transformer. A low power demand is required to charge the transformers. Such equipment is common for miniature applications, but large machines are available for large projection welding operations. These are often portal machines and have high force capacity with a fast follow-up, low inertia head. The heat input is relatively low compared to a.c. or d.c. power supplies.

Transistorised power supplies These are generally small to miniature supplies, up to about 5 kA. The current is pure d.c. and the pulse can be shaped accurately for fine control of the resistance heating of difficult material combinations or configurations, particularly in electrical and electronic applications.

In some cases, especially miniature applications in dissimilar materials, d.c. current is used and its polarity may be used to advantage in modifying the heat balance within a weld. The heating may be biased towards one electrode due to the Peltier effect.

10.2.1.3 Mains supply

When connecting resistance welding equipment to the mains supply, a number of factors need to be considered. As the primary current demand is high, the high voltage transformer (e.g. 11 kV) supplying the system should be of sufficient capacity that there is not an undue voltage drop on the mains voltage side. Cables connecting the machines do not necessarily need to be rated at the maximum continuous thermal rating for the size of machine being connected, as the duty cycle of the machine is usually low (except for seam welding). Account should be taken of the maximum anticipated duty cycle and any relevant local regulations. It is also important to consider the voltage drop associated with the supply cables, according to their size, length and the current demand. A reduction in supply voltage at the welding machine will reduce its capacity proportionally. The cable layout should also be so organised as to minimise reactive losses. Resistance welding equipment, particularly a.c. types have a reactive load and consequently a relatively low power factor. Occasionally, capacitive power factor correction equipment is used in the plant to reduce the voltage/current phase difference.

10.2.1.4 Resistance welding electrodes

Resistance welding electrodes play an important part in the achievement of good and consistent weld quality. The materials used are normally copper alloys, internally water-cooled, which provide a combination of high electrical and thermal conductivity, together with mechanical strength. This is required to withstand the electrode forces and a certain amount of hammering of the electrodes on initial contact. The dimensions of spot welding electrodes are covered by various ISO standards.

Electrode materials for resistance welding are covered by ISO 5182. The highest conductivity class 1 alloys, such as Cu/0.1%Zr, are used for spot welding coated steels and aluminium alloys. Harder, class 2 alloys with a conductivity of 75 to 80% IACS (International Annealed Copper Standard), such as Cu/1%Cr, are used for steels in general. Class 3 alloys, with 30 to 45% IACS, provide additional hardness for spot welding stainless steels and for projection welding dies, although tungsten/30%Cu inserts are also often used in projection welding. Refractory metals such as molybdenum or tungsten are also used for certain applications.

The diameter of the electrode contact face for spot welding should approximate to $5\sqrt{t}$, where t is the single sheet thickness in millimetres (up to 3 mm). This allows a weld of a similar diameter to be produced. In order to maintain weld quality, the electrode contact area and profile should be maintained by periodic electrode dressing or replacement by re-machined electrodes. An electrode dressing tool or form tool should be used where possible for greatest reliability. Automatic dressing equipment can be used in robotic applications. Typically, a few hundred spots for aluminium alloys, a few thousand for coated steels and several thousand for uncoated steels, are possible before electrode maintenance is required.

10.2.2 Welding process

10.2.2.1 Welding sequence control

In order to achieve the highest quality and repeatability in resistance welding, the control of welding current and its duration must be accurate. Modern electronic timers provide two functions: (a) the synchronous timing of the weld sequence and current pulse, measured in cycles of mains frequency, and (b) control of the current level by phase shift control. Furthermore, on air-or hydraulic-operated equipment, the timer controls a solenoid valve and the welding sequence is interlocked once initiated. This takes the control of the machine out of the hands of the operator and prevents the electrode force being released until the end of the hold time. The basic welding sequence shown in *Figure 10.51* comprises the 'squeeze time', during which the electrode force rises to its preset level, the 'weld time' during which current flows and the weld is formed and the 'hold time during which the weld is allowed to cool under pressure. The electrodes are then released. When spot welding 1 mm low carbon steel, the weld time would be about 0.2 sec, the welding current about 7 kA and the whole sequence less than 1 sec. More complex sequences can be used for special applications, and features include multiple current pulses, slope up of current and variation of force during the weld.

Solid state switches (thyristors) are used to control the flow of primary current to the transformer, the timer can be set to deliver the required duration of current, i.e. the number of cycles at 50 Hz mains frequency. The magnitude of the current can be adjusted finely by altering a heat or phase shift control. This changes the point at which the thyristors switch on during each half-cycle. The solid-state timers allow precise setting of time and current and often have constant-current control. This is based on feedback of the actual current measurement using a toroidal coil to adjust the phase shift (heat) control during the weld pulse. This compensates for mains voltage fluctuations and variation in secondary circuit impedance. Many also have programmable control to enable automatic equipment to select preset welding programmes, where one machine is required to weld a variety of thickness combinations, for example. Additional functions include diagnostics, fault detection and stepper functions, which allow welding current to be increased progressively to compensate for gradual electrode wear.

Prior to the introduction of modern controllers, weld timing developed from relatively crude control. Early machines that worked on a mechanical lever system incorporated the contactor for primary current within the lever system. Thus, the time of the weld was left to the judgement of the operator. This, however, led to unsuitable and unreliable welding conditions being used. By introducing simple timers and an electrically operated contactor, the duration of current flow was more reliable. Mechanical contactors were superseded by mercury vapour switches (ignitrons), which have now been replaced by thyristors.

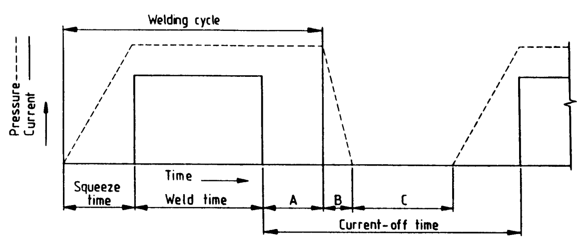


Figure 10.51 Timing sequence for spot, stitch and projection welding. A—hold time (forging time); B—pressure decay time (not critical); C—pressure off time

10.2.2.2 Welding parameters

The main welding parameters are electrode force, weld time and current. Recommended settings are available in the literature for many standard materials and applications, and guidelines are presented for spot welding uncoated and coated low carbon steels in BS 1140.

The electrode force required for spot welding low carbon steel is typically 1.5 to 2 kN per mm of its sheet thickness and is slightly higher for coated steels. The force required for stronger and high hot-strength materials such as stainless steel or nickel alloys may be 2 to 4 times this level.

Weld times for low carbon steels are normally about 7 to 10 cycles per mm of the single sheet thickness in the range 0.4 to 3 mm. The shorter times should be used in conjunction with the higher forces. Higher welding current is required at shorter weld times. However, it is not possible to compensate for insufficient current by excessively long weld times.

Welding current is adjusted to achieve a weld of the required size once other parameters are fixed. The current needed depends on the material type, the size of the electrode tip used and the other parameters set. Typically 7 to 10 kA is required for 1 mm and 15 to 20 kA for 3 mm uncoated steel. Higher current is required for coated steels because of the lower interface resistance.

It is important that welding current flows only through the electrode contacts and is not shorted through other parts of the tooling or components. Current can be lost through adjacent welds (current shunting). The degree of shunting depends on the material thickness and weld spacing. Welding current must be increased to compensate for close pitch welds (e.g. less than 3 times the tip diameter for thin sheet). Steel in the throat of the machine also causes a reduction in current on a.c. machines because of the increased inductive effect. Automatic compensation is possible in this case by using a constant current controller.

10.2.2.3 Weld quality and testing

The principal quality requirement of spot welds in sheet materials is weld size, and this is indicated by a destructive peel or chisel test to tear a plug or button from one of the sheets. The minimum acceptable weld diameter depends on the application standard but is typically $3.5\sqrt{t}$ or $4\sqrt{t}$ for sheet thicknesses up to 3 mm. A plug failure should normally occur and an interface failure may indicate the weld is weak due to lack of fusion or embrittlement.

Surface defects such as splash metal, cracks and excessive deformation are normally unacceptable, but metallographic examination of internal defects is usually only necessary for aircraft quality work.

For projection or butt welded joint configurations, testing in tension, shear, bend or torsion can be conducted to suit the component and service requirements.

Quality control in resistance welding is generally by process control and periodic destructive testing. Monitoring or routine checking of current, weld time and force can be done to ensure consistency of the main process parameters. A range of commercial in-process weld quality monitors and feedback controllers are also available that examine additional parameters such as weld resistance, weld energy or weld expansion. In order to exploit such monitors, the process must first be under control. A positive correlation between monitor output and quality must be demonstrated, and the monitor should be properly set up and maintained. Confidence in such monitors is easily lost if these criteria are not met.

Post-weld non-destructive testing of resistance welds is limited. Ultrasonic testing of spot welds requires a special-purpose high-frequency probe, incorporating a water column retained by a plastic membrane bubble, which is applied to the spot weld indentation. Skill and extensive training are required to interpret the multiple reflections on the flaw detector, but substantial reduction of destructive tests has been achieved by automotive manufacturers in particular.

10.2.2.4 Twin-spot welding

There are a number of cases where it is convenient to use twin-spot welding. These include welding components where access is limited to one side or where components are to be welded to large sheets. It is often possible to use a twin-spot method of operation where both electrodes are on one side of the material, the current being taken through a copper backing bar or plate below the bottom sheet (*Figure 10.52*(*a*)). If the lower sheet is significantly thicker than the upper sheet, the copper backing plate may be replaced by an insulated support to react to the load, or eliminated completely where a closed section is being welded.

An alternative technique, referred to as 'push–pull', involves initiating separate transformers simultaneously each side of the component, feeding two pairs of electrodes (*Figure 10.52*(*b*)). Series and push–pull welding allow small,

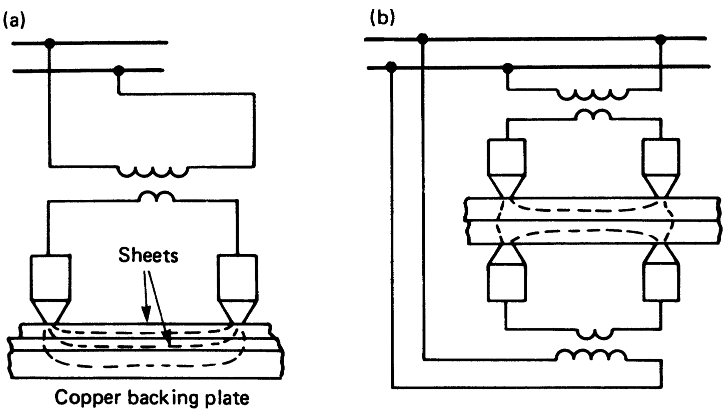


Figure 10.52 Twin-spot welding: (a) series weld; (b) push–pull weld

low inductive loss secondary circuits to be used, and minimise the amount of steel within the throat of the machine. This is an advantage on large components as smaller capacity equipment can be used.

10.2.3 Projection welding

In projection welding, the size and position of the weld or welds are determined by the design of the component to be welded. The force and current are concentrated in a small contact area between the components to be welded. This occurs naturally in cross wire welding, or is deliberately introduced by machining or forming. An embossed dimple is used for sheet joining and a V projection or angle can be machined on a solid component to achieve an initial line contact with the component to which it is to be welded. Nuts and studs are also widely projection welded. *Figure 10.53* shows some typical configurations.

Some of the advantages of projection welding are:

- Output is increased because a number of welds can be made simultaneously.
- Electrode life is extended because electrodes with large contacting surfaces may be used and these may have harder, sintered copper/tungsten inserts.
- The process is versatile, allowing a wide range of component designs to be resistance welded.
- Welds may be more closely spaced than practicable with spot welding without compensation for current shunting, and
- Minimum surface marking can be achieved on one side of the joints.

Consistency of projection height and shape, together with good electrode alignment and flatness are essential to ensure uniform share of the available force and current. Welding times are short, to ensure that sufficient heat is generated in the small contact area before the projection collapses completely. Rapid follow-up of the welding head ensures that the weld is consolidated as the projection collapses.

Projection welding machines operate on principles similar to those of spot welding plant, but are designed for much higher electrode force and current because it is usually required that several projections be welded simultaneously. Very large projection welding machines are available which can apply a total electrode force of several tonnes and deliver a welding current of over 500 kA. The larger machines are generally three-phase d.c., which gives a balanced mains demand and permits more even current distribution owing to a minimal inductive effect. Large capacitor discharge machines with low inertia heads have also been used for projection welding applications. The weld time of only several msec duration results in a weld with low residual heat input. Although the welding current is much higher than for normal a.c. supplies, the mains current demand is low during the few seconds charging stage.

10.2.4 Seam welding

Seam welding (*Figure 10.54*) consists of making a series of overlapping spot welds by means of copper alloy wheel electrodes to produce a leak-tight joint. The electrode wheel applies a constant force to the workpieces and rotates continuously at a controlled speed. The welding current is either pulsed to give a series of discrete spots, or continuous for certain high-speed applications, where up to about 6 m/min can be achieved for 1 mm low carbon steel.

In the conventional technique, the track width of the welding wheel is approximately $5\sqrt{t}$ mm and the minimum acceptable weld width is typically $4\sqrt{t}$ mm. However, a leak-tight weld as strong as the parent material can be achieved with a weld width only a little wider than the sheet thickness. In narrow wheel seam welding, a radiused electrode face is used, giving a smaller contact area (*Figure 10.55(a)*). Weld widths of 2–3 mm are made in sheet thicknesses up to about 2 mm. Narrow wheel seam welding is particularly suitable for coated steels. The wheels are driven by a roller, which bears on the edge of the wheel and planishes the contact face, to maintain a uniform condition.

When welding speed is increased above about 20 m/min for very thin material, the spacing of welds made at each half cycle of the mains frequency becomes too great to produce a leak-tight weld. Higher frequency supplies, typically 600 Hz are used to weld tin cans in 0.2 mm thick steel at speeds to over 70 m/min. In this case, a mash weld is produced (*Figure 10.55(b)*) where the initial overlap is only 1.5 times the sheet thickness, and the seam is crushed during welding. The effect of electrode contamination is avoided by using a copper wire (formed to a flat oval) which is passed over each electrode in turn. Thus, the electrode face is continuously renewed. D.c. current is not used for such applications as it gives less effective heat generation in this case.

10.2.5 Resistance butt and flash welding

Resistance butt welding is the simplest form of resistance welding and is used predominantly to butt join wires and rods, including small diameter chain. The components to be joined are clamped in opposing dies, with a small stick-out, and butted under pressure. Current from a resistance

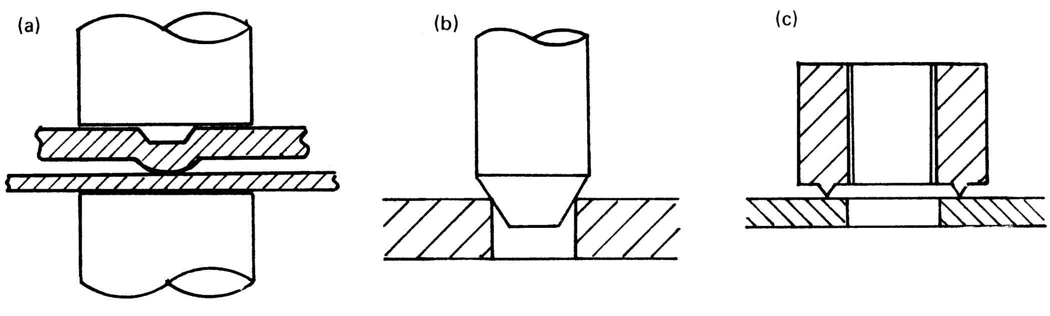


Figure 10.53 Examples of projection welding configurations: (a) embossed projection; (b) stud to plate; (c) annular projection

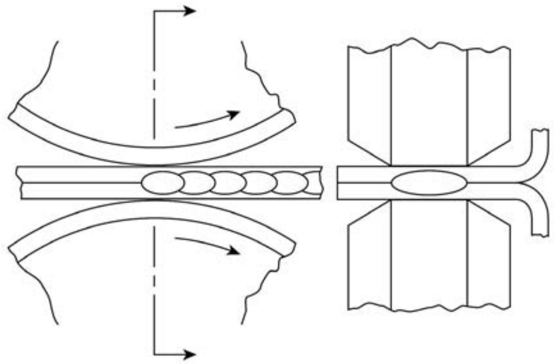


Figure 10.54 Conventional wide wheel seam welding

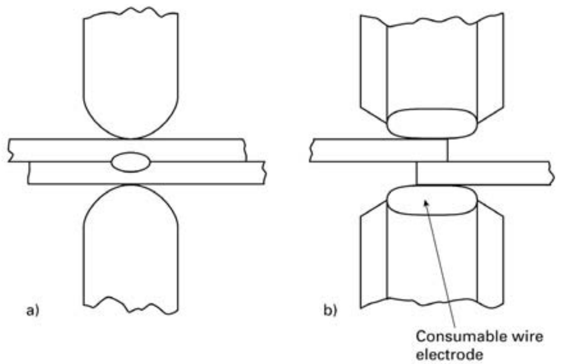


Figure 10.55 Alternative seam welding techniques: (a) narrow wheel seam; (b) mash welding with consumable wire electrode (shown prior to welding)

welding transformer is passed between the dies, causing heating of the weld area. The material deforms under the applied load giving a forge weld. The welding current is normally terminated once a preset reduction in length has occurred, although pressure must be maintained until after current has stopped flowing. Resistance butt welding is not normally suitable for larger components such as thin strip because of unevenness of heat generation. However, the use of d.c. power supplies together with programmed force and current cycles, has enabled components such as automotive road wheels to be welded on automatic equipment at up to 700 rims/hour.

Flash welding is used for a wide range of component shapes and sizes from bicycle wheel rims to rails. More efficient energy input, and a more localised and evenly heated zone, can be achieved compared with resistance butt welding. In this case, the components are clamped between dies and moved slowly towards each other with the current switched on. Current flows through successive point contacts, which heat rapidly, melt and blow out of the joint, giving the characteristic flashing action as the forward motion continues. After a preset material loss has occurred, sufficient to heat the material behind the interface to its plastic state, the components are forged together to expel melted material and contaminants, and complete a solid phase forge weld. The flash or upset metal may be removed while still hot using a shearing tool. When welding larger sections, the parts may be preheated to promote easier flashing. This is done by advancing and retracting the components to make repeated short-circuit contacts under pressure. The welding sequence and the welding machine are shown schematically in *Figures 10.56* and *10.57*.

Machines are predominantly single-phase a.c. in the power range 20–500 kVA. Such machines are designed with as small as possible secondary inductive loop as the flashing action is characterised by repeated breaks in the secondary circuit which cause transient arcs. The lower the inductance, the lower is the energy dissipated in the arc and the smoother are the melted surfaces prior to final forging. This helps to reduce the risk of weld interface flaws. Large d.c. flash welders have been produced to reduce the mains power demand, but there is a risk of sustained arcs produced during flashing, leading to undesirable deep melted areas at the interface. Modulated current may be used to counteract this tendency.

The flashing sequence must be accurately controlled and the forge applied with sufficient force and speed for best results. The forward movement of the components is normally accelerated as flashing progresses. The flashing speed

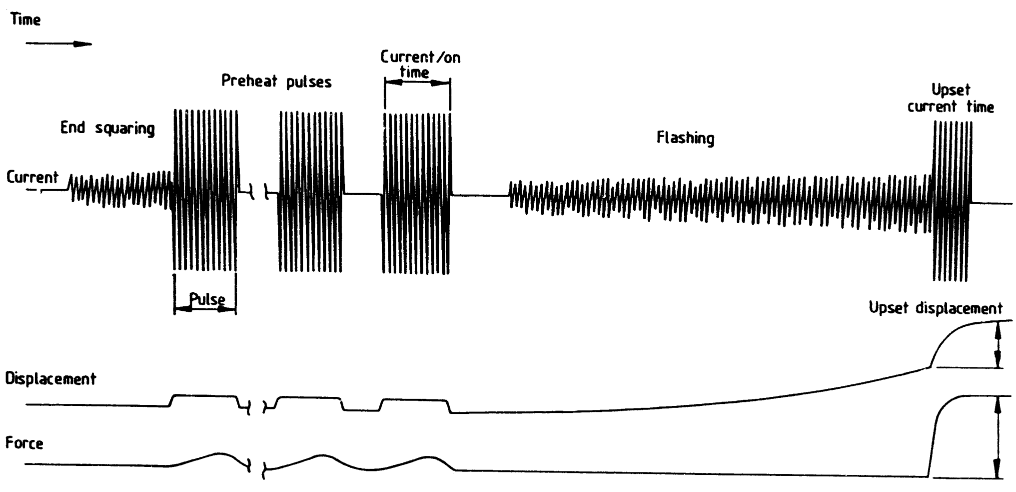


Figure 10.56 Generalised diagram of the flash welding sequence

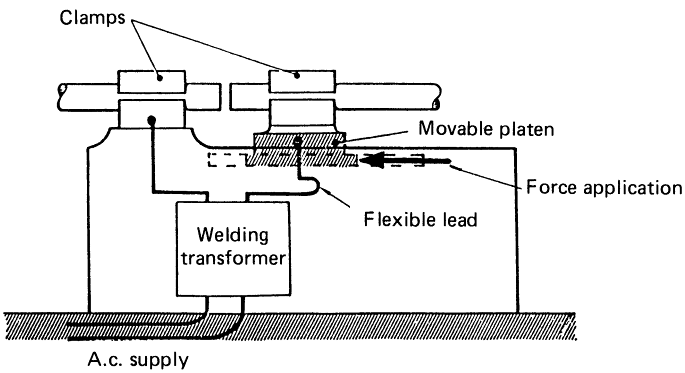


Figure 10.57 A flash welding machine

should be as fast as is practicable for a given applied voltage, whilst avoiding premature butting or 'freezing' of the parts. This ensures that the flashing action is continuous and not so coarse that deep craters are blown in the contacting surfaces with a risk of interfacial flaws. These take the form of a film or planar distribution of oxide inclusions known as 'flat spots'. Feedback control of the travel speed maintains an optimum flashing action.

Welding conditions vary considerably for different materials and component size, but may be generalised as follows for a material of thickness t, flashing length 0.7–1.5t and upset length 0.2–0.5t. Forge forces are between 60 N/mm^2 for low carbon steels and 150 N/mm^2 for stainless steels, with even higher forces required for heat-resisting materials. Flashing speeds are typically 0.5 to 3 mm/s, and upset speeds 25 to 350 mm/s. Guidance on process control and weld testing is provided in BS 6944 for butt welds in steel and BS 4204 for tubular joints in pressure applications.

10.2.6 Safety aspects of resistance welding

There are a number of potential hazards in resistance welding. Although the machines are intrinsically safe, it is important to observe good welding practice, provide adequate training and adopt the appropriate safety measures. Machines should be manufactured and installed to the appropriate standards such as EN 50063.

Mechanical hazards involve the risk of trapping fingers or other parts of the body between electrodes or other moving parts. Safety devices include various types of guard, interlocked two-hand button operation and low force electrode approach. Where practicable, spot welding electrodes should have a working gap of no more than about 6 mm.

Splash metal may be expelled under pressure from the weld. Eye protection and suitable protective clothing should therefore be worn. Burns and lacerations may result from careless handling of hot assemblies or materials with burrs or sharp edges. Suitable gloves and protective clothing should be worn.

Electrical hazards result from inadvertent contact with live terminals. Exposed conductors do not normally exceed 20 V, but mains voltage is connected to the control cabinet and to the transformer taps and primary windings. The machine should be installed and enclosed to the appropriate standards, using the correctly rated cables and protection devices. Equipment should be switched off at the mains before removing covers or opening doors, such as for the purpose of changing taps where a tap switch is not fitted externally. Ideally, such doors should be provided with safety interlocks. An additional hazard may be that the strong magnetic fields produced close to resistance welding equipment could affect the operation of heart pacemakers.

Fumes result from the vaporisation or burning of metal or organic coatings on material being welded, or from interweld adhesives, sealants, etc. This is not normally a major problem and adequate ventilation is usually sufficient. Local extraction may be required in some cases, depending on the type and concentration of the fumes.

10.3 Fuses

Fuses, which are now produced in vast numbers each year to protect electric circuits, were used as long ago as 1864 to protect submarine cables. In theory any conducting metal can be used as a fusible element. In practice, however, a variety of metals are used, ranging from cheaper materials such as copper to rarer and, therefore, more expensive materials such as silver.

The term 'fuse' is used in national and international standards to describe a complete assembly. In its simplest form, this consists of a piece of metal wire connected between two terminals on a suitable support; and at its most complex as a cartridge fuse-link mounted in a carrier and fuse base.

Modern cartridge fuse-links contain fusible elements mounted in rigid housings of insulating material. The housings are filled with suitable exothermal and arc-quenching powders, such as silica, and they are sealed by metal end-caps which carry the conducting tags or end connections. A typical fuse-link is shown in *Figure 10.58*. The metal parts, other than the fusible elements, are invariably of copper, brass, steel or composites and they must be capable of operating under the exacting thermal, mechanical and electrical conditions which may arise in service. The materials used for the fusible elements must enable predictable performances to be obtained under a wide range of conditions, from normal thermal cycling to the violent changes of state that occur when elements are subjected to arcing during the interruption of faults.

10.3.1 Fuse technology

Fuses operate for long periods during which they carry currents at levels up to those associated with healthy conditions on the circuits protected by them and they must be capable of interrupting overcurrents up to the maximum levels possible when faults occur.

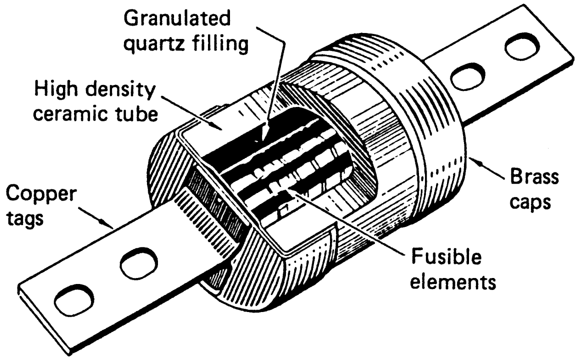


Figure 10.58 HRC fuse-link

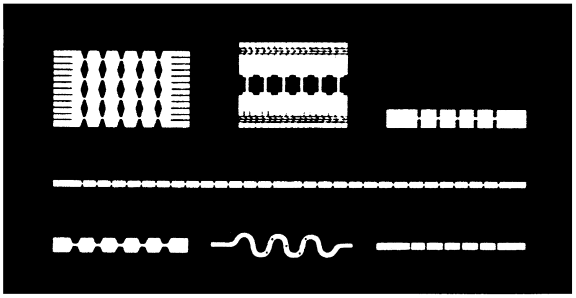


Figure 10.59 Shaped fuse elements

To satisfy these requirements, a fuse must be able to carry normal load currents and even transient overloads (and the thermal cycling which accompanies them) for a service life of at least 20 years, without any change of state that might affect its electrical performance. This property of 'non-deterioration' requires that the fusible element be both thermally and chemically compatible with the ambient media. It must also respond thermally to overcurrents by melting and subsequently interrupting its circuit.

The melting of an element is followed by a period of arcing during which the electrical energy input can be very high, its magnitude and the duration of arcing being dependent on the protected circuit. Successful fault interruption implies that the arcing is wholly contained within the fuse-link and the level at which this can be achieved is termed the breaking or rupturing capacity of the fuse-link. It must be recognised that unsuccessful interruption can result in disastrous changes to a circuit and its surroundings.

The operating time of a fuse-link varies inversely with the level of an overcurrent and discrimination is obtained in networks by choosing fuses with the necessary time/current characteristics and current ratings.

An important property of a high-breaking-capacity fuse-link is its ability to limit the energy fed to a fault, by melting and achieving arc extinction long before the fault current can rise to the levels which the circuit could otherwise produce, i.e. the 'prospective' values. This property is achieved by selecting the necessary element material and geometry.

10.3.2 Element materials

Silver, copper, tin, lead, zinc or alloys of these materials are used to produce fuse elements. In the past, silver was used in the majority of fuse-links but copper has been employed increasingly in recent years because of its much lower cost. Copper is now used in most industrial type fuse-links but silver is still required to obtain the performance required of fuse-links needed to protect semiconductor devices. The other materials listed above are used in fuse-links intended for low-power circuits.

Apart from its cost, silver is ideal for elements because of its physical properties. It is reasonably immune to corrosion in normal atmospheric conditions and is chemically compatible with silica and other media by which it is surrounded in fuse-links. Even when oxidation of an element does occur at elevated temperatures, the conductance is hardly affected because the conductivity of silver oxide is close to that of the parent metal. Silver is ductile and easily fashioned into the shapes needed, some of which are shown in *Figure 10.59*. It is easily joined or connected to other materials and is hard enough to be mechanically self-supporting. It can also be combined with other dissimilar materials (e.g. to produce the M effect referred to later) to produce eutectic alloys without affecting its stability during thermal cycling. The physical break-up which follows the melting of an element is regular and predictable for material of the prescribed purity. The vaporised metal can be made to disperse within the arc-quenching media to combine and condense so that the resulting 'fulgurite' becomes an insulator.

A silver element may be heated almost to melting and then allowed to cool without its state changing significantly. Such situations arise in service when large overcurrents are interrupted elsewhere in a circuit and it is important that the fuse-links involved should not, as a result, be weakened or change their designed time/current characteristics.

Whilst the properties of copper are not quite so good as those of silver they are, nevertheless, of standards which allow satisfactory elements to be produced for industrial fuse-links.

10.3.3 Filling materials

Cartridge fuse-links are invariably filled with granular quartz of high chemical purity the grain sizes being in the region of 300 μm. The filling material conducts heat energy away from fuse elements and, therefore, to obtain consistent performance it is necessary that a high and constant packing density be achieved. To further improve the consistency and raise the heat conduction it is now usual to employ inorganic binders in the filling material. This enables shorter operating times to be achieved and better performance is also obtained in d.c. applications.

10.3.4 Fuse-links with short operating times

All modern high-breaking-capacity fuse-links contain elements, usually with restrictions, of small cross-sectional areas connected between relatively massive end connections which act as heat sinks. To obtain rapid operation this principle is employed to a high degree. The extent to which the mass of the heat sink can be increased while reducing the length of the relatively thin element is determined by the requirement that the fuse should withstand the system voltage after the current has been interrupted (i.e. must not restrike). Considerable ingenuity has reconciled these two mutually incompatible requirements. More than one restriction may be used in series along the length of an element to cater for increased voltage, but this aggravates the problem of dissipating heat from the elements. The solution lies in an increase in the transfer of radial heat through the surrounding media. Thus the fuse element must not be looked at in isolation, but as a composite whole with the rest of the assembly.

The fashioning of fuse elements to produce elaborate shapes is economically limited by the means available to achieve the shape required. A variety of means is employed and these often influence the choice of material as regards its physical constants, e.g. the purity of silver as a factor in hardness, etc.

10.3.5 The M effect

The M effect, deriving from an exposition by Metcalf, refers to exploiting the thermal reactions of dissimilar metals in the control of time/current characteristics. The thermally most stable fuse element is a simple homogeneous metal. Such an element provides the highest degree of non-deterioration and reliability with adequate breaking capacity at higher overcurrents, but it may be insensitive at lower overcurrents. A lower melting temperature metal with higher resistivity and, therefore, greater thermal mass, can be made to respond more sensitively to lower overcurrents but may be unreliable at higher currents.

The M effect is a means by which these extremes can be combined to produce a desired characteristic, but it needs to be used with care in design to avoid compromising non-deterioration properties. An element incorporating the M effect is shown in *Figure 10.60*(*a*).

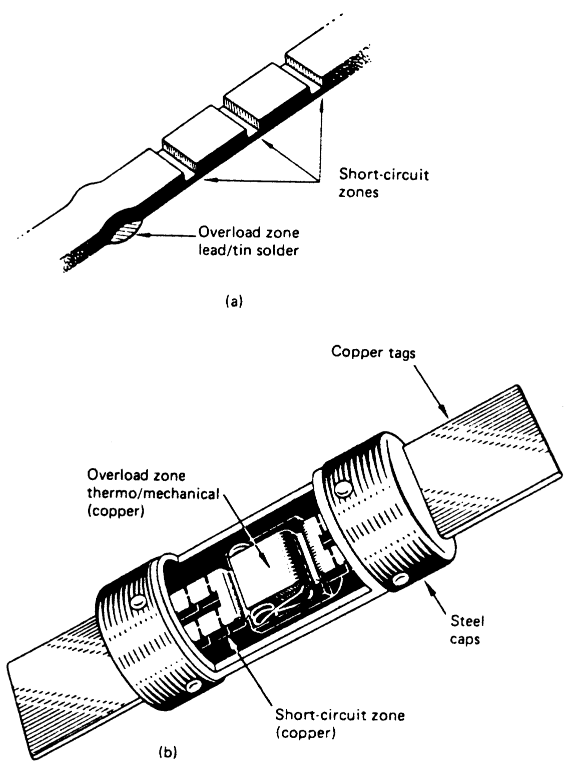


Figure 10.60 (a) Fuse element (English Electric); (b) dual-element fuse.

10.3.6 Composite or dual-element fuses

Satisfactory operation throughout the overcurrent and short-circuit ranges is sometimes obtained in the same package by combining what are, in effect, two fuses connected in series in the same cartridge (*Figure 10.60*(*b*)). Typical of these is the so-called dual-element design common in the USA. The short-circuit zone is similar to the homogeneous element used in single-purpose HRC fuses. The overload zone may take the form of a massive slug of low-melting-point alloy, or some electromechanical device, e.g. two copper plates soldered together and stressed by a spring so that when the solder melts the plates spring apart to interrupt the current. The variables in such designs are considerable and many ingenious ideas have been exploited with some success.

10.4 Contacts

Contacts may be classified according to the load they control and are here discussed under four basic headings:

(1) low voltage, light current;
(2) low voltage, high current;
(3) medium voltage (<660 V) and power levels; and
(4) high voltage, high power.

An indication of the physical properties of contact materials and the performance and application of contact alloys is given in *Tables 10.4* and *10.5*.

10.4.1 Low-voltage, low-current contacts

These contacts are required to make and break a very low electrical duty so contact erosion is not a problem. Ideally the contacts should have a low contact resistance which does not introduce electrical noise by electrothermal or electromechanical means. Importance is therefore placed on surface contamination and deterioration in use and in storage. Silver–nickel alloys are commonly used in low-current control circuits, but for low noise a plated gold surface may be applied which survives a signal level service but rapidly exposes the silver–nickel for higher current applications. Rhodium or palladium may also be used in combination with gold for higher mechanical duty applications.

10.4.2 Low-voltage, high-current contacts

Separation of contacts carrying a current will create an arc. Since an arc requires a minimum voltage to maintain itself, the arc rapidly extinguishes for low voltage. However, inductance in the load will cause an arc of longer duration and results in contact burning. The high current requires a low contact resistance and large contacts with high contact force are used. Contact materials may be silver–nickel, though some automotive applications will use copper alloys for economy.

Contact resistance is a function of the contact materials, the force applied and, to some extent, the shape of the contacts. The resistance of a pair of contacts may be expressed as $r = k/f^n$, where f is the force applied, and k and n are constants depending on the contact materials and shape.

Typical values for f and n for copper are given in *Table 10.6*. At the instant of contact closure a single contact point

Table 10.4 Physical properties of contact materials

Material		*Density* (kg/m^3 $\times 10^{-3}$)	*Melting point** (°C)	*Boiling point*†⇐ (°C)	*Hardness* (HV)		*Tensile strength* (N/mm^2)		*Elongation* (%)		*Thermal conductivity at 20°C* (W/K-m)	*Electrical conductivity* (m/Ω-mm^2)
					Soft	*Hard*	*Soft*	*Hard*	*Soft*	*Hard*		
Pure metals												
Silver	Ag	10.5	961	2200	30	80	200	360	30	2	419	62
Gold	Au	19.3	1063	2370	25	60	140	240	30	1	297	44
Platinum	Pt	21.5	1769	4400	40	95	140	400	50		72	9.5
Palladium	Pd	12.0	1552	4000	40	100	200	480	44	2	72	9
Rhodium	Rh	12.4	1966	4500	130	280	420		9		88	22
Indium	Ir	22.5	2454	5300	220	350					59	19
Copper	Cu	8.9	1083	2300	50	100	200	450	33	2	394	58
Tungsten	W	19.1	3400	6000	250	450	1000	5000			167	18
Molybdenum	Mo	10.2	2610	5560			600	2500			142	19
Iron	Fe	7.9	1539	2740	90	150					75	10
Nickel	Ni	8.9	1453	2730	80	200	450	900	50	2	92	14
Power engineering materials‡⇐												
Fine grain silver	0.15% Ni	10.5	960	2200	55	100	220	360	25	1	415	58
Silver–copper	3% Cu	10.4	900	2200	65	120	250	470	25	1	372	52
(hard silver)	5% Cu	10.4	850	2200	70	125	270	550	20	1	335	51
	10% Cu	10.3	780	2200	75	130	280	550	15	1	335	50
	20% Cu	10.2	780	2200	85	150	320	650	15	1	335	49
Silver–nickel	10% Ni	10.3	961	2200	50	90	220	400	20	1		54
	15% Ni	10.2	961	2200	55	92	240	420	17	1		
	20% Ni	10.1	961	2200	60	95	280	450	15	1		47
	30% Ni	10.0	961	2200	65	105	330	530	8	1		42
	40% Ni	9.8	961	2200	70	115	370	580	6	1		37
Silver–cadmium oxide	10% CdO	10.2	961	2200	70	100	300	460				48
	15% CdO	10.1	961	2200	80	125						42
Silver–cadmium oxide	10% CdO	10.2	961	2200	50	80	230	450				48
	12% CdO	10.2	961	2200	60	95						47
	15% CdO	10.1	961	2200	65	115	280	420				45.5
Silver–zinc oxide	8% ZnO	10.2	961	2200	60							49
Silver–graphite	3% C	9.1	961	2200	40							47
	5% C	8.6	961	2200	40							43.5
Tungsten–silver	20% Ag	15.4	961	2200	180	240					245	26–28
	35% Ag	14.8	961	2200	100	130					280	34–36
	50% Ag	13.5	961	2200	900	100						40
	65% Ag		961	2200	80	90						
	80% Ag		961	2200	70	80						42
Tungsten–carbide-	20% Ag	13.3	961	2200	400	470						25–35
silver	60% Ag	11.2	961	2200	100	130						
Tungsten–copper	15% Cu	16.0	1083	2300	190	260						
	20% Cu	14.7	1083	2300	180	240						24–26
	25% Cu	14.3	1083	2300	170	220						
	30% Cu	13.1	1083	2300	160	200						28–30
	40% Cu	12.7	1083	2300	140	170						
	50% Cu	11.8	1083	2300	130	150						
Molybdenum–silver	25% Ag		961	2200	190	210						
	35% Ag	10.3	961	2200	160	180						22
	50% Ag	10.3	961	2200	130	150						24
Light current materials‡⇐												
Fine grain silver	0.15% Ni	10.5	960	2200	55	100	220	360	25	1	415	58
Silver–palladium	60% Pd	11.4	1330	2200	100	170	380	720			29.3	2.4
	50% Pd	11.2	1290	2200	90	160	360	700	15	1	34	3.3
	40% Pd	11.1	1225	2200	70	140	350	630	20	1	46	4.9
	30% Pd	10.9	1155	2200	65	120	300	600	20	1	59	6.7
Palladium–copper	15% Cu	11.4	1370	2300	100	260	400	800	42	1		2.5
	40% Cu	10.5	1200	2300	120	280	450	850	39	1	37.7	2.7
Gold–silver–copper	20% Ag 10% Cu	15.1	865	2200	125	230	480	820	20	1	68	7.1
	25% Ag 5% Cu	15.2	940	2200	90	185	400	700	25	2	67	7.1
Gold–silver–nickel	26% Ag	15.4	990	2200	80	120	350	570	20	1		8.3
Gold–nickel	5% Ni	18.2	995	2370	105	160	380	640	25	1	52	7.3
Gold–platinum	10% Pt	19.5	1100	2970	45	160	260	410	20	1	54.5	8
	25% Pt	19.9	1220	2970	80	155						3.6
Gold–silver	8% Ag	18.1	1035	2200	30	100	150	320	25	1	147	15.8
	20% Ag	16.5	1035	2200	35	90	190	390	25	1	75	10.5
	30% Ag	15.4	1025	2200	40	95	220	380	25	1		9.8
Gold–silver–platinum	25% Ag 6% Pt	16.0	1050	2200	30	150	300	500	25	1		6.1
Platinum–tungsten	5% W	21.4	1830	4400	160	250						2.3
Platinum–nickel	8.5% Ni	19.2	1670	2370	180	260						3.7

* For alloys the solidus point is given, for sintered materials the melting point of the lowest-melting component.
† The boiling point of the lowest-boiling component is given.
‡ The composition is given in weight %.

Table 10.5

Material	*Properties*	*Area of application*
Base: tungsten or molybdenum W/Ag 80/20 ... 20/80	Very low wear, decreasing with increasing W content. High contact resistance, increasing with increasing W content. Resistance increases during life. High contact forces necessary. Bad arc mobility properties. Not workable.	Low voltage and high voltage circuit-breakers, miniature circuit-breakers (in particular American systems). Railway switches
WO/Ag 80/20 ... 40/60	Slightly better than W/Ag for erosion. Suppression of forming of tungstate	As W/Ag, in particular for simple pairs of contacts (no special arcing contacts)
Mo/Ag 80/20 ... 50/50	Similar to W/Ag	Similar to W/Ag
W/Cu 85/15 ... 50/50	Similar properties to A/Ag, but more prone to forming of oxide	High voltage-load breaking switches and circuit-breakers (contacts in air, oil, SF_6); transformer tap-changers (contacts under oil). Electrodes for spark erosion, electrolytic removal and welding.
Base: silver Ag	Highest electrical and thermal conductivity. Oxidation resistant but formation of sulphide. Material transfers. Easily worked	Control switches, microswitches, regulators and selector switches: voltages $U > 60$ V; currents $l < 10$ A
Ag/Ni 99.85/0.15 (fine-grain silver) Ag/Cu 97/3 ... 90/10 (hard silver)	Similar to Ag, but lower erosion. Contact resistance increases with increasing base metal content. Welding tendency low for peak currents below 100 A	Control-, micro-, selector-, relax switches, regulators, miniature circuit-breakers with ratings up to 5 A
Ag/Ni 90/10 ... 80/20	Contact resistance similar to hard silver, but less increase in resistance during life. Lower erosion. No welding for current peaks up to 100 A. Low and flat material transfer when switching d.c. Erosion debris on insulating materials non-conducting. Good arc extinguishing properties	Control switches, regulators, selector switches for d.c. and a.c. up to 100 A. Switches for domestic appliances. Miniature circuit-breakers up to 25 A rating. Motor control switches, contactors up to 25 A rating. Automative switches. M.c.b.s for d.c. and a.c. (unequal pairs with Ag/C). Controllers
Ag/Ni/ 70/30 ... 60/40	Contact properties similar to 10–20% Ni, but higher contact resistance and lower wear (increasing with increasing Ni content)	Circuit-breakers for d.c. and a.c. Automative horn switches. Controllers
Ag/CdO 90/10 ... 85/15	Contact resistance somewhat higher than for Ag/Ni 90/10. No welding up to peak currents of 3000 A. Low arc erosion in the range 100 to 3000 A. Very good arc extinction properties. Unfavourable arc movement properties. Limited workability	Low-voltage contactors, motor and motor-protection switches with ratings from 10 A. Low-voltage circuit-breakers with ratings up to about 100 A. Miniature circuit-breakers and earth leakage circuit-breakers with peak currents up to 3000 A. Lighting switches
Ag/C 97/3 ... 95/5	Low contact resistance. Very high reliability against welding (increasing with increasing C content). Good friction properties. High wear. Bad arc-mobility properties. Bad workability	Miniature circuit-breakers and earth leakage circuit-breakers. Low voltage circuit-breakers (unequal pairs with Ag/Ni). Capacitor protective relays. Sliding contacts with self-lubrication
Ag/ZnO 92/8	Similar properties to Ag/CdO, but arc erosion in the current range 100–3000 A somewhat larger and in the range 3000–5000 A smaller	Low-voltage circuit-breakers with ratings up to 200 A. Earth leakage circuit-breakers
Base: palladium Pd	Highly resistant to corrosion, but prone to catalytic reaction with organic materials (brown powder). Highly resistant to arc erosion. Low electrical conductivity	Switching contacts at voltages $U = 20$–60 V

cont'd

Table 10.5 *(continued)*

Material	*Properties*	*Area of application*
Ag/Pd 70/30 ... 50/50	Generally resistant to corrosion, but worse than Au alloys. For Ag compared to Ag/Pd 70/30 about 7 times faster and compared with Ag/Pd 50/50 about 100 times faster formation of surface films. Highly wear resistant	Switching contacts at voltages $U = 20$–60 V, e.g. for telephone relays and selectors. Usual material in telecommunications. Sliding contact in precision potentiometers
Pd/Cu 85/15 and 60/40	Corrosion behaviour similar to Pd, but at 40% Cu thin oxide layers form high resistance to arc erosion. Low tendency to transfer	Switching contacts at voltages $U = 6$–60 V. High switching currents
Base: platinum		
Pt/W 95/5 Pt/Ni 91.5/8.5	Resistance to corrosion better than for Pd alloys, but also formation of 'brown powder'. Low, even transfer. Very highly wear resistant	Switching contacts at high load currents and very long life
Base: gold		
Au, Au/Pt 90/10	Highest resistance to corrosion, contact resistance constant over long periods. Prone to cold welding. Material transfer	Opening contacts for very small currents and voltages (dry circuits), e.g. in measuring devices, need switches
Au with hardening additives, electrolytically produced (hard gold)	Similar to Au, but slightly higher contact resistance and less prone to cold welding	Plugs, slide rails, rotary and sliding switches. PCB edge connections
Au/Ag 92/8 ... 70/30 Au/Ag/Pt 69/25/6	Good resistance to corrosion. Higher hardness and resistance to wear and less prone to transfer than Au	Switching contacts with voltage <24 V and for small currents, e.g. circuits. Plugs for frequent operation
Au/Co 95/5	Resistance to corrosion similar to, hardness and wear resistance higher than Au/Ag alloys. Slight tendency to transfer. Less malleable	Switching contacts for long life, e.g. for flashers, measuring devices, clocks. Plugs with long life
Au/Ag/Cu 70/25/5, 70/20/10 Au/Ag/Ni 71/26/3	Good resistance to corrosion but slightly less than Au/Ag, decreasing with higher base metal content. Transfer worse than for Au/Ni and Au/Co	Switching contacts, e.g. telegraph relays at voltage < 24 V. Plugs for normal life at contact forces at about 0.5 N

Table 10.6 Constants for copper contract: $r = k/f^n$ with r in ohms and f in newtons

Form	*Surface condition*	*n*	*k*
Point	Normal	0.5	0.0007
Line	Normal	0.7	0.0015
Plane	Normal	1.0	0.004
(160 mm^2)	Lubricated	1.0	0.003
	Tinned	1.0	0.012
	Fine-ground, new	2.0	5

only may be considered; increasing force distorts the surface and more contact points are established in parallel with the first. With a 'soft' material and with a high force, contact is eventually established over an area which may represent a large proportion of the available contact area, resulting in a low contact resistance. This system would soon cause mechanical erosion of the contact surfaces and so such techniques are only applied to contacts which are only occasionally separated such as plugs and sockets or isolators. Sliding of the contacts may also be permitted to ensure clean surfaces are presented at each contact 'make'.

The contact shape has importance if the contacts are not expected to erode during their lifetime and thus change their original shape.

10.4.3 Contact design

The passage of current at the contacting face will cause heating and this may cause a local softening of the material with a resulting increase in contacting area and reduced contact resistance. This would appear to be an advantage but represents a dangerous condition since welding may occur. In the minimal case the contacts may be separated mechanically and the weld broken but in the worst case the contacts become permanently joined! Welding may also occur due to contacts arcing and particularly so when contacts 'bounce' while carrying current.

To discourage welding, contact 'alloys' are available which contain low resistance silver and a hard material such as nickel or tungsten or an oxide of cadmium, tin or zinc. Graphite may also be included to reduce welding but at the expense of increased contact resistance. Some forms of contact are shown in *Figure 10.61*.

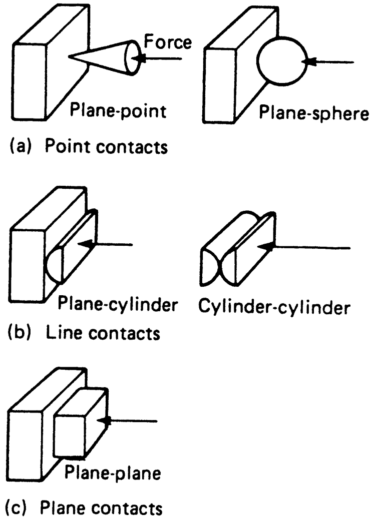


Figure 10.61 Basic forms of contact

10.4.3.1 Medium voltage (up to 660 V)

Make and break contacts for this industrial range are required to provide a useful life of many thousands of operations. The duty may be a motor load where the starting current is typically six times the running current. For this duty (AC3), a long life can be expected since little erosion occurs at contact close. However, bounce can cause welding so contacts need to be rated according to the duty. Contacts which make and break equal currents (AC4) would erode more rapidly. At high currents shaped contacts may be used so that a defined area of the contact breaks last and carries the eroding arc. The remaining area, by staying clean, provides a low resistance for the continuous load current. The best combination of contact force, size, shape and material has to be made for a contactor to control a wide range of loads; capacitive loads (fluorescent lights) are particularly prone to weld problems. Silver–cadmium oxide is a common choice of contact material because of its good erosion and weld resistance properties. Silver–tin oxide is a recent alternative. The granular structure of these sintered materials has a great influence on their performance. The ratio of silver to cadmium/tin/nickel is high and thus acceptably low contact-resistance is obtained. However, the thermal rating of the contacts normally decides their dimensions.

10.4.3.2 High voltage–high power (≥3 kV)

This application is generally required for a low duty since the operating rate is slower. The higher voltages may require a multiple contact break and external influences are used to extend the arc into a shute where it is cooled and extinguished. Sulphur hexafluoride gas and oils may be used to assist in deionising the arc. (The special behaviour of an arc in a vacuum is used in the vacuum contactor which is capable of interrupting current at a non-current zero (current chopping).) Contact materials for which high-power duty have to withstand higher temperatures and tungsten alloys are common. In oil, copper is acceptable for the load-carrying part of the contact since oxidation does not occur and the arc tips only are fitted with tungsten alloy.

The effect of a current passing through closed contacts is represented by I^2rt. The contact resistance, r, is considered low and stable, but t is large so the resulting heat needs to be dispersed. This is performed by conduction into the mass of the supporting contact backing and, in many constructions, into the cable connections. During the contact make and break, r is larger but t is small. The heat is dispersed only into the contact area, so the thermal capacity and thermal conduction of the immediate contact assembly is most significant. Good ventilation also assists in reducing contact temperature.

When separating contacts which are passing a current, the final contact is small so the resultant resistance produces considerable heat and high temperatures are reached. $\theta = kV^2/\gamma\rho$, where V is the contact voltage, γ is the thermal conductivity and ρ is the electrical resistivity of the contact materials. V has a major influence and temperatures in excess of 10 000 K are readily attained. Such temperatures cause vaporisation, thermionic emission and, together with electromagnetic forces, these cause destruction of the contact surfaces evidenced as erosion.

When the contacts are subjected to an arc during circuit interruption, it is advantageous to minimise the duration of the arc. An a.c. circuit carries current which passes through zero twice per cycle and at this instant there is no energy to support the arc which then extinguishes. The rise in voltage across the contacts may restrike the arc if any ionisation remains. The contacts must therefore be separated to a sufficient distance and the gap cooled and ventilated. For a d.c. circuit, no such current zero occurs and the contact separation is required to break the arc. This may be assisted by multiple break contacts, extending the arc by magnetic fields, forcing the arc against cooling plates and generally by a very fast separation of the contacts. The use of blow-out coils to create a magnetic field is commonly used in large units but these are not effective at low currents and a permanent magnet may be added to assist the low current performance.

The life of contacts is a function of the current and the number of operations, there being both mechanical wear and electrical surface disruption. With d.c. there is a tendency for material to transfer from one contact to another in a unidirectional manner and advantage can be taken of this by the use of dissimilar contact materials or even dissimilar contact sizes. With a.c., the reversal of the arcing current will average the erosion so that the contacts erode equally. The unidirectional transfer by d.c. generates a 'pip and crater' condition which may reach the state where the 'pip' wedges into the crater effectively locking the contacts together. This effect is noticeable on small contacts which have too small a separation force to break the pip clear of the crater. Very low force contacts as in reed switches are particularly susceptible and gold contacts may even cold weld when left closed for a long period. Precautions are necessary to reduce these effects and for d.c. low current applications RC suppression and resistance to limit current pulses through the contacts is generally used.

10.5 Special alloys

Many alloys have been developed for special applications either at elevated temperatures for heating elements or as heat-resisting materials or at room temperature where a minimum change of resistance or dimensions is required.

10.5.1 Heating alloys

There is a considerable range of alloys used for heating elements for a wide range of applications including electric fires, storage heaters and industrial and laboratory furnaces. These alloys usually contain nickel together with chromium, copper and iron in varying proportions and often with small amounts of other elements. Similar alloys are also used for the construction of fixed and variable resistors. For heating elements, a considerable resistivity is required to limit the bulk of wire required. In addition, the temperature coefficient of resistivity should be small so that the current remains reasonably constant at constant applied voltage. *Table 10.7* gives the properties and trade names of a range of resistance heating alloys.

The operating temperature of these alloys is dependent on the cross-section of the wire or strip and on the atmosphere in which the material is to be used. The manufacturer's literature should be consulted before any application is finalised.

For higher temperatures, ceramic rods are used. Silicon carbide may be used in applications ranging from below 600°C up to 1600°C in either air or controlled atmospheres, although the type of atmosphere will determine the recommended element temperature. For even higher temperatures there are various cermets. Molybdenum disilicide ($MoSi_2$) with additions of a ceramic glass phase may be used up to 1900°C and a zirconia material (Zircothal) is used up to 2200°C. These maximum temperatures depend on the type of atmosphere in which they are to be used.

10.5.2 Resistance alloys

Alloys for standard and fixed resistors are required to have a low-temperature coefficient of resistivity in the region of room temperature.

Manganin (84% Cu, 4% Ni, 12% Mn) This has been the traditional material for high-grade standard resistors. Its resistivity is about 0.40 μΩ-m and its temperature coefficient is about 1×10^{-5}/°C.

Karma and Evanohm Trade names for quaternary alloys (73% Ni, 21% Cr, 2% Al, 2% Fe or Cu) which are being used increasingly for standard resistors, especially those of high value. The resistivity is about 1.30 μΩ-m and the temperature coefficient is $\pm 0.5 \times 10^{-5}$/°C. Each of the above alloys has a low thermo-e.m.f. against copper. Normally joining the above alloys to copper should be by argon arc welding or if this is not possible hard soldering may be used.

Constantan, Eureka Advance and Ferry Proprietary names for copper-nickel alloys (55% Cu, 45% Ni) which are used for heavy-duty and fixed resistors, potentiometers and strain gauges. They have a resistivity of about 0.50 μΩ-m and the temperature coefficient varies between $\pm 4 \times 10^{-5}$/°C. The high thermo-e.m.f. against copper (−40 μV/°C) is a disadvantage for d.c. resistors but the effect is usually negligible in a.c. resistors. These alloys may be soft soldered satisfactorily.

10.5.3 Controlled-expansion alloys

These give a range of thermal expansion required in precision parts, control devices and glass-to-metal seals. The lowest expansion alloy is a 36% nickel–iron alloy and is variously called Invar, Nilex or Nilo. The expansion coefficient of these alloys can be less than 1 ppm/°C although this can only be attained over a limited temperature range. Other alloys in the nickel–iron series with additions of cobalt or chromium can be tailored to give the same expansion coefficient as various types of glass for use as metal-to-glass or ceramic seals for television tubes, integrated circuits and fluorescent lights. The expansion coefficient of these alloys will be in the range 4–10 ppm/°C.

10.5.4 Heat-resisting alloys

A range of nickel–chromium based alloys has been specifically developed to meet strict limitations on the permissible creep of vital components in gas turbines in severe conditions of time, mechanical stress and working temperature. A 43/37/18/2% iron–nickel–chromium–silicon alloy is heat resisting in oxidising conditions up to 950°C or higher if the atmosphere is reducing. Developed originally for wire-woven conveyor belts for electric furnaces, it is now used also for a wide range of high-temperature applications.

Table 10.7 Resistance heating alloys*

	Nichrome 80 Brightray S Nikrothal 80	*Nichrome 60 Brightray B Nikrothal 60*	*Nichrome 40 Brightray F Nikrothal 40*	*Resistalloy 134*	*Alferon Y Fecralloy Kanthal AF*	*Kanthal APM Fecralloy 145 Alferon 25*
Nominal composition (%)						
Ni	Balance	59	38	—	—	—
Cr	20	16	18	13/18	16	22
Fe	1	Balance	Balance	Balance	Balance	Balance
Y	—	—	—	—	0.4	—
Al	—	—	—	3.5/4.2	6	4.5 to 5.8
Si	1.5	0.35	2.2	—	—	—
Mn	0.4	1.0	0.5/1.2	—	—	—
Maximum cycling temperature (°C)	1150	1100	1050	1050	≤1375	≤1400
Resistivity (μΩ-m)						
At 20°C	1.08	1.12	1.06	1.25	1.37	1.30
At 1000°C	1.15	1.26	1.30	1.38	1.45	1.50

* These alloys are supplied by, Resistalloy, Sheffield (Fecralloy); Kanthal, Stoke On Trent (Nikrothal); Inca, Hereford (Brightray); and British Driver Harris, Stockport (Nichrome and Alferon).

10.6 Solders

Soldering is a process whereby metal components are joined together using a low-temperature filler metal, which is usually a tin-containing alloy. To assist in the wetting of the basis metal by molten solder, a flux, which is a weak acid, must be present to dissolve the thin oxide films already present on the surface of the components and to prevent further oxidation during heating of the joint.

10.6.1 Fluxes

Soldering fluxes are liquid or solid materials which, when heated, are capable of promoting or accelerating the wetting of metals by molten solder. Fluxes are usually divided into three groups by a classification based on the nature of their residues, namely corrosive, intermediate and non-corrosive fluxes. The National Standard for soft-soldering fluxes, BS 5625 (1980), incorporates a larger number of categories

Table 10.8 Rare and precious metals used for contacts

Metal or alloy	*Melting point* (°C)	*Vickers hardness (annealed)*	*Density* (kg/m^3)	*Resistivity at 20°C* (Ω-m $\times 10^{-8}$)
Light-duty contacts				
Gold	1064	20	19 200	2.2
Platinum	1770	65	21 450	10.6
10% Iridium–platinum	1780	120	21 600	24.5
20% Iridium–platinum	1815	200	21 700	30.0
25% Iridium–platinum	1845	240	21 700	32.0
30% Iridium–platinum	1885	285	21 800	32.3
25% Iridium–ruthenium–platinum	1890	310	20 800	39.0
7% Platinum–silver–gold	1100	60	17 100	16.8
30% Silver–gold	1025	32	16 600	10.4
30% Silver–copper–gold	1014	95	14 400	14.0
10% Silver–copper–gold	861	160	13 700	12.5
Rhodium	1960	40	12 400	4.9
Iridium	2447	220	22 400	5.1
Palladium	1554	40	12 000	10.8
40% Silver–palladium	1290	95	11 900	35.8
40% Copper–palladium	1200	145	10 400	35.0
Medium–duty contacts				
10% Gold–silver	965	30	11 400	3.6
20% Palladium–silver	1070	55	10 700	10.1
10% Palladium–silver	1000	40	10 600	5.8
5% Palladium–silver	965	33	10 500	3.8
Fine silver	961	26	10 500	1.6
0.2% Magnesium–0.2% nickel–silver	961	140	10 400	2.8
1% Graphite–silver	961	40	9 900	1.8
2% Graphite–silver	961	40	9 700	2.0
Standard silver	778	56	10 300	1.9
10% Copper–silver	778	60	10 300	2.0
10% Cadmium oxide–silver	850	50	9 800	2.1
10% Nickel–silver	961	40	10 300	2.0
15% Cadmium oxide–silver	850	60	10 000	2.3
20% Copper–silver	778	85	10 200	2.1
20% Nickel–silver	961	48	10 100	2.1
Cadmium–copper–silver	800	65	10 100	4.2
50% Copper–silver	778	95	9 700	2.1
Heavy–duty contacts				
10% Cadmium oxide–silver	850	55	10 000	2.1
15% Cadmium oxide–silver	850	65	9 800	2.3
40% Tungsten carbide–silver	960	90	11 900	2.5
45% Tungsten carbide–silver	960	95	12 200	2.8
50% Tungsten–silver	960	125	13 600	2.8
50% Tungsten carbide–silver	960	160	12 500	3.0
55% Tungsten–silver	960	140	13 400	3.0
60% Tungsten carbide–silver	960	200	13 200	4.8
65% Tungsten–silver	960	185	14 800	3.3
73% Tungsten–silver	960	220	15 600	4.0
78% Tungsten–copper	1080	240	15 200	6.1
68% Tungsten–copper	1080	160	13 600	5.3
60% Tungsten–copper	1080	140	12 800	4.3

which gives an indication of the chemical nature of each flux type and their application.

For electrical components and other applications where corrosive residues could be difficult to remove, a non-corrosive rosin flux is used. Solder wire with a continuous core, or cores, of rosin flux can be used for manual soldering operations. The National Standard outlining the requirements of such material is BS 441 (1980).

10.6.2 Solder types

A selection of solder alloys are available which melt at temperatures ranging between 60 and 310 °C. British Standard grades of solder, their maximum levels of impurities that are permissible and typical applications are listed in BS 219 (1977). For the soldering of electrical connections and high-quality sheet metal work, an alloy containing 60% Sn, 40% Pb (grade K) is often used. For the machine soldering of electronic assemblies a solder of equivalent alloy composition but with a lower level of impurities is recommended (grade KP). Tin solder alloys with lower tin contents are used for general engineering and the joining of copper conductors and lead sheathing, etc.

The shear strengths of soldered joints are generally within the range 20–60 N/mm^2 at room temperature. As the temperature is increased the strength of joints made with tin–lead solders can decrease significantly. For this reason several solder alloy compositions, such as 95% Sn, 5% Sb (grade 95A) and 96.5% Sn, 3.5% Ag (grade 96S) are recommended for use at service temperatures in excess of 100°C. There are various methods of mechanically attaching two components prior to soldering in order to give added joint strength.

Depending on the soldering method employed solder can be used in the form of a bath of molten metal, sticks, solid wire, flux-cored wire, powder, solder creams, solder paint, or as preforms stamped out of thin foil. Solder creams, which are a mixture of oxide free solder powder, flux and rheology modifiers, can be pre-placed onto the area to be soldered by screen printing or syringe dispensing prior to heating. This technique is called 'reflow soldering' and is now widely used for the joining of surface mount electronic components to printed circuit boards.

10.7 Rare and precious metals

One of the most important and widespread electrical uses of the rare and precious metals is for contacts in applications, ranging from everyday electrical appliances to heavy-duty switchgear and contact-breakers, as well as in scientific and precision instruments, and communication equipment. Contacts can be broadly divided into light, medium and heavy duty and in *Table 10.8* the materials within these groups are approximately arranged in order of descending cost.

Light-duty contacts require that the surfaces do not corrode appreciably, so the more noble metals and alloys are often used, while currents are low, so that resistivity is less important.

Medium-duty contacts handle heavier currents, so that low resistivity is important and, since contact forces are normally high, slight corrosion/tarnishing is less important, but higher hardness becomes desirable.

For heavy-duty applications severe arcing and heavy mechanical wear must be expected, so that higher resistivity can be accepted, in the interests of high hardness and arc resistance.

The choice of contact material is very much a compromise between the intrinsic initial cost, the ease and cost of replacement and the electrical and mechanical properties of the alloy.

Platinum and rhodium–platinum alloys are extensively used for high-temperature thermocouples, which are accurate and particularly stable, as well as for the elements of high-temperature furnaces. Iridium–platinum, and rhodium–platinum are also used as electrodes in cathode-ray tubes. Caesium salts are used in the manufacture of photo-electric cells.

Pure silver is commonly used for electrical fuses and also in certain types of batteries and in capacitors, while a wide range of precious metals and alloys are used for thermal fuses acting as overtemperature cut-outs in electric furnaces.

A number of precious metal alloys are used for precision variable resistances, where the contact resistance at the wiper brush must be minimised. Precious metals are extensively used in integrated circuit technology where resistance to tarnishing and oxidation are important as well as the high ductility essential to the drawing of fine wire and thermocompression bonding. The primary material used in these applications is gold, although platinum, palladium, osmium and iridium are also used. Gold is employed in fine-wire interconnections in packaging of devices and as a eutectic alloy with silicon, used to bond the chip to the header. In thin- and thick-film circuits gold alloys with chromium, copper, nickel, platinum and silver are extensively used in terminations.

New developments in circuit technology requiring ever higher density interconnections utilise tape automated bonding (TAB) and flip-chip techniques. In these techniques wire interconnections have been replaced by direct soldered connections between solder wettable pads on the chip and the substrate. The development of 'solder bumps' used in the bonding involves a gold plating stage to protect the metallised aluminium pads prior to deposition of the high-temperature solders necessary in these techniques.

10.8 Temperature-sensitive bimetals

Temperature-sensitive bimetals, commonly known as thermostatic bimetals, are produced by bonding together two metals having different coefficients of expansion and cold rolling the composite into strip. When subjected to a temperature change, the strip alters curvature in a precise and calculable manner. The bimetals can be used in forms such as the deflection of a straight strip, the rotation of spirals or helices and the snap action of dished discs. Applications include temperature indicators, thermostatic controls, energy regulators, temperature compensation and automotive fuel control devices.

The alloys used for the low-expansion components are normally Invars, 36% or 42% nickel–iron. The high-expansion components are mainly alloys based on manganese, iron or nickel. Alloys have been developed for special applications, such as shower temperature control units and steam traps, where the corrosion resistance is specially important. A range of bimetals with closely controlled resistivities are available for devices, such as overload circuit-breakers, where the bimetal is heated by the direct passage of current. These include a number of trimetals in which the centre component is a low resistivity metal such as copper or nickel.

Table 10.9 Thermostatic bimetals

*Bimetal type**	*Deflection Constant, K* (°C^{-1})	*Range of maximum sensitivity* (°C)	*Modulus of elasticity* (Kg/mm^2)	*Electrical resistivity* (μΩ-m)
200	19.3×10^{-6}	−25–200	13 500	1.11
140	14×10^{-6}	0–175	16 000	0.76
400	11.8×10^{-6}	0–310	16 000	0.70
188†	8.8×10^{-6}	0–130	17 500	0.87
200R17‡⇐	18.9×10^{-6}	−25–200	13 500	0.16
R 5 M‡⇐	13.4×10^{-6}	−20–200	16 000	0.06

* Telcon Limited.
† Corrosion-resistant type.
‡ Trimetals.

A straight bimetal strip of length L, thickness t, and width w, fixed at one end and free to move at the other, will produce a free end deflection of $d = 1.1\ K\,(\Delta T)L^2/t$ for a temperature change ΔT.

The force developed, if the free end is restrained from moving, is 1.1 $KE(\Delta T)wt^2/4L$, where E is its modulus of elasticity. Similarly, for a bimetal spiral or helical coil of radius r, the angular deflection is 130 $KL/(\Delta t)/t$ and the restrained force is 0.19 $KE(\Delta T)wt^2/r$.

The properties of a representative range of bimetals are given in *Table 10.9*.

10.9 Nuclear-reactor materials

10.9.1 Introduction

A detailed description of the engineering design and mode of operation of the principal reactor types is given in Chapter 19 of this book. Reference to that chapter shows how varied is the detailed design of the various commercial types and how this variation requires large differences in the materials used, particularly within the reactor core. In this section, these diverse materials are identified and the reasons for their selection highlighted.

Before proceeding, however, it is worth noting that all the important commercial reactor types are 'thermal', i.e. neutrons have average energies of <0.1 MeV. Such reactors use materials in six common applications:

(1) as fuel;
(2) as fuel cladding;
(3) as pressurised coolant;
(4) as a moderator which reduces neutron energies to thermal values;
(5) as a pressure vessel which contains the high-pressure coolant; and
(6) as radiation shields.

There is continuing interest in the *fast-reactor system* so-called because it produces nuclear fission using energetic, i.e. 'fast', neutrons with energies of >0.8 MeV. Such reactors have some of the components of the present 'thermal' designs (e.g. fuel, cladding and coolant), but they do not require a moderator or a pressure vessel since the coolant does not operate at high pressure. Again, Chapter 19 provides further details. Although prototypical reactors have been in operation for many years (e.g. in the UK and France), a larger European fast reactor power station is currently being designed. Final choices of alloys to be used within this system have yet to be made in important areas, e.g. the fuel cladding, and so the information given below will refer to the UK prototype fast reactor (PFR) at Dounreay in Scotland.

Table 10.10 summarises the various materials used within the cores of the major commercial reactor types but also including the PFR.

10.9.2 Fuels

The only naturally occurring fuel is the isotope ^{235}U, present in natural uranium to about 0.7% . Uranium occurs as a complex silicate ore, chiefly pitchblende, which also contains lead, thorium, iron, calcium, radium, bismuth, antimony and zinc.

However, kasolite (essentially, a lead uranyl silicate) and carnotite ($K_2O{\cdot}2UO_3{\cdot}V_2O_5{\cdot}3H_2O$) are also sources of uranium.

There are various methods of uranium extraction which depend in detail on the type of ore and the impurities it contains. In general, the ore is crushed (e.g. by ball milling), in order to increase chemical reaction rates, and then dissolved in either sulphuric or nitric acid. Thus, as an example, boiling of the ore in concentrated nitric acid would produce a nitrate solution of uranium as well as the principal metal impurities. Of the latter, radium may be precipitated by the addition of barium sulphate whereas iron, lead and manganese are removed by adding sodium carbonate. Uranyl nitrate may be decomposed thermally to produce UO_3. This higher oxide may then be reduced partially to UO_2 by high-temperature exposure to hydrogen-bearing gases or may be reduced completely to uranium metal by fluorination to UF_4 and subsequent reduction by magnesium.

Most modern designs of commercial nuclear reactors use uranium fuel (as UO_2) enriched in the ^{235}U isotope (see, for example, *Table 10.10*). Such enrichment is achieved by further fluorination of UF_4 to UF_6 and then making use of the different gaseous diffusion rates of $^{235}UF_6$ and $^{238}UF_6$ to achieve partial separation of the isotopes. An alternative technique of separation relies on the different masses of the isotopes and their response to centrifugal action. Such physical (rather than chemical) processes of separation are needed because the chemical properties of the isotopes are identical.

Early commercial reactors in Europe, USA, USSR and Japan relied on natural uranium metal as the fuel, but this technology has now been superseded by the world-wide use of UO_2 pellets. This change allows higher fuel temperatures to be used and higher conversion rates of the ^{235}U fuel. Both fuel types are enclosed in metal cans in order to

Table 10.10 A summary of the principal materials within the core of the main commercial reactor types

Reactor type	*Fuel*	*Fuel cladding*	*Coolant*	*Moderator*
MAGNOX	U metal (natural)	Magnox Al-80 (Mg/0.8% Al)	CO_2	Graphite
AGR	UO_2 (2% enriched)	20 Cr/25 Ni steel	CO_2	Graphite
PWR	UO_2 (3% enriched)	Zircaloy-4 (Zr/1.5 Sn/0.10 Cr/0.20 Fe)	H_2O	H_2O
BWR	UO_2 (3% enriched)	Zircaloy-2 (Zr/1.5 Sn/0.10 Cr/0.20 Fe/0.05 Ni)	H_2O	H_2O
CANDU	UO_2 (natural)	Zircaloy-4	D_2O	D_2O
RBMK-1000	UO_2 (2% enriched)	Zr–Nb alloy	H_2O	Graphite
PFR	PuO_2/UO_2 (24–30% enriched)	Type 316 stainless steel	Liquid sodium	None

MAGNOX = magnox alloy clad/U-metal fuel system
AGR = advanced gas-cooled reactor
PWR = pressurised water reactor
BWR = boiling water reactor
CANDU = Canada uranium deuterium
RBMK-1000 = Russian hybrid design
PFR = prototype fast reactor

contain the products of the nuclear reaction and to provide mechanical support and stability.

^{235}U fissions on interaction with a neutron having energy in the thermal range, typically $\leqslant$0.1 MeV—hence, its use in so-called 'thermal' reactors. By contrast, 'fast' reactors derive their name from the use of energetic neutrons (e.g. >1 MeV) to provide fission. ^{235}U cannot be used as a fuel in such cases and present fast-reactor designs employ ^{239}Pu as a fuel mixed as an oxide with UO_2.

10.9.3 Fuel cladding

The fuel cladding must provide structural support to the fuel stack and contain the fission products. Cladding materials must have a relatively low neutron absorption, have suitable low- and high-temperature strength and ductility, have good chemical compatibility with both the fuel and reactor coolant and have a resistance to property degradation as a result of neutron irradiation. Even though these requirements are particularly onerous, a number of cladding alloys have found service in commercial reactors.

The first generation of gas-cooled reactors used a magnesium–aluminium (Mg, 0.8% Al) cladding alloy, known as Magnox. This name has been adopted as the generic title of this reactor system. The alloy has a low melting temperature (ca. 923 K) and this, coupled with the use of uranium metal as fuel, means that only low T_2 temperatures can be used (ca. 685 K).

Accordingly, within the UK, the second generation of gas-cooled reactors (known as advanced gas-cooled reactors (AGRs)) made use of higher melting temperatures of both fuel and cladding: UO_2 for the former and 20% Cr, 25% Ni stainless steels for the latter. Although the latter material begins to melt at about 1630 K, normal operating temperatures will rarely exceed 1100 K, corresponding to a T_2 temperature of about 930 K. This relatively modest operating temperature, in relation to the solidus temperature, is dictated by the need to limit oxidation of the cladding in the CO_2 based coolant during normal operation and also to prevent melting under various postulated fault conditions. In addition, the conventional niobium stabilised steel cladding which is generally used, has relatively low creep strength at normal operating temperatures and this can result in mechanical interaction between the cladding and the UO_2 pellets during temperature and power changes. In the event that AGRs would ever be required to load follow, an alternative stainless-steel cladding, dispersion strengthened with titanium nitride particles, has been developed. The creep rate of this alloy at operating conditions is about a factor 10^3 less than that of the conventional alloy and, as a consequence, mechanical interaction with the pellet stack is much reduced.

However, the main development in thermal reactor systems world-wide has been to use pressurised water as coolant and a zirconium alloy as fuel cladding (*Table 10.10*). This alloy is nearly ideal under such conditions, having good neutron economy but also with high creep strength at operating temperatures (ca. 600 K) so that mechanical interaction with the fuel pellets is limited. Nevertheless, zirconium is chemically reactive both with the coolant and also with fission products contained within the fuel rod, particularly iodine. Operating constraints may be applied to limit such attack and the associated loss of load-bearing sections of the clad.

An important topical example is the potential problem of excessive waterside clad corrosion of zircaloy-4 in the pressurised water reactor (PWR) system at high power outputs or after extended dwell periods. Although zircaloy reacts readily with water at reactor temperatures to form ZrO_2, the rate of reaction decreases with time as a protective film of the oxide forms over the clad surface. For film thicknesses greater than about 2.5 μm, however, mechanical failure of the layer occurs and the corrosion rate increases. This sequence of events can repeat itself over the exposure period in reactor. This, in itself, is not a particular problem but the adherent surface oxide on the clad surface acts as a thermal insulation barrier which progressively raises the temperature of the oxide–metal interface as the oxide layer thickens. Obviously, the increase in temperature, for a given oxide thickness, is greater the greater is the heat flux, i.e. the greater is the power rating of the fuel. Since the corrosion rate appears to be determined by the temperature of the oxide–metal interface, a positive feedback is created which produces a progressive increase in corrosion rate with time.

Whereas all PWR systems can readily achieve their original design fuel burn-ups of 30 GW-d/te-U, waterside corrosion of zircaloy is now widely perceived to be the most economic threat to achieving significantly higher burn-ups, e.g. to 50 GW-d/te-U at useful power ratings. An associated issue is that a fraction, perhaps 10%, of the hydrogen released from water during the oxidation of the zirconium alloy enters the cladding and can produce mechanical embrittlement by precipitation of zirconium hydride platelets. This effect also is exacerbated at high burn-ups and, together with the issue of water-side corrosion, presents corrosion scientists with the challenge of improving the system's economics whilst still retaining high reliability and safety.

10.9.4 Coolant

Both the Magnox reactor system and the AGR use a pressurised CO_2 based coolant. Additions of CO, CH_4 and H_2O are made to this in a closely controlled manner to optimise gaseous reaction within the primary circuit. It is important to operate in a coolant which does not produce excessive oxidation of the graphite moderator since, in these reactor systems, the moderator also has a structural role and defines the location of fuel within the reactor core. This would be quite easily achieved by increasing the methane and/or carbon monoxide concentrations of the coolant but this also increases its carbon potential which could result in deposition of carbon on the fuel cladding and other core components. This is particularly important in the AGR since the steel cladding in this case contains both iron and nickel: elements which catalyse the deposition of carbon. Such deposits reduce the heat-transfer efficiency and will produce an increase in temperature of the cladding. Whereas, in practice, it is difficult to avoid some deposition, particularly in the AGRs, unacceptably bad behaviour can be prevented by good coolant control. Satisfactory current operation is achieved using a coolant with 1% CO.

Table 10.10 demonstrates that in the other principal thermal reactor designs the coolant is water, either light (H_2O) or heavy water (D_2O). Strict compositional control is also required in these cases. An excellent example of the balance that again needs to be struck between obtaining satisfactory fuel cladding behaviour without prejudicing other circuit or core components is offered by the PWR. In this case, the coolant is light water which contains up to 1200 volume parts per million (vpm) of boric acid which aids in reactivity control of the reactor. This addition lowers the pH of the water and produces an acidic solution which could dissolve iron rich components of the primary circuit. To minimise this, the coolant pH is raised (an ideal value would be to between 7.1 and 7.4) by the addition of an alkali. In nearly all Western plants, the alkali used is lithium hydroxide (LiOH), but its concentration tends to be limited to a maximum value of 2.2 ppm of lithium equivalent. This produces a coolant pH of 6.9, i.e. a little more acidic than the ideal. The reason for this is the wide-spread concern that higher lithium levels would increase the corrosion rate of the zircaloy cladding. This particular aspect is the subject of much world-wide investigation at the moment.

The generation of large quantities of heat in the relatively small core of a fast reactor necessitated the use of a liquid sodium coolant to achieve adequate heat transfer in the early conceptual designs of this system. This choice has been maintained in present prototypes. An advantage of such a coolant is that pressurisation is unnecessary but there are obvious disadvantages in the necessity to avoid water ingress from the secondary side of the heat-exchanger system and also in the need for separate heating circuits to avoid freezing during shutdown conditions. With recent advances in gas-circulator technology, it is now feasible to design a gas-cooled fast reactor using a pressurised CO_2 coolant.

10.9.5 Moderator

Thermal reactors require moderators to slow down fast neutrons to a sufficiently low energy to permit a fission reaction to occur with the ^{235}U isotope. In addition, the loss of neutrons within the moderator must be kept low in order that sufficient remain within the core for a chain reaction to proceed. Of the common moderator materials, *viz.* light water, heavy water and graphite, the last two provide good neutron economy and permit the use of unenriched fuel, e.g. in the Magnox and Canada Uranium Deuterium (CANDU) systems (*Table 10.10*); reactors moderated by light water, e.g. PWR and boiling water reactor (BWR), require some enrichment in the ^{235}U content of the fuel.

In the commercial gas-cooled reactors, graphite is used as a moderator. In practice, each pile consists of a vertical arrangement of fuel elements penetrating a large block of graphite fabricated from individual bricks. As has been pointed out earlier, the moderator in these cases has a structural role also and its oxidation in the CO_2 coolant is controlled by additions of CO, CH_4 and H_2O. Although the Magnox reactors operate with unenriched fuel, the AGR fuel pellets need to contain about 2% ^{235}U to compensate for neutron losses within the steel components of the core (e.g. the fuel cladding is an advanced stainless steel).

The use of heavy water as a moderator has been pioneered by the Canadians in their CANDU system. In this design (see Chapter 19), the moderator 'block' is termed a *calandria* and is a large stainless-steel vessel holding the heavy water at atmospheric pressure. Some 400 horizontal pipes or 'channels' exist within this block and these contain individual fuel elements enclosed in a pressure tube. The pressurised coolant which passes through each pressure tube is also heavy water and contributes to the overall moderation. Again it is possible to use unenriched fuel (as UO_2 in this case).

Light-water reactors, as their name implies, use light water as both coolant and moderator. However, there is no physical segregation of function, the coolant/moderator being allowed to flow freely through the reactor core. This leads to a particularly simple design and relatively small structures. Nevertheless, enriched fuel needs to be used (typically, up to 4% ^{235}U) to compensate for poor moderator economy.

A hybrid design has been developed on a large scale in the USSR. This, identified as the RBMK-1000 type in *Table 10.10*, uses light water as coolant but with graphite moderation. This combination of coolant and moderator can result in large positive void coefficients of reactivity; that is, an increase in core reactivity will occur following a reduction in coolant flow or increase in coolant temperature. For this particular design, such an increase in reactivity also produces an increase in reactor power, particularly at low power levels. The combination makes control difficult and was a contributing factor to the accident which befell this reactor type at Chernobyl.

10.9.6 Pressure vessel

All thermal reactors use a pressurised coolant so that the integrity of the primary system is a principal factor in reactor operation and safety. Most designs rely on a single, large pressure vessel but pressure-tube reactors enclose each fuel channel in a miniature cylindrical vessel or pressure tube.

The most widespread material for the construction of large pressure vessels is mild or low-alloy steel, manufactured to a wall thickness which varies with reactor type, e.g. 120 mm in the early Magnox stations to greater than 200 mm for PWR. A problem with such materials is the need always to demonstrate that brittle fracture of the vessel will not occur, particularly since neutron irradiation may itself tend to cause embrittlement. Only relatively simple cylindrical shapes are used for these vessels and contain a minimum of through-wall penetrations. As a consequence, the pressurised primary circuit extends beyond this pressure boundary and so similarly high standards of integrity need to be applied to the other components of this circuit, e.g. pipework, the recirculation pumps, steam drums, steam generators.

These difficulties were overcome in the later Magnox designs and in the AGR stations by the use of prestressed concrete vessels. These tend to be very large, e.g. 30 m high and 26 m in diameter, and contain the primary circuit components. The obvious disadvantages are the need for large on-site construction facilities, subsequent limited access and the requirement to use internal thermal insulation (based on stainless-steel-foil packages) to limit the temperature rise of the vessel.

A quite different approach is offered by the pressure tube reactors, e.g. CANDU and RBMK-1000. Here, the pressurised circuit is split into numerous small vessels or pressure tubes, each of which contains a single fuel channel. The tube wall is of a zirconium alloy (e.g. Zr, 2.5% Nb) which is separated by a gaseous (typically nitrogen) thermal insulation gap from the walls of the calandria in the CANDU system or is located within a graphite ring in the RBMK-1000 system. The obvious advantage is that the failure of a single pressure tube will not prejudice the integrity of the reactor, provided that such failure cannot propagate from one channel to another, e.g. by the release of high-energy debris. It is for this reason that much attention is paid to the corrosion rate of the inner surface of the pressure tube and the associated pick up of deuterium or hydrogen, since subsequent solid-state reaction with zirconium can lead to the precipitation of brittle intermetallic compounds.

10.9.7 Shield

The reactor shield must attenuate neutrons and γ-radiation. In most cases, the cheapest material is heavy concrete such as barytes concrete in which crude barium sulphate replaces the normal aggregate.

10.10 Amorphous materials

For many years soft magnetic alloys have been made by a casting, hot rolling and cold rolling regime. Development of such materials has concentrated on the reduction of impurities and the promotion of appropriate grain growth and metallurgical structure. More recently, a class of materials has emerged which uses quite different principles. Amorphous metals have no definite crystal structure and are cast from a melt in such a way that cooling to final thickness is very rapid (of the order of 10^6 °C/s). By an appropriate choice of composition which will include a ferromagnetic metal and 'glass forming' elements, plus the rapid cool, a structure is produced which is 'amorphous' in that no definite crystals are formed (as confirmed by X-ray crystal analysis). In such a structure, domain walls experience no lower energy in one position than another and so can move very freely to effect changes in magnetisation.

To achieve such very rapid cooling the material has necessarily to be very thin (of the order of 20–50 μm) and of quite high electrical resistance (of the order of 1.00–1.5 μΩ-m) due to the presence of glass formers such as boron. The combination of freely movable domain walls, high resistivity and low thickness combine to give a material of very low power loss.

Potential application areas for this new class of material can be broadly divided into two categories: power transformers, and electronic/high-frequency devices.

Table 10.11 Comparison of commercial grain-oriented silicon–iron and amorphous material

	3% Silicon–iron 0.3 mm thick	*Iron based amorphous alloy Metglas 2605S-2 0.33 mm thick*	*Consolidated amorphous strip POWERCORE 0.13 mm thick*
Curie temperature (°C)	745	415	415
Crystallisation temperature (°C)	—	550	540
Maximum working temperature (°C)	≈650	150	125
Tensile strength (MPa)	320–360	≥1500–2000 (as cast)	—
Yield strength (MPa)	300–320	1500–2000 (as cast)	—
Resistivity (μΩ-m)	0.45–0.48	1.37	1.37
Laminations factor (%)	95–98	80	90
Loss at 1.2 T, 50 Hz (W/kg)	0.64	0.11	0.12
Loss at 1.5 T, 50 Hz (W/kg)	0.83	0.27	0.28
Specific apparent power at 1.3 T (V-A/kg)	0.69	0.54	0.25
Specific apparent power at 1.5 T (V-A/kg)	0.94	2.33	1.3
Coercive force (A/m)	6.4	1.6–2.5	2.0
Saturation induction (T)	2.03	1.56	1.56

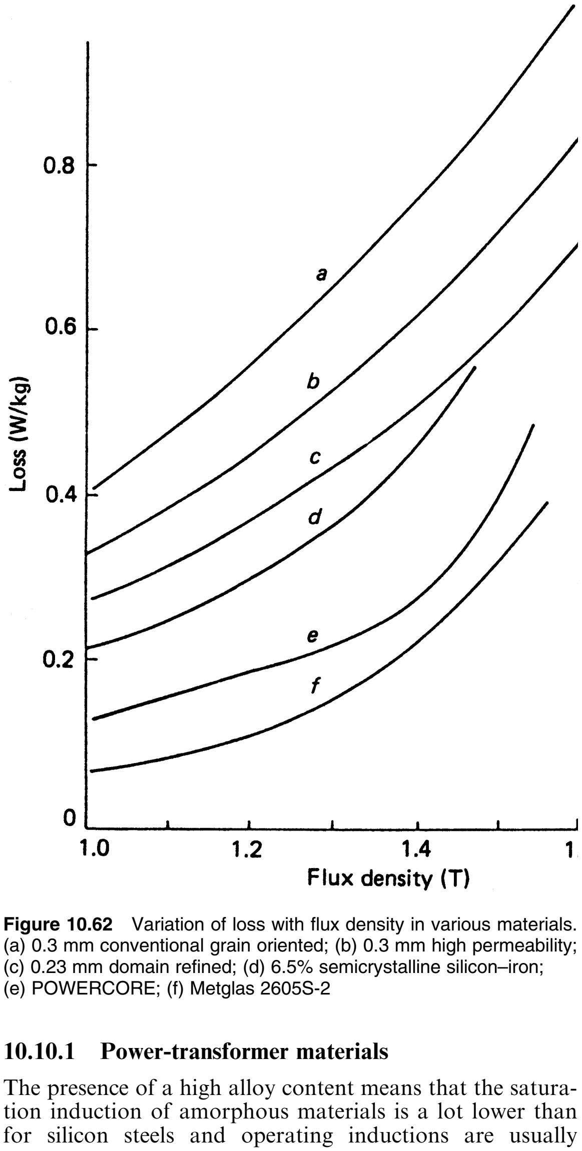


Figure 10.62 Variation of loss with flux density in various materials. (a) 0.3 mm conventional grain oriented; (b) 0.3 mm high permeability; (c) 0.23 mm domain refined; (d) 6.5% semicrystalline silicon–iron; (e) POWERCORE; (f) Metglas 2605S-2

10.10.1 Power-transformer materials

The presence of a high alloy content means that the saturation induction of amorphous materials is a lot lower than for silicon steels and operating inductions are usually confined to 1.5 T and below. At such inductions, power losses are of the order of one-third of those for grain-oriented electrical steels.

The mechanical properties of amorphous materials are less convenient. Amorphous materials are hard, brittle and difficult to cut accurately. Also, amorphous metals are very stress sensitive, so that cores must be built very carefully to avoid the degradation of magnetic properties which can follow from stress.

The production of power-transformer cores from amorphous metals is still at an early stage of development; however, transformers with wound cores designed to use thin amorphous ribbon directly are under widespread evaluation in the USA. In Europe where three-phase cut cores are more common, the employment of amorphous cores is more difficult.

Allied Signal Inc. in the USA has produced a multi-layered version of amorphous ribbon in which six or more layers of basic ribbon are bonded to give a composite strip which can be cut and stacked into three-phase cores. This material is sold by Allied Signal Inc. as 'Powercore'.

Magnetic and physical properties of a grade of amorphous foil material (Allied Signal Metglas 2605S-2) and of Powercore are given in *Table 10.11*.[1] *Figure 10.62* compares the loss versus induction performance of amorphous and cold-rolled materials.[1]

The future of amorphous materials in the electrotechnical world will depend on the equilibrium which may be reached between attractively low power losses, physical difficulty of employment, stress sensitivity, reduced saturation induction and cost.

Any trend making for increased energy costs and a drive towards the conservation of energy is likely to favour amorphous materials for at least some applications.

10.10.2 High-frequency-device materials

The amorphous alloys developed to compete with silicon iron for the large power transformer market have compositions which are based on relatively cheap elements, i.e. iron, boron and silicon. These alloys have a high magnetostriction which inhibits their ability to develop high permeabilities and low coercive force. It was therefore necessary to develop a different type of alloy based on cobalt or nickel, with a low magnetostriction, to enable the amorphous materials to extend their application potential. The typical properties of these alloys are detailed in *Table 10.12*.

Table 10.12 Properties of low magnetostriction amorphous alloys*

Material	$Fe_{40}Ni_{40}(MoBSi)_{20}$	$(CoFe)_{70}(MoBSi)_{30}$
Magnetostriction ($\times 10^{6}$ m/m)	8	0.3
Coercive force (A/m)	3	0.5
Saturation flux density (T)	0.8	0.55
Permeability at 0.4 A/m	25 000	250 000
Maximum permeability	200 000	500 000
Loss at 0.2 T, 100 kHz (W/kg)	65	35
Resistivity (μΩ-m)	1.3	1.3
Curie temperature (°C)	250	250
Crystallisation temperature (°C)	450	450
Hardness (VPN)	800	1000
Maximum operating temperature (°C)	120	80

* Alloys of this type are supplied by Vacuumschmelze, Germany and Allied Signal Inc., USA.
VPN = Vickers pyramid hardness.

Important characteristics to be noted are their low losses at high frequency, low coercive force, high permeability, and very high hardness. Hitherto, due to their expense and limited forms of supply, the commercial application of high-frequency-devices has been restricted to areas where these properties can be used to best advantage. These include inductive components for switched-mode power supplies, pulse transformers, transductors, electromechanical sensors and tape-recorder heads where their high mechanical hardness provides excellent wear resistance.

Great care has to be taken with amorphous alloys not to exceed the maximum operating temperature recommended by the manufacturers since the amorphous structure is unstable at elevated temperatures and can cause the alloy to crystallise. The magnetic performance of the crystalline alloy is substantially inferior to that of the amorphous form. It has recently been discovered, however, that if the crystal size is restricted to nanometres, in an alloy of composition $Fe_{73.5}Cu_1Nb_3\ Si_{16.5}B_6$, low field permeabilities of 10^4 can be obtained. These nanocrystalline alloys could find wider application than the zero magnetostriction amorphous alloys due to their low basic raw-material cost.

Reference

1 MOSES, A. J. *IEE Proceedings*, **137**, 233 (1990)