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J. S. Noel and A. A. Toprac

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16. Abstract

Electroslag welds for this research program were made along the long dimension between steel plates 2'-0" x 1 1/4" x 3'-6". Three different fabricators each prepared two butt weld specimens, one with ASTM A36 and the other with ASTM A588 steel plates. From the weldments, a total of nine A36 and nine A588 specimens were prepared for fatigue tests.

Each of the full-scale fatigue specimens provided a test cross section approximately 4" wide by 1 1/4" thick which was transversed, exactly at its mid-point, by the butt weld. In 15 of the specimens the weld reinforcement was removed by grinding. Strain gages were mounted on the specimens at a cross section near the weld to permit an evaluation of the eccentricity resulting from the load applied to the specimen.

The stresses used for plotting the data (stress range vs number of cycles to failure) were the maximum ranges indicated by any one of the four gages. Probably the most important observation made from these data is that of the 11 specimens with the reinforcement removed which failed, seven of the failures occurred in the base metal and only four within the weld metal.

Based on this observation it was concluded that electroslag butt welds between both A36 and A588 steel plates, if properly made, will not significantly reduce the fatigue strength inherent in the plate itself. Certainly the electroslag welds, with the reinforcement removed by grinding, perform as well under fatigue loadings as do butt welds made by more conventional methods.

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STATIC, FATIGUE, AND IMPACT STRENGTH OF ELECTROSLAG WELDMENTS

by

J. S. Noel
A. A. Toprac

Research Report Number 157-1F

Static, Fatigue, and Impact Strength
of Electroslag Weldments
Research Project 3-5-71-157

conducted for

The Texas Highway Department

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

December 1972

PREFACE

This report presents the results of a project to study the fatigue properties of electroslag welds in plain carbon and high strength low-alloy steels. The purpose of the study, sponsored in its entirety by the Texas Highway Department, was to develop sufficient confidence in the technique to permit its use in steel structures for Texas highways. The tests were performed at the Structures Fatigue Research Laboratory, Balcones Research Center, The University of Texas at Austin.

The success of the program, however, as always, was due to the personal attention and interest of many individuals. The contributions of Mr. Bob Stanford of the Federal Highway Administration, Mr. Kenneth J. Cunningham of the Bridge Division, and Mr. Kenneth R. Sandberg of the Materials and Tests Division added significantly to the value of the program.

The weldments tested were contributed by three firms which had prior experience with this type of welding process. They included the Linde Division of the Union Carbide Corporation, the Continental-Emsco Division of Youngstown Sheet and Tube Company, and Hobart Brothers Company. These specimens represented contributions of considerable monetary value but the advice and suggestions of their welding specialists were equally valuable. Mr. Bernard J. DeGeorge of Continental-Emsco was especially helpful early in the program by showing the project staff current shop practices for electroslag welding. Mr. James R. Hannahs of Hobart Brothers Technical Center and Mr. L. Van Dyke of the Linde Division of Union Carbide also contributed time and personal attention.

Mr. Ivan J. Taylor, with his broad background in instrumentation and testing, was an asset without whom the project could not have been a success.

J. S. Noel
A. A. Toprac

December 1972

ABSTRACT

The electroslag welds for this research program were made along the long dimension between steel plates 2'-0" × 1 1/4" × 3'-6". Three different fabricators each prepared two of these butt weld specimens, one using ASTM A36 and the other using ASTM A588 steel plates. From the weldments, a total of nine A36 and nine A588 specimens were prepared for fatigue tests. In addition, conventional tests were made on tension coupons and Charpy, side bend, and other specimens fabricated from the weldments.

The tests of these conventional specimens failed to reveal any dramatic or unexpected conclusions. Inevitably, the strengths of the weld metal exceeded those of the parent plate metals. The Charpy impact energies indicated all transition temperatures to be below 0° F.

Each of the full-scale fatigue specimens provided a test cross section approximately 4" wide by 1 1/4" thick. This test section was transversed, exactly at its mid-point, by the butt weld. In all but three of the 18 specimens the weld reinforcement was removed by grinding. Strain gages were mounted on the specimens at a cross section near the weld. These gages permitted an evaluation of the eccentricity (deviation from a purely axial load) resulting from the load applied to the specimen.

The stresses used for plotting the data (stress range vs number of cycles to failure) were the maximum ranges indicated by any one of the four gages. The points were compared to fatigue data reported in the literature and were found to be comparable. Probably the most important observation that was made from these data is that of the 11 specimens with the reinforcement removed which failed, seven of the failures occurred in the base metal and only four within the weld metal.

Based on this observation it was concluded that electroslag butt welds between both A36 and A588 steel plates, if properly made, will not significantly reduce the fatigue strength inherent in the plate itself. Certainly the electroslag welds, with the reinforcement removed by grinding, perform as well under fatigue loadings as do butt welds made by more conventional methods.

KEY WORDS: static, fatigue, impact strength, electroslag.

SUMMARY

A series of tests were conducted to develop confidence in the performance of electroslag butt welds between relatively thick plates (1 in. or greater) under a large number of repetitive loadings. Welds between both A36 and A588 steel plates were studied. Characterization tests were conducted to provide the data necessary to compare the weld properties with those of welds deposited by more conventional methods and to assure the specifications of the Texas Highway Department and the American Welding Society were satisfied. A radiographic inspection was made to insure the absence of flaws within the test specimens.

When the weld reinforcement was removed by grinding prior to testing, a usual procedure for girder flange welds, the welds were found to perform as well as the base plate metal. In any event, the fatigue strengths reported in the literature for conventional butt welds were found to approximate the strengths observed for the electroslag welds.

When the reinforcement was left as welded, a significant reduction in the fatigue strength was noticed. However, it was felt that this reduction was entirely due to the geometrical stress concentration.

As a result of the experimental study, it was concluded that the electroslag method is a fast, economical method for making near perfect butt welds between thick plates and is appropriate for use where repetitive loadings are anticipated.

IMPLEMENTATION STATEMENT

The research study carried out indicated that electroslag welds have fatigue life equivalent to welds made by other welding processes. The results indicate that this process can be safely used for splicing thick plates. Plate girder flanges and other structural members where butt welds are necessary can be made using the electroslag process.

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CHAPTER 1. INTRODUCTION

General

During the nineteen fifties a new method of welding especially appropriate for very thick plates was developed. The method, termed electroslag welding, requires but one pass and results in near perfect welds. It has been used extensively and successfully for welding both carbon and high strength low-alloy steels. Although most of the developmental activity took place in Russia, England, and Japan, the process is now becoming more commonly used in the United States. Some of the advantages and disadvantages of the welding technique are listed and compared in Table 1.

With the goal of eventually using the electroslag method for making butt weld splices in bridge girder plates, an experimental study was initiated to evaluate the fatigue resistance of such weldments when subjected to repetitive loadings. The tests were to be performed on full-size weldments which were also to be characterized using conventional tests such as those prescribed by the American Welding Society (see Refs 1 and 2).

This report describes the experimental tests and the conclusions which resulted.

Electroslag Process

The electroslag process uses the resistance of a molten pool of slag to generate the heat required to melt the electrode, maintain a molten pool of weld metal, and fuse the weld metal to the parent metal. As shown in Fig 1 the slag pool floats on the molten metal, serving to protect it from the contaminating atmosphere. Further, the slag cools and solidifies against the water-cooled copper forms which constrain the molten pools. This slag coating then prevents the filler metal from fusing to the forms.

Characteristically, the method is most advantageous for welding very thick, massive pieces in a single pass. Thus, it results in a single heating cycle of much longer duration that is more global in extent than a multipass weld, where the heat is more localized and dissipates more quickly. The maximum temperatures reached, however, are about the same.

TABLE 1. ADVANTAGES AND DISADVANTAGES OF ELECTROSLAG WELDING

Advantages	Disadvantages
(1) Great savings in man-time, especially for thicker sections.	(1) If welding process is discontinued it is virtually impossible to restart without leaving serious defects (this is not so important to electrogas as to electroslag welding).
(2) Near-perfect, flaw-free welds.	(2) Start-up and run-off plates are required (this difficulty, also, may be overcome by use of electrogas techniques).
(3) Smooth, predetermined contours on the reinforcement.	(3) The coarse grain structure sometimes leads to excessive brittleness near periphery of the weld.
(4) No edge preparation required.	(4) The columnar grain orientation sometimes leads to a tendency for hot cracking near the center of the weldment.
(5) No preheating required (generally).	(5) All welds must be made in a vertical or near vertical direction.
(6) More efficient use of electrical power.	
(7) Only a minimal loss of flux and no loss of weld material due to spatter.	
(8) Weld chemistry can be precisely controlled by adjusting welding parameters.	
(9) Because of symmetry of most vertical welds, problems with distortion are virtually eliminated.	
(10) Equipment required is relatively inexpensive and simple.	
(11) Good operator comfort.	

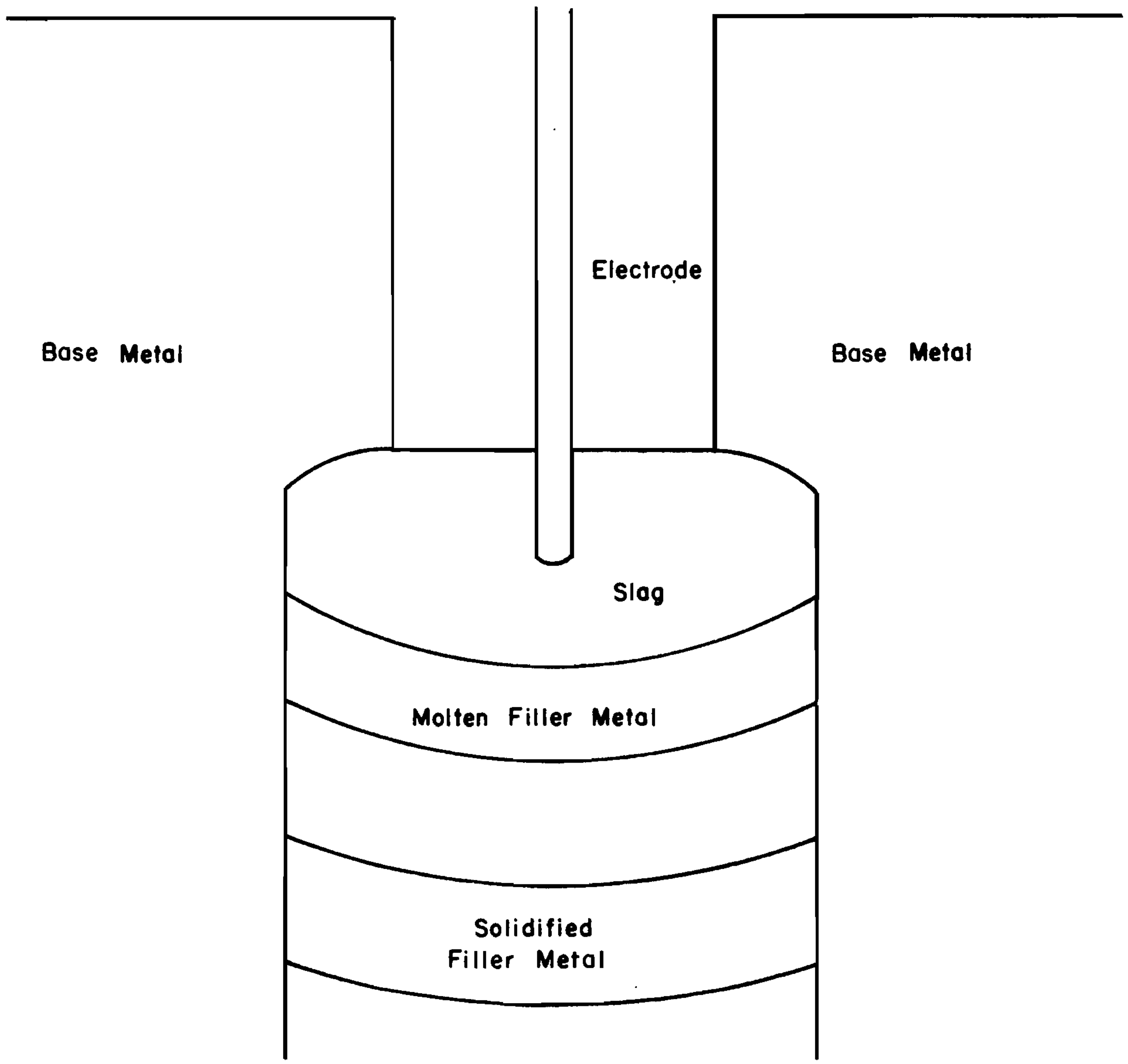

Fig 1. Schematic of the cross section of the electroslag welding process.

Typically the single heating and cooling cycle results in a coarse-grained structure which is uniformly oriented, the orientation depending on the width of the weld and other welding parameters. The theoretical implications of the coarse grains and their orientations are not well understood but some experimental observations of certain specific consequences have been made in the USSR (Ref 3).

The actual weld deposition can be made using three slightly different techniques, which are termed basic electroslag, consumable nozzle electroslag, and electrogas. The three terms actually characterize the equipment used to perform the welding since the process itself is about the same in each technique.

Basic Electroslag. In the basic electroslag process filler metal is added by feeding only the welding wire (electrode) into the molten slag pool. Flux is added separately in amounts required to maintain the slag. Usually the electrode feeder, the guide (nonconsumable), and the water-cooled shoes are all slipped upward at the rate at which the weld metal is being deposited (see Fig 2). This single electrode technique, without lateral movements of the electrode, is used for butt welding plates up to about 2 inches thick. For thicker sections either more electrodes or transverse oscillatory movement of the electrodes, or both, is used. Such arrangements can be made for welding plates of almost unlimited thickness but recorded experience indicates that use of three electrodes, each moving back and forth about 6 inches, to butt weld 20-inch-thick plates is well within the present state of the art.

Consumable Nozzle Electroslag. This method is very similar to the basic electroslag process except that the guides for the welding rod reach the slag pool and melt to add to the filler metal as the weld progresses. The guides usually are coated, which makes the separate addition of flux unnecessary or minimal. In this process the consumable nozzle, rather than the welding wire, acts as the electrode.* The outer flux coating serves as an insulator and so

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*There is some disagreement on this point. In his radiographic study of the electroslag welding process Lowery (Ref 4) points out that the guide tube does not melt at a continuous rate but, rather, intermittently. As the slag rises it makes contact with the guide, which promptly begins to melt. However, surface tension frequently keeps the slag and guide in contact until a considerable length has melted and the weight of the molten metal overcomes the surface tension. Once this molten metal collapses into the pool the end of the guide tube is left some distance above the slag and all of the current must pass through the wire.

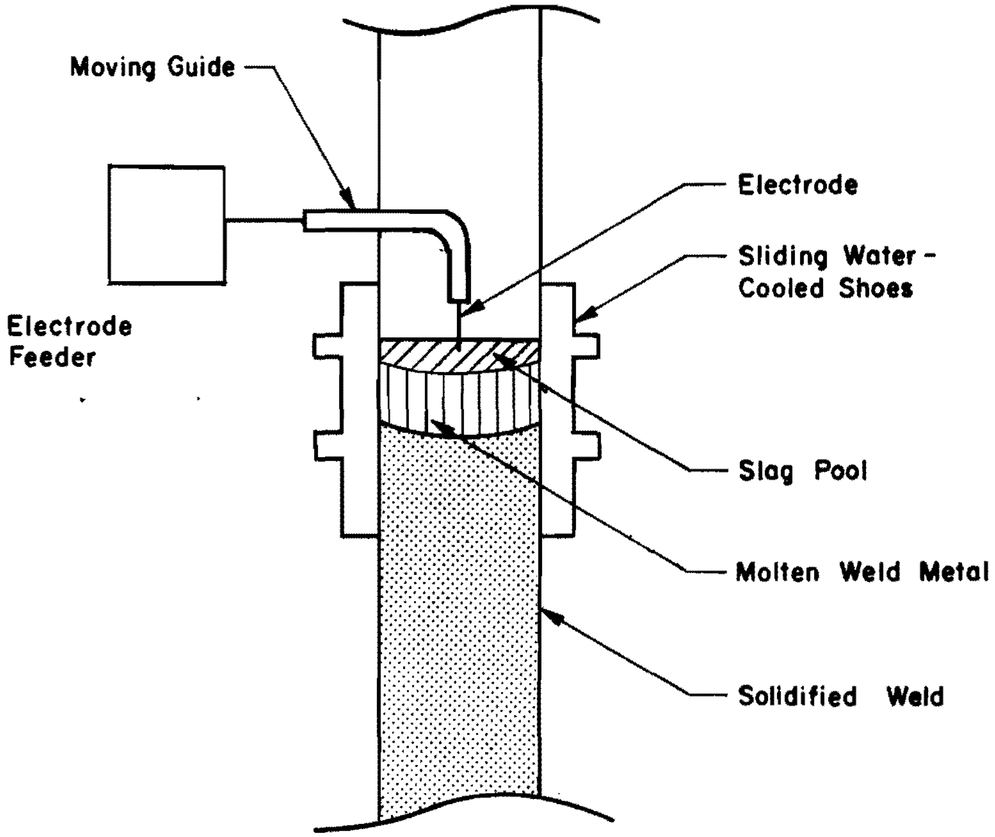

Fig 2. Cross section of the basic electroslag weld process. Only one electrode is being used.

the guide can be quite long and, if required, cored (see Fig 3). As with the basic electroslag technique more than one electrode or transverse oscillations or both can be used for greater thicknesses. The most significant characteristic in distinguishing this technique from the previous one is that the forms, which extend from end to end of the weld, do not move. Likewise, the top support of the nozzle is not required to move vertically.

The welds tested during the research that is reported herein were made using the consumable nozzle technique.

Electrogas. This method uses equipment quite similar to that of the basic electroslag technique but an inert gas is fed through the sliding form and provides additional protection to the molten weld metal from the atmosphere. However, the heat necessary for melting the electrode and parent metal is generated by an open arc between the electrode and the pool rather than by the resistance of the molten slag pool to current flow. Flux is provided by using a cored electrode and the resulting slag cover is much thinner than that required by the electroslag methods. The inert gases used include among others carbon dioxide and argon, the selection depending on the type of material being welded (see Fig 4).

The method is appropriate for thinner sections, being best suited for thicknesses of less than 3 inches. An advantage inherent in the method is that it is faster and thus has a shorter thermal cycle. One consequence of this is that the weld has characteristics more nearly resembling those of a conventional submerged arc weld than an electroslag weld. Another advantage is that in the event the welding process is interrupted it can be restarted more conveniently and with less chance of defects than can the other two methods.

Welding Procedure

Start-up is often one of the most difficult parts of the operation. Usually a starting trough is formed below the parts to be welded, as shown in Fig 5. A small ball of steel wool is stuffed down into the trough and this is covered with flux. Then the electrode is slowly lowered until its nearness to the steel wool starts a violent arcing action, which quickly melts the steel wool and, in turn, the flux. The tip of the electrode soon becomes submerged in the slag pool, and the electroslag process is underway.

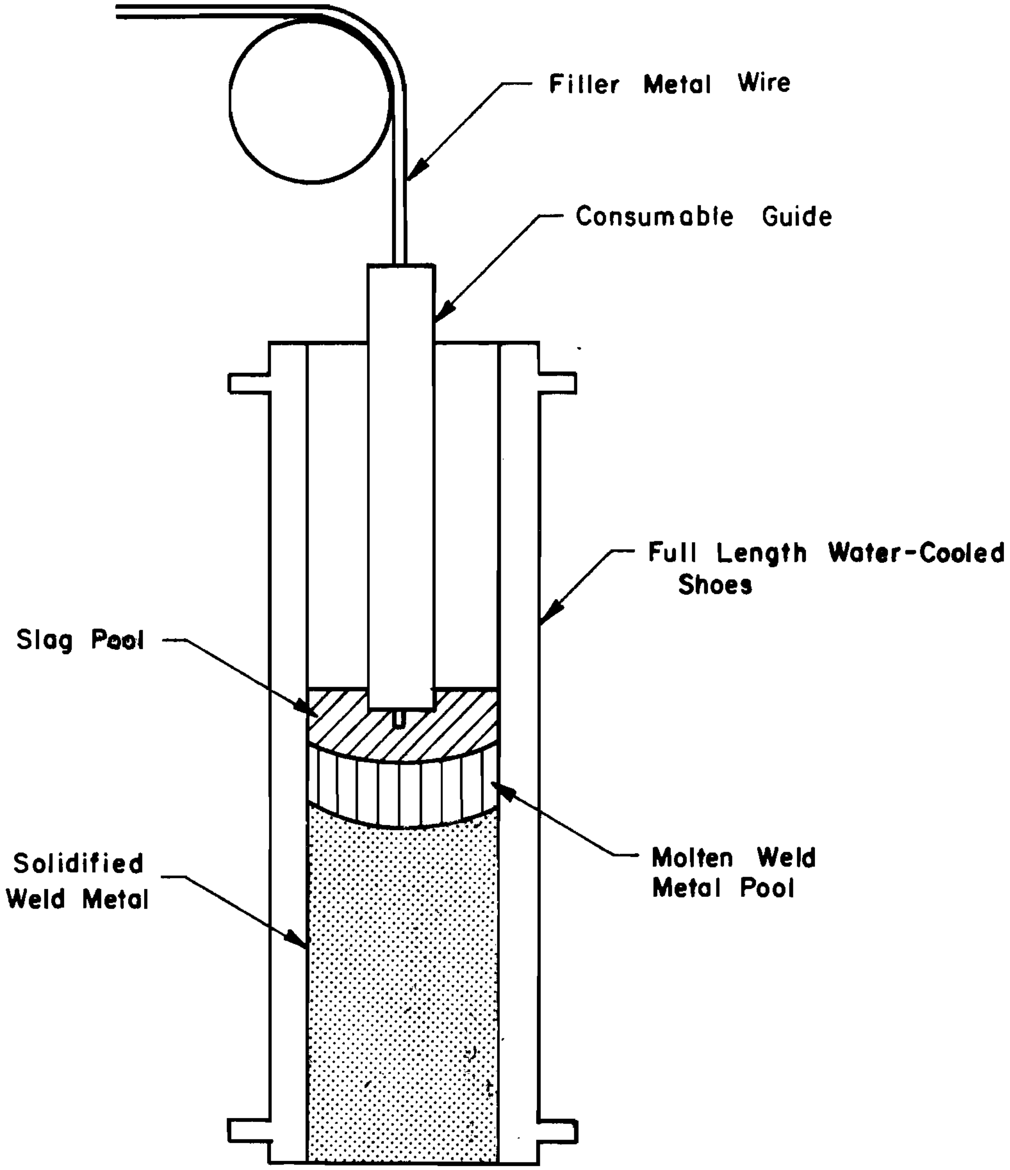

Fig 3. Sketch showing a cross section of the consumable nozzle electroslag process.

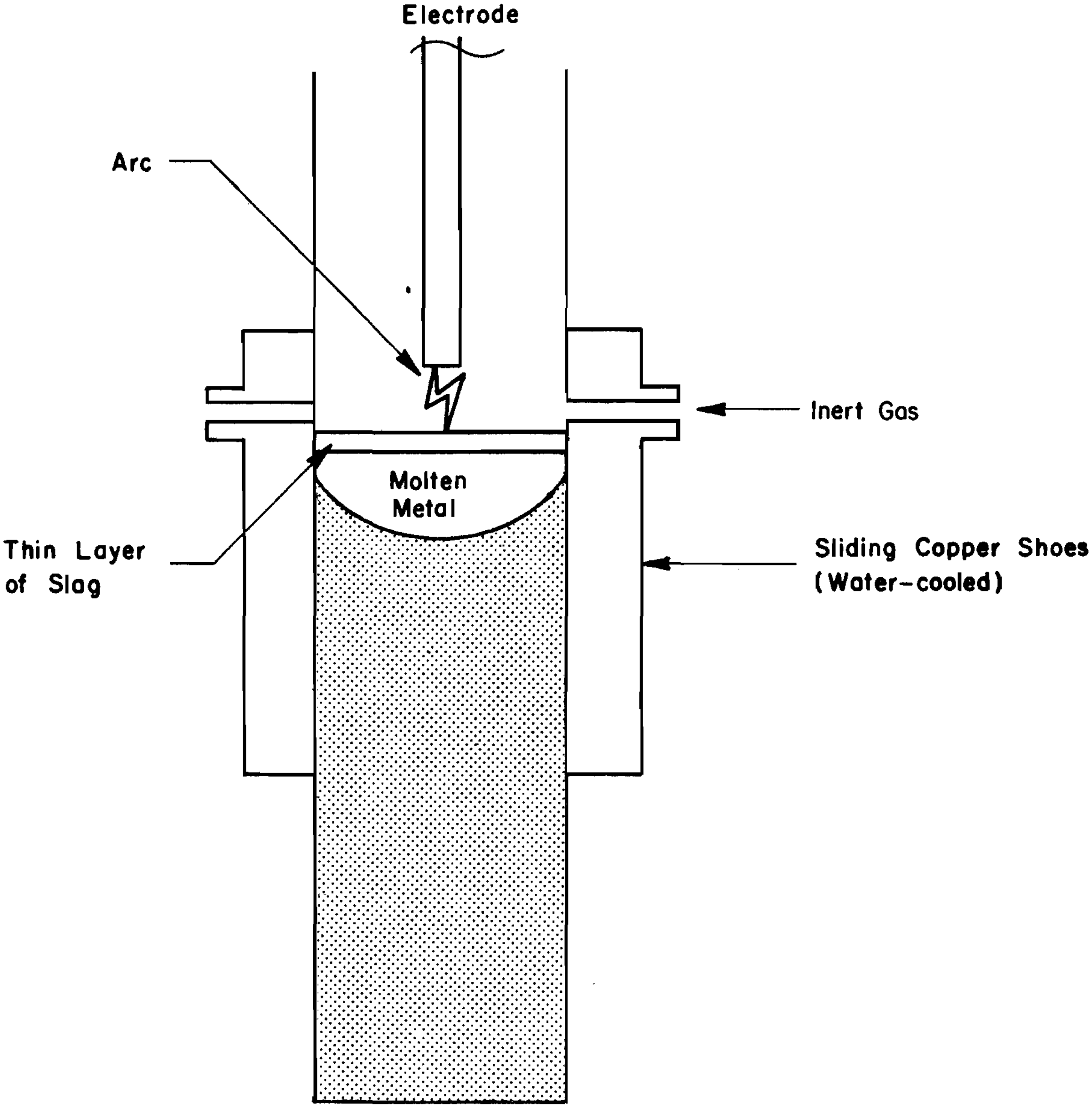

Fig 4. Schematic illustrating the electrogas method of depositing the weld metal.

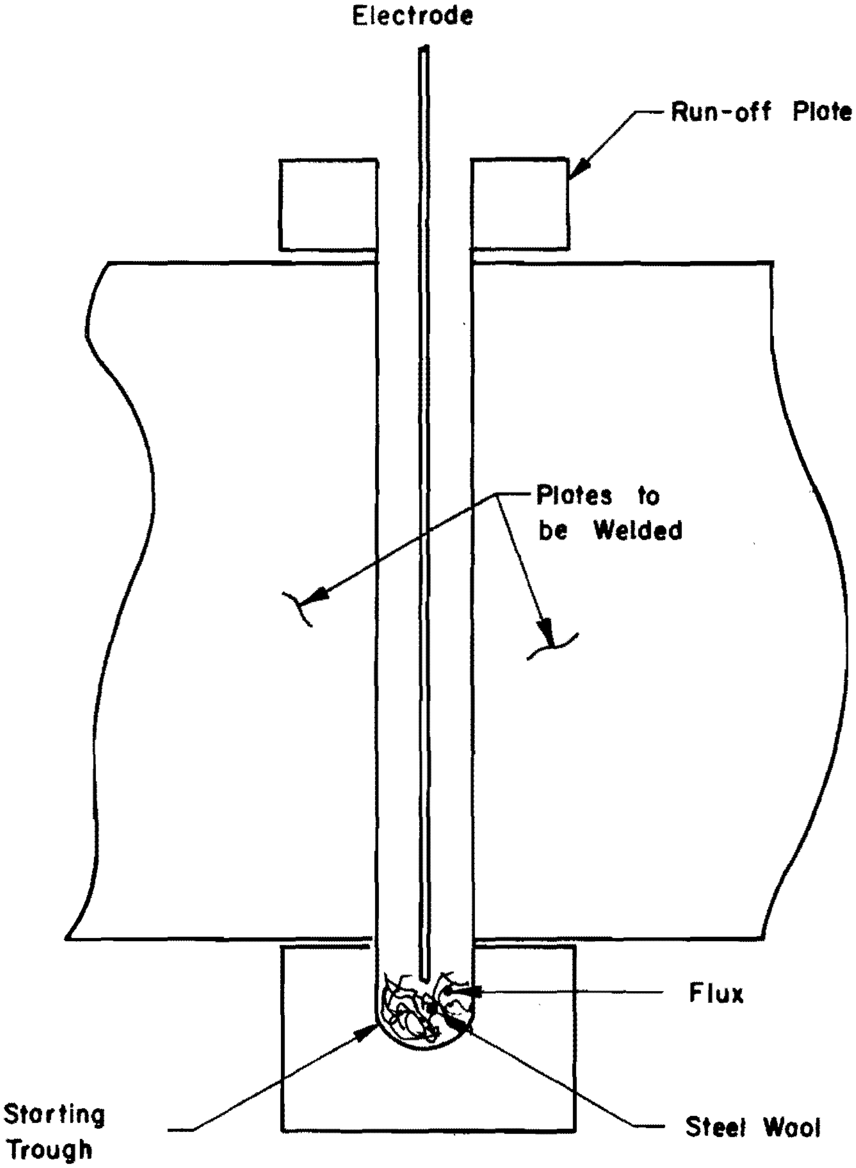

Fig 5. Diagram illustrating the start-up procedure. The electrode is lowered until it starts to arc as it nears the steel wool. Once the flux melts, the electroslag process commences.

Once welding commences it may be necessary to make minor adjustments in the current or the rate the wire is fed. The welding rate, depth of penetration, and pool shape can all be varied by changing the gap spacing of the plates, the voltage, the current, and the rate of wire feed. Obviously the effects of the parameters are closely interrelated. Typical voltage is high, ranging from 36 to 42 volts, and the current ranges from 350 to 800 amperes.

The electrode wires used in the electroslag process, more often than not, are the same as those that would be employed for gas metal-arc or submerged arc welding. For welding low-alloy steels, wires that form a weld that contains an alloy content near that of the base metal are chosen. Wire diameters vary from 3/32 to 5/32 inch, the smaller size being most frequently used with the consumable guides, which usually have inside diameters of 1/8 inch. Sizes larger than 5/32 inch would be difficult to feed because of their excessive stiffness.

Even though the flux consumption using the electroslag welding technique is only about one-tenth of that used with arc welding, the characteristics of the flux are nevertheless extremely important in determining the quality of the resulting weld. The characteristics most important for a desirable flux are that (1) it provides a slag pool having electrical properties which result in a stable welding process (that is to say, large variations in the pool size, the welding current, and the welding voltage will not result in process instabilities); (2) it results in a molten metal with wetting characteristics as required for pool fusion without edge undercuts, yet it is not so wet as to permit leaking around the shoes or molds; (3) it forms a slag crust, typically about 1/32 inch thick, which is uniform and readily removable.

Two methods can be used to greatly extend the range of material thicknesses for which either the basic or consumable nozzle electroslag techniques can be used. One is to slowly oscillate in a horizontal direction the electrode position in the slag pool and the other is to use more than one electrode. Often both methods are used simultaneously for making welds between very thick plates.

Historical Notes

The electroslag process was invented in the United States in the early nineteen thirties by Hopkins (Ref 5), but development of the modern technique was carried out in the USSR during the early nineteen fifties. It began to be more widely used in other countries in the late nineteen fifties, the acceptance being most widespread in Europe. Only in the last five years has it begun to be used in the United States.

Several striking examples of the efficiencies and superior welds which can result from using the electroslag process are available. The first of these, performed by the Ingersoll Machine Company, Rockford, Illinois, was a weldment between two 11-inch thick, 56-inch wide plates to form the base for a duplex scalping machine (Ref 6). Such parts had previously been welded using conventional methods. A saving of 65 man-hours in welding time alone, disregarding equipment cost, was achieved.

A second example (also in Ref 6) occurred during the fabrication of the ways for the rails of two large, numerically controlled, gantry-type milling machines. Included among the butt welds required was one between 12 3/4-inch-thick, 33-inch-wide plates of AISI 1010 steel.

Another example of the capability of the electroslag process to be used on very thick and very wide plates is shown in Fig 6. This weld, made by a Cincinnati based machine tool company, is between plates 8 inches thick and 13 feet wide. The fabricator reported that the consumable guide electroslag equipment used for making these welds paid for itself in making the first joint for which it was used.

Another widely noted use of the process was in fabricating the box columns used in the lower levels of the New York World Trade Center towers (Ref 6). Both the longitudinal plate to plate welds and the splice welds were made using the process.

The first highway bridge in the United States fabricated using the process was built for the Michigan Highway Department (Ref 7). The structure which will carry Lapeer Road over Michigan Highway 78 near Flint contains more than 30 girders with electroslag welds. The process has proven to be especially valuable for making butt welds in flange plates of differing thicknesses.

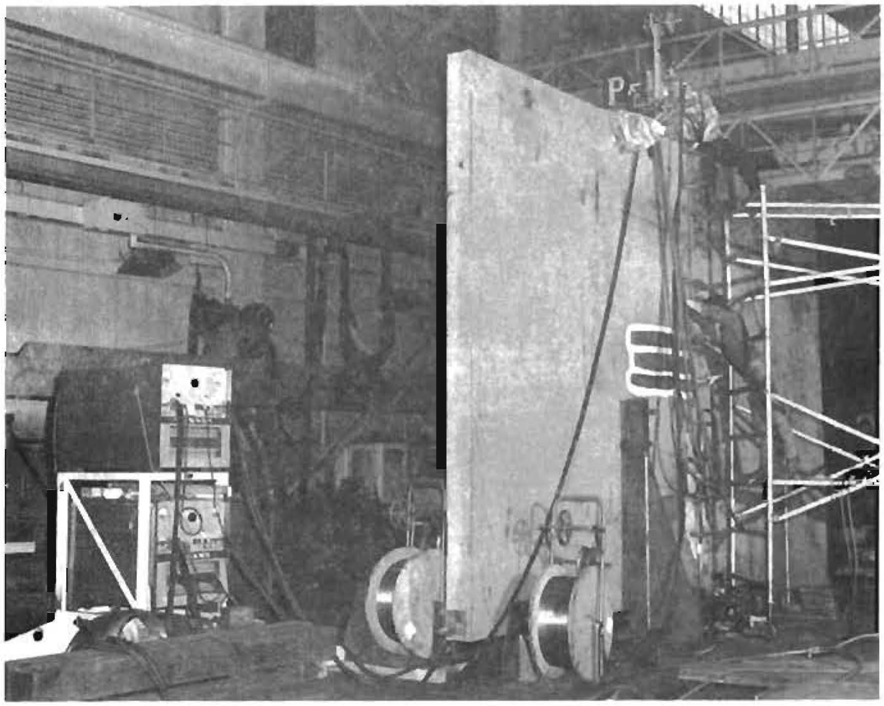

Fig 6. This photograph illustrates a weld 13 feet long between two 8-inch plates using the electroslag method. The weld was completed in four hours and twelve minutes.

Typically these flanges were 18 inches wide. The F. Yaeger Bridge and Culvert Company reports that one of their most significant findings during the fabrication was that the electroslag welding process results in welds which more easily pass the x-ray requirements than those prepared by conventional processes.

Types of Welds

Because the molten pool of weld metal and the covering slag must be constrained, electroslag welding is most satisfactory when the welding is performed in the vertical-up direction. As a consequence, the types of welds which may be performed using the method are slightly limited but include welds for butt joints, corner joints, and T-joints. Perhaps the butt welds are the most important, especially for Texas Highway Department purposes. It is important particularly in view of the capability of the technique for butt welding plates of different thicknesses and plates of different steels. Figure 7 shows a cross section of a typical butt weld between plates of the same thickness (1 inch) and Fig 8 between plates of different thicknesses (1-1/2 inches to 1 inch). Figure 9 illustrates the cross section of a corner weld that was made using the electroslag method and Fig 10 the cross section of a T-weld. Figure 11 shows the cross section of a fillet weld that was used to join a corner between two 1-inch plates with this method. Figures 7 through 11 were extracted from Ref 5.

In addition to the above conventional types of welds, the electroslag method of depositing metal has been used for more exotic purposes. For example, the Russians have reported the joining of ingots of 20-inch thickness. A recent British paper (Ref 8) describes using the consumable guide process with guides of different metal properties to form ingots with smooth gradients of the properties. This provides a method for making steel parts, transitioning from one type to another type of material. One other special application has been the surfacing of steel parts using movable shoes, typically for further machining of the added metal. In one specific application in Japan (Ref 9), the method was used to fabricate cylindrical pressure vessels, the metal from one end to the other being deposited by the electroslag process. Once complete, the surfaces were machined to the required thicknesses.

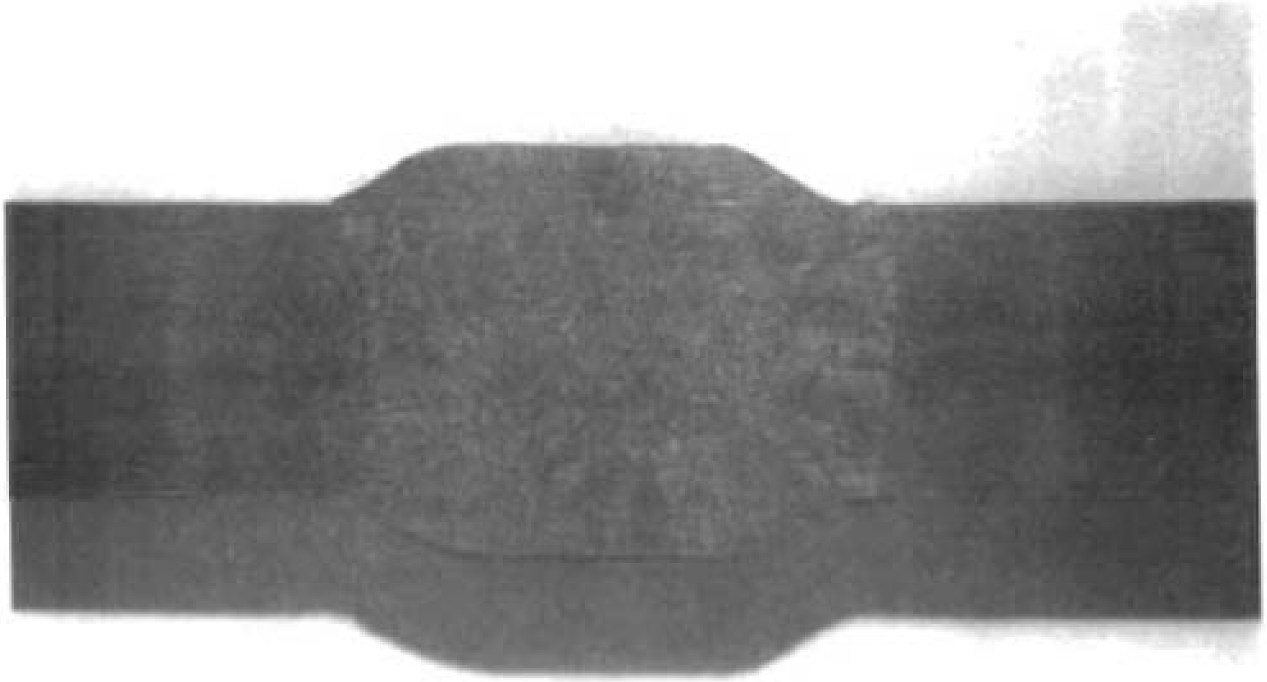

Fig 7. Cross section of butt joint in 1-inch plate.

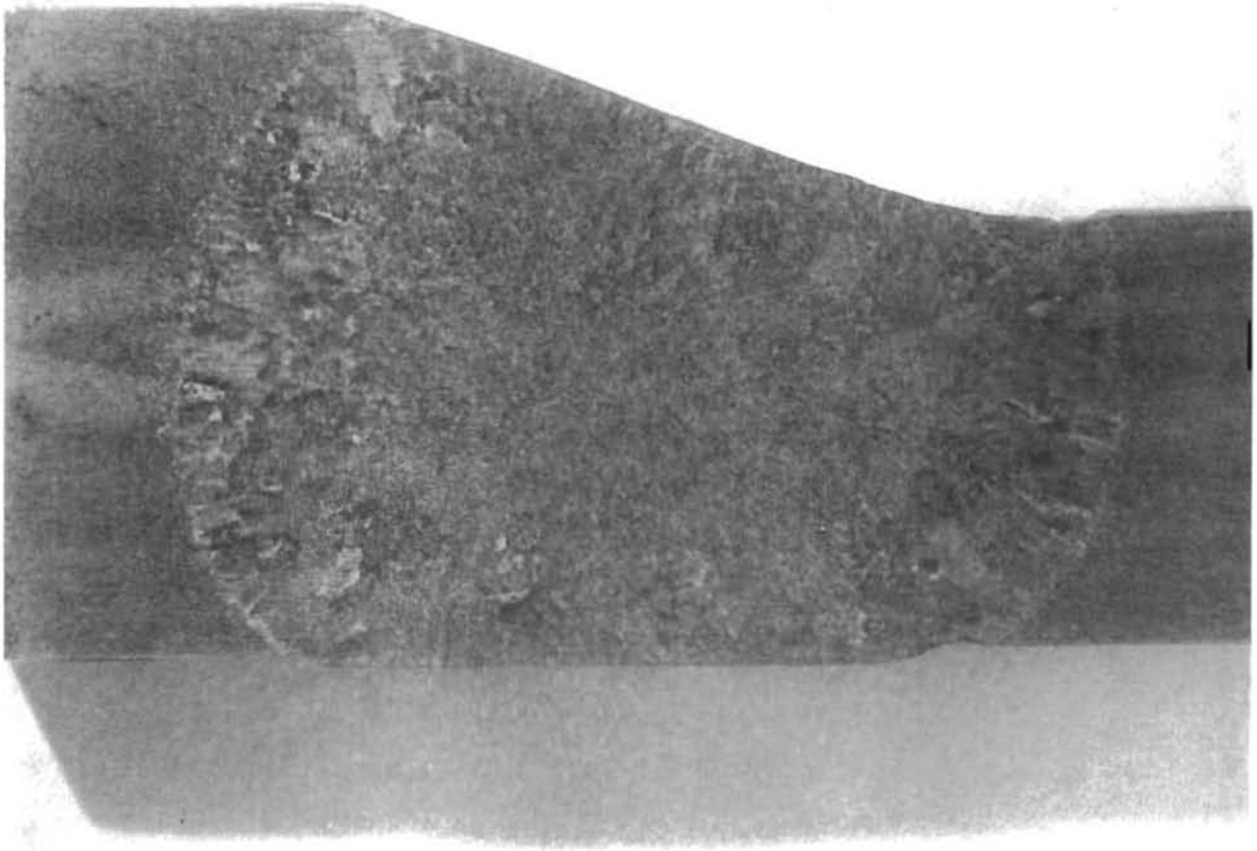

Fig 8. A butt weld between 1-1/2-inch plate and 1-inch plate.

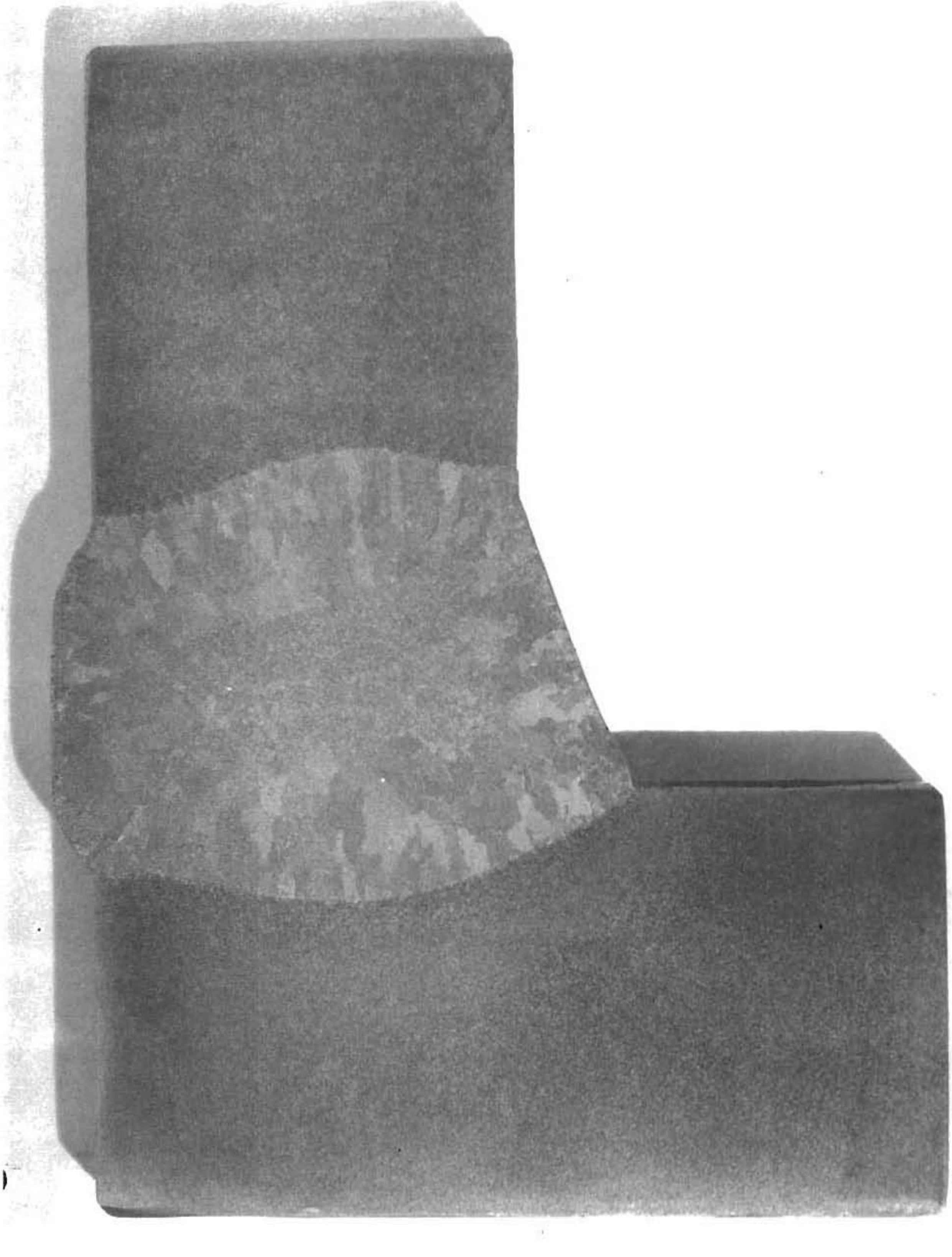

Fig 9. Cross section of a corner joint in 2-inch plate.

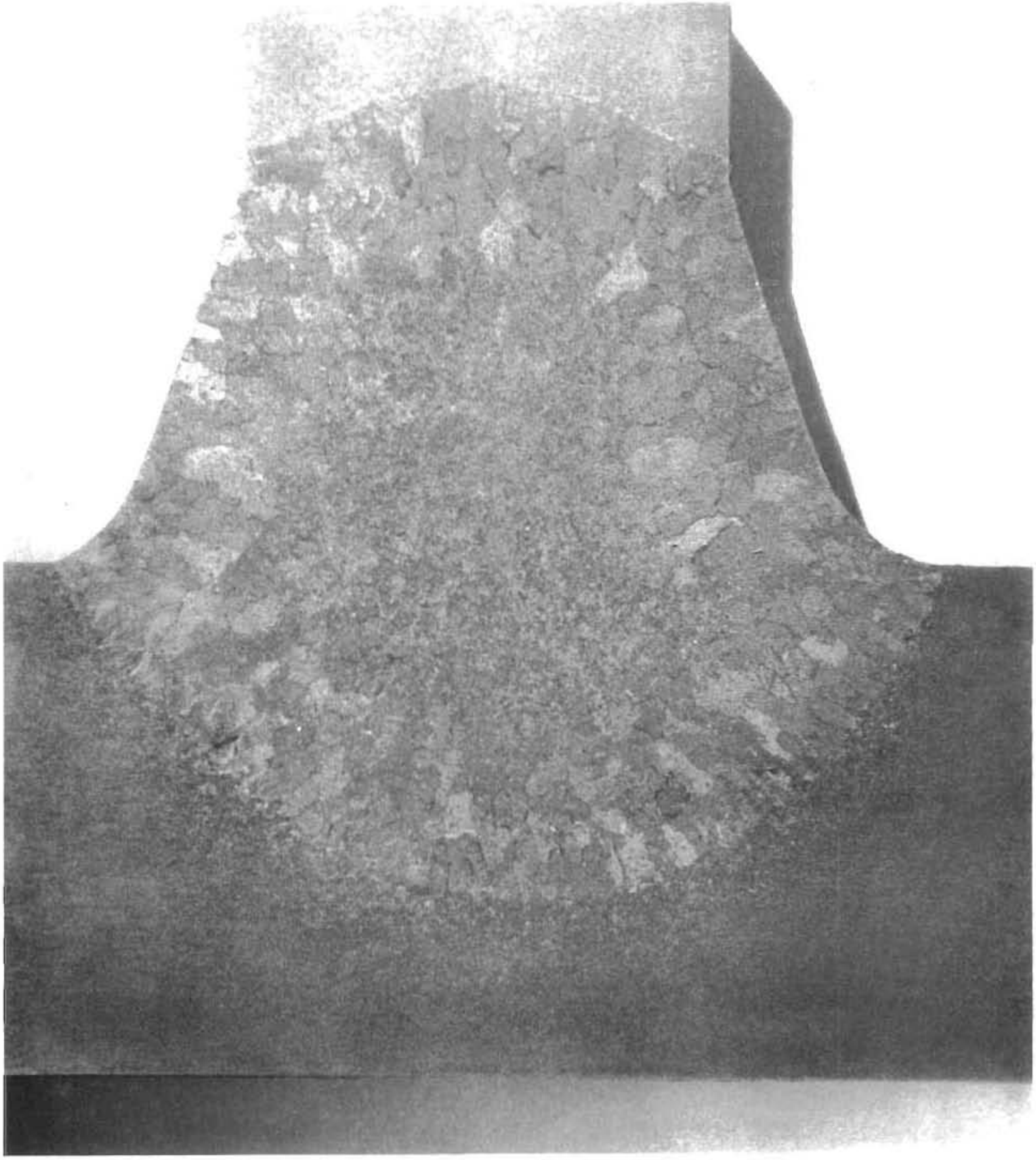

Fig 10. Cross section of a tee joint in 2-inch plate.

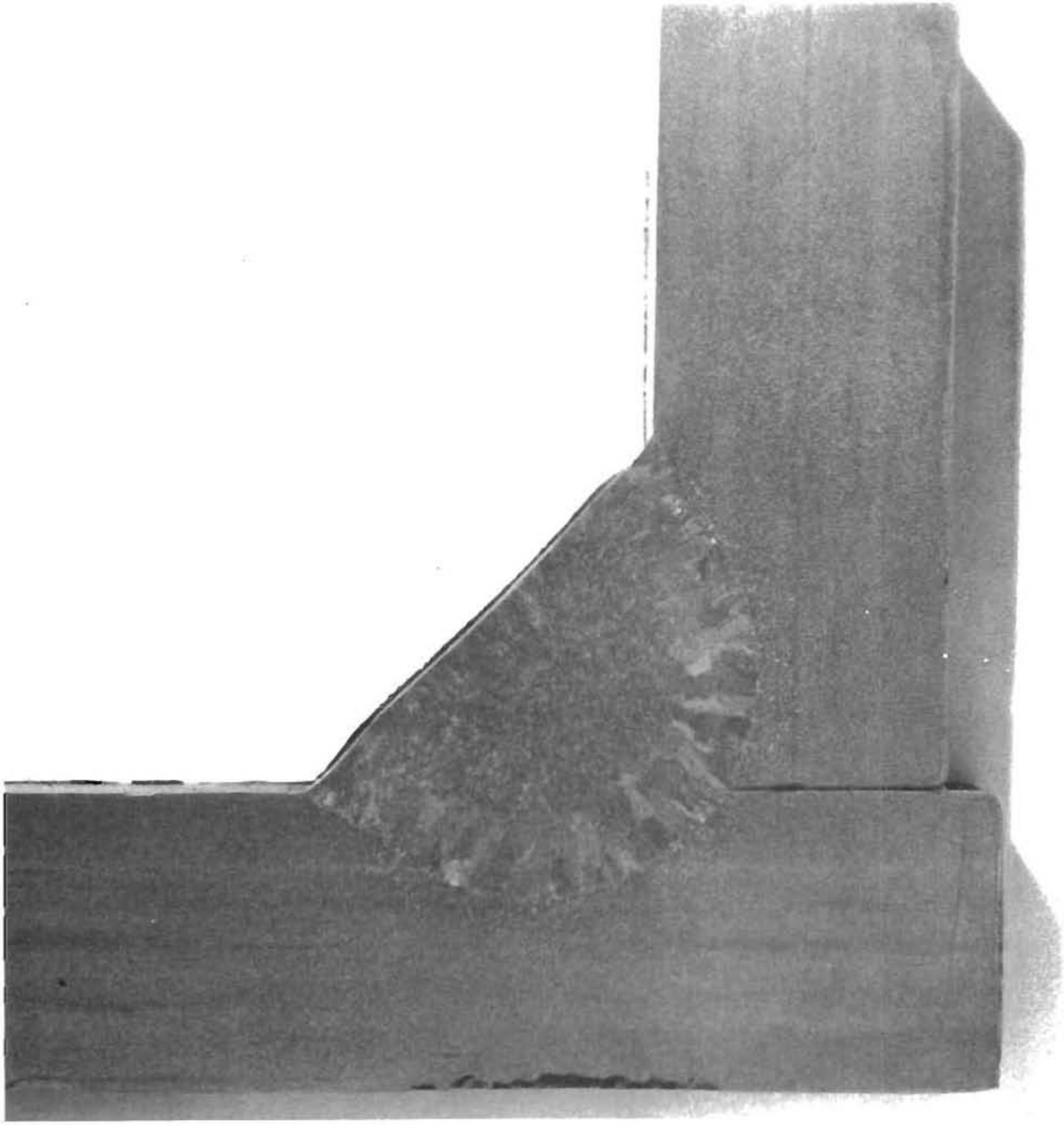

Fig 11. A 1-inch fillet weld done vertically up in a single pass.

Metallurgical Structure of Electroslag Welds

As suggested in the preceding paragraphs the primary source of heat in the electroslag process is within the slag pool. The slag pool temperature often reaches as high as 1500° C. During the one-pass process the heat and cooling cycle is much longer in duration and more global in nature than that experienced from other types of welds. This means that electroslag weld material can be likened more to cast steel than to typical weld metal. Figure 12 illustrates the time histories of the temperature cycles at a point in the weld metal deposited by the submerged arc process and the metal deposited by the electroslag process. There are two extremely important consequences of the differences between the two cycles; one is that the longer duration of the cycle has important effects on the metallurgical properties of the resulting weldment and the other is that because such a large volume of metal is subjected to the cycle the volumetric deformations become much more important. The effect of the deformations is usually magnified by the very large material thicknesses for which electroslag welds are appropriate. The compressive stresses experienced during heat buildup are not so significant. However, during the following cool-down progressing from the water-cooled shoes and from the massive plates inward, severe tensile stresses occur near the center of the weld. This, of course, is a dangerous state because of the possibility of so-called hot cracking.

The cooling process just described leads to the formation of large austenitic grains near the periphery of the welds. This is shown very clearly in Fig 13, which is the cross section of an electroslag butt weld between 4-inch-thick T-1 steel plates. Such a grain structure is detrimental in that it may hamper subsequent ultrasonic examination and may lead to a deficiency in the required ductility or notch toughness. Frequently when reduced ductility is a problem, normalizing is prescribed after welding. To increase the toughness several Russian investigators have suggested limiting the phosphorus, silicon, sulphur, and carbon contents.

A further influence of the grain structure on the weldment properties occurs because of a tendency for the grains to be oriented. When a very deep (large depth-to-transverse dimension) pool of weld metal is used the flow of heat tends to be more perpendicular to the direction of the weld and the

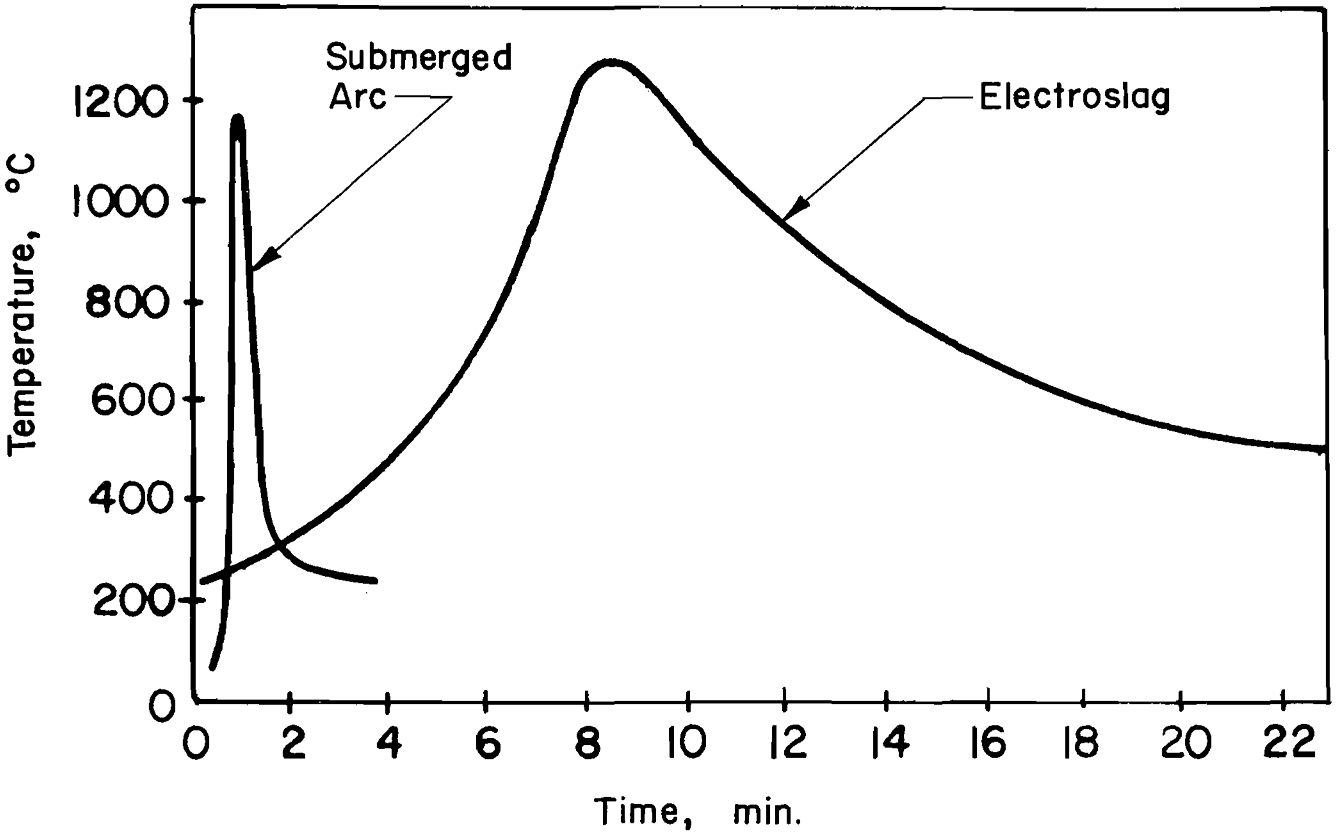

Fig 12. Comparison of the thermal cycles of submerged arc welding and electroslag welding (from Ref 10).

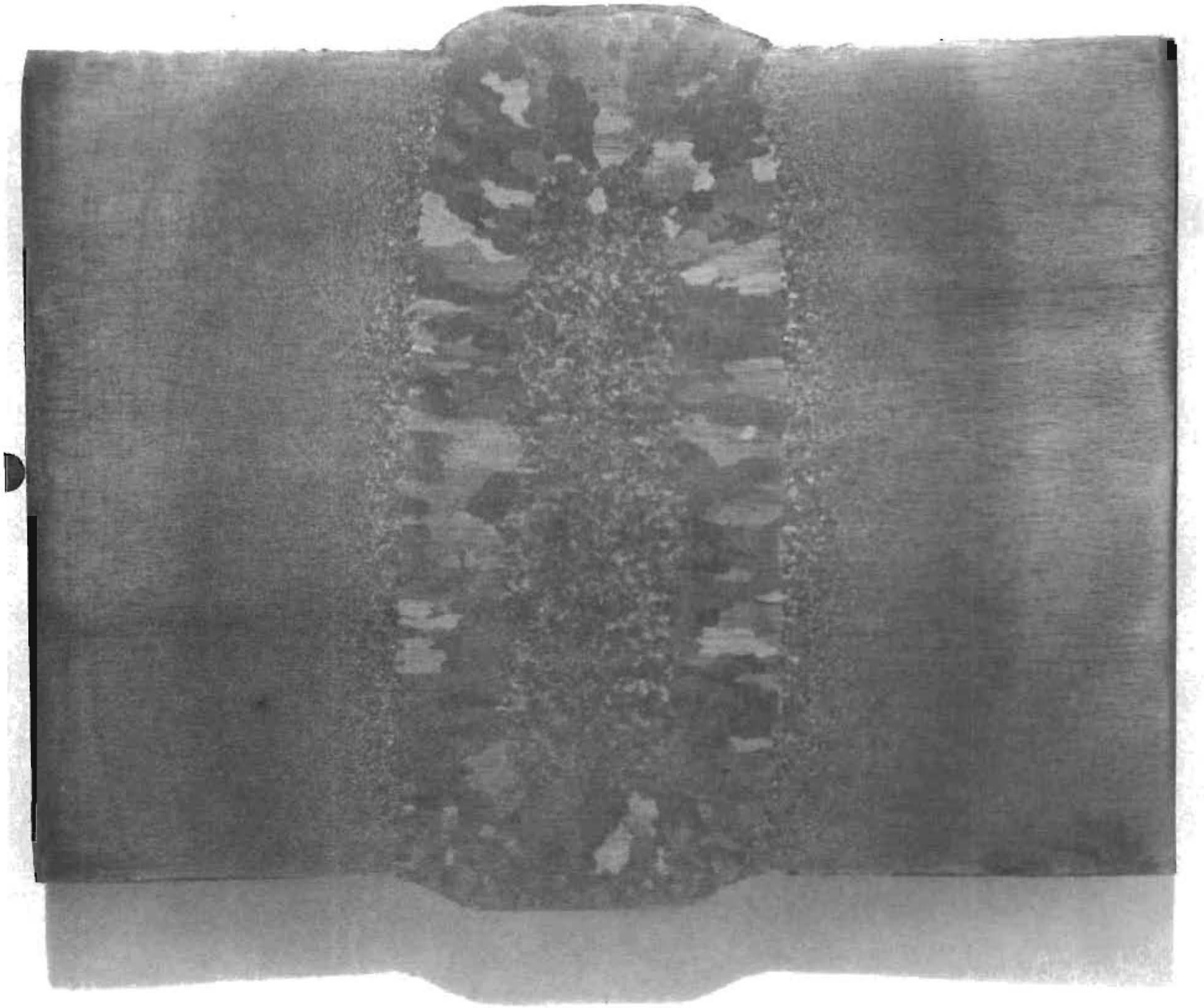

Fig 13. A cross section of an electroslag butt weld between 4-inch-thick T-1 steel plates illustrating the coarse grain structure near the periphery of the weld metal (from Ref 5).

resulting grains are oriented in the direction of the weld. This is illustrated in the cross section of an electroslag weld shown in Fig 14, taken from Ref 5. If the pool of molten metal is kept shallow this vertical grain orientation is not so pronounced and the resulting weld properties are enhanced.

Objectives

The use of electroslag welding in industry is increasing and is being used more and more for structures that will be subjected to fatigue loading, e.g., cranes, bridges, ships, presses. The amount of information published in the literature concerning the fatigue strength of electroslag welded joints is limited. In order to obtain data on the fatigue strength of butt joints made by this welding process and to develop confidence so that such welds can be used in steel bridges for Texas highway structures this testing program was initiated.

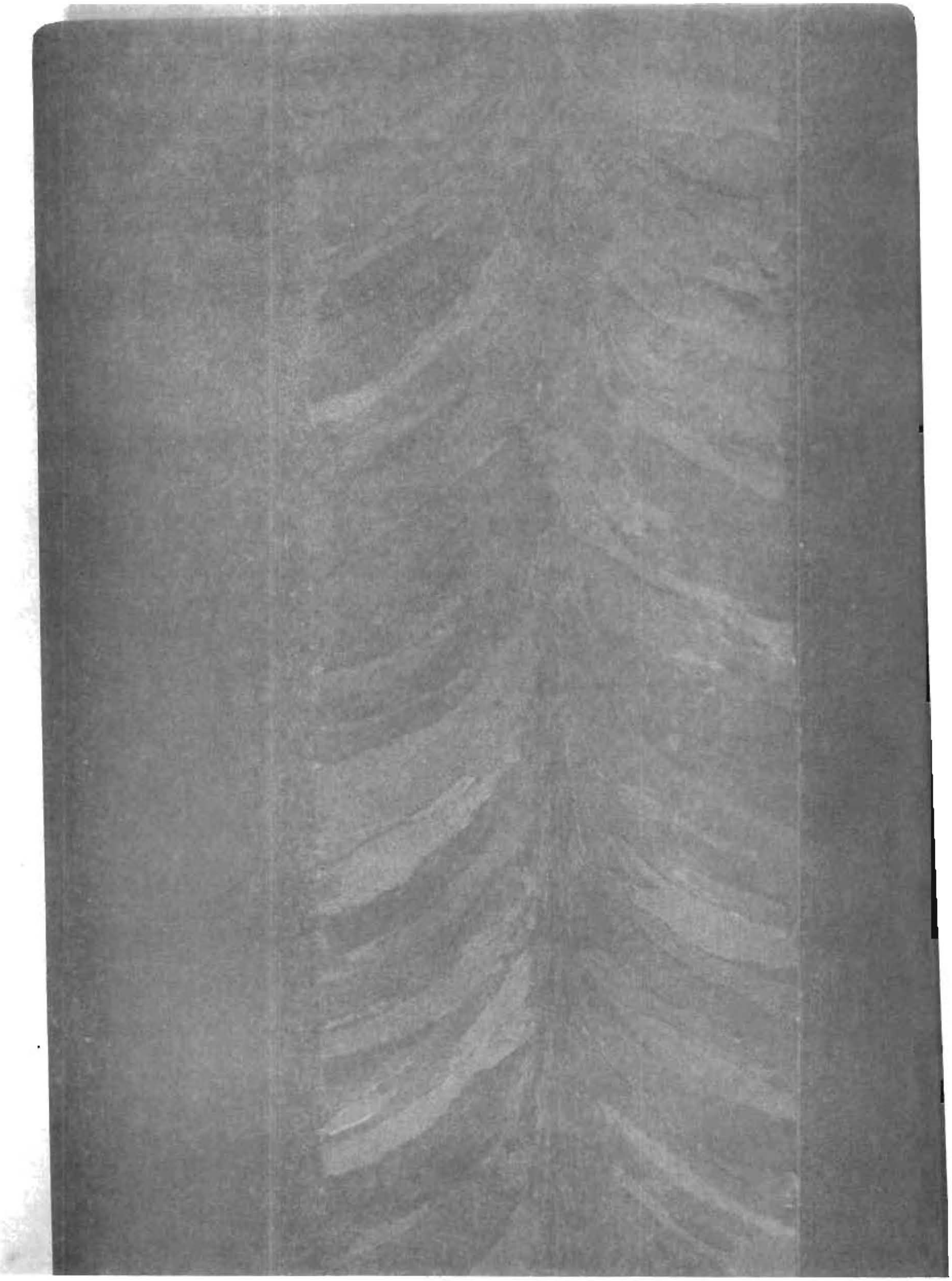

Fig 14. Vertical cross section of an electroslag weld (the weld direction was up) showing the rather severe orientation of the grain structure. This effect could have been minimized by generating a more shallow pool of weld metal (from Ref 5).

CHAPTER 2. SPECIMEN PREPARATION

Welding

Three firms contributed to the program, each preparing two samples. One sample was from two plates of ASTM A36 steel, the other from two plates of ASTM A588 Grade A steel. In every instance, two 1 1/4-inch plates with dimensions as shown in Fig 15 were butt welded together, giving a total of six geometrically similar samples. To avoid commercial use of the resulting data, the three fabricators are referred to as A, B, and C throughout the text of this report. The chemical compositions of the plate steels where known are summarized in Table 2.

The conditions for making the welds are summarized in Table 3. Engineers from the Texas Highway Department and the Federal Highway Administration witnessed the welding of the plates by two of the three fabricators. The data sheets for the welds made by the other fabricator were prepared by the personnel of its shop.

Three full-size fatigue specimens were flame cut in the shops of Combs Engineering Corporation, Houston, Texas, from each sample weldment. With the exception of one A36 sample, this step was taken after radiographic inspection. The one A36 sample was also x-rayed but only after flame cutting. The plan by which the specimens were cut is shown in Fig 16.

Cutting of the three full-size specimens from each weld sample yielded 18 such specimens for fatigue testing. Each specimen was numbered as shown in Table 4. Specimens for a conventional laboratory characterization were made from the remaining four pieces of scrap from each sample (see Fig 16). These included a round tensile test coupon (0.505-inch diameter) from each rolled plate and from each weld, tensile strength coupons from across each weld, Charpy impact specimens of the weld metal, and both side and face bend specimens. The numbers and origins of these conventional specimens are indicated in Table 5.

Radiographic Inspection

Prior to the cutting operation the portable radiographic equipment of the

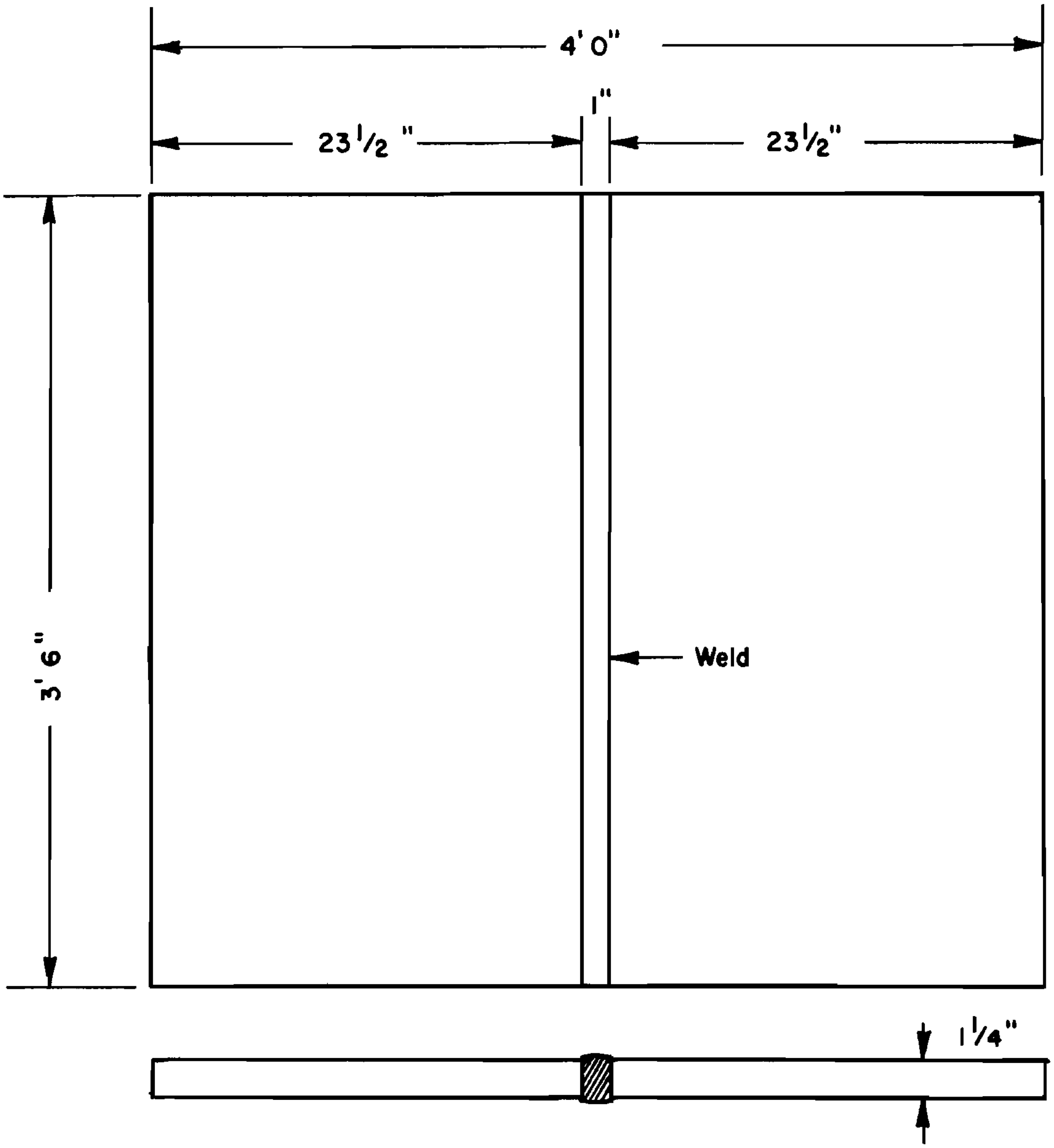

Fig 15. Details and dimensions for each of the six electroslag weldments.

TABLE 2. CHEMICAL CONTENTS OF BASE PLATE MATERIAL IN PERCENT

Shop	Base Metal	C	Mn	P	S	Cu	Si	Cr	V
A	A36	0.22	1.18	0.010	0.028		0.026		
	A588*	0.15	1.20	0.012	0.022				
B	A36	0.18	0.96	0.009	0.015				
	A588*	0.16	1.03	0.006	0.019	0.27	0.26	0.54	0.07
C	A36	Not Available							
	A588*	0.14	1.03	0.010	0.015	0.29	0.23	0.56	0.05

*All ASTM A588 Grade A.

TABLE 3. WELDING CONDITIONS

Shop	Base Metal	Voltage, volts	Current, amps	Wire Diam., in.	Guide Tube, in.
A	A36	36/37	550	1/8	5/8
	A588	36/37	550	1/8	5/8
B	A36	38	350	3/32	1/2
	A588	36	340	3/32	1/2
C	A36	38	480	3/32	5/8
	A588	38	475	3/32	5/8

TABLE 4. NUMBERING OF THE 18 FULL-SCALE FATIGUE SPECIMENS

Shop	Base Metal	Specimen Numbers		
A	A36	13	14	15
	A588	16	17	18
B	A36	7	8	9
	A588	10	11	12
C	A36	1	2	3
	A588	4	5	6

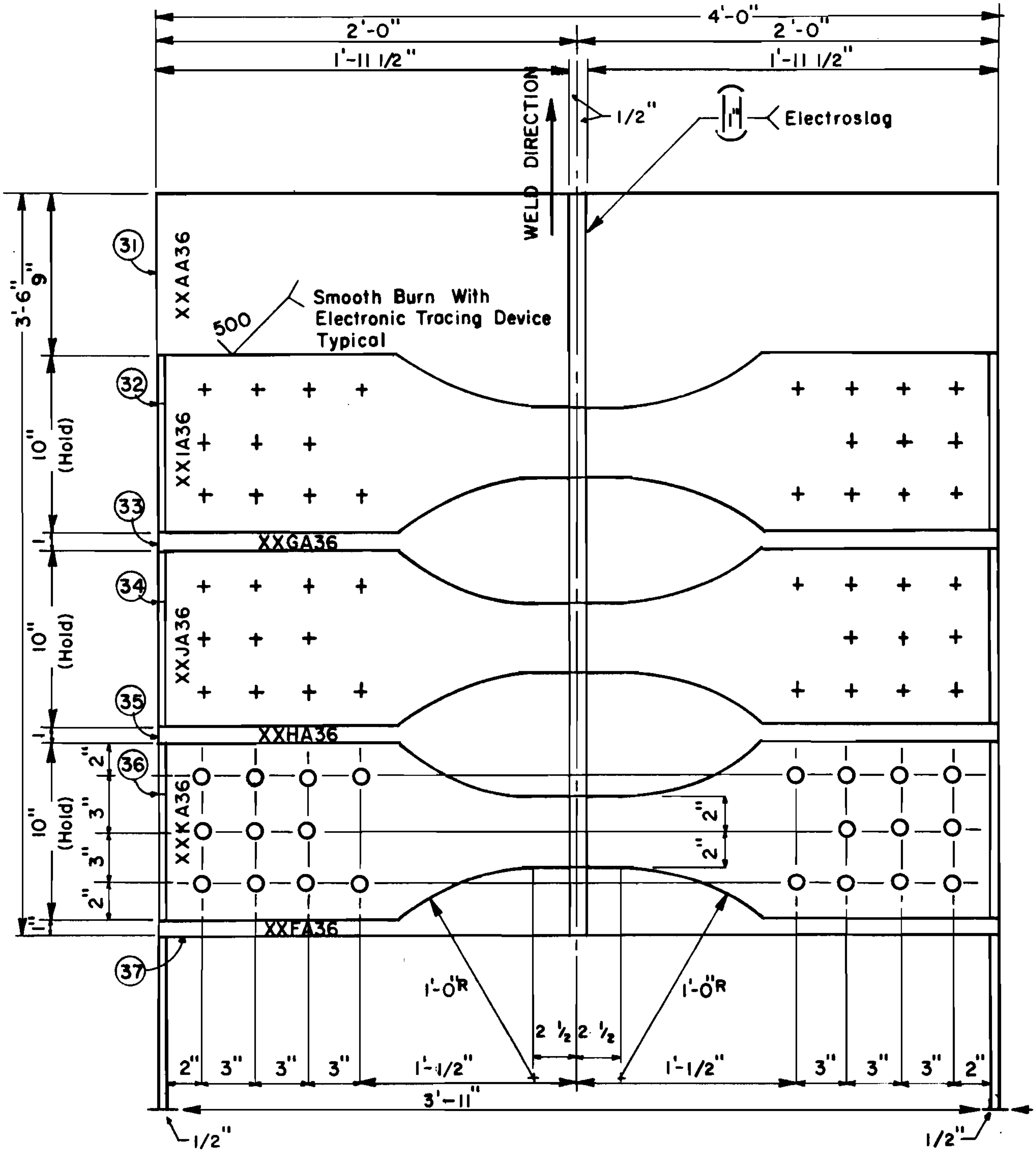

Fig 16. The pattern for cutting the full-size specimens from the welded plates.

TABLE 5. SUMMARY OF ALL TEST SPECIMENS

	Shop A		Shop B		Shop C		Total Specimens
	A36	A588	A36	A588	A36	A588	
Full-size fatigue specimens	3	3	3	3	3	3	18
Charpy impact specimens	12	12	12	12	12	12	72
Weld tensile coupons (0.505" diameter)	1	1	1	1	1	1	6
Base metal tensile coupons (0.505" diameter)	2	2	2	2	2	2	12
Reduced section coupons (1" × 1 1/4" test section)	1	1	1	1	1	1	6
Side-bend test specimens	2	2	2	2	2	2	12
Specimens for Brinell hardness			1	1	1	1	4

Texas Highway Department was used to make a complete X-ray inspection of all welds. Changes in penetration density as small as 2 percent could be detected by this inspection. This process was followed for every specimen except for the first plates welded by Fabricator C, whose A36 specimens were X-rayed after they had been cut into fatigue specimens.

Except for those at locations near the starting and stopping points, which usually lie within the start-up and run-off plates, only one flaw was found. That exception was a serious defect approximately 3 inches from the start-up point of the A588 specimen welded in shop A. Upon review of the inspection report it was noted that the welding operation had been terminated at this point due to binding of the wire electrode feed mechanism. The slab was immediately chipped away, a new guide tube was inserted, the wire was again lowered into position, and welding reinitiated, but the result of this stopping and starting was that the weld contained several defects and inclusions. Figure 17 shows a print of the weld X-ray and Fig 18 shows a photograph of the surface of the weld following the removal of the copper shoes. Because of the defects this portion of the weld was not used in the testing program.

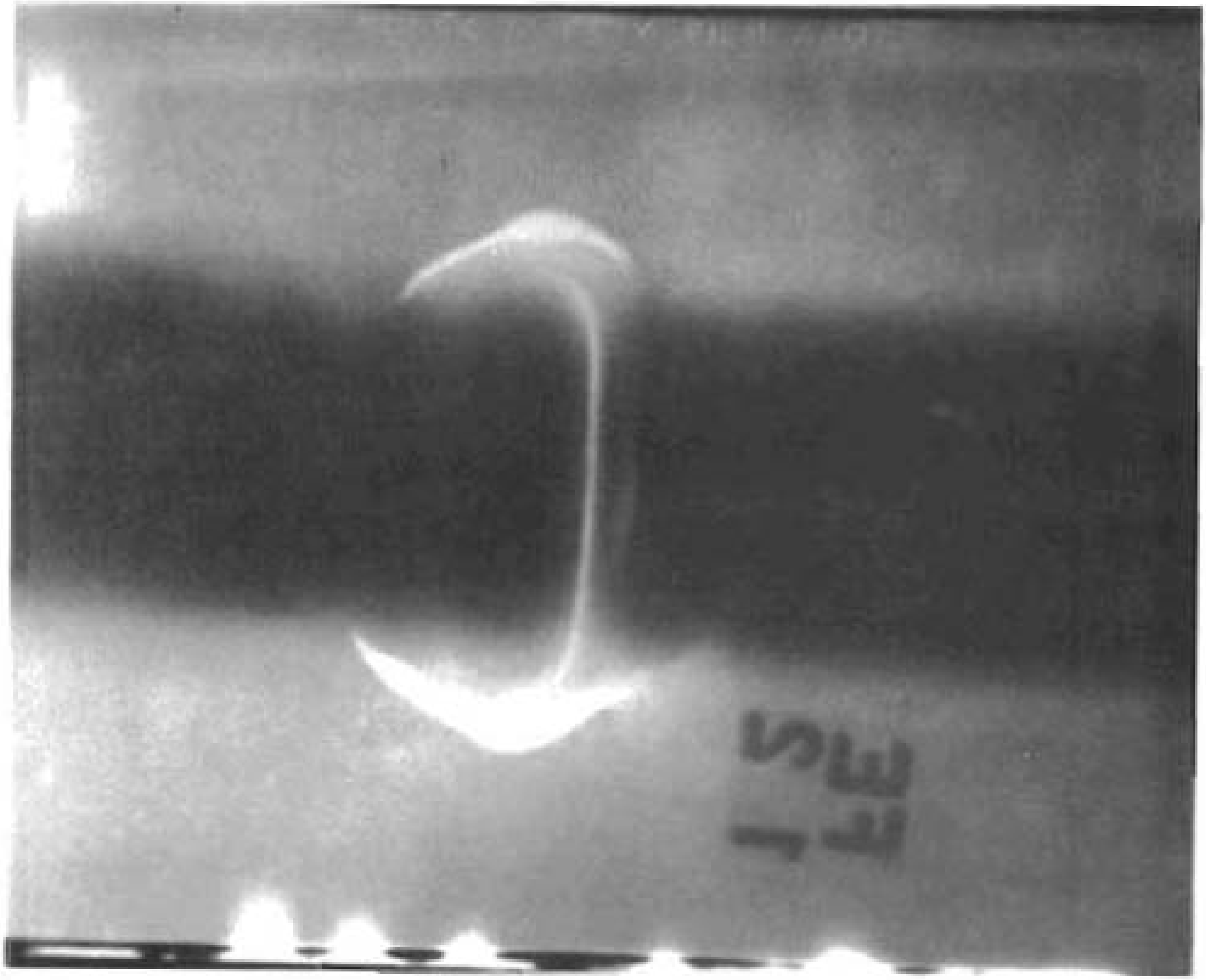

Fig 17. Print of the weld X-ray.

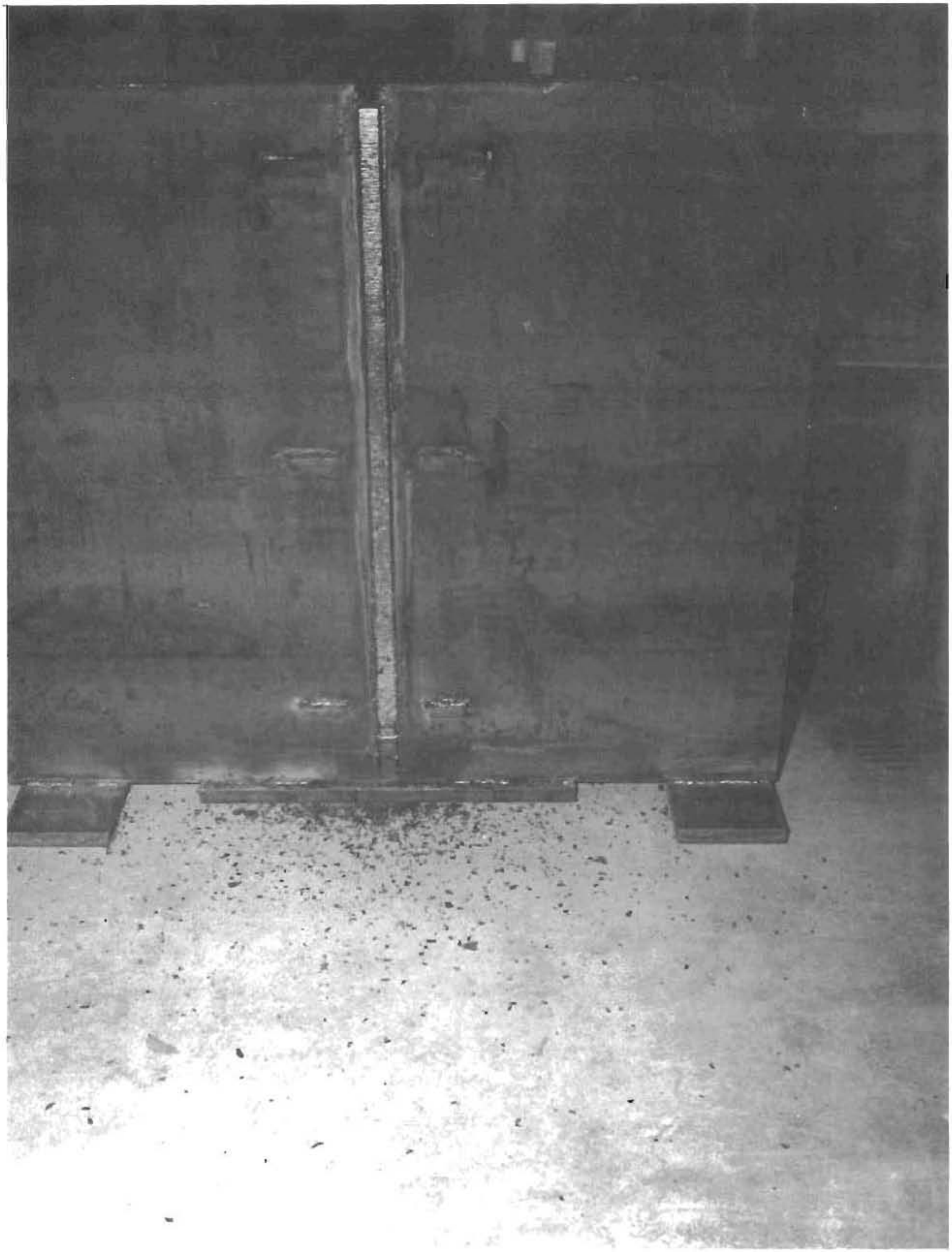

Fig 18. Weldment at end of welding operation. Notice discontinuity near bottom where welding was temporarily halted.

CHAPTER 3. CONVENTIONAL MATERIAL PROPERTY TESTS

Static Tensile Tests

Round, 2-inch-long tensile specimens, 0.505 inch in diameter, were extracted from every plate and from every weld.* These specimens were tested in tension in a universal testing machine to determine their yield point, ultimate strength, and elongation. It will be noted that the plate properties summarized in Table 6 essentially agree with those indicated by the mill certificates tabulated in Table 7. These results for the parent plate are shown in Table 6 and for the welds in Table 8.

Stress-strain curves were prepared using the data collected in the tensile tests of the welds (see Fig 19A). A mechanical extensometer was used to monitor the strains. Generally, definitive yield points were not found, so yield strengths corresponding to a 0.2 percent offset are reported. It is of interest to note that, except for the A588 specimen from Fabricator B, the yield strengths for the A588 welds were equal to or more than that required by AWS specifications (Refs 1 and 2), which are also in Table 8. Further, the welds were found to be quite ductile.

Brinell Hardness Tests

The Materials and Tests Division of the Texas Highway Department ran Brinell hardness tests from the center line of the weld outward, through the heat affected zone, well out into the parent plate material. These tests were performed on the specimens from Fabricators B and C. These tests consist of measuring the diameter, in millimeters, of the indentation produced by a small sphere pressed with 3000 kg of force onto the surface of the metal. The results are shown in Table 9.

Contrary to our preconceived idea, the region near the fusion of weld and base metal was not found to be harder than the undiluted weld metal. Rather, a gradual transition was found between the weld hardness and the plate hardness with no abrupt transition observable in the fusion zone.

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*Orientation of base metal tensile coupons with respect to plate rolling direction is unknown. These specimens were cut from strips normal to the length of the weld. Weld metal coupons were taken along the weld length as specified by AWS.

TABLE 6. AVERAGE TENSILE PROPERTIES FROM THE TWO PARENT (PLATE) METALS OF EACH SPECIMEN

Shop	Parent Metal	Yield Point, psi	Ultimate Strength, psi	Elongation, % (2" GL)
A	A36	56500	83100	28.8
	A588	55000	79300	28.2
B	A36	46300	68300	33.1
	A588	59000	86000	24.5
C	A36	44000	75300	34.5
	A588	56000	83000	31.5

TABLE 7. SUMMARY OF THE MATERIAL PROPERTIES REPORTED BY THE MILL TEST REPORTS AVAILABLE

Shop	Parent Metal	Yield Strength, psi	Ultimate Strength, psi	Maximum Elongation, %
A	A36	54500	78000	25
	A588	64720	88930	25
B	A36	41800	74100	27.5
	A588	60900	88100	23
C	A36	-----------Not Available----------------		
	A588	55600	80400	25.5

TABLE 8. SUMMARY OF THE WELD PROPERTIES AS DETERMINED AT THE UNIVERSITY OF TEXAS

Shop	Parent Material	Yield Strength, psi	Ultimate Strength, psi	Elongation, %	Young's Modulus, psi	Reduction of Area, %
A	A36	49900	75000	31	31.6×10^6	63
	A588	50000	74000	32	32.8×10^6	69
B	A36	51500	77000	32	31.7×10^6	64
	A588	48500	77000	26	32.7×10^6	64
C	A36	48300	75000	27	29.5×10^6	61
	A588	58500	101000	26	28.0×10^6	63
			Minimum			
Weld Properties Required by AWS D2.0-69	A36	36000	60000	24		40
	A588	50000	70000	21		40

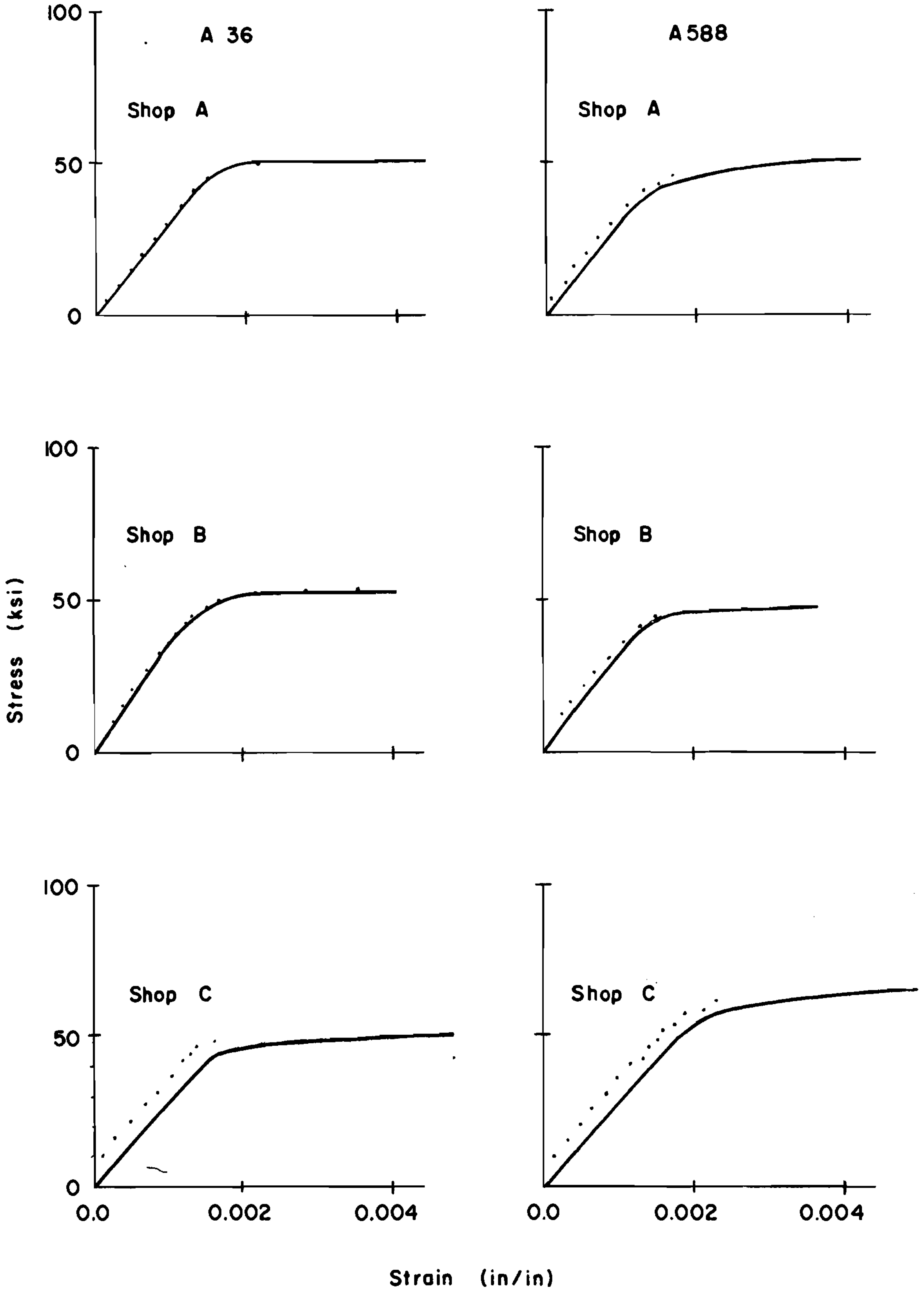
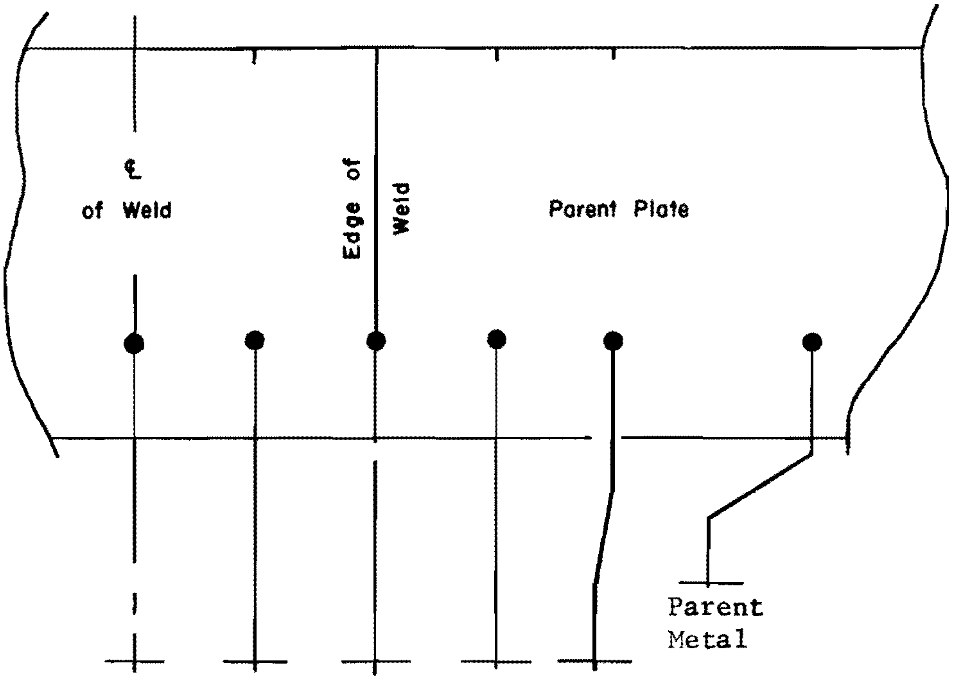


Fig 19A. Stress-strain curves of the six welds.

TABLE 9. RESULTS OF THE BRINELL HARDNESS TESTS



Shop							Parent Metal
B	A36	4.5		4.6	4.5	4.7	4.6
		4.6					4.7
		4.5					4.6
	A588	4.6		4.5	4.4	4.4	4.3
		4.6					4.4
		4.5					4.3
C	A36	4.7	4.6	4.8	4.9	5.0	5.1
		4.7					5.0
		4.6					5.0
	A588	4.1		4.1	4.3	4.7	4.5
		4.1		4.3	4.4	4.7	4.5
		4.1					4.5

There is an approximate relationship between the Brinell hardness and the Rockwell hardness and also the ultimate tensile strength. This relationship is tabulated in Table 10. Because they are more commonly used the Brinell numbers corresponding to the Brinell hardnesses are also shown. A comparison of the approximate tensile strengths deduced from the Brinell hardness tests and those measured for the round tensile specimens is given in Table 11.

Charpy Impact Tests

To get an estimate of the ductility at cold temperatures to evaluate the brittle transition points, twelve Charpy impact specimens were extracted from each of the six weldments. These specimens had dimensions as prescribed by AWS Specification D2.0-69 and were extracted according to Fig 19B. Six Charpy specimens were taken from the top and six from the bottom facing one another as shown in Fig 19B. All twelve were taken from the same section of the weld. The notches were machined from the inside faces. All of these steps were taken to minimize the effects of property gradients, both along the weld and through the thickness, on the measured impact energies. It should be noted that these specimens were machined with the notches at 90 degrees to the orientation indicated in Fig A10 of Ref 1. One specimen from each set was tested at a given temperature, the given temperatures ranging from less than -40°F to 74°F. This provided the data required to draw impact energy versus temperature curves for each of the six welds. These curves (Fig 20, A-F) indicate that the approximate transition temperature for every weld is below 0°F. The curves and the tabulation of Table 12 both indicate the welds were all ductile above 0°F, with the exception of the weld between A36 plates (Fig 20C) by Fabricator C. It is possible that the coarse grains and their orientations at the roots of the notches had some influence on the data scatter. However, these data do not appear to be much different from Charpy energies usually found in welds for these types of steels.

The method by which the tests were run was somewhat unique. The impact tester itself was moved into the large cold box used to condition the specimens so that rather than having to hurry the tests to insure that specimen temperatures did not change, it was possible to perform the tests deliberately and carefully without chance of significant temperature changes. Otherwise the tests were performed as prescribed by AWS specification.

TABLE 10. CONVERSIONS BETWEEN BRINELL HARDNESS AND ROCKWELL "B" HARDNESS; CORRESPONDING ULTIMATE TENSILE STRENGTH

Brinell No.	Brinell, mm	Rockwell "B"	Ultimate Tensile Strength, ksi
228	4.0	98	107
217	4.1	96	103
207	4.2	95	98
196	4.3	93	95
187	4.4	91	91
179	4.5	89	87
170	4.5	87	84
163	4.7	85	81
156	4.8	83	78
149	4.9	81	75
143	5.0	79	72
137	5.1	77	70
131	5.2	74	66
126	5.3	72	64

TABLE 11. COMPARISON OF MEASURED ULTIMATE TENSILE STRENGTH AND TENSILE STRENGTH DEDUCED FROM BRINELL HARDNESS TESTS

Shop			Measured Ultimate Tensile Strength, ksi	Ultimate Tensile Strength from Brinell Hardness Tests, ksi
B	A36	Weld	77.0	86.0
		Plate	68.3	83.0
	A588	Weld	77.0	85.0
		Plate	86.0	94.0
C	A36	Weld	75.0	82.0
		Plate	75.3	71.0
	A588	Weld	101.0	103.0
		Plate	83.0	87.0

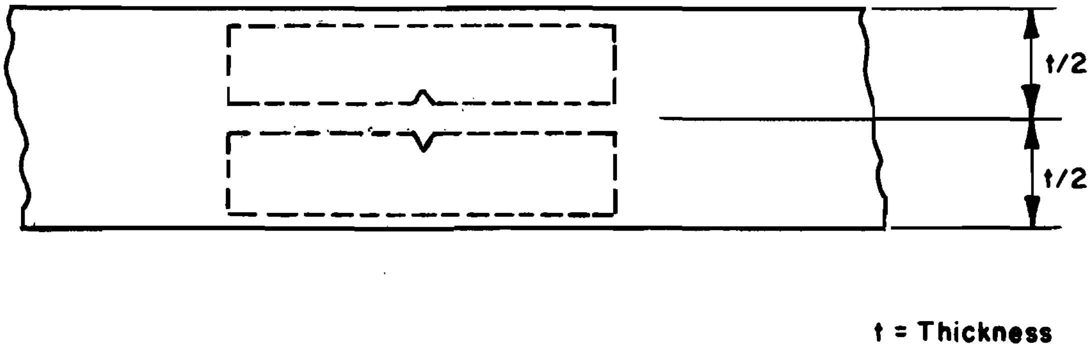


Fig 19B. Sketch showing orientation of the Charpy impact specimens taken from the weld.

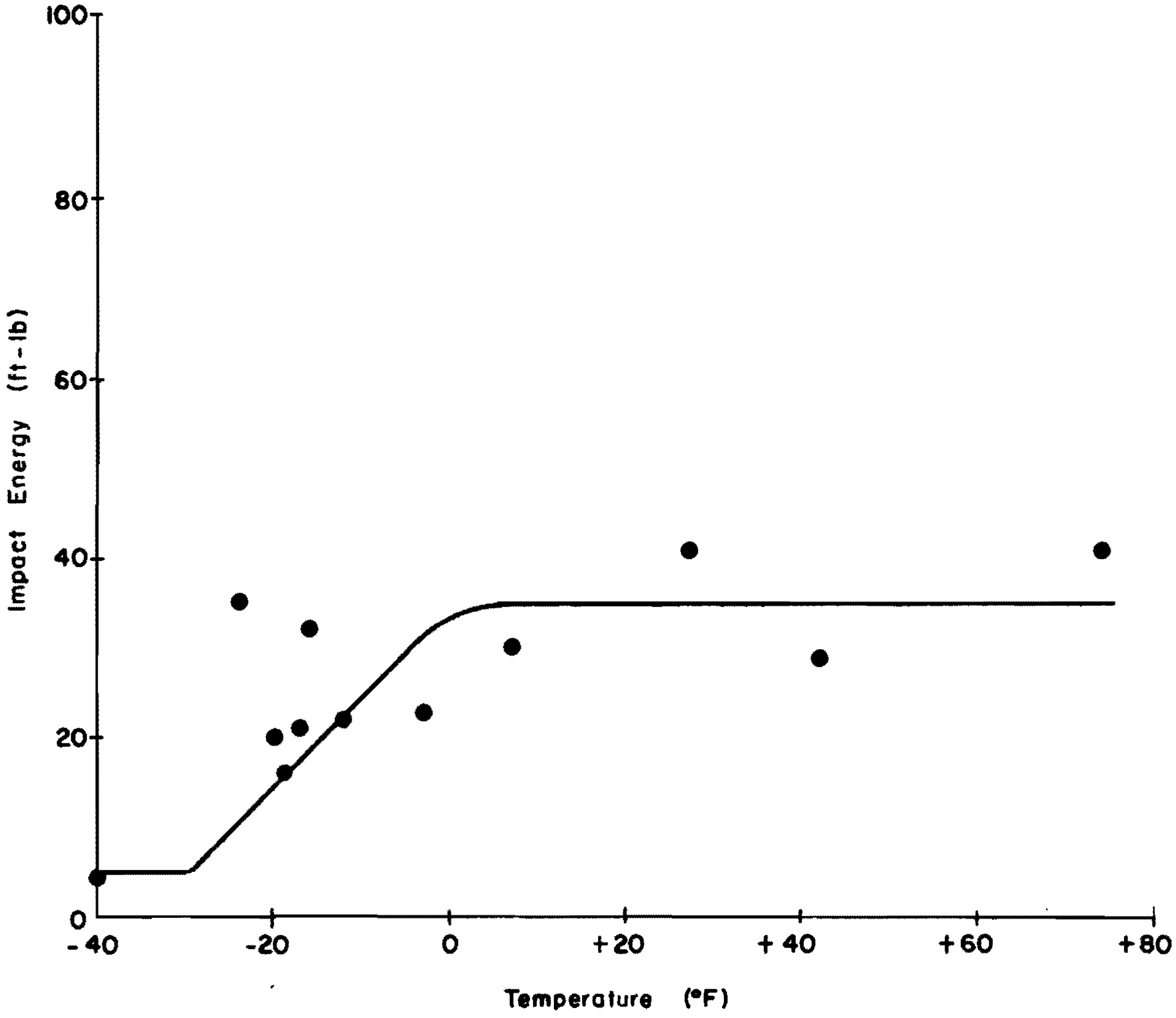


Fig 20A. Impact energy versus temperature, A36 weld metal, Fab A.

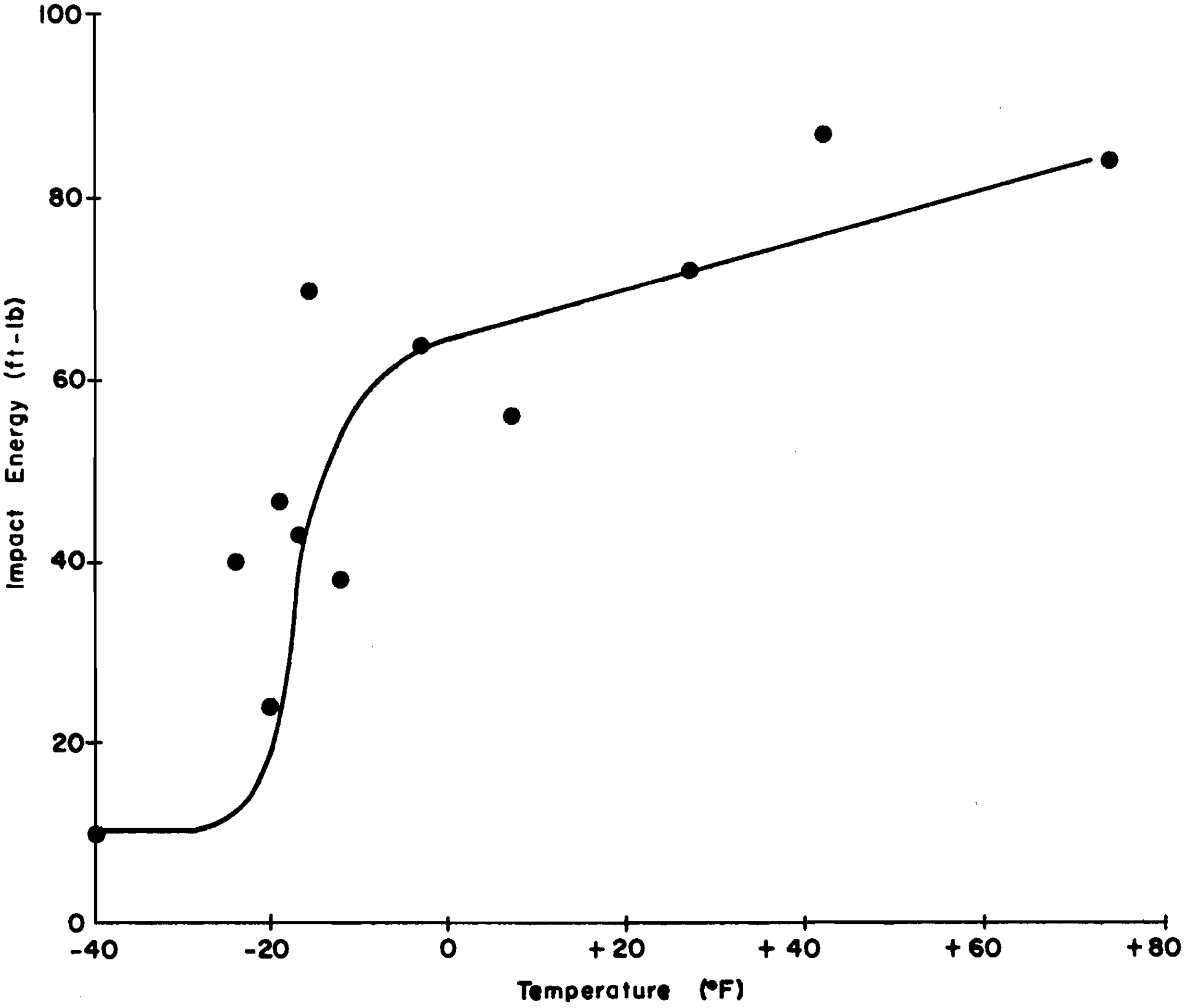


Fig 20B. Impact energy versus temperature, A36 weld metal, Fab B.

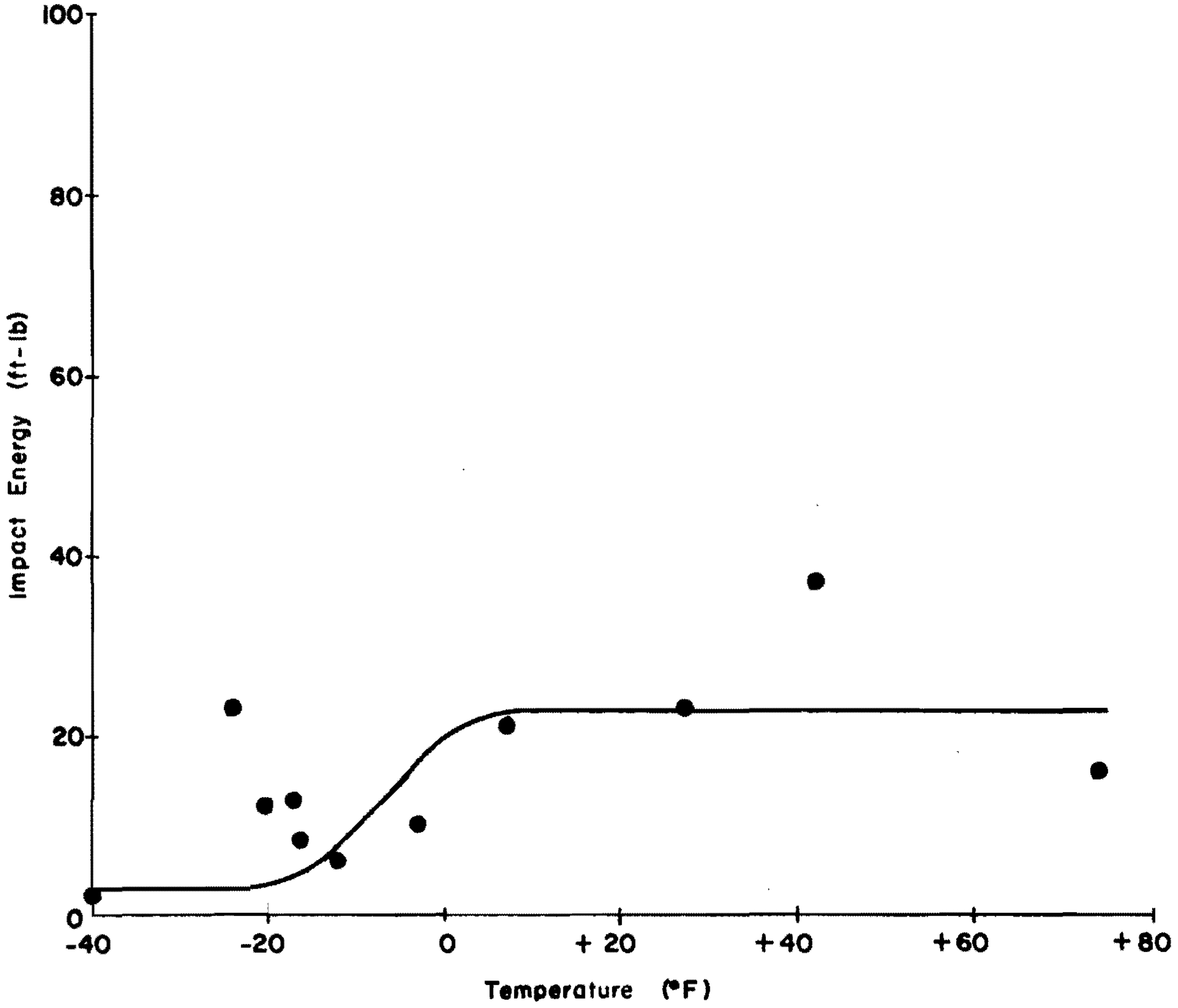


Fig 20C. Impact energy versus temperature, A36 weld metal, Fab C.

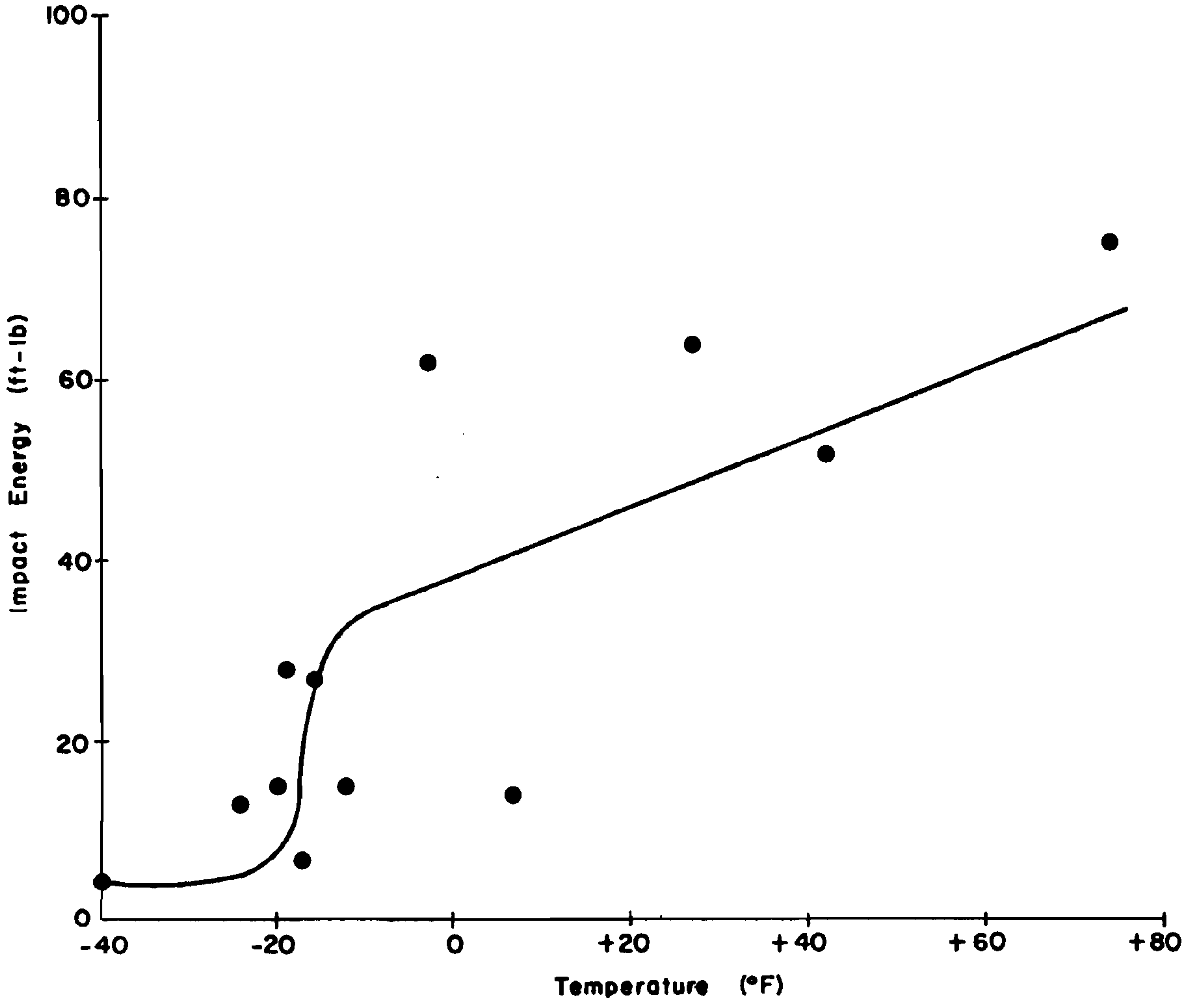


Fig 20D. Impact energy versus temperature, A588 weld metal, Fab A.

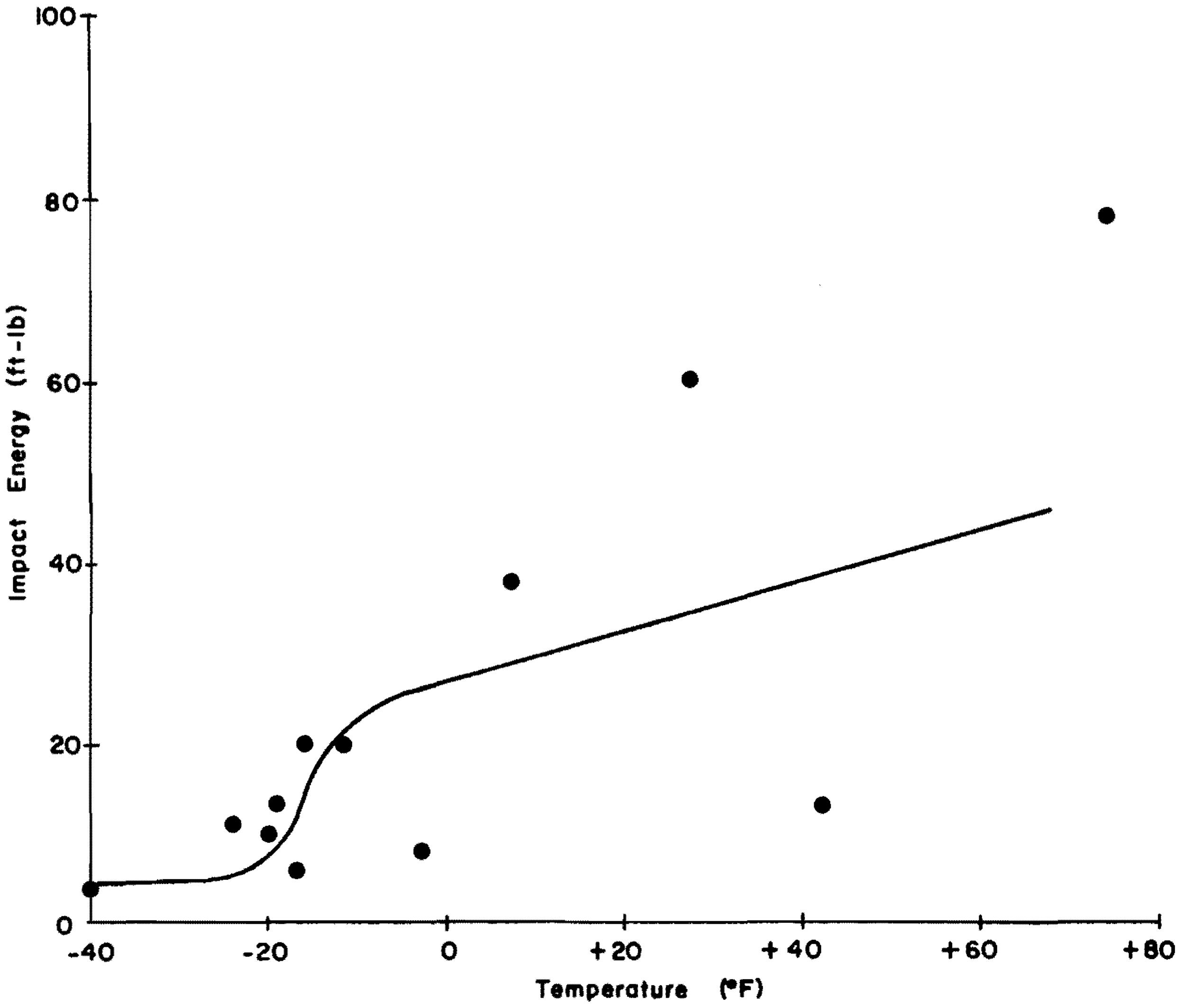


Fig 20E. Impact energy versus temperature, A588 weld metal, Fab B.

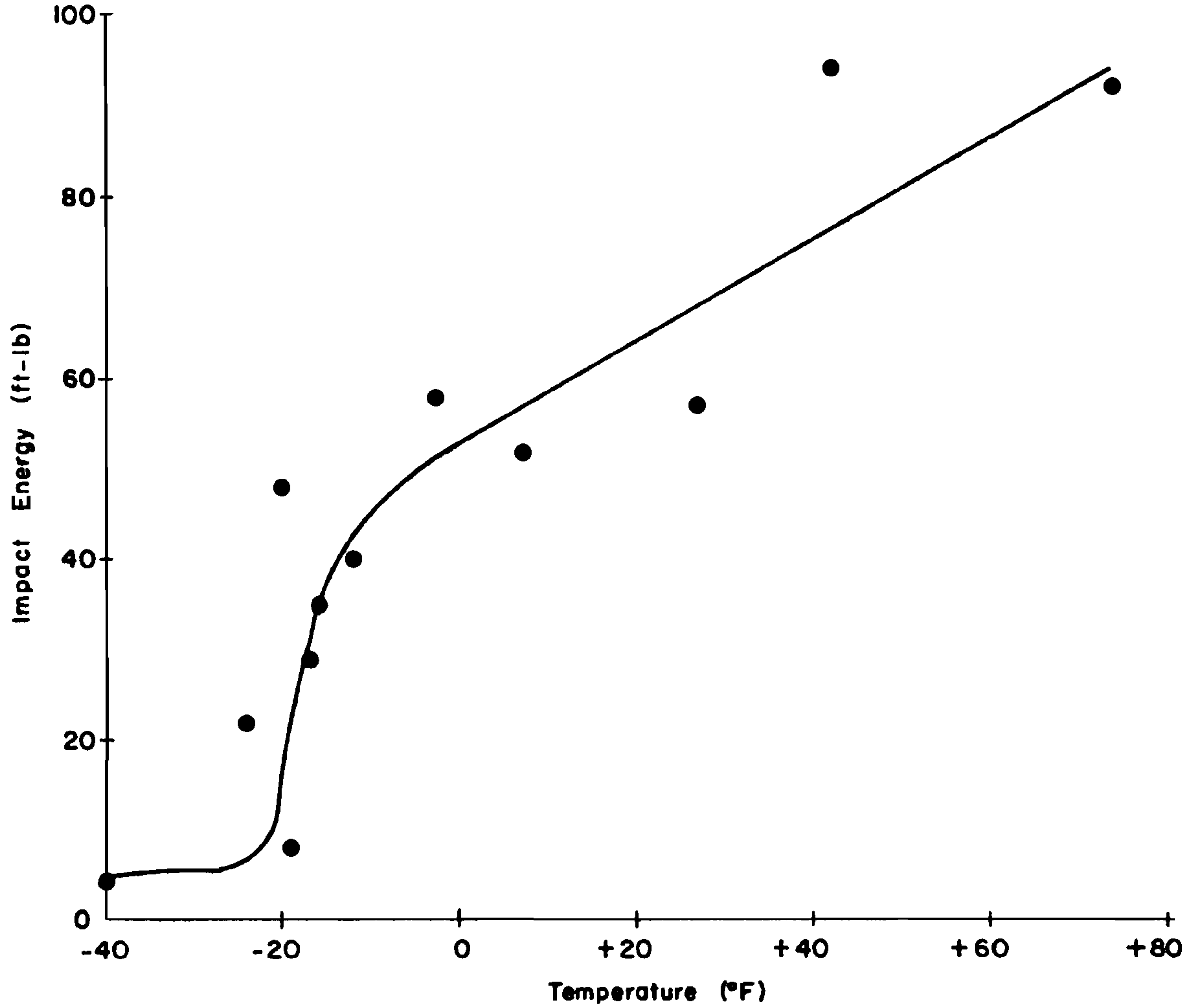


Fig 20F. Impact energy versus temperature, A588 weld metal, Fab C.

TABLE 12. ENERGY (FT-LB) ABSORBED IN CHARPY IMPACT TESTS

Temperature, °F	A36			A588		
	Fabricator			Fabricator		
	A	B	C	A	B	C
-40	4	10	2	4	4	4
-24	35	40	23	13	11	22
-20	20	24	12	15	10	48
-19	16	47	20	28	14	8
-17	21	43	13	7	6	29
-16	32	70	8	27	20	35
-12	22	38	6	15	20	40
- 3	23	64	10	62	8	58
+ 7	30	56	21	14	38	52
+27	41	72	23	64	60	57
+42	29	87	37	52	13	94
+74	41	84	16	75	78	92

Side Bend Tests

Side bend test specimens were machined from each weld specimen and tested as described in AWS Specification for Welded Highway and Railway Bridges D2.0-69 (see Fig 21). The convex surfaces of the specimens were examined for the appearance of cracks or other open defects. In no instance was a crack or open defect observed which exceeded 1/8-inch in length, measured in any direction. All welds were judged to have passed the side bend test.

Reduced-Section Tension Tests

Reduced tension tests were performed in accordance with AWS D2.0-69. The specimens were prepared as shown in Fig 22, which is taken directly from the specification.

Before the tests were performed the width and corresponding thickness of the reduced section were measured. The specimens were then pulled to failure and the maximum load was determined. The tensile strength was then calculated by dividing the maximum load by the cross-sectional area. These data are shown in Table 13.

In every instance, the tensile strength was greater than the minimum specified for the base metal so the welds satisfactorily passed the reduced-section tension tests.

Fig 21. Side bend test.

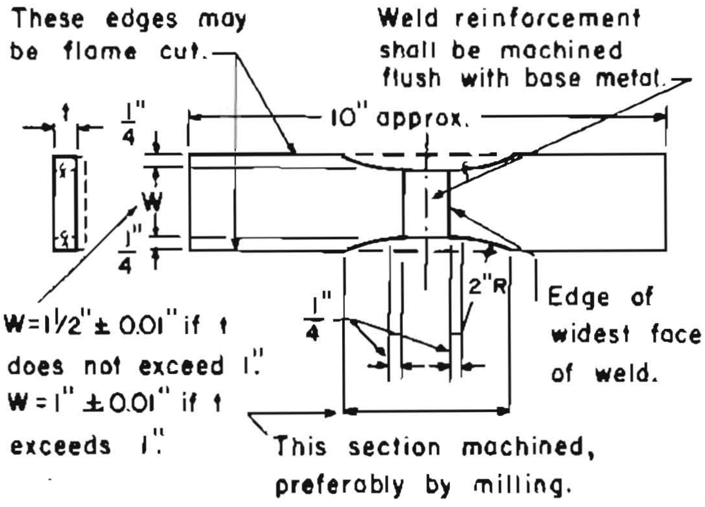


Fig 22. Reduced-section tension specimen (from Ref 1).

TABLE 13. RESULTS OF THE REDUCED-SECTION TENSION TESTS

Plate Material	Shop	Width, in.	Thickness, in.	Area, in^2	Ultimate Load, lb.	Tensile Strength, psi	Minimum Strength, psi*	Fracture Location
A36	A	1.002	1.200	1.204	94400	78400	58000	HAZ
	B	0.998	1.263	1.260	97600	77460		Weld
	C	1.000	1.241	1.241	98000	78960		Plate
A588	A	0.998	1.240	1.238	97100	78400	70000	Weld
	B	1.005	1.244	1.250	99100	79300		Weld
	C	1.004	1.260	1.265	113300	89300		Plate

*The ultimate tensile stress measured in the reduced-section tension test must be greater than the minimum strength specified for the parent plates.

CHAPTER 4. FATIGUE TESTS

Loading Apparatus

The fatigue loads were applied with a hydraulic cylinder activated by a Reihle-Los Universal Single-Acting Pulsator, which has the ability to apply either static or oscillating loads. The load magnitudes were monitored with two large dial indicators reflecting the percentage of the maximum pressure and load capacity of the ram. When oscillating loads are being applied both indicators are engaged, one reflecting the maximum (upper) pressure and the other the minimum (lower) pressure being reached during each excursion. During static loading both indicators reflect only the internal pressure, thus indicating an identical load. Although the testing machine is calibrated to an accuracy of one-fourth of one percent, the applied loads were double checked with a 100-kip load cell placed under the platen of the ram. The loads indicated by the cell, which was calibrated for use with a strain indicator, and those by the dials of the testing machine were found to be in agreement.

To transfer the load from the single-acting ram (push only, as opposed to push-pull) into the full-scale specimen it was necessary to design and fabricate a loading frame. The loading frame design is shown in Fig 23. The component parts of the frame were cut to shape in Houston and the holes were drilled and the frame erected by the project staff. While the distribution of stress through the specimen cross section could not be made exactly uniform, the design has proven to be satisfactory and has maintained its structural integrity through more than 25,000,000 loading cycles.

It will be noted that the specimens were mounted in the loading frame with 1-inch-Ø high-strength ASTM A325 bolts at each end, as shown in Fig 24. These bolts were torqued as required to obtain a friction type connection. In no instance was a failure initiated in the area of the bolt holes, indicating the suitability of such connections when performing fatigue type testing.

Three-inch diameter bearing pins in double shear provided the pinned joint through the large teardrop-shaped fittings at both the top and the bottom of the

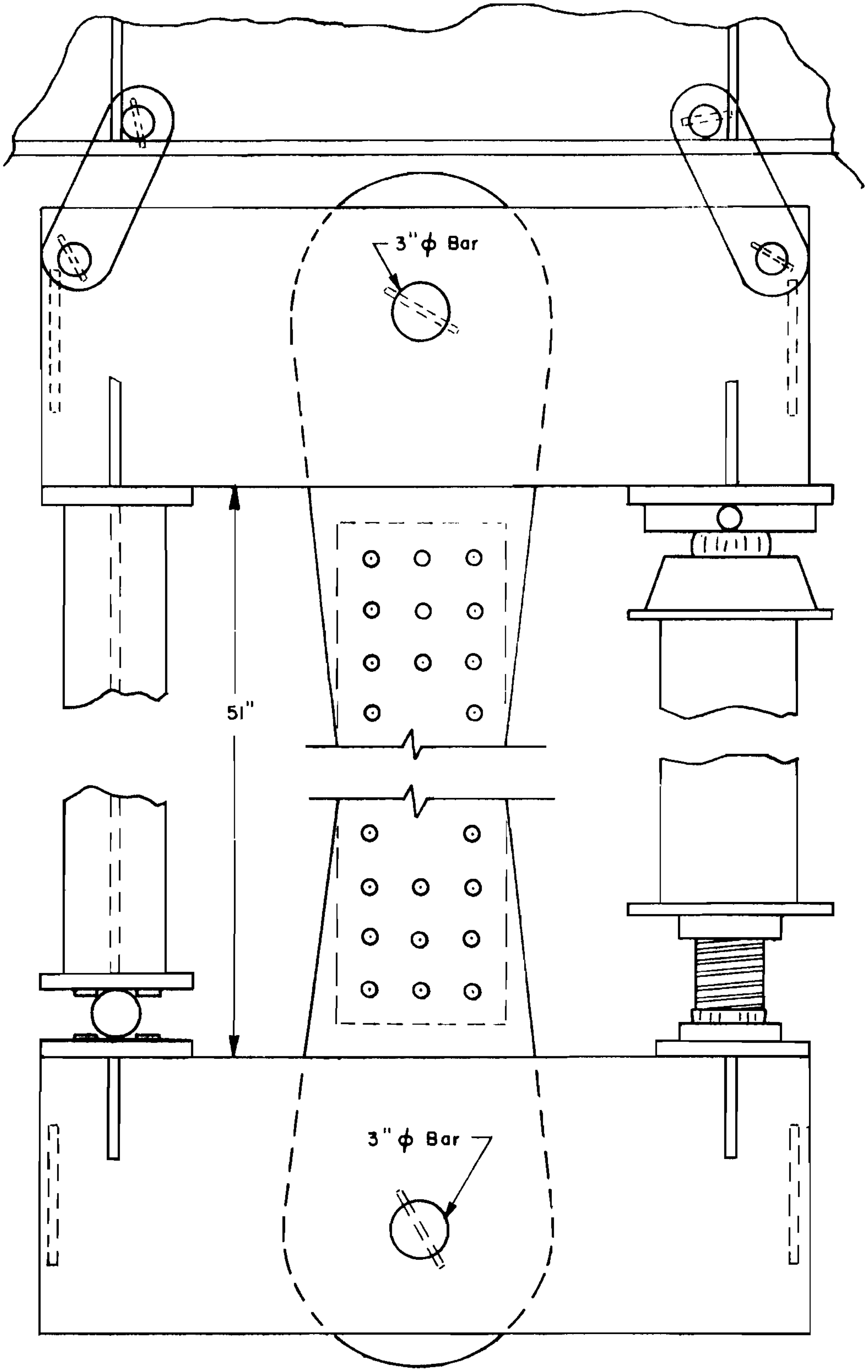


Fig 23. Loading frame.

Fig 24. Photograph showing the full-scale fatigue specimen ready for testing. The location of two of the four strain gages can be seen.

frame. Two fatigue failures of these pins were experienced during the testing sequence, but they could be quickly replaced and the testing program resumed.

Instrumentation

In order to measure the magnitude and distribution of the stresses on the cross section of the test specimens, wire-type electrical resistance strain gages were used. Four were mounted on each specimen at a cross section some distance away from the weld, typically at the centerlines of the flat surfaces, as shown in Figs 25 and 27. These gages could then be monitored with both a static strain indicator and a brush-type dynamic recorder.

The brush-type dynamic recorder proved to be the best method for monitoring the strains and, in turn, the stresses during the fatigue tests. Figure 26 shows a reproduction of the traces from gages 1 and 2, as shown in Fig 25. As was expected they appear to be continuous sinusoidal loadings, in this instance being applied at slightly more than 140 cpm. Typically the tests were run at slightly higher frequencies, usually about 175 cpm. Early in the program, exploratory checks of the brush recorder indicated no lag or inertia effects up to frequencies on the order of 1000 cpm, or higher. Because the tachometer of the Reihle-Los machine was out of order early in the program the frequencies were monitored simply by timed counts of the pulsations. This technique proved to be accurate to within 2 or 3 percent and provided preliminary estimates of the time necessary to apply a given number of cycles. A counter on the testing machine kept a continous indication of the total number of cycles that had been applied and so an accurate calculation of the frequency could be made after only a short period of testing.

Since nearly all the reported data reflect those collected using gages 1 and 2 in conjunction with the dynamic brush recorder, one might reasonably ask what purpose gages 3 and 4 played and what the benefit of the static strain indicator was. The answer is that static readings from all four gages could be used to initially align the specimen to get as near a uniform stress distribution as possible. Further, the static readings were then used to calibrate the dynamic traces to strain, i.e., relate the height of the trace to strain. Thus both the two extra gages and the strain indicator were used in setting up every test.

To evaluate eccentricities due to alignment and the moments, one specimen, number 6, was instrumented slightly differently from all the others. Rather

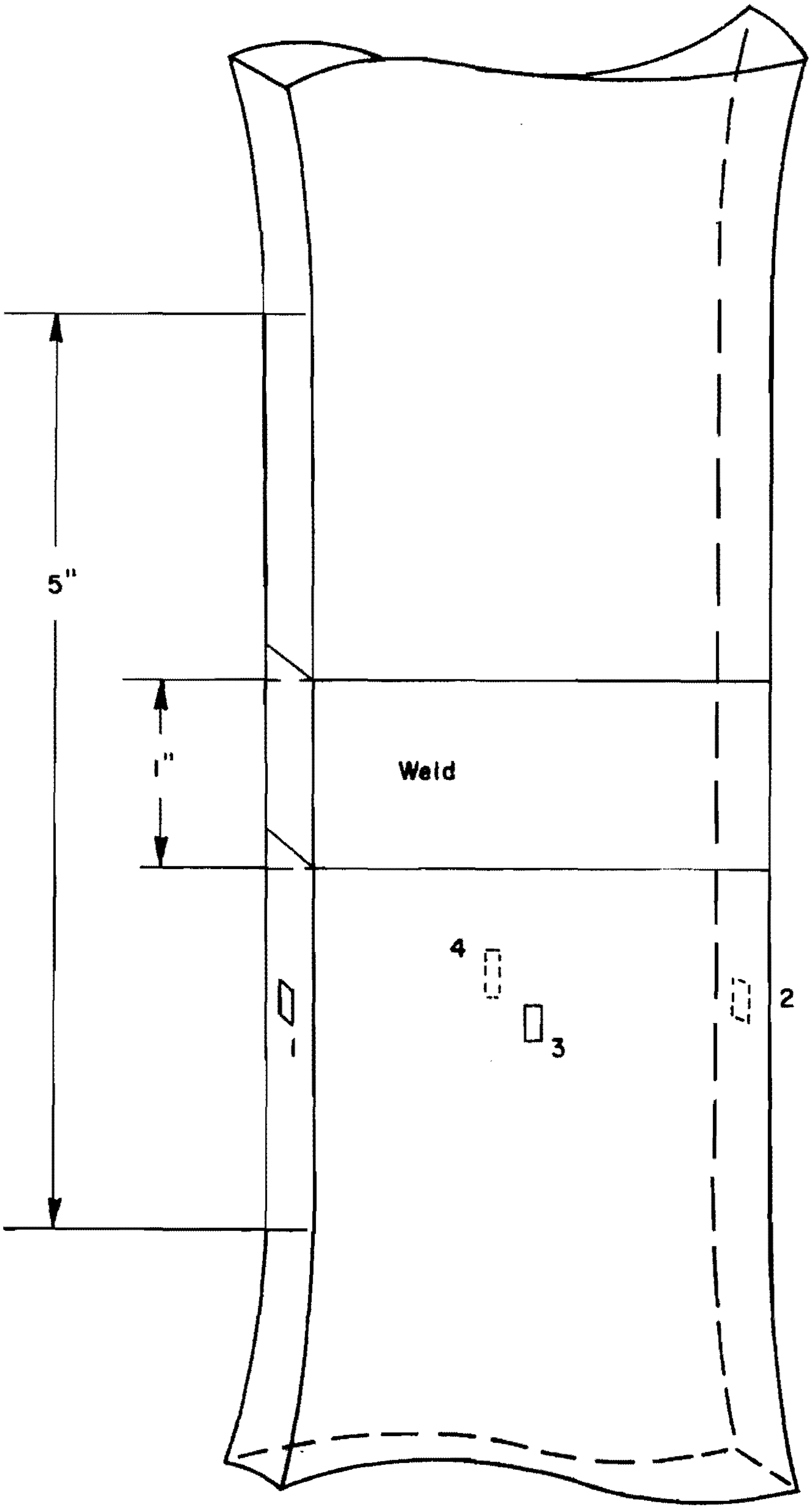


Fig 25. Sketch showing mounting of the four strain gages on the cross section of the full-scale test specimens.

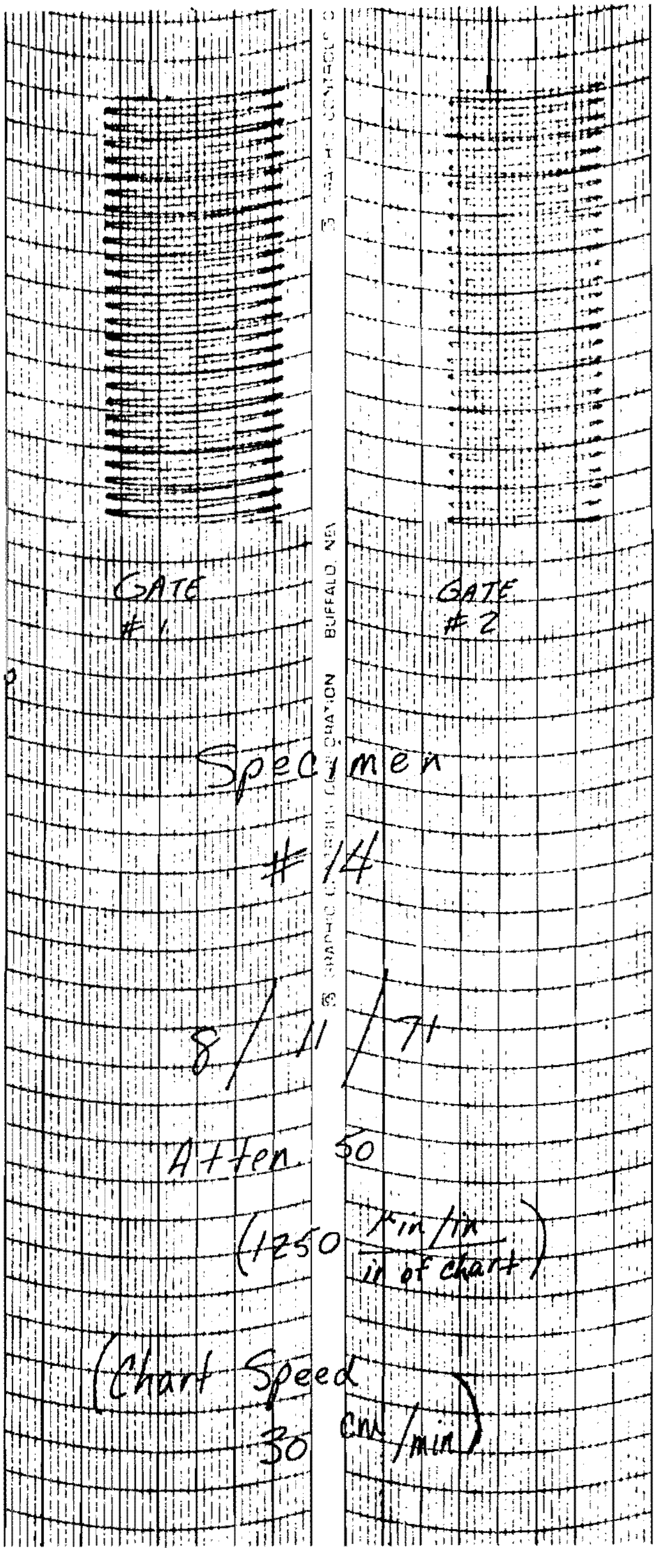


Fig 26. Reproduction of a trace using the brush recorder. The indicated frequency is just over 140 cpm.

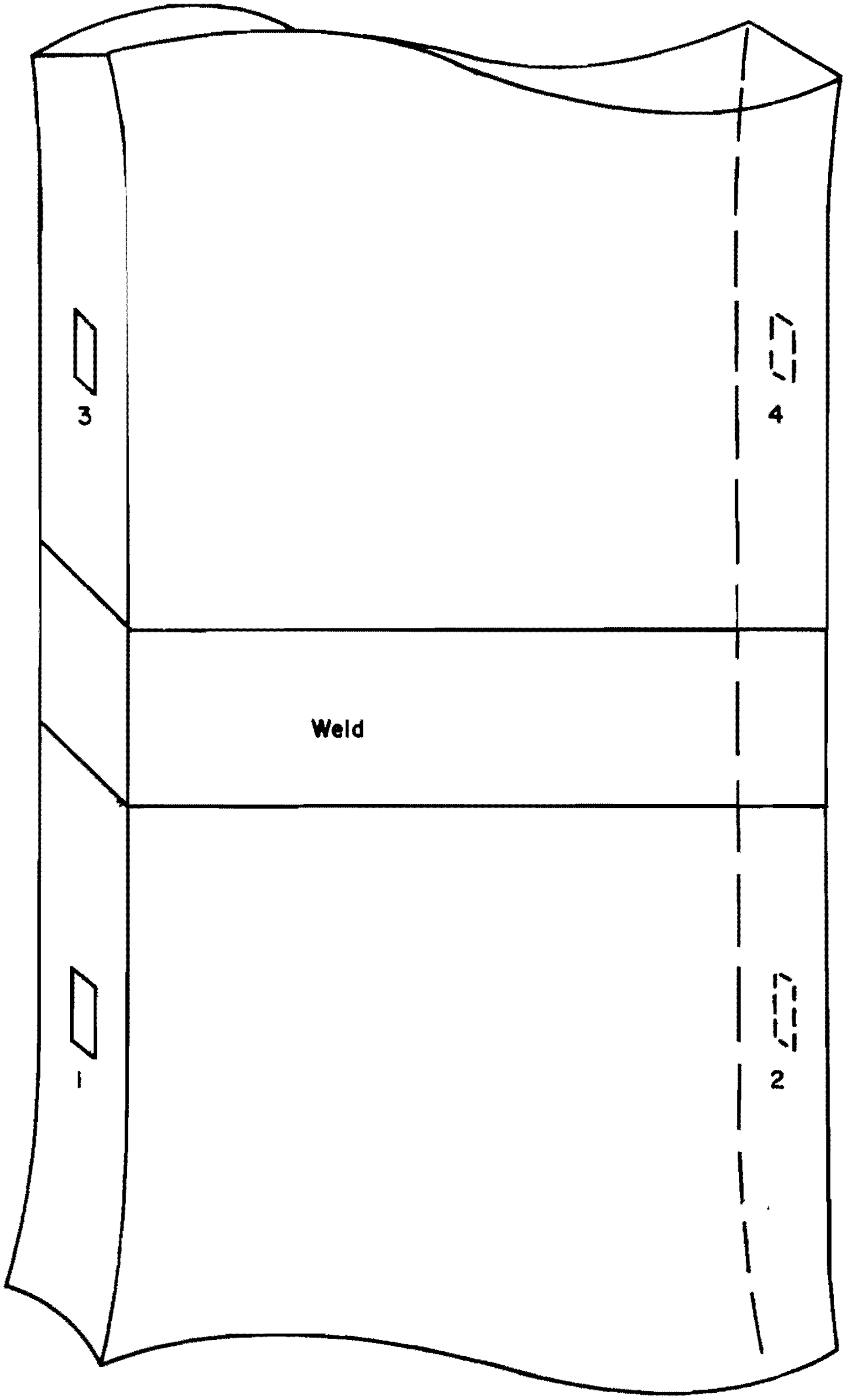


Fig 27. Sketch showing the location of strain gages 1 through 4 on specimen 6.

than having all four gages mounted at one cross section, two were mounted below and two above the weld, along the narrow edges, as shown in Fig 27. This gave an opportunity to determine the extent to which the moment on the specimen varies over the length of the specimen.

The static strain readings taken during such tests indicated that both the axial load (as statics dictate) and the moment are essentially constant over the length of the specimen. However, it was also noticed that the strains on one side, the side with gages 2 and 4, were usually greater than the average strain across the specimen.

Testing

Once the full-scale tensile specimens were received and prepared for test as described in the preceding section, they were bolted into the loading frame and subjected to repetitive loadings. Because of the characteristics of the test machine, it was necessary to subject these specimens to tension-tension histories even though it would have been preferred to use the so-called zero-tension history (R=0). As will be noted in study of the data reported in this section, the minimum stress applied as a rule was on the order of 5 ksi but varied from specimen to specimen. Table 14 summarizes the results of the failure tests of the 18 full-scale specimens. In this table the cycles to failure and the corresponding maximum stress range for each specimen are given.

Several failures occurred out in the tapered portion of the specimen, where the cross-sectional area was larger than that in the neighborhood of the weld. There were two possible explanations: one was that more severe edge defects caused by flame cutting the specimen had acted as a crack starter and the other was that the specimen alignment was so poor that large moment gradients existed from end to end of other specimens, causing the edge stresses in the curved region to be large.

The weld reinforcements were all ground away except for specimens 9, 15, and 18. Similarly the flame-cut edges (except for specimens 1, 2, and 3) were hand-ground to a surface finish which was superior to that required by the Texas Highway Department for the edge of plate girder flanges. Specifically, a maximum surface roughness of USASI 1000 (for plates less than 4 inches thick) is permitted with burn marks not greater than 3/16 inch deep (or else they shall be completely ground out with a finished grinding slope of less than 10:1).

TABLE 14. SUMMARY OF THE FATIGUE TESTS

		Specimen No.	Maximum Stress Range,* ksi	Cycles to Failure, thousands	Type of Failure
Shop A	A36	13	32.1	690	Weld
		14	34.8	2038	No failure
		15	31.5	188	Weld**
	A588	16	34.6	145	Parent metal
		17	33.3	560	Weld
		18	23.1	202	Weld**
Shop B	A36	7	29.1	514	Parent metal
		8	27.3	561	HAZ
		9	17.4	3023	No failure**
	A588	10	33.0	2016	No failure
		11	35.7	1457	Weld
		12	35.1	162	Parent metal
Shop C	A36	1	27.5	2637	No failure
		2	20.4	3010	Parent metal
		3	44.8	223	Parent metal
	A588	4	31.8	979	Parent metal
		5	22.8	4037	No failure
		6	27.7	1258	Parent metal

*Maximum stress ranges measured with strain gages and dynamic recording equipment.

**Specimens with weld reinforcement left as welded.

The edges of the specimens were ground well into the tapered regions on each end to minimize the possibility that failure would initiate from a cutting flaw there.

It will be noted that in only four instances did a fracture occur other than in the base metal. A study of the fracture geometries revealed that some of the fractures could be traced to an initial edge defect. However, both the surface and the edge in the neighborhood of the weld itself were ground to be as nearly identical as possible to those of the remainder of the specimens (base metal), so the fractures in the parent metal cannot all be laid to the presence of edge flaws (except for specimens 2 and 3). Further it will be noted that the minimum section of the tensile specimen is only about 8 inches long, of which 1 1/2 to 2 inches is weld and heat affected zone (HAZ). Thus, several failures would be expected within this region even if the weld were not present.

In every instance where the fracture occurred in or near the weld, the crack failed to propagate in a brittle mode completely through the specimen. Usually these fractures initiated within the heat affected zone at the edge of the specimen. They propagated along the heat affected zone and then turned into the weld metal itself, but the behavior here was unique when compared with the other fracture surfaces in the parent plates. Instead of propagating completely through the specimen, once it got about half-way through, the weld metal tended to neck down. In other words, once the stress became very large on the remaining cross section the weld metal yielded significantly in the neighborhood of the crack tip and the crack did not continue to grow across the specimen. Photographs of all the failures are shown in Figs 28 through 33.

Specimens 9, 15, and 18 were tested without any grinding. In particular, the weld reinforcement was left as welded during the test.

Because stress gradients existed across the cross section of the specimens, and because failures initiated invariably from the edge of highest strain, the maximum measured stresses (the larger of gages 1 or 2, see Fig 25) have been used to make the plots of stress range versus number of cycles. These data are shown in Figs 34 through 36. Figure 34 shows data from the tests that resulted in a failure in the parent metal while Fig 35 is for the tests that failed in the weld. In both figures the weld reinforcement had been removed by grinding, and points for those specimens which did not fail are included.

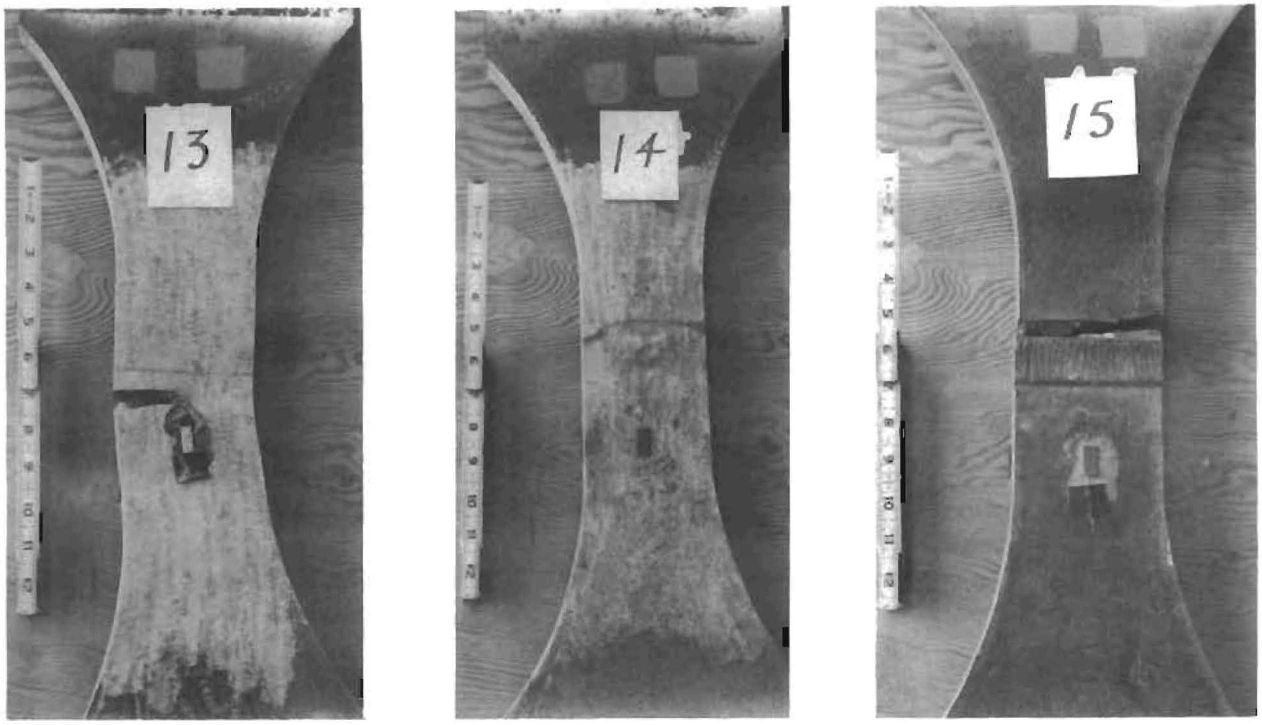


Fig 28. The A36 specimens from Shop A after testing.

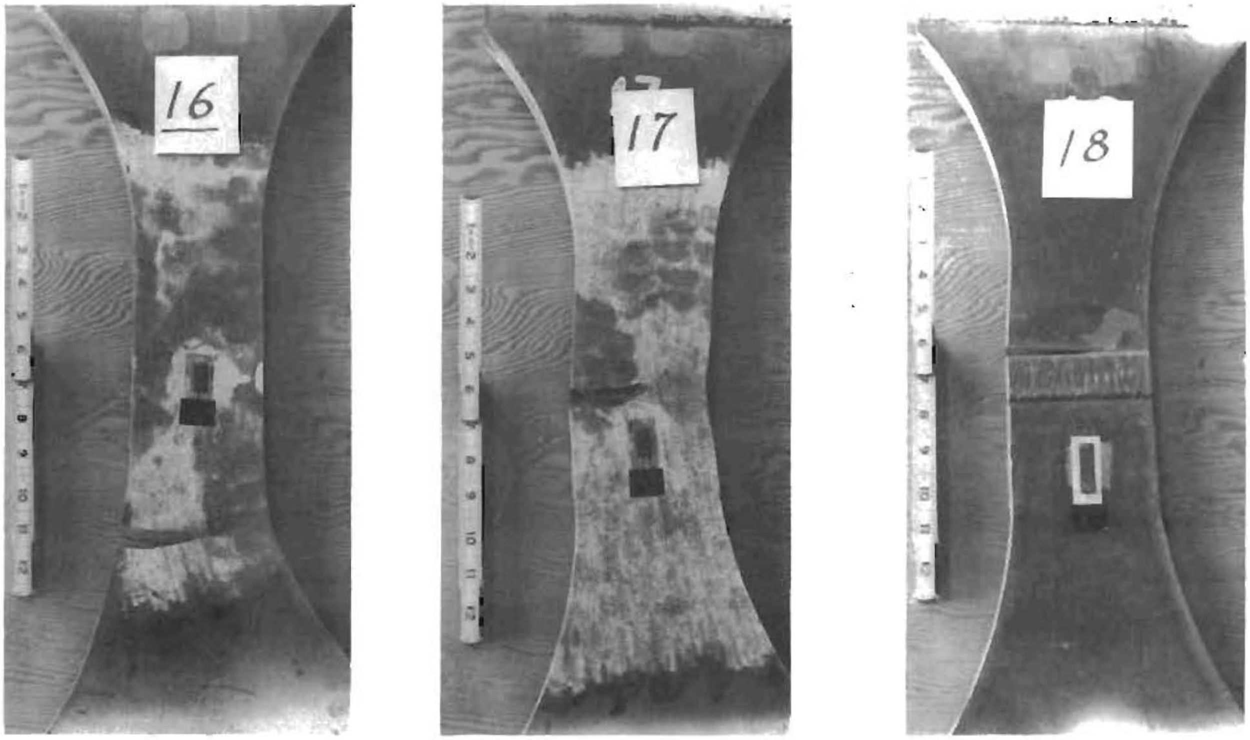


Fig 29. The A588 specimens from Shop A after testing.

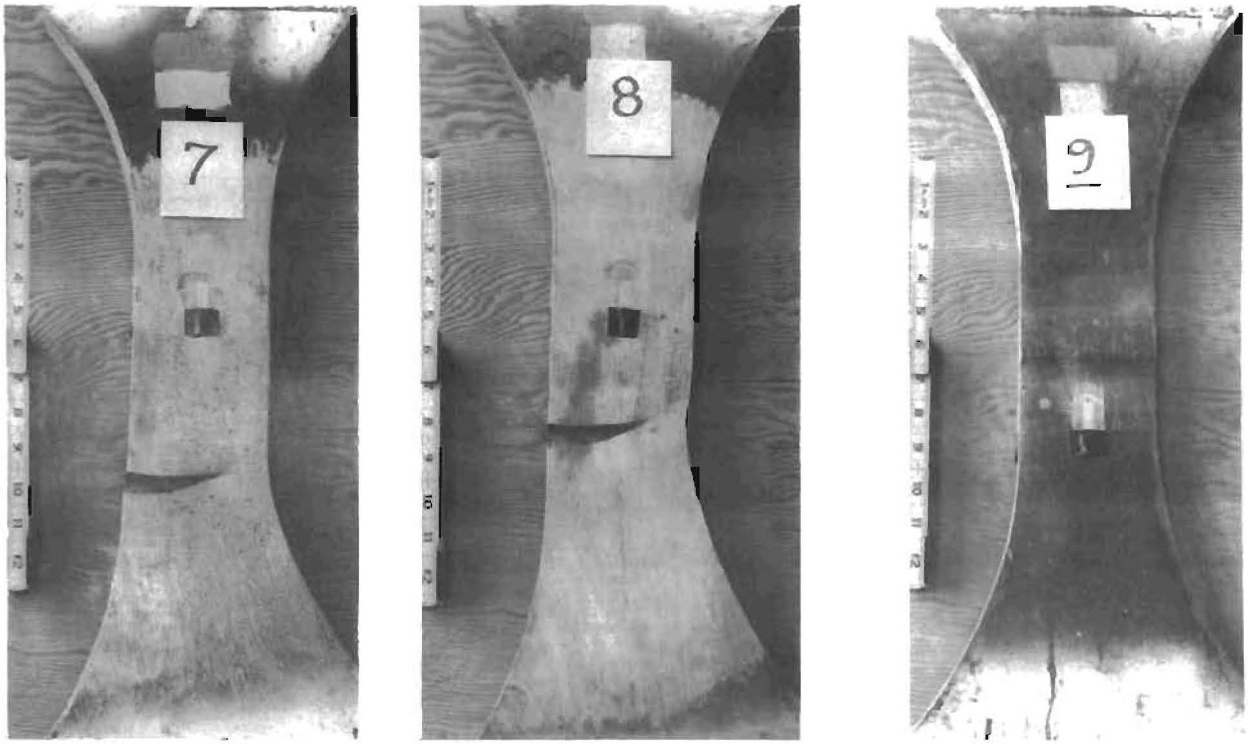


Fig 30. The A36 specimens from Shop B after testing.

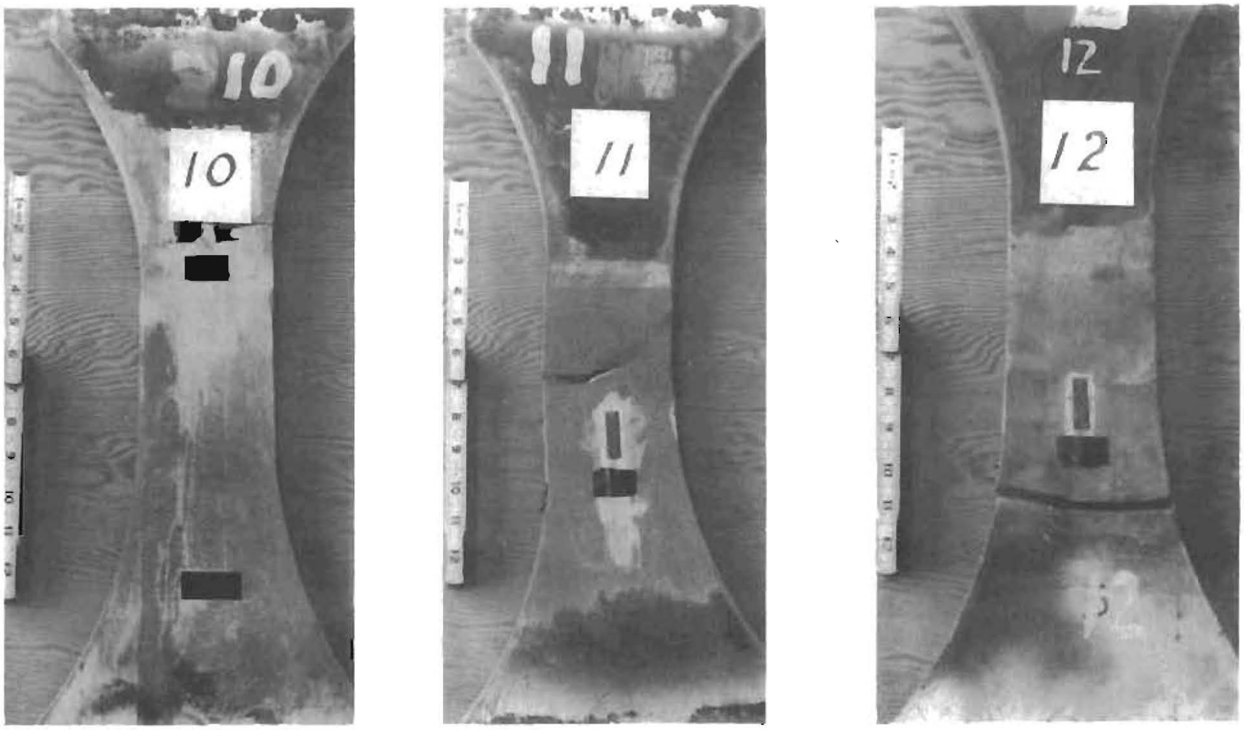


Fig 31. The A588 specimens from Shop B after testing.

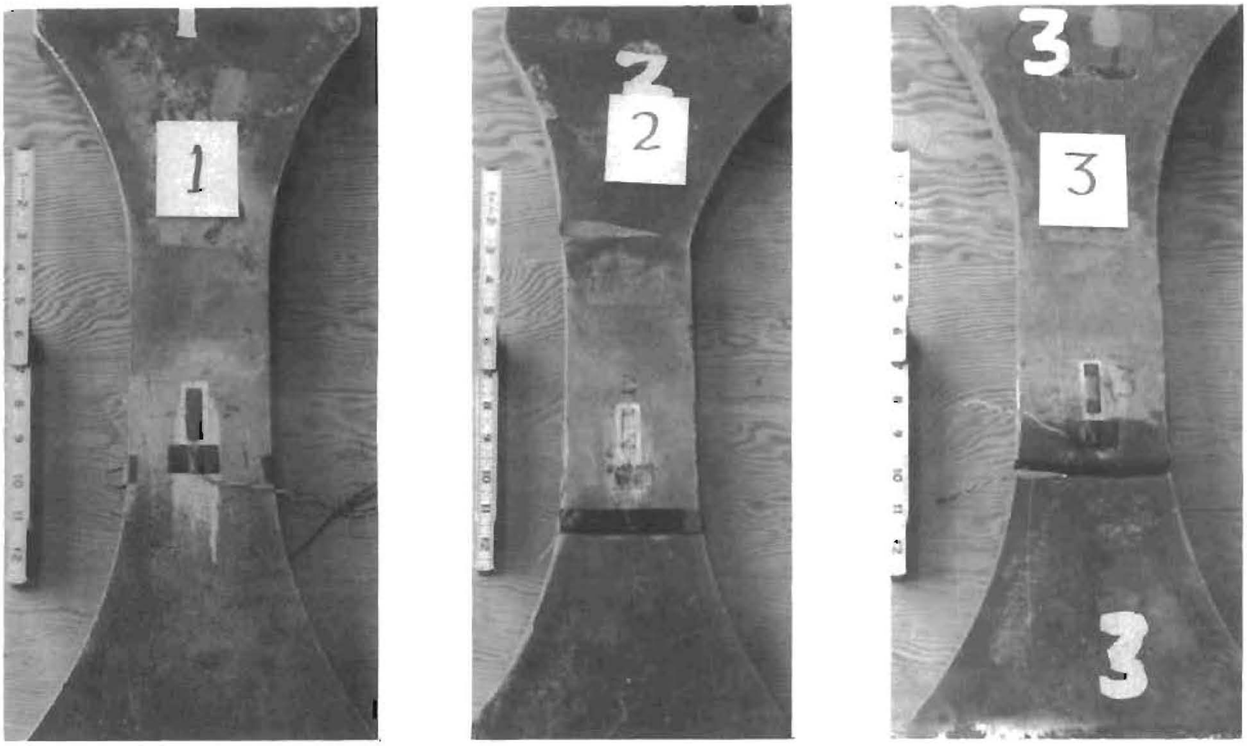


Fig 32. The A36 specimens from Shop C after testing.

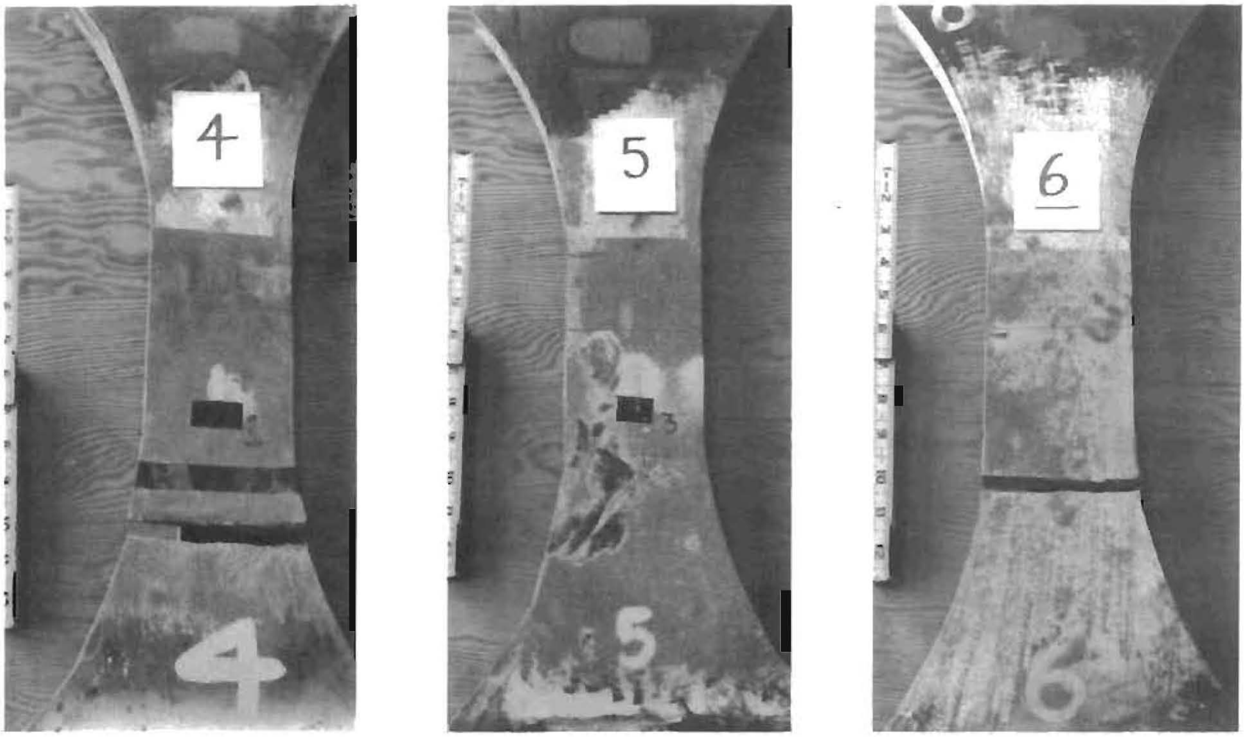


Fig 33. The A588 specimens from Shop C after testing.

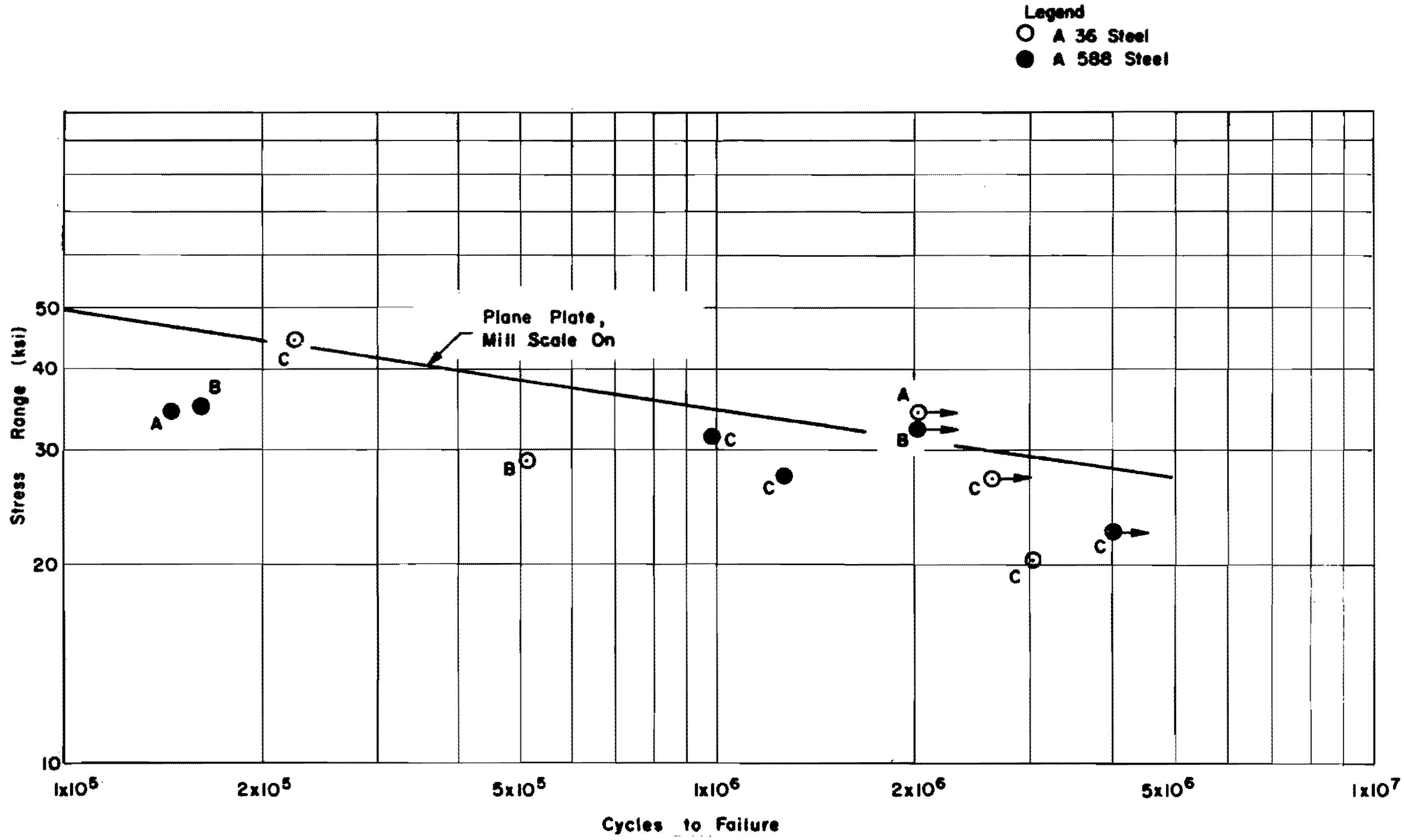


Fig 34. Fatigue tests resulting in parent metal failures. Maximum stress measured by strain gages.

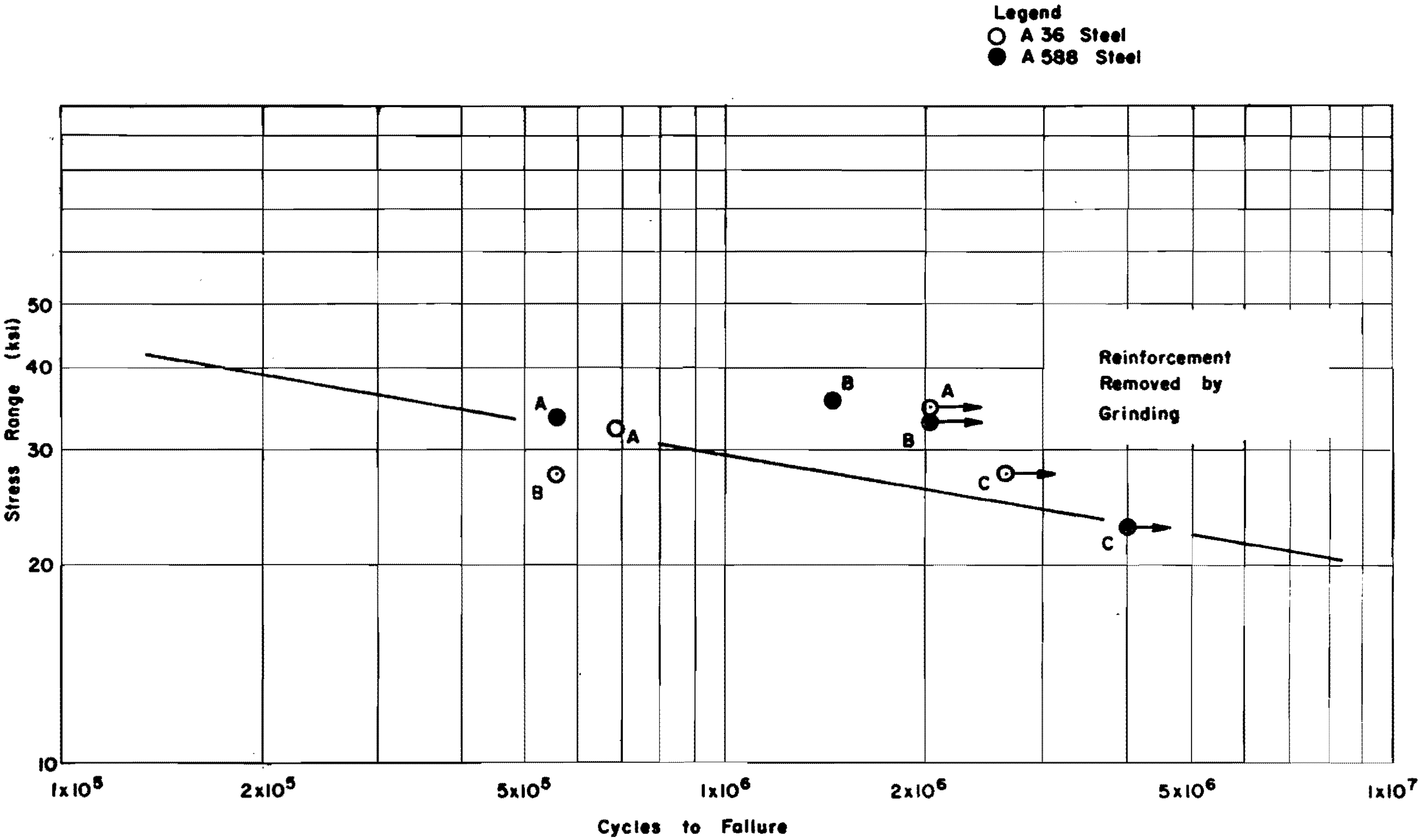


Fig 35. Fatigue tests resulting in failures in either the weld or the heat affected zone. Maximum stress ranges measured by strain gage.

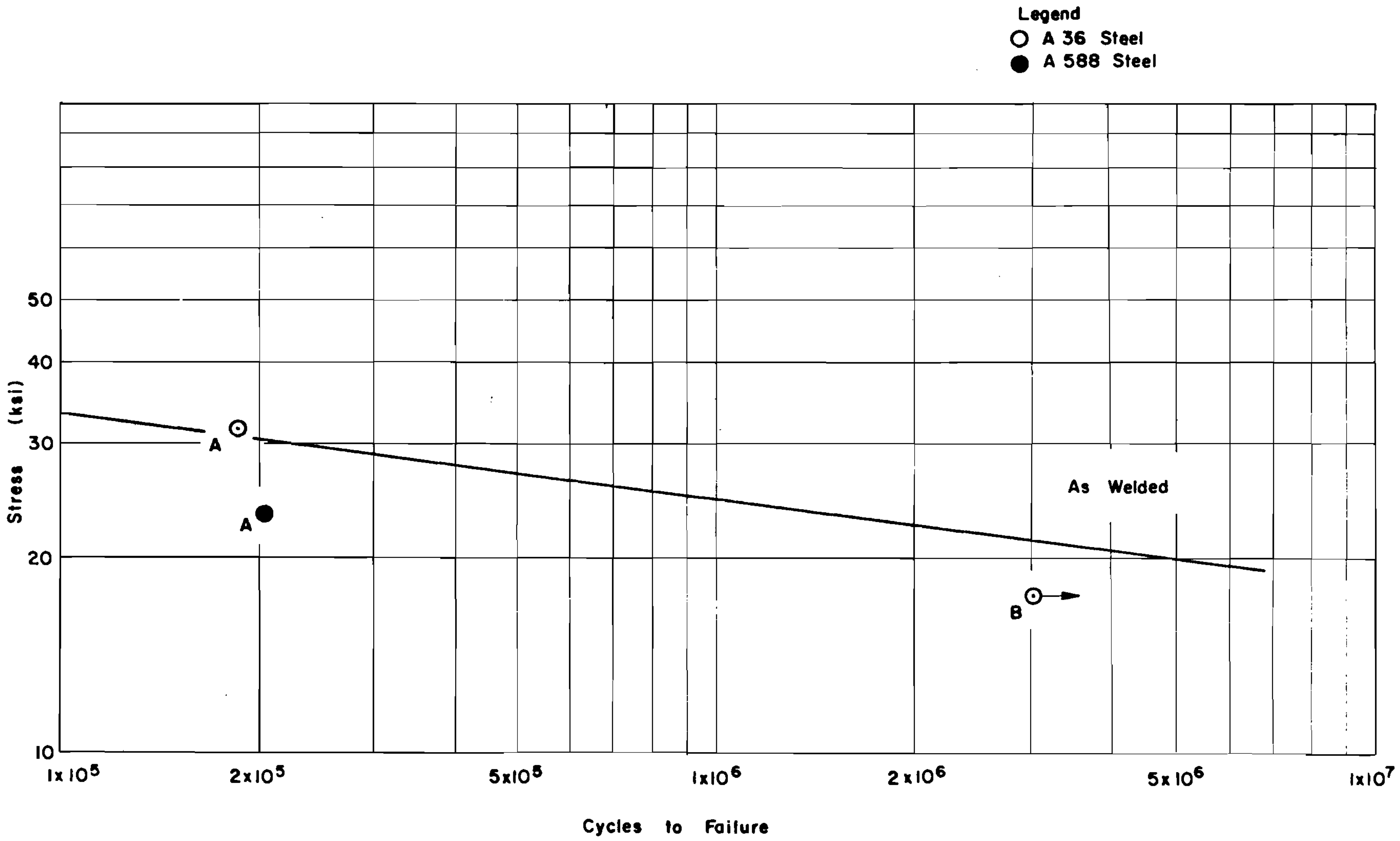


Fig 36. Results of fatigue tests with the reinforcement left intact. Maximum stress range measured by strain gage.

Figure 36, which contains only three points, is for those specimens which were tested with the reinforcement left intact.

The sloping lines drawn across the three figures reflect the expected fatigue failures as reported by Blodgett (Ref 11). The curve in Fig 34 is for plain carbon steel with the mill scale left on, in Fig 35 for a butt-weld with the reinforcement removed by grinding, and in Fig 36 for a butt-weld with the reinforcement left as welded. The data points from the few tests of this program are seen to agree with the data from the literature.

CHAPTER 5. DISCUSSION OF TEST RESULTS

The only deficiency of the welds revealed by the conventional material property tests was the slightly low yield strength indicated for the weld placed by one of the fabricators between A588 plates. The deficient yield was 48,500 psi (0.2 percent offset) and the AWS specified yield is 50,000 psi (Ref 1).

The Charpy tests were conducted six at a time, one from each weld at twelve different temperatures, ranging from less than -40°F to 74°F. This procedure differs from the AWS specifications, which require that five specimens be tested, all at 0°F. In all instances the transition temperature appeared to be below 0°F. The tests of the A36 welds appear to be low in energy even at the warmer temperatures but probably would have passed the AWS requirements. All other material characterization test results were judged to have been satisfactory.

Because of the small number of full-size specimens, the interpretation of the test results must be somewhat subjective. It must be stated fairly that the plotted stress ranges are not the averages (P/A) but rather the maximum stresses caused by specimen binding or misalignments. However, it must also be stated that these maximums were deduced from actual strain gage measurements. It may be argued that if the entire cross section had been subjected to the same stress levels experienced by the extreme fiber, failure would likely have occurred earlier, because of the greater probability that a more significant failure initiating flaw would have been subjected to the critical condition if the entire cross section were uniformly stressed. Even so, the difference (decrease) would surely have been small.

The comparison of the observed failure levels with those reported in the literature is good. In no instance is the scatter greater than would be expected of fatigue type loadings. The failures of the base metal appear to be somewhat on the low side (probably because of slight stress concentration and edge defects) but the failures observed in the welds appear to be slightly higher than the line indicating reported data from the literature. Generally it is felt that the test results are comparable to those that have been obtained by others.

The length of that portion of the specimen with a uniform (and minimum) area is about 8 inches, as can be seen in the photographs of Figs 28 through 33. The gap prescribed for welding was one inch. Assuming 1/4-inch penetration and 1/4 inch of HAZ, the total thickness of weld and HAZ is about 2 inches or one-fourth of the 8-inch of minimum cross section. Thus, if there were no weld present, one out of every four failures would be expected to occur in the central 2-inch length. From Table 14 and Figs 34 and 35 it can be seen that 4 out of 11 failures occurred in the weld (center 2-inch) region. This indicates that the presence of the weld causes only slight, if any, reduction in the fatigue strength of the base metal.

Of the three specimens tested with the reinforcement left intact, two were from Shop A and one from B. On the basis of only those three points (see Fig 36) there seems to be a significant reduction in fatigue strength. This is further confirmed by looking at the photographs of the two failures (specimens 15 and 18 in Figs 28 and 29), both of which are clearly along the line where the reinforcement fairs into the base metal. However, in fairness, the contours of the reinforcements of the welds from Shops B and C were better than from A and their fatigue strength reduction probably would have been less than that which is implied in Fig 36.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

Based on the observations and tests performed during this program, the following conclusions are apparent.

(1) The electroslag technique provides a reliable, rapid, and economical method for producing welds between plates. Butt welds can all be produced remarkably free of defects, voids, and inclusions.

(2) While the weld can be characterized as having coarse, oriented grains, it still appeared to be more ductile and fatigue resistant than the base metals (A36 and A588).

(3) Butt welds fabricated using the electroslag technique have a fatigue resistance as good as that of the parent metals (A36 and A588).

(4) The fabrication processes employed by the three shops which performed the welding were substantially different, but no great difference was observed in the fatigue properties, indicating a relative insensitivity to shop technique.

The weld reinforcement contour that results from the electroslag technique is controllable by shaping the interior surface of the copper shoes. Further, the external surface of the reinforcement is relatively flaw and pit free. Consequently, it is felt that the fatigue properties of the weld without grinding can, by careful tailoring of the shape of the reinforcement, be improved until they approach the properties of a butt weld with the reinforcement ground away. If significant economies would result it is recommended that tests be conducted to confirm this suspicion.

One of the greatest limitations on the electroslag method is the difficulty in restarting the process if it is inadvertently stopped. It is virtually impossible to do without leaving gross slag inclusions and flaws. The same difficulties exist during weld initiation, which accounts for the requirement for a start-up trough. If any auxiliary method could be devised for melting the slag prior to initiating the welding process, these difficulties would likely be overcome. Such an improvement should be the object of a continuing search.

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APPENDIX. BIBLIOGRAPHY

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Welding Production Engineering Journal and Metal Industry Digest,
April 1970, Vol 10, No. 4, pp 15-30.

A characteristic of the heavy fabrication industry over the last decade has been the introduction and increasing use of electroslag welding. Hardly known in 1959, the process is now the first choice for the welding of heavy plate above 38 mm in thickness. Several methods have been applied to improve the structure and notch impact properties of electroslag welds. The most popular and effective solution is a postweld normalizing treatment which eliminates the coarse structures in weld and heat affected zones and gives excellent notch ductility. This solution is certainly efficacious and suffers only from the extra cost of heat treatment and, with large structures, the dangers of serious distortion due to sagging at high temperatures. (Extracted from the Engineering Index.)

Svetil'nikova, L. N.,
Two-Position Arrangement for Electroslag Welding of Flanges,
Chemical Petroleum Engineering, January-February 1970, No. 1-2, p 73.

A two-position welding rig for electroslag welding of flanges up to 1200 mm in diameter has been developed, fabricated, and introduced into regular production work at the M. V. Frunze machinery factory in Sumy. The welding rig features two independent positions for mounting flanges to be welded. While a flange is being welded at one of these positions, the next flange to be welded can be set in position and prepared for welding at the other position. The use of this two-position rig for electroslag welding of the flanges made it possible to step up productivity and to shorten the time required to prepare flanges for welding. (Extracted from the Engineering Index.)

Zeke, J., Slabon, I., and Mosny, J.,
Electroslag Welding of Heavy Sections,
Revue de la Soudure, 1970, Vol 26, No. 1, pp 1-15.

A discussion of the use of electroslag welding for heavy sections, which includes sections up to 2000 mm (over 75 inches) thick. While many problem areas exist, such welds are currently being made and are the subject of continuing research activities.