National Cooperative Highway Research Program

RESEARCH RESULTS DIGEST

DIGEST 74 - JUNE 1975

Electroslag Weldments in Bridges

An NCHRP state-of-the-art digest derived from an interim report on NCHRP Project 10-10, "Acceptance Criteria for Electroslag Weldments in Bridges," by W. P. Benter, Jr., U. S. Steel Research, Monroeville, Pennsylvania.

THE PROBLEM AND ITS SOLUTION

Electroslag welding is an economical process for the fabrication of steels, but is not widely used in bridges because of uncertainties regarding the notch toughness of the resulting weldment. For this reason NCHRP Project 10-10 was undertaken at the U. S. Steel Research Laboratory. The over-all objective of the project is to develop and verify acceptance criteria for the use of electroslag welds in bridges. Research is being conducted in two phases.

The specific objective of Phase I, scheduled for completion by mid-1976, is to define necessary acceptance specifications based on a full review of the literature and on tests of laboratory specimens from full-size weldments. Phase II will consist of fabricating and dynamically testing full-size girders to determine the fatigue and fracture behavior of electroslag butt-welds in girder flanges in accordance with the detailed work plan submitted and approved as required under Phase I.

Accomplishment of Phase I objectives is to include the following tasks:

- Task 1. A thorough review of domestic and foreign literature on the subject.
- Task 2. Preparation of a state-of-the-art report on electroslag welding.
- Task 3. Testing of laboratory specimens taken from full-scale welds. (The program is very specific concerning the type of materials, joints, and tests.)

Task 4. Development of tentative acceptance tests and criteria for electroslag butt-welds based on the results of previous tasks.

Task 5. Submission of report summarizing the findings of the Phase I work and containing a detailed work plan for the conduct of Phase II.

Although Digests are normally intended to be very brief, the purpose of this issue is to provide early and wide circulation of the entire state-of-the-art report prepared pursuant to Task 2 inasmuch as the project will not conclude until 1976.

FINDINGS

Electroslag welding is defined as "a welding process wherein coalescence is produced by molten slag which melts the filler metal and the surfaces of the work to be welded. The weld pool is shielded by the slag, which moves along the full cross section of the joint as welding progresses. The conductive slag is maintained molten by its resistance to electric current passing between the electrode and the work *(1)*. Welding is done in the vertical or near-vertical position, and joints are generally accomplished in a single pass regardless of the thickness to be joined.

Russian scientists from the Paton Institute of Electric Welding in Kiev are generally given credit for development of the process as we know it today and development of the necessary machines and techniques in the early 1950's *(2)*. By 1959 the process was well developed and thoroughly described by the Russians *(3)*. Related work at the Bratislava Institute of Welding in Czechoslovakia was made available to engineers in Belgium, and thus to the rest of the western world *(4)*. The first electroslag unit was introduced in the United States in 1959. One of the first reported applications of electroslag welding in bridge construction was in 1965 *(5)*. Initial acceptance, as with many new welding processes, was slow; however, its use for buildings and similar structures is increasing rapidly. Its use in bridges is still limited.

The process is ideally suited for welding heavy plates that can be positioned in the vertical or near-vertical position, with the process becoming increasingly more economical as plate thickness increases. The most common use appears to be for plate thicknesses in the range 1 to 8 in. (25 to 200 mm). Equipment is commercially available for butt-welding plates as thin as 1/2 in. *(6,7)* (12 mm) and up to 36 in. *(8)* (91 cm). Special multiwire units can be designed for even thicker sections *(9)*.

Electroslag welding offers a number of advantages and disadvantages compared with submerged arc, shielded metal-arc, and flux cored arc welding for butt- and tee-joints of the type used in bridge and building construction. Some of these are listed in the sections that follow.

Advantages

1. The electroslag process, once started, is completely continuous (100 percent operating time). The weld is completed in one pass; therefore, there is only one setup and no need for interpass cleaning or repositioning of material or parts.

2. Extremely high deposition rates of 35 to 45 lb (16 to 20 kg) per hour per electrode are achievable.

3. Welding-material savings result because of no stub or spatter losses, and flux consumption is only about 5 percent of deposited-metal weight.

4. Joint preparation is minimized. Mill edges and square oxygen-cut edges are normally employed. Minor gouges and cutting irregularities can be tolerated.

5. Smooth, predetermined contours are produced on the weld reinforcement. Postweld cleaning is minimal.

6. High-quality, sound weld deposits are produced. The weld metal stays molten longer, allowing gases to escape and nonmetallic inclusions to float to the slag above the weld pool.

7. Weld chemical composition can be controlled precisely by adjusting welding consumables and parameters.

8. Because of the symmetry of most vertical welds, there is no angular distortion in the horizontal plane. There is minimum distortion in the vertical plane, which can be easily controlled.

9. Preheat is generally not required.

10. Electroslag welding is the fastest welding process for large, thick joints.

11. The process provides good operator comfort and ease of operator training.

For the foregoing reasons, electroslag welding is a very attractive process for making large welds in building and bridge construction as well for other applications requiring large heavy welds, and can result in sizable reductions in fabricating costs. The advantages are partly counteracted by process and metallurgical disadvantages.

Process Disadvantages

1. All welds must be made in a vertical or near-vertical position. (Deviations from vertical as much as 45 degrees, or $\pi/4$ rad, have been reported.)

2. Unless welding parameters are properly controlled, centerline cracking can occur because of unfavorable dendrite orientation. (This point is discussed in detail later.)

3. If the welding process is discontinued for any reason, restarting will generally result in a major defect that requires repair.

Metallurgical Disadvantages

The very high heat input of the process results in a protracted thermal cycle with very slow solidification and cooling rates. These have the following metallurgical effects:

1. The grains in the weld metal are large and columnar. They are oriented horizontally at the weld edges and turn to a vertical orientation at the center.

2. The weld heat-affected zone (HAZ) is extremely large and much of the HAZ is coarse-grained.

The effects of the metallurgical characteristics, particularly the coarse grain size of the weld metal and the HAZ, have raised questions regarding the suitability of electroslag weldments for certain applications and the need for, or advantages of, heat treatment after welding to refine the grain structure. These questions have generated a number of studies, many of which are described in this report.

Principles of Operation

There are a number of variations of the electroslag process; however, all have common characteristics. The process is initiated in a sump at the bottom of the joint. This sump is later removed and discarded, or at least is never considered (for structural purposes) a part of the finished joint. The electroslag weld is initiated by striking an electric arc beneath a layer of granular welding flux, like conventional submerged arc welding. Steel wool or iron powder is often used to aid in starting the arc. When a sufficient volume of hot molten flux forms, the arc action stops and the current passes from the electrode to the work piece through the electrically conductive slag. At this point, the welding progresses quietly and spatter ceases. The resistance heating of the molten slag is sufficient to melt the electrode and the edges of the work piece. The temperature of the slag is in the vicinity of 3500 F (1925 C) *(2)*. The liquid metal from the electrode and the molten edges of the work piece passes through the slag and forms a liquid-metal pool below the slag bath, which then solidifies. In this manner, the weld progresses vertically upward and is usually terminated in a run-off tab above the structural joint. The end of the weld often contains crater cracks and shrinkage voids that are removed when the run-off tab is removed.

Investigators, by study of the electrical characteristics *(10)* and by direct studies using radiography *(11)* and visual observation (quartz windows) *(12)*, found that the metal transfer from the electrode to the bath is in the form of discrete droplets and is accompanied by considerable turbulence. (Unpublished data indicate that the droplet size is reduced when metal-powder-core wires are used instead of solid wires *(13)*. This latter investigation also indicated that considerable gas is given off during welding *(12)*.

Conventional Wire Process

The conventional wire process is often referred to as the "basic" or "traditional" electroslag process. In this process the filler metal is added by feeding only the welding wire (electrode) into the molten-slag pool. The wire is fed through one or more nonconsumable guide tubes into the molten slag. The process is shown schematically in Figure 1. Retaining shoes are used to contain the molten-weld pool. Normally these are made of copper and are water-cooled. During welding the wire feed, guide tubes, and welding shoes move vertically upward to maintain an essentially constant stick-out (guide-tube--weld-pool distance). Vertical movement can be controlled automatically by heat sensors in the retaining shoes or by manual control by the operator. Flux is added in granular form to maintain a molten slag depth of approximately 1 to 2 in. (25 to 50 mm).

In this process the retaining shoe on the side where the wire or wires enter always slides up with the guide tubes, is made of copper, and is water-cooled. The shoe on the other side can take any of the following forms:

1. A sliding water-cooled copper shoe similar to the feed-side shoe.
2. A fixed copper shoe over the entire length of the joint. ("Leap-frogging" of shorter shoes may be used on longer joints.) This shoe is normally water-cooled; however, a more massive solid copper shoe can be used.

3. A solid-steel backing (not very common). This acts as a backing strip and becomes an integral part of the weld.

The normal joint geometry is a square butt joint with a gap of 1 to 1½ in. (25 to 35 mm). For thin plates (1 in. and under) a single-vee joint geometry is often used *(14)*. This reduces the amount of filler metal required and increases welding speed at the expense of added joint preparation. Deviations from a square butt joint and use of retaining shoes with different heat-extraction rates on the opposite side of the weldment can contribute to horizontal distortion.

The wire guides can be stationary (only move vertically) or can be oscillated across the joint. Oscillation increases the width that can be welded with each electrode. With oscillation, one wire is used for welding butt joints up to 5 in. (125 mm) thick, two wires for up to 11 in. (275 mm) thick, and three wires for up to 20 in. (500 mm) thick *(9)*. Units can be designed for welding joints more than 20 in. thick.

Consumable-Guide Process

Consumable-guide (consumable nozzle) electroslag welding is a modified version of the conventional wire process. The principal difference is that the consumable-guide method contains no moving parts other than the wire feed and the oscillating guide tubes, and thus the equipment is simpler (no vertically moving retaining shoes and welding head). The consumable-guide method uses a metal tube extending the full length of the weld to guide the welding wire and carry the welding current to the conductive slag. The guide tube melts in the weld pool as the pool rises, thus supplying additional filler metal. The process is shown schematically in Figure 2.

The consumable guides are steel tubes from 3/8 to 5/8 in. (9.5 to 16 mm) in outside diameter, with a center hole large enough to pass 3/32- or 1/8- in. diameter (2.4 or 3.2 mm) welding wire. Tubes 1/2 and 5/8 in. in diameter are the most popular. The tubes may be either bare or flux-coated. The flux coating, consisting of electroslag-welding flux plus binder, electrically insulates the tube from the side walls and provides most of the flux requirement for the slag after the weld is started. When bare tubes are used for long welds, ceramic insulators are usually used to prevent arcing to the side walls or retaining shoes. Specially shaped guide tubes with "wings" or flanges of plate steel attached to one or more tubes are also available. These can eliminate the need for oscillation in some situations and can be used for complex joints.

Electrically, the conventional and consumable-guide methods are very similar. The electrode wire transfers welding current from the end of the consumable guide to the molten slag, producing resistance heating of the slag bath as in the conventional wire process. As welding proceeds, the weld pool rises and the guide tube melts because of its proximity to the molten-slag bath. The welding wire extends for a short distance into the slag and is melted into droplets which transfer to the weld pool.

One or more tubes can be used with or without oscillation. Joint length is limited by guide-tube length and is further reduced when oscillation is used because of difficulty in controlling position of the guide-tube ends. One equipment manufacturer provides data for joints up to 20 ft (6 m) long with non-oscillating guide tubes and up to 10 ft (3 m) long with oscillating guide tubes

(8). Case histories of welds up to 12 ft (3.6 m) made without oscillation are described in the literature *(6,8)*.

For butt-welds the joint geometry is almost exclusively a square-groove joint with a gap of 3/4 to 1½ in. (19 to 38 mm). Fixed, water-cooled copper retaining shoes are generally used; however, compressed-air-cooled copper shoes, solid-copper shoes, and steel backup plates are also used.

Plate-Electrode Method

This is another variation in the electroslag process wherein a steel plate is substituted for the welding wire *(2)*. It offers certain economic advantages for short, thick joints; however, to date it has not been used much in the U.S. for the type of welds in building and bridge construction.

Electroslag-Process Comparison

For most electroslag welds of the type used in building and bridge construction, both the conventional and consumable-guide variations of the process are equally suitable and the choice is often a matter of equipment availability. From an operating standpoint, each type has special advantages. The sliding shoes of the conventional process often make joint fit-up very convenient-- no need for special fixturing or strongbacks to hold the shoes in place. Also, the length of the joint is restricted only by the length of the power cables. However, the sliding shoes are less tolerant of surface irregularities, variations in thickness, and alignment of the plates being welded. Slag leakage and shoe jamming can occur.

The conventional process also requires open access to one side of the joint. For this reason the consumable-guide method is often used for joints with restricted access. Parrot et al. *(14)* give examples taken from the shipbuilding industry which show how each of the processes can be used to the best advantage.

Equipment

Equipment for both conventional and consumable-guide electroslag welding is commercially available from several domestic and a number of foreign suppliers. Many of the auxiliary components are the same as those used for the submerged arc and flux-cored arc processes. In addition to differences between the hardware necessary to produce submerged arc and electroslag welds there are differences in the power supplies.

Power supplies for electroslag welding are of the constant-potential type and can be either a-c or d-c. In the U.S. most electroslag welding is done with direct-current machines with reverse polarity (electrode positive). In one study *(15)* this procedure (DCRP) was reported to produce the best weld-metal toughness, as measured by Charpy V-notch tests. The type of current and polarity can affect a number of variables, such as the amount of base-plate melting and the grain orientation. (It would appear that these effects should be studied in detail with particular attention directed toward optimizing the mechanical properties of electroslag weld metals and heat-affected zones in structural steels in the as-welded condition.)

Electroslag-welding power supplies are designed for high open-circuit and high welding voltages and are often equipped with special features to protect them during overloads and short circuits. This latter feature is particularly important when bare guide tubes are used. Typical power-supply ratings are 700 to 1,000 amp at 50 to 55 v with 100 percent duty cycle *(8,9)*.

Materials

Base Materials

Electroslag welding can and is being used for a wide variety of carbon, high-strength low-alloy, and stainless steels and certain nonferrous metals. The AWS Structural Welding Code recognizes electroslag welding as a suitable process for welding ASTM A36, A242, A441, A572 Grades 42 to 65, and A588 structural steels in all thicknesses with welds to be used in the as-welded condition *(16)*. It specifically prohibits use of the process on quenched and tempered steels. The ASME Boiler and Pressure Vessel Code approves the process for butt joints in ferritic steels and certain stainless steels (TP304, 304L, 316, and 316L) for use under Section I (Power Boilers) and Section III (Nuclear Power Plant Components) *(17)*. Of course, both AWS and ASME require detailed procedure qualifications and weld-inspection procedures.

There is general agreement that electroslag weldments in steels are suitable for all types of ferritic and martensitic steels provided they are given a heat treatment to refine the structure in both the weld metal and the weld heat-affected zone. Disagreement exists regarding the conditions under which electroslag weldments may be suitable for use in the as-welded or stress-relieved conditions. Many users are proceeding cautiously in this area *(18,19,20)*. Considerable work is in progress to establish the properties of the as-deposited weld metals and the as-welded heat-affected zones; this work is described in more detail later. In bridge applications the components are generally not heat treated after welding; therefore, martensitic steels are not being electroslag welded and are specifically prohibited by the Structural Welding Code.

Electrodes

The wires used for electroslag welding are similar to those used for submerted arc, gas metal-arc, and flux-cored arc welding. In practice, many of the wires developed for these older processes are being used for electroslag welding. Solid, flux-cored, metal-powder-cored, and braided wires are being used; however, solid wire has found more extensive application. Filler-metal manufacturers are developing wire compositions specifically for electroslag welding and have introduced some commercially.

The chemical compositions of the wires are designed to contain the desired alloying and deoxidizing elements to achieve the required strength, toughness, and soundness in the weld after taking into account that the weld metal will contain 30 to 50 percent base metal as a result of dilution. For carbon and high-strength low-alloy structural steels that are intended for use without postweld heat treatment, the electrodes generally contain less carbon than the base metal. To obtain the desired strength, alloying elements such as manganese, silicon, and nickel are increased.

For higher-carbon and alloy steels that are heat-treated after welding, it is necessary that the composition of the weld metal be compatible with that of the base metal with respect to heat-treating response and mechanical properties after heat treatment. For these applications, there is a trend to use electrodes matching or nearly matching in chemical composition.

At present there are no specification in the U.S. for electroslag consumables. The filler metals are qualified under specifications for other processes and are confirmed by the electroslag procedure qualifications for the structure being welded. The Filler Metal Committee of the American Welding Society has an active subcommittee that is developing specifications for filler metals and related materials for electroslag and electrogas welding. The International Institute of Welding (IIW), under their subcommission J of Commission XII, is also developing a classification of wires and fluxes for electroslag welding. Reports of the IIW progress indicate that they are considering qualification either on the basis of all-weld-metal deposits (deposited in copper molds) or on the basis of actual joints *(21,22)*.

Fluxes

The fluxes for electroslag welding are generally proprietary mixtures. The flux performs very critical functions even though the quantity used is relatively small (approximately 5 percent by weight of the filler metal deposited). Because most of the heat in the process is generated by resistance of the molten flux to the flow of electric current, its electric resistivity must be high enough to generate a sufficient amount of heat for melting purposes, yet it must not be so high that arcing from the electrode to the weld pool will occur. The slag viscosity must also be controlled because fluidity is needed for uniform transfer of heat, cleansing, and wetting of the surfaces, but a very fluid or low-melting slag may leak from the joint between the retaining shoes and the work piece. The molten slag must be stable over a range of temperatures from below the melting point of the plate being welded to at least 3600 F (1980 C) and must have relatively uniform resistivity and viscosity over this temperature range. The flux must be reasonably inert to the materials being welded, and preferably should be refining in nature. The flux used can have a major effect on the notch toughness of the weld deposits *(23)*. This is an area where additional work may be fruitful.

Fluxes for electroslag welding of steel are usually combinations of complex oxides of silicon, manganese, titanium, calcium, magnesium, iron, and aluminum, with additions of calcium fluoride to control viscosity and resistivity. Typical compositions are available in the literature (for example, 35% SiO_2, 40% MnO, 5% Al_2O_3, 7% CaO, 6% CaF_2, 3% FeO, 3% TiO_2, and 1% NaO) *(2,23,24)*.

Consumable Guide Tubes

For electroslag welding of steel by the consumable-guide-tube method, the guide tubes are usually mild steel. AISI 1018 steel is used by at least one supplier *(8)*. Guide tubes could be used to supply alloying elements, but there is no evidence that this is being done in production. When coated guide tubes are used, the covering ususally has a composition similar to that of the flux with an added binder. Because the flux in the guide-tube coating supplies most of the flux requirement for the weld, this method of adding flux results in the amount being carefully controlled. At least one manufacturer supplies guide tubes with different coating thicknesses (amount of flux per unit length), depending on whether single or multiple wires are used *(25)*. Single wires require more flux.

Process Variables

Joint Geometry

For butt joints, square-groove joint geometries are usually employed. (Single V-joints are sometimes used on thin plates welded by the conventional electroslag process.) Transition joints are made by chamfering one or both sides of the thicker member to the appropriate slope. The weld can be a butt joint as thick as the thinnest member, or the weld can be tapered to include part or all of the transition slope. Special retaining shoes are available for transition joints.

Tee-welds are also a common application of electroslag welding. With the consumable-guide method they are usually made in one pass with one or two electrodes, depending on thickness. Special shoes are available or can be fabricated with the desired fillet contour. In this type of weld it is sometimes necessary to place an additional cooling shoe on the "cross" portion of the tee to prevent burn-through. In conventional electroslag welding, tee-welds can be made in two passes with air carbon-arc gouging and grinding between the passes.

Many other types of joints can also be produced with special shoes. The process has also been used for overlays and built-up sections, and special setups can be used for circumferential welds.

Thermal Cycle

Probably the most significant difference between electroslag and the other arc-welding processes (shielded metal-arc, submerged arc, gas metal-arc, and flux-cored arc) is the extremely high heat input of the electroslag welding process. The heat input is more than an order of magnitude greater than the highest of the other welding processes. (An exception is the electrogas process, which is similar to the electroslag process with respect to heat input, and accordingly the metallurgical effects are similar.) Typical heat inputs for the electroslag processes are 2,000,000 to 3,000,000 joules per inch (80,000 to 120,000 joules per mm) per electrode without oscillation (with oscillation the heat input is even higher), whereas heat inputs for the other processes are typically 45,000 to 100,000 joules per inch (1,000 to 3,000 joules per mm) per electrode. As a result, the sizes of the molten weld metal, the slag pool, and the HAZ are much larger, the solidification rate of the weld is much slower, and the cooling rate of the weld metal and the HAZ is much slower in electroslag welding than in the other welding processes. In addition, with the single-pass electroslag weld there are no metallurgical effects of subsequent weld passes as in the other processes (no grain refinement or tempering, for example). These thermal differences have a major effect on the structure and properties of welds. Typical thermal cycles during electroslag welding are available in the literature *(3,8,26,27)*. Typical welds in heavy plates will show a red color, being above 1,200 F (650 C), for 15 min after welding, which is a good illustration of the very slow cooling rate of the process *(8)*.

Solidification Pattern

The thermal cycle during welding controls the solidification pattern. The molten pool in electroslag welding is similar in shape to a bowl. The heat is supplied at the top and is extracted from the sides and the bottom. Heat extraction is greatest on the sides in the region contacted by the retaining shoes and the relatively cool base metal, and is somewhat less from the solidified weld metal at the bottom. Solidification starts at the sides of the weld as dendritic growth and large elongated grains grow into the weld pool. The initial orientation is almost perpendicular to the sides and the grains curve upward toward the center, which is the last region to freeze. In a properly made weld, the grain orientation at the center approaches a vertical orientation and the grains meet at the center in an acute angle. This is discussed in more detail in the following section on "Form Factor." A typical horizontal and vertical cross section of a weld is shown in Figure 3. The coarse columnar grains may progress all the way to the center of the weld, or a finer columnar structure may form near the weld center. Both the thermal pattern and the weld-metal chemical composition can control the relative extent of each zone. Increased carbon and manganese in the weld metal increase the extent of the coarse columnar-grained region, and high metal temperature and slow cooling rates decrease the extent of the coarse columnar-grained region *(4)*. Vertical cross sections are required to characterize the weld-metal grain structure. On horizontal sections a fine equiaxed structure often appears near the center of the weld *(28)*. This is usually the fine columnar structure; however, it can be coarse columnar with the grains oriented vertically.

In general, a coarse-grained structure is considered detrimental because the coarse structure reduces ductility and fracture toughness; however, in the electroslag process there are compensating factors. The slow solidification rate allows time for nonmetallic inclusions and gases to float out, and the progressive growth of the coarse columnar grains floats the nonmetallic inclusions into the slag bath. This results in an extremely clean weld metal, which minimizes segregation of impurities to the grain boundaries and thus reduces the detrimental effect of the coarse structure.

Form Factor

The angle at which the grains meet on the centerline is an important factor in electroslag welding and is determined by the solidification pattern and/or the shape of the weld pool. The angle at which the grains meet determines whether the weld will be susceptible to centerline cracking. When the grains growing from each side meet at the center with an obtuse included angle, the cracking resistance is low *(3)*.

The shape of the weld pool, which determines the angle at which the grains meet, is called the "form factor" and is defined as the ratio of the total width (gap opening plus width of fusion into the sides) to its maximum depth. A high form factor (shallow depth with respect to width) provides a high resistance to cracking. Process variables, primarily voltage, current, and wire-feed rate, control the form factor. (Raising the voltage and/or decreasing the current, as well as a low wire-feed rate, increase the form factor.) Welding techniques to control this are well documented in the literature *(2,3,6,8)*.

Imperfections

Welds made by the electroslag welding process under normal operating conditions result in high-quality welds free of imperfections. However, as with all welding processes, imperfections can occur unless the process is applied and controlled properly, and it is well to be aware of the type of imperfections that can be produced.

A number of the electroslag-welding imperfections can be readily seen by visual examination. One of the most common is lack of edge fusion or incomplete melting at corners of the weld. This is generally caused by too low a voltage. Improper electrode spacing, wire cast, magnetic fields, and insufficient oscillation are also contributing causes. This condition is often worse at the start of the weld before sufficient heat has built up. This imperfection, if severe, is usually repaired by arc-air gouging and shielded metal-arc welding. True undercutting can also occur. This is often the result of too wide a weld for the shoes and results from the edge of the weld solidifying in contact with the flat portion of the shoe. It is also easily repaired. A more serious type of imperfection results from washouts wherein the molten material extends beyond the retaining shoes or the shoes do not fit properly so that metal and slag run out. This usually causes termination of a weld, therefore full-thickness repairs of the affected area are required. Small amounts of slag lost in this manner generally do not cause imperfections.

Arcing of the electrode or the guide tube can cause copper pickup in the weld. When a shoe is severely damaged, the copper goes into the weld. Minor arcing does not cause trouble, but if free copper can be seen on the weld surface, the possibility of liquid-copper penetration of the grain boundaries of the steel in the weld metal and resultant cracking should be investigated. One investigation, by the author, of a 3 in.-thick (76 mm) weldment made with two consumable guide tubes showed that copper penetrated to the center of the weld; however, the area of imperfections (grain-boundary films of copper and cracks) was confined to within 1/2 in. (12 mm) of the surface and within 3 in. in all directions of the visible spot on the surface. Cracks on the surface of electroslag welds are very rare because of the residual stress pattern, which is generally compressive at the surface.

Internal discontinuities in electroslag welds are detected by ultrasonic or radiographic inspection. Porosity is usually caused by moisture. It usually starts in the sump and will extend upward for considerable distances. Sources of moisture can be improperly stored fluxes (the flux, at least for starting, should be dried), leaking or sweating water-cooled shoes (on humid days, good practice prohibits starting water through the shoes prior to starting welding), and moisture from compounds used to seal between the work piece and the shoes. Asbestos fibers are particularly bad because they act as a wick for moisture.

Internal lack of fusion can occur when multiple guide tubes or electrodes are used. This can be controlled by proper electrode placement and voltage.

Internal cracking can occur in electroslag welding and at least three types have been observed. By far the most common is the centerline-type cracking discussed in the preceding section on "Form Factor." These cracks generally occur where the dendrite ends of columnar grains meet directly at an obtuse angle and do not occur in regions of fine grains along the weld axis *(29)*. Cracking has also been observed in the heat-affected zones in electroslag-welded structural steels. Such cracking is generally associated with nonmetallic inclusions containing sulfur *(30,31)*. The cracks may progress a short distance into the weld metal. On occasion, fissuring may occur within the weld metal. This is a separation at grain boundaries in the coarse-grained portion of the as-deposited weld *(29)*. The exact cause is not entirely clear. The degree of restraint is definitely involved. There is some, but not conclusive, evidence of chemical segregation at the grain boundaries *(30)*. Sulfur and phosphorus positive segregation has been reported *(29)*. Hydrogen is also a possible contributing factor.

The incidence of imperfections in electroslag welding of structural steels is generally considered to be less than for other arc processes. Also, the type of joints used makes them readily accessible for nondestructive inspection. Ultrasonic inspection is well suited for this type of weld and, when properly used, can detect any of the common types of imperfections. The coarse grain size in electroslag welds makes ultrasonic testing difficult and special operator training for electroslag welds is desirable.

Distortion and Residual Stresses

One of the advantages of electroslag welding is the relative freedom from distortion. When square-groove joints are used for single-pass butt-welds, there is essentially no angular distortion as is common in multipass welds by the other processes (no bowing of the plates). As with any welding or casting process with ferrous metals, solidification and cooling shrinkage occur, with resulting shrinkage distortion and residual stress. Both temporary and permanent distortions can result from electroslag welding.

Experience has shown that over-all shrinkage of the weld occurs and that it is greater at the top of the weld. For thick plates (4½ in.; 115 mm), the over-all shrinkage is about 3/16 in. (4.8 mm) *(20,Part I)*. To counteract the increased shrinkage at the top of a weld, many fabricators increase the gap at the top of a weld about 1/8 to 1/4 in. (3 to 6 mm) *(8,20,24)*. Procedures differ from shop to shop, depending on how the joints are held in place and on welding procedures. It is best to develop procedures for distortion compensation by trial and error.

The temporary changes in dimensions during welding are fairly complex and have been measured by a number of investigators *(3,20(Part I),32,33)*. The practical significance of these dimension changes is in their effect on residual stresses. Fixturing has a large effect on these distortions *(33)*. Stopping an electroslag weld that has been partially welded illustrates the magnitude of these effects. If a weld is stopped when approximately one-third completed, the weld top will come together as the weldment solidifies and cools, with resulting pinching of the electrode and breaking of welds on the strongbacks *(24)*.

In the welding of tee sections, angular distortion of the cross member is to be anticipated. Angular distortions of about 1 degree (0.017 rad) are observed because the weld is on one side of the plate *(20,Part III)*. Heat straightening has been used to correct this. If strongbacks are used on only one side of a tee weld, angular distortion of up to 4 deg (0.068 rad) is reported *(20 Part,III)*. This illustrates the importance of balancing strongbacks and fixturing on all types of welds, including butt-welds.

When single V-welds are used (for instance, in using the conventional electroslag process for thin plates), angular as well as vertical distortion can occur; however, such distortion apparently has not caused serious problems in production. A recent study of both temporary and permanent distortion during electrogas welding is directly applicable to electroslag welding *(33)*. This study presents extensive experimental and theoretical data on 1-in.-thick plates and covers the effects of strongbacks. The authors state that a similar study of thicker electroslag-welded plates will be published at a later date.

Few quantitative data on residual stresses in electroslag weldments are available in the literature. The observed distortion during electroslag welding indicates that residual stresses of yield-point magnitude must be present in the as-deposited condition, although some stress relieving may occur during the slow cooling process. During solidification and cooling, heat is extracted from the extremities of the weld, from the retaining shoes, and from massive plates being welded. This results in compressive stresses on the weld surfaces and high tensile stresses near the center of the weld *(34)*. When cracking does occur in electroslag weldments, it is generally found near the center of the weld and rarely at or near the surfaces. This general pattern is also confirmed by work on electroslag buildups *(35)*. Welding procedures can alter the residual-stress patterns, and of course, the stresses imposed by fixturing must be considered. Few quantitative data are available. In many applications of electroslag welding other than large structures of carbon and low-alloy steel, a postweld stress-relief heat treatment or a postweld normalizing heat treatment is employed *(20)*. These treatments reduce residual stresses but also alter other properties.

Mechanical Properties

The general opinion is that, with the exception of notch toughness, the mechanical properties of as-deposited electroslag weldments in hot-rolled structural steels can be made equal to, or better than, those of the base metal. For alloy steels and heat-treated steels, both quenched and tempered and normalized, appropriate postweld heat treatments are generally required. To obtain optimum notch toughness in the welds and heat-affected zones of structural steels, postweld heat treatments are also required. Current opinion regarding the mechanical properties of as-deposited electroslag weldments in structural steels is summarized in the sections that follow.

Tensile Properties

Many investigators have shown that there is no difficulty in meeting or exceeding the tensile properties of hot-rolled structural steels in as-deposited electroslag weldments. This is observed in both reduced-section tension tests (joint efficiency) and all-weld-metal tension tests of the types specified by AWS *(16)*. In all-weld-metal tension tests, the yield-to-tensile-strength ratio is generally lower in electroslag weld metals than in weld metals deposited by the same electrodes by using multipass techniques. The AWS Structural Welding Code recognizes this and requires that all-weld-metal tension-test results meet the yield-point, tensile-strength, and elongation requirements for the plates being welded *(16)*. Typical values being obtained on common structural-steel weldments are presented in References *2*, *8*, and *36*, as well as in many other studies.

As judged by hardness determinations, the tensile properties are very uniform across electroslag-welded joints, with the properties of all regions of the heat-affected zone and the weld metal being similar *(8,34)*. The slow cooling rate after welding prevents the formation of high-hardness low-temperature transformation products. This is an important feature in applications where stress-corrosion cracking could be encountered.

The ductility of electroslag weldments as judged by tensile elongation and reduction of area and by bend tests is excellent and is usually superior to that of the base metal and to that of the weld metal deposited by other processes in structural steels. The refining action of the electroslag process is probably responsible for the excellent ductility.

Notch Toughness

Notch toughness has caused the greatest concern in the application of electroslag welding, and methods of controlling toughness have been the subject of many investigations. At present, there is no general agreement on the best way to measure toughness in electroslag welds or on the acceptance criteria to be used for structural applications. A number of tests have been considered, including Charpy V-notch, wide-plate (Wells-type), crack-opening-displacement (COD), explosion-bulge, drop-weight, and dynamic tear tests.

In many electroslag weldments relatively low notch-toughness values, by conventional testing procedures, have been observed in the weld metals and the heat-affected zone. The coarse grain size and the grain-boundary orientation are strong contributing factors to the low values measured. As mentioned earlier, the detrimental effect of the large grain size in the weld metal can be partly counteracted by the refining action of the electroslag process; however, such refining action does not occur in the heat-affected zone.

Before discussing the significance of notch toughness in electroslag weldments, the results obtained by various testing methods are considered.

<u>Charpy V-Notch Tests</u>. For a number of reasons the Charpy V-notch test is the most common test used to evaluate the fracture toughness of electroslag weldments. It is a simple, convenient, and economical test for evaluating plate products and weldments, and the test results have correlated well with service performance in many applications. In electroslag weldments, the Charpy specimen has the advantage of being small enough to measure the properties of individual regions of a weldment. However, this small size may also be a disadvantage because the size of the fracture surface is the same order of magnitude as the weld-metal grain size. Thus, the test, depending on its location and orientation, can measure the toughness of a grain, a grain boundary, or any combination thereof, and not the over-all average properties of the microstructure. The Charpy V-notch results for electroslag welds show wide scatter (more than observed for plates or multipass weldments), even when care is taken to precisely locate the specimens *(24,28,34,36)*.

In addition to the previously mentioned scatter, there is considerable scatter of results associated with the location of the specimens with respect to the joint. In the weld metal there are generally two distinct zones, the coarse columnar zone at the periphery of the weld and the finer-grain-size zone near the center of the weld. The coarse columnar zone usually has better Charpy V-notch properties at all temperatures *(2,37,38)*. Both grain orientation and weld-metal cleanliness and purity are probably factors. Most investigators orient their specimens with the notch at the quarter-point on the weld centerline and normal to the plate surface as specified by AWS *(16)*. One investigator used specimens with the notch 90 deg ($\pi/2$ rad) from that specified by AWS and obtained values that were similar to those obtained with the standard orientation *(34)*. The Michigan Department of State Highways and Transportation has studied impact properties with specimens oriented at various angles to determine the worst location *(38)*. Investigators have also noticed variations in Charpy V-notch properties between the bottom (cold end) and top (hot end) of welds. Some report better properties at the top end and claim that the slower cooling rate is better *(15,38)*. One investigator using data developed by the California Department of Transportation Highway Laboratory found just the opposite effect *(36)*. (The author believes grain-boundary orientation with respect to the impact-test notch may be the controlling factor.)

The weld HAZ also shows a wide variation in Charpy V-notch results, with the coarse-grained region near the bond line showing the lowest values. These low values may be lower or higher than those of the base metal, depending on the steel and the welding procedure *(37,39,40,41)*. The values obtained are similar to those expected in hot-rolled steel with high finishing temperatures (not control-rolled). Steels that have been quenched and tempered are not used in the as-electroslag-welded condition. Steels requiring exceptionally high toughness levels, which have been normalized to refine the grain size and improve low-temperature notch toughness, are not used in the as-electroslag-welded condition. Structural steels such as ASTM A36, which have marginal notch toughness with respect to the AASHTO specification of Charpy V-notch energy absorbtion of 15 ft-lb at +40 F (20 joules at 4 C) may be normalized in production to ensure meeting these requirements. Steels of this type are sometimes used in the as-electroslag-welded condition.

When electroslag welds in structural steels are tested in accordance with the AWS Structural Welding Code, a wide range of Charpy V-notch values have been obtained *(6,8,36,42)*. Average values for structural steels range from about 2 to 60 ft-lb (2.7 to 81 joules) at 0 F(-18 C). A number of variables have been studied in an effort to improve the notch toughness of electroslag welds. One of the most important is the electrode *(6)*. The best properties reported for electrodes commercially available in the United States were obtained with very-low-sulfur nickel-containing wires *(6,41)*. However, values over 30 ft-lb (41 joules) at 0 F have been reported for both metal-cored and solid carbon-steel wires used in welding ASTM A36 and A441 steels *(8,12)*. Slightly lower values are reported for A588 steel weldments. Fluxes are also important, with basic fluxes producing better properties *(43,44)*. The greater desulfurizing power of basic slags is probably responsible *(45)*.

Increased welding speed with its corresponding decrease in heat input is a technique to improve both HAZ and weld-metal impact properties *(14,43,44)*. The reduction in heat input definitely improves the HAZ and has shown improved test results in the weld metal *(43)*. The increased speed is usually accomplished by keeping the joint dimensions small and reducing the amount of required filler metal. Speed is then increased to as close as possible to the point where cracking will occur as a result of an adverse form factor. Apparently the gain from reducing grain size is more beneficial than the loss in refining time during welding. Welding-procedure changes that affect the orientation of the grains can also control notch toughness as measured by Charpy V-notch test *(46)*.

In addition to the electrical parameters, the cooling rate can be affected significantly by the design and use of the cooling shoes. There is general agreement that when water-cooled shoes are used the water temperature should not be too low. Exit temperatures of 110 to 130 F (43 to 55 C) are typical, and even higher temperatures are recommended for high-speed welding *(12)*. Heat treatment after welding is the best way to improve the notch toughness of electroslag weldments. However, the effect of heat treatment is a subject that is beyond the scope of the present report except to note that a postweld stress-relief heat treatment is sometimes beneficial and sometimes detrimental *(21,22,40,47)*. Normalizing is generally beneficial.

Wide Plate Tests. Wide-plate tests conducted in England by Wells, et al., indicated that electroslag weldments perform better with respect to brittle-fracture initiation than would be expected from their Charpy V-notch properties *(48,49,50)*. Most of the results showed that the electroslag welds performed satisfactorily and are equivalent to shielded metal-arc welds. In the one exception, in which failure progressed through the weld metal with low prefracture plastic strain but at an adequate fracture stress, the weld metal was undermatching in strength *(50)*. The relative strengths of the various regions of weldments are very important in establishing fracture characteristics of the weldment.

Crack-Opening-Displacement Tests. Crack-opening-displacement (COD) tests have been used, particularly in England, to evaluate electroslag weldments *(39,47,51,52)*. Most investigators find a poor correlation between COD test results and Charpy V-notch test results. Dawes concludes that Charpy tests do not always rate different weld metals in the same order as the slow-bend COD tests, and for critical application weld metals should be evaluated by testing full-joint-thickness fatigue-cracked COD specimens at a loading rate relevant to that of the structure concerned *(52)*. Egan *(47)* in his study of carbon-manganese steels concluded that as-deposited electroslag welds in 2-in.-thick plate can, under static or low-strain-rate loading, tolerate 1/4-in.-deep surface defects or 1/2-in.-long buried defects at a stress level of 2/3 the yield strength. Most British investigators favor the COD test for evaluating the fracture toughness of electroslag weldments; however, Dawes states that Charpy V-notch tests can be used for noncritical applications *(52,53)*.

Explosion-Bulge Tests. Limited use has been made of explosion-bulge tests, of the type developed by the Naval Research Laboratory, for evaluating electroslag weldments. In three separate investigations, good performance was shown without cracks propagating along the weld or the HAZ in spite of low Charply V-notch values in these regions *(41,54,55)*. The tests showed that electroslag welds can exhibit excellent toughness at moderately low temperatures. However, the extent and rate of loading produced by the explosion-bulge test are much greater than those which bridge-steel fabrication is designed to resist.

Drop-Weight Tests. The drop-weight test (ASTM E208) for determining nil-ductility-transition (NDT) temperature offers possibilities for evaluating the fracture toughness of electroslag weldments. Although no references to the use of this test for this purpose were found in the literature, it is being included in the experimental program of NCHRP Project 10-10. The drop-weight test has the advantage that the specimen is larger than the Charpy V-notch specimen, and this provides a more representative sample. The test also provides some opportunity for the crack to preferentially follow weak or brittle zones in the microstructure. The significance of the NDT temperature is that a sharp increase in the dynamic fracture toughness is developed as the temperature increases above NDT *(56)*. Unpublished work conducted at U. S. Steel Research and not a part of the project reported here, indicates that electroslag welds and heat-affected zones can exhibit better toughness than the base plate. The correlation between NDT and Charpy V-notch test results was not very good. The results are summarized in Table 1.

Significance of Fracture-Toughness Tests. The level of fracture toughness required of electroslag weldments for structural steels in intermediate-strain-rate applications (such as bridges) has not been established. Electroslag welds have been used extensively in building construction. For example, the Sears Tower in Chicago contains more than 45,000 electroslag welds made by the consumable-guide method *(57)*. Electroslag welds have also been used to a lesser

TABLE 1

SUMMARY OF DROP-WEIGHT NDT AND CHARPY V-NOTCH TEST RESULTS

Steel	Thickness (in.)	Location	Drop-Weight NDT, (°F)[a]	Charpy V-Notch Energy Absorbed (ft-lb) +40 F	0 F
A588 Gr A	1	Base metal	+70	18	13
		HAZ	+20	-	-
		Weld metal	-70	23	17
A36	2	Base metal	+20	9	4
		HAZ	0	67	11
		Weld metal	-40	58	21
A36	4	Base metal	+50	16	6
		HAZ	+20	30	16
		Weld metal	0	52	41

1 in. = 25.4 mm; C= 5/9 (°F - 32); 1 ft-lb = 1.36 J.
[a]P1 specimens for A588 welds and P3 specimens for A36 welds.

extent in bridges and in other structures subject to intermediate and/or dynamic loading (such as blast furnaces). These welds have an excellent record of performance in these applications. Documentation of brittle service failures in electroslag welds is almost nonexistent. It is recognized that some minimum toughness level is required and that this toughness level for welds should be somewhat greater than that required for the base plate. Greater toughness is desired because of the greater possibility that imperfections will be present in welds and that these imperfections may be oriented to propagate under fatigue loading in service. But the level of fracture toughness required and the method of measuring it has not been entirely resolved.

Not only is it necessary to establish the level of notch toughness required for satisfactory service of a given type of structure, but it is also necessary to establish some higher level of notch toughness to be required for qualification tests to insure that actual weldments will have the required toughness. Determination of this second level of notch toughness requires an assessment of the effects of minor process variables and establishment of essential variables whose change should require requalification.

At present, the AWS Structural Welding Code specifies Charpy V-notch impact testing of electroslag weld metal and designates specimen location and acceptance levels as well as essential variables requiring requalification. There are no known structural steel specifications in use in the United States requiring other types of tests or requiring testing of the HAZ. There have been objections to the AWS location of Charpy specimens (quarter point along weld axis). Some engineers believe that the worst portion (weld center), orientation, and location along the weld length should be tested and used for qualification *(36,38)*. In the author's opinion, however, when Charpy tests are used, the specimen orientation should be governed by the applied-stress pattern. For example, the specimen should be oriented so that the toughness is measured at the location and in the direction in which cracks are likely to propagate in service. For most applications, because of bending moments, stresses are higher at or near the surface than the center.

NCHRP Project 10-10 is designed to resolve many of these concerns. Extensive Charpy V-notch drop-weight, and plane strain fracture toughness (K_{Ic}) determinations will be made on a variety of weldments to furnish toughness data that will be correlated with fatigue and other mechanical property data and used as a guide in establishing fracture-toughness requirements and methods of testing.

Other Properties

Other mechanical and physical properties of electroslag welds, such as modulus of elasticity and density, have not been reported in detail; however, there is no reason to expect that these properties would be appreciably different from those of cast steels or other weld metals of similar composition.

Fatigue

An extensive literature survey of the fatigue properties of electroslag welds was conducted by Harrison *(58)*, and his findings based on the survey and on fatigue tests that he conducted indicate that the fatigue strength of electroslag welds is adequate. Electroslag welds with the reinforcement removed have fatigue strengths as high or higher than those of the parent material. Machined electroslag welds (reinforcement in place) have fatigue strengths as high or higher than those obtainable for butt welds made by other processes. The fit and design of the retaining shoes control the fatigue strength of these welds. These results were convincingly confirmed by a study of consumable-guide-welded ASTM A36 and A588 plates *(34)*.

APPLICATIONS

In 1971 the International Institute of Welding (IIW) surveyed the member nations to determine the acceptance and testing required by classification bodies for electroslag weldments *(59)*. They found that, with some exceptions, the classification societies accept electroslag welding for practically all types of applications. One notable exception is that Japan does not accept electroslag welding for bridges. For the application of electroslag welding, essentially the same qualification is required as for other welding processes, although some agencies require a wider range of tests and stricter criteria. No agency specifies a limiting weld-metal or HAZ grain size. Some agencies specify HAZ impact tests. For a number of applications a normalizing heat treatment after welding is required.

In the United States most structural electroslag welding is governed by the AWS Structural Welding Code, which requires joint-efficiency tests, all-weld-metal tension tests, and bend tests, with the provision for weld-metal Charpy V-notch impact requirements if specified *(16)*. (Fabrication conducted under the ASME Boiler and Pressure Vessel Code *(17)* is beyond the scope of this report. Application of electroslag welding to bridges is generally handled on an individual basis. Most states will permit use of electroslag welds provided the AWS Structural requirements, including impact tests, are met. Some states are withholding approval on an over-all basis and others on specific designs. There is no known bridge classification agency specifying mechanical-property testing in addition to that required by AWS; however, some agencies require additional nondestructive inspection. Presumably, application of electroslag welding in bridge construction will increase as more experience is gained.

The available literature on electroslag welding has been reviewed and the features applicable to structural welding of the type used in buildings and bridges have been summarized in this state-of-the-art report. Equipment and consumables are readily available and the process is quite suitable for welding plates more than 3/4 in. (19 mm) thick that can be positioned in the vertical or near-vertical position. When properly applied, sound welds can be produced consistently with a minimum of distortion.

An analysis of the literature indicates that the strength, ductility, and fatigue performance of these welds in the as-deposited condition are as good as or better than the corresponding properties of standard structural-steel weldments made by other processes. The notch toughness of the coarse-grained weld metal and the heat-affected zone, as measured by Charpy V-notch tests, can be less than that of some structural steels and welds made by other processes. (Fracture toughness as measured by other methods appears to produce more favorable results.) Inability to measure the notch toughness of electroslag weldments properly and to interpret the measurements in terms of structural suitability appears to be the major factor limiting application of this welding process to bridges. The current research (NCHRP Project 10-10) is designed to resolve this limiting factor.

REFERENCES

1. Terms and Definitions, AWS A3.0-69, American Welding Society, 1969.
2. Welding Handbook, 6th edition, Chapter 48, American Welding Society, 1970.
3. Electroslag Welding, ed. by B. E. Paton, (translated from the Russian edition of 1959), American Welding Society, 1962.
4. R. D. Thomas, Jr., "Electroslag Welding—A New Process for Heavy Fabrication," Welding Journal, Vol. 39(2), February 1960, pp. 111-117.
5. P. E. Masters and R. S. Zuchowski, "Vertical Submerged-Arc Welding," Welding Journal, October 1965, pp. 829-837.
6. "Procedures for Consumable Guide Electroslag Welding," F-51-220, Linde Division of Union Carbide Corporation, February 1969.
7. "High-Deposition Vertical Welds Automatically," 51-225A, Linde Division of Union Carbide Corporation, September 1971.
8. "Porta-Slag Welding," EW-412, Hobart Brothers Technical Center, 1970.
9. "Filler Metals and Equipment for Welding," 17220, Arcos Corporation.
10. D. A. Dudko, I. N. Rublevskii, and G. S. Tyagum-Belous, "Some Features of Droplet Transfer From Heavy Electrodes in Electroslag Welding," Avtomaticheskaya Svarka, May 1959.
11. J. F. Lowery, "A Radiographic Study of the Electroslag Welding Process," Welding Institute Report, No. P/32/68, July 1968.
12. D. A. Dudko, et al., "Research Using Cinematography and Photography Through an Opaque Medium Into the Electroslag Process," Avtomaticheskaya Svarka, No. 2, 1971, pp. 15-17.
13. Private communication with M. Nakabayashi, Linde Division of Union Carbide Corporation, Ashtabula, Ohio.
14. R. W. Parrott, S. W. Ward, and G. D. Uttrachi, "Electroslag Welding Speeds Shipbuilding," Welding Journal, April 1974, pp. 218-222.
15. L. Lanzie and J. Zeke, "The Influence of the Current and Polarity and the Atmosphere on the Properties of the Weld Metal in Electroslag Welding," Revue de la Soudure Lastijdschrift, No. 1, 1970.
16. Structural Welding Code, AWS D1.1 Rev 2-74, American Welding Society, 1974.
17. Interpretations of ASME Boiler and Pressure Vessel Code, Case 1355-2, American Society of Mechanical Engineers, January 14, 1969.
18. B. E. Paton, "Forecasts of the Development of Welding," Automatic Welding, No. 7, 1971, pp. 4-7.
19. G. Z. Voloskevich, et al., "Certain Methods of Improving Electro-Slag Welding," Automatic Welding, No. 12, December 1972.
20. D. J. Ellis and A. F. Gifford, "Applications of Electroslag and Consumable Guide Welding," Parts 1-6, Welding and Metal Fabrication, April 1973—November 1973.
21. D. N. Shackleton and M. Weldl, "The Classification of Electroslag Welding Consumables," DOC-XII-J-32-73, International Institute of Welding.
22. D. N. Shackleton and M. Weldl, "Classification of Filler Materials for Electroslag Welding—Weld Tests," DOC-X11-J-31-73, International Institute of Welding.

23. C. E. Jackson, "Fluxes and Slags in Welding," Bulletin No. 190, Welding Research Council, December 1973.

24. H. C. Campbell, "Electroslag, Electrogas, and Related Welding Processes," Bulletin, No. 154, Welding Research Council, September 1970.

25. Union Carbide Welding Products, Chapter 15, F-3307/17, Union Carbide Corporation, October 1, 1973.

26. G. V. Nazarov, "Calculating Thermal Cycles During Electroslag Welding," Automatic Welding, Vol. 19, No. 8, 1966.

27. L. P. Eregin, "Influence of Electroslag Welding Settings on the Thermal Cycle in the Heat Affected Zone," Svar. Proiz., No. 2, 1971.

28. "Fracture Toughness and Fatigue Properties of Steel Plate Butt Joints Welded by Submerged Arc and Electroslag Welding Procedures," Michigan Project 72 F-124 Proposal, Michigan State Highway Commission, March 1972.

29. S. A. Ostrovskaya, "Some Problems of Crystallization Cracking in Electroslag Welding," Avtomaticheskaya Svarka, Vol. 10, 1957, pp. 33-47.

30. A. M. Makara, et al., "The Connection Between Tears and Nonmetallic Inclusions in Electroslag Welding," Automatic Welding, May 1969.

31. A. M. Makara, Y. Y. Kovalev, and I. V. Novikov, "Liquation Cracks in the HAZ in Structural Steels During Electroslag Welding," Automatic Welding, May 1972.

32. V. A. Vinokurov, "Temporary Thermal Deformation During Electroslag Welding," Automatic Welding, Vol. 19, No. 4, April 1966.

33. T. Maeda, T. Yada, V. Nakamura, and M. Fukuzawa, "Study of Distortion During Electrogas Welding and Prevention Thereof," IHI Engineering Review, Ishikawjima Harima Heavy Industries, Vol. 7, No. 2, May 1974.

34. J. S. Noel and A. A. Toprac, "Static, Fatigue, and Impact Strength of Electroslag Weldments," Center for Highway Research, University of Texas Research Report 157-1F, Project 3-5-71-157, December 1972.

35. G. V. Ksendzyk, "Residual Stresses in Cylindrical Components After Arc or Electroslag Building Up," Automatic Welding, October 1969.

36. C. E. Hartbower, "The Toughness of Electroslag Weld Metal (Without Post-Weld Heat Treatment)," U. S. Department of Transportation, Federal Highway Administration, to be published.

37. G. Bowers, "Reconstruction and Repair of Blast Furnaces," Metal Construction and British Welding Journal, August 1970.

38. Private communications with J. D. Culp, principal investigator of Reference 28.

39. J. L. Kaae, "The HAZ Fracture Toughness of Controlled Rolled, Nb Treated, Low C:Mn Steels," Metal Construction and British Welding Journal, August 1969.

40. K. P. Bentley, "Toughness in Electroslag Welds," British Welding Journal, August 1968.

41. W. P. Benter, Jr., "Welding of a Normalized High Strength Low Alloy Plate Steel of Structural Quality," Welding Journal, December 1972, pp. 591-598s.

42. W. C. Clark and R. S. Rote, "Electroslag Welding—Procedures and Results," Iron and Steel Engineer, September 1965.

43. B. M. Patchett, F. W. Collins, and R. L. Apps, "Process Parameters and Mechanical Properties of High Speed Consumable Guide Welds," Welding and Metal Fabrication, June 1973, pp. 216-224.

44. N. E. Anderson, "Consumable Guide Electroslag Welding of Vertical Beam Joints," Svetsaren (ESAB), No. 1, 1973.

45. Y. M. Zaitsev and G. S. Tyagum-Belous, "Desulfurizing Capacity of Fluxes in Electroslag Welding," Avtom. Svarka., Vol. 11, 1958, pp. 57-60.

46. A. M. Makara, S. V. Egorova, and I. V. Novikov, "Assessing the Brittle Fracture Resistance of Electroslag Welded Joints Which Have Not Been Normalized," Avtom. Svarka., No. 3, 1973, pp. 52-55.

47. G. R. Egan, "An Assessment of Defects in Welded Carbon Manganese Steels, Part II—The Significance in Butt Welds in C/Mn Steels With Special Reference to Fitness for Purpose," The Welding Institute, March 1971.

48. C. C. Woodley, F. M. Burdekin, and A. A. Wells, "Electroslag Welded Wide Plate Tests on 3-Inch-Thick Mild Steel," British Welding Journal, Vol. 13, No. 3, 1966, pp. 165-173.

49. C. C. Woodley and F. M. Burdekin, "Wide Plate Tests on Two Electro-Slag Welded Steels," British Welding Journal, Vol. 13, No. 6, 1966, pp. 387-397.

50. M. G. Dawes and F. M. Burdekin, "Testing 2-Inch-Thick Mild Steel for Use in Bridge Building," Metal Construction and British Welding Journal, Vol. 1, No. 4, April 1969, pp. 198-204.

51. F. M. Burdekin, M. G. Dawes, G. L. Archer, F. Bonomo, and G. R. Egan, "Selection of Weldments to Avoid Fracture Initiation," British Welding Journal, December 1968.

52. M. G. Dawes, "Designing to Avoid Brittle Fracture in Weld Metals," Metal Construction and British Welding Journal, Vol. 2, No. 2, February 1970.

53. E. Banks, "Toughness Properties of HAZ Structures in Structural Steel," Welding Journal, July 1974, pp. 299-306s.

54. P. C. Arnold and D. C. Bertossa, "Multiple Pass Automatic Vertical Welding," Welding Journal, Vol. 45, No. 8, August 1966, pp. 651-660.

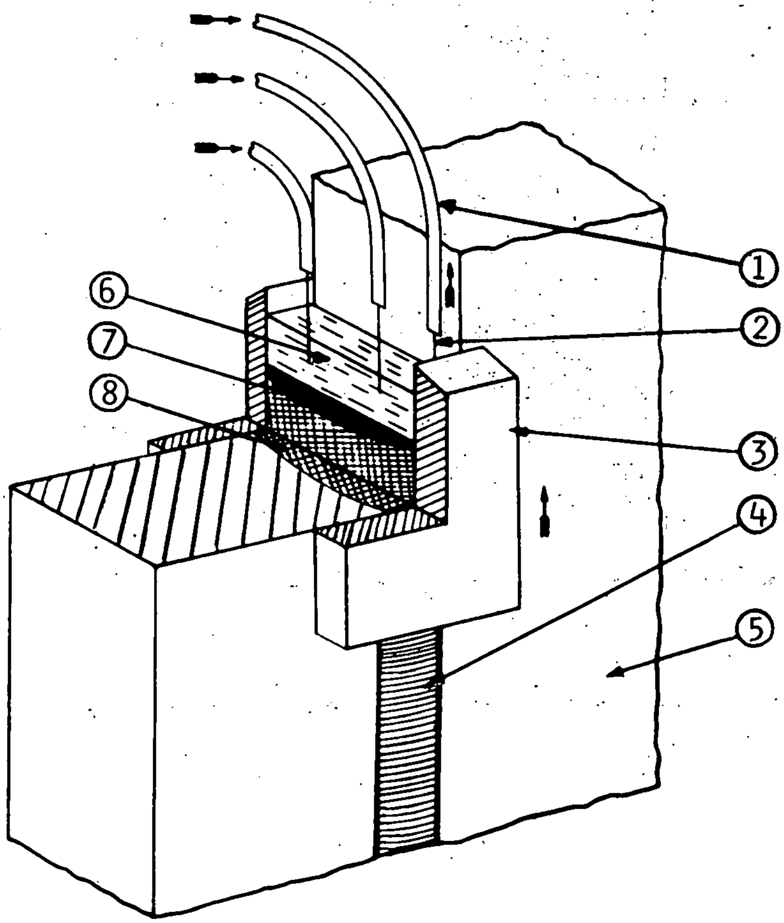
55. R. Bockholt, "Explosion Tests With Welded Test Plates," British Welding Journal, Vol. 11, No. 11, November 1966, pp. 572-585.

56. W. S. Pellini, "Principles of Fracture-Safe Design—Part I," Welding Journal, Vol. 50, March 1971, pp. 91-109s.

57. Private communication, P. E. Masters, American Bridge Division, United States Steel Corporation.

58. J. D. Harrison, "Fatigue Tests of Electroslag Welded Joints," Metal Construction and British Welding Journal, Vol. 1, No. 8, August 1969.

59. "Report on the Attitude of Classification Societies to Electroslag Welding," Welding in the World, Vol. 9, No. 5/6, 1971.



(1) CURVED WIRE-GUIDES
(2) ELECTRODE WIRES
(3) COOLED SHOES
(4) WELD SURFACE
(5) PLATES BEING WELDED
(6) MOLTEN-SLAG POOL
(7) LIQUID-METAL POOL
(8) SOLIDIFIED WELD METAL

Figure 1. Schematic view of conventional wire method of electroslag welding (from Ref. 2).

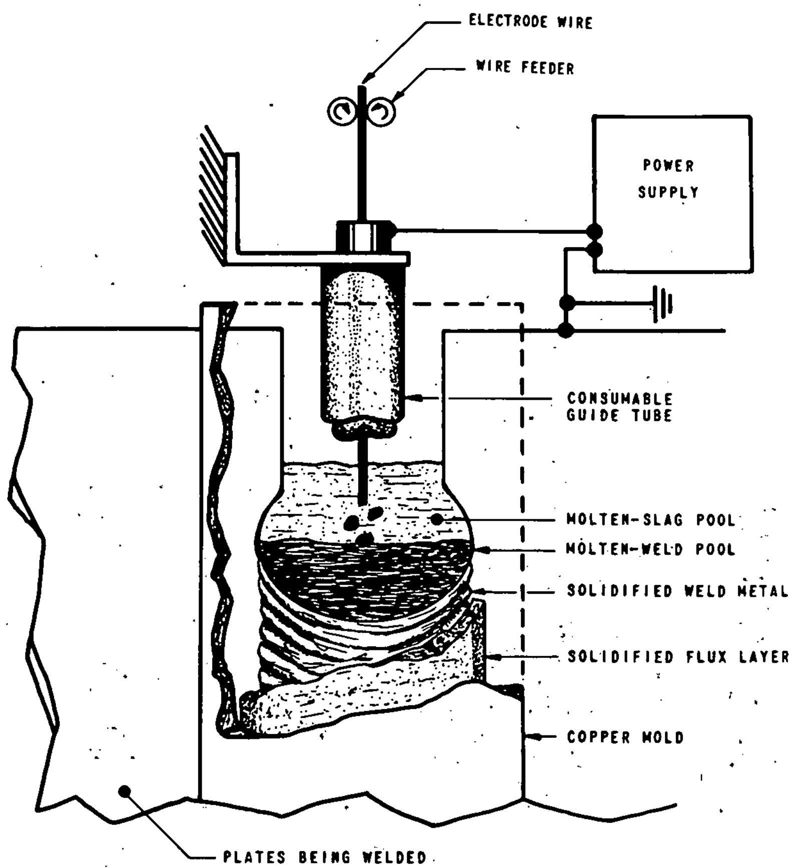
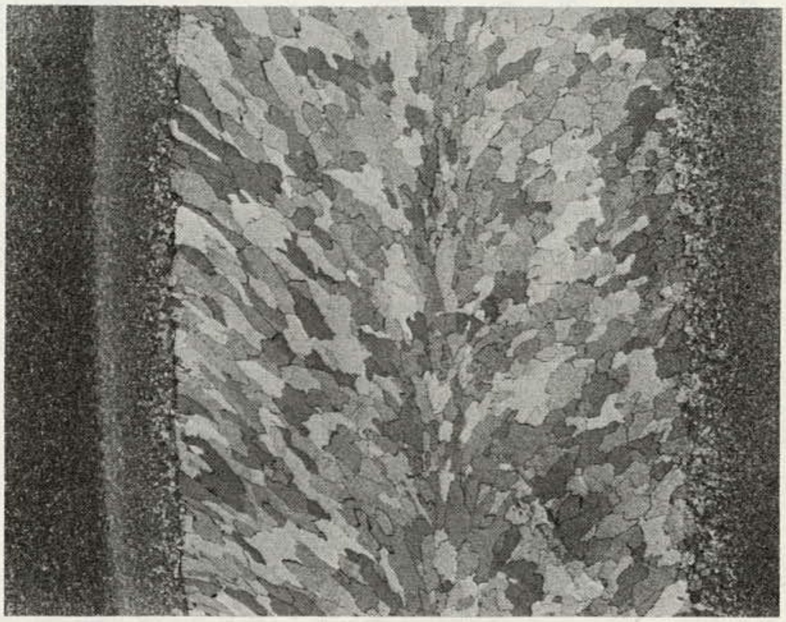
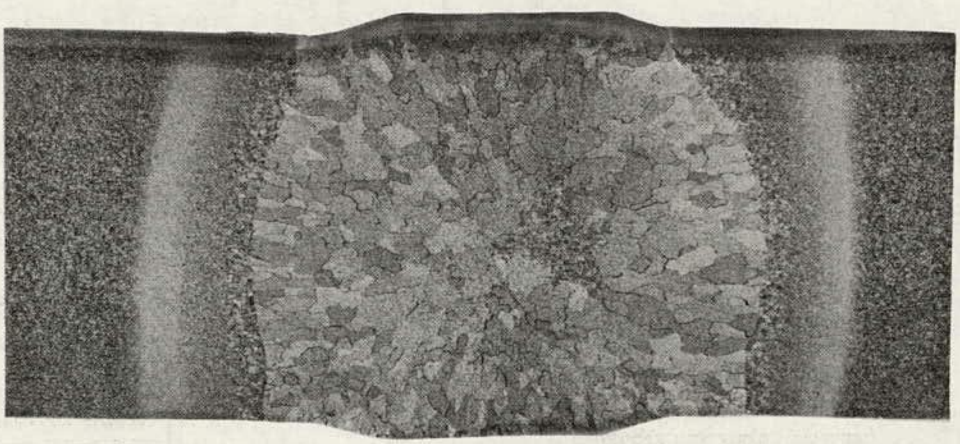


Figure 2. Consumable-guide welding (from Ref. 2).



Vertical cross section.



Horizontal cross section.

Figure 3. Vertical cross section (upper) and horizontal cross section (lower) in 2-in.-thick (51 mm) A36 steel. IX.

TRANSPORTATION RESEARCH BOARD

National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

ADDRESS CORRECTION REQUESTED

NON-PROFIT ORG.
U.S. POSTAGE
PAID
WASHINGTON, D.C.
PERMIT NO. 42970

000015M001
JAMES W HILL

IDAHO TRANS DEPT DIV OF HWYS
3311 WEST STATE ST POBOX 7129
BOISE ID 83707