

COMISION NACIONAL DE ENERGIA ATOMICA
DEPENDIENTE DE LA PRESIDENCIA DE LA NACION

TERCER CURSO PANAMERICANO DE METALURGIA

SOME SUBJECTS ON WELDING TECHNOLOGY

Dr. R. L. Apps
(The College of Aeronautics, Cranfield, Inglaterra)

Departamento de Metalurgia
Buenos Aires - Argentina
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Pressure Welding
(No Fusion)

Cold Hot
Roll Indent- Ultra- Roll Friction Die Forge
Bonding tation sonic Bonding Welding Welding Welding

Fusion Welding

Resistance Oxy- Gas Electro Electron Laser
Arc Slag Beam

Flash Resistance Pro- Seam Spot
Butt Butt jecton

Inert Gas Shielded

Slag Shielded

Non-consumable Electrode

Plasma Arc

Atomic Hydrogen

TIG

Carbon Arc

Consumable Electrode
(MIG)

MIG- Argon Helium shielded

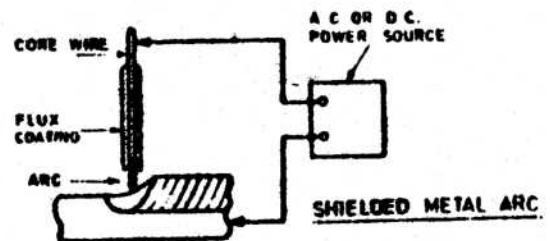
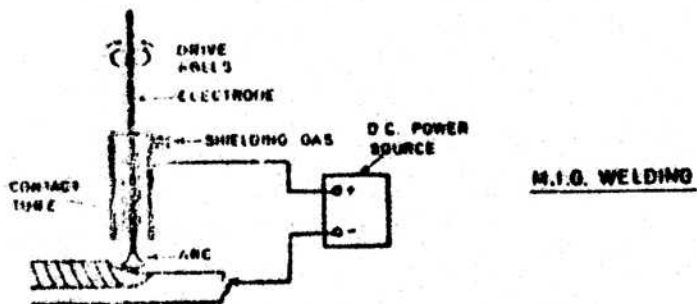
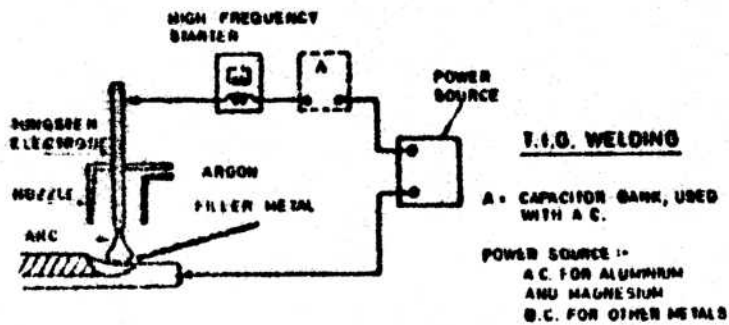
Flux Cored Processes

Shielded Metal Arc

Submerged Arc

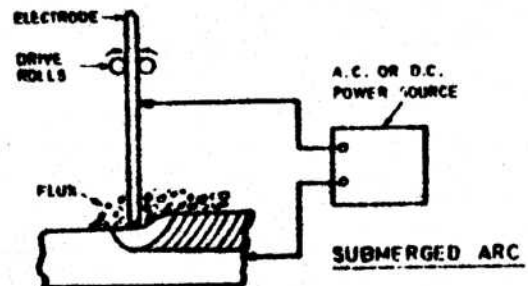
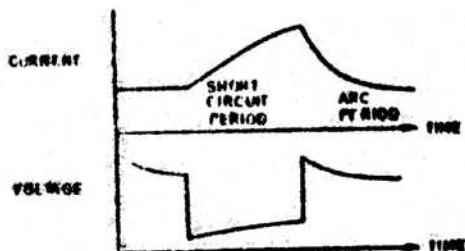
MIG-CO₂ shielded

Spray transfer Dip transfer

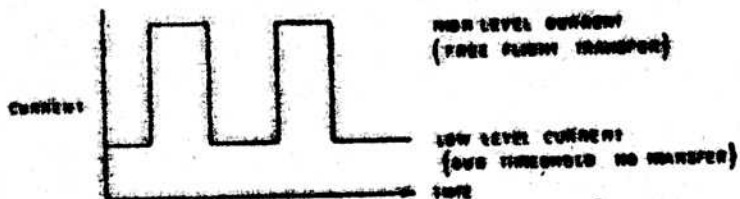


MIG WELDING WAVEFORMS

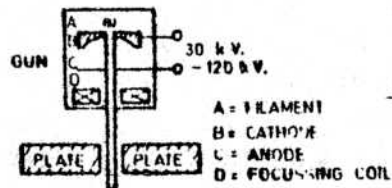
DIP TRANSFER - CO₂ SHIELD



PULSED TRANSFER

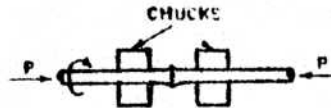


ELECTRON BEAM WELDING

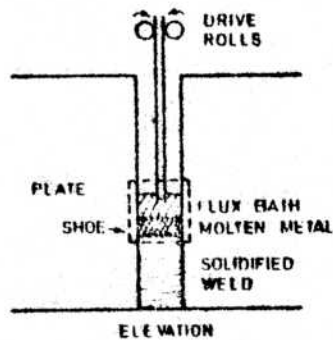


NOTE:- WELDING CARRIED OUT UNDER VACUUM

FRICTION WELDING

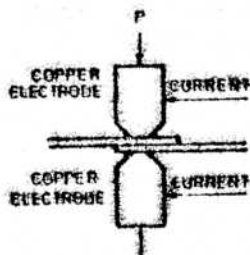
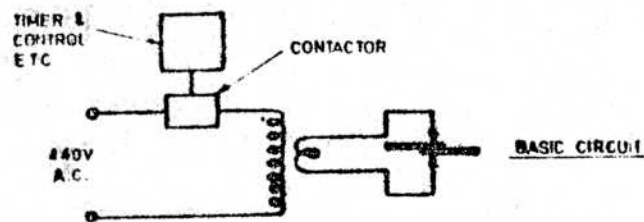


ELECTROSLAG

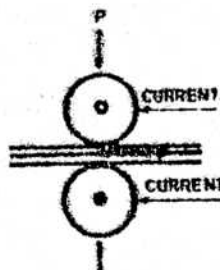


A = WATER COOLED COPPER SHOES
E = ELECTRODE

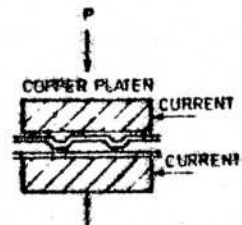
RESISTANCE WELDING.



RESISTANCE SPOT WELDING



RESISTANCE SEAM WELDING



PROJECTION WELDING

DEFECTS IN MILD OR LOW ALLOY STEELS

Should introduce by saying that defects can be introduced as the fault of operator technique, weld settings, faulty equipment, wrong choice of equipment. First two are most usual, third growing with automatic welding.

Aim should be to produce defect free welds, which means careful control at all stages i.e.

- (1) Design and Drawing Office - detailed for welding with full information, dh welding where possible.
- (2) Selection of materials - optimum weldability consistent with properties.
- (3) Preparation of materials - cutting to size, edge preparations, cleanliness.
- (4) Equipment - must be adequate for job, well maintained.
- (5) Welding - correct preheat, welding conditions, efficient welder, supervision, electrodes.
- (6) Post-heat treatment, (stress relief or anneal etc.) - correct control - can get cracking if heating too rapid.
- (7) Inspection - use of various methods where justified.

Use of detailed records (allocate responsibility), inspection.

DEFECTS IN ARC WELDS

1. Incomplete penetration

Weld metal fails to reach root of joint or to fuse with root faces of parent plate - voids or slag in root.

Penetration depends on correct electrode size and type in relation to joint (N.B. Penetrating power of electrode must also be considered e.g. - close butt welds need deep penetration electrodes.), correct welding current, suitable joint preparation to allow proper manipulation of electrode. Accurate joint preparation and fit up essential and should be specified.

To obtain complete penetration for double V or V preps. (butt welds) may be necessary to chip out or flame gouge the root of first run - this is normally always carried out on high class work (Class I).

In fillet welds too large an electrode can give lack of penetration but the use of a small electrode does not necessarily give an improvement. Should use largest possible electrode consistent with ease of manipulation and heat capacity of work. Slag inclusions and cracking frequently associated with this defect in fillets - with very low current may merely bridge gap.

Where practicable welds should be made in DH position - use of positioners.

Automatic welding requires care that machine accurately follows joint - or get offset welds, i.e.

Incomplete penetration causes local stress concentrations at root and under pulsating or

fluctuating loads will seriously reduce fatigue life. May also reduce strength through shear lack of metal, but not generally serious. May reduce impact strength.

This defect can only be corrected by completely removing defective seam. Surfaces should be re-cleaned and room altered for necessary manipulation of electrode.

2. Lack of Fusion

Discontinuity between weld metal and parent metal, or weld metal and weld metal (i.e. lack of inter-run fusion).

Get boundaries of unfused metal, should not be confused with incomplete penetration.

This defect results mainly from presence of oxides, slag, scale or other non-metallics which prevent underlying metal from reaching melting point. Can normally be avoided by ensuring cleanliness of joint - with multi-runs careful attention should be given to deslagging between runs. If individual runs are badly placed or surfaces hinder deslagging they should be chipped or ground. Care needed on welding current, too low frequently gives lack of fusion but if too high may give excessive deposition rate which may cause operator to increase welding speed so that underlying weld is not heated to melting point.

Defect tends to reduce both fatigue and static strength of joint (impact if in right direction).

Again defect can only be rectified by removing the seam and rewelding.

3. Undercut

Groove or channel in parent metal along a toe of the weld. Gives continuous or intermittent reduction in section of parent plate. May occur in parent plate at toes of welds or at fusion faces of multi-run welds - butt or filler.

Defect commonly associated with excessive welding current but may be caused by incorrect technique such as too high a speed, excessive weaving or wrong angle of electrode. May sometimes be due to inherent welding characteristics of electrode, use of damp electrodes or presence of heavy mill scale.

Fatigue strength reduced even by very slight undercut. Slight and intermittent undercut has no effect on static strength.

Fault may be corrected by adding weld metal where it occurs. Deep undercut, especially if slag present, must be chipped before further deposition, or will give incomplete fusion. Final control of weld should not be greatly altered.

With high tensile steels correct welding procedure should be used at all times.

4. Edge of Plate Melted Off (Lap Joint)

Melting of free

edge of lap welds.

Particular case of incorrect weld size and profile - reduction in thickness of plate and reduction in throat thickness.

Caused by incorrect manipulation of electrode, insufficient lap or using electrode that is too large for plate thickness. To avoid melting exposed corner the size of the weld should be $1/16$ " less than the edge thickness.

Effect on static and fatigue strength of lap or strap joint is reduction in so far as reduction in true throat thickness. Corrected by additional run or runs to restore throat thickness to required size.

5. Overlap

Imperfection at toe of weld caused by overflow of metal on to parent plate without fusion. May exist at isolated points or occur continuously. Often associated with fillets where it gives an apparent increase in weld size.

Caused by incorrect electrode manipulation in flat or HV welds allowing weld metal to flow away from fusion zone. Too large an electrode for welding position can cause it. Too low a welding speed can also cause this defect.

Single run fillets over $5/16$ " in leg length, if made in HV pos. tend to sag and cause overlap at toe of horizontal leg. Should use more than 1 run for this size of fillet.

Not a serious fault in static loading but under pulsating or fluctuating loads act as stress raisers and should be corrected.

Overlap can be removed by grinding away excess weld metal but care needed to leave smooth bead and avoid deep grinding marks.

6. Slag Inclusions

Slag or other foreign matter entrapped in weld. Refers to any nonmetallics. Usual source is slag formed by electrode coatings but also could form if weld faces, etc. are not clean. i.e. heavy scale, loose rust, dirt and grit.

May be forced in by the arc during welding, in which case it will generally be finely dispersed or it may be trapped in cavities caused by undercut or uneven or convex preceding runs. In latter cases it will appear as long line of slag.

Light scale oxide from gas cutting, light oil layer generally not important but heavy stuff must be removed. Fusion faces should be smooth and free from irregularities that could cause pockets.

Welding characteristics of electrodes are important, particularly slag viscosity which affects ease of control. Slag should float free and be easily removable after solidification.

Wire brushing and light chipping should remove slag but heavier chipping may be needed with irregular weld surfaces or if the wrong electrode currents and voltages have been used. Often associated with lack of penetration.

For lower runs in V groove the weld bead should have flat or slightly concave surface.

Small globules of slag will not affect static or even fatigue strength but large irregular or elongated lines of inclusions may reduce strength. These may also give rise to radiating hair line cracks. Source of brittle fracture.

Minor inclusions need not be removed but longer inclusions need chipping, cleaning and re-welding.

7. Porosity

Gas pores in a weld may cause:

- (a) Piping (worm hole) - elongated or tubular (trapped gas)
- (b) Blowholes.

Piping and large blow holes (sometimes partially filled with slag) are fairly rare, but small scattered or clustered porosity is quite common.

Caused by entrapment of gas evolved during welding. Composition of plate and wire important especially S content, excessive moisture in covering or scale on weld preparation also causes.

Use of low welding current, too long or too short an arc and other factors which promote rapid freezing promote porosity - sometimes advisable to "puddle" weld metal.

Small finely dispersed porosity not generally effective in reducing static or fatigue strength but dense porosity or very large pores can considerably reduce load carrying area and act as stress raisers.

Excessive porosity must be removed and the joint re-welded.

8. Cracks

Discontinuities caused by tearing of metal above solidus, tearing when in plastic condition or fracture when cold.

May occur in weld metal or haz of plate.

Weld metal cracks may be classified - longitudinal, transverse, crater or hairline (often associated with slag).

The cracks may be longitudinal (adjacent to edge of weld seam), transverse (which often originate from weld cracks) or "under-bead".

(a) Weld Metal Cracks - caused by highly localised stresses in the joint arising from shrinkage of weld metal and resistance to movement of parts during welding; therefore necessary to give consideration to joint conditions and degree of restraint opposing movement caused by weld shrinkage. Order of assembly should allow shrinkage to take place as freely as possible.

Size of individual runs should be large enough to withstand shrinkage stresses. This is particularly important in welding of heavy plates or sections or under restraint. Rapid cooling increases tendency to cracking.

Badly fitted parts or incorrectly prepared joints frequently result in lack of fusion and penetration or slag inclusions, and these may initiate "hair-line" cracks which can then propagate through the weld.

Longitudinal cracks more likely to occur in first layer of weld, if not cut out may propagate (one of reasons for back chipping). Cracks often result from poor shape or position of deposit in which case it may be necessary to change welding procedure. Long cracks may also originate from crater cracks and deep craters should be avoided (craters should be examined and chipped where necessary).

Transverse cracks generally associated with joints having high degree of restraint and may extend into parent plate haz, especially if haz has hardened appreciably during welding.

S content of most commercial mild steels does not normally affect weldability. Excess S in plate or core wire may cause weld metal cracking however due to low m. pt. sulphides. Other impurities, e.g. Ni, Cu, can cause hot cracking.

With automatic welding crater is often large and should therefore use run off plates (manual as well on occasions). These plates should be same thickness as joint. - should be welded for full width to prevent seam opening up during welding and causing cracking.

Crater cracks

b) Parent metal Cracking - normally associated with high tensile steels (medium C, low alloy or high alloy steels) but may occur in thick sections of mild steel. Cracks generally within hardened haz and are attributable to composition of parent plate associated cooling rate after welding and degree of restraint, thickness of plate rate of heat input, atmospheric temperature.

Hardness of haz results from rapid cooling after welding and so increases with thickness of plate (rapidity of heat dissipation). Danger of cracking increases, therefore with plate thickness especially in joints of high restraint, therefore rate of cooling should be retarded to avoid formation of excessively brittle zone and reduce rate at which shrinkage stresses are developed. Reduction in cooling rate can be achieved by pre-heating, immediate post-heating or increasing rate of heat input by means of suitable welding procedure, e.g. large runs, heavy weave. Multi-run welds should be deposited so that heat is maintained in surrounding plate and succeeding runs made as soon as possible.

Small tack welding of hardenable steels should be avoided if preheating cannot be applied. Avoid arc strikes outside weld groove as may give local hard spot and small surface cracks.

Low temperature pre-heating recommended even on mild steel if temperature is at or below 0°C and chill should be taken off parts above 1½". Use of special electrodes may be advantageous - low H rods. Can also get hot cracking in the haz if very brittle or low melting point grain boundary.

Cracks will seriously reduce static and fatigue life and should never be permitted.

Can only be corrected by complete removal of cracked volumes - care needed to avoid leaving cracks. May be necessary to modify welding procedure to prevent recurrence of cracking.

9. Incorrect Weld Size and Profile

Undersize fillet welds, fillet welds of variable size as measured by minimum leg length - may result from excessive concavity or convexity, irregular weld face or unequal leg lengths.

In Butt welds one has lack of reinforcement, excessive reinforcement, or irregularity of deposit.

These defects are generally a result of faulty technique. Convexity or concavity may be a characteristic of the specific electrode but more often is due to incorrect welding current (convexity - low current, concavity - high current.)

Unequal leg lengths in fillet welds generally caused by faulty manipulation or incorrect positioning of the workpiece when welding in the downhand position (i.e. work tilted). Welds of over 5/16" in any other position than dh should be made in more than one run.

If get poor fit up the effective leg length will be reduced.

Excessive, or lack of reinforcement in butt welds is caused by use of wrong welding procedure, and should not arise if joint preparation, rod size and welding current, number of runs, welding speed and, possible, length of run per electrode, are specified and followed. Note, however, that some latitude over current and technique should be allowed to the welder, who will have his own personal idiosyncracies, and on high class work much will be decided by procedure tests and welder approval tests.

Excessive concavity and unequal leg lengths reduce the throat thickness of fillet welds and reduce the ultimate strength of weld. Excessive convexity may give equivalent static strength but often indicates lack of penetration and fusion. May also be associated with overlapping which will seriously reduce the fatigue strength of the fillet.

Both excessive and lack of reinforcement will reduce fatigue strength and the second defect may also cause reduced static strength.

In so far as these faults in fillet welds may indicate other subsurface defects, it may be necessary to re-weld for high quality work particularly if fatigue strength is important. Otherwise concavity and unequal leg length can be corrected by further (expensive?) runs. Convexity needs the chipping away of excess metal, and care should be taken to leave a smooth surface (NB. care in cleaning and de-slagging).

In butt welds reinforcement may be increased or decreased by further runs or chipping and grinding.

Again it should be emphasized that these faults should not occur if the correct procedure is laid down.

10. Poor Surface Appearance

Non-uniform ripples, surface porosity, included slag, faulty junction and craters.

Caused mainly by faulty welding technique although the electrode characteristics can have an effect. Welding position must also be taken into account. Note that accessibility is important and the operator must always be allowed adequate space for manipulating the electrode.

These faults will not normally affect static strength but by acting as stress raisers may seriously reduce fatigue life.

Can be corrected by grinding or chipping and re-welding.

11. Spatter

Main objection is waste of metal and cost of removal. Generally caused by excessive welding current or dampness in the coating. Some electrodes are naturally more prone to spatter than others.

Has no effect on strength and may be removed by chipping and wire brushing the small globules from the surface of the plate.

OXYACETYLENE WELDING

1. Inadequate or Excessive Penetration - caused by insufficient bevelling of edges, too wide a root opening, too great a welding speed, or poor torch and filler wire manipulation.
 2. Excessive or Insufficient Reinforcement
 3. Undercut
 4. Overlap
- 1 - 4 are visual defects.
5. Incomplete Fusion - Insufficient heating of base metal, too rapid welding speed, gas or dirt inclusions.
 6. Porosity - Trapped gases, usually CO or water vapour, may be avoided by correct manipulation, choice of materials, adequate fluxing.
 7. Cracking - Hot or cold - depends on choice of materials welding technique.
 8. Hard Spots - Incorrect manipulation, parent material (metallographical characteristics).
 9. Excessive Grain Growth in HAZ - excess temperature.

RESISTANCE WELDING

1. Lack of Symmetry

Caused by dissimilar thicknesses of same metal, dissimilar metals, different rates of heat extraction, electrodes of uneven sizes or different materials, misshaped electrodes, misaligned electrodes, too much tip radius.

Can lead to indented surfaces, lack of penetration into one sheet with lowering of strength.

2. Surface Indentations

Cannot be eliminated but can be minimised, i.e. by having short welding times keeping heat conduction beyond weld zone to a minimum.

Defects characteristic of welds made with too great a heat generation in weld - expulsion of molten metal often accompanies it. Caused by high welding current, low electrode force, insufficient electrode contacting area, improper alignment of electrodes, dirty metal surfaces, excessive time of current flow, improperly mating surfaces.

3. Surface Melting

Generally a defect

Caused by insufficient pressure or insufficient time with excessive current, or both. It is aided by inadequate electrode cooling, inadequate squeeze and hold times, fouled electrodes or scaly or dirty material surfaces.

4. Excessive Sheet Separation

Pulling apart of mating surfaces of spot weld caused by expansion and contraction of molten metal and forging effect of electrodes. Similar affect caused by poor fit up of sheets. Related to surface indentation.

Caused by steeply tapered electrodes at high pressures acting as a male punch. Misaligned electrodes will also cause it, particularly on one side of weld.

Sheet separation will always occur on gauges of .060" and up.

This defect is undesirable because it tends to increase the bending moment on joint when stressed in shear, and it will also increase distortion of assemblies.

5. Interface Expulsion

Indication of incorrect welding conditions. Usually result of too great a rate of heat generation caused by excessive current, insufficient pressure, undersize electrode contact area, and dirty metal interface, or welding too near an edge.

Results in internal cavitation of weld and a reduction in weld strength.

6. Internal Defects

Cracks, porosity (spongy metal), cavities (caused by expulsion), inclusions (with coated metal).

In general have no significant effect on static or fatigue strength when located in centre of weld nugget even if extend to outside surface. Defects at periphery of weld are very serious however.

Porosity - often present. Caused by overheating, inadequate pressures, premature release of (adequate) pressure, too late an application of forging, pressure, absorbent gases on sheet surface. Porosity can be reduced by using lower rates of heat build up, lower maximum temperatures and higher pressures.

Cracks - generally caused by overheating, improperly applied electrode forces during welding or use of wrong schedules in cracks sensitive materials.

In flash and upset welds cracks may be caused by excessive cooling rates or forging at too high or low a temperature.

SOFT SOLDERING

Causes of failure of soldered joints are:

1. Joint not thoroughly cleaned.
2. Metal was not heated above melting point of solder or was heated too far above this temperature.
3. Wrong flux used, giving inadequate cleaning.

BRAZING

Voids, lack of wetting of parent material, presence of films, changes in structure of parent material (caused by overheating and, perhaps, diffusion of braze metal, hot cracks (penetration of Cu along grain boundaries) inclusions. Main cause is incorrect fluxing, flux inclusions, overheating and underheating.

CLAD STEELS

These steels demand high quality welds to maintain corrosion resistance and strength. Main causes of trouble are incorrect joint preparation and fit-up, departure from correct procedures.

INERT GAS PROCESSES

Most of defects are common with metal arc defects. An addition is tungsten inclusions.

Common causes of porosity and other troubles are contamination of Argon or CO₂ (generally with water vapour) and contamination of electrode wire, often by adsorption of water vapour on surface.

Cracking

Cracking is perhaps the most serious of weld defects, although fortunately it is not as common as porosity. Three types of cracking may be found in welded joints: cold cracking, hot cracking and delayed cracking. Cold cracking occurs in the weld metal or heat affected zone at temperatures well below the solidus, it may occur during cooling after welding or, in special cases, a few hours after welding. Hot cracking occurs during welding at temperatures at or above the solidus and may occur in the weld metal, heat affected zone or at the fusion line. Delayed cracking has been found in creep resisting steels and occurs in the heat affected zone during post weld heat treatment or in subsequent high temperature service. It has been suggested that a similar form of cracking is possible in any material where excessive grain strengthening occurs.

Cold Cracking

This type of cracking can occur in all materials where ductility is low and heavy restraint exists. The shrinkage strains generated during cooling cannot be accommodated because of the low ductility and cracking occurs at the lower temperatures of the cooling cycle. Cold cracks caused by restraint generally occur longitudinally in the weld metal and is often initiated by slag inclusions or lack of fusion in multi-run welds (Fig.1). A special case of cold cracking known as underbead cracking can occur in the heat affected zones of hardenable steels when these are welded by a process which introduces hydrogen into the weld. Underbead cracking, which will be discussed in detail in Chapter 4, takes several hours or even days to appear and this can be dangerous since cracking may not occur until after inspection.

Hot Cracking

Hot cracking is more prevalent than cold cracking and more difficult to control; it is essentially inter-crystalline with cracks occurring along grain boundaries or between dendrites. The general mechanism for hot cracking is similar for weld metal, heat affected zone or fusion line cracking although most investigations have been confined to weld metal cracking. The basic explanation lies in the inability of the material to withstand contractional and external stresses imposed during cooling. It is generally agreed that this weakness occurs at temperatures at or above the solidus and is caused by the presence of liquid metal at the grain boundary faces.

Two suggestions have been made to explain weld metal cracking, both of which are supported by some experimental evidence. One school of thought considers that cracking results during solidification when the growing dendrites interlock and prevent free movement of the remaining liquid metal. In this temperature range (the 'shrinkage-brittleness' range) the weld metal has little strength and no ductility, so that contraction strains cannot be accommodated, resulting in cracking. If sufficient liquid is available and can reach the cracks 'healing' can occur, but otherwise the cracks will persist. The alternative suggestion considers that cracking occurs at or near the solidus temperature during the last period of solidification when the grains are virtually fully formed and only a liquid film persists. The ratio of interphase and grain boundary energies will then define cracking tendency. In contrast to the shrinkage-brittleness approach, it is argued that cracking cannot occur at intermediate temperatures between liquidus and solidus since shrinkage strains are uniformly distributed. In this second suggestion the

presence of low melting point segregates which are molten below the equilibrium solidus of the metal are particularly dangerous.

Borland¹ has recently attempted to reconcile the above suggestions and to develop a generalized theory of super-solidus cracking. Solidification may be considered to occur in three stages (Fig. 2).

- i) primary dendrite formation,
- ii) dendrite interlocking, during which both the liquid and solid phases are continuous but the liquid remains capable of free circulation around the dendrites.
- iii) grain boundary development, where solidification is considerably advanced with a semi-continuous network of grains restricting free passage of liquid; a stage which continues to the solidus temperature at which the remaining liquid freezes.

The temperature (a_c) at which dendrites interlock is known as the coherent temperature and cracking is possible once the cooling metal has reached this temperature. However, free movement of the liquid will allow healing of cracks during this stage, whereas in the third stage starting at the critical temperature, a_c , and the solidus temperature, a_{cs} . The width of the critical range is also important and crack susceptibility should be at a maximum for the composition possessing the greatest critical temperature range, as shown in Fig. 3. The greatest range occurs theoretically at the limit of solid solubility, but although experimentally the variation of crack susceptibility is found to increase to a maximum with increasing alloy content before falling away, the maximum crack susceptibility was found to occur at a lower alloy content than the limit of solid solubility. Pumphrey² has suggested that his discrepancy is a result of the non-equilibrium cooling conditions which will alter the limit of solubility. Further depression of the solidus can also be caused by lack of diffusion and, in some cases, by the presence of low melting point segregates. Increase of the alloy content will result in larger quantities of eutectic liquid being available for healing and with a certain critical proportion of eutectic liquid (estimated at 20% for aluminium-silicon alloys) cracking will be prevented.

The existence of a critical solidification range has been argued above for a eutectic system with limited solid solubility but it can also explain hot cracking in other types of alloy systems.

From the above discussion, certain other constitutional factors might be expected to effect susceptibility to cracking. Any factor tending to depress the solidus, such as undercooling or low melting point segregates, will increase susceptibility, conversely the presence of a second phase with a high solubility for atoms that tend to produce low melting point films will be beneficial. The crystal shape and grain size must also be considered. A crystal shape giving a high degree of entrapment is detrimental whereas a fine grain size, such as can be produced by a flat temperature gradient which encourages nucleation will reduce the tendency to cracking.

Borland suggests that the relative values of interphase (solid-liquid) and grain boundary (solid-solid) free energies are of importance in deciding the dihedral angle and hence the distribution of liquid at the grain boundaries. The relation is:

$$= \frac{SL}{SS} = \frac{1}{2 \cos \frac{\theta}{2}}$$

where

SL = interphase energy (solid-liquid)
 SS = grain boundary energy
 = dihedral angle

The ratio, $\frac{SS}{SL}$, varies upwards from 0.5 ($\theta = 0^\circ$). At a dihedral angle of 0° liquid will cover all grain faces, at an angle of 60° ($\frac{SS}{SL} = 0.57$) liquid is concentrated at grain edges, whilst at angles above 60° ($\frac{SS}{SL} > 0.57$) the liquid collects at the grain corners. Where liquid completely covers the grain faces strains are well distributed and fissures or cracks would not be expected, provided that sufficient liquid is available, while at dihedral angles of 60° and above sufficient contact should have developed to give a strong bond and thus prevent fissure formation. With intermediate conditions, however, only small areas of the solid grains may be joined and these may fracture readily under contraction strains. Under these conditions the dihedral angle may prevent healing.

The interphase and grain boundary energies can be found experimentally and it may be possible to deduce alloy compositions that are not susceptible to hot cracking, once the effect of minor additions on the energies have been determined. The main problems still to be evaluated by the theory lie in the effect of crystal shape and size (for example, the significance of columnar growth), and the effect of the moving weld pool.

Hot cracking in the heat affected zone occurs by a similar mechanism to that operating in weld metal cracking, and it is suggested that liquid films at the grain boundaries are necessary for cracking to occur. The same relationship between the dihedral angle and interphase free energies is applicable. In this case, however, a supply of molten eutectic is not available, so that eutectic healing cannot occur. This mechanism of cracking presupposes the existence of strain in the heat affected zone and it follows that if the weld metal solidifies at a lower temperature than the liquated films, stresses will not be induced until the danger has passed, and cracking will not occur. Thus, choice of weld metal can reduce heat affected zone cracking problems, and is of particular importance in the welding of aluminium alloys.

This mechanism of cracking assumes a liquid film and the origin of this film is problematical. In a cast structure, coring will give low melting point segregates at grain boundaries, but this can hardly persist in hot worked material. It may, indeed, be necessary to look at each material individually, and it has been suggested that a concentration of low melting point segregates can occur as a result of phase changes. For example, in austenitic steels, Parks³ considers that ferrite stabilisers, such as silicon and phosphorus, diffuse into the ferrite since their free energies of solution are less in ferrite than austenite. On subsequent cooling and as the ferrite transforms a concentration of these elements occurs and may lead to liquation of the ferrite/austenite interface during the weld thermal cycle. An experimental correlation between cracking and the presence of liquid films has not yet been satisfactorily achieved and it is suggested that other mechanisms should be considered.

With fusion line cracking, intergranular cracks run into the heat affected zone at right angles to the weld, and in certain circumstances may also extend into the weld metal. The crack mechanism is again believed to be similar to those for weld and heat affected zone cracking, in that a liquid film is necessary at the interface. It has been suggested that preferential absorption of certain elements occurs at the weld metal/base metal interface, and that these elements may penetrate the grain boundaries, lowering the solid/liquid interfacial energy and forming a base metal liquid film. Cracking will then occur in the presence of stresses and the absence

of entectic healing. This suggested mechanism is of interest since, it explains the presence of base metal cracks in material that is free from fusible intergranular segregates. If partial healing occurs from the weld pool these fusion line cracks may, in fact, appear to be heat affected zone cracks.

Delayed Cracking

Delayed cracking is found in high temperature austenitic and ferritic steels after post-weld heat treatment or during subsequent high temperature service. These cracks, which have been particularly troublesome in austenitic superheater steam lines operating at 550°C and above, are intergranular and occur in the heat affected zone. In many cases they appear to originate from a minor weld defect such as undercut or a hot tear at the toe of a weld (Fig.4). During the welding cycle the utility of a heat affected zone is severely reduced by the strain assisted precipitation of particles (often carbides) on dislocations. Thus localised strain during postweld heat treatment or subsequent service cannot be accommodated and cracking occurs.

References

1. Borland, J.C., 'Generalized Theory of Super-Solidus Cracking in Welds (and Castings)' British Welding J., 7, 508, (1960) .
2. Pumphrey, W.I., 'Researches into the Welding of Aluminium and Its Alloys', Research Report No. 27, Aluminium Development Association, (1955).
3. Parks, J.M., Welding J., 34, 568, (1955).

Steel will generally only fail after considerable plastic deformation but over the last 100 years there have been reports of sudden failures occurring without any prior warning. With mechanically joined steel structures these failures were few and rarely catastrophic but with the advent of welded structures the incidence of failures and the size of cracks increased markedly.

DEFINITION

Brittle failure occurs when the material fractures in a sudden extensive manner with little plastic deformation or absorption of energy, often under relatively low mechanical stress. Failure is generally by cleavage instead of shear.

RECOGNITION

Brittle fracture can be recognised by the suddenness with which it occurs and by the absence of local deformation. Fracture surfaces are characteristic - generally the crystal faces are quite obvious. Brittle fracture often occurs at rather low temperatures although this is not always the case.

The fracture plane is generally approximately perpendicular to the plate surface with less than 2% reduction in plate thickness. There is very little plastic deformation and paint or scale near to the fracture is not cracked or flaked. The fracture surface is bright and granular (crystalline as opposed to fibrous) and often exhibits a chevron pattern with the apices of the chevrons pointing to the fracture source. Many fractures show regions of shear adjacent to the plate surface (shear lips) which accounts for virtually all the reduction in thickness.

FACTORS INVOLVED IN BRITTLE FRACTURE

- (1) Liability to brittle fracture is temperature dependent: there is an upper temperature above which a crack cannot propagate without marked plastic deformation, energy absorption and application of considerable stress, whereas below a certain temperature a crack will propagate with little plastic deformation or energy absorption and at stresses below yield. These two temperatures constitute a transition temperature range which can vary widely for steels.
- (2) The presence of a stress concentration, e.g. a notch represents a potential source for crack initiation.
- (3) The geometry of a notch influences crack initiation but not crack propagation. The sharpness of a notch can influence the transition temperature.
- (4) Susceptibility to brittle fracture increases with plate thickness. The effect is partly metallurgical, but greater thicknesses also restrict freedom of plastic flow, while larger defects remain undetected.
- (5) Cracks may be initiated and propagated under a steady stress but only after a high degree of work hardening at the point of initiation. Cracks are more likely to be initiated by an

impact load and in this case the work hardening may be less.

MAT-110

(6) Even in mild steel at low temperatures a certain amount of plastic deformation occurs before the crack develops.

(7) For propagation to occur the applied stress must be such to ensure the necessary intensity of stress at the crack root and to supply the necessary energy. In general this is supplied internally.

(8) Brittle fractures are more frequent and extensive in welded than in rivetted structures. Thus welding is a contributory factor:

(i) residual stresses may facilitate crack initiation and can provide energy for propagation.

(ii) the welded structure provides a continuous fracture path.

(iii) local structural changes can facilitate crack initiation and propagation.

(iv) weld defects can act as crack initiation sources.

(9) Metallurgical structure, composition and prior history can affect susceptibility to brittle fracture.

(10) Irradiation can raise the transition temperature.

METALLURGICAL ASPECTS OF BRITTLE FRACTURE

(a) Carbon content and Manganese: Carbon ratio.

The transition temperature increases with carbon content although the condition of the carbon is important. Manganese increases pearlite fineness and refines ferrite grain size and is considered to be beneficial.

(b) Impurities: Interstitial impurity atoms greatly increases the transition temperature.

(c) A fine ferrite grain size and fine pearlite give the lowest transition temperatures.

(d) Degree and method of deoxidation: Deoxidised steels have lower transition temperatures than rimming or semi-killed steels.

(e) Finishing temperatures after rolling: This should be low for the best results.

(f) Normalising affects the grain size, and hence the transition temperature.

(g) Cooling rate from hot rolling or normalising temperature: Effects ferrite grain size and pearlite distribution.

(h) Cold work in manufacture and fabrication. Plastic deformation raises the transition temperature.

(5) Quench ageing, strain ageing and temper brittleness. All these effects will markedly increase the transition temperature.

(6) Stress relieving heat treatment: Very beneficial in reducing residual stress but also can remove ageing effects so that it can be metallurgically worthwhile.

PRODUCTION OF NOTCH DUCTILE STEELS

Steps that can be taken to improve resistance to brittle fracture are:

- (1) reduction of carbon content.
- (2) reduction of phosphorus and nitrogen contents.
- (3) increase in manganese content.
- (4) use of a killed or semi-killed steel in place of rimming steel.
- (5) ensure a fine ferrite grain size by controlling roll finishing temperature or by normalising.
- (6) reduction of austenite grain size by fine grain practice, e.g. addition of aluminium followed by normalising.

A series of notch ductile steels have been introduced (BS.2762:1956) which give guaranteed impact properties; composition and properties are given in Table II. N.D.I. and II are balanced (or semi-killed) steels, the first "as rolled" and the second normalised. N.D.III is silicon killed and normalised and N.D.IV is aluminium grain refined and normalised.

TABLE NOTCH DUCTILE STEELS (BS.2762:1956)					
Specification	Temp. °C	Energy Absorption (Charpy V-notch) ft.lbs.	Composition, %		
			Carbon (Max)	Silicon	Manganese (Max)
N.D.I.	0	20	0.20		1.50
N.D.II	-15	20	0.20		1.50
N.D.III	-30	20	0.17	0.10-0.35	1.50
N.D.IV	-10	45	0.17	0.10-0.35	1.50
	-20	40*			
	-30	35*			
	-40	25*			
	-50	20*			

* According to agreement between manufacturer and supplier.

1. Commission IX of the International Institute of Welding:

"A metallic material is considered to be weldable to a certain degree by a given process and for a given purpose, when a continuous metallic connection can be obtained by welding using a suitable procedure, so that the joints comply with the requirements specified both in regard to their local properties and their influence on the construction of which they form part".

2. Welding Handbook:

"the ease with which the effects of welding can be controlled".

FACTORS CONTROLLING WELDABILITY

Design

Restraint
Accessibility

Physical Properties

Electrical conductivity
Thermal conductivity
Thermal expansion
Modulus of elasticity
Viscosity
Emission characteristics

Metallurgical Properties

Effect of thermal cycle on parent material

Grain growth
Annealing
Formation of metastable structures
Strain induced precipitation
Overageing
Underbead cracking
Hot cracking
Delayed cracking

Structure and properties of the weld metal.

Weld metal structure
Porosity
Hot cracking
Restraint cracking

Structure and properties of the weld metal.

Weld metal structure
Porosity
Hot cracking
Restraint cracking

Chemical Properties

Oxidation resistance
Nature of surface films
Impurity content and minor alloy additions

ASSESSMETN OF WELDABILITY

Knowledge of design fabrication
Knowledge of chemical and physical properties
Material condition
 cold worked
 annealed
 age hardened etc.
Isothermal and continuous cooling transformation characteristics
Tendency to precipitation hardening
Cracking tests - heat affected zone
 - weld metal.

Fe-0.15%C

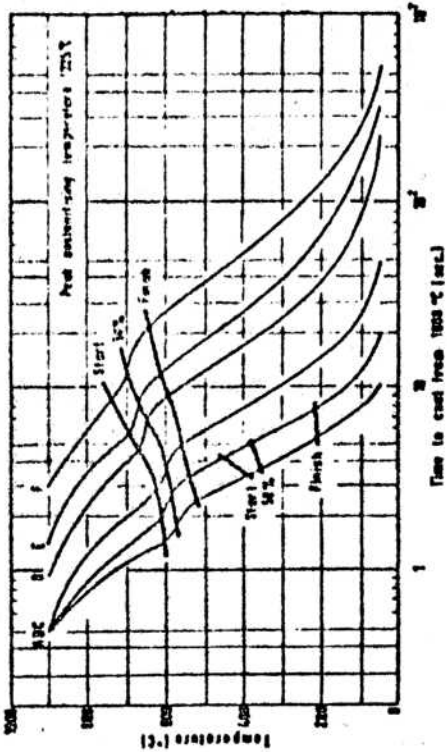


Fig. Continuous cooling transformation (CCT) diagram for a typical mild steel

STEEL: 0.20%C, 1.0 Mn

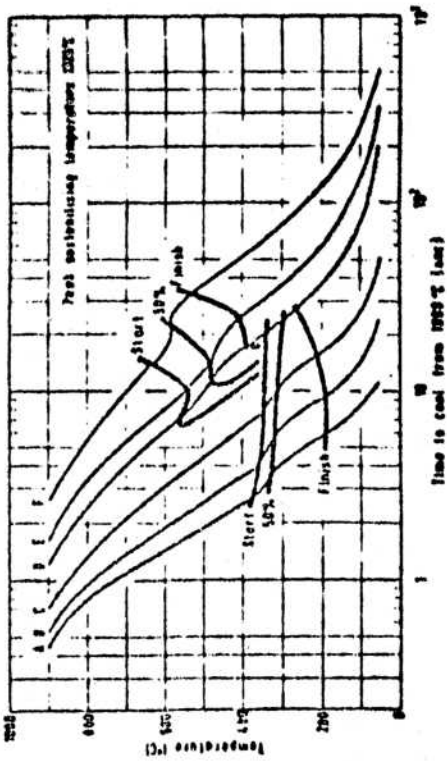


Fig. CCT diagram for 0.20%C, 1.0 Mn steel

STEEL: En 80

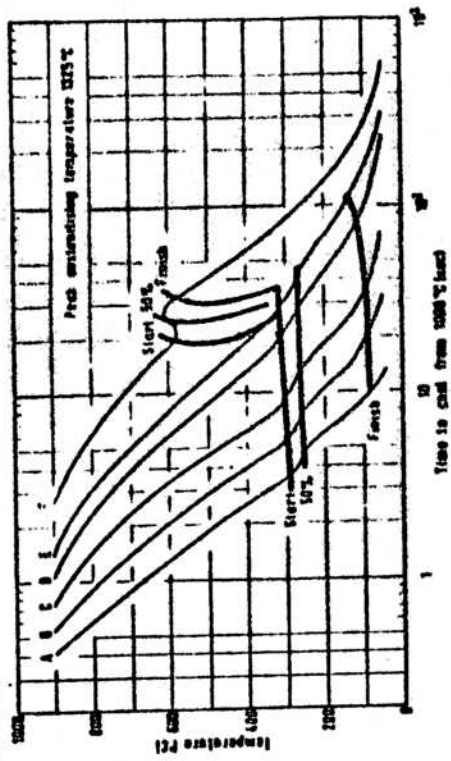


Fig. CCT diagram for Steel En 80 (0.45%C)

STEEL: En 27

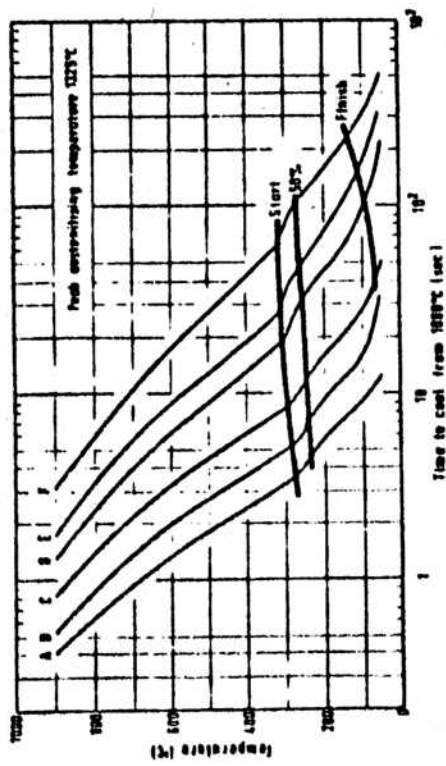
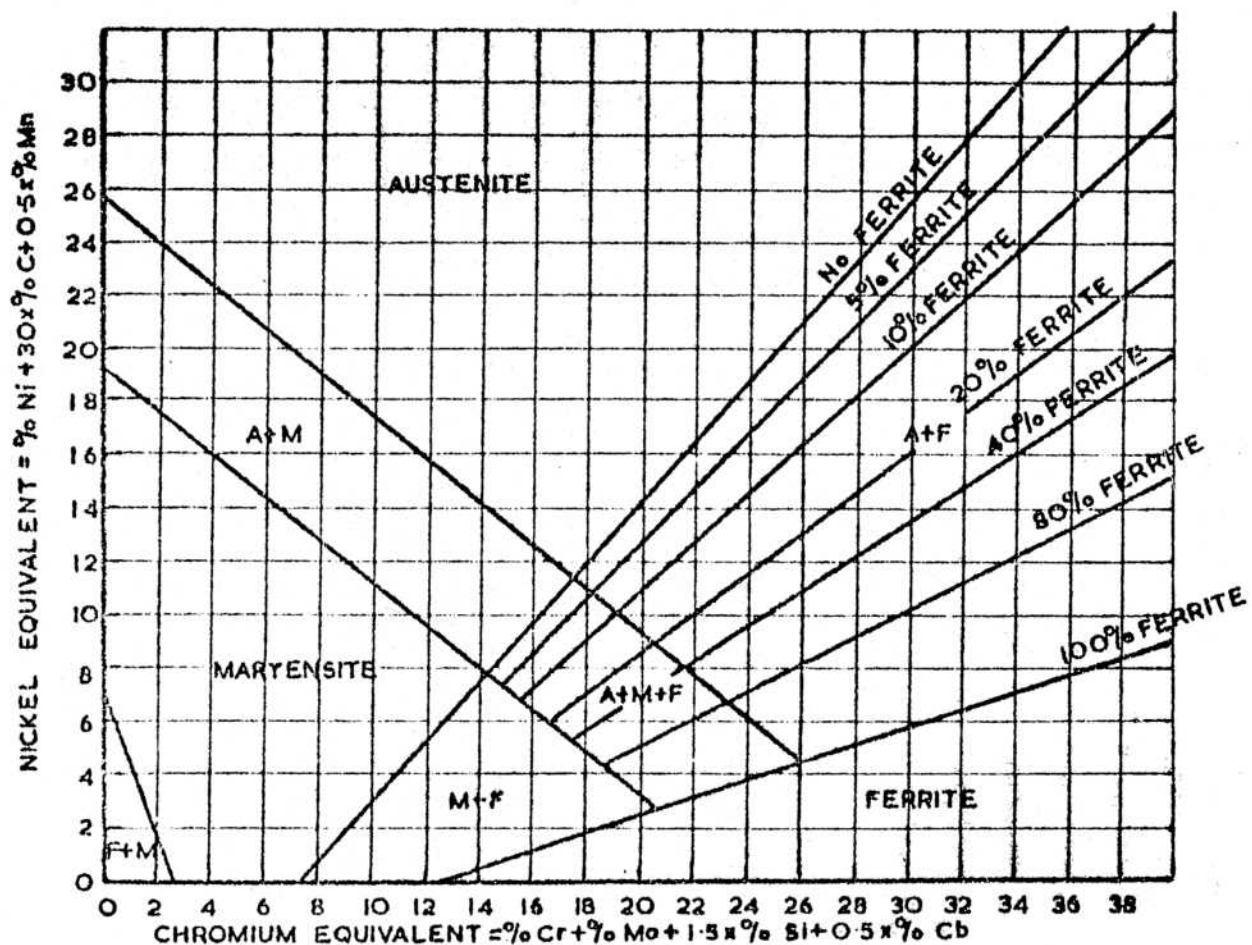


Fig. CCT diagram for Steel En 27 (3% Ni-Cr-Mo)



CONSTITUTION DIAGRAM FOR AUSTENITIC CHROMIUM-NICKEL STEEL WELD METAL

HISTORICAL BACKGROUND

Metal arc welding started as bare wire welding with fence wire attached to the normal power lines. Development occurred in a number of ways. It was noticed that rusty wire gave better stabilisation of the arc; so did a dip coating of lime. Similarly, wrapping the wire in cotton waste gave some protection against oxidation and increased burn-off rate and penetration. Development of power sources gave generally better results. From these unpromising beginnings, metal arc welding began - though its reputation still suffers from those early results.

POWER SOURCES

A welding power source needs to be designed to prevent excessive surges of current on short circuiting (and so prevent excessive spatter and sticking of the electrode) and to give adequate recovery of voltage to prevent extinction of the arc. Thus the source must give sufficient running voltage i.e., 15-25v for bare or lightly coated electrodes, 20-40v for normal covered electrodes up to 45v for special electrodes, plus an open circuit voltage for arc re-ignition. This used to be 90v or so but with better electrodes it now needs to be only 65v. Current range is 30-500 amps (generally only 300a) for manual welding and up to 700 amps for automatic welding.

Types of Source

1. D.C. Generator or Rectifier with variable voltage characteristic.
2. D.C. Generator with constant voltage characteristics.
3. Existing D.C. supply with resistors to reduce voltage and current.
4. A.C. transformers.

1 is the most used, 2. is used for multi operator sets and 3. is rarely used as the characteristics are not suitable - emergency use only. Welding transformers have variable voltage characteristics and may be single or multi operator. A.C. electrodes gave arc instability trouble at first but this was largely cured by ionising constituents in coating. A.C. also has advantages that it eliminates arc blow giving easier handling, improved soundness and appearance at corners. Also gives lower power costs (5-10% of total welding cost) and lower maintenance costs (no moving parts).

Volt-Amp Characteristic

To enable easy manipulation one does not want change in arc length i.e., arc voltage, to effect a large change in current. A drooping characteristic will result in constant current output. Sometimes with a fluid weld metal or difficult welding position it is an advantage to have a slightly flatter characteristic to allow greater operator control. Even so the droop is pronounced.

MANUFACTURE AND QUALITY CONTROL OF ELECTRODES

The core wire used normally is rimming steel i.e., a mild steel which has been allowed

to solidify without the addition of deoxidants. Alloy wire is often used for ferritic weld deposits but alloying constituents may be added through the coating. Austenitic electrodes may use austenitic core wires although mild steel wires can be used.

Rimming steel solidifies with an outer rim of almost pure iron with the impurities segregated in the centre. This makes it ideal for wire drawing. In addition the gas content is distributed as micro-porosity which seems to be beneficial and to aid metal transfer. Finally the elements used to 'kill' or deoxidise steel - Si or Al - tend to destabilise the arc.

= The coating normally consists of a mixture of mineral silicates oxides, fluorides, carbonates, hydrocarbons and powdered metal alloys, plus a liquid blinder. The coating is mixed and then extruded on to the core wire at high speeds. Finished electrodes are dried in huge ovens in batches, which cause the main production delays.

Quality control covers analysis and mechanical properties of core wire and sampling of the coating ingredients for grain size impurities, moisture and gas contents. Finished electrodes are sampled for checks on concentricity, coating thickness, dryness and welding quality. Periodic tests are made for mechanical properties of the weld deposit.

ELECTRODE COATINGS

The coating is used to provide: gas shielding for the arc, easy striking and arc stability, a protective slag, to improve bead shape, to improve weld metal quality by slag/metal reactions e.g., deoxidation, and for alloy additions. The coating is not normally electrically conducting.

In more detail, the ideal coating should give:

1. A weld metal with the correct mechanical and metallurgical properties - gas shielding, slag protection, deoxidation, alloy additions.
2. Ease of manipulation - good slag control.
3. Freedom from cracking.
4. Freedom from porosity.
5. Easy slag removal.
6. No spatter.
7. Arc stability.
8. Ease of striking.
9. Adequate penetration.
10. High deposition rates.

11. Good surface finish (clean, smooth, even edges).

12. No electrode overheating.

13. Good weld contour.

14. Resistance to moisture pick up.

15. No smell or toxic fumes.

16. Robustness and flexibility of coating.

Many of these points are incompatible and demand a compromise - which probably explains why there are so many electrode types doing any one job.

Coating constituents

This can best be put in the form of a table:

Coating Constituent	Arc Stabiliser	Slag Former	Reducing Agent	Binder	Coating Strengthener	Oxidising Agent	Gas Shield	Alloying
Gum and/or Resin			B	A				
Cellulose			B		B		A	
Feldspar	B	A						
Clay (Al Silicates)	B	A						
Talcs (Mg Silicates)	B	A						
Titanates (Rutile etc)	A	A						
Iron Oxides	B	A				A		
CaCO ₃	A	B				B	A	
Asbestos	B	A			A			
Ferro manganese		A	A					B
Potassium Silicates	A	A		A				
Sodium Silicates	B	A		A				
Powdered Alloys								A

(A = principal function B = minor function)

Some of these we must consider a little further.

The use of titania (TiO₂) as rutile or ilmenite gives a highly fluid, quick freezing slag, as well as being an arc stabiliser, which makes it a very important constituent in many electrodes. The carbonates give a basic slag (as does CaF₂). Iron and manganese oxides are used to adjust the fluidity and properties of the slag. Mention must also be made of the use of iron powder to increase the deposition rate for a given size of core wire.

Recovery of Elements from the coating

Element	Form in Coating	Recovery %
C	Graphite	75
Mn	Ferromanganese	75
P	Ferrophosphorus	100
Si	Ferrosilicon	45
Cr	Ferrochrome	95
Ni	Electrolytic Nickel	100
Cu	Metallic Copper	100
Nb	Ferrocolumbium	70
Ti	Ferrotitanium	5
Mo	Ferromolybdenum	97
V	Ferrovandium	80
Be	Copper-Beryllium	0
S		100

In practice never use Ti or Be because of low recovery (toxicity of Be).

Types of Electrodes

(1) Rutile 50% TiO_2 Developed about 1935

General purpose electrode giving easily controllable slag, low spatter, medium penetration and a fairly high deposition rate. The low arc voltage makes these rods suitable for AC.

Weld has a good finish and sound properties.

(2) Gas Shielded 30% organics as alpha flock, wood flour, etc. This gives a voluminous gas shield which travels at high velocity combined with small amount of slag which gives poor bead appearance and rather high spatter loss, but good penetration and mechanical properties. Thin friable slag and slow burn-off rate makes it usable in any position and very suitable for pipelines, tanks and site construction. Can be used for vertical down and stove pipe welding. High arc voltage necessitates DC. In GB a heavily coated electrode of this type used for deep penetration.

Very popular in U.S.A. where originally developed.

(3) Iron Oxide/Silicate

With thin coatings were used as general purpose all position rods but now superseded and only used (with thick coatings) for flat welding.

The voluminous slag makes control difficult but gives good bead appearance and mechanical properties, high deposition rates low spatter loss and good penetration (can be base for deep penetration electrodes). Slightly concave profile makes it excellent for fillets and deep grooves. Low arc voltage makes it suitable for DC or AC.

(4) Basic (or Low Hydrogen, Lime-Ferritic, Lime-Fluorspar)

Contains a high proportion of CaCO_3 and CaF_2 . Clays, asbestos and other minerals with combined water kept to a minimum to ensure very low hydrogen content in weld metal (for this reason they are also baked at a higher temperature than other types). Generally all position with a fluid slag gives a convex to flat profile. Generally DC +, but some can be used with AC.

Mechanical properties (especially impact and reduction in area) are superior to other types and they have a high resistance to hot and cold cracking which makes them very good for welding higher strength steels. In fact, most alloy electrodes are of this type. Low hydrogen electrodes are less sensitive to plate quality than other types which make them used for high C and S steels and for unknown compositions.

Electrodes have medium speed of deposition, moderate penetration and good appearance. Special techniques required for good results especially a short arc length - care needed in weaving and stops and starts.

The characteristics of electrodetypes can be summarised in tabular form:

Electrode Class	Rutile	Gas Shielded	Iron Oxide /Silicate	Basic
Ductility	4	2	3	1
Penetration	4	1	2	3
Absence of Undercut	1	4	3	2
Absence of Spatter	2	4	1	3
Deposition Efficiency	1	4	3	2
Deposition Rate	2	4	1	3
Soundness	3	4	1	2
Ease of Handling	1	3	4	2
Ease of Re-striking	1	2	3	4
Resistance to Cracking	2	3	4	1

NB This is often only a matter of degree - rutile rods give the lowest ductility but this is still quite adequate for most purposes.

USES OF ELECTRODES

We have covered the uses of electrodes in the above. The most used type are the Rutile rods. These are easy to handle and give a good quality weld deposit. However they can give porosity and rather lower ductibility than the other types. Resistance to cracking is good but there is a danger of the presence of micro-cracks or fissures (visible at X 500). For really high quality work, basic low hydrogen electrodes are used. These give better weld metal properties (especially impact and ductibility) and absence of microdefects, but are more difficult to handle. Also the fume is more unpleasant.

BASIC ELECTRODES

The importance of these electrodes in high quality work makes it necessary for us to look at the reason for their usage. This is due solely to the deleterious effects of hydrogen in weld metal. The source of this hydrogen is largely the electrode coating (minor effects are moisture on parent plate, rust and impurities). In low hydrogen electrodes care is taken to avoid the use of coating constituents that contain combined water, storage is controlled to avoid moisture pick up. Typical figures are 2cc/100 gr weld metal compared with 10-15cc/100 gr for other types.

Recent work has also emphasized the deleterious effects of nitrogen and oxygen on weld metal properties. Basic coated electrodes are also effective in reducing the amounts of these elements in the deposited weld metal.

Effects of Hydrogen on Service Behaviour

(Ref: Christensen, Welding Journal, April 1961, 40, (4), 145-s)

Hydrogen is present in weld metal (and parent metal) in two forms, one as free atoms which can diffuse out of the metal given time or moderate temperature (say 100°C or even less), the second in a micro-segregated form which cannot be removed by heating (diffusible and total hydrogen contents.).

Diffusible hydrogen can result in a temporary deterioration in mechanical properties - lower ductility and room temperature, impact, raised impact transition temperature. Presence indicated by 'fish eyes' on fracture surfaces. This hydrogen is lost after storage for a few weeks, or on warming slightly when properties are restored.

Micro-segregated hydrogen can result in permanent damage - micro-fissures - and these can result in an increase in the transition temperature and if many micro fissures are present, in lowered ductility and impaired performance under alternating stresses. Micro-fissures can occur in both mild and low alloy steels and tolerance for them must depend very much on service requirements.

It must be remembered that these can only be seen at about X 500 magnification and would be missed under normal inspection. They are particularly a problem if low temperatures are likely in service (brittle fracture).

Hydrogen can also cause permanent damage if martensite forms in the HAZ ('underbead cracking') as it does in many high strength steels. Martensite results in severe local stresses and these, combined with hydrogen, can result in cracking which increase the danger of brittle or failure under fatigue conditions.

EFFECT OF NITROGEN AND OXYGEN IN WELD METAL

Having dealt at length with hydrogen it is convenient to have a brief look at the effect of nitrogen and oxygen.

Nitrogen increases the ambient and elevated temperature strength of weld metal at the expense of ductility and notch toughness. It also contributes to the incidence of microfissuring and porosity.

Oxygen is not so serious as hydrogen or nitrogen but it can react with the carbon in the weld metal to give CO. This can result in porosity and even decarburisation. Evidence also points to oxygen lowering the impact properties and thus resistance to brittle fracture.

IRON POWDER ELECTRODES

These electrodes are heavily laden with iron powder in the coating and increase the deposition rate for a given size of core wire.

SELECTION OF ELECTRODES

It is difficult to say anything general about electrode selection - it must always depend upon the specific job. Points to be kept in mind are:

- a) Material to be welded - type and condition.
- b) The actual fabrication - fit up, position, site or shop.
- c) Quality required - need to meet any standards.
- d) Economy - need lowest cost - affected by cost of electrodes speed of construction.
- e) Labour available - operating characteristics may affect choice of electrode type and make.

I INTRODUCTION

1. Description of Process

Submerged arc welding is a true arc welding process carried out within a blanket of granulated flux. The electrode consists of consumable filler wire and the arc operates between this and the parent material. The whole operation is protected by a layer of granulated flux but around the arc this breaks down and provides some gases and a highly protective thermally insulating molten container for the arc which allows high concentration of heat making the process very efficient and highly suitable for heavy deposits at fast speeds. After welding the weld metal is protected by a layer of fused flux and then by a layer of unused flux.

This is by far the most used form of this process but multi-electrode welding is also carried out.

2. Multi-Electrode Processes

Multiple arcs increase the deposition rate, help control of arc blow and increase welding speed.

3. Welding Position

Submerged arc welding is basically a process for downhand welding of butts and fillets, but it can also be used for HV welding of fillets and butt welds. The Russians claim to have used it for inclined and vertical welding - there is nothing impossible about this but a number of purely technological difficulties have to be overcome. Obviously, higher welding speeds are obtained in the DH position.

For most purposes in butt welds can use a close butt technique and can weld in one or two passes - single pass generally limited to $\frac{3}{4}$ ".

Where better quality or thicker plates are butt welded can use a multirun technique - in HV welding of nuclear pressure vessels may use 80 or more runs in 3" plate. The more runs the better the weld metal properties but the greater the cost. Even so joint preparations are narrower than for manual welding.

Fillets can be made smaller than with many other welding processes because of the high penetration. Again one prefers to weld DH even if it means tilting the work but can do HV fillets (often from 2 sides at once). Fillets can be made up to $\frac{3}{8}$ " in a single pass but above this need

2 or more passes.

The deep penetration relatively small weld preparations, high localised heat input and high welding speeds all reduce distortion which is another useful aspect of the process.

4. Joint Preparation

Plate up to $\frac{5}{8}$ " thick can be welded quite comfortably without bevelling but above this use a W or double V preparation.

Even so, a narrow included angle of 30° is generally satisfactory, although care is needed in slag removal.

With double-V preparations it is necessary to have good fit-up and an adequate land to prevent burn-through. Back chipping is only likely to be encountered on high quality work.

Filletts can be made without bevelling in plates up to $\frac{3}{4}$ " thick.

(J.T. - 2 pass welds on 4" plate - c. 2000 amps.)

Backing: This is essential in single pass weld of any size because of the comparatively large weld pool. Can use:

- i) Backing strip of parent material permanently fused to joint.
- ii) A backing bar
- iii) Flux backing - not much used in U.K.
- iv) Manual backing runs
- v) Impregnated tape.

Cleanliness: This is important and all heavy scale and rust, paint, oil, grease and moisture should be removed. Light scale (say from flame cutting) does not need to be removed. Certain fluxes are more tolerant of dirt than others - this can generally be determined from the manufacturers.

II APPLICATIONS

Submerged arc welding has the advantage of all automatic welding processes - high deposition rates. In addition absence of glare and spatter and smooth weld finish is important (compare Fusarc tolerance to rust and dirt, rather better notch toughness).

Applications are varied regarding both materials and actual jobs.

The great majority of work is done on mild steel of various grades but alloy welds are also possible using alloy wire or an active flux. Stainless steel can be welded up to thicknesses of 8". Little is heard in this country or the U.S.A. about the submerged arc welding of non-ferrous metals but in Russia it is used for Al, Cu, Ni, Co and Ti - quality is not known but depends on protective and fluxing actions of the flux. Reports indicate good quality.

Applications cover the fields of pipes, boilers, prefab. girders, pressure vessels, railways rolling stock, cars, ships, aircraft (only a little), machinery frames, rotary kilns, earth moving equipment, electrical equipment and ordnance.

The process is also useful for cladding, hard facing, and building up of worn surfaces.

III EQUIPMENT

1. Welding Head

This unit carries the electrode wire with its current contacts, guide tubes and wire feed motor and controller. A flux hopper is included together with means for depositing the flux where required.

The head may be mobile, i.e. mounted on a tractor (e.g. deck welders) or a moving boom, or stationary in which case the work is moved underneath the head.

2. Control of Arc Length

Arc length control is necessary to:

- (a) control the arc at the instant of striking to prevent it freezing to the work.
- (b) maintain the correct arc length during welding, even though there are variations in the distance from the jaws to the work.

Of these striking is the more critical.

Types of control are:

- i. Arc voltage control - starting with work stationary, electrode in contact with work, retract start. In this type of control the wire can be moved either way requiring considerable control on the motor.

This type of unit is best for

- (a) most sensitive control, especially at high speeds and on any low current density work.
- (b) starting and stopping on work without run off tabs (unit generally includes crater filling)
- (c) Quick changes in contour.

- ii. Arc voltage control in one direction only - simplest control with feed motor armature directly across the arc. Not very sensitive but suitable for high current density work.

- (a) economical installation.
- (b) can be used with petrol engined welding machine for field work.
- (c) simplest set up for a.c. power sources. Generally start with piece of wire wool.

- iii. Current control - modified constant potential power source. Constant wire feed speed with very high short circuit current gives self adjusting arc.

This allows a very short arc length to be held without the electrode sticking.

- (a) used for 18 swg or other low voltage applicators.
- (b) tendency to melt into backing bars through wide gaps is minimised.

(c) Allows "hot" starts (work or electrode moving before contact).

Self adjustment in submerged arc welding is little used in this country at present self adjustment is adequate with "drooping" power source of higher currents.

3. Selection of Process

Submerged arc welding can be semi-automatic (hand gun), automatic (requiring man during welding) or fully automatic. Selection of process depends very much on the type of work contemplated.

a. Semi-automatic Welding (up to 700 amps) should be used for:

- i) Out of position welding where large molten pool would spill (e.g. inclined)
- ii) Short welds lengths.
- iii) Light gauge welding (10 swg.)
- iv) Small non-repetitive jobs.
- v) Jobs where fit up cannot be controlled.
- vi) Jobs where it would be difficult to retain flux because of shape of work.

b. Automatic Welding should be used for

- i) Jobs where advantage can be taken of the increased deposition rate at higher currents.
- ii) Where continuous wire feed will increase the duty cycle.
- iii) Work sufficiently repetitive for proper procedure and practice to be worked out.
- iv) Where complicated shape makes fixturing too difficult for fully automatic operation.

c. Fully Automatic Welding should be used wherever it is practical and economic. Complete automation should provide:

- i) Push button automatic arc striking
- ii) Heavier equipment construction (very high duty cycle)
- iii) Higher current capacity
- iv) Self contained travel mechanism.

Can be used only for highly repetitive jobs which can be well jigged and manipulated.

IV POWER SOURCES

The first important point to note with submerged arc welding is that the duty cycle is much heavier than with manual metal arc welding, and power sources therefore need higher ratings.

Volt-Amp Characteristic

It is usual to use a drooping characteristic power source the same or similar to those used for metal arc welding. Actually a shallower droop might be more suitable (as it would give more self adjustment) but there is no published information on the subject.

Constant potential (very slightly drooping) sources are used for self adjustment with lower currents (up to 600 amps) although not to any extent in the U.K. Main advantage is rapid correction during welding and 'hot' starting.

With a constant potential source there is some indication that better welds result with more even bead contour and penetration, whilst greater variations in joint conditions can be tolerated. Also simple control equipment required. Main advantages are in high speed welding of thinner gauges.

Alternating or Direct Current

A.C. and D.C. of both polarities are used at voltages of 25 - 40 v.

D.C. provides more versatile control over bead shape, penetration and speed, whilst arc striking is easier. D.C. is preferred where

- a) fast, accurate striking is required.
- b) close arc control is needed
- c) difficult contours are to be followed at high speed.

Control of bead shape is best with D.C. + which gives better wash in and a smaller molten pool. Highest deposition rate is obtained with D.C. - but penetration is lower than D.C. + on A.C.

A.C. minimises arc blow, which is increasingly important at higher currents - above 1000 amps. A.C. is generally used, as it is in multiple arc welding. The lower cost of A.C. equipment is another important factor.

Current densities of up to 100,000 amps/sq.in. are used. Generally 20,000 - 70,000 amps/sq.in. compared to 3,000 - 10,000 amps/sq.in. for metal arc welds. (Welding speeds of over 20 in/min. compare with manual speeds of 3 in/min.)

V ELECTRODE WIRE

The wire needs to be clean with a bright surface to allow easy and continuous current pick up, and reduce corrosion and improve weld metal. For this reason generally use Cu coated wire, although the Russians do occasionally use mill coils direct in integrated works (weld quality might suffer in consequence.)

In the welding of ferritic and martensitic steels mild steel wire (rimming quality) is generally used.

However, alloy wires (e.g. UM 41 & 42) can be used with an inert or an active flux for low alloy and austenitic steels. Again, a fabricated cored electrode may be used with alloying elements in the core.

Electrode consumption is relatively low because of no or small edge preparation (high dilution) and absence of spatter and stub ends.

The high dilution of heavy deposits can be good or bad. It can mean wire composition is of little importance. If bad, can be reduced by multi-run welding.

VI NATURE OF THE PROCESS

At one time there was considerable discussion as to whether the Submerged Arc Process was a true arc process or not. Then it became generally acceptable that it was an arc process-looking at bead on plate sections one would endorse this view since most sections show a typical arc "finger" effect that originates probably from the plasma jet effect.

Work was done in 1947 by L.N.Kushnarev (reported in Welding Journal, 1951, 30, 340-s), when he examined submerged arc welding from 200 - 1500 amps. (A.C. Voltage not given). Using a C.R.O. he took voltage traces arguing that an arc would give a "square" wave and a resistance slag bath a sinusoidal wave.

A sinusoidal wave was obtained at 300 - 400 amps. with a small electrodeplate gap, low welding speed, so that at low currents the process may not be an arc process, under some conditions. He also found cases of alternating arc and resistance heating.

This seems fairly conclusive although one is still not sure whether Kushnarev obtained resistance heating under true welding conditions.

One may also wonder if this was the original guide to electro-slag welding.

VII PROPERTIES OF SUBMERGED ARC WELDS

References: I.L.Stern, N.A.Kahn & H.Nagel, Welding J., 1957, 36, 226-s.
B.Augland & N.Christensen, Brit.Welding J., Oct. 1961, 8 (10), 473.
W.Santini & V.Girardi, Symp.on Welding in Shipbuilding, Oct.Nov.1961, Paper 23.
(other papers also of interest)
J.Wilson D.A.E.Thesis, 1963.

It is first necessary to make the point that very few published results are available. This is probably because only recently has submerged arc welding been considered for quality work.

Christensen looked at both single and multilayer welds and found that both gave acceptable transverse tensile and bead results. With impact tests multi-layer deposits gave transition temperatures markedly lower than those for parent material. Single layers welds gave considerable variation in impact results on either side of those for parent plate. Transition temperatures were not good enough for N.D.111 or NDIV. steel but were adequate for mild steel of N.D.1 or even N.D.11 quality.

Christensen makes the comment that the notch toughness seems more dependt on base material than number of runs. This is probably due to heavy dilution.

Santini looked at bend and impact properties in welds in 15 mm. and 35 mm. plate.

With 15 mm. plate joint bends were satisfactory for plate compositions of .19% C., .035% S, but failure occurred at a composition of .23% C, .05% S. Results were similar for 35 mm. plate but the chamfered edge preparation gave less dilution and results were better though more scattered.

Impact values were given for several wire/flux combinations. Transition curves are given as energy absorption and lateral expansion. Wire/flux combinations give a wide range, but good results, (i.e. low transition temperatures) could be obtained by careful selection. With 15 mm. plate best results were obtained with .18%C steel but this was not observed with 35 mm. plate (less dilution?). Multi-layer welds gave better results than double pass welds with certain fluxes.

I have done some tests with $3\frac{1}{2}$ ins. plate using wide vee multipass techniques. No difficulties were found in meeting nuclear Class I requirements for soundness, tensile and bend properties, whilst impact properties were also within specification, though less good than those of manual metal arc welds.

PROCESSES

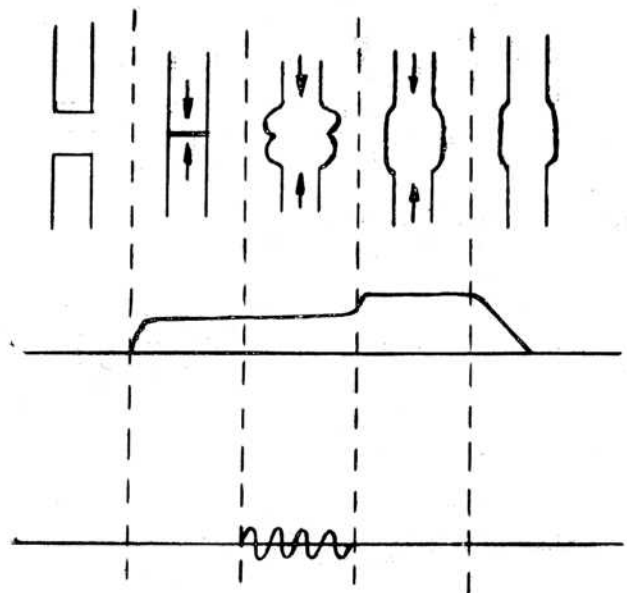
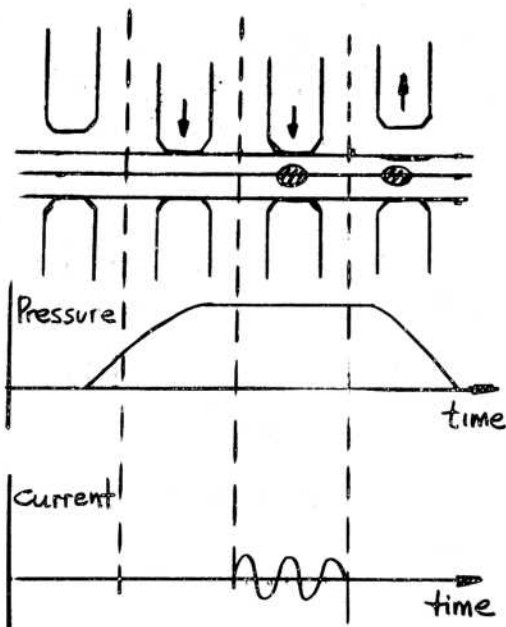
The processes making up resistance welding are linked together because they utilise the contact resistance of metal surfaces for the welding heat source. The exception is flash welding and this is an historical effect - due to this process being developed from resistance butt welding:

The distinguishing factors are:

1. Heating the interface to be welded by passage of current.
2. Joining by pressure.
3. A third characteristic is the short time cycle of the operation.

These processes depend on there being sufficient interface resistance to bring the necessary currents down to an acceptable level. Even so currents of 100,000 amps. or more may be used.

- a) Spot welding: the most common process, Cu-bar electrode to locate current.
- b) Seam welding: multi-spot welding with overlapping spots to give leak tightness. Cu bar electrodes replaced by wheels.
- c) Projection: in this projections are made in one of sheets to be welded and these are used to locate and concentrate the current.
- d) Resistance Butt Welding: for butt welding wire and light gauge rod.
- e) Flash butt welding: if the rods to be welded are connected to the power source before being brought together arcing occurs. Heat generated is much more because the current path resistance is increased, allowing heavier gauge to be flash welded than resistance butt welded.



POWER SUPPLY

The requirement is high currents for short times. Current ranges (peak current) from 600 amps. for fine wires (valve filaments) to 220,000 amps. for 3/16 in. Al. Potential needed to overcome contact resistance is 1 -20 V.

Time is short and generally measured in cycles. Times are generally from 1/50 sec. (1 cycle) to 2 secs. (100 cycles).

The simplest way of getting this current supply is by means of a transformer with a very heavy single turn secondary winding reducing the voltage to 20 or less and increasing current proportionally.

Single phase transformers are by far the most used, but two other methods can be found:

1) Three phase welding utilises 3 phase supply giving low frequency current pulses in (balanced power supply) the secondary. Initial cost is higher but power costs are cut markedly, a longer electrode life is obtained and weld quality is improved. In fact, for the thicker gauges of light alloy 3 phase welding is a must.

Slower build-up of current . . . less pick-up.

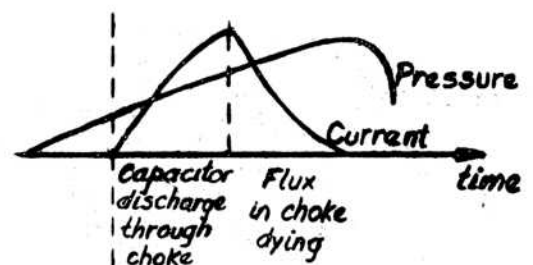
2) Energy storage, say by capacitor discharge machines, giving a d. c. pulse. Battery sources are also used occasionally.

The use of single phase transformers gave problems in the welding of the high conductivity light alloys. First, was the problem of getting sufficient heat at the interface before it was conducted away. Secondly, high electrode wear occurred due to the 50 cps giving skin effect and uneven heating.

A general disadvantage of single phase is unbalanced loading, low power factor.

This led to the development of energy storage machines that gave a single d. c. pulse. The most common, and one still found in the U. K. , was the capacitor discharge machine which used a 3-phase supply to charge a bank of capacitors (for circuit see Bv J. Sept. 1959. Capacitors discharged at a predetermined pressure - high current, short period. Also use induction storage. In neither case can the discharge time be controlled.

With both these machines the sharply rising current can lead to sticking and contamination of electrodes or work.



During the 1950's came the development of 3-phase welding using 3-phase transformer - balanced load low frequency (2 - 3 cps) - virtually d. c. for most welding ops. Even heating, low wear. Now, trend for 3-phase, rectifier welding.

ADVANTAGES

Resistance welding processes are basically automatic processes, the automation varying only in degree. This gives several advantages:

- 1) Use of semi-skilled or unskilled labour.
- 2) Machines can be readily built into production lines.
- 3) Can use automatic loading, unloading and transfer of components.
- 4) No filler metals or fluxes required.
- 5) Heat treatment can be carried out on the machine.
- 6) No subsequent treatment (except in flash welding).
- 7) Distortion minimised as heating confined to a very small area.

Disadvantages of the process are the restrictions of the types of joint (lap welds only for seam, stitch, spot and projection welding), the limitation on component thickness and size, and the lack of portability of units.

The percentages of fusion and resistance welding are an indication of the degree of the development of a country.

Reason for this lies in the relative fields of application of fusion and resistance welding. Fusion welding covers fabrication of capital and heavy goods, which are most needed in under developed countries. Resistance welding is mainly used for the less necessary consumer goods such as cars, washing machines etc.

In the U. S. ^A, resistance welding has tended to catch up with fusion welding, even surpass it. IN Great Britain, fusion welding has reached a plateau; applications of resistance welding are still growing rapidly.

PROCESSES

Spot Welding

This is used for lap joints where leak tightness is not required - the most common resistance welding process. Single spot welds made by two electrodes. Applicable to all types of steels, Al alloys, Mg alloys, Ni alloys, Ti alloys, and some Cu alloys (those with the higher resistivities).

Thicknesses range from 30 s.w.g. up to 3/16" or even more in some specialist applications. Generally, however, used in sheet metal fabrications.

Its main features are its versatility (making it suitable for small production runs) and the simplicity of most spot welding machines.

Stitch Welding

This is spot welding but operation of the foot pedal produces automatic welding

cycles, the electrodes opening between each cycle to enable the work to be moved. Quicker than straight spot welding. Can be used for overlapping spots.

Seam Welding

Lap welds, occasionally mash welds, bar electrodes replaced by wheels one of which is power driven to move the work. The current passes intermittently with wheels rotating continuously, giving a series of overlapping spot welds.

Used for pressure tight lap welds, e. g. fuel tanks.

Roller Spot Welding

Here the wheels move intermittently stopping for each spot. Used for normal spot welding in long production runs. Quicker but less versatile than spot welding.

Projection Welding

This machine uses flat platten electrodes, the projections replacing the bar electrodes of spot welding. Enables 3 - 5 welds to be made at a time - machines normally of larger electrical capacity than spot welders.

Used for joining sheets and attaching studs, washers, bolts, etc. to plate, T joints.

The making of projections puts up component cost, and the process is used mainly for mass production.

Weld appearance often better than in spot welds (less depression).

Electrodes have a longer life and require only infrequent dressing.

Resistance Butt Welding

In this process the transformer circuit is similar to those used for spot welding. Current is not passed until the faces of the rods or wires are in contact.

In this process it is essential that the end faces should be clean and flat (preferably machined). Otherwise there is a danger of oxide inclusions at the weld interface with subsequent loss in strength. Due to the upset there is some thickening of the rods around the weld but this is generally low, so that subsequent machining is unnecessary.

Flash Butt welding

In this process the welding transformer gives a higher voltage than with other resistance welding processes. Power is on as the components are brought together at a slow controlled speed. Faces of joints not cleaned up or machined. This results in heavy power passing through the first points in contact, causing them to melt explosively. The process continues in this way with considerable removal of metal, heating the ends of the component.

When the temperature is high enough the ends are forced together by an increase

in pressure and the current switched off. This sudden loading squeezes out all the overheated metal and gives a good quality pressure weld between the hot uncontaminated metal behind. (N. B. Flashing can be used to give pre-heat).

Welds can be made without prior preparation but the flash on the finished product often needs to be removed (especially inside of tube bones). A. S. E. A. method. As with other resistance processes heat treatment can be incorporated.

Compared with resistance butt welding heating is more localised, power consumption is less and the process is faster. In addition, it gives easier welding of dissimilar metals.

Uses cover bar to bar joints (e. g. drills), tube to tube, sheet and strip (in continuous mills), Longitudinal tube welds; Bevel joints (e. g. window frames), Rail sections.

CONTROL

The factors that affect weld quality are (in order of importance):

1. Welding current.
2. Weld time.
3. Electrode force.
4. Resistance.

These variables are interrelated and in general

- (a) weld time may be reduced by increasing the current;
- (b) increasing the pressure decreases interface resistance, thus needing an increase in current for good results.

There are other effects, of course, that are important. Thus increasing the force and current can give excessive indentation and sheet separation, expulsion of metal, or cold collapse of projections in projection welding. Too low a force can lead to severe internal defects in the weld.

Electrode Force

Problem is the short time cycle high reproducibility required. On smaller machines electrode force is governed by a spring and loading is applied by pressure from the foot. On larger machines electrode force is governed by an Air cylinder on the machines, or even an oil cylinder (though most machines are air operated). The accuracy of control depends on the pressure regulator and circuit which in some machines can be very accurate. Our Sciaky projection welder has a diaphragm in the air cylinder with varying pressures on either side, which allows fine control of electrode loading and a 3-pressure cycle during the welding operation. This gives low inertia - rapid response.

Current Control

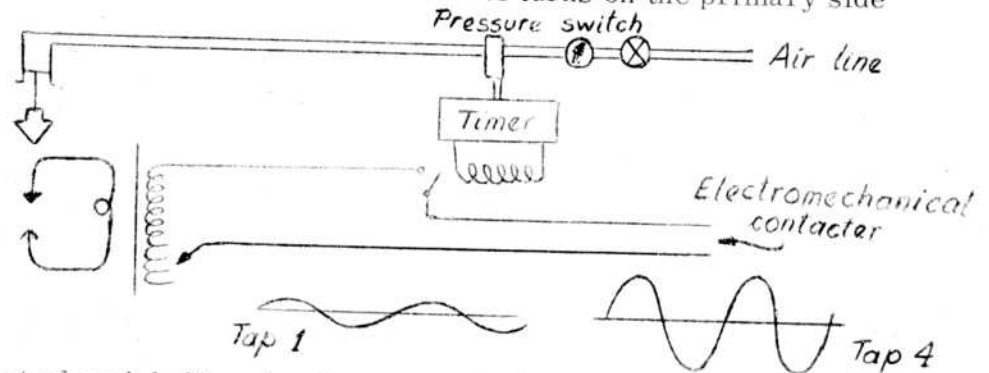
Current is switched on and off by either an electromechanical contactor (in the

case of the lower current and less complex machines) or by ignitron valves, both located in the primary (low current) circuit. Each "switch" is controlled by a timer which is, in turn, initiated by some device on the welding machine, e.g. air pressure switch. Weld times may vary from $1/100$ sec. to 2 secs. ($\frac{1}{2}$ - 120 cycles) for spot welds or even longer for resistance butt or flash butt welds.

The amount of current can be controlled in two ways:

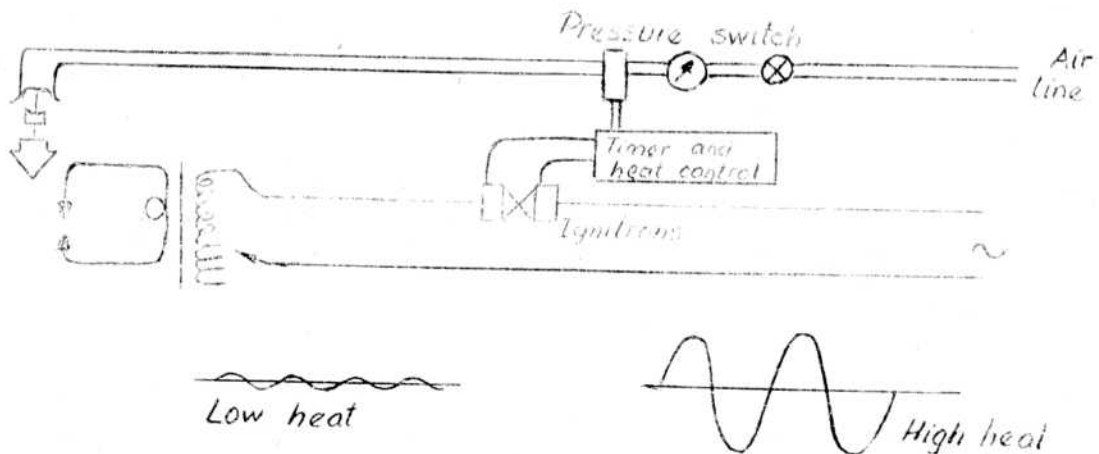
- (1) Changing the transformer tapings, i.e. the number of turns on the primary side

This is used in all machines but is the only source of control in the cheaper ones.



- (2) By altering the amount of each half cycle of a.c. flowing into the work - "Phase-shift heat control". This is done by triggering the ignitions to conduct current for only part of each half cycle.

This method is much more accurate and controllable, and is generally used in conjunction with (1) above for the better machines.



A further refinement - synchronous time control - ensures that the current is always switched on at the start of a cycle i.e. "no voltage". This stops initial current surges and ensures complete reproductibility in regard to the total number of weld cycles - important in $\frac{1}{2}$ - 5 cycles range.

These units can also be arranged to give constant welding current irrespective of changes in mains voltage or amount of magnetic material within the jaws of the welding machine. Additional modifications can give gradual increase and decrease in power at the start and finish of welding (slope control) and the use of lower current lends for post heat treatment.

The point is, that with the use of electronic switching and control any sort of heating cycle can be used and can often be combined with a variable forge pressure cycle.

Resistance

Heat Generated, $H = I^2 R t$ $I = \text{current}$) - readily controllable.
 $t = \text{time}$)

The resistance is a problem.

(i) Contact resistance, electrodes - workpiece. Need for cleanliness of electrodes.

(ii) Interface resistance.

Contact resistance needs to be kept low, but interface resistance should be high and uniform to facilitate welding.

(iii) Secondary circuit - amount of steel within jaws - magnetic effect.

(iv) Electrode force as pressure increases, resistance decreases.

For reproducibility we need to keep the resistance constant - consistent surfaces on workpieces. This generally means that one carries out some surface preparation - removal of heavy scale, loose rust, paint, degreasing. Maintenance of correct tip size is also important.

MATERIAL PROPERTIES THAT AFFECT RESISTANCE WELDING

1. Electrical and Thermal Conductivity

The higher the electrical and thermal conductivities the more difficult it is to make welds - less heat is generated and it is conducted away quicker.

Spot welding of pure Cu is impossible and for Al heat input must be as rapid as possible (∴ 3-phase welding). Rapid cooling also presents problems of shrinkage necessitating maintenance of electrode force.

With low conductivity materials (stainless steel) the problem is to get rid of heat - otherwise get boiling and expulsion. Lowering current and increasing time gives excessive distortion so that one normally uses short welding times and very high pressures.

2. Surface Condition

Uniform, natural oxide films can give irregular welds due to irregular break down of the film (which is an insulator). Weld shape can be affected and local overheating can result in expulsion.

It is important, therefore, that the oxide is removed before welding - chemically,

wire wool, or wire brushes. This applies to Al and Mg alloys but with stainless steel and the Ni alloys (mimonics) the films cause no trouble and are not removed.

Localised defects such as rust, mill scale, paint, and grease give similar effects to thick oxide films.

Metallic coatings (Zn, Sn) do not generally interfere with welding but reduce electrode life.

3. High temperature Strength

This effects the electrode force necessary to prevent expulsion - hence high pressures needed for heat resistant alloys.

4. Expansion Coefficient

Affects contraction during cooling. High contraction necessitates high pressure (maybe a 2 pressure cycle) to prevent shrinkage defects.

5. Oxidation Resistance

Not generally a problem except with the most reactive metals.

PRACTICAL CONSIDERATIONS IN SPOT WELDING

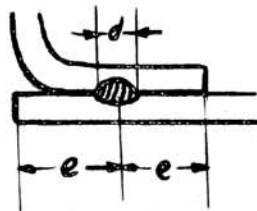
We need to know a few points about fit up, tip diameter and shunt losses, before going on to consider evaluation of welds.

Fit-up is important in quality work. If the electrodes are used to bring and hold components together we have an effective loss of electrode force, inconsistent heating, and also wrong positioning of the spot is possible.

Shunt losses through previous welds. The first weld is larger than subsequents ones, therefore do not test first weld normally.

Spot size This should be governed by penetration. Require .60% penetration of total thickness. Overlap, e , = $1\frac{1}{2}d$

Distance between spot should be not less than 3 x spot diameter (For closer welds must increase current to allow for shunt losses.)



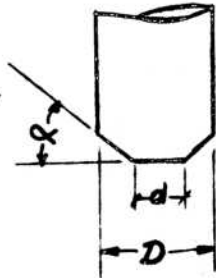
$$e < 1\frac{1}{2}d$$

Electrode Tips

Tip diameter = $\sqrt{t}$ (UK,) 2t + 3 mm on Continent (smaller)

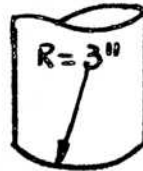
Tip pressure= 10,000 psi for low C M. S., Cr - Cu electrodes

Electrode either tuncated cones or domed.



$$\alpha = 20^\circ \text{ (U. S. A.)}$$

$$\alpha = 30^\circ \text{ (G. B.)}$$



Evaluation of resistance Welds

We shall consider non-destructive (BWRA Bulletin Nov. 1961) and destructive (BWRA Bulletin September 1962) tests.

Non-Destructive Tests: Ref: BWRA Bulletin November 1961.

- 1) Importance of material control-electrode cleanliness and reproducibility workpiece surface quality and dimensions.
- 2) Welding Conditions- record force time and current - not a complete but a reliable guarantee of consistent weld props. Expense makes complete record including oscilloscope trace not feasible but O. K. for periodic check test.

Commercial current meters and cycle counters (e. g. our Hirst) are widely used. Good for trouble shooting, BUT:

- a) Current meter only reads peak current, nor variations in current level during welding.
- b) Phase shift and slope in and out can give misleading readings.
- c) For repetitive welds (seam and stitch) interpretation is difficult, not permanent record.

3. Radiography. The depression will show dark on a radiograph but does not necessarily indicate finish - it is claimed one can tell by experience (Handley Page).

Large defects show, but not small or wrongly oriented cracks. Since size is not too important compared with location this may be a problem.

4. Dye penetrant - leak tightness.

5. Magnetic - maybe.

6. Vacuum leak detection.
7. Ultrasonics - Russian work. Recent developments in U. S. A. and U. K.
8. Other methods used are surface coloration after welding, surface hotness after welding and amount of indentation.
9. Head Movement.

Destructive Tests

These are generally more useful and more used. One cannot rely solely on non-destructive tests, not even head movement.

Uses are:

- 1) Setting up of machine.
Selection of welding conditions - trial and error, experience, books.
Effect of variations from recommended settings - would expect toleration of variables as below.

$\text{Current} \pm 10\%$
 $\text{Time} \pm 3 \text{ cycles}$
 $\text{Force} \pm 10\%$
- 2) Test piece production - strength values.
- 3) Check tests - during production run.

It must be accepted that good test piece results do not guarantee satisfactory production welds - problems of configuration and fit up.

The tests and their value and limitations are covered in the hand-out.

The most used are chisel or peel test (crude but effective) and shear test (not much use). The cross tension test is very useful but still not widely used.

TABLE 1 Tensile Properties of Mild Steel Weld Deposits

Welding Process	U.T.S. tsi	Yield Point tsi	Elongation on 3.54 x diameter %	Reduction Area %	Impact ft - lbs	Hardness VPN
Shielded Metal Arc Cellulosic Class 1	32	26	30	60	-	-
Rutile Class 2	30/34	26/29	28/32	45/65	55/70 Izod	170/190
	31/34	24/30	28/35	50/65	45/65 Izod	180/200
	32	25	34	65	73	-
	35	31	32	61	55 Izod	176
Rutile Class 3	30/33	24/28	29/33	50/65	50/60 Izod	180/200
	31	25	33	62	68 Charpy	-
	32	26	33	60	62 Izod	-
	34	24	38	65	85 Izod	-
Iron Oxide-Silicate Class 4	31	24	36	62	65 Izod	-
	34	27	33	60	55/80 Izod	170
Basic Low Hydrogen Class 6	27/32	22/29	33/41	70/77	60/150 Charpy	-
	29	24	38/41	75/77	100/170 "	-
	32/36	29/30	30/34	55/70	100/170 "	180
	34	25/29	37	75	80/100 "	170/200
Iron Powder	30	-	34	57	-	-
	32	26	28	61	63 Izod	-
	34	26	33	69	-	-
Submerged Arc	28/32	19/20	32	60/65	65/72 Charpy	-
	30	27	33	62	51/59 "	-
	33	29	30	65	38/73 "	-
	35	28	28	55	78/74 "	-
	36	30	30	62	52/74 "	-
Electro Slag	31	22	35	63	42/76 Charpy	-
	33/35	24/27	28/31	57/63	48/109 "	150/160
	34/35	-	30	64	42/50 "	-
	36	23	30	57	22/25 "	-
MIG/CO ₂ (Dip Transfer)	38	31	25	58	56 Charpy	
	39	35	26	59	36 "	
	40	32	29	63	43 Charpy	
	45	36	24	46	40 "	

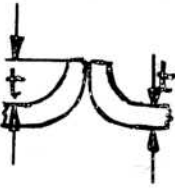
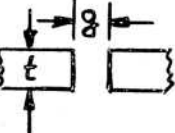
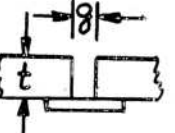
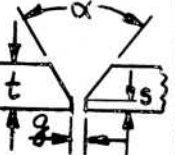
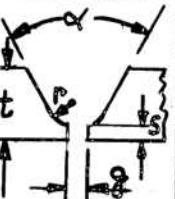
TABLE II Effect of Electrode Coating on the Usability, Performance and Quality of Ferrous Weld Deposits

This table indicates the relative characteristics obtained from the use of various types of coatings

Electrode Class	Rutile	Gas Shielded	Iron Oxide-Silicate	Basic
Usability	4th	2nd	3rd	1st
Penetration	4th	1st	2nd	3rd
Absence of Under-cutting	1st	4th	3rd	2nd
Absence of Spatter	2nd	4th	1st	3rd
Deposition Efficiency	1st	4th	3rd	2nd
Deposition Rate	2nd	4th	1st	3rd
Soundness	3rd	4th	1st	2nd
Arc Force	4th	2nd	1st	3rd
Ease of Handling	1st	3rd	4th	2nd
Ease of Re-striking	1st	2nd	3rd	4th
Current Carrying Capacity	3rd	4th	2nd	1st
Resistance to Cracking	2nd	3rd	4th	1st

Rockwell "Electric Arc Welding Equipment"

JOINTS PREPARATIONS

Preparation	Process	Thickness t ins.	Gap g ins.	Root s ins.	Radius r ins.	Includ- ed Angle α	Depth d ins.
(i) <u>Flanged</u> 	Oxyacetylene Atomic Hydrogen Carbon Arc TIG	1/16 max.	-	-	-	-	-
	Submerged Arc	5/16 max.	-	-	-	-	-
(ii) <u>Square Butt</u>  	Oxyacetylene, 1 side only	1/4 max.	$\frac{t}{2} \text{ to } \frac{t+1}{2 \cdot 32}$	-	-	-	-
	both sides	1/6 to 1/2	$\frac{t}{2} \text{ to } \frac{t+1}{2 \cdot 32}$	-	-	-	-
	Shielded Metal Arc	1/6 to 3/8	0 to 3/32	-	-	-	-
	Submerged Arc, both sides	1/8 to 5/8	1/32 max.	-	-	-	-
	Shielded Metal Arc, steel backing	1/8 to 5/16	0 to 5/16	-	-	-	-
	deep penetration, steel backing	3/16 to 5/16	0 to 1/8	-	-	-	-
	Submerged Arc, steel backing	1/4 to 3/8	5/32 to 3/16	-	-	-	-
(iii) <u>Single-V</u> 	Oxyacetylene	1/8 to 1/2	$\frac{t}{4} \text{ to } \frac{t+1}{4 \cdot 32}$	0	-	60 - 70°	-
	Shielded Metal Arc	3/16 to 3/4	$\frac{1}{16} \text{ to } \frac{3}{16}$	1/8 max.	-	60 - 70°	-
	Submerged Arc	1/4 to 1 1/2	$\frac{1}{32} \text{ max}$	1/8 to 3/8	-	45° min	-
	Shielded Metal Arc	3/4 to 2	$\frac{3}{32} \text{ to } \frac{5}{32}$	$\frac{1}{16} \text{ to } \frac{3}{16}$	$\frac{1}{4}$	20 - 45°	-
(iv) <u>Single-U</u> 	Submerged Arc	3/4 to 2	$\frac{1}{32} \text{ max.}$	1/4 min.	$\frac{1}{4}$	20° max	-

Preparation	Process	Thickness t ins.	Gap s ins.	Root s ins.	Radius r ins.	Included Angle α	Depth d ins
(v) Double-V 	Oxyacetylene	Over 1/2	$\frac{1}{32}$ to $\frac{3}{32}$	0	-	70 - 80°	over $\frac{1}{4}$
	Shielded Metal Arc	5/8 to 1.1/2	$\frac{1}{16}$ to $\frac{7}{32}$	0 to 1/16	-	60 - 70°	over $\frac{3}{8}$
	Submerged Arc	3/4 to 2	$\frac{1}{32}$ max.	1/4 min.	-	45° min	
	Shielded Metal Arc	1 to 3.1/2	$\frac{1}{16}$ to $\frac{7}{32}$	0 to 1/16	-	60-70° 60-90°	$d' \frac{2}{3} t$ $d' \frac{1}{3} t$
	Submerged Arc	1 to 3.1/2	$\frac{1}{32}$ max.	1/4 min.	-	45° min	$d' \frac{2}{3} t$ $d' \frac{1}{3} t$
(vi) Double-U 	Shielded Metal Arc	Over 1.1/2	$\frac{1}{32}$ to $\frac{5}{32}$	$\frac{3}{32}$ to $\frac{1}{8}$	$\frac{1}{4}$	20°-45°	-
	Submerged Arc	Over 1.1/2	$\frac{1}{32}$ max.	1/4 min.	$\frac{1}{4}$	20°	-

References: "Recommended Joint Preparations for Fusion Welding of Steel", International Institute of Welding, Commission XV, Brit. Welding J, Jan. 1962, 9, (1), page 13. AWS Welding Handbook, Section I, Chapter 6, 1957.

MAT.65/RLA

RESISTANCE WELDING ELECTRODES

Material	Hardness V.P.N.	Conductivity %	Softening Temp. °C	0.2% Proof Stress tsi	U.T.S. tsi	Elonga- tion %	Uses
Hard drawn high con- ductivity copper	95	90	150	20	24	10	Spot-seam welding of Al & its alloys
Cd - Cu	94 - 114	85	250	25	30	20	Spot-seam welding of coated steels
Cr - Cu	138 - 150	80	500	31	34	15	Spot-seam welding of steels
Be - Cu	363 - 420	23	300	67	75	4	Flash welding dies, spot- seam welding high temp. alloys.
Cu-Co-Be	180 - 240	50	500	40	45	10	As above
Cu - W composites							Flash - butt welding dies Projection welding electrodes.

TABLE III **Scope of Non-Destructive Testing Techniques**

NDT Method	Position of Defect			Permanent Record	Cost	Safety	Present Usage on Welding
	Surface	Sub-Surface	Internal				
Visual	✓	-	-	No	Low	Good	Wide-spread
Dye Penetrant	✓	-	-	No	High if used widely	Can Cause skin troubles in some cases	Fairly low
Magnetic	✓	✓	-	No	Low	Good	Moderate
Radiographic	✓	✓	✓	Yes	Expensive	Radiation problems	Wide-spread
Ultrasonic	Difficulties with un-dressed welds	✓	✓	Only with expensive recording equipment.	Moderate	Good	Fairly wide, increasing

Welding Defects in Steel

One may distinguish between two groups of welding defects.

- a) The commonplace defects that are caused by erroneously chosen welding conditions, poor edge preparation and positioning, negligence on the part of the welder while carrying out the work such as incomplete slag removal between individual passes etc. The subsequent defects may be insufficient penetration, lack of fusion, slag inclusions etc.
- b) The welding defects that are contingent upon the material and which are to be discussed in the following. These defects will be closely associated with the kind of materials used; parent metal and filler metal.

Hot cracks

Hot cracks in the weld are formed, as indicated by their name, at elevated temperatures, usually at a temperature just below or just above the solidus temperature. These cracks are in steel characterized by oxidized crack faces and interdendritic paths that show how the cracks were formed between the original, solidified, columnar crystals. Such hot cracks will normally result from shrinkage when this begins before all the metal has solidified. The larger the solidification range for a material is, the greater is the danger of hot cracks. Mainly sulphur and carbon are responsible for hot cracks in steel. Both these elements show a marked tendency for segregation. Crystals grow perpendicularly out from the liquid solid interface when the molten metal starts solidifying and the content of sulphur as well as of carbon is low in the crystals first formed. The molten metal in between the constantly growing crystals is gradually enriched on carbon and sulphur and finally a rather thin film which stays molten down to a relatively low temperature, may exist between the crystals. If shrinkage stresses now are created in the weld, no tension can be carried by the molten material on the grain boundaries and cracks are easily formed between the crystals. The shrinkage stresses are especially dangerous at the time when only a very thin film of molten material exists between the crystals because molten material will be unable to flow in from other locations and fill the void if a crack is formed. Weld metal with a large solidification range is most prone to hot cracking because the metal is in an unfavourable state throughout a longer period of time and down to lower temperatures where the shrinkage effect is increased.

In Fig. 45 is shown how hot cracks appear in a fillet weld. The cracks tend to lie about in the centre of the weld and along the longitudinal direction of the weld.

It is obvious that electrode composition plays an important part in deciding whether or not hot cracks are to be formed. The metal in the weld zone will, on the other hand, have mixed into it melted parent metal to a larger or lesser degree, and one should be aware of the fact that even though a steel has low nominal carbon and sulphur contents, these elements may, because of segregation, exist in higher concentrations in certain parts of the parent metal. In rimmed steel there will be a segregation zone in the centre, with higher concentration of carbon and sulphur than in the material close to the surface, and with certain shapes of grooves one may be welding right in this segregation zone, fig. 46a and 46b. The weld may here be so enriched on sulphur and/or carbon that hot cracks are easily formed. Rimmed steel will, on the other hand, exhibit an outer zone relatively free from carbon and sulphur, and if the weld is located as in fig. 46c, the segregation zone is of no consequence.

Hydrogen in Steel Welding

Hydrogen is of special interest as a contributing factor in formation of various welding defects in steel.

The solubility of hydrogen in steel is very low at room temperature and atmospheric pressure. It increases with increasing temperature and pressure, see fig. 11, and is greater in austenitic (γ -crystals) than in ferrite (α -crystals) for the same temperature and pressure. The solubility in the molten state is about 2.5 times what it is after solidification.

Water vapour will, during arc welding, be dissociated in the arc atmosphere and yield atomic hydrogen that is rapidly dissolved in the molten metal. Sources of water vapour and consequently of hydrogen in the welding arc, are

- (1) Humidity of the air (this has little direct bearing),
- (2) Groove surfaces, dirty and rusty groove surfaces usually contain considerable amounts of humidity that can cause water vapour in the welding arc.
- (3) The electrode coating (see table 4).

TABLE 4

Hydrogen in the Deposit from Covered Mild Steel Electrodes

Type of electrode	Hydrogen contents in the deposit	
	ml H ₂ /100 g deposit	% by weight
Acid electrodes	15 - 25	0.0013 - 0.0022
Rutile electrodes	15 - 25	0.0013 - 0.0022
Normal basic electrodes	5 - 10	0.00043 - 0.00087
Especially low hydrogen basic electrodes	2 - 3	0.00017 - 0.00026

It should be noted that TIG and MIG welding, as well as CO₂ shielded arc welding are "low hydrogen welding processes" when care is taken that electrodes are clean and dry and the shielding gases are pure and dry.

The major part of the hydrogen in the arc atmosphere and consequently of the hydrogen supplied to the weld, comes from the electrode coating as water of crystallization, water of hydration and humidity absorbed from the surroundings. Another source of atomic hydrogen in the welding arc is dissociation of organic elements in the coating, for example, cellulose.

Hydrogen absorption in the molten metal is extremely rapid during welding. The solubility drops drastically during solidification and the hydrogen does not always manage to diffuse out fast

enough and a supersaturated solution results in the weld. The solubility decreases further during cooling in the solid state and the hydrogen constantly tries to escape. Usually only part of the hydrogen manages to diffuse out to the surface and escape to the atmosphere.

The parent material close to the weld zone has a low hydrogen content and is during welding austenitized. Because of the relatively high solubility of hydrogen in austenite, part of the hydrogen in the weld zone will diffuse into the heat affected zone. During the subsequent cooling of the material the solubility suddenly drops as the austenite is transformed to ferrite and continues to decrease as the temperature goes down further. As a result even the heat affected zone close to the weld zone receives hydrogen from the electrode coatings or other sources, but that also the heat affected zone close to the weld zone can receive hydrogen via the arc atmosphere and the weld pool.

The most dangerous effect of the hydrogen appears to be that when the steel becomes supersaturated with hydrogen, then the hydrogen atoms, which diffuse very rapidly, will have a tendency to diffuse to minor defects in the material. These defects may be microscopical in the form of fine slag inclusions or pores. Or they may be submicroscopical defects such as dislocations or defects in the crystal lattice. When atomic hydrogen is concentrated in such defects, molecular hydrogen H_2 , with a low diffusion velocity, will be formed. A substantial gas pressure may build in this locations and is calculated possibly to rise to several thousand atmospheres. This hydrogen pressure causes a triaxial state of stress which again leads to embrittlement of the material. In the most critical cases the pressure may be so great that the ultimate strength of the material is exceeded and cracks result.

Cold Cracks in the Weld Metal Zone (Microcracks)

A varying number of fine cracks (normally not larger than 0.05 - 1 mm) will once in a while show up in mild steel welds. The cracks usually lie perpendicularly on the weld direction, fig. 47. These cracks which may be found in large quantities, have no connection with hardening effects in the metal and they may be found in steel of very low carbon content (0.06%C). It appears to be quite clear that hydrogen is a governing factor in creating cracks. The cracks, called microcracks, appear only when electrodes are used that yield a hydrogen content in the deposit above 10 - 12 ml per hundred grams of metal deposit. The tendency of forming microcracks increases clearly with increasing hydrogen content in the metal deposit. Other factors of importance are cooling rate and degree of restraint. The cracks first appear after the temperature has dropped below 200 - 250°C.

The following explanation of how these cracks are initiated has been offered by Dr. N. Christensen (7):

The solubility of hydrogen is greater in austenite than in ferrite. When the transformation of austenite to ferrite begins during the cooling down of the weld, the remaining austenite will constantly be enriched on hydrogen as the ferrite grains grow (micro segregation). Thus high hydrogen concentrations may arise on the boundaries between growing ferrite grains and remaining austenite. It has also been shown metallographically that most cracks are found close to the grain boundaries of the relatively large ferrite grains in the weld. To produce a high hydrogen concentration on the boundaries between growing ferrite grains and austenite, a high cooling rate is required so that the hydrogen concentration is given no time to distribute throughout the austenite by diffusion. At extremely high cooling rates, however, the hydrogen is trapped in the ferrite and no cracks are formed.

The actual forming of cracks is probably caused by the hydrogen atoms where the concentration is supersaturated, diffusing to dislocations and other locations of defects in the metal where they associate to form H_2 molecules. The molecules diffuse very slowly and a high hydrogen pressure gradually builds up in these locations and may create local stresses that exceed the ultimate strength of the metal.

The cracks can be avoided if the cooling of the weld is slow. The primary precautionary measure to avoid microcracks is to choose electrodes that yield a low hydrogen content in the weld. In actual practice this means low hydrogen electrodes. Secondly one may choose welding conditions to ensure sufficiently slow cooling. If the cooling is halted at 200 - 250°C for a few minutes, a homogenization of the hydrogen distribution occurs through diffusion and cracks are avoided.

Microcracks are very small, as already mentioned, but may occur in large numbers. It is obvious that a series of small cracks in a weld will lower the strength and notch ductility. Because they are so tiny and besides very narrow, the cracks are often hard to find by normal testing methods. The cracks can be shown metallographically, but this requires a very thorough preparation of the specimen.

Fish Eyes

A phenomenon closely related to microcracks are the so-called fish eyes. They can sometimes be observed in fracture surfaces through arc welds and they appear as circular or oval bright spots with the appearance of brittleness. The spots will be noticeably brighter than the rest of the fracture surface and is easily distinguishable from it. One normally finds a tiny slag inclusion or pore in the centre of the spot. Examinations have shown these spots that in reality are local brittle fractures, to appear only after the metal has been strained beyond the yield point. In a welded tensile specimen for example, these miniature fractures or fish eyes shown up during loading when the metal is stressed above the yield point.

A clear connection has been shown between hydrogen content in the weld and the occurrence of fish eyes. A large number of fish eyes in a weld will lower the ductility. The fish eyes are not cracks existing before the metal has been deformed plastically. This is indicated for example by the fact that one can prevent the formation of fish eyes by heating the metal somewhat above room temperature for a sufficiently long time to let the hydrogen diffuse out of the weld. Had the cracks existed even before heating, they would also have existed afterwards. Cracks can never be removed by heat treatment. As opposed to fish eyes microcracks can not be removed by heat treatment because they already exist when the metal is cooled down after welding. One must believe that fish eyes are caused by local hydrogen pressures that build up in and around metal defects such as slag inclusions and small pores, as hydrogen diffuses to such defects when the metal yields. Specimen broken impact tests do not show fish eyes, as yielding takes place too fast for diffusion to take place before the specimen is broken.

Underbead Cracks (Quenching Cracks)

Underbead cracks are cracks in the heat affected zone of the parent metal i.e. outside the weld metal zone itself, but as indicated by the name, the cracks are located close to it and usually rather parallel to the weld fusion line. The underbead cracks do not normally extend

out to the surface and this frequently makes them difficult to find by non-destructive testing. Fig. 48 shows underbead cracks from a single bead weld a) and from a fillet weld, b).

One does not today have any fully acceptable explanation of the mechanism responsible for underbead cracks. Various theories have been proposed, but none that have received general recognition. One thing is clear, however that several factors contribute in producing the cracks. They are:

1. Quenching effects in the heat affected zone close to the weld.
2. Hydrogen in the heat affected zone.
3. Degree of restraint.

The tendency for martensite formation caused by rapid cooling, is greatest close to the weld fusion line. Here the maximum temperature has been very high and the temperature gradient will therefore be correspondingly high. Besides, the high austenitizing temperature increases hardenability. Even in mild steels with low carbon content, the critical cooling rate may under adverse conditions be exceeded so that a layer of martensite is formed close to the weld fusion line.

As previously mentioned, hydrogen has a tendency of diffusing from the weld into the parent metal while this is austenitic. When the cooling is so rapid that the austenite is subcooled with subsequent transformation to martensite, then the hydrogen will be trapped in the martensitic lattice structure because of the sudden drop in hydrogen solubility and thus increases the brittleness of the martensite. A rapid cooling will also cause considerable residual stresses in the material because of the steep temperature gradient. In addition to this, the transformation from austenite to martensite is accompanied by a volume expansion which also creates stresses in the material. All these factors together, i.e. the tendency of hydrogen to make the material brittle, stresses caused by steep temperature gradients and stresses from volume expansion in connection with transformation from austenite to martensite, can result in underbead cracks. There appears to be two conditions that have to be fulfilled for underbead cracks to be formed at all: firstly, martensite has to be produced along the weld boundary. Secondly, a certain amount of hydrogen must be present.

Martensite of low carbon content such as in normal structural steel, has a relatively low hardness, see fig. 28 and is also comparatively ductile. Underbead cracks are therefore not produced only as a result of stresses arising during rapid cooling. For the cracks to be produced, a relatively large amount of hydrogen must be present at the same time. Underbead cracks do not on the other hand appear even with high hydrogen content if the transformation of austenite takes place at a higher temperature so that no martensite is formed.

The forming of underbead cracks is closely connected to the cooling rate in the temperature range 400 - 100°C, i.e. in the range of martensite formation, see fig. 27. The faster the cooling is in this temperature range, the greater is the danger of cracking.

Because the chance of martensite appearing in the weld zone increases very rapidly with increasing carbon content in the steel and similarly with increase in amounts of other alloying elements, the danger of underbead cracking increases correspondingly. One must be altogether very careful with welding steel when the carbon content exceeds 0.20 - 0.25%. Similarly one

must take great care when welding low alloy structural steels.

Concerning precautionary measures to avoid underbead cracks, one may concentrate on one or more of the factors that are of important to their formation:

1. One tries to prevent the weld from picking up hydrogen. This can be done by choosing electrode types that yield very low hydrogen content in the metal deposit, or welding methods that introduce very little hydrogen.

This means in reality that when there is danger of martensite in the heat affected zone, one should select special, low hydrogen, basic electrodes. Beside, one must take care to store the electrodes in a dry place until use to prevent the coating, which often is hygroscopic, from absorbing moisture from the air. If necessary one should dry out the electrodes before use. Also one should take care that the groove faces are clean, free from rust and other kinds of contamination and that they are dry.

2. The cooling rate in the weld zone can be adjusted so as to avoid martensite formation. This, however, usually requires so much preheating of the parts to be welded, that one rather settles for a sufficiently slow cooling through the critical temperature range, below about 400°C , to prevent underbead cracks. Frequently it is sufficient to provide adequate heat supply per unit length of weld during welding (high welding current, low welding speed) or one may regulate the cooling rate by preheating. Even a slight preheating may have decisive influence on the cooling rate below 400°C .

From fig. 3a is seen that in a specific case (the welding conditions are stated on the diagram) a preheat of 100°C (from 200 to 1200°C) reduces the cooling rate at 300°C , w300, from about $10^{\circ}\text{C}/\text{sec}$ at room temperature to about $2.5^{\circ}\text{C}/\text{sec}$. The higher the carbon content of a steel is or the higher alloyed it is, the more preheating is required to avoid underbead cracks.

It may even be necessary with postheating for steels with slow transformation and this must then be done before the temperature of the heat affected zone has dropped to the M_s temperature.

One should specifically note the danger of underbead cracks in short weld beads and particularly in tack welds where heat supplied is very little and cooling rates become high. If it has been established that the material requires preheating to be welded, then preheating must be removed by the subsequent weld bead and thus remain in the weld as hazardous stress risers. It is a further rule in arc welding that tack welds be above a certain minimum length. They should at least be 2-3 cm long.

Pores

Pores are gas evolved during solidification that is trapped in the weld. The three gases oxygen, hydrogen and nitrogen are all soluble in relatively large quantities in molten steel. Also they all have much greater solubilities in molten than in solid steel. Considerable amounts of gas are therefore liberated during solidification. Normally, however, the gases will escape because the solidification starts on the bottom of the weld pool and there is also violent motion of the metal in the weld pool which aid in bringing the gas bubbles to the surface so that the gas escapes to the atmosphere.

Nevertheless gas pores are not rare in steel welds and are usually caused by either carbon monoxide or hydrogen. Carbon monoxide is formed during solidification when oxygen is present to react with the carbon of the metal. This may, for example, occur when welding steel with heavy mill scale. The scale is iron oxide and a reaction between the carbon in the steel and the oxygen in the scale may occur because the carbon has great affinity to oxygen. Acid electrodes (iron oxide inflated slag) will also supply the weld pool with some oxygen and may when used for steel of high C-content, give pores. The gas shield provided by the electrodes may not be sufficient to keep the air away from the weld pool if a long arc is used in welding and a reaction between oxygen from the air and carbon from the steel may result and give pores. Basic electrodes (low hydrogen) are normally so well deoxidized that pores do not appear. These electrodes have so much deoxidizing elements added, usually silicon or manganese, that the oxygen appearing during welding is taken care of. On the other hand basic electrodes when the arc length is great, do not give sufficient protection from the air and this may lead to pores in the weld.

Hydrogen pores in steel may occur when using basic (low hydrogen) electrodes that have absorbed moisture. Another type of hydrogen pores appear when welding sulphur containing steels with acid electrodes or rutile electrodes. The pores are often called sulphur pores. The mechanism of producing the pores is not quite understood, but it is believed that hydrogen and sulphur reacts to form H_2S during the solidification. This type of pores may appear even when welding steels of relatively low sulphur content when the welding is done in the segregation zone where the sulphur concentration can be relatively high. The danger of getting this type of pores is also much less when using basic electrodes (low hydrogen) than when using acid or rutile electrodes because a certain refining of the weld pool for sulphur takes place through reactions between the slag and the molten metal and partly also because the hydrogen content is sufficiently low with these electrodes, if they are kept dry.

Weldability of Steel

Every experienced welder know that to obtain sound welds without defects is not as easy with all types of steel. Some obviously do not present any difficulties, others on the contrary, require special precautions or techniques in order to secure a satisfactory weld quality and to avoid welding defects as pores, hot cracks, underbead cracks, and others. In this connection one talks about "Weldability".

Weldability, however, is not a property that is easy to express precisely and quantitatively, it is a very complex quality. The following definition is formulated by commission IX of the IIW (International Institute of Welding)(9):

"A metallic material is considered to be weldable to a certain degree by a given process and for a given purpose, when a continuous metallic connection can be obtained by welding using a suitable procedure, so that the joints comply with the requirements specified both in regard to their local properties and their influence on the construction of which they form part".

As seen from this definition, weldability is not purely connected to the metal as a metals property, but is also connected to the welding processes, as one metal may well show a high degree of weldability when one welding method is used, weldability, however, may be poor with another welding process.

A high degree of weldability actually means that satisfactory weld quality may be obtained without special precautions and that the welding conditions may be chosen within a wide range. A low degree of weldability on the other hand, usually requires special precautions to ensure satisfactory welds, and also that welding conditions have to be kept within very close limits.

The properties that primarily determine the degree of weldability, may vary for different types of steel. For most types the mechanical properties obtainable, are of greatest importance, but when it comes to austenitic stainless steels, weldability usually means to what degree welding will reduce the corrosion resistance in the heat affected zone.

Plain Carbon Steels

For the unalloyed structural steels, weldability comprises the following:

- (a) Tendency to the formation of hot cracks, pores and other defects in the weld metal.
- (b) Hardenability or tendency to martensite formation in the heat affected zone, which again increases the risk of underbead cracks, etc.
- (c) Risk of brittle fracture.

The tendency to hot cracks, pores, and other defects in the weld metal does not depend entirely on the base metal, but often to an even greater extent on the filler metal. In arc welding with covered electrodes the main part of the weld metal is deposited metal, and molten base metal is rather small part.

Hardenability

Hardening effects in the weld zone appear by preferences in the heat affected zone when unalloyed and low alloy steels are welded with appropriate electrodes. Martensite as mentioned before, is most often found in a narrow zone up to the fusion border and martensite here is a condition for the formation of underbead cracks. Such cracks often will be normal to the tensile stresses in the finished part, and act as dangerous stress risers.

Whether martensite is formed adjacent to the fusion border, depends on the hardenability of the base metal, and the actual cooling rate. The hardenability is greatly increased by additions of carbon, and also by additions of other elements although their effect is never as pronounced as the effect of carbon.

Martensite is but one of the contributions to the formation of cracks in the heat affected zone, hydrogen and stresses being the others. However, hardenability is the factor which is most closely connected with the properties of the base metal. Because the carbon content has such strong influence on the hardenability and because increasing carbon content so strongly increases the hardness and brittleness of martensite, it is most important from a weldability point of view to restrict the carbon content, and keep it as low as possible.

Efforts have been made to find a method of determining the hardenability and thereby find an equation whereby weldability can be expressed quantitatively and calculated on the basis of the composition of the steel. In the literature many formulas have been suggested for calculation of

a Carbon Equivalent which is the amount of carbon that alone should give the same "hardenability" as all the alloying elements together. Such Carbon Equivalents as a measure of weldability do not seem to apply generally, and will not be dealt with any further as a means to express weldability and to classify steels. The reason why it is difficult to formulate equations for the calculation of a Carbon Equivalent which is generally applicable, is that the effect of an element on hardenability is not always the same, but is more or less influenced by the presence of other elements.

Tendency to Brittle Fracture

One of the main characteristics of brittle fractures, is that they are generally formed without plastic deformation. The faces of the fracture normally have a brittle appearance and the energy absorption which is necessary for initiation and propagation of brittle fracture, is very small.

Propagation is extremely fast, the velocity approaching the velocity of sound in the metal.

The reason the question of brittle fracture is of such importance in connection with welded structures is that conditions often are favourable for the initiation as well as the propagation of brittle fracture. In welded structures there will be continuous metallic connection between the different parts and thus brittle fractures can easily propagate across the welded joints from one part to another. There are several examples where brittle fracture has started in a secondary member of no importance to the actual strength of the structure, the fracture, however, having propagated across welds into the main parts of the construction with the result of complete breakdown.

Usually the initiation of brittle fracture is due to various factors. High stress concentrations together with triaxial stress conditions which prevent plastic flow, are contributing factors, and likewise the properties of the steel at the actual service temperature.

The propagation of an initiated brittle fracture also depends on the state of stress and the mechanical properties of the steel at the service temperature.

In welded structures welding defects often act as dangerous stress risers, and so do poorly designed joints. In large structures complicated stress conditions are often unavoidable and the risk of brittle fracture is usually greater the larger and more complicated the structure becomes and increases also with increasing plate thickness.

As a rule brittle fractures that have occurred in welded constructions have started from welds, from severe welding defects, or places with sharp notches because of poor design. One factor that should not be overlooked in this connection is the presence of residual stresses, weld stress, which normally will be of the magnitude of the yield stress of the metal. These weld stresses increase the risk of brittle fracture.

Both the initiation and the propagation of brittle fracture strongly depend on the toughness of the steel (expressed by the notch ductility). In a brittle steel the risk of brittle fracture is much greater than in a steel with better notch ductility. If the notch ductility is sufficiently great, a brittle fracture that has started may come to a stop as conditions for further propagation are lacking.

Because welding defects are dangerous from a brittle fracture point of view and must be avoided, it is necessary to state certain minimum requirements to the quality and composition of steels for welding purposes. As both initiation and propagation of brittle fracture depend on the notch ductility of the steel, this property is of major importance when weldability of steels is considered.

The notch ductility is strongly dependent on temperature. All steels having good notch ductility at room temperature, become brittle at some lower temperature. The transition from notch ductile to brittle behaviour usually takes place over a temperature range, transition range, in which the steel becomes brittle. Several test methods exist for determination of notch ductility. Transition temperature or rather temperature range determined by the different methods vary from one method to the other, and none of the methods tells us how a steel will behave in service, that is to say in different constructions, under different loading conditions and service temperatures.

Even if test results cannot be directly used to determine the service behaviour of a steel, the transition temperature measured by the Charpy V-notch impact test seems at present to be the best basis for evaluating the tendency to brittle fracture.

Fig. 49 shows schematically a characteristic transition curve of a structural steel, where the fracture energy determined by the Charpy V-notch impact tests is plotted against testing temperature. The Charpy V-notch transition temperature is defined as the temperature corresponding to a fracture energy of 2.8 kgm (20 ft. lbs) or expressed specifically 3.5 kgm/cm².

The transition temperature of a steel is determined by several factors as chemical composition, mechanical and thermal treatment, grain size and type of structure. Additions of nickel or manganese up to about 2% normally lowers transition temperature. Most other elements, however, carbon inclusive, raises transition temperature. Silicon and aluminium in small amounts as deoxydants may tend to lower transition temperature. The effect of the single element may vary from one steel to another depending on the amount of other elements present.

Nitrogen increases the transition temperature of the common structural steels considerably. Ageing effects, quench ageing as well as strain ageing, raises transition temperature and both types of ageing are supposed to be due mainly to nitrogen in solid solution. Altogether in the plain carbon structural steels, nitrogen is thought to be one of the most important factors raising the transition temperature and increasing the tendency to brittle fracture.

Steel produced by the converter methods (acid and basic Bessemer) where air is blown through the molten iron, generally has a higher nitrogen content than steels produced by the open hearth, and electro-furnace methods, or if a pure oxygen blast is used as for instance in the L.D. process. From this reason many specifications and standards require that steels used in welded structures should be produced by one of the latter methods. Bessemer steels being disapproved of.

The Choice of Steels for Use in Welded Structures

In document IIW-22-59(9) directions are given for the choice and classification of mild and C-Mn structural steels of grades from 34 to 52 kg/mm² (22 - 33 tons/in²). (minimum specified tensile strength).

The steels are classified in four qualities from A to D, where A offers the lowest and D the greatest resistance to brittle fracture. The criterion used in this classification is the Charpy V-notch transition temperature. Because the notch ductility of steel as other properties, so strongly depend on the mechanical and thermal processing, selection of steel should be based upon the properties of the final product. The IIW -22-59 also gives directions for the selection of steel quality taking into account conditions of loading, service temperature, section thicknesses and so on.

The IIW - classification is in the main presented in table 6 for steels with an actual ultimate tensile strength up to 52 kg/mm^2 (33 tons/in^2).

Note: This table is not complete and only meant for information, therefore anyone who intends to use the IIW-classification of steels is referred to the original document(9).

For C-Mn structural steels with an actual ultimate tensile strength between 52 kg/mm^2 (33 tons/in^2) and 65 kg/mm^2 (41 tons/in^2) the following limits of composition should not be exceeded.

Qualities B and C: C = 0.22%, Mn = 1.50%, Si = 0.55%, S = 0.05%,
P = 0.06%,

Quality D: C = 0.22%, Mn = 1.50%, Si = 0.55%, S = 0.05%,
P = 0.05%.

Low Alloy Structural Steels

Today there is an increasing interest in using steels with higher ultimate tensile strength for welding purposes. These steels also have a higher yield stress in proportion to the ultimate tensile stress than the mild carbon steels.

An increase in ultimate tensile strength and in yield stress may be obtained by increasing the carbon content, but this should be avoided because of the risk of hardening effects and cold cracks.

In high tensile steels for welding purposes, the carbon content must be kept at a low level, instead higher strength is obtained by additions of other elements and also by heat treatment processes. Today a great many high tensile steels are commercially available, which show great differences in compositions. To make the situation somewhat more simple, only three main classes are dealt with as most of the steels can be classified in one of these.

Class 1 comprises steels with an ultimate tensile strength of approximately $52 - 60 \text{ kg/mm}^2$ ($33 - 38 \text{ tons/in}^2$). The steels in this class are mainly of the carbon - manganese type with maximum 0.22% C and up to 1.6% Mn. Normally they do not present great welding problems and when moderate thicknesses are welded, no preheat is necessary if basic (low hydrogen) electrodes are used. They have good notch ductility and a low transition temperature. Welding of heavier plates may require a moderate preheat.

Class 2 comprises ferritic-pearlitic steels which as a rule is supplied in normalized and

tempered condition. The rise in tensile strength is principally attained by additions of the elements Mn, Ni and Cu, of which Mn and Ni are soluble in ferrite and the solution leads to an increased strength of the ferrite. The steels in this class too will normally have a good notch ductility and a very low transition temperature.

Class 3 are steels which in addition to Mn mainly contain Cr, Mo, and V which all combine readily with carbon, forming carbides. The increase attained in tensile strength for these steels are mainly due to finely dispersed carbide precipitations. The steels are either supplied normalized and tempered, whereby the structure normally becomes bainitic or they are quenched and tempered, the tempering temperature being relatively high. This latter treatment renders a considerably higher tensile strength than normalizing and for these steels also a better notch ductility. The low alloy steels in the quenched and tempered condition, have the highest strength with an ultimate tensile strength up to about 100 kg/mm² (64 tons/in²) and yield stress up to 90% of the ultimate tensile stress.

In normalized high tensile steels, the strength is not appreciably influenced by welding. In the quenched and tempered steels, however, the strength and toughness may be considerably altered in the heat affected zone.

Generally speaking, in low alloy structural steels, even if the carbon contents are low, there is always a risk of cracks forming in the heat affected zone, and thus the welding conditions must be chosen after careful considerations, and often weldability tests should be performed. Only basic (low hydrogen) electrodes should be used.

Any cracking test must be designed to investigate a specific type of cracking and, preferably, a particular range of materials. Ideally, a cracking test should be:

- a) Economical in material, time and labour.
- b) Simple in interpretation of results.
- c) Capable of giving direct correlation with actual structure.
- d) Free from the human element.
- e) Reproducible and consistent.
- f) Of high sensitivity, to allow distinction between the effects of all welding variables.

These ideal requirements can never be completely reached, indeed some of them are self-contradictory and demand a compromise with the result that cracking tests are really only sorting tests, capable of placing a series of materials in order of susceptibility to a particular type of cracking, but not capable of quantitative interpretation for an individual material. The main difficulty lies in defining restraint as it occurs in welded fabrications, and in putting a quantitative figure to any degree of restraint. Restraint is known to be important in most types of cracking but the quantitative variation of restraint in cracking tests has so far proved impossible to achieve.

It is not possible to consider all cracking tests here. Borland¹ describes 30 tests and even this list is not complete.

The majority of cracking tests were developed for carbon and low alloy steels, and very few for other materials. Tests for underbead cracking are, of course, restricted to these steels but tests for weld metal cracking have found more general application. Cracking test results may be in the form of crack/no crack indications or on the length of cracking before arrest. The former tests will require several test specimens in which the factors affecting cracking (e.g. restraint or cooling rate) can be varied whereas the latter tests provide a continuous variation in the affecting factors (e.g. restraint in the Houldcroft fishbone test) and theoretically a single test should provide a unique indication of crack susceptibility. In practice, however, control of the variables is never exact enough to allow reliance on a single test and several tests are necessary to obtain a positive result. Most tests involve a butt or fillet weld, others require simply a bead on plate test, but few bear any direct relation to actual welded assemblies. The B.W.R.A. test for delayed cracking in austenitic steel (see below), however, relates directly to the steampipe header joint in which this form of cracking was first recognised, whilst some industrial companies are known to use test specimens that simulate the more difficult joints that they actually encounter. These latter tests are generally nearer to procedure and welder approval tests than to tests of the crack susceptibility of a specific parent or filler material.

Most tests for heat affected zone cracking are concerned with underbead cracking in steels, and these range from a simple bead on plate test incorporating little restraint, to heavily restrained fillet weld tests such as the Reeve test and Cruciform test. The most developed test for underbead cracking is the Controlled Thermal Severity (or C.T.S.) test which has been adopted by the International Institute of Welding as the standard test for collaborative work. The C.T.S. test incorporates less restraint than some tests and may give negative results for materials in which restraint makes a large contribution to crack susceptibility. This test has been extended to cover electrodes and preheat temperatures but in these cases great care must be exercised in interpreting the results. The B.W.R.A. test for austenitic steels was developed

specifically to examine delayed cracking in steam leaders; it has been suitable for this purpose but is unlikely to be used for other materials.

Tests for weld metal cracking generally involve some form of restraint, e.g. patch test, Lehigh restraint test, although the Murex hot cracking machine applies strain to a fillet weld while it is being deposited. Crack length is taken as a measure of crack susceptibility where restraint is varied continuously in a single specimen whereas the crack/no crack criterion is used in specimens with a specific restraint.

Since no cracking test will give a direct correlation with practice the utility of the more elaborate tests may well be questioned. Unless a lot of background experience is available or a direct correlation with a practical fabrication has been found, the authors see an advantage in using the more simple tests. The larger and more complex the test the greater the cost in materials and labour.

Several cracking tests are described below, covering some of the more widely used tests.

Tests for heat affected zone cracking:

In the simple bead on plate test² used by the Battelle Memorial Institute a small weld bead is deposited on the steel under test using a cellulosic coated electrode; this type of electrode ensures that hydrogen will be present in the heat affected zone. The welding variables are all controlled, i.e. electrode size, current, voltage, and welding speed, as is the initial plate temperature. After welding, the steel plate is held for 24 hours at 150°C to enable the cracks to develop, tempered for 1 hour at 595°C and sectioned longitudinally (Fig.1). The longitudinal section is examined for cracks metallographically or by magnetic crack detection. The susceptibility to cracking is indicated by the ratio of total crack length to bead length; at least ten tests are needed for reliability.

The C.T.S. test^{3, 4} was developed by Cottrell at B.W.R.A. and is based on the assumption that underbead cracking is based on the cooling rate at 300°C (in effect the microstructure of the steel), provided that hydrogen is present. The degree of restraint is assumed to have little effect on the amount of cracking. The test assembly is shown in Fig.2, the contact surfaces being ground to give efficient thermal contact. The bolting of the two plates and the anchor welds provides some restraint although this is not as severe as with the Reeve test⁵, from which the C.T.S. test is derived.

Two test welds are deposited in the downhand position as indicated, the assembly being cooled to room temperature before each weld is made. For a given type and size of electrode and fixed welding conditions the cooling rate, and hence the degree of cracking, is greater with the final (trithermal) weld. After welding the test assembly is kept at room temperature for 48 hours before being sectioned and examined microscopically for cracks.

The first weld has two paths along which heat can be conducted and the second weld three paths, which explains the use of the terms bithermal and trithermal. For any given test piece dimensions the trithermal weld will have a greater cooling rate than the bithermal weld. The unit for heat conduction has been arbitrarily taken as one section of $\frac{1}{4}$ inch thick plate and from this is derived the concept of thermal severity in terms of plate thickness. Thus the

bithermal weld in two sections of $\frac{1}{4}$ inch plate has a thermal severity number (TSN) of 2 and the trithermal weld one of 3. For other plate thicknesses the thermal severity numbers are given by

$$\begin{array}{ll} \text{TSN} = 4 (t + b) & \text{for bithermal welds} \\ \text{and } \text{TSN} = 4 (t + 2b) & \text{for trithermal welds} \end{array}$$

(see Table I) and the relation between TSN and cooling rate is shown in Fig. 2 for different levels of heat input and weld sizes.

Cracking at any particular TSN is determined on a crack/no crack basis and the concept of a Weldability Index (Table II) has been proposed using fillet welds of $\frac{1}{4}$ inch leg length. The incidence of cracks at a given TSN (i.e. cooling rate) results in a material being rated from A to G in the Index. A rating of A indicates virtual freedom from underbead cracking whereas a rating of G indicates a very high susceptibility.

The type of electrode coating has a large effect on crack susceptibility and hence the Weldability Index rating, by controlling the amount of hydrogen available in the weld metal. Thus, for the Weldability Index rating of a material to have any significance it must be prefixed by the coating group of the electrode used; a material may have an Index rating of C or D with rutile electrodes but this may be improved to A for basic electrodes. For most general material tests rutile electrodes are used since these give the greatest susceptibility to cracking.

Because the electrode coating can affect the Weldability Index the C.T.S. test has been used as a test for electrodes whilst it has also been used to investigate the influence of preheat, which affects cooling rate and hence the TSN. In other tests the severity of the restraint has been increased by the use of high tensile weld deposits or by altering the notch at the root of the fillet welds. These variations can give useful information but care must be taken in comparing tests made under these different conditions.

The B.W.R.A. test for delayed cracking in Cr-Ni austenitic steels⁶ is shown in Fig. 3, welds are made with coated electrodes in the sequence indicated. Each run is made in two 180° segments followed by cooling to room temperature. The rigidity of the specimen is often sufficient to cause minor hot cracking at the toe of the weld and these propagate on subsequent heat treatment. A series of tests are necessary to define the temperature range over which cracking may occur.

Tests for weld metal cracking:

A large number of these tests exist ranging from simple pad tests to the production of butt and fillet welds under considerable restraint.

The simplest for weld metal cracking consists of depositing a pad of weld metal on a $\frac{1}{2}$ inch thick plate of the material to be welded⁷. Cracking is then assessed by micro-examination. This test has been used largely for assessing austenitic weld deposits but since it involves little restraint it does not always give positive results. The effect of dilution of the weld metal by the parent plate is obviously avoided in this test.

Several versions of T fillet weld test exist, including one adopted by the British

Standards Institution for testing covered electrodes for mild⁸ and medium high tensile steel⁹. Each test requires a T joint to be produced in the plate material ($\frac{1}{2}$ inch thick for BS 2549), welds on either side of the T being produced successively (see Fig. 4a). Details of plate preparation, preheat and welding conditions are standardised to allow reproduction of the restraint and the second weld is produced under a greater degree of restraint than the first. After visual examination for cracking the fillet welds may be broken open (Fig. 4b) and examined for further evidence of hot cracking.

The Lehigh restraint test¹⁰ was developed to study the effect of restraint on cracking in steel weld deposits; it consists of a slotted plate with a machined centre groove in which the weld is deposited (Fig. 5). The restraint is controlled by the depth of the slots and is measured as the width of the plate between the slots. In general only a root run is deposited and cracking is determined by macro-examination. The test may also be used to study cracking in the weld h.a.z.

The Murex hot cracking machine^{11, 12} places a stress on a cooling weld deposit and offers a useful method of distinguishing the hot cracking tendencies of different electrodes. For this test a 3 inch fillet weld is deposited in the V formed between two 3 inch x 2 inch x $\frac{1}{2}$ inch plates (see Fig. 6). One of the plates is rotated at a constant speed, 5 seconds after the welder starts depositing the electrode. A total rotation of 30° is effected giving a maximum fillet angle of 120°. The speed of rotation can be varied for different tests; a speed of 1.100°/sec. has been found suitable for low alloy electrodes. Any cracks obtained tend to be longitudinal and the length of crack a good measure of the crack susceptibility of the electrode, but is less sensitive when considering the effect of plate composition, probably due to the small amount of dilution that occurs.

Patch tests^{13, 14} have been used extensively to examine hot cracking in a wide range of ferrous and non-ferrous materials. The most usual test for materials up to 1/8 inch in thickness (Fig. 7) consists of a 6 inch square from which a 2 inch diameter circular patch is trepanned. The patch is welded back into the square and the crack susceptibility expressed as a percentage of total weld length or by the angle subtended by the weld start and point of crack initiation. The restraint will vary throughout welding and cracking will not start until a sufficient level of restraint has been reached. Experiments with austenitic steels have shown that variation of the plate to patch ratio had no effect on the results but that an increase in welding speed increases the severity of the test. A suggestion has also been made that a simple circular welding bead in a square of test material would give the same results as the true patch test; a test made in a light alloy is shown in Fig. 8. Patch-tests are also used for thicker materials¹⁵, in which case larger plates are used with an appropriate edge preparation.

The Houldcroft fishbone test was developed to examine the crack susceptibility of light alloy sheet during TIG welding, with or without filler additions. The test has since been used for other sheet material. It is based on the concept that if a weld is started on the edge of a sheet, a crack can initiate and will then propagate until the restraint is reduced. In the fishbone test restraint is progressively reduced by a series of slots of gradually increasing depth as shown in Fig. 9. The test weld is made along the centreline of the specimen and full penetration and a constant bead width is essential; manual welding generally gives a more uniform bead although automatic TIG welding has also been used. The test specimen is not restrained externally but rested on a carbon block which provides good electrical contact but poor heat conduction. The crack susceptibility is measured in terms of crack length, a mean of 6 tests being taken. On

the basis of work on 1/16 inch thick Al-Mg-Si alloys Houldcroft has suggested that, for welding speeds around 8 ins/min and bead widths of $\frac{1}{4}$ inch, a crack length of less than $\frac{1}{2}$ inch indicates a fully weldable material whereas a crack length greater than $1\frac{1}{4}$ inches indicates a high crack susceptibility. Although the test is generally discriminatory between different alloys it does fail to distinguish between the crack susceptibility of some alloys of similar compositions e.g. Al-3.5 Mg and Al-5Mg alloys, and some scatter is found between nominally identical specimens. It was suggested¹⁷ that these problems resulted from a variation in heat flow pattern at the weld starts and an unslotted portion was added to the testpiece to enable the heat flow pattern to become steady before the first slot was reached. This modification improved the discrimination of the test at lower welding speeds but did not reduce the scatter.

A recent comparison of the Houldcroft and patch tests¹⁸ have shown that the latter test covers a more limited range of crack susceptibilities than the former. Over this more limited range, however, the patch test appears to bear a closer relation to practical welding behaviour.

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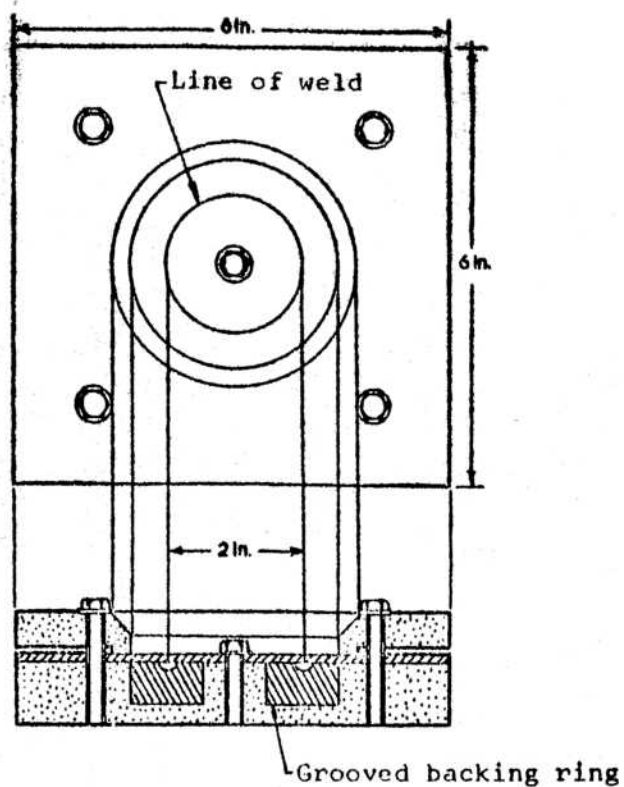


Fig. 7. Jig for patch test in sheet material

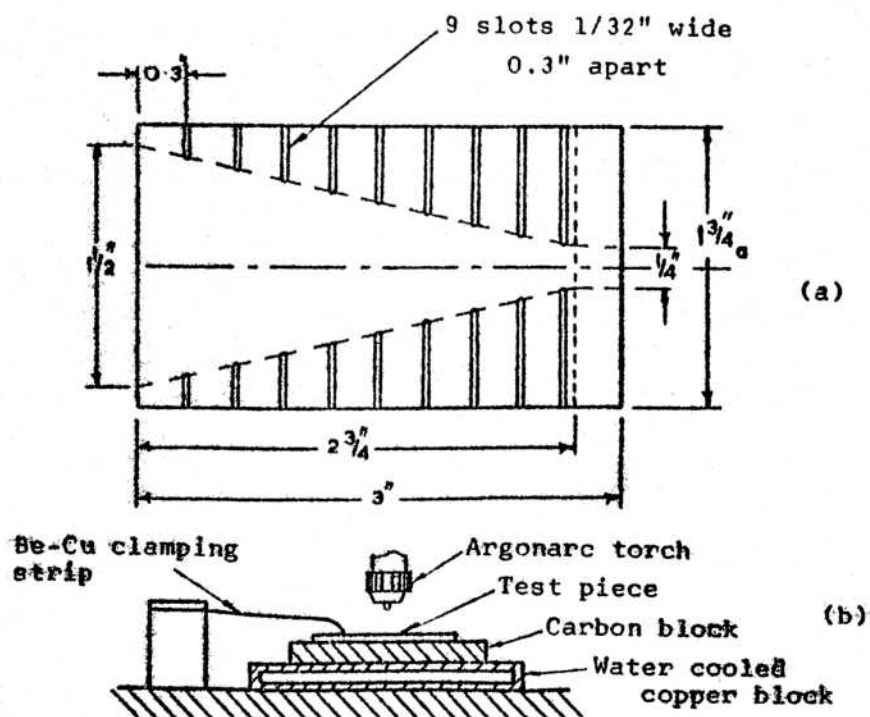
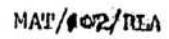


Fig. 9. Houldcroft fishbone specimen:
 (a) For 1/16 in. thick material
 (increased by 50% for 1/8 in sheet);
 (b) section through test assembly.



Section for
crack
measurement

Fig.1. Longitudinal bead weld cracking specimen

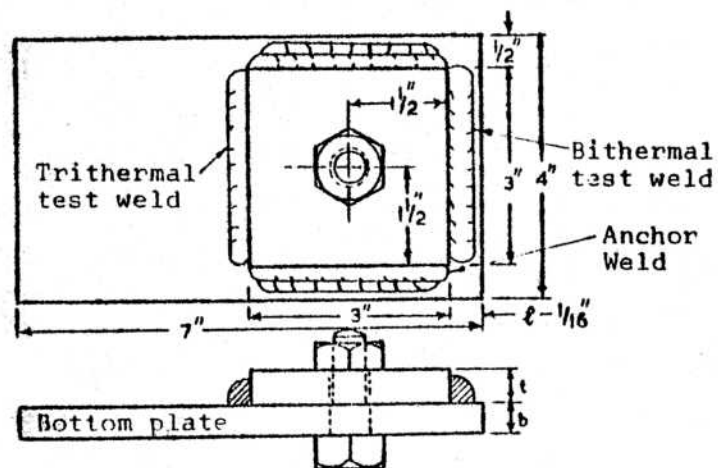


Fig.2. C.T.S.test assembly for alloy steels

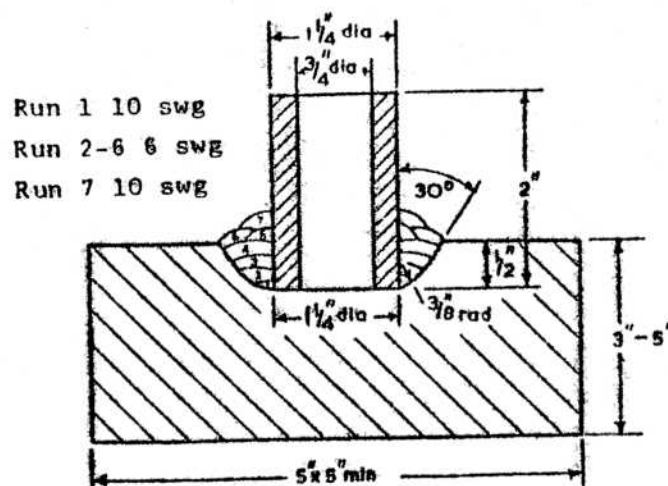
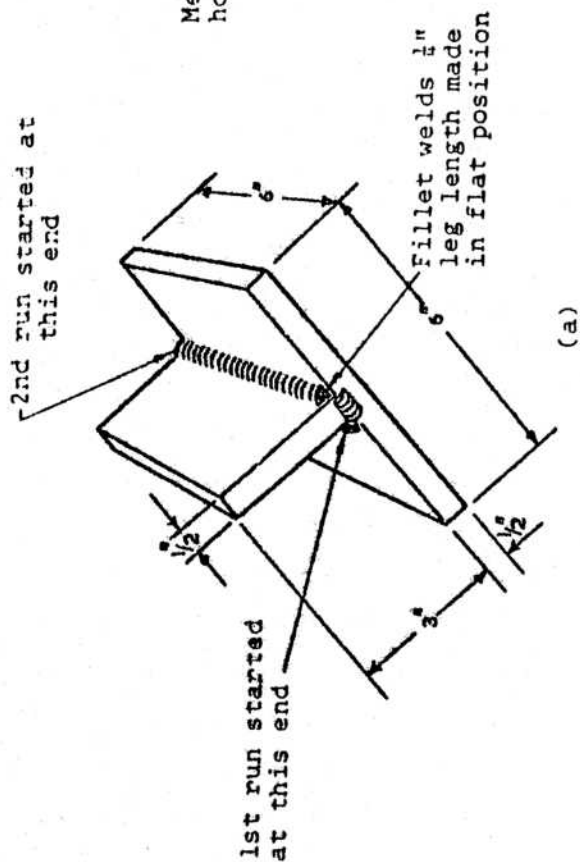


Fig.3. B.W.R.A. austenitic steel
base-metal cracking test



Method of breaking hot cracking test

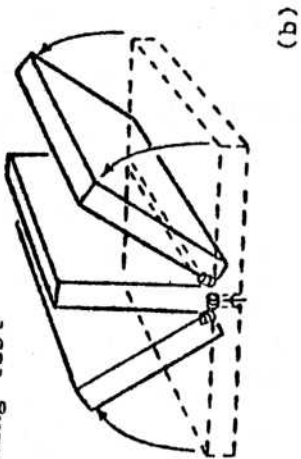


Fig. 4. British Standard single-T test specimen

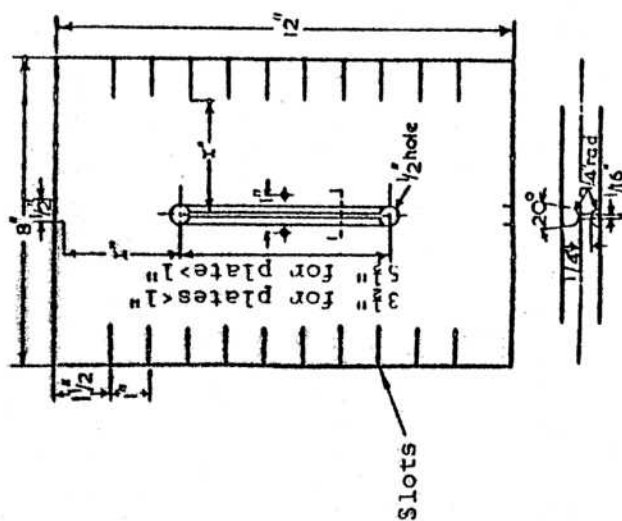


Fig. 5. British Standard single-T test specimen

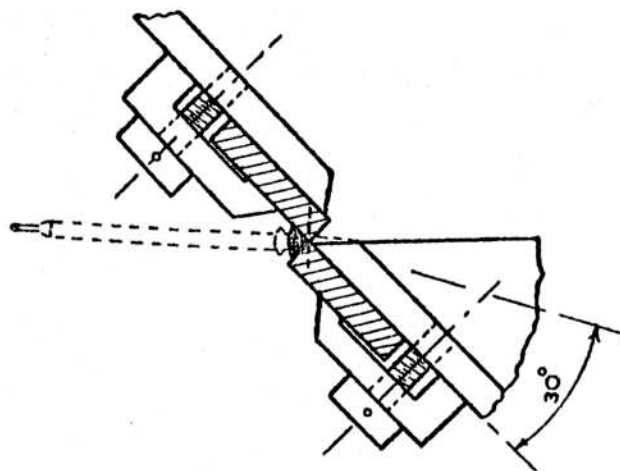


Fig. 5. Principle of Murex hot crack machine

Several properties of magnesium and its alloys can affect fusion welding characteristics. The oxide film on magnesium-base materials presents problems of removal and protection similar to those with aluminium alloys whilst the high thermal conductivity and coefficient of expansion can lead to distortion, restraint cracking, and residual stresses. These problems may be minimised by attention to technique but stress relief (at 150° - 350°) is necessary with alloys susceptible to stress corrosion, i.e. aluminium containing alloys. The wide freezing range of some alloys can lead to hot cracking in heavily restrained joints although cracking is not such a problem as with the aluminium alloys, and can generally be avoided.

For many years oxyacetylene welding, using highly active chloride-base fluxes, was the only suitable fusion welding process, until the TIG process was introduced in 1940. At present TIG welding is the most widely used process for magnesium and has almost completely replaced oxyacetylene welding, whilst MIG welding is also used in the United States.

TIG welding was originally developed for magnesium, using helium shielding and direct current, electrode positive. This technique was inefficient since 60% of the heat produced appeared at the tungsten anode, necessitating a large diameter electrode to prevent melting and giving shallow weld penetration, wide weld beads and wide heat affected zones. It was soon found that alternating current gave adequate oxide removal (with helium or argon shielding) and lower power consumption, with better penetration and narrower heat affected zone, and a.c. with argon, helium or argon-helium mixtures has now completely succeeded the use of d.c., electrode positive. The use of d.c., electrode negative with helium shielding has been reported but Lockwood has recently started that it is unsuitable, resulting in serious oxide contamination of the weld deposit and arc instability at currents above 170 amps.

Some arc instability is often found during a.c. TIG welding, particularly with argon shielding, and this can cause difficulty in welding. This arc instability which is characterised by a change in arc appearance (from a blue to a green colouration) and sound, has been studied by Kenyon using a high speed camera, oscilloscope and visual examination and a superimposed high frequency current component was detected when the magnesium was in the negative half cycle. The result of this instability, which has been attributed to a variation in electron emission from the magnesium, is surface roughness and occasional surface cracking (Fig.). It had earlier been found empirically that the addition of 0.15% nitrogen to the argon shield eliminated arc instability when welding Magnox AL80 and gave a smooth surface (Fig.), but had apparently no effect on other alloys. It was found to be due to the elimination of the high frequency component in the magnesium negative half cycle and attributed to a change from a plasma emission to a field emission mechanism for producing electrons. Nitrogen in larger quantities and at longer arc lengths was also found to be effective with other magnesium-base alloys and it was presumed that nitrogen was generally effective provided that the shielding atmosphere was largely argon and not magnesium vapour.

Argon shielded MIG welding (direct current, electrode positive) is feasible using spray transfer arcs for thicknesses above 0.190 in. and a short circuiting arc for thicknesses down to 0.025 in. With spray transfer in particular, burn-off rates are much higher than with aluminium (Fig.) requiring high wire feed rates and welding speeds. A problem with both types of metal transfer is that the arcs are stable only over limited current ranges; excessive currents lead to turbulence with high spatter and contamination.

Oxyacetylene welding is now obsolescent but is still used occasionally for the alumi-

nium - 1½% manganese and magnesium - 6% aluminium - 1% zinc alloys. In addition to the general problems of a distributed heat source with wide heat affected zone and considerable distortion, the chloride-based fluxes used for oxide removal are highly reactive and can lead to rapid weld corrosion if left on the weld surface. Flux entrapment in zirconium containing alloys cannot be avoided due to interconnecting microporosity and these alloys must not be gas welded. Attempts have been made to modify existing fluxes and to develop new non-corrosive fluoride-based fluxes but these have been unsuccessful, largely due to the high melting points of these non-corrosive flux mixtures.

WELD DEFECTS

A number of defects can occur in magnesium alloy welds, the majority are due to incorrect welding techniques although some are influenced by arc instability or metallurgical factors.

The weld profile can be very difficult to control in manual welding and this can lead to poor appearance and reduced fatigue strength. A poor weld profile is often accompanied by heavy surface oxidation; this is generally caused by insufficient gas shielding although occasionally heavy arc instability may cause turbulence in the inert gas shield. Oxide and nitride films (Fig.) may also be entrapped in the weld, reducing static and fatigue strength. These films may be caused by insufficient shielding, draughts, dirty weld edges or filled rod; welding technique is also important. The low volume heat capacity of magnesium alloys can make control of weld penetration difficult and even with trained welders it is possible to get uneven penetration or even drop-through if backing is not used. Microporosity is found in several alloys, particularly those containing zirconium or with high aluminium contents, but is not detrimental unless the micropores entrap flux and interconnect with the surface, in which case rapid corrosion can occur. Gas cavities and massive porosity will result from the presence of moisture or oily weld surfaces or filler wire and may be detrimental to weld strength. Because of arc instability, tungsten inclusions occur in TIG welding in magnesium rather more frequently than with many other materials, but they appear to have little effect on weld properties.

Hot cracking can occur in several magnesium alloys and may appear in the weld metal, weld/heat affected zone junction or weld crater. Heavy restraint markedly increases the incidence of cracking and manual welds are more sensitive than machine welds. However the problem of hot cracking should not be overemphasized and it is less of a problem than with many aluminium alloys. The presence of zinc reduces the resistance to hot cracking in both the aluminium and zirconium containing alloys. Suggested reasons for this reduced resistance are the increase solidification range and the presence of a grain boundary zinc-rich phase (possibly MgZn). The 6% aluminium 1% zinc alloy has good weldability but increase in either zinc or aluminium content markedly increases the crack susceptibility. Zirconium gives a fine grain size and confers some resistance to cracking but this tends to be overshadowed by the detrimental effect of zinc in the magnesium-zirconium-zinc alloys. Thorium or the rare earth elements tend to offset the effect of zinc by producing a crack resistant grain boundary phase and thorium or rare earth additions are matched to the zinc content in many alloys. Since the high temperature magnesium alloys invariably contain thorium or mischmetal they tend to be fully weldable. Minor additions of calcium between 0.04 and 0.2% greatly increase the susceptibility to junction cracking; West attributes the effect of calcium to an increase in the solidification range but Emley considers it is due to low melting point grain boundary films. Early versions of the Magnox AL80 nuclear

canning alloy contained calcium, which was beneficial for oxidation behaviour, but its use had to be discontinued due to severe hot cracking in the end cap sealing welds.

A further form of cracking is stress corrosion cracking which is found in aluminium containing magnesium alloys. It can be prevented by stress relief after welding.

FILLER METAL

Filler materials are generally of identical or similar compositions to the parent material. More highly alloyed filler compositions with lower melting points and narrower solidification ranges are sometimes beneficial in reducing weld cracking and may also give higher strengths. Particular care must be taken to avoid welding zirconium containing alloys with fillers containing aluminium or manganese, since this results in insoluble intermetallics in the weld metal.

Weld deposits generally have a fine grain size (Fig.) and show reasonable strength and ductility. With TIG welds joint efficiencies of 90% are possible in all wrought alloys except magnesium - 1½% manganese and failure generally occurs in the heat affected zone where grain growth has occurred. With the magnesium - 1½% manganese alloy joint efficiencies are reduced to 60% for both TIG and gas welds due to the very coarse grain size, although peening can improve the efficiency to 75% or more. Typical joint properties are shown in Table I.

Postweld heat treatment will improve properties only rarely, but it is generally employed for stress relief and to correct distortion. Postheat treatment is essential for aluminium containing alloys to prevent stress corrosion. With castings, postweld stress relief in the range 250° - 300°C (according to the particular alloy) is mandatory, whilst preheat in the same temperature range is also generally employed.

DEFINITION

Severence of metals by means of chemical reaction of high purity O_2 with base metal at elevated temperatures.

I INTRODUCTION

1. Principles. Metal preheated in small area to a given temperature. Confined stream of O_2 blown onto area. O_2 oxidises metal in a narrow area and the molten oxide and metal is removed by the kinetic energy of the O_2 stream, leaving a parallel sided gap between the cut edges.

2. Essential Qualities of the Cut

A high quality cut must have the following essential features:

1. Squareness of top edge
2. Smoothness of the cut surface
3. Cut face must be at the predetermined angle to the top and bottom surface
4. Absence of tenacious slag

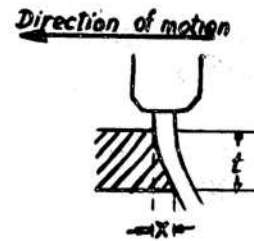
Cut should be a 'drop-cut'.

3. Drag = measure of trailing angle of the O_2 stream, or the lag of the cutting stream at the bottom of the cut.

Drag is expressed as % of thickness of plate.

$$= \frac{\text{distance between top and bottom of cut in direction of travel}}{\text{plate thickness}} \times 100$$

$$= x/t \times 100\%$$



Zero drag - O_2 stream along axis of nozzle.

Get drag if a) high speed - if speed too high will lose cut.
b) too little cutting O_2

Obviously require low drag to get more efficiency - high drag = in a sense, to increase in plate thickness

4. Kerf = gap created by cutting jet.

For accurate cutting it is essential that the kerf width is kept as nearly constant as possible. On plates up to 2in. thick kerf width can be maintained to a limit of $\pm 1/64$ ".

Since the metal from the kerf is obviously wasted, kerf width should be kept to the minimum consistent with good cutting.

Kerf width depends on:

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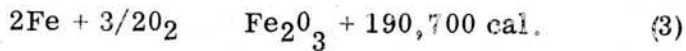
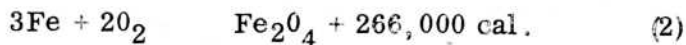
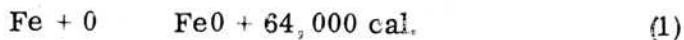
1. size of nozzle
2. speed of cutting
3. quantity of gas used
4. pressure of gas stream at mouth of nozzle
5. type of nozzle

Thicker material requires more O_2 . . . greater kerf width.

II CHEMISTRY

1. O_2 Ignition Temperature = Temp at which material will ignite when subject to an atmosphere of high purity O_2 .

2. Reactions. When iron or steel is heated to O_2 ignition temperature in an atmosphere of O_2 , Fe will oxidise rapidly.



Eqn. (3) occurs to some extent in heavy cutting, but (1) and (2) predominate.

Stoichiometrically 4.6 cu.ft O_2 oxides 1 lb Fe to Fe_3O_4 - in practice less O_2 is required because not all Fe Fe_3O_4 . Slag analyses show 30% Fe not oxidised.

3. Sequence

- a) Heat generated by combustion of Fe to oxide melts some of the metal adjacent to reaction surface.
- b) Molten Fe swept away by cutting stream.
- c) Concurrent oxidising reaction heats layer of Fe at active cutting front - not instantaneous . . . heat liberated at lower level . . . must supply heat at uppermost level of kerf to maintain thermal balance . . . must keep preheat flame burning.

Alloying elements in small amounts are dissolved in slag and removed. In large quantities, however, alloying elements, especially Cr, will retard and even stop cutting, by either decreasing the fluidity of the slag or producing a tenacious oxide film over the surface, which prevents further oxidation of the iron which is essential to the cutting operation. Overcome by the use of an iron rich powder which is introduced into the cutting area and which increases the fluidity of the slag and removes the oxide layer on the surface of the cut - known as ' Powder cutting '.

4. Oxygen Purity . The speed and efficiency of cutting is related to the purity of the oxygen used.

For good cutting the oxygen must be better than 99.5% pure.

A 1% decrease in purity gives:-

- a) 25% drop in cutting speed
- b) 25% increase in O_2 used
- c) poor quality cut
- d) slag increases in bulk and tenacity

Below 95% purity get 'melt and wash'.

III BOUNDARY LAYER THEORY

In the practice of oxygen cutting many anomalies have been observed. Desirable to have a consistent theory which would explain these.

Work at B.W.R.A. by Wells (British Welding Jnl., March '61, p.86) has produced the Boundary Layer Theory.

Have seen that the rate of combustion depends on oxygen purity. With impure materials can explain the reduced rates by the presence of a gaseous layer at the surface - products of combustion + impurities from O_2 - through which O_2 must permeate to continue cutting. This theory can be applied to oxygen cutting if the effect of thin molten oxide layer can be ignored.

For steady diffusion, at constant temperature, of a given gas through a stagnant layer of a 2nd gas, Stefan has shown that the rate of diffusion can be expressed by:-

$$N = \frac{DP}{RTx} \log \frac{1}{en}$$

N in gm.mol/sec.

D = diffusion constant

P = total pressure

R = gas constant

T = °K

x = thickness of boundary layer

n = volumetric fractional impurity of diffusing gas.

Rate will be lower as x and n. i.e. rate of cutting will be lower.

In accordance with this theory would expect increasing C, P and S content in steel will reduce rate of combustion - agrees with practice, carbon being most effective. The carbon will form CO_2 which must be removed by diffusion back into the main gas stream which must be contaminated. Independent factors can be calculated for these impurities = c , p and s which must be added to in the above equation. Obviously the distribution of carbon is important. Thus flake graphite in cast iron will cause high local contamination and no combustion. If the carbon is well distributed as spheroidised globules combustion proceeds at normal or calculated rate. Similarly with Swedish and Armco Irons, anomalies can be explained by the presence of grain boundary carbide films which affect combustion rate.

IV FUEL GASES

1. Choice of gas. Various gases can be used for the preheat flame. Must be evaluated for a specific application. The factors which must be taken into consideration:-

- a) Time differentials when preheating for various locations - sq. edge
rounded corners
piercing
- b) Effect on cutting speeds for various types of cut
- c) Effect of 1 and 2 on work output and cutting O_2 consumption
- d) Cost of fuel gas
- e) Cost of preheat O_2
- f) Ease of handling and availability of cylinders.

Torches and tips must be specifically designed for gas being used.

2. Function of Preheat Flame

- 1. To raise temperature to O_2 ignition temperature and to maintain it during cutting
- 2. Dislodges rust, scale, paint, etc. that would otherwise retard progress of cutting

3. Acetylene

Advantages are:

- 1. availability
 - 2. high flame temperature - very useful when preheat time is an appreciable % of total time.
- Against - somewhat costly.

4. Hydrogen

Preferred for underwater cutting because can be compressed safely to high pressures - cannot do this with acetylene - high cost, low c.v.

5. Propane

Low cost, high c.v. Requires $3\frac{1}{2}$ to $4\frac{1}{2}$ x O_2 (by vol.) for combustion a factor which offsets low cost.

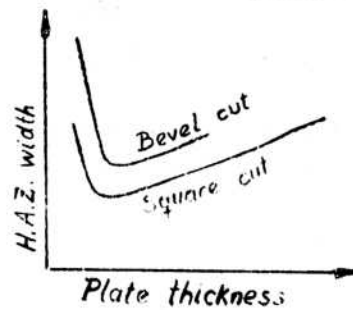
6. Towns Gas

Low flame temperature - can be adv. for thin materials. Low c.v., low supply pressures, use depends on local economics.

V EFFECT OF OXYGEN CUTTING ON BASE PLATE

Since oxygen cutting is basically a thermal process a heat affected zone will be produced in the base plate adjacent to the cut edge. In very low carbon steels this will be of little signi-

ficance but with higher carbon contents, important metallurgical changes can occur. These will be dealt with in a later lecture. It will be seen from the Fig. that the extent or depth of the heat affected zone varies according to the thickness of the plate. There is also a slight difference between square and bevel cut edges.



It is also of interest to compare the extent of the affected zone in oxygen cutting with those observed in other cutting processes. Oxygen cutting compares very favourably with machining and is appreciably better than shearing or friction sawing.

VI EQUIPMENT

The equipment used for oxygen cutting is basically quite simple. The main points of interest lie in the torch. Provision must be made for independent control of the fuel gas and of both the oxygen used for preheating and that for cutting.

Unlike the oxy-acetylene welding flame, the preheat flame is operating under conditions where a considerably back pressure is being applied to it and the danger of 'back-fire' or 'burn-backs' is very real.

Modern torches have eliminated this by the use of one piece nozzles used in conjunction with a nozzle mixing device. The nozzles are swaged from solid copper and hence operate at a lower temperature and nozzle mixing eliminates the presence of a long column of pre-mixed gases which can burn back into the body of the torch itself.

With machine cutting, the same nozzles as those used for manual cutting are employed. Most of the problems of the design of the machines lie in the mechanics of producing devices which will propel the cutting nozzles along predetermined paths - achieved either by means of a template or a photoelectric tracing head. Recently computer controlled machines have been developed which facilitate the programming of quite complex cutting operations.

VII SCOPE AND ECONOMICS OF PROCESS

Oxygen cutting can be used on a very wide range of thicknesses of steel from sheet material to ingot

Economies result from the use of O_2 cutting because of the following factors:-

- 1 Speed
- 2 Wide application (i.e. versatility)
- 3 Material can be used in the 'as-cut' condition
- 4 Portable

VIII STACK CUTTING AND GOUGING

Two special applications are worthy of consideration.

1. Stack Cutting

MAT['] No. 91

Technique used when a number of pieces of the same shape are to be cut from sheet or thick plate.

The sheet or plates are clamped together to give a 'stack'

The sheets must be clean and clamped tightly in order to avoid cutting back between sheets.

The operation is ideally carried out on a machine cutter and considerable skill is required in preparing the stack and setting the cutting conditions.

Accuracy of cut appears to be related to total thickness of the stack:-

2 in. - edge tolerance $1/32$ in.

2-4 in. - edge tolerance $1/16$ in.

2. Gouging

If an oxygen cutting torch is inclined at an acute angle to the surface of the plate a gouge or groove can be produced - special nozzles have been developed for this and the process can be used for gouging out the back of welds or for removing surface defects in plates etc. Considerable skill is required to achieve uniformity of the cross-section of the groove.

I INTRODUCTION

A heat source for use in fusion welding must satisfy four basic requirements:

- (1) It must produce heat at a high rate of availability.
- (2) It must produce heat at a high temperature.
- (3) It must produce heat in a sharply delineated zone.
- (4) It must not inflict metallurgical damage on workpiece or filler.

In conjunction with (4) it can be reasoned that the process must be able to provide adequate protection of the weld pool against the atmosphere.

Probably the first heat source used for fusion welding was a gas flame. A variety of fuel gases can be used to produce a high temperature flame:-

Av. flame tem. °C - (note average)

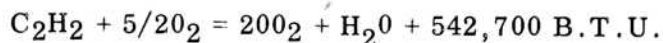
Oxy-acetylene	3,000°C
Oxy-propane	2,500°C
Oxy-hydrogen	2,200°C
Oxy-coal gas	2,000°C

Of these the only one that satisfies the first 3 requirements is oxy-acetylene. Acetylene (C_2H_2) has a high heat of combustion and gives an intense, concentrated flame when burnt in oxygen. It is therefore suitable for welding.

II THEORY

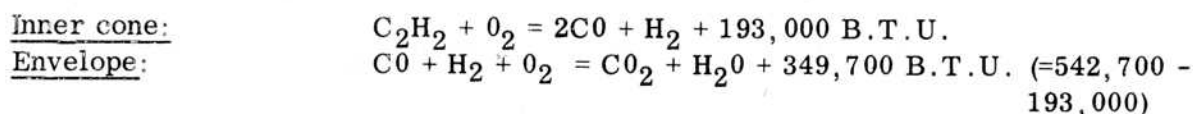
The flame can be considered in two distinct parts. It consists of an inner cone surrounded by an envelope. Combustion takes place in both zones.

In the presence of excess oxygen, acetylene burns according to the following reaction:-



In an oxy-acetylene welding flame, this reaction takes place in two stages, firstly in the inner cone where the oxygen is supplied via the torch, and secondly in the envelope where some or all of the oxygen will be drawn from the atmosphere.

If the mixed oxygen and acetylene supplied by the torch are in a 1:1 mole (or volume) ratio, the reactions will be as follows:-



By varying the ratio of oxygen: acetylene in the mixed gas supplied by the torch, it is possible to vary the efficiency of the combustion and thus alter the nature of the flame.

$1C_2H_2:1.1-1.7O_2 -$	'Oxydizing' flame - most complete combustion, temperature at the tip of the inner cone is hottest with an oxy-acetylene welding flame - advantage when welding materials having a high thermal conductivity e.g. Cu and Ag. The flame will decarburise steels and deplete the weld pool of silicon.
$1C_2H_2:1O_2 -$	'neutral' flame - most commonly used. Temperature at tip of inner cone is somewhat lower than with oxidizing flame (c.500°F lower). No excess oxygen.
$1C_2H_2: 1 O_2 -$	'carburising' flame - get excess C_2H_2 which decomposes. $C_2H_2 \rightarrow 2C + H_2 + 133,000 \text{ B.T.U.}$ Produces sub-microscopic particles of carbon which readily go into solution in molten steel - used in 'Linde welding' (see later). High carbon content in ferrous based material gives greater fluidity. Sometimes used with stainless steel - very dangerous metallurgically.

The ratio of $C_2H_2: O_2$ also has marked effect on the appearance of the flame.

The temperatures observed in the flame have been estimated by various authorities. In a neutral flame, near the tip of the inner cone temperatures of the order of 3,000°C can be observed, whilst in the centre of the flame and at the tip of the envelope, temperatures are about 2100°C and 1,260°C respectively.

The temperature of the flame depends on:

1. specific heat of gases involved
2. rate of heat loss from the flame

If it is assumed that heat leaves the flame only via the reaction products then it is possible to calculate the theoretical maximum or adiabatic flame temperature.

The calculation is simplified if it is remembered that the enthalpy change is independent of reaction path. Thus it can be treated as though the reaction went to completion at room temperature and that the enthalpy went entirely to heating the reaction products.

With these assumptions

$$H_{R.T.} = \sum m_{R.T.} \int_{R.T.}^T C_p dT \quad C_p = \text{specific heat}$$

summation taken over n moles of each of m reaction products.

The reaction products may undergo change of state. ∴ deduct Latent Heat from $H_{R.T.}$. A further deduction must be made from H_{RT} to allow for the heat required to raise the temperature of the nitrogen introduced into the outer envelope.

(For use of this eqn. see Udin, Funk and Wulff Chp. 9, p. 213)

In actual fact the temperature of the flame as a whole is less than adiabatic. Whilst the inner cone, being surrounded by hot gases is only slightly below adiabatic, heat losses occur in the outer envelope giving rise to a marked difference from the theoretical maximum. Also, since the envelope reaction relies on diffusion of air from the atmosphere, the temperature will be far from uniform;

(For a theoretical treatment of combustion of oxy-acetylene refer to Miller, 'Acetylene' Vol. 1).

It will be seen that whilst the oxy-acetylene flame provides a gas 'blanket' which will, to some extent, protect the pool, it will not remove oxides etc. - i.e. it will not clean the surface. It is therefore necessary to use an active flux with metals which have refractory oxides e.g. stainless steel and aluminium.

III APPLICATION

1. Thickness of material

Oxy-acetylene welding tends to be slower than other fusion welding processes for two reasons:

- a. The super-temperature over melting temperature is low.
- b. Heat must be transferred from the flame to the plate.

Typical welding speeds on mild steel are:

- 1/16 in. thick plate 25-30 ft/hr.
- 1/8 in. thick plate 18-20 ft/hr.
- 1/4 in. thick plate 10-12 ft/hr.
- 1/2 in. thick plate $4\frac{1}{2}$ -5 ft/hr.
- 1 in. thick plate $2-2\frac{1}{2}$ ft/hr.

2. Techniques

a. Leftward and Rightward Welding

Two main techniques exist - Leftward and rightward, sometimes called forehand and backhand or forward and backward, welding. Terms confusing

In Leftward welding torch heats plate ahead of weld

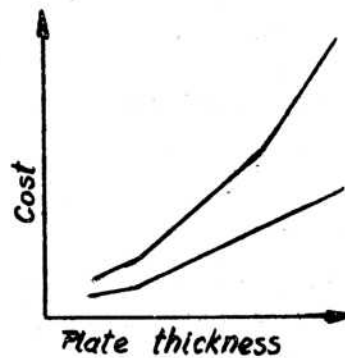
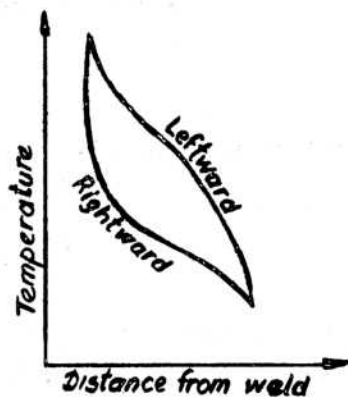
In Rightward welding torch heats weld pool.

- (i) Leftward - C.I. and most non ferrous materials

Mild steel up to 3/16 in. thick.

- (ii) Rightward m.s. 3/16 in. - on thicker sections faster than leftward.

Narrower heat affected zone.



b. Linde Welding. Technique used to increase carbon content of a mild steel pool. Carburising flame used ($1 \text{ C}_2\text{H}_2 : 0.90 \text{ O}_2$). Excess carbon in flame is absorbed into weld - can get up to 0.5% C. (note:- this lowers m.p. and hence incidentally increases speed by 30% because less heat required - however main object is to increase strength). Use Si-Mn rods with the rightward technique. Skilled operator required.

IV. EQUIPMENT

General layout can be seen in laboratory. Consider at present only torch and regulators.

1. Torch - Two problems exist in torch design:

- mixing of oxygen and acetylene to get uniform combustion
- stable flame

a. Mixing - Method depends on acetylene supply.

Acetylene 1 lb/in^2 - use positive pressure mixer (Fig. 1).

Since both gases under positive pressure will feed readily into chamber and mix.

Acetylene 1 lb/in^2 - as supplied from carbide generator - not often used now. Acetylene must be drawn into the mixing chamber - therefore use injector type where oxygen is introduced in centre into a Venturi arrangement which acts like a pump. (Fig. 2).

b. Flame Stability

For a stable flame the rate at which the mixed gas is supplied must balance the rate at which the flame moves backwards. Must therefore have good valves. Also good mixing essential.

Nozzle must not overheat otherwise gases will be a) preheated give v. high, unmanageable rates of flame propagation or b) be raised above the ignition temperature giving spontaneous combustion in the mixing chamber.

Overcome by using long copper nozzles with heavy cross section.

2. Regulators

Oxygen supplied in cylinders at $1500 - 2000 \text{ lb/in}^2$.

Acetylene supplied in cylinders at $150 - 220 \text{ lb/in}^2$ (note-acetylene cannot be compress-

ed it is therefore dissolved in acetone).

Regulators need to reduce pressure to workable level and to give constant pressure irrespective of level in cylinder.

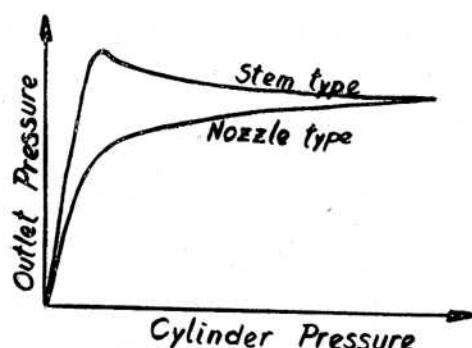
a. Reduction

Consider a simple orifice which restricts the flow of gas. After passing through the gas expands and the pressure is, therefore, reduced. This is the basic principle upon which all regulators operate. The gas flow and pressure on the outlet side will depend on the size of the orifice for a given input pressure.

b. Simple Regulator

Reduces from cylinder pressure to operating pressure - known as single stage (Fig. 3).

Gas from cylinder flows in at A - opens seating, against spring H. flows into chamber F and expands. As F fills, diaphragm G moves upwards acting against pressure on stirrup at D. acts with spring. At given pressure, valve at D will close. Level will depend on tension in spring H, which can be preset. Gas, at reduced pressure, flows out at K - pressure in F reduces - valve at D opens etc. Known as nozzle type (fig. 4). Alternative is stem type (fig. 5).



c. Two-stage regulators

With both these simple single stage types, the output pressure for a given setting of the spring depends to some extent on the inlet (cylinder pressure).

To achieve constant output pressure, two stages are normally used, the first stage giving a fixed reduction to about 30 lb/in² and the second being fitted with a larger diaphragm or lighter springs is left to reduce the pressure to that required for the torch. This gives the additional benefit of finer adjustment. Two stage regulators may be a combination of the nozzle type for Stage 1 and stem type for stage 2 or both stages may be modified forms of the stem type. Later developments have led to the introduction of more refined single stage regulators.

General references:-

Welding Engineer, 1961, Feb. p. 34.

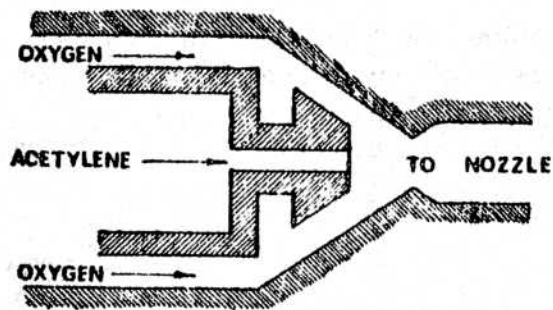


FIG.1 MIXER TYPE

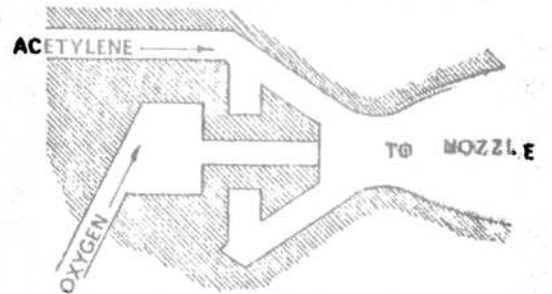


FIG.2 INJECTOR TYPE

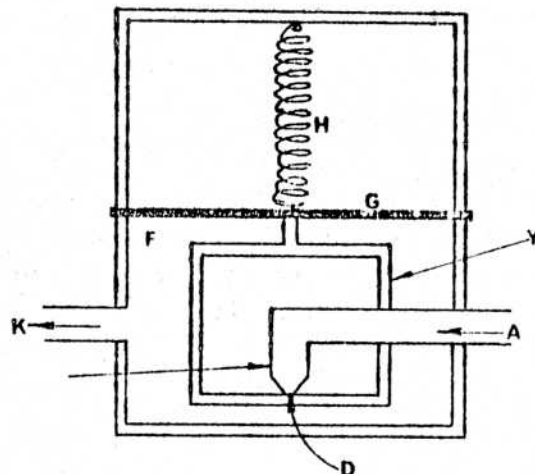


FIG.3 DIAGRAMMATIC REPRESENTATION OF REGULATOR

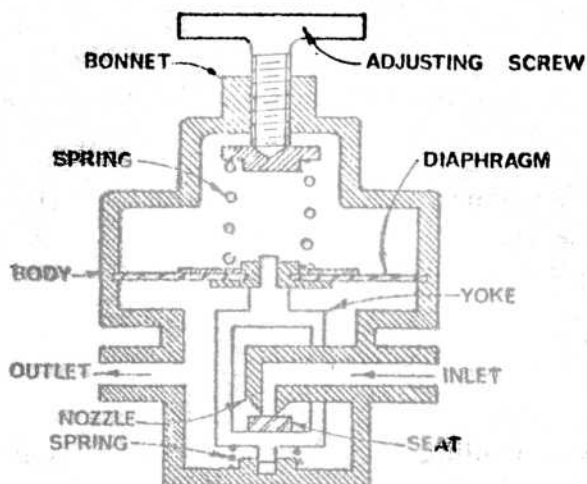


FIG.4 NOZZLE TYPE REGULATOR

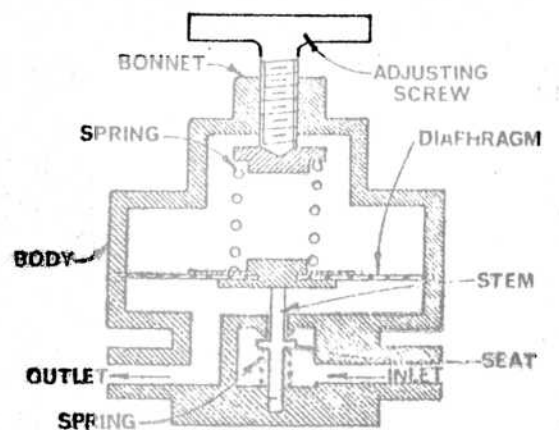


FIG.5 STEM TYPE REGULATOR

I. DEFINITION

T.I.G. Welding = Tungsten inert gas welding. (Also known by various trade names e.g. Argonarc). Basically consists of a tungsten electrode surrounded by an inert gas shield. (Fig. 1) Either d.c. or a.c. can be used.

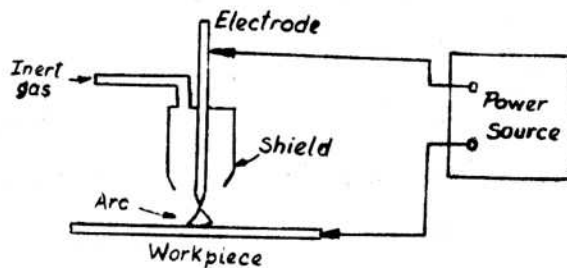


Fig. 1

The arc is used as a heat source and filler metal, if required, is added to the weld pool.

II. THEORY

(i) D.C. Arcs. A d.c. tungsten arc can obviously have two configurations i.e. electrode. (The cathode spot can wander over the surface due to changes of the work function with temperature, etc.) Conventionally the electrode is tapered to concentrate the cathode spot onto the end of the electrode and thus provide a more stable arc. The emission of electrons is from the electrode to the plate and more heat is developed in the plate than in the electrode. Good penetration is obtained.

b. Electrode positive: Here the cathode spot is formed on the plate and the flow of electrons is from the plate to the electrode. More heat is developed in the electrode than in the plate. Compared with electrode negative using the same electrode diameter and current, the temperature at the tip of the positive electrode is much higher and normally a molten globule is formed. The tip is thus rounded in shape. A given size of electrode can carry as much as five times more current when connected to the negative pole. Penetration with electrode positive is low and a wide pool is formed.

A particularly desirable property of this type of arc, however, is its ability to disperse the tenacious oxide film which occurs on aluminium and magnesium. This property is not possessed by electrode-ve systems and is said to be the result of cathodic emission from the base plate.

(2) Arc characteristics.

A specific relationship exists between arc voltage and arc current for a given value of arc length (Fig. 2). Except at the low current end, the curves have a small positive slope. Similar curves apply for both electrode negative and positive, but for a given arc length and current, the voltage is higher with electrode positive.

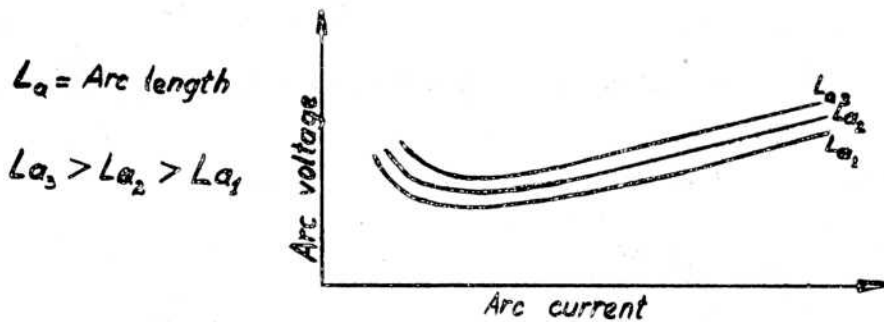


Fig. 2

It will be seen that a small change in voltage or arc length will produce a larger change in current. For a stable arc in manual welding it is necessary, therefore, to use a power source which has a 'drooping' characteristic i.e. shows little change in current for a larger in voltage. A stable working point will thus be obtained at the intersection of the power source and the arc characteristic curves.

(3) Arc Ignition

Before an arc can be established it is necessary to ionise the gap between the electrode and the workpiece. This means that the applied potential must be high enough to exceed the ionisation potential of the gas in the gap. Such a high voltage is undesirable for safety reasons and because it increases the difficulties of designing a suitable power source.

At the same time as the high potential is applied it is desirable that the surface temperature of the cathode should be raised to facilitate the emission of electrons necessary for the establishing of an arc.

These two requirements can be realised by the use of a spark or high frequency discharge across the gap. To achieve this the arc gap is incorporated in a tuned discharge circuit; an H.F. discharge having a high potential and a frequency of between 350 kc/s and 3 Mc/s is injected into the arc gap. Having a high potential this discharge will ionise the gas in the gap and will, at the same time, raise the surface temperature of the cathode - it should be stressed that this is a surface phenomenon. Note: the H.F. flows along the surface of the electrode. An arc can now be established at about 80 V (p.c.v.).

It is observed that the arc is easier to ignite when the electrode is negative. This is a function of the relative ease with which emission of electrons can be produced in a tungsten cathode as compared with a base metal cathode.

It should also be noted that the physical features of the electrode will have an effect because of their influence on the formation, dimension etc. of a cathode spot. Further, a hot electrode will strike more readily than a cold one and with electrode negative it is often possible to establish an arc without the use of H.F.

(4) A.C. Arcs

Reference has been made to the ability of electrode positive arcs to remove oxide film on aluminium. This advantage is offset by the difficulty of cooling the electrode and by the small penetration obtainable. A solution to the problem is to use a.c. in which oxide removal occurs during the positive half cycle and electrode cooling and base plate penetration are achieved during the negative half cycle.

In an a.c. tungsten arc the arc current and voltage are in phase but the arc current lags the open circuit voltage (Fig. 3).

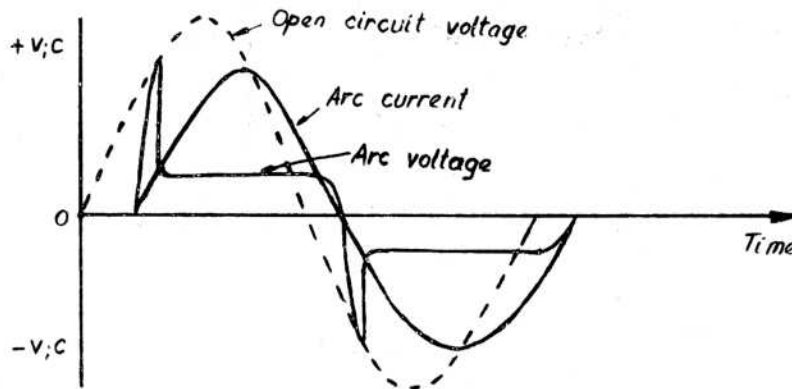


Fig. 3

(5) Rectification in a.c. arcs.

The arc voltage and current, therefore, go through zero every $1/100$ th of a second i.e. the arc is extinguished and needs to be reignited 100 times per second. At the instant the arc is extinguished the voltage rises to O.C.V. and if a high enough potential is reached re-ignition will occur. If, however, the O.C.V. is not sufficiently high for self re-ignition ancillary means, e.g. H.F. discharge can be used. It is important to note that both self and assisted re-ignition depend on having a suitable O.C.V. available at the instant the arc extinguishes. There must, therefore, be sufficient lag, due to circuit reactance, to allow for this. If the degree of lag is too small the restrike will be delayed and the positive current will be reduced. (Fig. 4) (A delay of 1 millisecond reduces the r.m.s. current by about a third). This effect is known as PARTIAL RECTIFICATION.

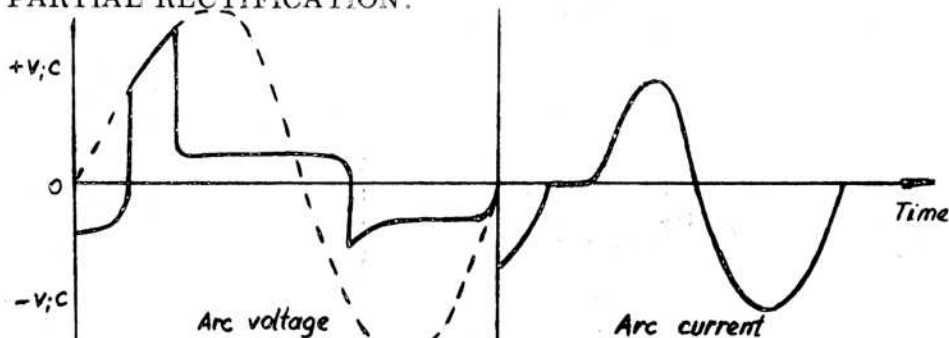


Fig. 4

If there is no re-ignition at all during the positive half cycle COMPLETE RECTIFICATION occurs (Fig. 5).

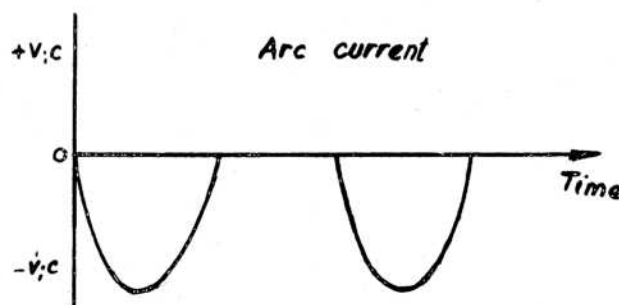


Fig. 5

Note that problems rarely exist when the arc is going from positive through zero to negative.

A further form of assymetry results from the difference between the arc voltage for a positive and a negative electrode. A higher arc voltage during the positive half cycle means that a smaller positive current flows for a shorter period. (Fig. 6) The general effect of this assymetry is similar to that of a shift in the time axis such as would result from a d.c. bias voltage being applied to the arc. This is known as **INHERENT RECTIFICATION**. The duration of the positive half cycle is approximately proportional to the inverse ratio of the arc voltages.

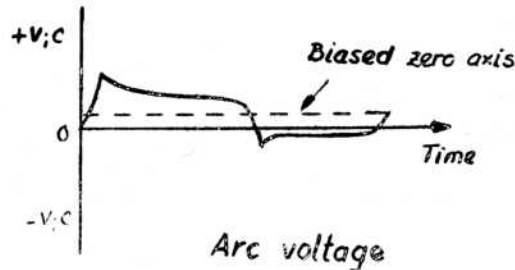


Fig. 6

Note that: (a) Complete and partial rectification result from the problem of arc reignition.
(c) Inherent rectification arises from a fundamental property of the arc.

(6) The d.c. component in a.c. arcs.

The combined effect of partial and inherent rectification is to produce an excess negative current which can be measured on a d.c. meter. This is conventionally called the d.c. component. Inherent rectification alone can account for a d.c. component equal to 20% of the r.m.s. current. The presence of a d.c. component means that there is less oxide removal on Al and Mg. At the same time it can cause magnetic saturation of the core of a transformer giving overheating and distortion of the primary waveform. In addition it can result in a poor power factor. Thus it is desirable to suppress the d.c. component.

The method of suppression depends on the source of the component:-

- (a) if due to partial or complete rectification-introduce auxilliary arc initiation devices.
- (b) if due to inherent rectification-(i) supply an e.m.f., either from a storage battery or rectifier, to oppose the d.c. component
- (ii) couple large capacitor in series with the arc.

Note: The d.c. component is not removed by these devices since the basic cause, i.e. the difference between arc voltages during the positive and negative half cycles, is still present. The action of a capacitor or a battery is to cancel out the effect by adding a voltage to balance the waveform.

The capacitor works thus:

- (a) electrode negative: - capacitor charged; positive charge on electrode side.
- (b) electrode positive: transformer voltage is increased by capacitor charge and more positive current flows.

The positive current will only partially discharge the capacitor because initially negative current is greater than positive current.

During the next negative half cycle the applied (transformer) voltage is effectively lower, thus the negative current is lower. The positive current steadily increases and the negative current decreases until a balance is reached.

(7) Inverse rectification in a.c. arcs.

The inclusion of a capacitor in the circuit of an a.c. arc sometimes makes initial ignition of the arc difficult. In this case the arc conducts only during the positive half cycle - hence the name 'Inverse Rectification'. This situation persists for several cycles until the electrode has reached a temperature at which sufficient emission occurs at which point current is conducted during the negative half cycle.

Striking is hindered by the fact that during this time the capacitor is charged in opposite sense (because there is no negative current) and the positive current is therefore reduced. Thus a longer time is required for the electrode to heat up.

(8) Electrode considerations

So far have only considered the electrode as being tungsten. Any electrode for T.I.G. welding must give easy emission of electrons. Attempts have been made, therefore, to increase the level of emission. Normally achieved by adding Thorium or Zirconia to the electrode. The benefits achieved by these additions are illustrated in Fig. 7. from which it will be seen that a high level of emission is achieved with thoriated electrodes at appreciably lower temperatures. Must beware of too high a level of emission, (resulting from composition, physical form, etc.) It is believed that if emission is greater than the needs of the arc a negative space charge is built up at the cathode and a cathode spot is not formed. It is suggested that this affects the arc in a similar way to a decrease in arc length, in which case over the original arc length, cathode potential part is too low.

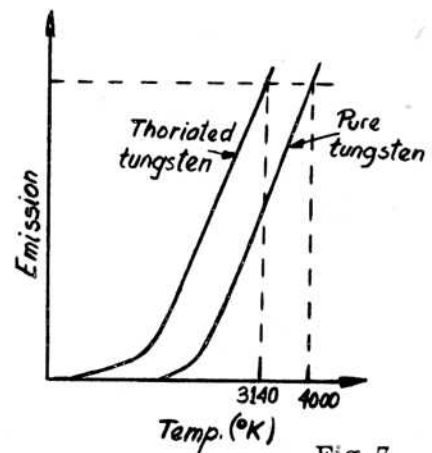


Fig. 7.

(9) Gas shield

The gas shield fulfills two functions (a) to provide suitable, ionisable atmosphere for the arc,

from contamination by oxygen etc.

(b) to protect the weld pool from contamination by oxygen etc.

Ideally the gas should flow in a laminar, non-turbulent stream. Can design nozzles to ensure Reynolds Number below 2,300 for a cold gas.

$$\text{Reynolds Number} = R = \frac{du}{V}$$

d = diameter of nozzle in ft.

u = air velocity in ft/sec.

V = kinematic viscosity.

Little is known, however, about the behaviour when the arc is conducting. Two effects are observed (a) effect of high temperature on properties and velocity of gas (b) "pumping" effects in the arc due to pressure variations.

Experience has shown that for $\frac{3}{8}$ in. diam. nozzles a maximum flow rate of 29 cu.ft./hr. of argon is acceptable, whilst with $\frac{1}{2}$ in. diam. nozzles this figure can be increased to 38 cu. ft. In some cases these figures can be exceeded with safety.

The nozzle to plate distance is also important because even under laminar flow conditions can get diffusion of nitrogen against the flow of argon.

(10) Thermal pinch effect

If the temperature gradient from centre of arc column to outside is increased the arc is constricted and the diameter of the arc column is decreased. This is known as the "Thermal pinch effect". Can be achieved by increasing the gas flow (Fig.8.) or by physically reducing the orifice through which gas flows. For a given arc length and current, the arc voltage is increased. (Fig. 9.) and penetration is increased.

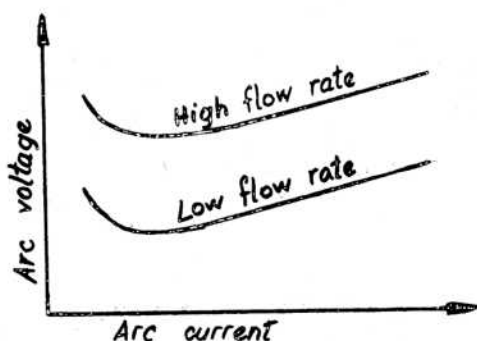


Fig. 9.

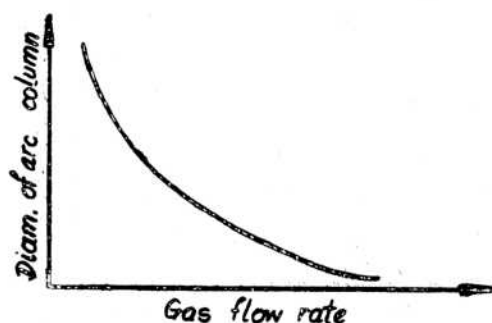


Fig. 8.

III EQUIPMENT

(1) Power Source

Transformer (plus rectifier for d.c.) with either:

- (a) moving core - not very often used.
- (b) variable or tapped reactor (if a.c.)
- (c) saturable reactor - most common.

Alternatively, a motor generator for d.c. can be used; rectifier sets are becoming more common for d.c. because less maintenance etc.

For d.c. welding o.c.v. = 65 - 80V

For a.c. welding o.c.v. = 80 - 100 V. (except when Surge Injector used- see below).

All these power sources produce a drooping static characteristic.

Usually the power source incorporates control valves for gas and cooling water, with suitable delay devices to ensure that the tungsten is protected from the atmosphere during the cooling period after the arc has been extinguished.

(2) High Frequency units

The basic layout of a high-frequency unit is shown in Fig. 10. The operation is as follows:

Transformer charges capacitor - when the voltage is sufficiently high the spark gap breaks down and an oscillatory discharge is produced with a frequency from 300 Kc/s. to 3 Mc/s. The output is inductively coupled into the welding line. The oscillations are heavily damped and last for about $\frac{2}{3}$ rd of half cycle, after which the process is repeated. A "dead" period of $\frac{1}{3}$ rd of half cycle is thus produced.

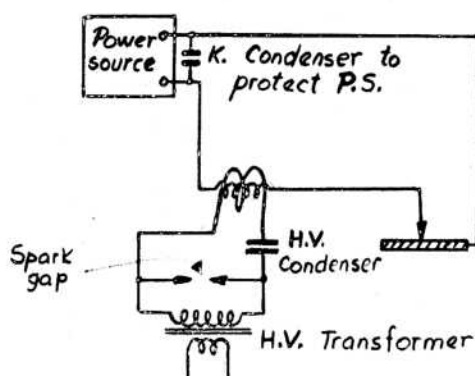


Fig. 10.

The simple unit just described has a wide bandwidth and gives severe interference with radio communications. Modern sets aim at limiting the frequency band. This has led to the development of the spark starter which generates a series of discrete high voltage sparks (see Walker, B.W.J. Sept. '58, P. 407).

When an H.F. unit is used for a.c. reignition the dead period may coincide with the arc current zero. This may give delayed reignition and partial rectification. In this case it is essential to arrange the circuitry so that there is some degree of phase shift between the mains supply to the welding transformer and the supply to the H.V. transformer of the H.F. unit.

(3) Surge injectors

For many applications a H.F. unit with a 100V transformer is satisfactory for a.c. reignition. However, in some applications (e.g. automatic welding, where there is no opportunity to "improve" the bead as would exist with manual welding) and with certain materials (e.g. magnesium) the risk of partial rectification cannot be tolerated and 100% reignition is required. In these cases a surge injector is desirable.

- Basically the surge injector is a device which feeds into the arc a high voltage surge at the precise instant of the current zero. A block diagram of such a unit is shown in Fig. 11. The high voltage source (H) is normally not conducting. The trigger (T) senses the arc voltage and causes the high voltage source to conduct at the arc voltage and current zero. A high voltage surge is therefore injected into the arc to promote instantaneous reignition.

In addition to precise reignition the incorporation of a surge injector enables a low o.c.v. transformer (50 volts) to be used (ref. Walker). The surge injector cannot be used successfully to give initial ignition of the arc and it is usual to include some starting device as part of injector unit.

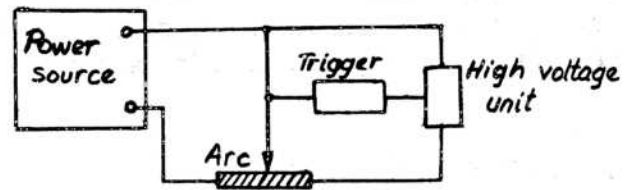


Fig. 11.

Although these units are highly successful they tend to be expensive and to require careful maintenance if the correct triggering is to be consistently achieved. They are also less robust than the H.F. or spark starter unit.

(4) Supression of D.C. Component

- | | |
|---------------------|---|
| (a) Batteries: | must balance d.c. component to be satisfactory.
cumbersome, required maintenance. |
| (b) Capacitor bank: | automatic correction, therefore no balancing required.
Capacity must be large enough to avoid large voltage drop.
No maintenance required. May make starting difficult. |
| (c) Bias supply: | in a.c./d.c. units, rectifier can be used to provide a d.c. bias to offset d.c. component. Again, must try to achieve good balance. Not as satisfactory as a capacitor, specially at high currents, but is cheaper. |

(5) Crater filling

As many T.I.G. welds in thin sheet are made without the use of filler metal, a crater is commonly found at the end of a weld run. Frequently severe cracking is associated with this crater. In many materials the crater can be eliminated by either:

- (a) reducing the current gradually at the end of the run, or
- (b) retracting the electrode and thus increasing the arc length.

The precise mechanism of crater filling is not fully understood but it has been established the degree of filling obtainable is related to the thermal conductivity of the metal. Thus with a low thermal conductivity (e.g. stainless steel, Nimonic alloys etc.) the surface of the weld bead is raised above that of the parent metal. With high values, however (e.g. aluminium) crater filling by these techniques is not possible. In titanium, which has a conductivity between those of stainless steel and aluminium, the surface of a filled crater is flat and almost coincides with the surface of the parent metal.

Of the two techniques quoted above, current decay is most common since it is simple to apply. Retracting the electrode can sometimes give better results but can also lead to

complications in torch design. Current reduction can be continuous or stepwise. The latter is particularly suitable with saturable reactor controlled power sources and is achieved by automatically switching resistors in the d.c. control supply to the reactor.

IV' CHOICE OF GAS SHIELD

- (1) Argon
- (a) Smooth, quiet arc action.
 - (b) Low arc voltage at given current value-useful in welding thin material.
 - (c) Good cleaning action in a.c. arcs on aluminium etc.
 - (d) Good for positional work.

Hydrogen can be added, raising the arc voltage slightly. It is claimed that hydrogen additions give improved penetration and increased speed of welding on stainless steel (McElrath and Gorman, Jan. 1947, p. 28 . Am. Weld. Jnl).

- (2) Helium High arc voltage, useful for welding thick material and metals with high thermal conductivities.
- (3) Nitrogen Cheap. Can be used for welding of copper.
- (4)Hydrogen Has been used for the welding of molybdenum. Very high arc voltage.

V. APPLICATION

(1) Range of materials

T. I. G. welding can be use on a very wide range of metals. It is especially valuable for the welding of highly reactive materials where by use of an argon chamber or of a special nozzle, welds virtually free from contamination can be produced.

The behaviour of metals during T. I. G. welding can be related to the free enery of formation of the oxide and therefore to the stability of the oxide.

METAL BEHAVIOUR IN T. I. G. WELDING (AFTER LANCASTER)

Oxide Type	Metal	Free Energy of Formation at M. P. (Kcal/mole)	Typical Defect	Method of over-coming Defect
Easily reducible.	Ag	not stable	)	Deoxidiser in filler wire
	Cu	38	) Porosity	
	Ni	35	)	
	Fe	70	)	
Stable-insoluble in metal.	St. Steel	Approx. 100	) Surface oxidation, oxide	Protect underside of weld.
	Inconel		) entrapment.	
	Nimonic		) Wrinkling of	
			) under-bend	
Stable-soluble in metal	Nb	80	) Hardening and	Extensive protection of weld metal and parent metal.
	Ta	86	) embrittlement	
	Zr	171	) due to O ₂ and	
	Ti	180	) N ₂ absorption	
Refractory oxide	Al	215	Removal of oxide film	Use A. C.
	Mg	240		

(2) Thickness and Types of Joint

T. I. G. welding is not normally used on thicknesses above $\frac{1}{4}$ in. and finds its main application in sheet welding. In some cases however, it may be used on thicker sections, e. g. multi-pass, stringer bend techniques to avoid hot cracking; thick sections in reactive metals; root runs in joints to be subsequently completed by M. I. G. or metal arc. The latter is a particularly important application especially in pipe work where by use of a positive pressure of argon on the underside of the joint, controlled penetration can be achieved.

Since filler metal is added to the pool, either manually or automatically, the process tends to be slow. Welding can be achieved in all positions on butt and fillet welds, but it should be emphasised that this process, when used manually, requires a highly skilled operator if satisfactory results are to be achieved.

(3) Automatic welding

The process lends itself to inclusion in automatic and fully automated production

lines. Examples are: tube production (longitudinal seam); end cap welding; butt welds between sheets in rolling mills; automatic welding of bellows units in thicknesses from 0.003 in. to .065 in.

(4) Time to start weld

Especially important in automatic welding. Before weld run can be commenced, must establish a pool of suitable size. For a given thickness and current the time to produce a pool is inversely proportional to the thermal diffusivity. With diffusivities greater than 1 starting a weld can be difficult.

Silver 1.8	Aluminium 0.81
Copper 1.1	Iron 0.11

(5) T. I. G. Spot Welding

Introduced to meet the need to spot weld from one side only. Achieved by fusing a slug between the two sheets. Typical applications are sandwich sections, attachments etc. Used widely in the construction of Bristol Supersonic Fighter (T. 188).

Equipment consists of a d.c. power source, timer and crater filler. The arc length is preset and is maintained long enough to just penetrate the two sheets - attempts have been made to control this by the use of photo-cells on the underside. The degree of penetration is a useful inspection check.

Strengths achieved are comparable with resistance spot welds, but note that process does not compete with resistance spot welding; it supplements it.

Has been applied to mild and stainless steel, Nimonic, Titanium and aluminium.
(Ref: Copleston & Gourd, B. W. J. 1958, Sept. p. 394.
Gourd & Copleston, W. M. F. 1960, Sept. p. 368).

The crater filled surface can be ground off to give a smooth finish; sometimes advantageous. On aluminium, however, it is not possible to achieve crater filling by current decay and a small amount of metal must therefore be added. (Ref: Clayden & Copleston, W. M. F. 1963, p. 303).

The first patented use of friction as a heat source occurs in 1944 in the U.K. taken out in the name of Frictionheat Ltd.

The idea was not exploited commercially until 1957 when Friction Welding as a process was announced in Czechoslovakia and Russia.

I PRINCIPLE

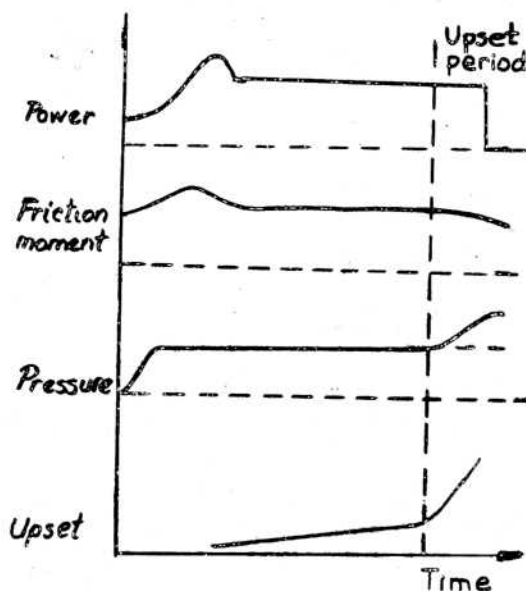
The principle of the process is to rub two surfaces together at high speed under pressure. Heat is generated at the interface. When the metal is sufficiently plastic the joint is upset and bonding occurs at the interface the upsetting having removed any oxidised metal.

Only a small volume heated by fast direct conversion of energy . . . relatively low energy consumption.

II PROCESS

Consider process in greater detail. Surfaces brought together . Start to rub. Friction moment rises until surface becomes plastic - then falls slightly to more or less constant level. It should be noted that during this period of 'dry' friction any surface roughness will be removed - hence a straightforward saw cut is a sufficient preparation.

The heat developed is proportional to $(\text{linear vel})^2$ and in the initial stages the distribution of heat and therefore of temperature, is parabolic. Heat developed is also dependent on pressure and hence as the process develops areas will become plastic and greater pressure will therefore be exerted on the cold areas where more heat will be developed. This, coupled with the normal process of thermal transfer, leads to a more uniform distribution of temperature i.e. the 'equilibrium' temperature is reached.



When the surface become plastic, axial flow begins and upsetting occurs.

At the end of the preheating period, pressure is increased and the upsetting pressure is applied before rotation is stopped - the plastic metal at the interface is forced outwards.

Opinions differ about the possible existence of a fluid layer at the interface just prior to upsetting. Russian work suggests that in a properly conducted operation, the temperature of the metal does not exceed its melting points. Work at Central Research Laboratory (Am. Machine and Foundry Co.) has shown fluid layer exists.

It is possible therefore to consider friction welding as a specific case of hot pressure welding in which friction is used to generate the heat.

III EQUIPMENT

Original machines were converted lathes. Essentially machine consists of a rigid bed onto which are mounted chucks to hold the workpiece. A means of rotating one or both of the components must be provided either one component can be rotated, the other being clamped, or both can be rotated in opposite directions.

The biggest problem in the construction of a friction welding machine is the provision of some means of rapidly stopping relative motion. Various methods can be employed - hold one piece clamped and then release and allow to rotate with moving component, use brakes etc.

Almost any form of motor can be used provided it is possible to obtain constant speed sufficient torque and a good control of speed.

IV WELDING VARIABLES

Four main variables must be considered:

- 1) Speed range from 1,000 - 6,000 rev/min. Lower speeds give finer grain size. This suggests lower equilibrium temperature.
- 2) Preheating pressures will vary according to material. Range from 3.2 - 11.0 Kg/mm². Must remember that a high preheat pressure requires high power.
- 3) Upsetting pressure. May be equal to or greater than preheating pressure depending on plastic properties of the parent metal at elevated temperatures. The pressures required for upsetting in friction welding are much the same as those employed in flash butt welding. Upset pressure is also important in controlling the grain size - if sufficient deformation during upset (50%) get marked grain refinement.
- 4) Time delay between applying upset and stopping motion - if braking is not sufficiently rapid can get shearing at the interface.

The time of welding is governed by all these factors and ranges from 3 - 40 secs.

- 5) Power Consumption is low compared with flash butt welding.
 $8 - 20 \text{ VA/mm}^2$
 $5,200 - 12,900 \text{ VA/in}^2$.

6) Typical Conditions 20 mm. bar (rod)

<u>Material</u>	<u>Pressure (Kg/mm²)</u>		<u>Welding Time</u> (sec.)
	Preheat	Upset	
Mild steel	3.2	6.4	10
1% Cr steel	3.2	6.4	14
.4% C to 12% Cr steel	6.4	6.4	17
.4% C to 18/9 S/S	6.4	6.4	9
C.I.	6.4	6.4	25
A /A	0.8	0.8	4
Brass	3.3	3.3	3

V METALLURGICAL EFFECTS

The process gives a satisfactory metallurgical joint. The heat affected zone is very small (narrow) and within this zone a fine grain size is usually observed. This results from the heavy deformation that takes place in the interfacial layers. There is a danger however that grain growth can take place if the critical combination of deformation and temperature occurs.

Joints between dissimilar metals can be readily produced.

In tensile tests on joints in ferrous materials fractures normally occur away from the joint and the weld can be bent round 180° without failure except in the case of high carbon material where 90° is readily obtained.

In nonferrous materials if fracture does not occur in the parent material, joint efficiencies are usually above 80%.

VI APPLICATIONS

Friction Welding is applicable to a wide variety of materials but only where the materials is available in circular cross section. Where the components are too large to be rotated an insert can be rotated between the two surfaces.

Stud welds can be produced. Will recommends that the ratio of the thickness of sheet to the diameter of the peg should not be greater than 0.25 - 0.3.

The process can also be used for surfacing.

In general, it is desirable to automatically control the process to give consistency of results

Friction welding is especially suited to inclusion in mass production lines, but would appear to have only limited potential for 'one-off' work.

Advantages claimed for the process are:

1. Simplicity.
2. Suited to repetition work and automatic operation.
3. Low installed energy input.
4. Absence of ' peak loading '.
5. No sparks or flashing - ideally suited to use in production lines with other machines.

I INTRODUCTION

Brazing consists of introducing, between the sheets to be joined, a filler metal whose liquidus is below the solidus of the parent metal. Thus in the strict sense of the word brazing includes soldering, but conventionally the term brazing is used where the filler metal melts at a temperature above about 400°C. Soldering is usually confined to the application of fillers with melting points below 300°C.

In brazing, unlike welding, the workpiece must be heated uniformly. Thus a variety of heating methods can be employed - the most common are oxy-gas flame, furnace, salt bath, high frequency and resistance.

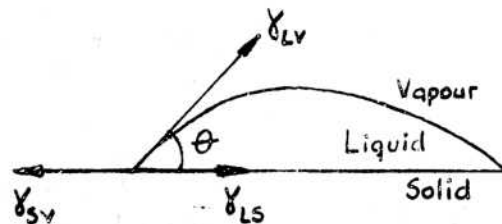
The filler metal must have certain attributes:

1. It must wet the surface of the parts to be brazed - may have to use flux.
2. M. p. (liquidus) must be below the solidus of the plate.
3. It must form a good diffusion bond with the parent material without the formation of brittle intermetallic compounds.

II THEORY

When a droplet of liquid is dropped onto the surface of a plate, it will take up a shape which minimises the surface energy of the system.

At the point of contact, the angle between the tangent and the surface will be characteristic of the system = contact angle = θ .



θ will depend on:

- a) surface tensions of the solid and liquid phases,
- b) interfacial tensions between the two phases.

References: Funk and Udin, Welding Jnl.
31, 247s, 1952
Udin, Funk and Wilff -
Chapter 14.

Feather: Mass, Length and Time

On the line of contact of the gas, liquid, and solid phases, the surface forces are in equilibrium, parallel to the solid surface.

Then

$$\gamma_{SV} = \gamma_{LS} + \gamma_{LV} \cos \theta$$

In brazing, we are concerned with the case where complete wetting occurs. For this θ will be 0 and $\cos \theta = 1$.

$$\therefore \gamma_{SV} = \gamma_{LS} + \gamma_{LV}$$

In the usual solid metal-liquid metal-air systems θ is usually greater than zero. To achieve wetting the vapour (i.e. air) phase is replaced by a flux. Under these conditions:

$$\gamma_{SF} = \gamma_{LS} + \gamma_{LF}$$

With this arrangement it is easier to find a combination of flux and filler metal which will give wetting of the surface of a given metal. It should be noted that the flux itself must wet the surface completely, i.e. θ for the flux-solid must be zero, and:

$$\gamma_{SV} = \gamma_{FS} + \gamma_{FV}$$

2. Capillarity

In confined spaces the same tendency to minimise the surface energy occurs and a meniscus is formed - hemispherical in small bore tubes and semi-cylindrical between // plates; in larger tubes flatter surfaces occur. In brazing consider as semi-cylindrical or semicircular.

Because the surface is curved, the pressure under the surface is less than that of the surrounding atmosphere. It can be shown that the pressure across the surface

$$\Delta P = \frac{2\gamma \cos \theta}{D} \quad \gamma = \text{sfce tension}$$

Consider two plates thrust into liquid, surface energies cause contact angle θ to be developed.

Pressure under the surface away from the plates = atmospheric

Pressure under curved surface = atmospheric - ΔP

$\therefore$ column rises until weight of column = ΔP at height 'h'.

Then $\Delta P = \rho gh$ ρ = density of liquid
 g = acceleration due to gravity

Thus if liquid is rising between infinite plates

$$-\rho gh = \Delta P = - \frac{2\gamma \cos \theta}{D}$$

$$\therefore \gamma = \frac{D\rho gh}{2 \cos \theta}$$

For complete wetting $\cos \theta = 1$

then $\gamma = \frac{D \rho g h}{2}$

∴ maximum height that can be reached, $h_{\max} = \frac{2\gamma}{D\rho g}$

3. Flow in brazed joints

Consider now a horizontal lapjoint. Advancing front is curved as a result of surface tension. The pressure driving the liquids between the plates =

$$\Delta P = \frac{2\gamma}{D}$$



Can assume laminar flow - gives non-linear velocity distribution, can be shown that if t is the time taken to flow a given distance x ,

Then $t = \frac{3\mu x^2}{\gamma D}$

$$x = \sqrt{\frac{\gamma D}{3\mu} t} \quad \mu = \text{viscosity.}$$

∴ distance flowed in a given time is related to:

- Physical properties of brazing alloy (γ and μ)
- Plate separation (D)

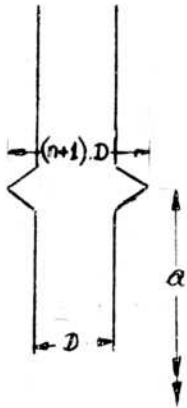
For brazing a high γ/μ ratio is therefore required. Usually achieved by reducing viscosity.

Effect of temperature is implicit in μ . As the temperature rises, the value of μ falls and that of the ratio γ/μ therefore increases. Thus a high temperature would appear to be advantageous but this is limited, however, by metallurgical factors.

A comparison of the times to flow a given distance in horizontal or vertical joints shows that times are of the same order when $h/h_{\max}$ in vertical is low, but horizontal can be faster when $h/h_{\max}$ is high. However times are very short, therefore differences are hardly significant.

4. Capillary Dams = obstruction caused by change in cross-section.

Consider vertical joint.



$$h_{\max} = \frac{2\gamma}{\rho g D} = \frac{\gamma}{\rho g D/2}$$

If plates are close, $D/2 = \text{radius of curvature} = R$.

$$h_{\max} = \left(\frac{\gamma}{\rho g} \right) \frac{1}{R}$$

as R increase, $h_{\max}$

the wider the dam the lower the height reached.

If dam occurs between $h_{\max}$ and $\frac{h_{\max}}{n+1}$, flow will be stopped.

5. Constrictions - may affect time, but will only affect height if sufficiently small to seriously impede flow.

Avoid dams and constrictions in joint design. Also avoid deep machine marks at right angles to direction of flow.

III METALLURGY

1. General considerations

In the brazing process a molten metal is brought into intimate contact with a clean surface. Because a concentration gradient exists, diffusion will occur, the rate being accelerated by the temperature. This diffusion is not an essential part of the bonding process, but will almost always occur. The extent of the diffusion is a function of:

- a) temperature
- b) time
- c) diffusion characteristics of system.

Thus at the interface, dilution of the filler metal by the plate material can occur and brittle intermetallic phases can be produced. Dilution of the filler metal as a whole is not appreciable. The formation of brittle intermetallics is obviously a serious problem and temperature and time must be kept at the minimum consistent with adequate filling of the joint. Selection of the filler wire must take into consideration the formation of brittle intermetallics.

With alloys for high temperature use, however, attempts have been made to utilise the diffusion process. Alloys containing appreciable amounts of boron are used. The boron is very mobile and diffuses into the parent plate.

Since it will be distributed over a wide area, the boron concentration in the plate will be low. The filler metal will thus be low in boron and will therefore have a higher melting point. It can thus be used at temperatures higher than the melting point of the original filler.

2. Filler metals for brazing

a) Aluminium - 10% Silicon used on aluminium and alloys containing less than 2%Mg.
Melting range 520 - 630°C.

b) Copper based

Cu for steels - use H_2 atmosphere 0.002" maximum clearance allowable .1085°C.

Cu-Ph - usually used for Cu alloys. Phosphorus content may cause embrittlement with ferrous based materials. Self fluxing on Cu. 640 - 900°C.

Cu-Zn - very widely used for steels etc. - Zn volatilisation will cause blow holes if overheating occurs. Not used on S/S or Cu because of corrosion problem. Must flux.
855 - 935°C

c) Silver based (Silver solders)

Applicable to wide range of materials. In the main, contain Cu and Zn as alloying elements. Cadmium, phosphorus or nickel may be added. Sometimes Lithium added to give self fluxing properties.

By adjusting the composition can get melting points within the range 600-790°C.

Appropriate fluxes must be used.

d) Nickel based used for high temperature work. Main alloying elements are Cr, Si and boron. Alloys tend to have high solubility for many base plate materials. 960-1140°C.

Newer materials containing Palladium and Chromium are being developed.

e) References

Colbus et. al. Welding Jnl. Sept. '62, pp. 413s.
B.S. 1723: 1951

3. Fluxes for Brazing

A flux used in brazing must fulfill two basic functions:

Firstly it must cause the filler metal to wet the surface of the parts to be brazed.

Secondly it must also dissolve oxides on the surfaces (this is of course a pre-requisite for wetting) and provide protection against further oxidation.

It follows that usually the flux should melt at a temperature lower than the melting point of the filler metal.

In the majority of work, the flux is applied to the workpiece in the form of a paste, but in

some applications a volatile flux can be introduced into the gas flame. This latter method can only be used where the flame can impinge directly onto the surface to be covered with filler metal. It is not very effective on joints relying on capillary flow to give filling.

- a. Borates Na, K and Li. For use above 760°C. Good oxide dissolving characteristics and good protection. Alkyl borate used as vapour flux.
- b. Fluoborates Na and K - better oxide dissolving and better fluidity than borates. Used for high temperature materials - shorter duration of protection. Must beware of fumes. Some authorities suggest boron contamination in certain materials.
- c. Fluorides Na, K, Li - Very active - increase capillary flow. Used especially on Al and cv materials - dangerous fumes. Rapid corrosion is left on component. Various authorities argue about the importance of water of crystallisation.

Boron trifluoride is used as vapour flux but special precautions must be taken because of high toxicity of gas.
- d. Chlorides Similar to fluorides but less effective.
- e. Boric acid calcined base for many fluxes - good cleaning agent - reduces viscosity of flux - makes removal easier.

IV PRACTICE

1. Methods of Heating

A variety of heat sources can be used. The main essential is that the heating should be uniform and easily controlled. Two broad types exist - 1. hand operated and 2. permanently installed.

The first group offers the advantages of low capital cost and flexibility. Complex work can often be successfully completed although unsuitable for other methods. The main objections to manual brazing lie in the need for skilled operators and the effect of the human factor on the quality and consistency of the process. The fuel gas used will dictate the type of torch used.

Acetylene, with oxygen, enables welding type torches to be employed. With this fuel gas high rates of heating and high temperatures are obtainable and in complex jobs heat can be localised if necessary. The high temperatures can, however, be a source of danger - i.e. overheating can readily occur. The use of coal gas and compressed air can be attractive on smaller components and the danger of overheating is negligible.

Permanent installations vary in size and complexity. The more commonly used types include fixed gas burners, muffle furnaces (with or without protective atmospheres), H.F. induction heaters, and electric resistance equipment. Flux and molten metal baths are used for some special applications. All these equipments suffer from having a relatively high initial cost and

usually some specialist knowledge is required to develop the technique but once this has been established, relatively unskilled labour can be used to operate the equipment. Maintenance or servicing costs must also be taken into consideration. These methods are ideal for mass production or where a reproducible standard is required. It is almost essential to employ simple joints which can be readily assembled before brazing.

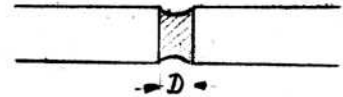
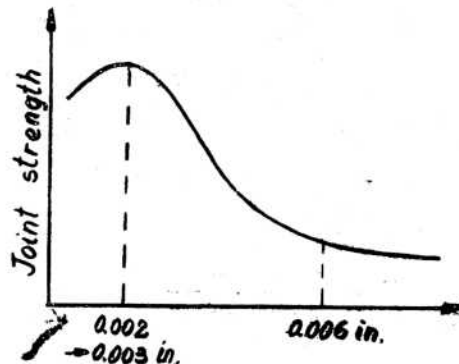
(Ref.: Low Temperature Silver Brazing - J. and M. Industrial Brazing - Brooker and Beatson).

2. Strength of Brazed Joint

Before considering brazed joints in practice, it is as well to consider first the strength of a brazed joint.

Normally, the material used as a filler for brazing has a lower strength than the parent metal. The strength of a brazed joint can, however, be appreciably higher than that of the filler. Consider a butt joint between two rods.

If plot strength, in tension, against D get curve thus:



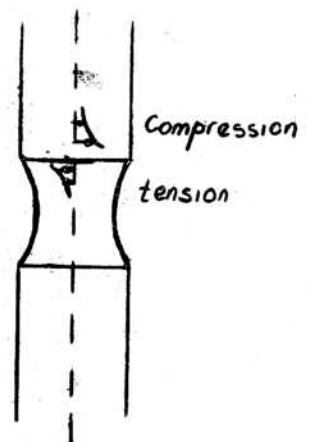
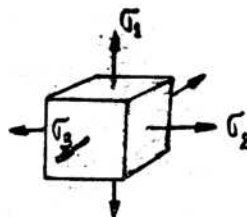
Consider joint - when stress applied brazing alloy starts to yield, having lower yield stress than parent metal.

The plastic deformation of the filler will be constrained by the presence of the parent metal to an extent dependent on the spacing between the faces of the parent metal. When this constraint occurs shear stresses will be set up at the interface normal to the longitudinal axis of the sample.

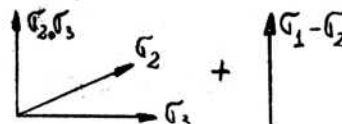
Consider an element of the filler. The stresses can be represented thus:

$$\sigma_1 > \sigma_2 \text{ or } \sigma_3$$

$$\sigma_2 = \sigma_3$$



This stress system can be considered in two parts:



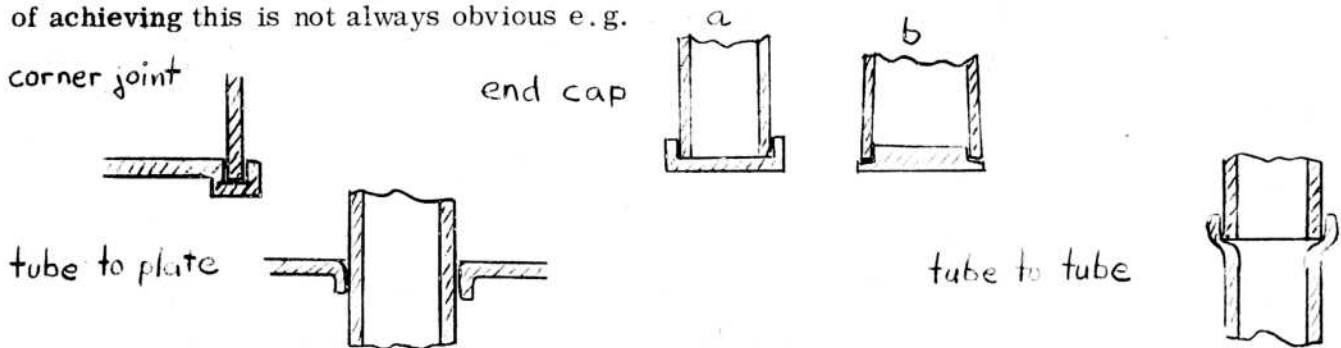
i.e. it can be visualised as a balanced system (hydrostatic) onto which is applied a uniaxial stress. In the case of the balanced (hydrostatic) system no deformation will occur. Any further deformation which occurs in the filler metal will therefore be produced by the uniaxial stress ($\sigma_1 - \sigma_2$). This uniaxial stress is a measure of the resolved shear stress in the slip planes and yielding and fracture will occur at the normal levels of this stress. In terms of the load applied to the sample as a whole, fracture will occur therefore at a higher level than the U.T.S. of the filler because the uniaxial stress which produces fracture is only a part of the applied stress.

Note that the above treatment is only strictly correct for a butt joint (which is not common in brazing). The same principles apply, however, to lap joints but the analysis is complex.

3. Joint Design for Brazing

Much has been written about the correct design of joints for brazing. Attention has already been drawn to the need to avoid capillary dams and the importance of the gap between parent metal surfaces.

As a general principle, the actual brazed joint should be in the form of a lap. The method of achieving this is not always obvious e.g.



The exact type of joint used will depend on whether the filler metal is to be preplaced or fed by hand; thus in the case of the end cap, b. would be used for a preplaced filler where a. would be preferable for hand feeding of the filler.

In specifying tolerances account must be taken of expansion, especially if dissimilar metals are being joined.

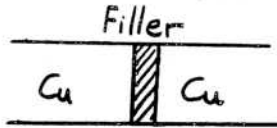
When using preplaced fillers, incidentally giving the maximum economy of filler metal, the size of the preformed ring must be determined carefully. Various formulae exist for this, but the calculations are based on simple geometric considerations. Generally an excess of 25% of brazing metal over the theoretical requirement is recommended.

(R f. J. and M. - Low temperature silver brazing).

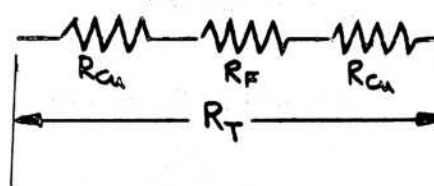
4. Brazing of Electrical Conductors

Whilst electrical conductivities of various filler metals can be obtained by experiment, these give little guide to the effect of a brazed joint on the resistance of e.g. a copper busbar.

Consider a butt joint between two pieces of Cu.



Can be represented thus:



$$R_T = 2R_{Cu} + R_F$$

If the filler metal is removed i.e. a solid copper is substituted as a simple approximation, the total resistance will be $2R_{Cu}$.

$$\begin{aligned} \therefore \% \text{ increase in resistance} &= \frac{R_T - 2R_{Cu}}{2R_{Cu}} \times 100 \\ &= \frac{R_F}{2R_{Cu}} \times 100 \end{aligned}$$

Example

If the ratio of the conductivities of C_u and filler is 100:6

$$\% \text{ increase} = \frac{1/6 \times l_f}{2 \times \frac{1}{100} \times l_{Cu}} \times 100$$

l_f = length of filler

l_{Cu} = length of Cu

suppose $l_f = .002''$, $l_{Cu} = \frac{1}{2} \text{ in.}$

$$\% \text{ increase} = 3.3\%$$

Will be seen that the longer the C_u bar the smaller the percentage increase in resistance.

In practice would use lap joints (1-3 x thickness) when increase in resistance becomes negligible.

V BRONZE WELDING

Sometimes known as Braze Welding. Not strictly welding and not used to weld bronze.

An oxy-acetylene welding torch is used and the techniques employed are very similar to those used in the oxy-acetylene welding process but the parent metal is not melted. On thick plate bevelled edges are employed. Butt and fillet joints can be completed in all positions.

Three main types of filler metal are used - all based on Cu - Zn alloys.

<u>Filler</u>	<u>Composition</u>	<u>M.P.</u>	<u>U. T. S.</u> ton/in ²	<u>Y.S.</u> ton/in ²	<u>Application</u>
Silicon bronze	Cu/Zn/Si/etc.	875°C	29.0	11.0	Brass and Cu sheet and tubes-domestic
Nickel bronze	Cu/Zn/Ni	910°C	37	17	Steel or malleable iron-building-up of wearing surfaces
Manganese bronze	Cu/Zn/Mn	895°C	30	14	All types of C.I. Bearings surfaces where Nickel undesirable.

Must use appropriate flux.

Main outlet for bronze welding is in the joining or repair of C.I.

Is used on steels where undesirable to use high temperatures. Finds wide application on galvanised sheet where the presence of a full fusion steel joint would lose the corrosion resistant properties of the zinc coating.

I INTRODUCTION

Whilst investigating methods of improving the resistance spot welding of aluminium alloy sheets and ways of simplifying pre-weld cleaning techniques, Jones and his co-workers in U.S.A. found that by superimposing an ultrasonic pulse on the welding current, a marked reduction in electrical resistance at the interface could be achieved. Thus it appeared that the use of ultrasonics assisted in the dispersion of the oxide film separating the two sheets. Subsequently, Jones et al found that satisfactory welds could be made by the use of ultrasonics alone.

In its basic form, ultrasonic welding is the application of ultrasonic vibrations to a joint which is clamped locally so that the area to which the vibrations are applied is under pressure.

The essential part of an ultrasonic spot welder are shown in Fig. 1.

The Ultrasonic Generator produces electromagnetic waves having a frequency which is usually between 5 Kc/s and 60 Kc/s. These waves are fed to a Transducer which converts the electrical energy into mechanical energy in the form of a reciprocating motion. This lateral displacement is amplified by means of a coupling horn and is then transferred to the upper member of the welding system (the Upper Sonotrode). The top end of the upper sonotrode is fixed and thus the lower end or tip is displaced laterally in sympathy with the movements of the transducer and therefore at the same frequency as the output from the ultrasonic generator.

The two sheets to be welded are clamped between the tip of the upper sonotrode and the Reflector Sonotrode, which is designed so that it will not vibrate at the ultrasonic frequency. Thus, assuming no movement of each sheet relative to the sonotrode with which it is in contact, the sheets will move relative to one another, causing sliding at the interface. Under pressure this sliding results in a metallurgical bond between the two surfaces.

By varying the form of the upper sonotrode, the process can be used to produce continuous seam welds in sheet or butt welds in rod (Fig. 2).

II EQUIPMENT

Consider now each section in detail:

1. Ultrasonic Generator - can be either a motor generator or valve oscillator. Whilst the former is more reliable, it is probably not of great use because control of the frequency is not easily achieved.

For the welding of foil and thin sheets, relatively low powered units have been used having outputs of 300 - 400 watts, but according to American work optimum results on 16 swg Al require an output of about 4 kW. Work in the U.K., however, suggests that with a more efficient coupling system, the figure could be reduced to about 1 kW.

In most reported work, frequencies between 16 and 20 Kc/s have been used - the latter

having the advantage of being outside the audible range. Frequencies should be stable to within ± 15 c/s, i.e. $\pm 0.1\%$.

2. Transducer - the function of the transducer is to convert the electrical energy into mechanical energy. Electrostrictive transducers (specially cut crystals) suffer from the disadvantage of low resistance to mechanical shock and a low Curie point (i.e. the temperature above which the electrostrictive properties are lost). Lead zirconate is the exception, having a high Curie point. Difficulty is also experienced in bonding the crystal transducer to the coupling horn.

Magnetostrictive transducers are most commonly used since they are more robust and, with adequate water cooling, will handle large powers. This type of transducer consists of a stack of nickel laminations around which is wound the output coil of the generator.

3. Coupling system -

This is perhaps the most critical part of the equipment since for maximum power efficiency both the acoustic horn and the upper sonotrode must resonate at the same frequency as the transducer.

The coupling horn amplifies the displacements produced by the transducer. - The determination of the correct dimensions for the horn follows standard acoustical theory, but various opinions exist about the most suitable shape. In American practice the cross-section of the horn varies exponentially along its length or consists of two cones (truncated).

Mullards suggest, however that better results can be achieved with a straightforward two diameter array.

The effective length of the horn should be such that a node occurs at about the centre.

The horn should be made of a material having a low damping capacity if power losses are to be avoided. In the U.S.A., Monel is widely used, but Mullards claim that greater efficiencies are achieved by the use of titanium. They also recommend that the Upper Sonotrode should be an integral part of the horn for maximum efficiencies. Under these conditions, it is suggested that 1 kW should be sufficient for 16 s.w.g. sheet.

The coupling system must be carefully designed and manufactured if premature failure by fatigue is to be avoided.

III MECHANISM OF BONDING IN ULTRASONIC WELDING

Very little information has been published on the mechanism of bonding in ultrasonic welding.

Holmes has shown in pressure welding that bonding can occur below the threshold value of deformation if sliding occurs between the surfaces to be welded. In ultrasonic welding although clamping pressures are between 200 - 500 lb., the amount of deformation is only of the order of 5 per cent. At this level of deformation, according to Holmes, the beneficial effect of sliding is very marked.

The role of clamping pressure is not clear at present but it has been observed that the shear strength of the weld increases with increasing pressure up to a given value of load, after which the increase is less marked. It has been suggested that, since the amount of deformation is small, the main function of the clamping load is to provide intimate contact

between the surfaces to be welded. Thus the optimum load required will depend on the properties of the alloy. This is consistent with the observed relationship between shear strength and load. It should be noticed that higher loads require greater power to overcome the compliance of the welding arrangements.

Due to friction, heat will be generated at the interface. Various estimates of this temperature have been made which range from 100 - 500°C depending on the material. The temperature at the interface will be a function of the rate of energy dissipation and Antonevich proposes the following expression for this rate:

$$E = 2 K N f X$$

E = Rate of energy dissipation
K = Coefficient of kinetic friction
N = Clamping force
f = Frequency
X = Displacement

Note inclusion of clamping force.

It has been shown by Jones and Meyer that the shear strength of an ultrasonic weld is related to the temperature.

The heat generated at the interface will also allow flow to take place in this region in many materials which are brittle at room temperatures.

It would seem that in its simplest form, ultrasonic welding can be considered as a special form of pressure welding in which ultrasonic vibrations are used to disperse the oxide film and to raise the temperature at the interface, which is maintained in intimate contact by the clamping pressure, will occur. The elevated temperature will increase the mobility of the atoms . . . assisting diffusion and will encourage re-crystallisation of the heavily worked surface layers.

IV APPLICATIONS

By far the largest amount of development work has been done on aluminium and its alloys. The efficient cleaning of surfaces during the welding cycle itself means that pre-cleaning costs are reduced to a minimum. This, together with the absence of heat except in the interfacial layers, makes the process attractive for the welding of heat treated aluminium alloys. Jones and Collins have independently obtained results on a range of alloys which are well in excess of the minimum specified by the U.S. Army for resistance welding.

Ultrasonic welding has also been used to weld dissimilar joints in a range of ferrous and non-ferrous materials. In theory the process can be applied to any metal which has sufficient rigidity to transmit the ultrasonic vibrations to the interface. Soft materials such as lead, except in thin sections, may give problems due to the sheet material being deformed remote from the interface.

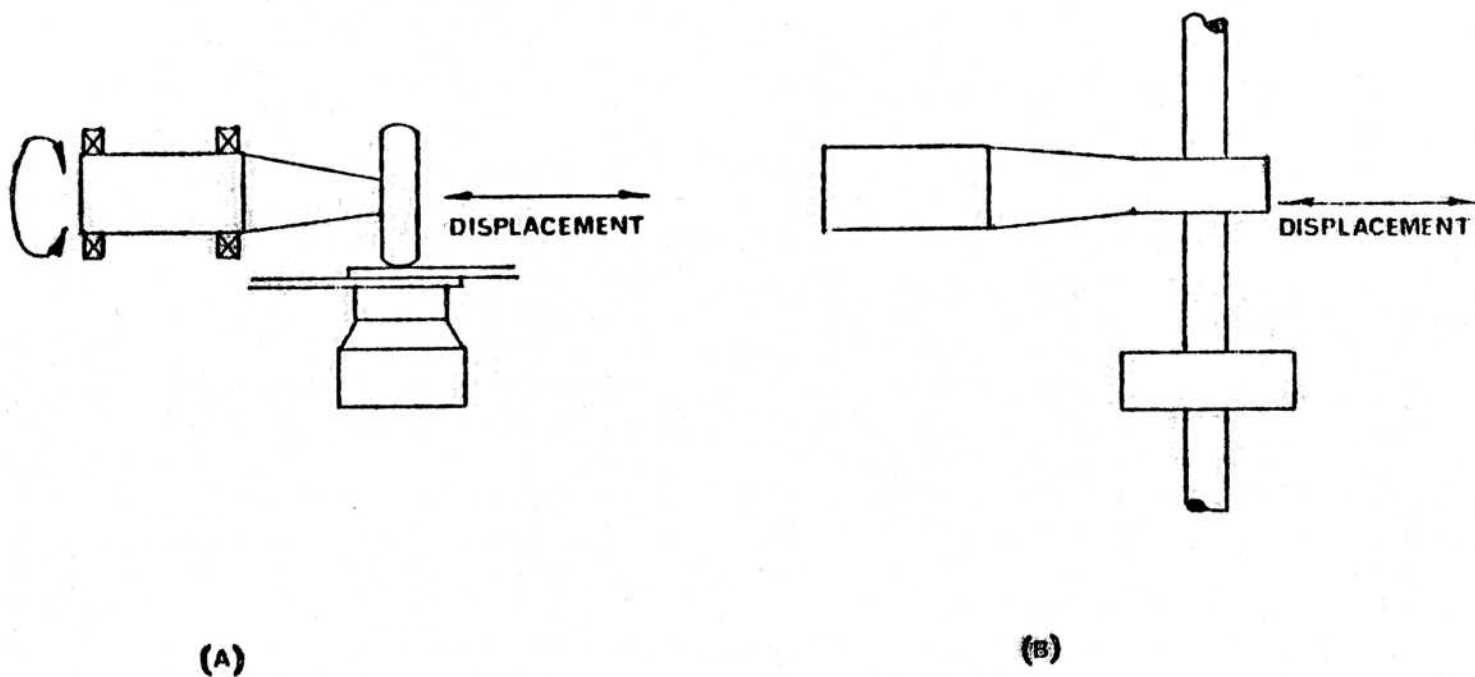
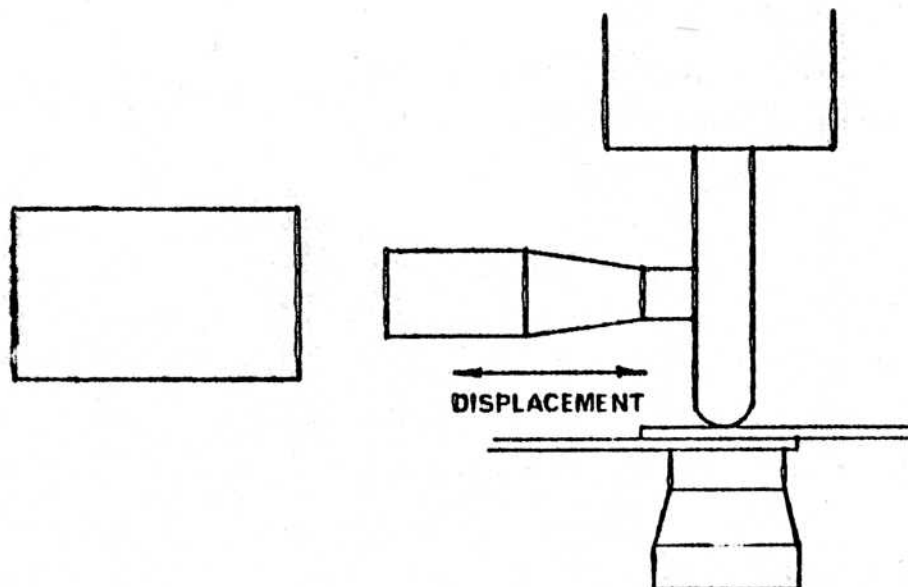
The main limitations to the process, at the moment appears to be the problem of designing and constructing systems capable of delivering sufficiently high levels of power to the interface. Probably one of the biggest outlets is in the continuous seam welding of foil to

produce air tight packages for food etc. , in the production of such things as insulation blankets for jet engines and in the manufacture of electronic components.

'Pulsonic' welding has been advertised in the U.K. and would appear to be an ultrasonic system using resistance heating, presumably to reduce the power required. Little information is available.

Ref.: Neville - B.W.J. April '61, p. 177.
A.W.S. Handbook.

FIG.1 BLOCK DIAGRAM OF ULTRASONIC SPOT WELDER



**FIG.2 BLOCK DIAGRAMS FOR :- (A) CONTINUOUS SEAM WELDING
(B) BUTT WELDING**

INERT - GAS SHIELDED METAL-ARC WELDING (Mig)M.I.G. - Metal Inert GasPrinciples

An electric arc is formed between a consumable wire electrode and the work; the electrode is melted and the metal transferred across the arc. The arc and weld pool is surrounded by a gas which may be completely inert or relatively inert under a particular set of conditions. The best welding characteristics are obtained with a D.C. power source, electrode positive.

Shielding Gases Used

Argon

Argon + 1% O₂Argon + 2% O₂Argon + 5% O₂Argon + 20% CO₂Argon + 15% CO₂ + 5% O₂CO₂Application

Non-ferrous metals

Austenitic steels

Ferritic steels (downhand)

Ferritic steels downhand (sheet)

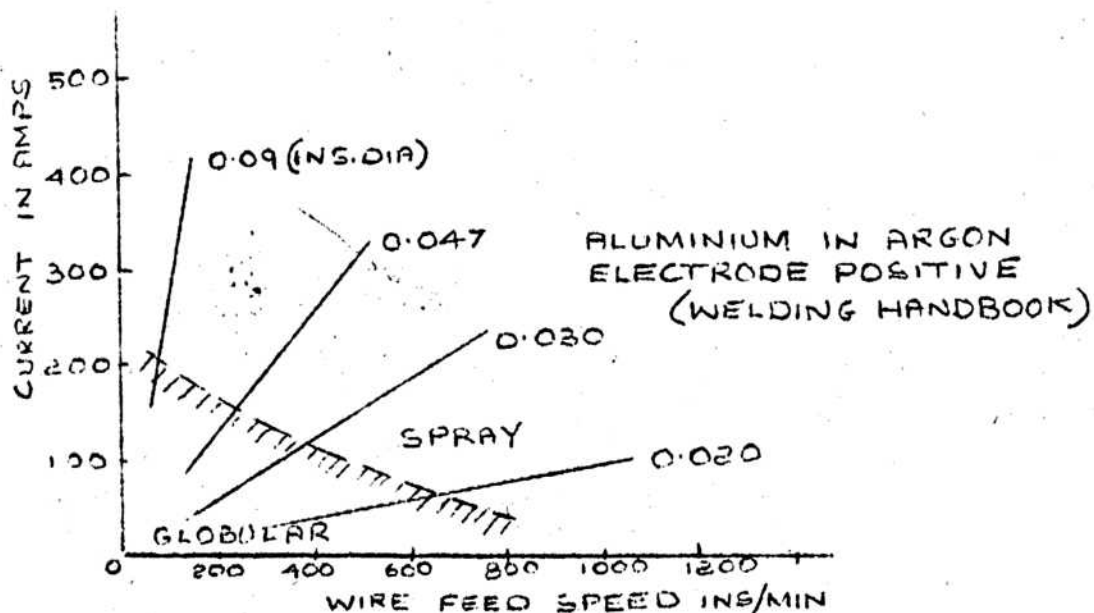
Ferritic steels all positions.

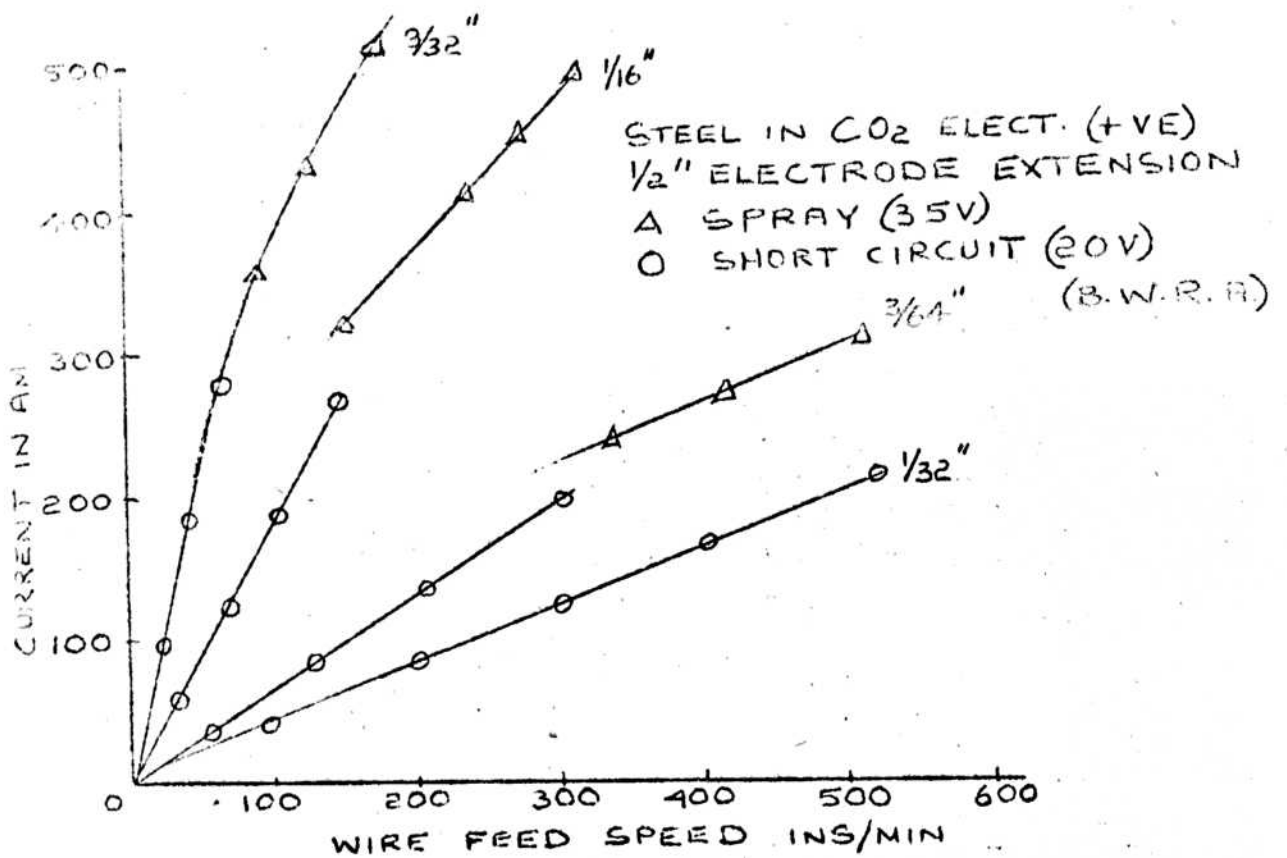
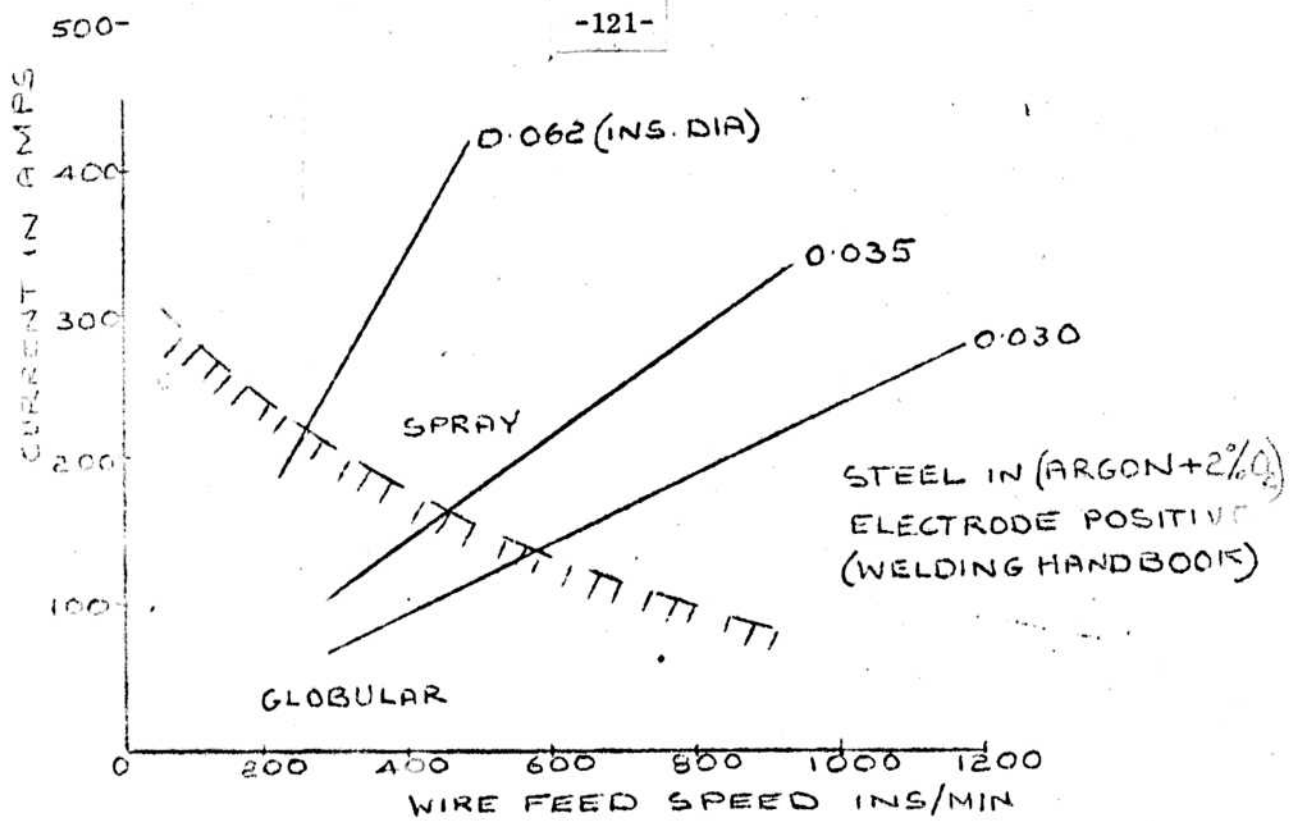
Ferritic and austenitic steels - all positions

Ferritic steels - all positions

Arc Characteristics

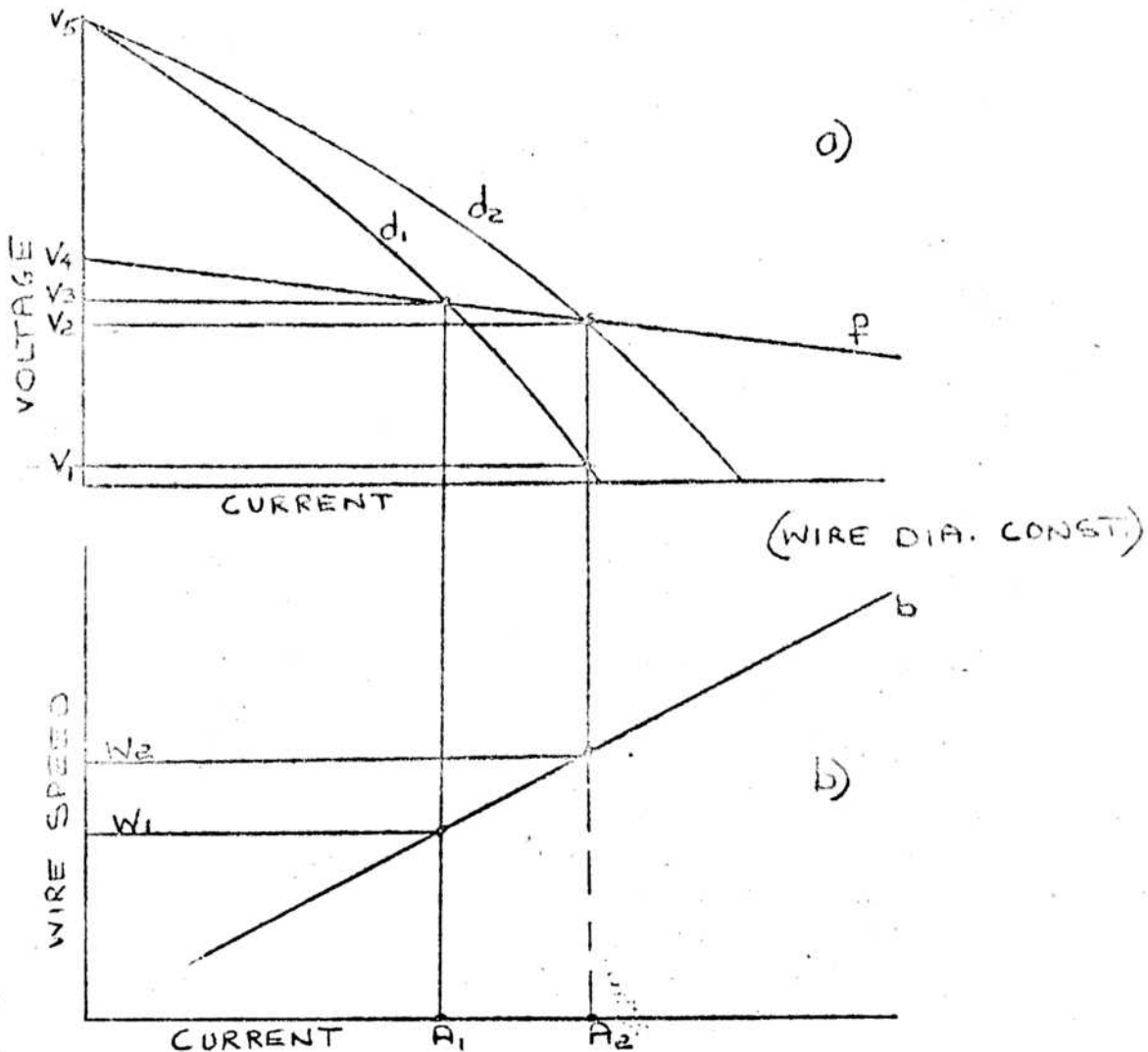
Unlike welding with covered electrodes, where larger gauges are used for higher currents, the same diameter wire can be used over a wide range of current. 'A near linear relationship exists between the rate at which wire is fed into the arc and the current required to burn it off to maintain an equilibrium arc length'. This is known as the burn-off relationship and is a characteristic property of each filler wire composition and diameter.





The curves (Sketch Page 142) illustrate the burn-off characteristics of aluminium in argon and steel in argon/oxygen mixtures and CO_2 . It will be seen that to alter the welding current a proportionate increase in the wire feed rate is required. The smaller the diameter of the wire the faster the wire speed required to reach the same current.

The related curves shown below define precisely the variables controlling the arc characteristics in gas shielded welding.



The upper graph (a) is the volt-ampere characteristics of two power sources. The curves labelled (d) are those of a 'drooping characteristic' (constant current) power source and the one labelled 'f' the 'flat output characteristic' (constant potential).

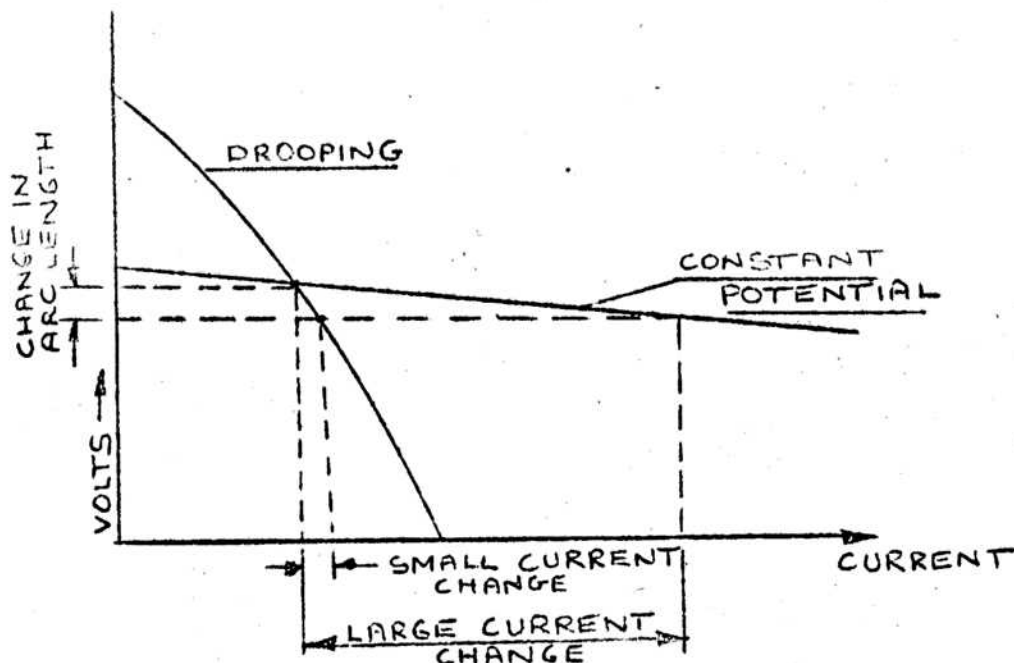
The lower graph (b) represents the typical burn-off characteristics of a wire and depicts the increase in current which results from an increase

in wire speed. With the wire speed set at W_1 ins/min. the lower graph shows that A_1 amperes are required to burn off this particular wire diameter at this speed.

Projecting up to the source curves shows that this current can be supplied at V_3 volts on both power sources (f) and (d_1). If the wire feed is now increased to W_2 in/min, the burn off characteristic curve (b) indicates that A_2 amperes are required to burn off this amount of wire. Projecting to graph (a) shows that the constant potential power source can supply this higher current at practically the same voltage as previously (V_2 compared with V_3) but the drooping characteristic source can only supply A_2 amps at V_1 volts (d_1). This is an impractical low arc voltage and the arc would be extinguished. A new curve d_2 must be selected on the drooping power source (current is increased) so that the desired current A_2 can be supplied at the right voltage V_2 .

Because of the greater latitude in setting welding conditions, and the independent control of current by the wire feed speed, constant potential power sources are by far the most popular for MIG welding. The control of current with this type of power source merely involves selecting a wire speed from the burn off characteristic, the current will rise automatically to the required value at a voltage not greatly below the selected open circuit voltage.

Another important property of the constant potential power source is its ability to produce a self adjusting arc length.



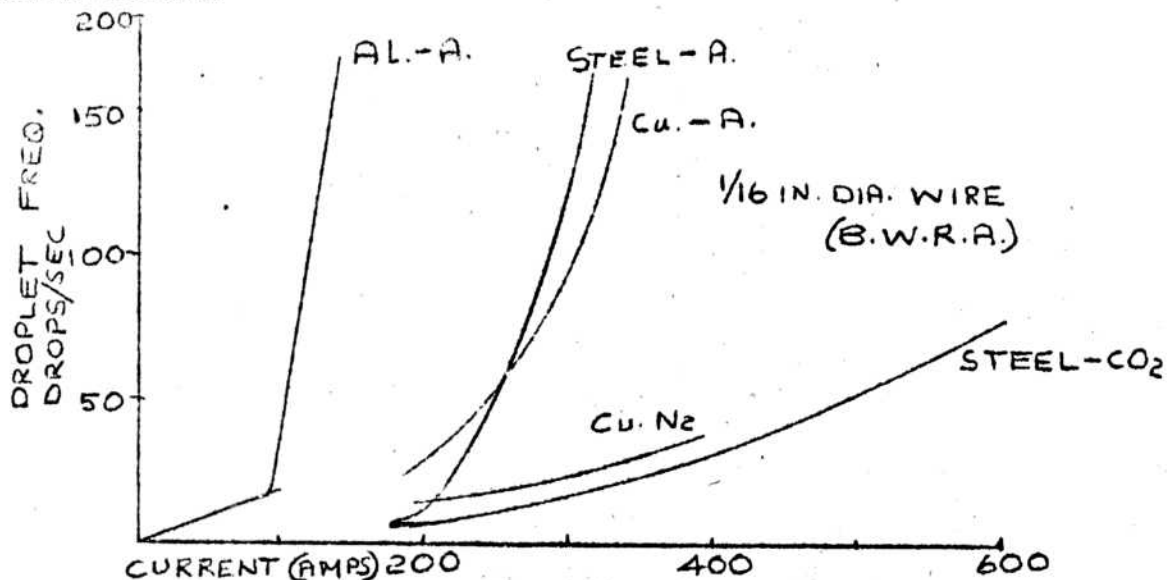
The sketch above illustrates the output curves of a drooping and a constant potential power source. The former used in manual metal arc welding

will produce little change in current due to fluctuations in arc voltage. Changes in arc voltage will however produce marked changes in current with a constant potential power source. Thus, if the arc length is shortened, there will be an increase in current resulting in a faster burn off rate and the arc length will be adjusted. A longer arc length would increase the arc voltage resulting in less current a slower burn off rate; the arc length would shorten.

Self adjustment will only operate successfully when the change in current, produced by voltage fluctuations is sufficiently large to produce a large alteration in burn off and a rapid response rate and correction which the disturbance cannot beat. With large wires the change of current will not alter the current sufficiently to produce a marked change in burn off and the disturbance will be faster than correction. A 100 amp change in current will produce a 10 in/min change with $\frac{1}{8}$ inch wire in CO_2 , compared with 30 in/min with $\frac{3}{32}$ inch, 70 in/min. with $\frac{1}{16}$ inch and 400 in/min with $\frac{1}{32}$ inch wire. It is necessary, therefore, with large diameter wires (and with drooping power sources where the current change is insufficient to correct an arc disturbance) to use a controlled arc system of machine control. When the arc gets too long the wire feed motor speeds up and so helps the inherent self-adjusting arc action. The controlled arc machine functions by means of an arc voltage sensing circuit which controls the wire feed motor speed. Since wire speed rate is not set on the machine, but is a varying quantity controlled by fluctuations in the arc voltage, current is controlled on the power source so that drooping power sources are used with controlled arc machines.

All manual CO_2 guns and most automatic heads use wires not greater than $\frac{1}{16}$ inch in diameter and operate on a self adjusting arc principle.

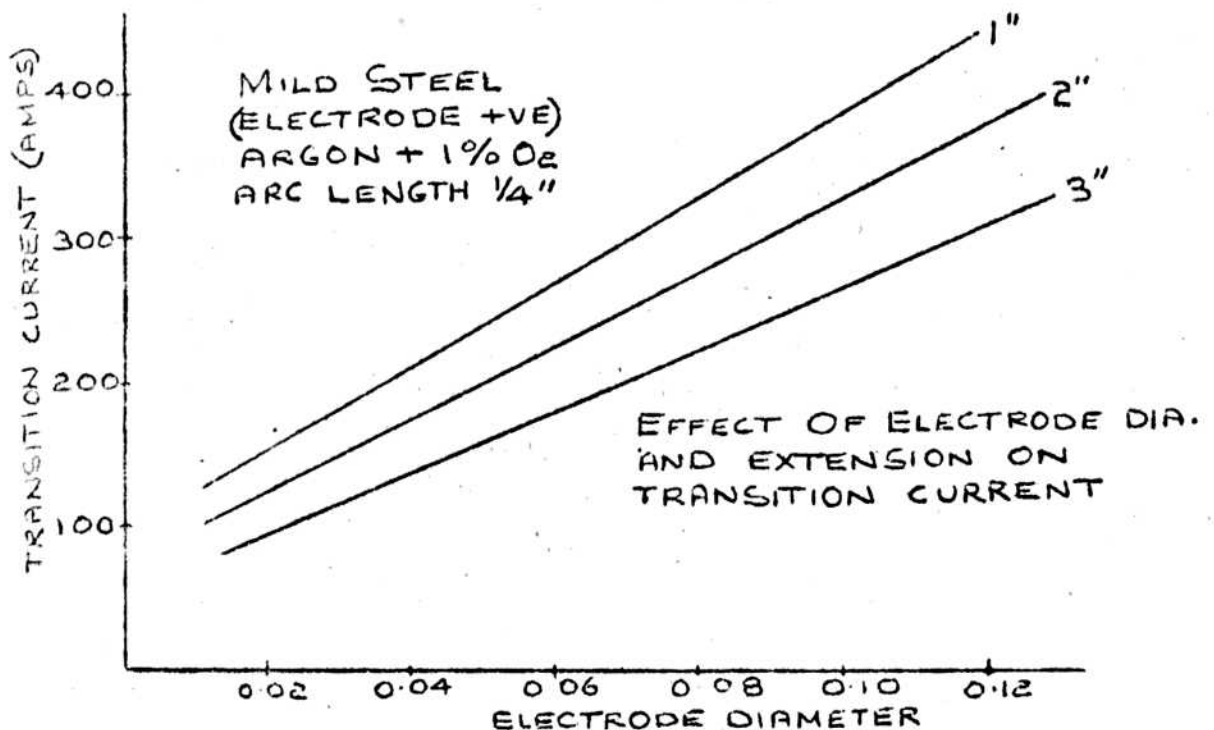
Metal Transfer



The curves (Sketch page 5) illustrate the mode of transfer of various wires in different atmospheres. In argon gas the arcs magnetic field produces a streaming action or anode jet which detaches small globules in rapid succession to produce what is known as SPRAY transfer. With dissociable gases such as N_2 and CO_2 the rapid detachment of small globules, if it occurs at all, does so only when high current densities are used. To achieve a rate of 50 drops/sec. requires about 500 amps with a 1/16 in. diameter steel wire in CO_2 but only 250 amps in argon.

Transition current

This is the current at which the mode of transfer changes from globular to spray and will depend on electrode composition, diameter, extension of the electrode (distance between point of current pick up and the arc) and arc atmosphere.

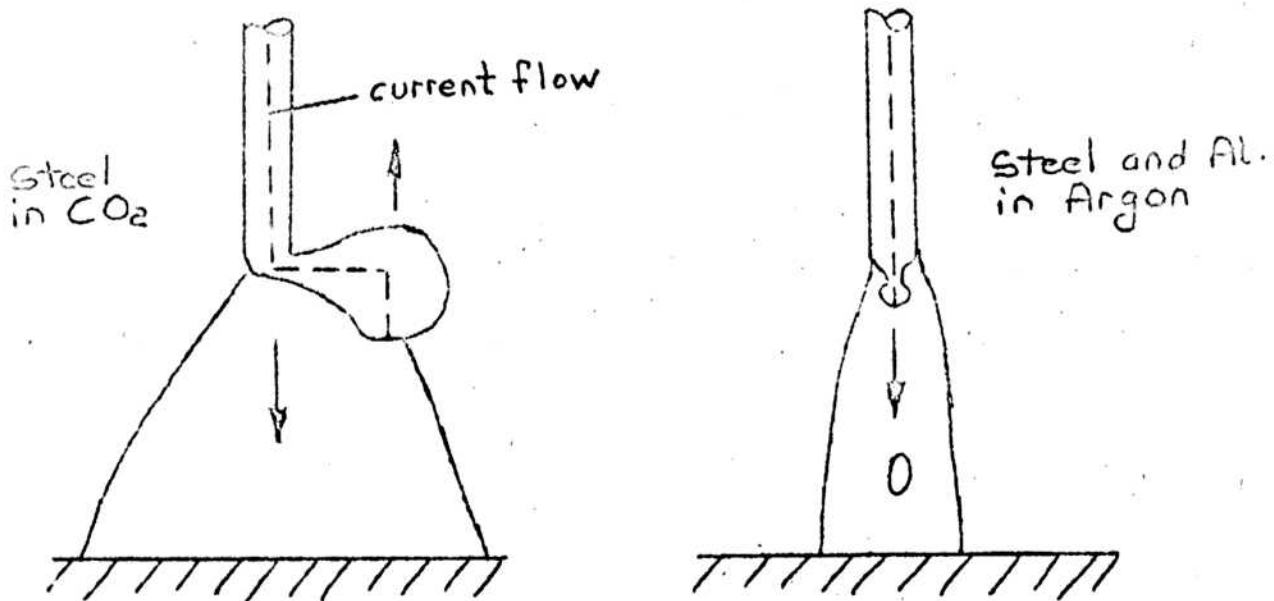


The maximum current which can be used is determined by the formation of a spatter-forming rotation of the arc and electrode tip, termed 'jet rotation'. Can be minimised by the use of large diameter electrodes and a short extension.

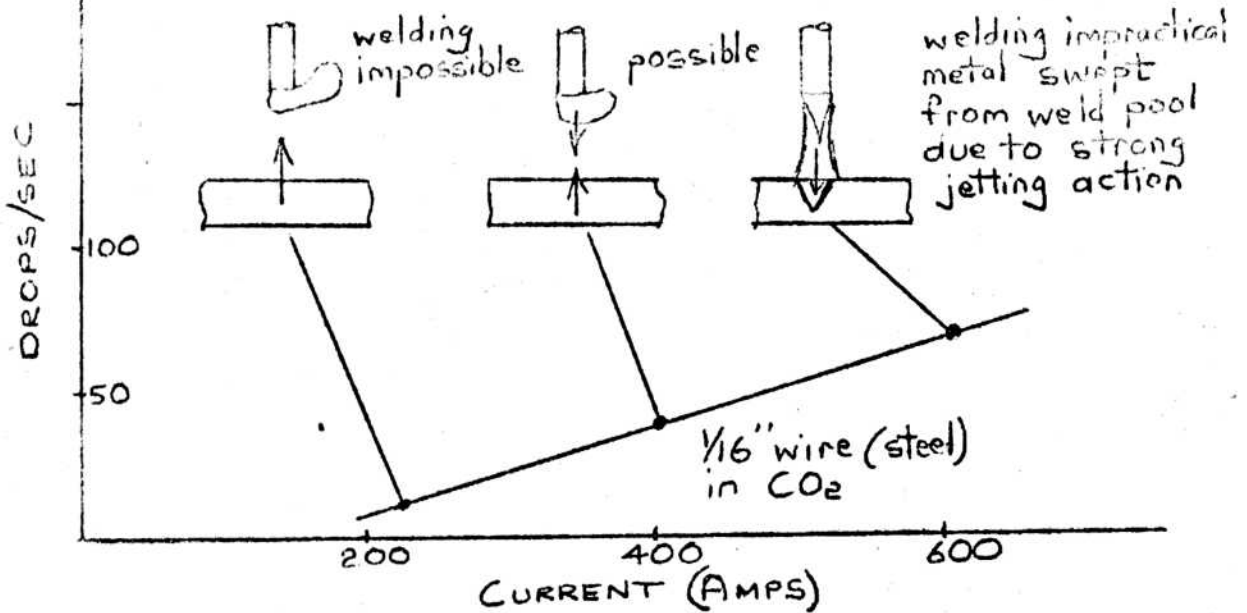
Electrode Negative

Not effective, arc unstable much spatter. Large globules are

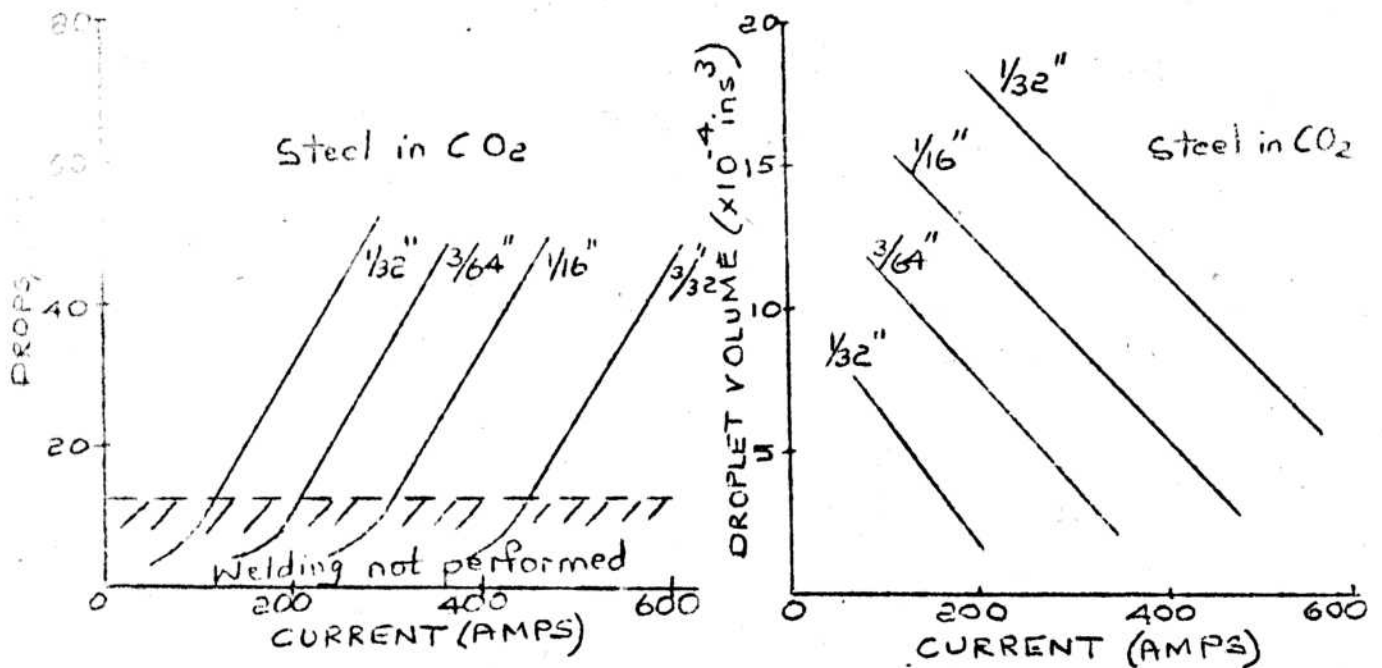
formed, these are propelled away from the workpiece. Appears to be due to a concentration of current on the cold cathode spot which is due to poor thermionic emission. Metal transfer in steel can be improved by the use of wash coatings on the electrode or, when using argon, the addition of a small amount of oxygen. Forms surface oxides which have better thermionic properties. Melting rate of electrode higher with electrode negative.



The sketches above illustrate typical plasma shapes obtained in argon and CO_2 . In argon the plasma surrounds the molten globule, electro magnetic compression produces axial transfer. In CO_2 repulsive force and the local interaction of compressive forces sets up a torque or motor effect. The magnitude of the current will determine the predominant force. At low currents the globules have been seen to move 'away' from the weld pool.



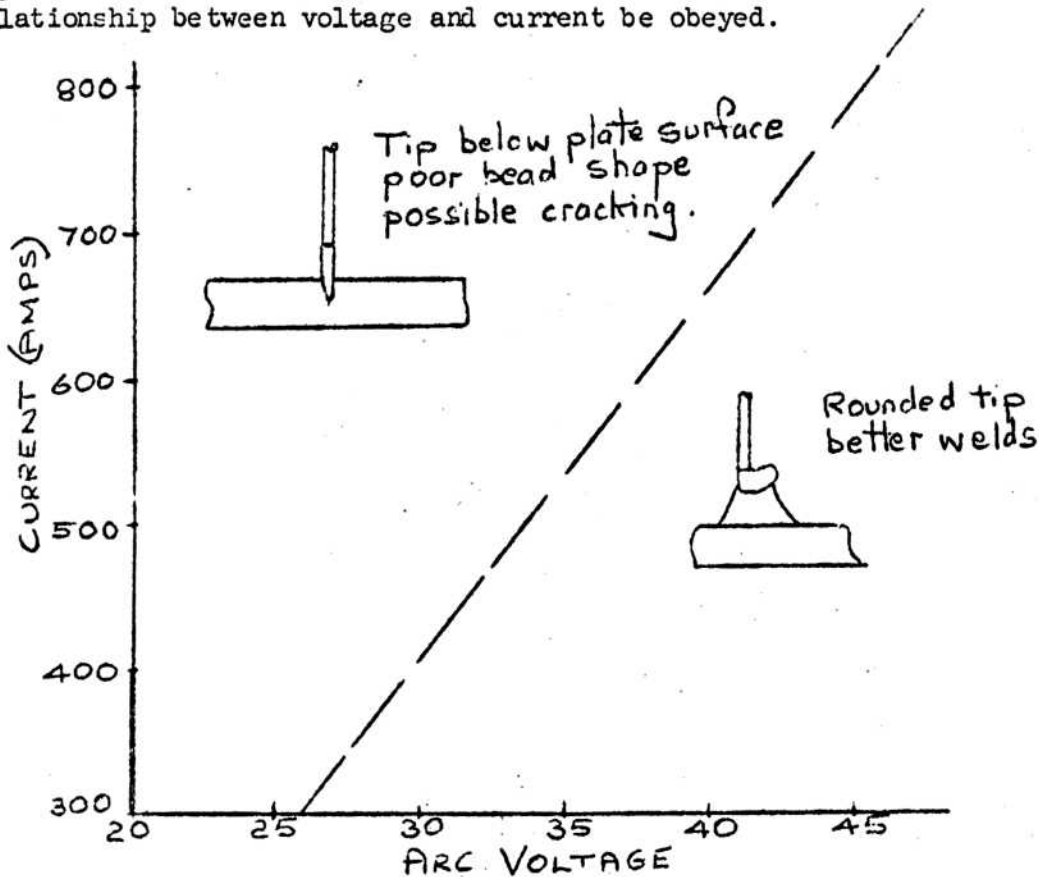
Effect of Wire Diameter on Drop Frequency and Volume



Free Flight or Spray Transfer in CO₂

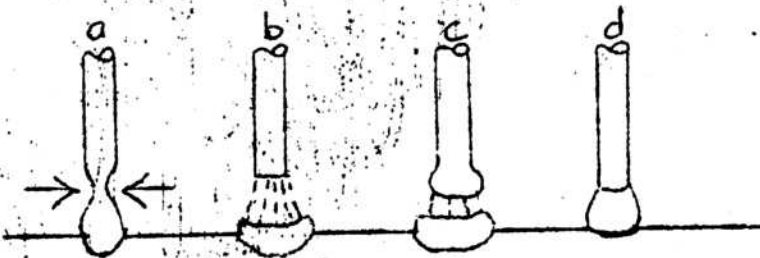
Spray transfer will produce maximum penetration which increases

approximately linearly with current. It is important that the relationship between voltage and current be obeyed.

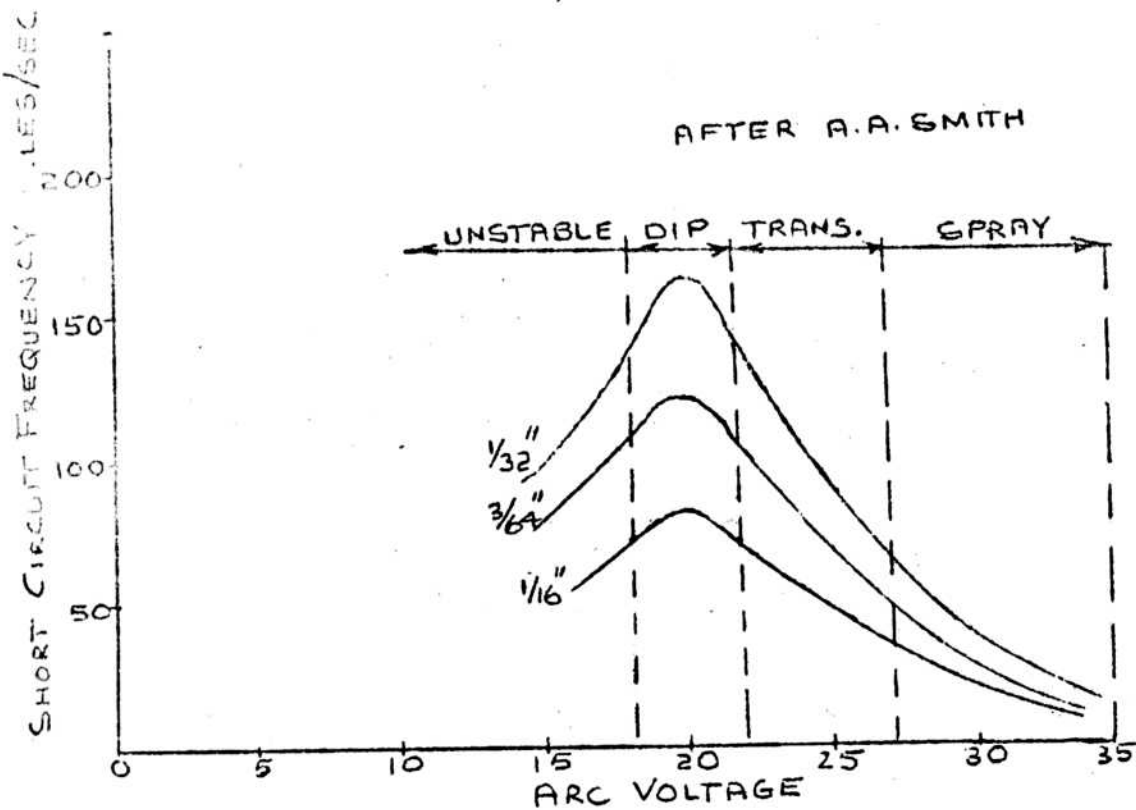


If the arc voltage too low penetration is increased at the expense of bead width (heat transfer most efficient when electrode tip below surface of plate). This produces a deep narrow fused zone which is susceptible to solidification cracking. Cracking can usually be avoided with a penetration depth to width ratio of not more than 1.2 to 1. Arc voltage can be adjusted to control arc characteristics up to 900 amps.

Short Circuiting or 'Dip Transfer'



Metal is transferred during contact between wire and work i.e. short circuiting conditions. In the sketch (page 9) at (a) wire in contact with work, voltage falls and there is a sharp increase in current. The magnetic pinch effect and surface tension detach molten globule. (b) Globule detached arc formed. Current falls, volts increase. (c) Molten globule forming. (d) Short circuit, cycle repeats.



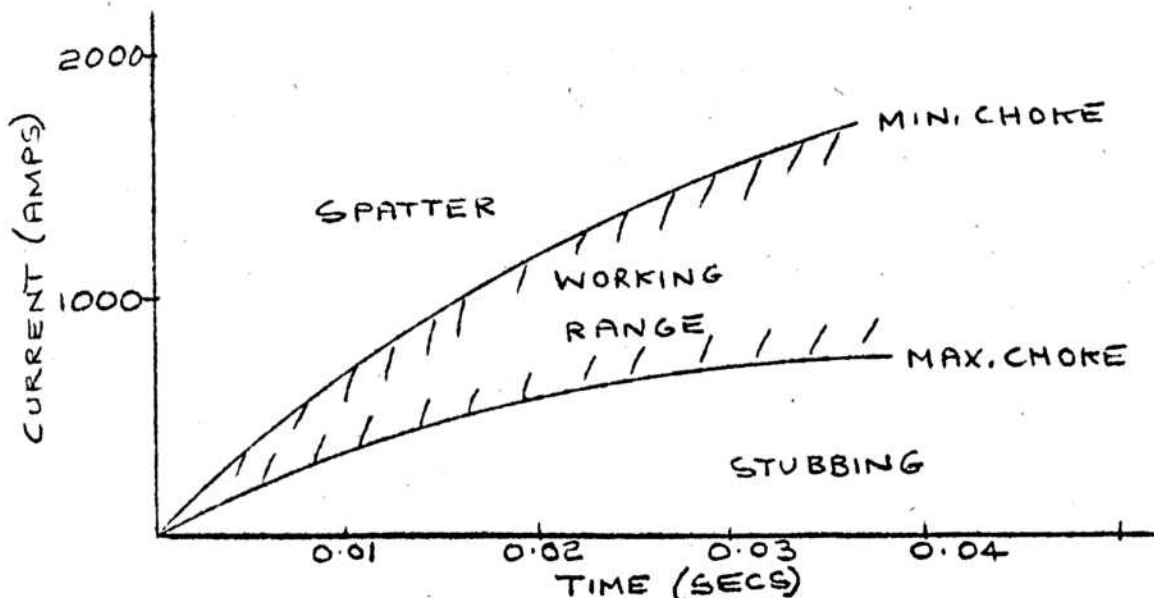
Sketch shows relationship between short circuiting frequency and arc voltage for three common wire sizes. At fairly high arc voltages (approx. 30V) few short circuits, spray type transfer. Low voltage (18-22V approx.) many short circuits dip transfer. Medium voltage- transition zone. Larger globules transferred during short circuiting conditions. This is often used for downhand welding at medium currents where penetration, similar to that obtained with spray is possible without spatter associated with non-axial droplet transfer.

The table below gives the operating ranges for the three main types of metal transfer in CO₂.

Mode of Transfer	Operating Range		Arc Type Application
	Arc Volts	Current	
Short Circuiting	16-22	40-190	Sheet in all pos. Plate in vertical and overhead positions
Semi-short Circuiting	24-28	200-300	Medium gauges downhand
Spray	28-40	200-500	Plate downhand

After A.A. Smith

Short circuiting metal transfer makes special demands on the power source. Spray transfer depends on the static output curves; for short circuiting dynamic conditions must be satisfied. When short circuiting occurs current must be supplied at the correct rate to enable melt off of the molten globule and re-establish the arc, e.g. 300 amps required in 0.005 secs for 3/64 in. wire. Too high a response will produce heavy current surges and an explosive effect during short circuiting resulting in high spatter loss. To obtain optimum welding conditions it is necessary to use a constant potential power source fitted with a 'tuned choke'. This consists of an iron cored heavy copper coil which can be made infinitely variable by using a rotary contact. With this it is possible to control the current surge during short circuiting.



	1/32 in	3/64 in	1/16 in
Wire Feed Rate in/min	200	100	70
Arc Voltage	18	19	20
Average Current	100	130	160
Response Rate kA/sec.	50-150	40-130	20-75

After A.A. Smith

Optimum Short Circuiting Arc Operating Ranges for 3 Wire Diameters.

The use of dip transfer techniques for the positional welding of steel plate has led to problems associated with lack of fusion. Heating of the workpiece is obtained during the 'arcing time' of the welding sequence. The use of 1/16 in. wire and little choke will produce quick melt off during short circuiting and provide maximum arcing time thus providing maximum heating of the parent metal. Lack of fusion however still occurs. Research into the problem has produced a new technique known as 'Pulsed Arc' welding.

Pulse Controlled Arcs

This is a new technique developed to give the control required for positional welding with free flight (spray type) transfer. The following advantages are claimed for the process.

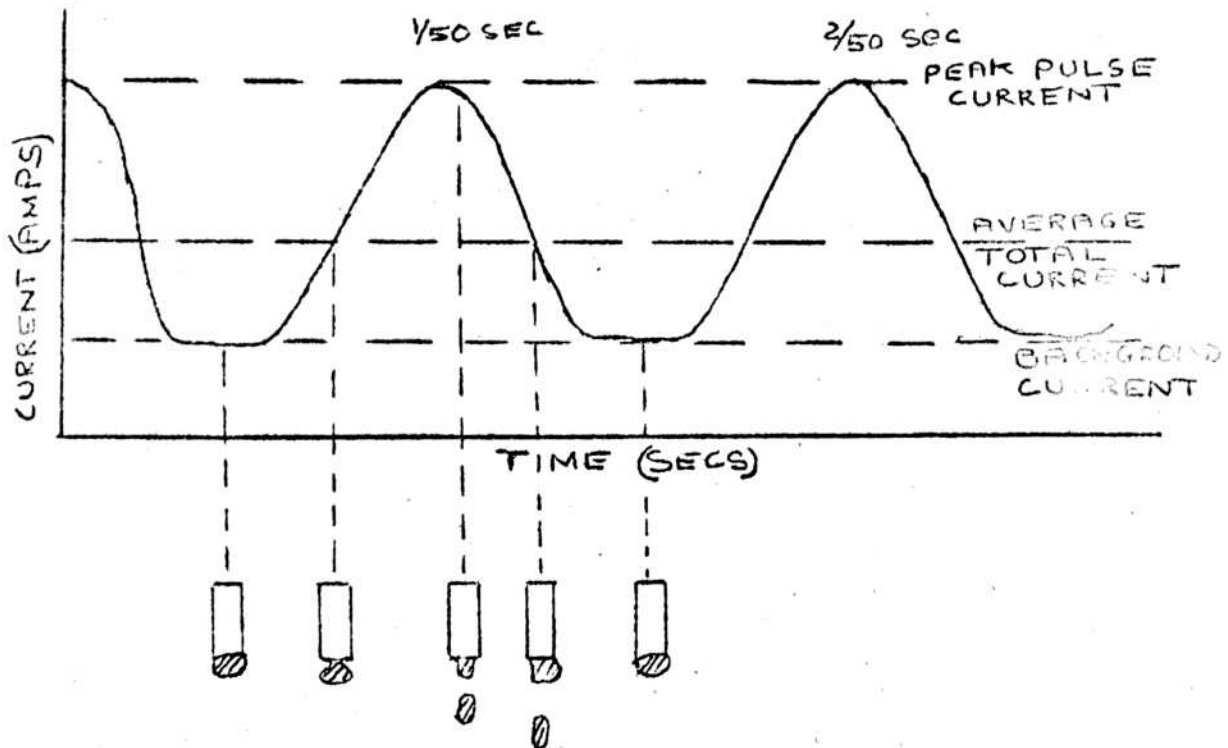
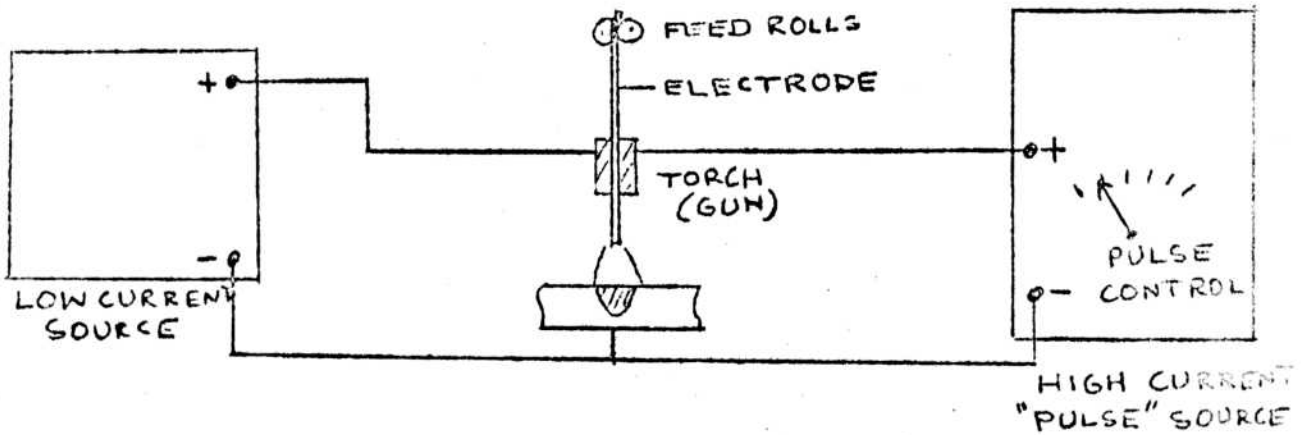
1. Complete spatter-free welding.
2. Exceptional regularity of weld finish.
3. Unusually constant penetration.
4. Ability to weld in all positions.
5. Higher ratio of heat input to metal deposition than with dip transfer.
6. Reduced weld metal carbon content than with CO₂ welding. (Argon or argon mixtures used).
7. Extended amperage range on all wire diameters.

Principle of Controlled Transfer

The forces necessary to detach and transfer the molten globule from the wire to the weld pool is proportional to the square of the current. With low current densities, large globules form and transfer is due mainly to gravity, high current densities provide high detachment forces and spray transfer is achieved. 'In pulsed arc welding the high current density is provided at suitable intervals to detach and transfer the molten globule which has been forming during a period of relatively low density current flow'.

Two D.C. power sources are used; one to supply the 'background' current

sufficient to maintain an ionized medium. The other provides high density current pulses to provide high detachment forces. The average total current will determine the burn off rate of the electrode.



Cycle of events in pulsed-arc welding

There is a minimum value of peak current required which is dependent of the average total current. By fixing the mean peak value for any given pulse frequency, variation in average total current can then be made by adjusting the background current. Too high a peak current will produce undercutting, too high a background current leads to globular transfer. (Molten globule builds up faster than pulses).

Pulse Frequency

The lower the current density the lower the pulse frequency required. With low frequencies, travel speed is restricted (wetting problems) and the 'flicker' may disturb the operator. For a given current density, the smaller the wire diameter, the higher the pulse frequency. Recent development work indicates that the use of 50 or 100 pulses/sec allow controlled transfer over a wide range of currents using 1/32 in., 3/64 in. and 1/16 in. wires.

Applications

Mild Steel

U preparation with no root gap.

Root gap necessary with Vee preparations.

Operating conditions for 1¹/₄ in. butt weld in vertical position. Double Vee preparation, 1/16 in. wire, 98/2% Argon-oxygen.

	<u>Root run</u>	<u>Intermediate</u>	<u>Capping</u>
Wire feed speed in/min	96	72	68
Average total welding current, amps.	185	155	140
Average arc voltage, V	20	21	20
Pulse frequency, cycles/sec.	50	50	50

This welding technique may be the answer to controlled penetration beads; results to date are encouraging. Best results obtained with Argon plus 1 to 5% oxygen.

Low Alloy Steels

Only a limited amount of work to date, but results indicate that the recovery of alloying elements is better than with CO₂ shielding.

Stainless Steel

CO₂ not really satisfactory because of carbon pick-up. No increase in carbon using controlled transfer with argon + 1% oxygen.

Aluminium

Conventional MIG spray transfer techniques are used for thin materials

but require thin wires (0.030 in. diam. and less) and spool on gun equipment. (Difficult to 'push' soft thin wires). Controlled transfer techniques will allow thicker wires to be used therefore less expensive equipment. Also, thicker wires decrease the surface area to volume ratio which will reduce hydrogen pick-up from surface films.

Operating conditions for a vertical butt weld in $\frac{1}{4}$ inch thick aluminium plate, single Vee preparation, 90 included angle, 1/16 in. wire, pure argon shield. Made in two passes.

Wire feed speed	- 100 in/min
Average total welding current	- 120 amps.
Average Arc voltage	- 21V
Pulse frequency	- 100 cycles/sec.
Welding speed	- 13 in/min.

Equipment for CO₂ welding

Power Source

Three basic types, all of which have D.C. output.

1. Motor generator, flat characteristic. Voltage 16 - 50V. Will supply up to 400 or 750 amps. Short circuiting current up to 1500 amps.

2. Constant Potential Transformer-Rectifier

Switched tapings on primary or secondary to alter turns ratio and give voltage control. Choke to alter current rise during short circuiting. Selenium and silicon (most recent) rectifiers used. Voltage range from about 14 to 42V. Short circuit current can be from 1,000 to 4,000 amps dependant on capacity of power source which is usually 200A, 400A, 600A or 850A.

3. Slope Controlled Transformer-Rectifier

Tapped secondary gives open circuit voltage and a magnetic amplifier gives fine voltage control and slope control. Some power sources rely on the reduced current rise during short circuiting obtained by the alteration of slope. This is satisfactory with 1/32 inch wires but for 1/16 in. wire a choke is necessary to prevent excessive rise in current and spatter loss.

4. Wire Feed Unit

A.C. or D.C. motor driven, 50 - 1,000 in/min. Speed controlled by variable speed motor or variable speed gear box. Turbines with valve to control air supply also used. Wire fed by rollers, knurled or plain, straightening rollers, located in advance of feed rolls, are necessary with hard wires. Roll drive control is usually electronic though mechanical methods are used.

Guns

Lightweight, air-cooled, up to 200 amps.

Water-cooled hand gun up to 400 amps.

A self contained 200 amp unit which has the wire drive motor in the gun butt and carries a 2 lb. reel of wire. Used for 'fine wire welding' (0.020 in. dia.).

Water-cooled automatic, up to about 600 amps.

All guns are designed to provide laminar gas flow. Wire feed and gas flow are controlled by a trigger switch.

Contact Tube

Provides current pick-up. Wear is inevitable and regular inspection is required. The point of current pick-up may wander resulting in unstable arc conditions and uneven penetration. Continued cleaning up not recommended. Regard as consumable and carry sufficient spares.

Ancillaries

Pressure Regulator

Necessary to reduce cylinder pressure. (300 - 1,000 lbs/in²) to a normal working pressure of 10 to 40 lbs/in².

Flow Meter

20 - 45 ft³/hr of gas required depending on nozzle diameter and ambient conditions.

Heater

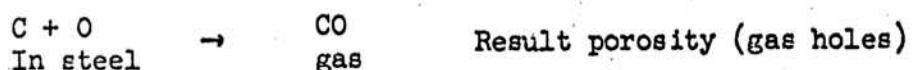
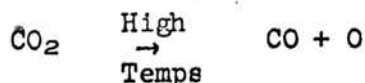
Used to prevent freezing of the regulator when the liquid CO₂ is changed to a gas. 'It does not dry the gas'.

WELDING WIRE FOR MILD STEEL

Must be smooth and drawn close tolerances (+0, -0.025 mm). Copper coated to improve current pick-up and extend shelf life. Correct temper (hardness) to ensure free running.

Composition

Special composition required to withstand the oxidizing nature of the arc atmosphere.



This is prevented by overkilling with silicon and manganese. Aluminium, titanium and zirconium are also used. The reaction of these deoxidizing elements produce small islands of slag on the surface of the weld.

Typical Composition of CO₂ Mild Steel Wire

	<u>Type 1</u>	<u>Type 2</u>
Carbon	0.12 max.	0.12 max.
Silicon	0.9 - 1.2	0.3 - 0.9
Manganese	0.9 - 1.6	0.9 - 1.6
Phosphorus	0.03 max.	0.03 max.
Sulphur	0.03 max.	0.03 max.
Copper	0.2 max.	0.2 max.
Aluminium	-	0.6

About 50% of the silicon and manganese may be lost in the arc. With a relatively slow rate of droplet transfer, reaction time between the globule and arc atmosphere is increased and can lead to porosity due to excessive loss of silicon. At least 0.3% silicon is required in the weld metal to avoid porosity. Silicon content of more than 1% can lead to hot cracking problems. Increasing the arc voltage from 30V to 45V with a 0.8% Si 1.4% Mn wire will reduce the silicon content of the weld metal from 0.45% to 0.16% and the manganese from 0.9% to 0.6% and produce porosity.

Welding Rimmed and Killed Steels

The production of rimming steel requires residual oxygen in the molten steel when teeming into ingot moulds. Killed steels are fully deoxidized. The table below indicates the effect of killed and rimmed steels on the recovery of silicon and manganese and subsequent weld quality.

	C	Si	Mn	Radiograph
Wire	0.12	0.84	1.58	-
Rimming Plate	0.18	0.03	0.54	-
Weld	0.13	0.02	0.62	Porosity
Killed Plate	0.18	0.16	1.11	-
Weld	0.12	0.34	1.2	Sound

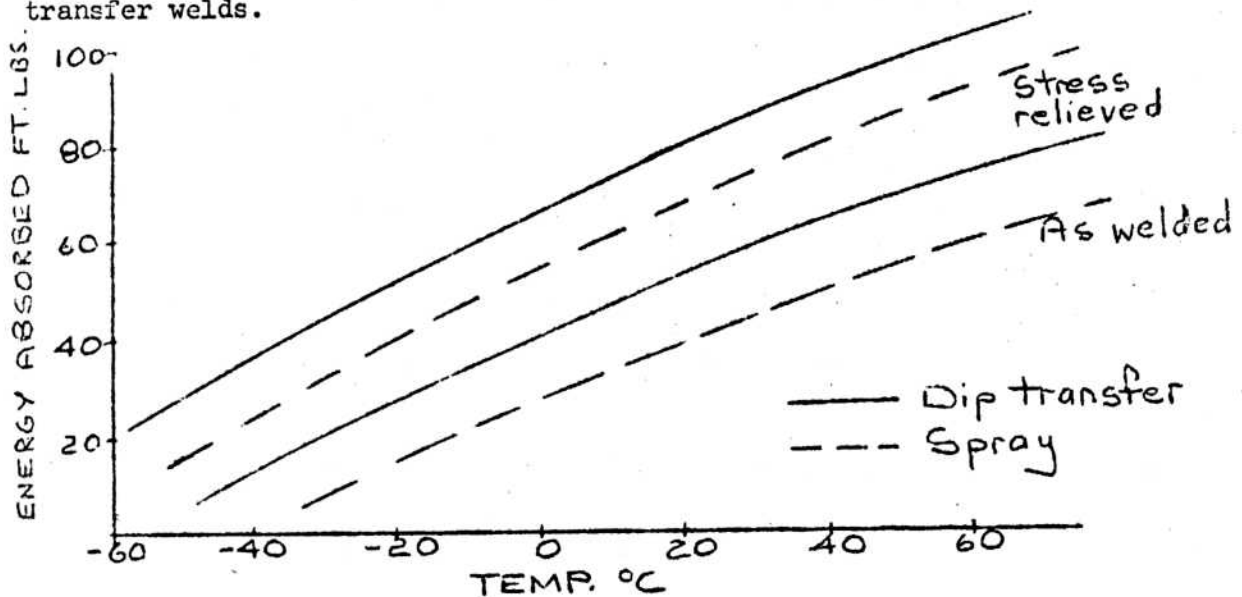
Mechanical Properties

Tensile strength can vary between 35 and 45 tons/sq.ins; it depends on weld metal composition and an accurate assessment can be obtained from the carbon equivalent of the weld metal.

$$U.T.S. = 33 (C. equiv.) + 26 \text{ tons/sq.in.}$$

$$\text{Where } (C. equiv.) = C + \frac{Si}{7} + \frac{Mn}{5} \%$$

Impact properties of the as deposited metal give a Charpy energy absorption of 15 ft lbs at about -30°C . This can be improved on, with silicon manganese wires, by stress relieving at 650°C , e.g. 15 ft lbs at -50°C . Dip transfer weld metal has slightly better impact properties than spray transfer welds.



	% C Si Mn Cu				Impact Props. ft.lbs at - 60 C	
					As Welded	Stress Relieved 650°C
Wire 1						
Copper Coated	0.21	1.04	1.46	0.41	-	-
Short Circuit	0.11	0.67	1.01	0.41	20	20
Spray	0.11	0.69	1.03	0.39	5	5
Wire 2	0.13	0.96	1.44	0.04	-	-
No Coating						
Short Circuit	0.12	0.69	1.12	0.04	22	30
Spray	0.13	0.71	1.14	0.04	10	30

Spray - 300 amps, 32V. 1/16 in. wire

Short Circuit - 150 amps. 20V. 1/16 in. wire.

Copper reduces impact properties at low temperatures. Uncoated wire is available for critical applications. Shelf life is limited.

CO₂ Shielding Gas

Available in the solid, liquid or gaseous form. Liquid CO₂ is the most popular for welding. Supplied in cylinders or bulk storage tanks (up to 15 tons capacity) used with a ring main system.

CO₂ 'Gas' Cylinders

Gaseous CO₂ is drawn off from the top of the cylinder, some liquid CO₂ evaporates to replace that removed. High discharge rates may result in freezing of the liquid CO₂. Discharge rates should not exceed 6 lb/hr. (48 cu. ft/hr) to prevent freezing. High moisture content in the last 25% of gas used.

CO₂ Syphon Cylinders

Plastic syphon tube extends to bottom of cylinder ensures that CO₂ is always drawn from liquid phase while liquid is present. Provides CO₂ with a relatively low moisture content at all times and this type is normally supplied for welding. An electrical heater is required to vaporise the CO₂ before it passes to the pressure reducing valve.

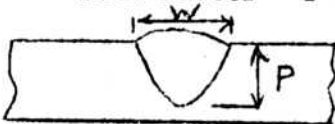
Gas Flow

The width of the shielding gas flow, its 'stiffness' to resist deflection by draughts and its smooth flow is determined by the gas flow rate and the diameter and length of the nozzle. The gas nozzle should be as long as possible to obtain streamline flow and best shielding characteristics. Spatter build up on the inside of the nozzle can lead to turbulence and nitrogen pickup.

Weld Preparations

No preparation required up to about $\frac{1}{4}$ in. Joint design important with thick plate to avoid hot cracking.

$$\text{Bead Factor} - F = \frac{P}{W}$$



P = depth of penetration

W = bead width

When F is greater than unity an unfavourable weld metal crystallization pattern results which can lead to cracking. The deep penetration characteristics of CO₂ welding can produce this condition.

