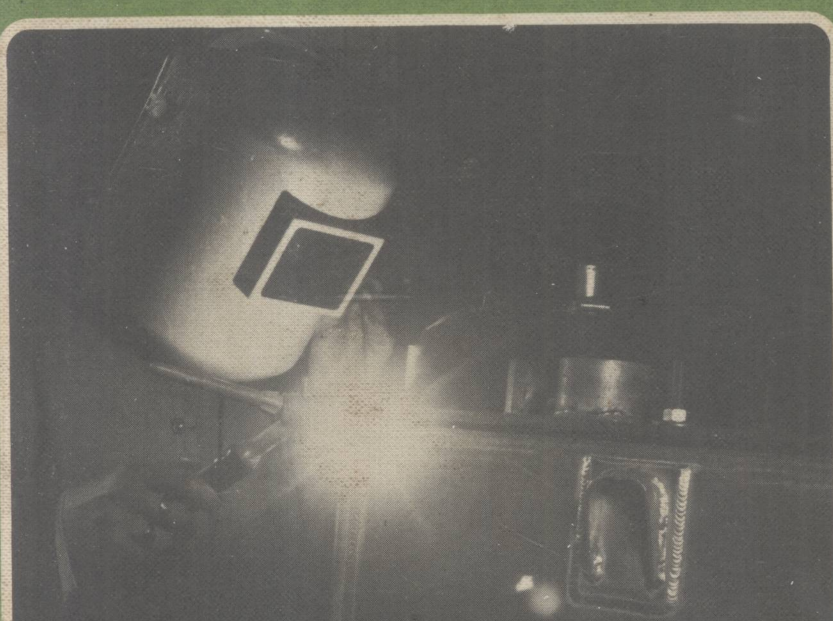
THE SCIENCE AND PRACTICE OF WELDING

SEVENTH EDITION

A.C. DAVIES



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The science and practice of welding

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The science and practice of welding

Preface

The book has been extensively revised with new sections on submerged arc, stud (arc and capacitor), explosive and gravity processes. A new chapter has been added on resistance welding and many sections have been brought up to date including the new processes in iron and steel production, and additional information is included in the chapters on TIG and MIG processes. The new electrode classification to BS 639 1976 has been included together with impact machines and testing.

My thanks are due to each and all of the following firms who have helped me in every way by offering advice and supplying information and photographs as indicated.

A.I. Welders Ltd: flash butt welding technology and photograph.

Air Products Cryogenic Division: the welding of aluminium alloys and stainless steel, with illustrations and details of impact tests.

Avery-Denison Ltd: impact testing machines and photographs.

British Oxygen Co. Ltd: oxy-acetylene welding equipment and photographs, industrial gases and diagrams, manual metal arc welding electrodes and filler wires, manual metal arc, TIG, MIG and plasma welding plant and plasma cutting with diagrams and photographs.

Copper Development Association: the welding of copper and its alloys.

Crompton Parkinson Ltd: stud welding with diagrams.

ESAB Ltd: manual metal arc welding electrodes and filler wires, manual metal arc, TIG, MIG, submerged arc, gravity, and electroslag welding equipment, positioners, and robot welding with illustrations and photographs.

G.K.N. Lincoln Ltd: submerged arc welding equipment, wire electrodes and fluxes.

British Railways Board: details of flash butt and thermit welding of rails and diagrams of 'adjustment switch'.

British Steel Corporation, Library and Information Services of the Sheffield Laboratories: modern blast furnaces, direct reduction of iron ores, basic oxygen steel, electric arc steel with illustrations.

KSM Stud Welding Ltd: stud welding with diagrams.

Pirelli General Cable Co.: welding cables.

The Welding Institute: information on the classification of electrodes.

Cooperheat Ltd: pre- and post-heating equipment with photographs.

Sciaky Ltd: spot, seam projection and other types of resistance welding with photographs, laser beam welding with photograph.

Henry Wiggin Ltd: the welding of nickel and nickel alloys.

Union Carbide UK Ltd: TIG and MIG technology, plasma welding, cutting and surfacing technology with diagrams.

Yorkshire Imperial Metals Ltd: explosive welding with diagrams.

Birlec Ltd: induction furnace photograph.

Rockweld Ltd: photographs of CO_2 welding equipment.

Gamma-Rays Ltd: information on non-destructive testing with photographs of radiographic equipment.

I would again like to express my thanks to the City and Guilds of London Institute for permission to reproduce, with some amendments, examination questions set in recent years and to Mr D. G. J. Brunt, T.ENG (C.E.I), F.I.T.E., ASSOC. MEM.I.E.E., M.WELD.I., for help in the reading of proofs, and to Mr M. S. Wilson, B.SC., M.MET., for help in the revised sections in metallurgy.

Abstracts of British Standards are included by permission of the British Standards Institution, 2 Park Street, London, from whom copies of the latest complete standards may be obtained.

The terms TIG, MIG and CO_2 have been retained for these welding processes, pending revision of BS 499, as they are so widely used. The use of gas mixtures of inert and active gases (argon–oxygen, argon–oxygen–CO_2, argon–hydrogen, etc.) as the shielding gas together with the pulsed, modulated feed, modulated arc length and flux cored processes, etc. have made the present terminology rather inadequate.

Oswestry
1977

A. C. Davies

Preface to the sixth edition

I would like to express my thanks to the following firms for their co-operation and help during the writing of the previous five editions of this book:

Air Products Ltd; Associated Electrical Industries; Aluminium Federation; B.E.A.M.A.; British Aluminium Co. Ltd; British Insulated Callenders Cables Ltd; British Oxygen Co. Ltd; British Welding Research Association; Buck and Hickman Ltd; Copper Development Association; Deloro Stellite Ltd; English Electric Co. Ltd; English Steel Corporation; Firth Vickers Stainless Steels; Samuel Fox and Co. Ltd; Fusarc Co. Ltd; Gamma Rays Ltd; Kelvin Hughes and Co. Ltd; Laurence Scott and Electromotors; Lincoln Electric Co. Ltd; Magnesium Elektron Ltd; Magnesium Industry Council; Metalectric Furnaces; Mond Nickel Co.; Murex-Quasi-Arc Ltd; Rockweld Ltd; Siemens UK Ltd; Thorn and Hoddle Ltd; Weldcraft Ltd.

The change from the Imperial to the SI system of units is already well under way in the welding industry and it was felt that an SI edition of this book would be acceptable to students of welding.

The book has been extensively revised with new chapters on TIG, plasma arc, gas shielded metal arc (MIG, CO_2 and mixed gases) and additional sections have been included on electrical and welding technology with a view to the needs of the welding technician.

My thanks are due to all of the following firms who have been helpful in every way by supplying information as indicated.

Air Products Ltd: techniques used in TIG, MIG and pulse fabrications in aluminium alloys and stainless steel.

A.I. Welders Ltd: friction welding and photographs.

Aluminium Federation: the weldability of aluminium and its alloys.

British Aluminium Co.: the weldability of aluminium and its alloys.

British Oxygen Co. Ltd: basic technology of TIG, plasma, MIG, pulse arc processes and their applications, metal-arc welding and metal-arc

welding electrodes, industrial gases, and the provision of many diagrams and photographs.

Copper Development Association: the weldability of copper and its alloys.

Distillers Co. (Carbon Dioxide) Ltd: production of carbon dioxide.

Firth Vickers Stainless Steels Ltd: the metallurgy and weldability of stainless and heat-resistant steels.

G.K.N. Lincoln Ltd: the CO_2 welding process, and photographs.

Magnesium Elektron Ltd: the weldability of the magnesium alloys.

Pirelli General Cable Co. Ltd: welding cables and recent developments.

Sandvik UK Ltd: stainless steel welding wire details.

Union Carbide Ltd: TIG, MIG, and plasma welding technology and diagrams.

Henry Wiggin Ltd: the metallurgy and weldability of monel and nickel alloys.

I would also like to express my thanks to the City and Guilds of London Institute for permission to reproduce, with some amendments, examination questions set in recent years and to Mr D. G. J. Brunt, M.I.T.E., ASSOC. MEM.I.E.E., M.WELD.I., for help in the reading of proofs.

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The metric system and the use of SI units

The metric system was first used in France after the French Revolution and has since been adopted for general measurements by all countries of the world except the United States. For scientific measurements it is generally used universally.

It is a decimal system, based on multiples of ten, the following multiples and sub-multiples being added, as required, as a prefix to the basic unit.

Prefix	Symbol	Multiplying factor		
pico-	p	0.000 000 000 001	or	10^{-12}
nano-	n	0.000 000 001	or	10^{-9}
micro-	μ	0.000 001	or	10^{-6}
milli-	m	0.001	or	10^{-3}
centi-	c	0.01	or	10^{-2}
deci-	d	0.1	or	10^{-1}
deca-	da	10	or	10^{1}
hecto-	h	100	or	10^{2}
kilo-	k	1 000	or	10^{3}
mega-	M	1 000 000	or	10^{6}
giga-	G	1 000 000 000	or	10^{9}
tera-	T	1 000 000 000 000	or	10^{12}

Examples of the use of these multiples of the basic unit are: hectobar, milliampere, meganewton, kilowatt.

In past years, the CGS system, using the centimetre, gram and second as the basic units, has been used for scientific measurements. It was later modified to the MKS system, with the metre, kilogram and second as the basic units, giving many advantages, for example in the field of electrical technology.

Note on the use of indices

A velocity measured in metres per second may be written m/s, indicating that the second is the denominator, thus: $\frac{\text{metre}}{\text{second}}$ or $\frac{\text{m}}{\text{s}}$. Since $\frac{1}{a^n} = a^{-n}$, the velocity can also be expressed as metre second^{-1} or m s^{-1}. This method of expression is often used in scientific and engineering articles. Other examples are, pressure and stress: newton per square metre or pascal (N/m^2 or Nm^{-2}); density: kilograms per cubic metre (kg/m^3 or kg m^{-3}).

SI units (Système Internationale d'Unités)

To rationalize and simplify the metric system the Système Internationale d'Unités was adopted by the ISO (International Organization for Standardization). In this system there are six primary units, thus:

Quantity	Basic SI unit	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
temperature	kelvin	K
luminous intensity	candela	cd

In addition there are derived and supplementary units, thus:

Quantity	Unit	Symbol
plane angle	radian	rad
area	square metre	m^2
volume[1]	cubic metre	m^3
velocity	metre per second	ms
angular velocity	radian per second	rad/s
acceleration	metre per second squared	m/s^2
frequency	hertz	Hz
density	kilogram per cubic metre	kg/m^3
force	newton	N
moment of force	newton metre	Nm
pressure, stress	newton per square metre	N/m^2 (or pascal, Pa)
surface tension	newton per metre	N/m
work, energy, quantity of heat	joule	J (Nm)

Quantity	Unit	Symbol
power, rate of heat flow	watt	W (J/s)
impact strength	joule per square metre	J/m^2
temperature	degree Celsius	°C
thermal coefficient of linear expansion	reciprocal degree Celsius or kelvin	$°C^{-1}$, K^{-1}
thermal conductivity	watt per metre degree C	W/m°C
coefficient of heat transfer	watt per square metre degree C	$W/m^2°C$
heat capacity	joule per degree C	J/°C
specific heat capacity	joule per kilogram degree C	J/kg°C
specific latent heat	joule per kilogram	J/kg
quantity of electricity	coulomb	C (As)
electric tension, potential difference, electromotive force	volt	V (W/A)
electric resistance	ohm	Ω (V/A)
electric capacitance	farad	F
magnetic flux	weber	Wb
inductance	henry	H
magnetic flux density	tesla	T (Wb/m^2)
magnetic field strength	ampere per metre	A/m
magnetomotive force	ampere	A
luminous flux	lumen	lm
luminance	candela per square metre	cd/m^2
illumination	lux	lx

[1] *Note*. N m^3 is the same as m^3 at normal temperature and pressure, i.e. 0 °C and 760 mm Hg (NTP or STP).

The litre is used instead of the cubic decimetre (1 litre = 1 dm^3) and is used in the welding industry to express the volume of a gas.

Pressure and stress many also be expressed in bar (b) or hectobar (hbar) instead of newton per square metre.

Conversion factors from British units to SI units are given in the appendix.

1 metric tonne = 1000 kg.

Contents

1

Welding science

HEAT

Solids, liquids and gases: atomic structure

Substances such as copper, iron, oxygen and argon which cannot be broken down into any simpler substances are called elements; there are at the present time over 100 known elements. A substance which can be broken down into two or more elements is known as a compound.

An *atom* is the smallest particle of an element which can take part in a chemical reaction. It consists of a number of negatively charged particles termed electrons surrounding a massive positively charged centre termed the nucleus. Since like electric charges repel and unlike charges attract, the electrons experience an attraction due to the positive charge on the nucleus. Chemical compounds are composed of atoms, the nature of the compound depending upon the number, nature and arrangement of the atoms.

A molecule is the smallest part of a substance which can exist in the free state and yet exhibit all the properties of the substance. Molecules of elements such as copper, iron and aluminium contain only one atom and are mon-atomic. Molecules of oxygen, nitrogen and hydrogen contain two atoms and are di-atomic. A molecule of a compound such as carbon dioxide contains three atoms and complicated compounds contain many atoms.

An atom is made up of three elementary particles: (1) protons, (2) electrons, (3) neutrons.

The *proton* is a positively charged particle and its charge is equal and opposite to the charge on an electron. It is a constituent of the nucleus of all atoms and the simplest nucleus is that of the hydrogen atom which contains one proton.

The *electron* is 1/1836 of the mass of a proton and has a negative charge equal and opposite to the charge on the proton. The electrons form a cloud around the nucleus moving within the electric field of the positive charge and around which they are arranged in shells.

The *neutron* is a particle which carries no electric charge but has a mass equal to that of the proton and is a constituent of the nuclei of all atoms except hydrogen. The atomic number of an element indicates the number of protons in its nucleus and because an atom in its normal state exhibits no external charge, it is the same as the number of electrons in the shells.

Isotopes are forms of an element which differ in their atomic mass but not in some of their chemical properties. The atomic weight of an isotope is known as its mass number. For example, an atom of carbon has 6 protons and 6 neutrons in its nucleus so that its atomic number is 6. Other carbon atoms exist, however, which have 7 neutrons and 8 neutrons in the nucleus. These are termed isotopes and their mass numbers are 13 and 14 respectively, compared with 12 for the normal carbon atom. One isotope of hydrogen called heavy hydrogen or deuterium has a mass number 2 so that it has one proton and one neutron in its nucleus.

Electron shells. The classical laws of mechanics as expounded by Newton do not apply to the extremely minute world of the atom and the density, energy and position of the electrons in the shells are evaluated by quantum or wave mechanics. Since an atom in its normal state is electrically neutral, if it loses one or more electrons it is left positively charged and is known as a *positive ion*; if the atom gains one or more electrons it becomes a *negative ion*. It is the electrons which are displaced from their shells, the nucleus is unaffected, and if the electrons drift from shell to shell in an organized way in a completed circuit this constitutes an electric current.

In the *periodic classification*, the elements are arranged in order of their mass numbers, horizontal rows ending in the inert gases and vertical columns having families of related elements.

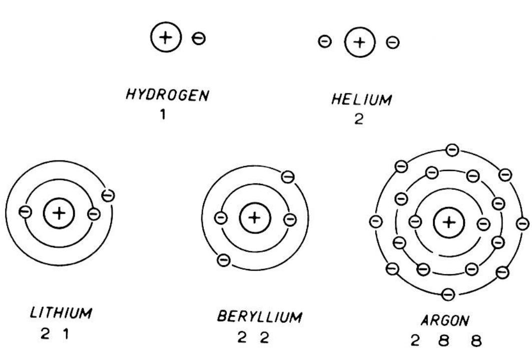

Fig. 1.1

The lightest element, hydrogen, has one electron in an inner shell and the following element in the table, helium, has two electrons in the inner shell. This shell is now complete so that for lithium, which has three electrons, two occupy the inner shell and one is in the next outer shell. With succeeding elements this shell is filled with electrons until it is complete with the inert gas neon which has two electrons in the inner shell and eight in the outer shell, ten electrons in all. Sodium has eleven electrons, two in the inner, eight in the second and one in a further outer shell. Electrons now fill this shell with succeeding elements until with argon it is temporarily filled with eight electrons so that argon has eighteen electrons in all. This is illustrated in Fig. 1.1 and this brief study will suffice to indicate how atoms of the elements differ from each other. Succeeding elements in the table have increasing numbers of electrons which fill more shells until the table is, at the present time, complete with just over 100 elements.

hydrogen 1	helium 2						
lithium 2 1	beryllium 2 2	boron 2 3	carbon 2 4	nitrogen 2 5	oxygen 2 6	fluorine 2 7	neon 2 8
sodium 2 8 1	magnesium 2 8 2	aluminium 2 8 3	silicon 2 8 4	phosphorus 2 8 5	sulphur 2 8 6	chlorine 2 8 7	argon 2 8 8

The shells are then filled up thus:

2	8.				
2	8	8.			
2	8	18.			
2	8	18	8.		
2	8	18	18.		
2	8	18	18	8.	
2	8	18	32	18.	
2	18	18	32	18	8.

The electrons in their shells possess a level of energy and with any change in this energy light is given out or absorbed. The elements with completed or temporarily completed shells are the inactive or inert gases helium, neon, argon, xenon and radon, whereas when a shell is nearly complete (oxygen, fluorine) or has only one or two electrons in a shell (sodium, magnesium), the element is very reactive, so that the characteristics of an element are greatly influenced by its electron structure. When a metal filament such as tungsten is heated in a vacuum it emits electrons, and if a positively charged plate (anode) with an aperture in it is put in front near the filament, the electrons stream through the aperture attracted by the positive charge and form an electron beam.

This beam can be focused and guided and is used in the television tube, while a beam of higher energy can be used for welding by the electron beam process (see p. 508).

If the atoms in a substance are not grouped in any definite pattern the substance is said to be amorphous, while if the pattern is definite the substance is crystalline. Solids owe their rigidity to the fact that the atoms are closely packed in geometrical patterns called space lattices which, in metals, are usually a simple pattern such as a cube. The positions which atoms occupy to make up a lattice can be observed by X-rays.

Atoms vibrate about their mean position in the lattice, and when a solid is heated the heat energy supplied increases the energy of vibration of the atoms until their mutual attraction can no longer hold them in position in the lattice so that the lattice collapses, the solid melts and turns into a liquid which is amorphous. If we continue heating the liquid, the energy of the atoms increases until those having the greatest energy and thus velocity, and lying near the surface, escape from the attraction of neighbouring atoms and become a vapour or gas. Eventually when the vapour pressure of the liquid equals atmospheric pressure (or the pressure above the liquid) the atoms escape wholesale throughout the mass of the liquid which changes into a gaseous state and the liquid boils.

Suppose we now enclose the gas in a closed vessel and continue heating. The atoms are receiving more energy and their velocity continues to increase so that they will bombard the walls of the vessel, causing the pressure in the vessel to increase.

Atoms are grouped into molecules which may be defined as the smallest particles which can exist freely and yet exhibit the chemical properties of the original substance. If an atom of sulphur, two atoms of hydrogen, and four atoms of oxygen combine, they form a molecule of sulphuric acid. This molecule is the smallest particle of the acid which can exist since if we split it up we are back to the original atoms which combined to form it.

From the foregoing, it can be seen that the three states of matter – solids, liquids and gases – are very closely related, and that by giving or taking away heat we can change from one state to the other. Ice, water and steam give an everyday example of this change of state.

Metals require considerable heat to liquefy or melt them, as for example, the large furnaces necessary to melt iron and steel.

We see examples of metals in the gaseous state when certain metals are heated in the flame. The flame becomes coloured by the gas of the metal, giving it a characteristic colour, and this colour indicates what metal is being heated. For example, sodium gives a yellow coloration and copper a green coloration.