Further Developments in Consumable Guide Welding

By K. P. BENTLEY and E. O. LAWRANCE*

The development of consumable guide welding has considerably extended the potential field of application of the electroslag process. In this article the authors give practical information on the use of the process and describe methods devised at BWRA for making containing shoes and electrode guides.

The use of electroslag welding for thick steel has been limited in its field of application mainly to joints having a good fit-up and of comparatively simple geometry. The high cost and physical size of the equipment have restricted its use to work which can conveniently be brought to the machine in fabricating shops where there is a steady throughput of suitable work, such as the long seam welds in thick walled boiler drums or large pipes. With sliding shoes the conventional electroslag process demands a fairly high standard of fit-up and matching of plate thicknesses, otherwise slag spillage is liable to occur and weld beads of variable width can be formed.

With the advent of consumable guide welding, much cheaper and mechanically simpler equipment can be used and electroslag welding is now a proposition to be considered in wider fields such as ship building, machine frame manufacture and structural fabrication. The equipment is readily portable to work hitherto inaccessible for the large conventional machines and a much lower capital outlay is involved.

As fixed shoes are used, matching of the plates is less critical and joints of a geometrically complex nature become a possibility for electroslag welding This aspect of the process was described previously (*BWRA Bulletin*, 1965 6, 3, 61-65) and since then further developments in consumable guide technology have been made at BWRA. The present article aims to provide practical information of value to would-be users of the process who are contemplating its introduction to their fabricating shops.

THE PRINCIPLE OF CONSUMABLE GUIDE WELDING

The Consumable guide process is a single pass vertical welding technique which uses the same principle as a conventional electroslag welding machine, *i.e.* the generation of heat by the passage of a high current through a molten slag bath from a consumable electrode wire which melts off in the slag bath.

The wire is fed to the molten zone through a guide which is clamped rigidly in the weld gap and the guide is melted away as welding proceeds and the molten zone rises up the joint. A simple variable speed wire feed unit is mounted above the joint and power leads from the power source are clamped directly to the top of the guide. Two pairs of fixed cooling shoes which contain the molten zone are clamped to each side of the plates and these leapfrog each other up the joint as welding proceeds (see Fig. 1).

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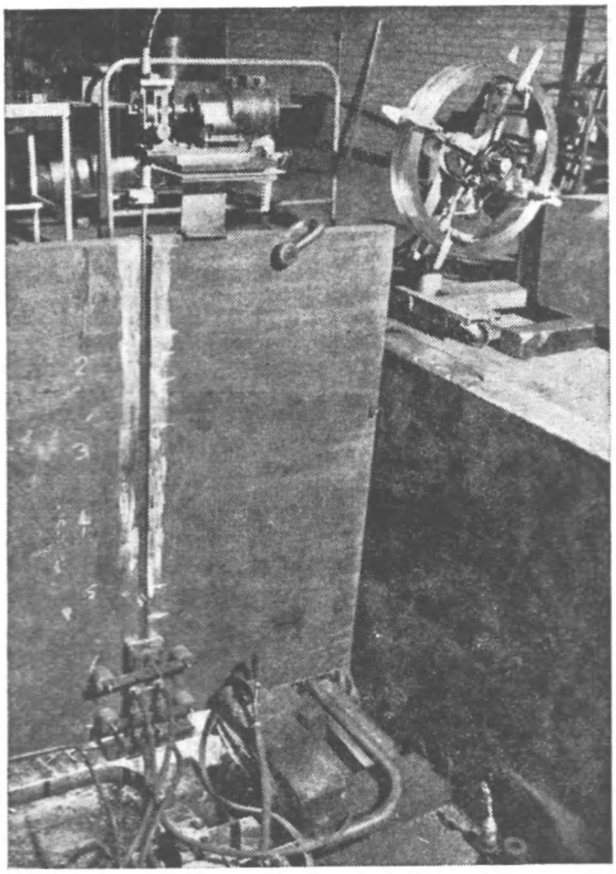


Fig. 1. The vertical butt joint being made in 2 in. thick material showing wire feed unit, consumable guide and cooling shoes.

EQUIPMENT

Power Sources

Flat and drooping output-characteristic power sources have both been used successfully for consumable guide welding. These have been a.c. transformers and d.c. transformer rectifiers and motor generators. A fairly flat characteristic having a slope of no more than about 4-6 V/100 A is preferred, since the welding conditions can be more easily set up with this type of power source, and the greatest flexibility was found with a d.c. motor generator giving 2V/100A. At the beginning of a weld when the molten zone is being established it is desirable to operate at about 50V so that arcing occurs. During steady running however about 35V is usual and the power source should be capable of delivering at least 600A andpreferably 800-900A for each electrode wire used.

Wire Feed Unit

Before equipment for consumable guide welding became available, it was generally found convenient to use a submerged arc welding machine for feeding the electrode wire. Alternatively a simple frame to hold the wire drive rolls can be set up above the weld gap with an electric motor mounted alongside to drive the rolls. It is often convenient to mount the entire wire feed unit on one of the plates being welded and, if this is done, care should be taken to insulate the motor from the plates which carry the earth return to the power source.

The size of the wire feed motor will depend on the power transmission system employed and the number of wires being fed. Furthermore as the welding current is determined by the wire feed speed, it should be possible to vary the speed of the motor. The speed control of the drive motor can be either mechanical or electrical and, since in the consumable guide process lightness of the equipment is an essential feature, an electrical control which can be remote from the wire feed unit is often preferable. In addition the welding conditions can be adjusted conveniently by the operator in the vicinity of the weld zone ; however, in some equipment the wire feed speed is controlled automatically by the welding voltage.

For $\frac{1}{8}$ in. diameter electrode wire for instance, an electrode wire feed speed range of 70-200 in/min should be adequate and the usual working condition would probably require about 120 in/min.

Cooling Shoes

In some applications it is possible to contain the weld zone by means of steel plates which become fused into the weld and are left there after welding to form part of the structure. Generally speaking a thickness of $\frac{1}{2}$ in. is sufficient to contain the weld, and observation of the glowing heated area on the shoe can give a useful indication of the depth of fusion being achieved.

Usually, however, a non-permanent type of shoe similar to that used in conventional electroslag welding is required and these are usually made of copper which is water cooled. Although it is possible to use water cooled steel shoes, it is difficult to ensure that the cooling is sufficiently uniform to avoid the formation of hot spots, especially at the edges of the weld bead, and fusion of the shoe is liable to occur. The cooling provided by the shoes must be efficient to avoid overheating of the weld metal or plate material and, if a constant width of penetration is to be achieved along the joint, the cooling must be uniform. This is not always possible if the plates are at all bent or warped since the shoes which are rigid will inevitably not fit very closely in some places and at these points an increased depth of penetration will be experienced. For this reason it is sometimes possible to get spillage of the slag between the cooling shoe and plate material, especially if the shoes are longer than about 8 in. One of the principal advantages of the consumable guide technique is that, because the shoes are static, this danger can easily be overcome by the application of ganister to the shoe-plate junction. Furthermore, surface wear of the shoes which is experienced in time with the conventional sliding shoe method does not occur and the need to reface the shoes periodically is avoided.

The shoes can be of solid copper with holes drilled for the water channels. The size of these holes is generally arranged so that the minimum wall thickness is $\frac{5}{16}$ in., but as no wear of the surface is likely to occur, this dimension can probably be less. Alternative methods have been used such as a copper faceplate to the back of which are brazed copper or steel tubes to carry the cooling water. Steel cooling tubes, however, have the disadvantage that excessive distortion is likely to occur owing to the differential expansion of the two metals.

To overcome this difficulty and at the same time to avoid the tedious drilling operation required for solid copper shoes, a simple method of fabricating shoes has been developed at BWRA. This consists of using a $\frac{1}{4}$ in. thick copper faceplate, to the back of which bolts are silver soldered. A light steel box in 16 swg material is made to fit on the back of this copper faceplate and a rubber gasket is used to make a watertight seal. Pieces of angle are resistance spot welded into the box to make water channels inside, and holes are drilled in the back of the box to take the bolts on the faceplate. Rubber washers are again used to ensure a watertight seal (see Fig. 2).

A water flow of 8 gallons/min through each shoe is normally used and no leakage has been experienced when operating on a closed circuit water supply at a water pressure of 50 lb/in^2. The water feed pipes should preferably be situated at the bottom end of the shoes, since there is a danger of a steam lock forming and stopping the flow of cooling water with top-fed shoes.

During welding a layer of slag freezes against the shoes. To accommodate this and thereby avoid undercutting at the bead surface, it is necessary to machine reinforcement grooves on the copper faceplates (see Fig. 3). These are usually $\frac{1}{8}$ in. deep with

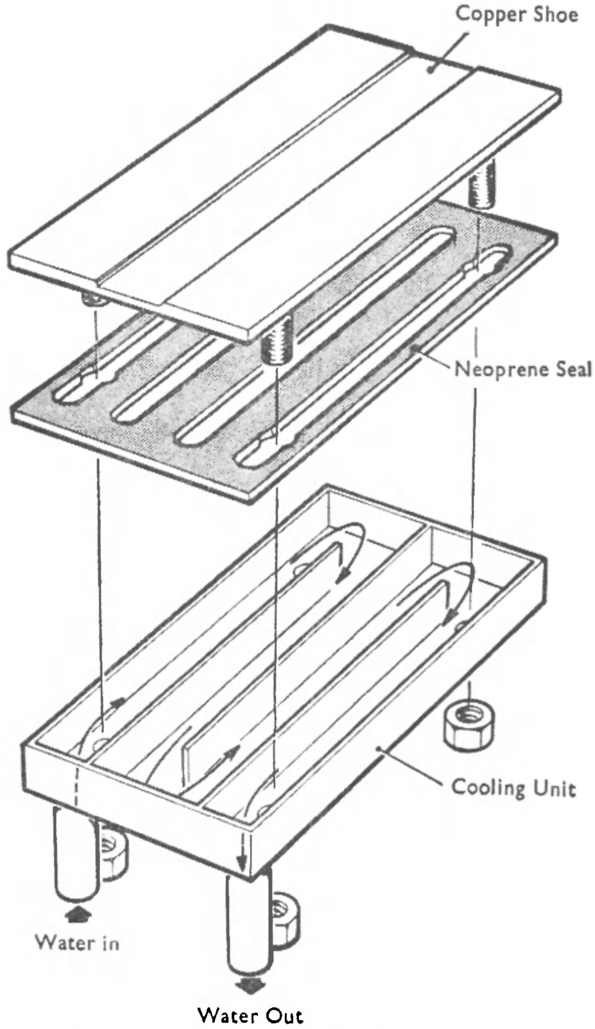


Fig. 2. The component parts of fabricated cooling shoes for consumable guide welding.

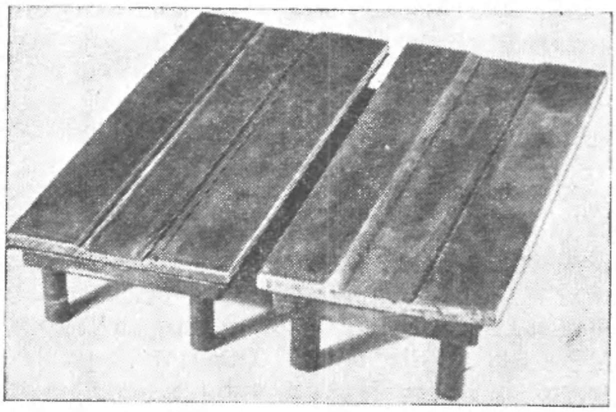


Fig. 3. A pair of cooling shoes showing reinforcement grooves machined on the surface.

rounded sides at the width of the weld gap. Work currently in progress aims at reducing the thickness of the copper faceplate to achieve a greater flexibility of the shoe which would be useful in the welding of bent plates or castings where intimate contact between the shoes and the materials to be welded is difficult to achieve.

The containing shoes can be held on by magnetic clamps or by any convenient mechanical means, but it is helpful if the shoes can be replaced and repositioned easily and quickly during welding.

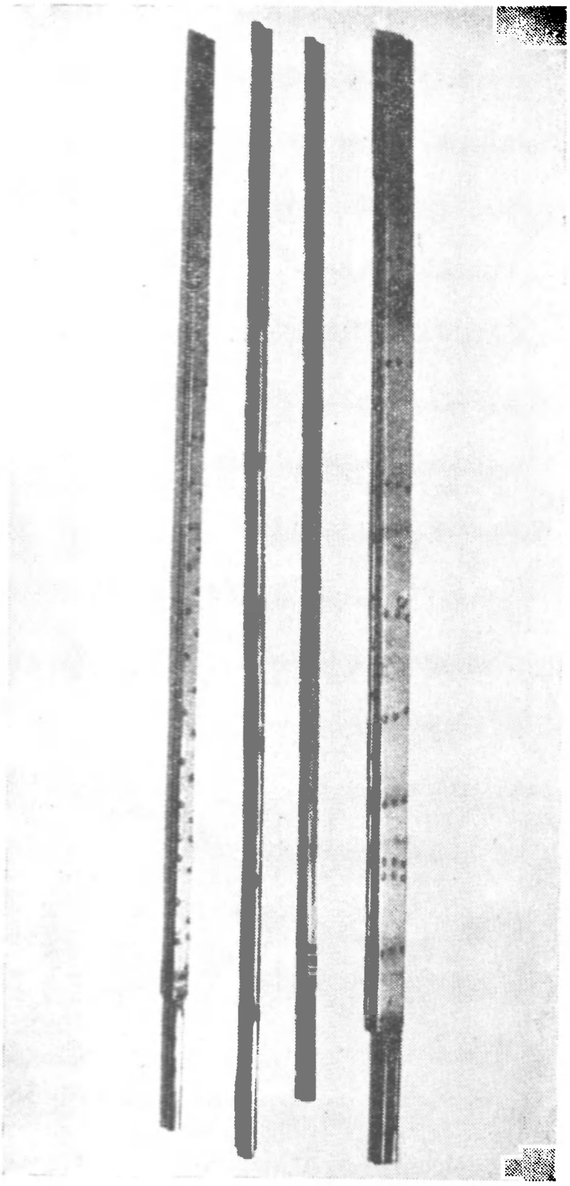


Fig. 4. A selection of fabricated and tubular consumable grids.

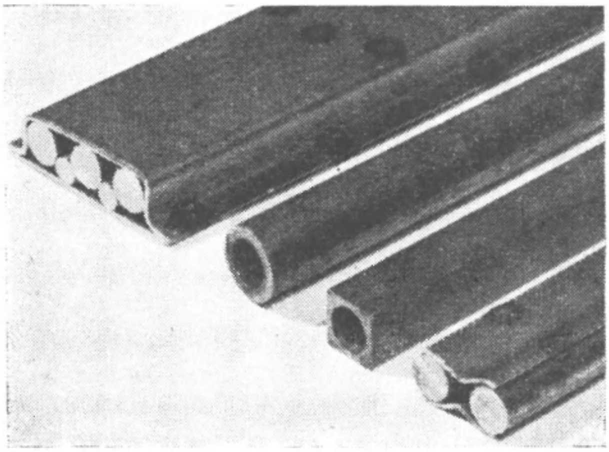


Fig. 5. Cross sections of consumable grids shown in fig. 4.

CONSUMABLES

Wire

In electroslag welding the environment of the molten metal pool is oxidising not only from the atmosphere above the molten slag layer, but also because the slag itself is rich in oxides.. As a result it is necessary to use an electrode wire containing deoxidising elements. Large quantities of silicon are best avoided since this element can reduce the toughness of the weld metal, and an electrode wire containing 2% manganese is commonly used. This can also take care of any excessive pick-up of sulphur from the parent materials. For higher strength steels a 2% Mn : ½% Mo wire is sometimes used and for the low alloy heat resisting steels containing chromium and molybdenum, wires of matching composition have been used successfully. Although losses to the slag of chromium and molybdenum occur, an equilibrium composition of the slag is quickly reached in the early stages of welding and thereafter a deposit of composition similar to that of the wire is obtained.

With single wire working, steel thicknesses up to 3 in. can be welded satisfactorily. Double wire feeding would be necessary for greater thicknesses up to about 5 in. and for still greater thicknesses three wires would be required.

Consumable Electrode Guides

The consumable guide usually contributes only a small volume percentage to the weld metal and its precise composition is therefore not very critical. However, it is essential that it should not contain excessive quantities of such elements as carbon, sulphur, phosphorus or silicon which might impair the properties of the weld metal and in particular its toughness. Most of the BWRA work has been done with guides of En3B material.

The essential mechanical feature of a consumable guide is rigidity. During welding the guide can get quite hot (about 350°C) over a considerable part of its length and, if it is too flexible, it may distort far enough to touch the sides of the weld gap. The current then short circuits and welding is stopped in the molten zone. To stop this happening various methods have been employed such as clamping the guides from an external frame, or inserting wedges of insulating materials such as glass, wood or wads of silica cloth which are not harmful to the slag bath if they should happen to fall down the gap. A particularly successful method used at BWRA is to wrap the guide in silica cloth.

The guides themselves need not be of any particular cross section, and several different shapes have been used (see Fig. 4). Both round and square thick walled tubes have given good results on steel plates up to 2 in. thick, the latter giving a higher guide to weld gap area ratio. However, it has been found very convenient to fabricate guides from rods and thin sheet, and these have been particularly useful for welding materials up to $5\frac{1}{2}$ in. thick. A trough $2\frac{1}{2}$ in. wide is bent from 16 s.w.g. sheet and rods of $\frac{3}{8}$ and $\frac{1}{4}$ in. dia. are placed inside as shown in Fig. 5, so that when the guide is closed with a second flat steel sheet the whole structure is sprung tight. Final closure is made by resistance spot welding, metal arc, CO_2 shielded or oxy-acetylene welding. The number of rods added can be varied to accommodate any number of electrode wires. Those shown in Fig. 5 are suitable for single and double wire working. A particular advantage of the fabricated guides is that thin rods of very high alloy content, such as Nimonic alloys or stainless can easily be incorporated into the fabrication giving low alloy steel weld metals. In this way, weld metals have been deposited having strengths to overmatch quenched and tempered steels with yield stresses greater than 40 tons/in^2.

Flux

In electroslag welding the flux used must have certain special properties. The variation of electrical conductivity with temperature is particularly important since the resistance of the slag determines the production of heat. The variation of viscosity with temperature is also important since, if the slag is too fluid, it will cut too far into the plates on each side giving excessively deep penetration and may also flow out between the shoes. If it is too viscous, it will freeze too readily against the shoes giving severe undercut and may eventually push the shoes away from the weld joint. The type of flux most commonly used is a mixture of oxides, principally manganese silicate with additions of CaF_2, Al_2O_3, CaO, FeO and MgO. Fluxes richer in lime are generally recommended for the welding of cast iron and austenitic materials but a stable welding condition is more easily maintained with the manganese silicate type. As the electrical characteristics of fluxes vary with their composition, often considerably, different fluxes require slightly different operating conditions. Fabricators who use electroslag fluxes produced by more than one manufacturer should be prepared, if necessary, to make slight alterations to the welding conditions when changes of flux are made and also sometimes between batches of the same flux. The necessary adjustment to the heat input is often most easily accomplished by varying the voltage, 2 or 3 V usually being enough.

OPERATION OF THE PROCESS

Setting Up

No special edge preparation of the plates to be welded is required for consumable guide welding. Square flame cut edges can be used quite satisfactorily, though it is important to avoid very sudden changes of weld gap since this can lead to lack of fusion difficulties. Provided the plate edge is fairly smooth, however, no further treatment is required.

When starting the electroslag process it is some little time before the molten zone is properly established and the slag begins to be an effective source of heat. Consequently, full fusion is not obtained initially and for this reason it is necessary to attach run-on blocks of sufficient length for the hot molten bath to be formed. Similarly, run-off blocks are attached at the top of the weld so that the slag layer is clear of the plate edges when welding ceases.

The Gap Size

The size of the gap between the plates is an important variable. It should be set at the minimum distance compatible with avoiding short circuiting of the guides against the side walls. This will minimise the volume of wire required and also permit a faster speed of welding or rate of rise of the molten zone.

For guides $\frac{5}{8}$ in. wide the following gap sizes have been found to be most suitable :

$\frac{7}{8}$ in. for 1 in. plate
1 in. for $1\frac{1}{2}$ in. plate
$1\frac{1}{8}$ in.—$1\frac{1}{4}$ in. for 2 in. plate

If the gap is excessive, welding will be slow and it will be more difficult to obtain full fusion on each side. Dilution from the plate, however, is less with a wider gap and this may be an advantage when welding materials such as medium carbon steels.

It should also be remembered that the gap will close at the top during welding as the completed weld lower down cools. However, this does not usually amount to more than $\frac{1}{8}$ in. in welds up to three feet long and $\frac{1}{4}$ in. is thought to be sufficient in welds greater than 12 ft in length.

Starting and Setting the Conditions

To start the weld, a small ball of wire wool is placed under the electrode wire tip which protrudes from the end of the consumable guide. The guide is usually situated about 2 in. from the bottom surface of the run-on block. An alternative method is to mix iron powder with the flux at the start. This provides a conducting path for the current in the early stages when the slag is still an effective insulator. At the start of welding a high voltage (usually about 45 V) should be used. This will cause arcing and conditions will be very erratic. It is, however, possible to start welding with quite low voltages, and with a d.c. flat characteristic power source welds have been started at less than 35 V.

Current is kept low at the start of the weld since this limits the quantity of cold metal being fed into the hot zone. The slag only becomes an effective source of heat above about 1,000°C. It is important to ensure a good supply of flux in the early stages and the initial arcing tendency found with the high voltage condition is eventually smothered by additions of dry flux.

It is better to have too deep rather than too shallow a slag bath and the operating depth is normally about $1\frac{1}{2}$ in. This can be tested quite easily by probing the molten zone with a piece of electrode wire and observing the length of solidified slag on the withdrawn wire.

When the molten pool is thoroughly established the voltage can be lowered, usually at the power source, to give the desired width of penetration for the particular gap size and type of flux being used. For most of the manganese silicate fluxes commonly used this will be about 35 V for the gap sizes quoted above. Experience will tell which is the correct value of voltage to adopt and by carefully observing the slag bath during welding the extent to which fusion is being achieved on each side of the weld can be judged by the rate at which the slag flows round the pool.

If the voltage is too low, inadequate penetration and possibly lack of fusion may result and if it is too high, the dilution will be excessive and the hot welding condition may impair mechanical properties of the joint and also make slag detachment after welding difficult.

It is important to keep the guide situated at the centre of the weld gap in order to ensure that an equal depth of fusion is obtained on both sides of the weld. At the same time, the curvature imparted to the wire by its spool may persist until the wire emerges from the guide and this can sometimes cause deeper penetration on one side of the joint. This can be corrected by fitting an efficient wire straightener or as a last resort moving the guide off-centre.

The welding current is controlled by the wire feed speed, higher speeds drawing greater currents from the power source. A good rule is to operate with 600—650 A per electrode wire and it is useful to have an independent control of the wire feed speed. Clearly the speed of welding is linked with the wire feed speed and with the welding conditions quoted previously for single wire working. welding speeds would be about 8 ft/hr for 1 in. thick material ; 5 ft/hr for $1\frac{1}{2}$ in. thick material and 3 ft/hr. for 2 in. and upwards. Greater speeds can be achieved by raising the guide-to-gap area ratio or increasing the number of electrode wires, and corresponding improvements in the heat affected zone impact properities can be expected. However, if the speed is excessive, cracking of the weld metal at the centre line can occur owing to the type of solidification pattern in the molten pool. This tendency is aggravated if the carbon or sulphur contents (or worse both) are high and, if the restraint on the joint is excessively high, weld metal having moderate levels of these elements has been known to crack. However, for the welding speeds quoted, cracking would not be expected in butt joints held at the top by a small strongback, for weld metal compositions with less than 0.2% carbon, 0.04%s ulphur and 0.8% manganese. It must be emphasised, however, that these figures are purely speculative and are based largely on reported data.

During consumable guide welding it will be noticed that quite large fluctuations of current and voltage are liable to occur. This is due to the way in which the guide melts off into the molten pool. When the surface of the slag bath touches the guide, surface tension draws the hot slag some way up the guide, which then melts back rapidly (see Fig. 6). This continues for some seconds until about $\frac{1}{8}$ to $\frac{1}{4}$ in. of the guide has been melted and surface tension can no longer support the culumn of hot slag which thereupon falls back into the pool leaving a gap of about $\frac{1}{4}$ in. between the slag bath surface and the end of the guide. The electrode wire is easily visible passing across this gap (see Fig. 7), and the molten slag level gradually rises until it again touches the end of the guide, and the process is repeated.

When the guide is actually melting away, current rises sharply and the voltage falls by an amount depending on the output characteristic of the power source. The shape of the guide also determines the periodicity and magnitude of the voltage fluctuations, since surface tension can hold the slag to a round guide for much longer than to a flat fabricated guide. With a $\frac{5}{8}$ in. dia. round tube and a power source with a slope of about 6 V/100 A, the voltage sometimes varied by as much as 10V. This occurred about every 15 sec. and the melting time was about 5 seconds.

When the top of the weld is reached, power is switched off and the wire feed stopped. If possible, the electrode wire should be withdrawn before it freezes into the cooling slag bath. Because the solidified slag is very hard and often difficult to remove from the weld gap, one of the shoes should be removed as quickly as possible when welding has stopped to allow the slag to pour out while it is still fluid.

Properties of Consumable Guide Welds

The mechanical properties and microstructures of welds made by the consumable guide process are generally very similar to those of conventional electro-slag welds.

Weld metal is characteristically clean and free from large slag inclusions and provided a correct and fairly stable welding condition has been maintained, no fusion defects should be present and a good weld profile can be expected.

The composition and mechanical properties of the weld metal can be varied easily by making alloy-rich additions to the consumable guides. This can be particularly useful when deposits are required having compositions for which there are no commercially available electrode wires.

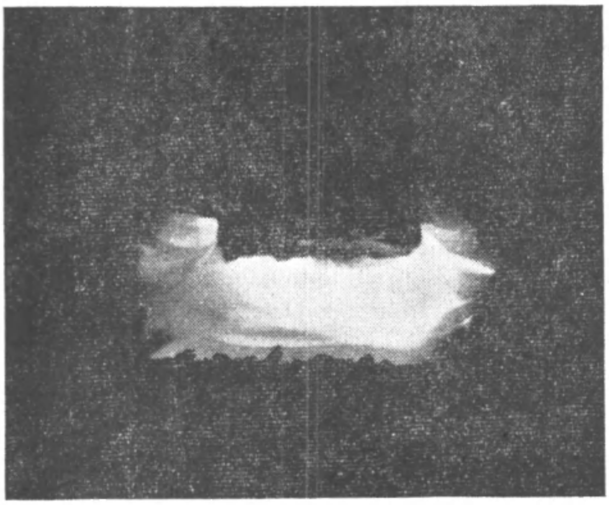


Fig. 6. The consumable guide melting into the slag.

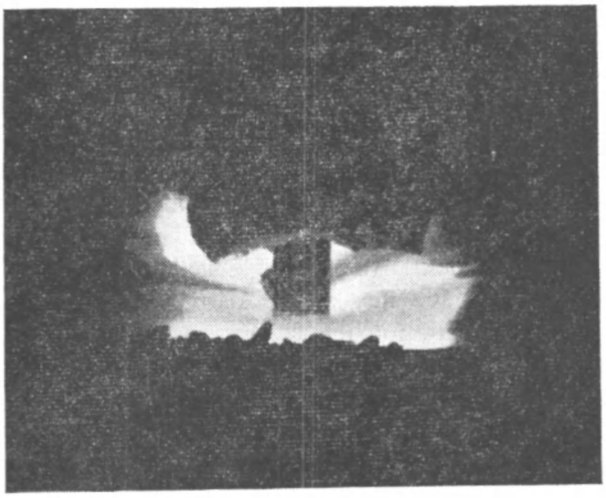


Fig. 7. Electrode wire passing from the consumable guide into the slag bath with no melting of the guide.

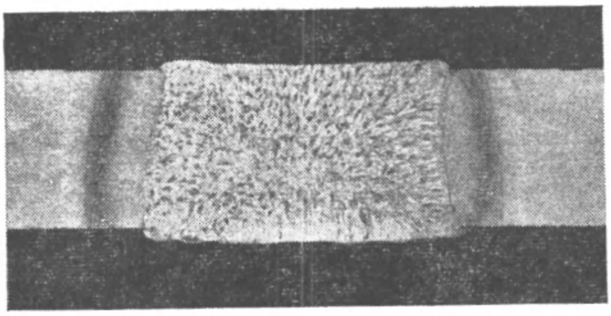


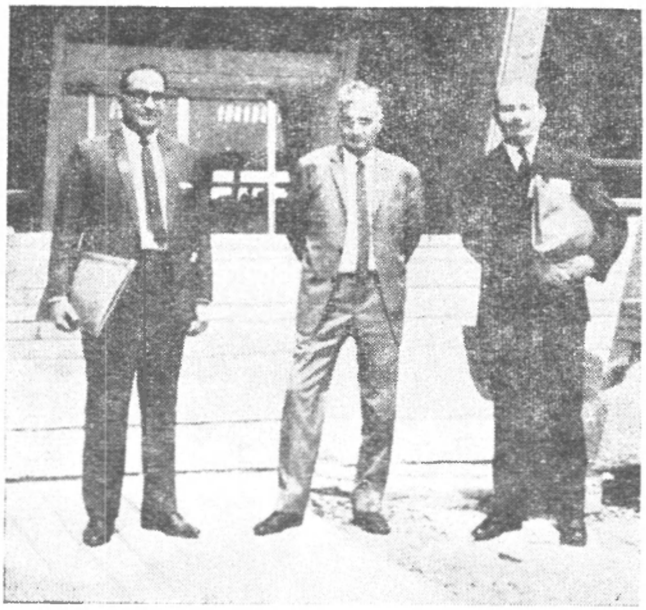
Fig. 8. Typical appearance of a high speed consumable guide weld.

A characteristic feature of electroslag welding is the slow heating and cooling cycle experienced by the heat affected zone, and it is common to find a region of low notch ductility adjacent to the fusion boundary where excessive grain growth and possibly burning of the steel have occurred. A post weld normalising treatment is therefore very often specified to correct this loss of toughness, especially in pressure vessel and boiler drum construction.

For many steel compositions and in many applications, the embrittlement may not be important, but increasing the speed of welding and thereby shortening the thermal cycle in the heat affected zone can be expected to improve the toughness of electroslag welds in this region.

By using the consumable guide technique, faster welding speeds become possible as the ratio of the guide area to the weld gap area is increased. Improvements in the toughness of the zone immediately adjacent to the fusion boundary of welds in 1 in. thick material have been measured with faster welding speeds achieved in this way, and microstructures have been considerably refined (see Fig. 8). At speeds of 5 and 13 ft./hr for instance, the room temperature energy absorption values were 15 and 35 ft. lb. respectively. At 19 ft./hr however, the toughness improved still further to 45 ft. lb.

Although it is on the thinner sections such as this that welding speeds can be raised most readily by this method, some advantages should also be gained on material of greater thicknesses. It is this aspect of the consumable guide process which is believed to be one of its most important features, since welds in a wider range of steel compositions should become acceptable for many more and perhaps quite critical applications without the necessity for post weld heat treatment. Further work on these lines is now in progress aimed at expanding the field of application of the process.



A delegation from The Indian Institute of Welding attended the Annual Assembly of International Institute of Welding held in Japan from 12th to 19th July 1969. The members of the delegation were (from left to right) Mr J K Ahluwalia, Mr I T Mirchandani and Mr K Hartley, President, The Indian Institute of Welding.