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HIGH DEPOSITION RATE GAS TUNGSTEN ARC (TIG) WELDING OF HIGH STRENGTH STEELS

H. R. Miller

FOREWORD

This Final Technical Report covers all work performed under Contract AF33(615)-2714 from 1 June 1965 to 31 January 1968. The manuscript was released by the author on 15 May 1968 for publication as an AFML Technical Report.

This contract with the Union Carbide Corporation, Linde Division, Newark, New Jersey was initiated under Manufacturing Methods Project 8-314, "Gas Tungsten-Arc (Tig) Welding." It was accomplished under the technical direction of Mr. F. R. Miller of the Advanced Fabrication Techniques Branch (MATF), Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

Mr. H. R. Miller, Project Engineer at the Newark Laboratories was the engineer in charge. Dr. E.C. Nelson, Special Projects Engineer, J.F. Saenger, Project Engineer, F.A. Poper, Development Engineer, and E.J. Gavaletz, Welding Technician, also assisted in the program. Fracture toughness testing and a production application analysis were performed by the Wright Aeronautical Division of Curtiss-Wright Corporation, Wood Ridge, New Jersey under the direction of Mr. K.R. Notvest. This report has been assigned Linde Laboratories Report No. L-1197.

This project has been accomplished as a part of the Air Force Manufacturing Methods Program, the primary objective of which is to develop, on a timely basis, manufacturing processes, techniques and equipment for use in economical production of USAF materials and components.

Suggestions concerning additional Manufacturing Methods development required on this or other subjects will be appreciated.

This Technical Report has been reviewed and is approved.

JACK R. MARSH, Chief
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ABSTRACT

HIGH DEPOSITION RATE GAS TUNGSTEN ARC (TIG) WELDING OF HIGH STRENGTH STEELS

Reliable procedures were established for high deposition Tig welding of three high strength steels. Since resistance melting of the filler metal facilitates independent adjustment of the filler metal deposition rate and the heat input of welding, a wide variety of parameters can be chosen. However, the selection of welding procedures is a function of the metallurgical behavior of each weld metal.

Because a postweld quench and temper heat treatment homogenizes most structural variations, the properties of welds made in D-6ac are virtually independent of welding parameters. Welding procedures are controlled by joint design, bead shape, appearance and other practical considerations.

Although the postweld maraging heat treatment of welds made in 18 Ni (VAR) steel makes the tensile properties independent of welding procedures, the fracture toughness of such welds can vary. Toughness is a function of the amount of grain refinement and thermal cycling achieved in multipass welds. By balancing filler deposition rates and welding heat input, pass size can be adjusted so fracture toughness of welds will be equivalent or superior to conventional Tig welds.

The as-welded tensile and impact properties of welds made in HP 9 Ni-4 Co-.20 C steel are very sensitive to welding conditions. Grain refinement and self-tempering must be maximized; yet the amount of ferrite in the microstructure must be minimized. Despite these restraints, high deposition welding procedures will develop weld metal properties equivalent to Tig welding.

Since these high strength steels can be welded at relatively high filler metal deposition rates with no sacrifice of weld metal integrity or mechanical properties, the Tig-hot wire process should offer significant cost savings to aerospace fabricators. It is estimated that the welding time of critical rocket motor case manufacture, for example, can be reduced by at least 50 per cent.

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I

INTRODUCTION

During the past 20 years, the conventional gas tungsten-arc (Tig) welding process has achieved a prominent position in the aerospace industry because of its ability to reliably produce high quality welds in a wide variety of materials. Despite comparatively low welding speeds, Tig welding is used almost exclusively for fabricating rocket motor cases and most other aerospace hardware. As the size and wall thickness of these cases increase, the use of conventional Tig welding becomes time consuming and costly and more economical welding methods are constantly being sought. In general, results with the faster Mig and submerged arc processes have been unsatisfactory due to inferior weld soundness and mechanical properties.

After several years of investigation, the Linde Division of Union Carbide Corporation has developed a unique method* of continuously melting filler metal by the resistance heating effect of a current passing through a conductor. With this system filler metal can be deposited into a weld puddle developed by a separate heat source at deposition rates comparable to submerged arc welding. When combined with a conventional Tig arc, hot wire welds can be produced at deposition rates and travel speeds typical of the Mig process.

Early development studies on mild and stainless steels indicated that Tig-hot wire deposition rates can be three to ten times greater than conventional cold wire addition. Moreover, resistance heating of the filler metal drives off volatile surface contaminants before they are carried into the molten puddle and weld quality is exceptionally good.

The purpose of this program was to develop methods for applying the Tig-hot wire process to selected high strength steels suitable for fabricating large rocket motor cases. The materials used were D-6ac, 18 Ni (200) VAR maraging and Republic HP 9 Ni-4 Co-.20 C steels. Other major objectives were (1) to obtain a quantitative measure of the amount of surface contamination actually being removed by resistance heating of filler metal, (2) determine the feasibility of Tig-hot wire welding in the horizontal position, (3) establish the feasibility of using hot wire addition with the plasma arc process, and (4) evaluate the technical and economic merits of Tig-hot wire welding relative to conventional Tig procedures used to fabricate 120-in. diameter D-6ac cases.

*Proprietary process covered under U. S. Patents 3,122,629 and 3,274,371.

II

SUMMARY

High deposition rate welding procedures were established that develop high levels of quality and fracture toughness in aerospace steels. In two of the three high strength steels investigated, welding parameters had to be balanced in accordance with the metallurgical behavior of the weld metals to achieve the desired properties.

The D-6ac alloy was welded satisfactorily using a wide range of parameters. Arc current, travel speed and deposition rate were readily adjusted to produce good penetration, side wall fusion, and bead contour. Any coarse grain structure obtained at high deposition rates was erased by the postweld austenitizing, quenching and tempering treatments used to develop mechanical properties. The fracture toughness and tensile properties of Tig-hot wire welds made at deposition rates up to 8 lbs./hr. and a travel speed of 19 ipm--the practical limit on 3/8-in. test plate--were equal to similar properties of conventional Tig welds.

The tensile properties of welds in 18 Ni (200) VAR maraging steel were unaffected by variations in welding parameters. However, the toughness of high deposition rate welds, as measured by precracked Charpy energy absorption, was sensitive to pass size and rate of heat input. Welding parameters had to be adjusted to produce essentially the same bead size and rate of heat input as a conventional Tig weld to achieve comparable toughness. This was accomplished by escalating travel speed in proportion to deposition rate and adjusting arc current to produce the proper rate of heat input. With this special technique, welds made at deposition rates up to 7.6 lbs./hr. exhibited precracked Charpy energy absorptions and fracture toughness (K^*_{IC}) comparable to conventional Tig welds.

The tensile properties as well as precracked and standard Charpy energy absorptions of welds in HP 9 Ni-4 Co-.20 C steel were sensitive to pass size and to a lesser degree rate of heat input. The pass size of high deposition rate welds had to be small, the same as a typical Tig weld, to achieve comparable as-welded properties. As material thicknesses increased and more passes were used, the greater amount of thermal cycling experienced by the weld metal improved permitting the use of somewhat larger pass sizes. During this study, travel speeds greater than 12.5 ipm produced centerline cracking in a typical U groove joint preparation. This limitation precluded use of deposition rates above 2.5 lbs./hr. on 0.6-in. material and 5.0 lbs./hr. on 1-in. material. Within these limits Tig-hot wire welds exhibited as-welded yield strengths, CVN energy absorption and fracture toughness comparable to conventional Tig welds.

When deposition rates were increased without a proportionate increase in travel speed, pass size became too large and as-welded properties deteriorated. Under these conditions, moderately low properties were improved to satisfactory levels by a low temperature postweld tempering treatment.

Direct comparisons of the hydrogen contents of several types of filler metal and arcless hot wire deposits demonstrated that resistance heating removed virtually all of this major source of porosity. Oxygen and nitrogen levels were also reduced significantly where measurements were taken.

The feasibility of making high deposition rate welds in the horizontal position was established on 18 Ni steel. Welds made at a deposition rate of 7 lbs./hr. had satisfactory penetration, side wall fusion, and bead contour. Mechanical properties were comparable to downhand welds made with similar parameters.

The feasibility of using the hot wire technique with the plasma arc process was also established during this study. The mechanical properties of plasma arc-hot wire welds made on 0.6-in. 18 Ni steel at deposition rates up to 7 lbs./hr. were comparable to properties of Tig-hot wire welds made under similar conditions.

An analysis of test data by the Wright Aeronautical Division of Curtiss-Wright Corporation showed that use of the Tig-hot wire process in place of conventional Tig will result in a 50 per cent reduction in the arc time and interpass cleaning required to fabricate 120-in. diameter Titan III C rocket cases.

III

DISCUSSION

BACKGROUND AND DESCRIPTION OF THE TIG-HOT WIRE WELDING PROCESS

The concept of using resistance heating to increase auxiliary filler metal deposition rates evolved from studies of the melting characteristics of consumable electrodes. As early as 1956, Jackson, et al[1] showed that I^2R heating in the electrode extension between the contact tip and the arc can contribute substantially to the melting rate. More recent studies of short-circuiting type of Mig welding led to the conclusion that it should be possible to continuously melt an electrode on a base plate without an arc if the wire feed rate and power are properly balanced. Using a conventional Mig system, deposition rates of 15 to 20 lbs./hr. were easily achieved with 0.045-in. diameter steel wires.

There is no theoretical limit to the amount of metal that can be deposited by I^2R heating. However, since only enough energy is supplied to melt the wire, the deposit is not fused to the base plate (Figure 1). By itself the system has little practical value for welding. Further work by Manz[2] demonstrated that resistively melted wire can be deposited in a weld puddle produced by another heat source and the technique became a practical method of adding auxiliary filler metal with the Tig, Mig, and plasma arc processes. The hot wire technique has been used to greatest advantage with the Tig process as deposition rates can be increased three to five times the normal cold wire rate while retaining the ultimate in weld quality.

Because the filler metal is melted by its own power source and deposited in the molten state at the trailing edge of the weld puddle, the arc is free to concentrate on the workpiece and high deposition rates can be employed without losing penetration. Also, the filler metal deposition rate can be varied independently of arc current. This affords a new dimension of control not available with any other welding process.

The major components of the Tig-hot wire welding system are shown schematically in Figure 2. In addition to a standard Tig welding torch and a conventional D.C. constant current power source, the system is comprised of a high speed wire drive unit, a specially designed hot wire "torch" which provides electrical contact and guides the filler wire into the weld puddle, and a second A.C. power supply to provide current for I^2R melting of the electrode.

After the weld puddle is established by the Tig arc, the hot wire power source and wire drive unit are energized and wire is fed into the weld puddle, completing the wire melting circuit. The hot wire power source is adjusted to deliver just enough current to melt the wire as it enters the weld puddle. Sufficient energy is supplied to raise an increment of filler metal from room temperature, at the contact tip, to its melting point, at the weld puddle. As an example, carbon and low alloy steels require about 0.16 kilowatt-hour per pound. This results in a range of operating conditions of 75-300 amperes at 5 to 18 volts with 0.030- and 0.045-in. diameter wires for commonly used melting extensions of 1-1/4 to 2 inches.

An alternating current power source is used for melting the filler wire because the magnetic field it produces around the wire causes only a small net effect on the arc. When hot wire currents are kept below about 60 per cent of the arc current, the amplitude of arc oscillation has no significant effect on the welding operation. For this reason, wires of 0.045-in. diameter or smaller are preferred as deposition rates approaching 20 lbs./hr. can be obtained without exceeding the desirable wire current-arc current ratio. If direct current is used as a wire heating source, severe arc blow either toward or away (depending on polarity) from the hot wire can prevent establishing satisfactory operating conditions.

The volt-ampere characteristic of the hot wire power source plays an important part in achieving smooth wire melting. As seen on Figure 3, a conventional high open circuit, steep volt-ampere characteristic would not be satisfactory. Its drooping characteristic diverges widely from that of the wire melting rate and small changes in wire feed speed or power supply output would make smooth wire melting impossible.

For example, on Figure 3, an operating point of 190 amperes and 10 volts is shown for a steel wire deposition rate of about 12 lbs./hr. If the wire feed rate were to decrease to 10 lbs./hr., the power requirement for smooth melting would change to about 175 amperes at 9 volts. With the conventional power supply, a small reduction in current is accompanied by a relatively large increase in voltage. This causes excess power to be supplied to the wire, and it melts off before reaching the weld puddle. As it does, the circuit is broken and the full open circuit voltage of the power supply appears at the end of the wire and establishes an undesirable arc. If the feed rate were reduced when using a power supply with a relatively flat characteristic and low open circuit voltage, the wire can also melt and pinch off above the puddle. However, the open circuit voltage is well below ignition voltage so an arc will not start and the wire will continue to alternately feed into the puddle and burn back until a simple adjustment of the power supply or wire feed can be made.

When the wire speed is increased from the operating point shown on Figure 3, the available power from the drooping power supply rapidly approaches zero at about 200 amperes. This causes the wire to stub violently into the puddle. With a flat characteristic transformer, the available power decreases only slightly, and the process is not disrupted.

PROGRAM WELDING FACILITY

The equipment installation used for this program is shown on Figure 4. The control console, shown on the right, sequences all welding functions, starts and stops torch cooling water, maintains a preset travel speed, regulates and maintains a constant preset hot wire feed rate, automatically controls arc length, and programs welding current sloping functions. The main welding power supply is also contained within this console. An A.C. welding transformer used to melt the filler wire is shown adjacent to the console. The welding operation is controlled from the remote station shown at the extreme left of this photograph.

A close-up view of a development model hot wire feeding attachment, an in-line Tig welding torch, the control station, and the A.C. power source is shown on Figure 5. The filler wire is fed through a conduit system by a standard wire feed unit mounted on a side beam carriage. Arc initiation is accomplished by a conventional high frequency generator. A close-up view of an improved hot wire attachment incorporating running adjustments for positioning the wire in the weld puddle is shown on Figure 6. Auxiliary shielding gas is fed through the hot wire torch to protect the heated wire and also provide a trailing shield for the weld puddle.

The wire is positioned to strike the crest of the weld puddle as it rises behind the arc. An angle of 60° - 90° from the horizontal ensures good electrical contact with the puddle and minimizes changes in wire position caused by variations in electrode-to work distance. Wire introduced to the puddle in a manner similar to conventional cold wire addition frequently "skips" across the puddle and shorts to the electrode.

A block diagram of the Tig-hot wire welding system is shown on Figure 7.

TEST MATERIALS

Three high strength steels were used to evaluate the utility of the Tig-hot wire process for fabricating large solid fuel rocket cases. The alloys selected were D-6ac, 18 Ni (200) VAR maraging steel and Republic HP 9 Ni-4 Co-.20 C steel. Each of these materials develops a yield strength in the range of 180-200 ksi by a different strengthening mechanism and has good fracture toughness.

D-6ac High Strength Steel

Ladish D-6ac steel is a typical low alloy quench and tempered type material requiring a high temperature postweld austenitizing and tempering treatment to develop properties. It is used more extensively than any other high strength material for fabricating solid fuel rocket cases and aircraft structural assemblies. In order to enhance the comparison of Tig-hot wire and conventional Tig-cold wire weld properties, 3/8-in. (nominal) test plate and 0.062-in. diameter filler metal were obtained from heats of steel used by the Wright Aeronautical Division of Curtiss-Wright Corporation to fabricate Titan III C rocket cases.

The chemical composition and tensile properties of the test plate are shown in Table I. The fracture toughness (K_{IC}) of this material is 103 ksi$\sqrt{in}$. The chemical composition and gas content of the filler metal are shown in Table II.

18 Per Cent Ni (200) VAR Maraging Steel

The 18 per cent Ni maraging steels have been the subject of much intensive investigation and several types have been used successfully in experimental rocket case programs. The 200 ksi nominal yield strength vacuum-arc remelted type will probably be used most extensively for future rocket case applications as it produces the most consistent results and the best fracture toughness.[3, 4, 5] The relative simplicity of the low temperature post-weld maraging treatment used to develop weld properties is advantageous to rocket case fabricators.

The test plate for this program was procured from two heats of 200 ksi yield, VAR material produced by Cameron Iron Works for Sun Shipbuilding and Dry Dock Company's 260-in. diameter rocket case program. Two material thicknesses were used--0.6-in. (nominal) from heat #50264 and 1-in. (nominal) from heat #50234. The chemical composition, tensile properties, and pre-cracked Charpy energy absorption of the 0.6-in. plate are shown in Table III. Similar data from the 1-in. plate are shown in Table IV.

The apparent fracture toughness (K^*_{IC}) of the 0.6-in. and 1-in. thick plate, determined by slow notch bend tests, is 147 ksi$\sqrt{\text{in.}}$ and 108 ksi$\sqrt{\text{in.}}$, respectively.

The filler metal used for this phase of the program was 0.045-in. diameter 18 per cent Ni (200) VAR maraging steel (heat #02105) produced by Armetco Inc., Wooster, Ohio. The purchase specification, chemical and gas analyses and all-weld metal tensile properties of this material are shown in Table V. The limits of chemical composition particularly the "hardening" elements aluminum and titanium were patterned after specifications used during Sun Ship's 260-in. diameter rocket case program. Carbon, silicon, nitrogen, oxygen and sulfur were kept as low as practicable to maximize toughness.[6 - 10] Hydrogen was restricted to very low levels to ensure weld metal integrity.

The chemical composition of the wire met the purchase specification but gas contents were higher than anticipated. The oxygen, hydrogen, and nitrogen content of four randomly selected spools of wire exceeded the purchase specification limits as indicated in Table V. Samples of this wire were re-processed by Armetco to remove surface contaminants, but the overall gas level was not reduced significantly. In order to ascertain the suitability of this filler metal, test welds were prepared using both cold and hot wire techniques, maraged for 3 hours at 900° F., x-rayed and tested for longitudinal tensile properties and precracked Charpy energy absorption. Radiographic and ultra-sonic examination disclosed that the welds were free of porosity or other defects. The yield and ultimate strengths of the welds were somewhat lower than similar welds made with 18 Ni filler metal (heat 09944) obtained from Sun Shipbuilding and Dry Dock Company. However, tensile ductility and energy absorption values were slightly higher. Comparative data are shown in Table VI. It was concluded that the relatively high gas content of this wire would not be detrimental, and it was accepted for use in this program.

Republic HP 9 Ni-4 Co-.20 C Steel

The third test material used in the program was Republic Steel's HP 9 Ni-4 Co-.20 C alloy. This is a quench and tempered martensitic steel that develops excellent toughness at 180-200 ksi yield strength. Additionally, filler metals which are modifications of this alloy produce base plate properties in the as-welded condition when used as cold wire with the Tig process. These unique characteristics are highly attractive for rocket case fabrication, and this alloy is a leading contender for future applications.

Test plate was purchased in two thicknesses from Republic Steel Corporation heat No. 3951995. The chemical composition and heat-treated tensile properties of both the 0.6-in. and 1-in. (nom.) thick material are shown in Table VII. The standard ASTM and precracked Charpy energy absorption of both materials are shown in Table VIII.

The apparent fracture toughness (K^*_{IC}) of the 1-in. plate, determined from slow notch bend tests, is 153 ksi$\sqrt{in}$. The apparent fracture toughness of 0.6-in. plate was not determined.

The chemical composition, gas content, and tensile properties of the 0.045-in. diameter HP 9-4 filler metal used in the program are shown in Table IX. The tensile data shown are an average of properties obtained from three conventional Tig welds made using cold wire addition at a deposition rate of 1.6 lbs./hr.

TESTING TECHNIQUES AND EQUIPMENT

The principal objective of the program was to develop high deposition rate Tig-hot wire welding procedures for D-6ac, 18 Ni (200) VAR and HP 9 Ni-4 Co-.20 C steels. The criteria for determining the acceptability of these procedures were weld integrity, tensile properties and toughness of conventional Tig welds made with cold wire addition. The testing techniques and equipment used to measure these properties and to make other routine analytical tests are described in the following sections. All mechanical property data were obtained at room temperature.

Evaluation of Weld Toughness

As yield strengths exceed about 180 ksi, fracture toughness becomes the ultimate criterion for evaluating the quality of highly stressed rocket case weldments. However, in a procedure development program involving hundreds of welds, use of either the slow notch bend or surface flaw tensile testing technique to determine the critical stress intensity factor (K_{IC}) would be inordinately time consuming and expensive. Additionally, the large size test specimens recommended by ASTM Committee E24[11] to obtain valid measurements in relatively tough 200 ksi yield strength materials such as 18 Ni and HP 9-4 could not be obtained from the test materials used in this program. The use of sub-size test specimens would cast considerable doubt on the validity of the data. For these reasons, it was elected to screen the toughness of preliminary welds with the precracked Charpy impact test and limit fracture toughness testing to final weldments.

Precracked Charpy Energy Absorption Tests

The precracked Charpy test specimen used throughout the program is shown on Figure 8. All test specimens were placed transverse to the weld with the fatigue crack oriented vertically in the thickness direction. When tested, the fracture propogates along the length of the weld as with a standard Charpy specimen. The addition of side notches eliminates shear lips and reduces the scatter generally encountered with this test. All test specimens were machined, heat treated (when required) and then fatigue cracked on a Manlabs Fatigue Precrack Machine, Model FCM-300B. Following this, the specimens were broken in a Manlabs Charpy Impact Test Machine, Model CIM-128. The W/A values were calculated by dividing the absorbed energy by the area of the fractured surface.

Conventional Charpy Energy Absorption Tests

In order to establish some correlation between precracked Charpy energy absorption data and standard ASTM Charpy impact data, published by Republic Steel and other investigators, both types of tests were run on 5/8-in. and 1-in. HP 9-4 welds.

Standard 0.394-in. X 0.394-in. test specimens were located 1/8 in. below the top surface of the plate in all cases. Precracked specimens were located flush with the top of the plate in the case of 5/8-in. welds and 1/8 in. below the top of 1-in. welds.

Linear regression analysis of 60 CVN values as a fraction of W/A yielded the following relationship with an unadjusted index of correlation of 0.685.

$$CVN = 9.13 + 0.0134\ (W/A)$$

A plot of CVN vs. W/A is shown in Figure 9.

Fracture Toughness Testing

Fracture toughness testing was performed by the Wright Aeronautical Division of Curtiss-Wright Corporation as a subcontractor. The fracture toughness (K_{IC}) of 18 Ni and HP 9 Ni-4 Co-.20 C was determined by the slow notch bend technique. It is noted, however, that the maximum thickness (B_n) test specimen obtainable from 0.6-in. and 1-in. weldments is less than recommended by ASTM Committee E24 for valid measurements in materials with this level of strength and toughness.

Recommended thickness: $B = 2.5\left(\frac{K_{IC}}{\sigma y}\right)^2$ in.

$= 0.875$ in. for $K_{IC} = 120$ ksi $\sqrt{\text{in.}}$ and $\sigma y = 200$ ksi (18 Ni)

$= 1.22$ in. for $K_{IC} = 140$ ksi $\sqrt{\text{in.}}$ and $\sigma y = 200$ ksi (18 Ni)

$= 1.60$ in. for $K_{IC} = 160$ ksi $\sqrt{\text{in.}}$ and $\sigma y = 200$ ksi (HP 9 Ni-4 Co-.20 C)

Nominal Specimen Thickness in.	Range of B_n in.
5/8 18 Ni	0.474-0.530
1 18 Ni	0.672-0.805
1 HP 9-4	0.775-0.834

Where B_n = thickness of specimen between side notches.

Data from these tests are reported as apparent fracture toughness and indicated herein as K^*_{IC}.

The fracture toughness of D-6ac weldments was determined by the surface flaw tension testing technique used by Curtiss-Wright during their Titan III C rocket case program. Thus, direct comparisons were possible between Tig-hot wire weld data and conventional Tig weld data developed under production welding conditions.

Curtiss-Wrights report on details of testing procedures, specimen configurations, and test data is shown in the Appendix.

Tensile Testing

Standard ASTM procedures and test specimen configurations were used to determine base plate and longitudinal all-weld metal tensile properties. The transverse tensile properties of final welds were determined using the specimen configurations shown in Figure 10.

All specimens were broken in a 120,000-lb. Baldwin BTE Universal Testing Machine with stress strain Autographic Recorder.

Nondestructive Testing

Weld integrity was evaluated by radiographic and ultrasonic techniques. Radiographs were taken with a 250 KVA General Electric (OX250) machine using appropriate penetrameters to obtain 2 per cent sensitivity with Kodak AA film. Ultrasonic testing was performed with a Sperry Products Type UM715 Reflectoscope.

Metallography

Microscopic examination of weld structures was performed with various microscopic equipment including a Bausch and Lomb Balphot I Metallograph with motor-driven carbon arc light source.

Chemical Analyses

The chemical composition of the test materials used in the program was determined with a Jarrell Ash 1.5 meter Atomcounter equipped with a 22-channel sequential electronic scaler readout and tape printout system. This instrument is programmed for 20 specific elements in iron, aluminum and copper base alloys. Complimentary equipment included a Norelco helium path multi-element direct reading spectrometer with five-channel pulse height analyzer and three analyzing crystals.

Carbon and sulfur determinations were made by a combined gravimetric and titrimetric combustion procedure. Phosphorus determinations were made by a photometric "wet" chemical method. The instrumentation used for "wet" chemical photometric procedures was a Hitachi-Perkin Elmer 139 UV-VIS spectrophotometer.

Gas Analyses

Analyses of the gas contents of base plate and filler metal were performed by the Union Carbide Corporation, Metals Division, Technology Analytical Laboratory.

Oxygen and hydrogen determinations were made by the vacuum fusion technique. Nitrogen determinations were made by a "wet" micro Kjeldahl procedure.

EFFECT OF I^2R HEATING ON REMOVAL OF FILLER METAL SURFACE CONTAMINANTS

From the early development stages it had been observed that Tig-hot wire welds were free of porosity. This inherent characteristic is a fortuitous by-product of resistance heating the filler metal to deposit it in the molten state. As a segment of wire moves from the hot wire torch contact tip to the weld puddle, it is brought up to its melting temperature in an inert atmosphere and volatile surface contaminants are driven off before they are carried into the weld.

An extreme example of the hot wire effect is illustrated by the radiographs shown in Figure 11. These two multipass bead-on-plate deposits were made with an experimental Mn-Ni-Mo-V wire that caused severe soundness problems with Mig and Tig welding. With the conventional Tig process and a deposition rate of 3 lbs./hr., this wire produced the porous deposit shown at the top of the figure. The same wire used with the Tig-hot wire process and a deposition rate of 8 lbs./hr. produced the sound deposit shown below.

To obtain a quantitative measure of the surface contamination actually being removed by resistance heating, comparisons were made of the gas contents of several filler wires and "arcless" hot wire nuggets deposited in an inert gas filled chamber. Since no arc was used, the nuggets did not fuse to the base plate and consisted entirely of resistance-melted filler metal. One group of nuggets was immediately refrigerated in a liquid nitrogen cryostat to capture retained hydrogen. A second group was allowed to cool to room temperature in the chamber and subsequently analyzed for O_2 and N_2.

Three types of wire were tested: (1) 18 Ni (200) VAR maraging steel from heat Nos. 02105 and 08950; (2) an experimental Cr-Mn-Ni-Mo filler metal used for welding HY-130/150 steel and (3) the previously mentioned experimental Mn-Ni-Mo-V filler metal. The D-6ac and HP 9 Ni-4 Co-.20 C filler metals used in this program were not available when these tests were conducted.

The results of these tests are shown in Tables X and XI. In every case hydrogen (Table X) was nearly eliminated while oxygen and nitrogen (Table XI) were substantially reduced where measurements were taken. With the Tig-hot wire technique, all wires produced porosity-free welds over a wide range of welding conditions. Thus, it is evident that the hot wire technique provides additional protection against the formation of porosity in critical aerospace weldments.

ALLOY TRANSFER EFFICIENCY

Filler metal deposited by the hot wire technique is added to the trailing edge of the weld puddle and does not pass through or under the arc. The transfer efficiency of the process is, therefore, very high and comparable to conventional Tig. This was demonstrated by determining the alloying constituents of multipass 18 Ni steel all-weld metal pads produced by hot and cold wire techniques. Test specimens were taken from the top of each pad and were representative of undiluted filler metal.

The analyses of both welds together with the composition of the filler wire (heat 02105) are shown in Table XII. These data indicate that both processes transfer virtually 100 per cent of the filler metal alloys to the weld. The slight discrepancies in the Ni analyses were caused by a change in calibration standards.

FEASIBILITY OF HORIZONTAL WELDING

As the size and weight of large rocket cases increase, the cost of precision fixturing for downhand welding multiplies. Vertical tooling is more economical, but it is seldom used due to difficulties encountered in making Tig welds in the horizontal plane at normal cold wire deposition rates. When deposition rates are reduced to very low levels to minimize sagging, the increased welding costs largely offset the economic advantages of vertical fixturing.

The Tig-hot wire process has two characteristics which make it feasible to weld in the horizontal position at economically attractive deposition rates: (1) filler metal is deposited behind the arc and there is less tendency for it to run out of the weld puddle and (2) filler metal is added in the molten state; therefore, less base metal has to be melted to produce a sound deposit.

During the program, defect-free horizontal welds were produced in 0.6-in. 18 Ni steel using a 0.060-in. root face, 0.156-in. radius, 30° included angle joint configuration. Results in several Vee groove joint preparations were unsatisfactory due to inconsistent root penetration. In the U groove, satisfactory root passes were obtained with a shallow groove copper backing bar at deposition rates up to 6 lbs./hr. By positioning the wire 1/16 in. above the electrode, surprisingly flat fill passes were achieved at deposition rates up to 12 lbs./hr. However, cover pass deposition rates have to be reduced somewhat to prevent excessive sagging.

The tensile properties, precracked Charpy energy absorption and apparent fracture toughness of a test weld made with the parameters shown in Table XIII were comparable to the properties of similar welds made in the downhand position. These data are shown in Table XIV. Photographs of the horizontal welding facility and a cross-section of typical welds are shown in Figures 12 and 13. It is to be noted that horizontal welding studies were completed before downhand welding procedures were established for 18 Ni steel. The toughness of horizontal welds in 18 Ni steel can undoubtedly be upgraded by use of the special techniques described later in the report.

FEASIBILITY OF PLASMA ARC WELDING WITH HOT WIRE ADDITION

The plasma arc process can be used advantageously for keyhole welding square butt joint preparations between 0.090 in. and 1/4 in. in most aerospace materials. Above this thickness range, heavy nose Vee joint preparations must be used. Fill and cover passes are then made with filler metal addition. A recent evaluation of plasma arc welding 120-in. diameter, 0.375-in. (nom.) wall D-6ac steel Titan III C rocket cases[12] demonstrated that aerospace quality welds can be produced in about one-half the time required with the conventional Tig process. However, as material thicknesses increase and a greater percentage of the weld has to be completed with cold wire addition, this economic advantage decreases rapidly.

The objective of this task was to demonstrate the feasibility of using high deposition rate hot wire addition with the plasma arc process to improve the economics of welding heavier sections. The test material used was 0.6-in. nominal 18 Ni maraging steel.

A brief evaluation of keyhole-type root pass welds made on four single-vee joint preparations (Figure 14) showed that the best surface and underbead contour are obtained with a 1/4-in. root face, 75° included angle. The welding conditions used for each joint preparation evaluated are shown on Table XV, and cross-sections of each weld are shown in Figure 15. After adapting a hot wire torch to a conventional plasma torch, complete welds were easily produced at deposition rates up to 7 lbs./hr. The root passes were comprised entirely of fused base metal. The fill and cover passes were made by the conventional melt-in technique with hot wire addition. Radiographic and ultrasonic inspection of several welds showed them to be free of defects.

The tensile properties, precracked Charpy energy absorption (W/A) and apparent fracture toughness (K^*_{IC}) of a typical weld (40-37), made using the conditions shown on Table XVI, are shown on Table XVII. A cross-section of weld 40-37 is shown in Figure 16. The longitudinal all-weld metal tensile data were obtained from 0.252-in. diameter test specimens machined from the top half of the weld and indicate the properties of the plasma arc-hot wire deposits. Standard test specimens could not be machined from the narrow keyhole root pass, and no tensile data were obtained from this portion of the weld. The precracked Charpy and slow notch bend test specimens used to determine weld toughness were oriented so their notches and fatigue cracks ran vertically through the weld. The W/A and K^*_{IC} values shown are, therefore, an "average" of the toughness of fused base plate and deposited filler metal.

The tensile properties obtained from this weld were comparable to conventional Tig and Tig-hot wire welds, Table XVII. The W/A and K^*_{IC} values were comparable to similar data obtained from Tig-hot wire welds made at about the same deposition rate and travel speed.

The scope of this study did not include investigating methods for improving fracture toughness. Therefore, the K^*_{IC} data shown in Table XVII should not be interpreted as optimum for plasma arc-hot wire welds in 18 Ni steel.

Additional data on plasma arc welding of 18 Ni steel and several other aerospace materials are available in reports of a more comprehensive program being conducted by the Aerojet-General Corporation, Downey, California under Air Force Contract AF 33(615)-5353.

EVALUATION OF JOINT PREPARATIONS FOR TIG-HOT WIRE WELDING

Prior experience with Tig-hot wire welding of mild steel using typical Tig joint configurations demonstrated that adding molten filler metal behind the arc reduces cushioning and increases the depth and consistency of root penetration. In view of these results, several joint designs were evaluated to determine the potential for welding in smaller openings and to establish a suitable joint configuration for high deposition rate welding of 18 Ni and HP 9 Ni-4 Co-.20 C steels. A 90° included angle, 0.090-in. root face, single-Vee preparation similar to the one employed for conventional Tig welding of 120-in. diameter Titan cases was used for procedural studies on D-6ac steel.

The joint configurations evaluated were 45° and 60° included angle single-Vee and 30° and 40° included angle single U grooves. Detailed drawings of these configurations are shown in Figure 17.

The criteria used to evaluate these preparations were: general ease of welding, bead contour, consistency of root penetration, and adequate side wall fusion.

Weld tests conducted on 5/8-in. thick type A-201 carbon steel indicated that satisfactory results can be achieved in a 60° included angle, 1/16-in. root face design. There was a strong tendency for the arc to wander up the side walls of the smaller 45° angle preparation and root penetration was inconsistent.

Penetration was also erratic in the 60° included angle preparation in the more sluggish 18 Ni and HP 9 Ni-4 Co-.20 C steels. This difficulty was overcome by increasing the opening to 75°.

The 75° included angle, 1/16-in. root face preparation is recommended to assure an adequate margin of safety and to compensate for variations in machining and fitup encountered in a production welding situation.

Consistent penetration was obtained with both of the U groove preparations in 18 Ni and HP 9 Ni-4 Co-.20 C steels. At high deposition rates, there was a tendency for incomplete fusion to the side walls of the 30° included angle design, and it was discarded. Satisfactory results were obtained in the 40° U groove at deposition rates up to 12 lbs./hr. Since this preparation is the same as employed in the fabrication of 260-in. diameter 18 Ni cases, it was adopted for use in this program.

CIRCUMFERENTIAL WELDING PROCEDURES

Over the years, very reliable procedures have been developed for starting and stopping circumferential Tig welds. With minor exceptions, these same basic procedures are used with the Tig-hot wire process.

Tig-hot wire root passes are typically made at deposition rates on the order of 4 to 5 lbs./hr. and arc current, travel speed and wire feed programming are essentially the same as used with cold wire addition. After initiating the arc, wire feed is delayed until a weld puddle and full penetration have been established. It is then increased gradually, along with arc current, to its full operating level. When the start has been overlapped, wire feed is stopped and arc current decayed to eliminate crater cracking.

In the case of high deposition rate fill and cover passes, both travel and wire feed should be delayed until the arc current reaches its full operating level and the weld puddle is large enough to accept the filler metal. Travel is then initiated followed closely by wire feed. The filler wire feed rate is started at a low level and increased gradually to its operating level. Fill and cover passes are terminated in the same manner as the root pass.

These techniques were demonstrated by preparing six weld overlap areas on an 0.6-in. 18 Ni test plate using deposition rates of 4 lbs./hr. for the root pass and 8 lbs./hr. for the fill and cover passes. The starting and stopping sequences used are shown in Figure 18. The underbead and surface of the root pass and the surface of the cover pass in overlap areas are shown in Figure 19. These areas are essentially the same as obtained with cold wire addition. A radiograph of the completed test panel is shown in Figure 20.

A weld intersect was also prepared at a deposition rate of 8 lbs./hr. (Figure 21) and x-rayed to determine weld quality. The negative, shown in Figure 22, indicates good quality.

PROCEDURAL STUDY - D-6ac STEEL

Prior experience with plasma arc welding D-6ac steel[12] indicated that the normal postweld austenitizing, quenching and tempering treatments used with this material would refine any coarse grain structure obtained at high deposition rates and minimize the effects of heat input on weld properties. Attention was, therefore, immediately directed toward a comparison of the properties of Tig-hot wire welds and a conventional Tig weld made using parameters developed by the Wright Aeronautical Division of Curtiss-Wright Corporation for welding Titan III C rocket cases.

Tig-hot wire welds were prepared at deposition rates of 2, 5, and 8 lbs./hr.--8 lbs./hr. was the practical limit for the 3/8-in. thick test plate. In each case, travel speed was adjusted to produce good wetting and a relatively flat bead surface. All root pass welds were made without filler wire addition using 290 amperes, 11 volts, and a travel speed of 4.5 ipm. The joint preparation and fill pass welding conditions are shown in Table XVIII. All welds were made using a preheat and interpass temperature of 500 - 550° F. and subjected to a postweld treatment of 600 - 650° F. for 1 hour.

Round longitudinal and flat transverse tensile specimens and surface flaw tension specimens were taken from each weld and heat treated as follows to obtain properties:

Austenitize	-	1650° F./2 hrs.
Salt Quench	-	400° F./10 min.
Snap Temper	-	400° F./2 hrs. & 600° F./2 hrs.
Final Temper	-	1125° F./4 hrs.

All heat treating and fracture toughness testing was performed by the Wright Aeronautical Division of Curtiss-Wright Corporation using procedures employed during their Titan program. The tensile data and K_{IC} values obtained from these welds and base plate are shown in Table XIX. Photomacrographs of weld cross-sections are shown in Figures 23 through 26.

A comparison of these data indicates that D-6ac hot wire weld properties are unaffected by deposition rate and are equal to similar properties of a conventional Tig weld made with cold wire addition.

PROCEDURAL STUDY - 18 NI (200) VAR MARAGING STEEL

Preliminary Investigation

Past experience with several grades of 18 Ni steel has shown that the Tig process with conventional cold wire addition produces better weld properties than either Mig or submerged arc welding. The superior results obtained with the Tig process have generally been attributed to use of inert gas shielding and inherent weld soundness. Because the Tig-hot wire process produces equivalent weld quality, it could be assumed that high deposition rate hot wire welds would have typical Tig weld properties. However, a comparison of data from 5/8-in. thick conventional Tig-cold wire welds made using 260-in. diameter rocket case parameters developed by the Sun Shipbuilding and Dry Dock Company and initial high deposition rate Tig-hot wire welds indicated that all properties are not equal.

The longitudinal all-weld metal tensile properties of a Tig-cold wire calibration weld and an open Vee "hog trough" hot wire weld made using a coil of filler wire obtained from Sun Ship were the same. A 3-hr., 900° F. maraging cycle was used to age all 18 Ni welds discussed in this section.

	YS (ksi)	UTS (ksi)	% Elong. in. 1.4 in.	R. A. %
Tig-cold wire	205	212	10.7	47.7
Tig-hot wire "hog trough"	202	216	10.4	49.7

The yield and ultimate tensile strengths of a series of Tig-hot wire welds and a Tig-cold wire weld made with filler wire from Cameron Iron Works, heat 02105, are shown plotted against deposition rate, travel speed and total rate of heat input in Figures 27, 28, and 29. Welding conditions are shown in Table XX. The very small effects of travel speed and possibly rate of heat input on properties were considered insignificant for all practical purposes. It was concluded from these data that the tensile properties of welds in 18 Ni steel are unaffected by variations in welding parameters. Additional tensile testing was discontinued except for final weld panels.

The precracked Charpy energy absorption (W/A) of Tig-hot wire welds made at deposition rates between 3 and 12 lbs./hr. varied from 2735 to 943 in. lb./in.^{2} These values are the average of six tests conducted on each weld. The range of values obtained from a given weld was less than 10 per cent and the number of tests per weld was subsequently reduced to three.

These data (Figure 30) showed a definite trend toward lower toughness at the higher deposition rates. However, under certain conditions, the toughness of high deposition rate welds was comparable to conventional Tig. For example, the range of W/A values from welds made at 8 lbs./hr. is the result of deliberate variations in welding parameters. Also at low deposition rates, the toughness of hot wire welds can be substantially higher than cold wire welds. Weld toughness was also seen to be sensitive to the rate of heat input as shown in Figure 31. Thus, it became evident that the toughness of high deposition rate welds in 18 Ni steel is affected by factors other than weld soundness and alloy integrity.

Examination of Tig-hot wire welds having high and low precracked Charpy energy absorptions showed a distinct difference in their as-welded macrostructures. Photomacrographs of two representative welds are shown in Figure 32. The superimposed outline shows the approximate location of the precracked Charpy test specimen used to measure toughness.

The high toughness weld (2735 in. lb./in.^{2}) shown at the bottom of Figure 32 was made at a deposition rate of 3 lbs./hr. and a travel speed of 8 ipm and required 13 passes to complete. Because the individual weld beads are small and staggered, the deposited metal was reheated and partially remelted many times. This repetitive thermal cycling produced a predominately fine grained structure. The low toughness weld (1078 in. lb./in.^{2}) shown above was made at 8 lbs./hr. and 10 ipm and required 6 passes to complete.

This combination of parameters produced a defect-free weld with good wetting and bead shape but a relatively coarse grain structure. Also, the top one-third of the weld was completed in a single pass and received no refining at all.

Initial attempts to improve the toughness of high deposition rate welds by refining the last fill pass with a fusion cosmetic pass were only partially successful. As shown in Table XXI, the addition of a 300-amp. cosmetic pass to 8 lbs./hr., 10 ipm welds did not produce any significant improvement in precracked Charpy energy absorption (W/A) or apparent fracture toughness (K^*_{IC}). It is reasonable to assume that a somewhat higher toughness could have been achieved by optimizing cosmetic pass parameters. However, no attempt was made to do this as the technique affects only the top layer of deposited metal, and its benefits are limited on multipass weldments.

An increase in precracked Charpy energy absorption was achieved by a variation of technique known as "progressive groove welding."[13] With this technique deposition rate and heat input are increased progressively from the bottom to the top of the weld so that bead thickness remains constant and ideally each layer of deposited metal receives the proper thermal treatment from the succeeding pass. A test weld made with the parameters shown in Table XXII had a W/A value twice that of the 8 lbs./hr., 10 ipm weld shown in Figure 32 and slightly higher than a standard Tig weld (2082, 1078, 1775 in. lb./in.^{2}, respectively).

Again, significantly higher toughness probably could have been achieved by optimizing parameters. However, the use of a different set of welding conditions for each pass in a multipass weld was considered impractical and attention was directed toward a simpler method of improving the toughness of high deposition rate welds.

Influence of Pass Size on Weld Toughness

Examination of the parameters used to produce the four hot wire welds exhibiting the highest W/A values (Table XXIII) showed that a combination of 3 lbs./hr., 8 ipm and about 30 Kji produced superior toughness. It was also noted that as deposition rate increased with all other parameters held essentially constant toughness decreased (Figure 33). Additionally, data from weld 1187-80 indicated that this trend can be reversed by increasing arc current along with deposition rate.

Based on these observations, a series of high deposition rate welds was made with parameters adjusted to produce approximately the same bead size and rate of heat input as the low deposition rate-high toughness-hot wire welds. To keep the pass size small and maximize thermal cycling, welding speeds were increased in proportion to deposition rate. Arc current was then adjusted to produce a total rate of heat input of about 30 Kji at the higher travel speeds. This total is comprised of arc plus hot wire heat energy.

A typical calculation is illustrated below using a deposition rate of 5 lbs./hr.:

$$\frac{\text{Low deposition rate (3 lbs./hr.)}}{\text{Low travel speed (8 ipm)}} = \frac{\text{High deposition rate (5 lbs./hr.)}}{\text{High travel speed}}$$

High travel speed = $\frac{5 \text{ lbs./hr.} \times 8 \text{ ipm}}{3 \text{ lbs./hr.}}$

= 40/3 = 13 ipm

27,000 joules/in. (Tig Arc) = $\frac{IV \times 60 \text{ sec./min.}}{13 \text{ ipm (high travel speed)}}$

IV = $\frac{27{,}000 \text{ watt sec./in.} \times 13 \text{ in./min.}}{60 \text{ sec./min.}}$

= 5850 watts

Assuming a 12-volt arc I = 488 amp.

Similar calculations for deposition rates of 6 and 7 lbs./hr. yielded the following combinations of parameters:

Deposition Rate lbs./hr.	Arc Current amp.	Travel Speed ipm
6	555	16
7	657	19

During this program, the practical implications of welding at arc currents above 600 amperes precluded the use of higher deposition rates. Also to evaluate the criticality of the system, the highest arc current and deposition rate were changed to 600 amperes and 7.6 lbs./hr., respectively.

A series of welds made with these parameters exhibited highly refined weld metal and improved toughness. A comparison of photomacrographs (Figure 34) of a 3 lb./hr. weld made at 8 ipm and 7.6 lb./hr. weld made at 19 ipm shows that their structures are very similar. The W/A values obtained from this series of welds are compared to a low deposition rate hot wire weld and a standard Tig-cold wire weld in the following table:

Weld No.	Dep. Rate lbs./hr.	Arc I Amp.	Arc E Volts	Hot Wire I Amp.	Hot Wire E Volts	Travel Speed ipm	W/A in.lb./in.^{2}
88-47	5.2	490	12	130	4.9	13	2140
66-46	6.0	550	13	140	5.3	16	2520
88-48	6.0	550	13	145	5.3	16	2785
88-45	7.6	600	12	160	6.0	19	2523
88-34	3.0	340	11	100	4.2	8	2735
1187-98	3.0	370	11	Cold Wire		8	1775

In all cases, the precracked Charpy energy absorptions of the high deposition rate "stringer bead" type welds were comparable to the low deposition rate weld and higher than a typical Tig-cold wire weld. The improvement in toughness obtained by the stringer bead technique is shown graphically in Figure 35.

Influence of Minor Process Variations

Further study of this technique showed that details of welding procedure influence the degree of thermal cycling experienced by the deposited metal and hence precracked Charpy energy absorption. Collectively, these factors can cause considerable variation in the toughness of welds made with the same nominal parameters.

Because resistively melted filler metal is added to the trailing edge of the weld puddle, arc cushioning is greatly reduced but not entirely eliminated at the higher deposition rates. Variations in arc cushioning caused by deliberately changing the position of the filler metal relative to the tungsten electrode can affect depth of penetration and the thermal gradient in previously deposited metal.

For example, hot wire is normally positioned 1/4 to 1/2 in. behind the tungsten electrode so it enters the crest of the weld puddle. Positioning the wire closer to the electrode tends to increase cushioning and decrease penetration. Conversely, a larger separation tends to reduce cushioning and increase penetration.

The effect of extreme variations in electrode positioning was evaluated by preparing three identical hot wire welds with the filler metal positioned 3/16 in., 1/2 in. and 3/4 in. behind the tungsten electrode. Precracked Charpy tests yielded the following W/A values:

Hot Wire Spacing in.	W/A in.lb./in.^{2}
3/16	1690
1/2	1760
3/4	1789

These data indicate that electrode positioning is not critical. However, extreme deviations from the normal 1/4- to 1/2-in. spacing can contribute to scatter in toughness measurements.

Bead placement and interlacing of heat-affected zones also have an influence on weld toughness. This affect is illustrated by the photomacrographs shown in Figures 36 and 37. Both welds were made with the same parameters but exhibited a difference in W/A values of 659 in. lb./in.^{2} Weld No. 88-45 (Figure 36) had more interlacing of heat-affected zones and a W/A value of 2523 in. lb./in.^{2} Weld No. 88-95 had less bead interlacing and a W/A value of 1864 in. lb./in.^{2}

The stringer bead technique automatically provides a high degree of bead interlacing even in relatively narrow joint preparations such as the one used throughout the program. Better bead interlacing and somewhat higher toughness can undoubtedly be achieved in larger included angle joint preparations.

Effect of Plate Thickness

Application of the high deposition rate parameters developed for 5/8-in. thick material to a single U groove joint preparation in 1-in.

material produced somewhat coarser grain structures and significant differences in precracked Charpy energy absorptions. Toughness measurements were made with the same size (0.600 x 0.394) test specimen used on 5/8-in. welds. Photomacrographs of typical 3 lb./hr. cold wire and 7.6 lb./hr. hot wire welds are shown in Figures 38 and 39.

Data from test specimens located 1/16 in. and 3/16 in. below the top surface of Tig-cold wire and hot wire welds showed that W/A values vary with specimen location. The relative difference in the location of test specimens can be seen by comparing Figures 38 and 40.

Deposition Rate lbs./hr.	W/A in. lb./in.^{2} 1/16 in.	3/16 in.
3.0 Tig-cold wire	1266	1989
3.0 Tig-hot wire	1500	2171
5.0 Tig-hot wire	1346	1800
7.6 Tig-hot wire	1264	1700

The difference in W/A values is caused by variations in the amount of refined material contained in the test specimen. For example, the tougher group of specimens was located lower in the weld and was comprised mainly of refined material. The group located closer to the top of the welds contained a greater percentage of unrefined cover pass material and had lower toughness. Photomacrographs of representative pairs of maraged test specimens are shown in Figure 41. The outlines of the side notches have been accentuated for clarity.

These comparisons confirm the effect of thermal cycling and suggest that toughness may vary considerably from the bottom to the top of a weld. Additionally, the sensitivity of the precracked Charpy test and importance of maintaining constant specimen location were emphasized.

A comparison of precracked Charpy specimens and W/A values from 1-in. and 5/8-in. welds led to a more significant observation. A full plate thickness specimen from a 5/8-in. weld contains about the same percentage of refined material as a specimen taken from the top of a 1-in. weld and less refined material than a specimen located lower in a 1-in. weld. However, the W/A value of a full plate thickness specimen from a 5/8-in. weld is considerably higher than a similarly located specimen from a 1-in. weld made with the same parameters. It is also about equal to the value of a specimen comprised mainly of extensively refined 1-in. material.

Deposition Rate lbs./hr.	W/A in. lb./in.^{2} 1/16 in.	3/16 in.	Avg. 5/8-in. Data
3.0 Tig-cold wire	1266	1989	1775
3.0 Tig-hot wire	1500	2171	2440
5.0 Tig-hot wire	1346	1800	1920
7.6 Tig-hot wire	1264	1700	1980

It must, therefore, be assumed that the refined portion of a 5/8-in. weld is somewhat tougher than the refined upper portion of a 1-in. weld. Thus, it is evident that weld toughness is influenced by weld metal cooling rate--the only factor changed by a variation in plate thickness.

Mechanical Properties

The effectiveness of the "stringer bead technique" was verified by testing a series of high deposition rate welds in 5/8- and 1-in. material for longitudinal and transverse tensile properties, precracked Charpy energy absorption and fracture toughness. The longitudinal and transverse tensile properties of this group of welds are shown in Tables XXIV and XXV. Similar properties are essentially the same for all welds tested. These results confirmed the earlier conclusion that tensile properties of Tig welds in 18 Ni steel are unaffected by wide variations in welding parameters.

Fracture toughness measurements were made using the slow notch bend technique. These data are summarized in Tables XXVI and XXVII together with precracked Charpy data from the same welds. Detailed fracture toughness test data are shown in the Appendix. In some cases, the K_{IC}^* data do not correlate very well with W/A values. It should be noted, however, that the maximum thickness (B) test specimen obtainable from 5/8-in. and 1-in. weldments is less than recommended by ASTM Committee E24 for valid measurements in materials having this level of strength and toughness.

These data show that the toughness of high deposition rate "stringer bead" type welds is comparable to conventional Tig welds made in similar joint preparations and material thicknesses.

Metallurgical Considerations

Having demonstrated that weld toughness is related in a complex manner to welding parameters, details of welding procedures and material thickness, an attempt was made to establish a metallurgical basis for the observed relationships. Metallographic examination of welds having different precracked Charpy energy absorptions showed that increasing toughness correlated fairly well with the amount of dark etching microstructure formed in the lower portions of the welds. This observation ruled out simple recrystallation as this would be effective between adjacent passes throughout the weld and toughness would have correlated directly with number of passes. Increasing amounts of reverted austenite were also found in the dark etching microstructure as the toughness of welds increased.

Since it presently is believed that austenite reversion is harmful to weld metal toughness,[14] it is proposed that the observed increase in toughness is the result of a time-temperature reaction whose kinetics are similar to austenite reversion. It is possible that the toughness increase is caused by grain size effects in the submicroscopic structure of the dark etching material.

Although details of the toughening mechanism cannot be identified, the welding data can be analyzed in terms of its assumed characteristics. If toughness is a function of time within a certain temperature range, the toughest welds should be those in which the greatest volume of material is subjected to an optimum thermal cycle. This hypothesis reduces the variables to two terms: (1) the number of passes in a given thickness and (2) the time-temperature cycle experienced by the weld metal.

The time a fixed point in each of the welds shown on Table XXVIII would spend above 1100° F. was calculated by Rykalin's[15] equations. This is an arbitrary criterion but serves to put the different welding conditions and plate thicknesses in the proper order with respect to the assumed characteristics of the toughening mechanism. An adjusted material thickness of 13/16 in. was used for welds 88-92, 96, and 97 to compensate for the lower position of the precracked Charpy specimens.

When weld toughness (W/A) is plotted against time above 1100° F. (t) and the number of weld passes (N), Figure 42, it can be seen that the hypothesis correlates very well with the experimental data. In order to include data from 1-in. welds, the number of passes was reduced to an estimated equivalent for a 5/8-in. weld. This introduced some error into the analysis.

This hypothesis also accounts for the low W/A values obtained from 1-in. welds made in a double U groove joint preparation (88-64, 65, 66, 69, Table XXVIII. Previously, these data were thought to be invalid because much of the first three passes had to be ground out and rewelded due to severe arc blow in this joint configuration.

Linear regression analysis of W/A values obtained from stringer bead-type hot wire welds as a function of time above 1100° F. (t) and number of passes (N) produced the following equation with an unadjusted index of determination of 0.775. This degree of correlation is considered good for experimental toughness data.

$$W/A = -1967 + 251\ (t) + 206\ (N)$$

The fact that the data show toughness increasing with increasing time in the elevated temperature range should be regarded with caution and not extrapolated beyond the limits of the present data. There probably is an optimum time associated with the toughening mechanism after which toughness will decrease. Regardless of this unknown factor, increasing time ultimately will increase the amount of reverted austenite to the point where it will offset any beneficial effects of thermal cycling and toughness will decrease.

Summary

In summary, the tensile properties of Tig welds in 18 Ni (200) VAR maraging steel are determined by the postweld aging treatment and are unaffected by wide variations in welding parameters. Precracked Charpy energy absorption, however, decreases as deposition rates are increased and pass size becomes larger. The rate of heat input used during welding also significantly influences weld toughness. By properly balancing travel speed, deposition rate and arc current, satisfactory toughness can be achieved at high deposition rates.

Although the details of the toughening mechanism of this material are not fully understood, it is evident that grain refining and a time temperature reaction whose kinetics are similar to austenite reversion are the principal factors influencing weld toughness. High deposition rate welding parameters must be adjusted to produce essentially the same bead size and rate of heat input as a conventional Tig weld in order to achieve comparable levels of precracked Charpy energy absorption. These requirements can be easily met at deposition rates up to 8 lbs./hr. by selecting parameters in accordance with the following general relationships:

1. Adjust travel speed so the ratio of travel speed-to-deposition rate equals 2.7:1.

2. Adjust arc current (and voltage) so the rate of heat input is equal to about 27,000 joules/inch.

High deposition rate welds made under these conditions will have mechanical properties comparable to conventional low deposition rate Tig welds.

PROCEDURAL STUDY - HP 9 NI-4 CO-.20 C STEEL

Preliminary Investigation

Republic's HP 9 Ni-4 Co-.20 C steel is a low-carbon martensitic material that develops nominal room temperature properties of 150 ksi$\sqrt{\text{in.}}$, 45 - 55 ft. lbs. and 3000 - 4000 in. lbs./in.^{2} at 180 - 200 ksi yield strength after suitable quenching and tempering treatments.[16, 17] Unlike higher carbon quench and tempered steels this alloy can be welded in the heat-treated condition without postweld treatments. The as-welded properties of conventional low deposition rate Tig welds made with modified and matching base plate composition filler metals are comparable to base plate properties.[17, 18]

During this program, conventional Tig welds made with filler metal from heat 60320 at a travel speed of 8 ipm and deposition rates of 1.0 and 1.6 lbs./hr. exhibited the following range of as-welded properties. Complete data are shown in Tables XXIX and XXX.

Longitudinal Yield Strength ksi	Transverse Yield Strength ksi	CVN ft. lbs.	W/A in.lb./in.^{2}
188-201	181-197	41-53	2533-3172

The yield strengths of hot wire welds made in 0.6-in. plate at deposition rates between 2.4 and 7.6 lbs./hr. varied with the number of passes as shown in Figure 43. As the number of passes increased and pass size decreased, yield strength improved from 156 to 186 ksi. This same general relationship was observed in conventional Tig weld data published by TRW Inc.[18] The yield strengths of 0.5-in. (nom.) welds made with two-wire compositions containing 0.20 per cent carbon varied with the number of passes as shown in Figure 44. The range of data shown on Figure 43 is superimposed for comparative purposes. Other welds made by TRW with higher carbon wires exhibited the same general relationship but at a higher strength level. Yield strength was also influenced by cooling rate[15] but in a much less definitive manner. These results can be explained best by considering the effects of pass size and cooling rate on the metallurgical characteristics of the material.

Metallurgical Considerations

Metallographic examination of weld microstructures showed ferrite in the as-deposited cover passes. In general, the extent of individual ferrite plates tended to be limited by the high alloy, high hardenability material at the solidification cell walls. As cooling rates decreased, progressively more ferrite was apparent and individual plates began to penetrate across cell walls. This condition is shown in Figure 45, the as-deposited cover pass region of the lowest strength weld 88-84 (Table XXIX). This weld experienced a cooling rate of 33° F./sec. and contained 9 passes.

Further metallographic examination of low strength welds made at conditions that produced large passes and low cooling rates showed that there were significant amounts of ferrite in areas that had been reheated almost to the melting point by the next pass. In these regions, ferrite tended to form in coarse plates that extended across the width of prior austenitic grains.

The microstructure of the grain coarsened region of low strength-large pass size weld 88-84 (156 ksi) is shown in Figure 46. This can be contrasted to the microstructure of an equivalent location in high strength (201 ksi)small pass size Tig weld 186-53 (Table XXX) shown in Figure 47. In this latter case, the grain size is exceedingly small and ferrite in amount and shape is about the same as in as-deposited material.

The hardenability of this weld metal composition is not adequate to suppress the formation of ferrite at low cooling rates. However, as pass size decreases and the number of passes increase, the beneficial effects of grain refinement and tempering[16, 18] overshadow the transformation problem and yield strength increases.

The thermal cycle imposed by subsequent passes also influences the extent of tempering in previously deposited metal. Slow cooling rates increase the amount of time spent at the tempering temperature and improve strength by this mechanism. However, slow cooling rates also reduce strength by decreasing the amount of martensite present. Thus, the as-welded properties are related to two opposing phenomena, whose relative contributions in a given weld could not be separated. This is the source of scatter in the strength data shown in Figure 43 which cannot be resolved as simple functions of welding parameters.

Effect of Plate Thickness

A series of welds made in 1-in. plate using the same parameters employed on 0.6-in. plate exhibited significantly higher yield strengths (Table XXX). This increase in yield strength cannot be attributed to improved high temperature tempering as pass size remained essentially the same in comparable welds. The 1-in. weldments experienced a higher cooling rate but as previously noted the overall effect of cooling rate on yield strength cannot be evaluated. Quenching a portion of Tig weld 186-54 (Table XXX) in liquid N_2 increased its yield strength to 199 ksi as compared to 188 ksi in the as-welded condition. This increase in strength could only have been caused by transformation of retained austenite. It is, therefore, believed that the increased thermal cycling resulting from the larger number of passes in the 1-in. welds produced a relatively long distance-low peak temperature transformation of retained austenite.

Welding Procedures

It is evident from the foregoing discussion that pass size is the predominant factor influencing the strength of welds in the 9 Ni-4 Co-.20 C (nom.) alloy system. Pass size must be kept small to assure adequate grain refinement and tempering and excessively low cooling rates should be avoided.

Attempts at increasing travel speed in proportion to deposition rate to maintain the same pass size as a conventional Tig weld were only partially successful. During this program, conventional Tig welds made at travel speeds five times greater than the deposition rate (8 ipm - 1.6 lbs./hr.) consistently exhibited longitudinal yield strengths above 187 ksi with CVN energy absorptions above 40 ft. lbs.

Tig-hot wire welds can easily be made at this same ratio of travel speed-to-deposition rate (same pass size) up to 4 lbs./hr. and 20 ipm. At higher deposition rates, travel speeds become excessively high for large rocket case fabrication. However, in the U groove joint preparation used, travel speeds above 12.5 ipm produced centerline cracking in the first three to four passes. This restriction limited deposition rates to about 2.5 lbs./hr. on 0.6-in. material. When the ratio of travel speed-to-deposition rate was reduced to 4:1 to facilitate using higher deposition rates on 0.6-in. material, yield strengths were unsatisfactory. The strongest weld made at this lower ratio (186-60, 3.0 lbs./hr. - 12 ipm, Table XXX) had a longitudinal yield strength of 181 ksi with CVN energy absorption of 55 ft. lbs., but transverse yield strength was only 165 ksi.

Satisfactory properties were obtained at somewhat higher deposition rates on 1-in. material due to less retained austenite. With travel speed set at 12 ipm to prevent cracking, a weld (186-57) made at 3.0 lbs./hr. (4:1 ratio) exhibited a longitudinal yield strength of 197 ksi and CVN and pre-cracked Charpy energy absorptions of 62 ft. lbs. and 4030 in. $lb./in.^2$ All transverse tensile properties were satisfactory. A weld made at 5.0 lbs./hr. deposition rate exhibited a longitudinal yield strength of 186 ksi with CVN and precracked Charpy energy absorptions of 48 ft. lbs. and 2174 in. $lb./in.^2$ Transverse yield and ultimate tensile strengths were satisfactory but elongation and reduction of area were low.

Complete data from these welds and a Tig-cold wire weld made at 1.6 lbs./hr. are shown in Table XXX. Photomacrographs of cross-sections of a conventional Tig weld (186-53) and 3.0 (186-57) and 5.0 (186-56) lbs./hr. hot wire welds are shown in Figures 48, 49 and 50.

As noted previously, the effect of cooling rate on mechanical properties is not clear. Accordingly, optimum arc currents could not be established precisely. In general, arc currents between 300 and 350 amperes produced satisfactory results at travel speeds up to 12 ipm.

Procedural Modifications

Postweld Heat Treating: Limited tests demonstrated that the 0.16 carbon filler metal used in this program has a low temperature tempering response similar to 0.20 carbon base plate.[16] Postweld tempering of a 5.0 lb./hr. weld that exhibited a moderate yield strength in the as-welded condition produced the following improvement in properties:

Weld No.		YS (ksi)	CVN (ft. lb.)	W/A in. lb./in.^{2}
186-1	as-welded	167	40	2320
	3 hr. @ 400°F.	182	49	3070
	3 hr. @ 1000°F.	182	43	2629

These results suggest that inadequate properties of high deposition rate welds could be upgraded to acceptable levels by a moderate postweld tempering treatment.

Joint Preparation: The beneficial effects of increased thermal cycling observed in 1-in. weldments suggested that use of a wider joint preparation would improve as-welded properties. This was verified by results obtained in a 1-in. thick 60° included angle, 1/4-in. root opening single-vee preparation with a backing strap. Weld No. 186-61 (Table XXX) made at 7.6 lbs./hr. and 16 ipm in this preparation contained 31 passes as compared to 24 in weld 186-55 made with identical parameters in a 40° included angle, 0.156-in. radius, 0.060-in. root face U groove. The additional thermal cycling and grain refinement improved yield strength from 180 to 197 ksi, CVN energy absorption from 40 to 58 ft. lbs. and precracked Charpy energy absorption from 2265 to 3734 in. lbs./in.^{2} Moreover, no cracks were detected in the open-vee joint preparation. A photomacrograph of weld 186-61 is shown in Figure 51.

Program scheduling did not permit a reevaluation of joint preparations for high deposition rate welding of this material. It is reasonable to assume, however, that improved properties could be achieved at high deposition rates in a wider (3/32-to 1/8-in. land) U groove preparation.

Summary

In summary, pass size is the most critical factor influencing the as-welded properties of welds made with the 0.16 carbon filler metal used in this program. To achieve yield strengths above 180 ksi with room temperature CVN energy absorptions above 40 ft. lbs., high deposition rate welds must be made with small passes comparable to conventional cold wire Tig welds. On 0.6-in. plate, travel speeds must be on the order of five times the deposition rate. As material thicknesses increase and a larger number of passes are required to complete a weld, increased thermal cycling improves weld properties. Thus, somewhat larger passes are tolerable in thicker weldments. For example, in 1-in. welds pass sizes corresponding to travel speed-to-deposition rate ratios greater than 2.5:1 produced satisfactory as-welded properties.

These ratios can easily be maintained at high deposition rates with the Tig-hot wire process because deposition rate is virtually independent of arc current. However, cracking tendencies in the U groove joint preparation employed in this study precluded using travel speeds over 12.5 ipm. This restriction limited deposition rates to about 2.5 lbs./hr. on 0.6-in. material and 5.0 lbs./hr. on 1-in. material. These boundary limits are shown schematically in Figure 52.

The cracking encountered in the lower portions of the U groove joint preparation was associated with concave bead contours resulting from excessive side wall wetting. Use of a wider joint preparation will minimize this condition and facilitate welding at higher travel speeds and deposition rates. Additionally, the greater number of passes required to fill a wider opening improve weld properties. Thus, the boundary limits shown in Figure 52 extend upward and to the right for wider joint preparations.

A low temperature postweld tempering treatment will also improve weld properties. Therefore, under certain circumstances, it may be economically attractive to increase deposition rates to the point where as-welded properties are moderately low and upgrade them to satisfactory levels by a localized low temperature postweld heat treatment.

PRODUCTION APPLICATION ANALYSIS

The Wright Aeronautical Division of Curtiss-Wright Corporation evaluated the merits of the Tig-hot wire process relative to conventional Tig welding for fabricating large rocket motor cases. Their experience and data[19] obtained from production welding of 120-in. diameter D-6ac Titan III C rocket motor cases and a prototype 156-in. diameter 18 Ni motor case that was welded in the horizontal position[20] were used as a basis for the evaluation. Data obtained from Tig-hot wire test welds were extrapolated to equal the thickness of the production motor case welds. Tig-hot wire welding procedures were then developed and compared with Tig-cold wire production experience. The relative merits of the Tig-hot wire process were derived from the following considerations; (1) welding rates, (2) weld quality and (3) position of welding.

Welding Rates

The schedule for production welding of 120-in. diameter Titan III C motor case girth welds is presented in Table XXXI along with comparable data derived from Tig-hot wire welds in the same material and thickness. The weld tooling and equipment are essentially the same for both processes as well as joint preparation, setup and postweld operations. These costs are considered constant and are not included in the analysis.

The fusion (root) pass is the same for both processes. The number of fill passes using the hot wire process would be reduced from four to two. Total arc time including the root pass is 4.4 hours for conventional Tig and 2.25 hours for a hot wire weld. As interpass cleaning operations would also be reduced from four to two, an additional hour of machine time and one hour of labor for each of the three men in the welding team would be saved. The maximum deposition rates of the hot wire process cannot be utilized on the relatively thin Titan sections and maintain good bead contours. Even with reduced deposition rates of 5.75 lbs./hr., filler metal was added 3.3 times as fast as conventional Tig welds. Based on conservative welding procedures designed for freedom from weld defects, the arc time and associated weld costs of the Tig-hot wire process would be reduced 50 per cent relative to the same joint welded with the conventional Tig process.

Weld Quality

An important aspect in comparing welding processes is the frequency of weld defects requiring repairs. With large diameter rocket motor cases, the time required for locating and repairing defects plus reinspection is of the same order of magnitude as the original welding. The most frequent type of weld defect encountered with conventional Tig welding is random or scattered porosity. This is often caused by contaminated filler wire either from drawing compounds embedded in the wire surface or random contamination due to handling or exposure. The hot wire process by virtue of preheating the filler wire in an inert atmosphere, before entering the arc zone, volatilizes these contaminants before the filler is melted into the weld puddle. Spools of filler wire, known to promote a high level of porosity in cold wire welds, have shown a pronounced reduction of porosity when run with the hot wire process under similar conditions.

Additional benefits from the hot wire process result from adding the filler wire behind the arc relative to arc travel. This permits the tungsten arc to obtain satisfactory fusion in the weld groove before the filler is added. This is particularly important with the first fill pass after a fusion (root) pass when the weld groove is apt to be slightly scalloped or irregular. Experience with Titan motor case welds has borne out that this factor is apt to cause bridging or lack of fusion, usually accompanied by some porosity. Special weld settings were developed featuring reduced wire feed in order to obtain good fusion and optimum weld quality. Although this technique resulted in an extra weld pass, the additional costs were more than recovered by a subsequent reduction in weld repairs. The hot wire process inherently provides for weld fusion with the groove walls and high deposition rates are feasible without sacrificing weld quality.

The weld defects in a series of motor case girth welds with conventional Tig practice are shown in Figure 52. Defects 0.030 in. or larger, including surface indications, would be cause for rework and the inch of weld containing the indication would be considered defective. Each rejectable indication must be individually located, routed out, inspected to insure removal, preheated, rewelded, postheated, stress-relieved and re-inspected. Therefore, the presence of a relatively few isolated defects add a cost factor in welding greater in magnitude than the arc time associated with the original weld.

The reduction of weld defects shown in Figure 52 was the result of a constant program of weld surveillance and process improvement. The Tig-hot wire process is believed to provide a logical extension in the quality improvement program capable of significant gains in control of weld porosity and lack of fusion.

Position Welding

Welds made in the horizontal position with the Tig-hot wire process were equal in weld quality and deposition rates to equivalent flat position welds. No problems were encountered at deposition rates up to 8 lbs./hr. with horizontal welds in 0.625-in. 18 Ni plate. The fundamental advantage in horizontal welding rocket motor cases is the reduced initial cost of weld tooling and fixtures due to greatly simplified construction.

The hot wire process was compared with a conventional Tig weld in a prototype 156-in. diameter motor case. Data generated by the Linde

Laboratories with the hot wire process (test weld 1187-99) were adjusted for section thickness and compared with the 156-in. diameter girth weld production record, as shown in Table XXXII. Both welds were made in the horizontal position. Total arc time for the 156-in. diameter weld was 9.5 hours and the deposition rate averaged 2.0 lbs./hr. An equivalent weld with the hot wire process would have been completed in 3.8 arc hours and with an average deposition rate of 7 lbs./hr. Three less weld passes would be required.

Summary

The Tig-hot wire process can displace conventional Tig welding advantageously in motor case welds 0.250-in. thick and above. Increases of up to three times cold wire deposition rates are practical in many applications, including horizontal position welding. A reduction of 50 per cent in arc time and interpass cleaning can be anticipated with Tig-hot wire welding of Titan III C rocket cases.

Internal weld quality obtained with the Tig-hot wire process was found to be consistently better than that of conventional Tig welds on the same materials and thickness. Preheating of the filler wire in an inert atmosphere before entering the arc zone drives off adhered contaminants on the surface of the wire, a known source of weld porosity. Adding the filler wire behind the arc permits more consistent fusion with the weld bevels and reduces the possibility of weld metal bridging.

Ease of bead placement and process control should appear to welding operators, and no difficulty is expected in training to use the Tig-hot wire process.

IV

CONCLUSIONS

The following conclusions can be drawn from the results of this study:

1. The high deposition rate Tig-hot wire process can be used advantageously to fabricate D-6ac, 18 Ni (200) VAR maraging and HP 9 Ni-4 Co-.20 C steel rocket motor cases and other aerospace hardware.

2. When the proper welding procedures are employed, the mechanical properties of high deposition rate welds are comparable to conventional Tig weld properties.

3. Welding time can be reduced at least 50 per cent as compared to conventional Tig welding.

4. Resistance heating of the filler metal volatilizes most surface contaminants and virtually eliminates this major source of porosity.

V

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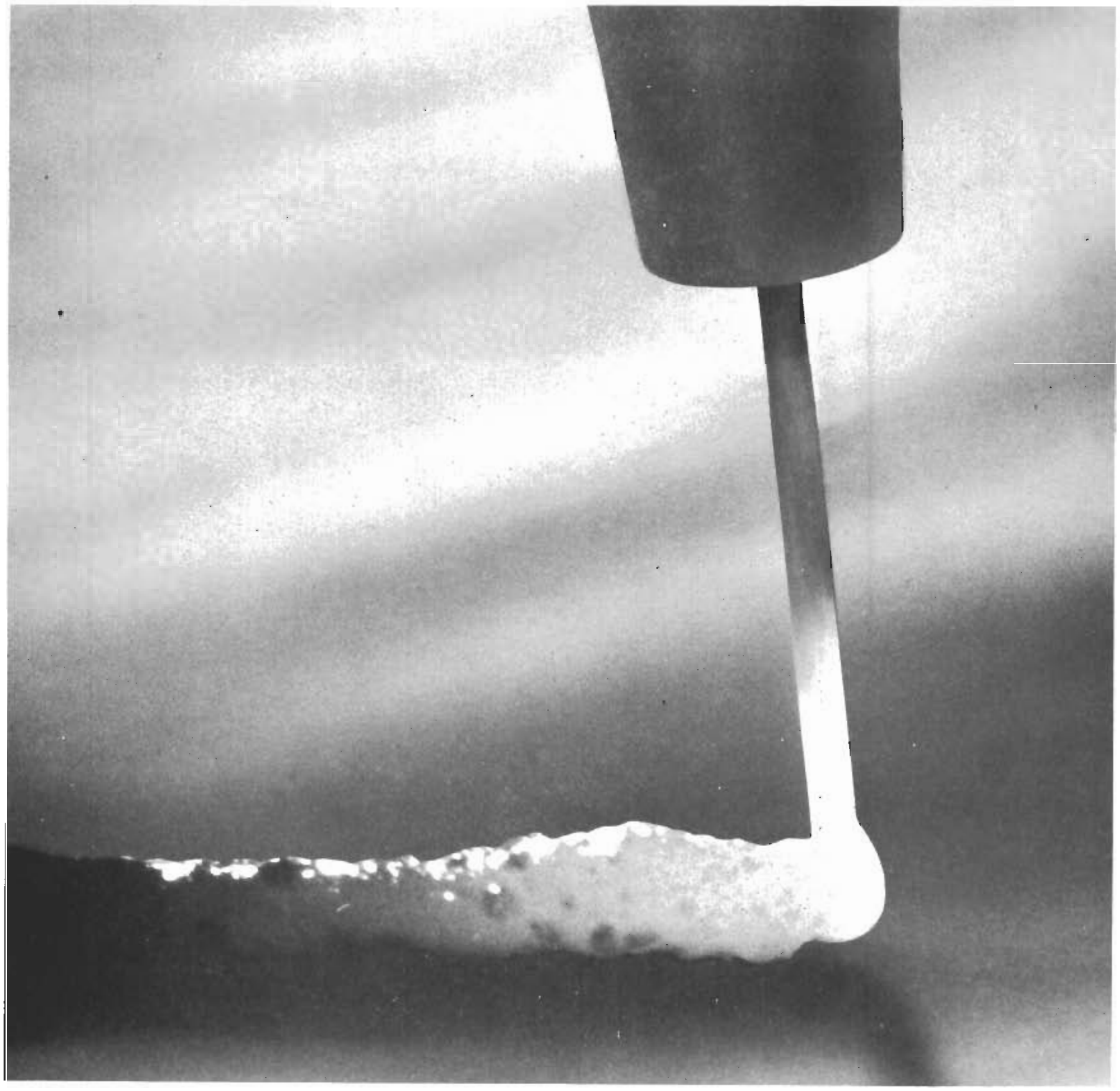


FIGURE 1

ARCLESS HOT WIRE DEPOSIT

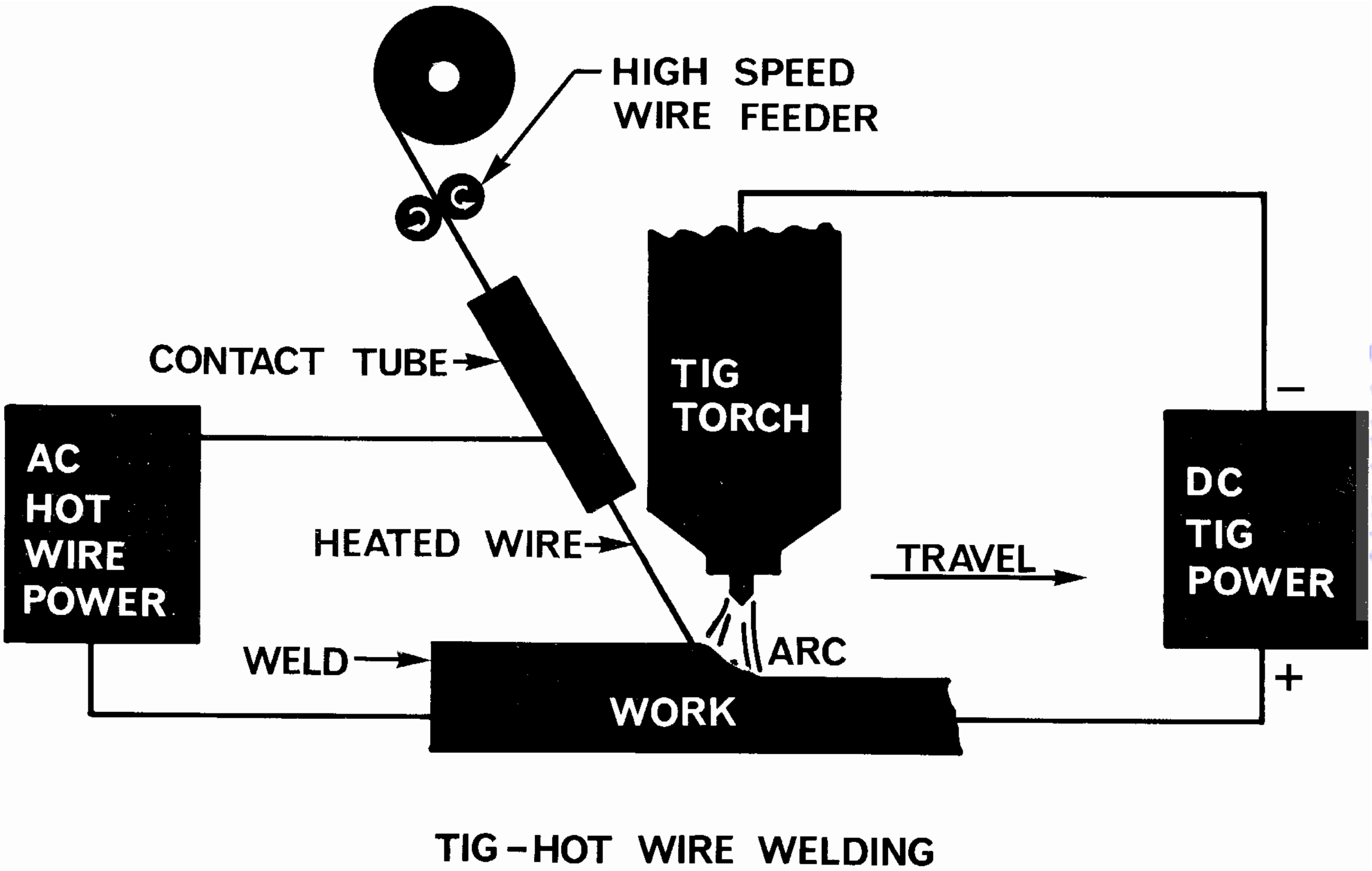


FIGURE 2

SCHEMATIC OF TIG-HOT WIRE WELDING SYSTEM

23058

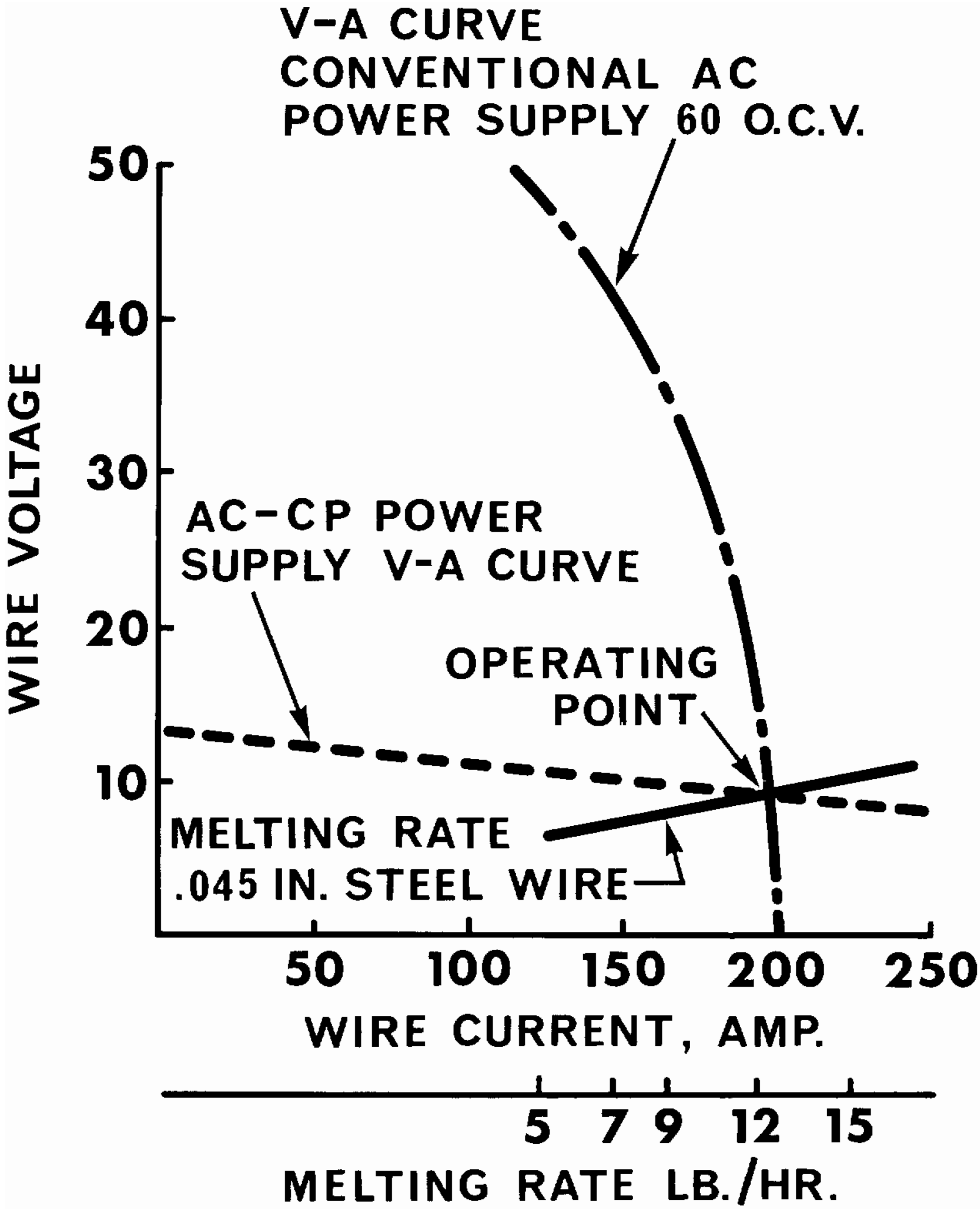


FIGURE 3

POWER SUPPLY CHARACTERISTICS

21810

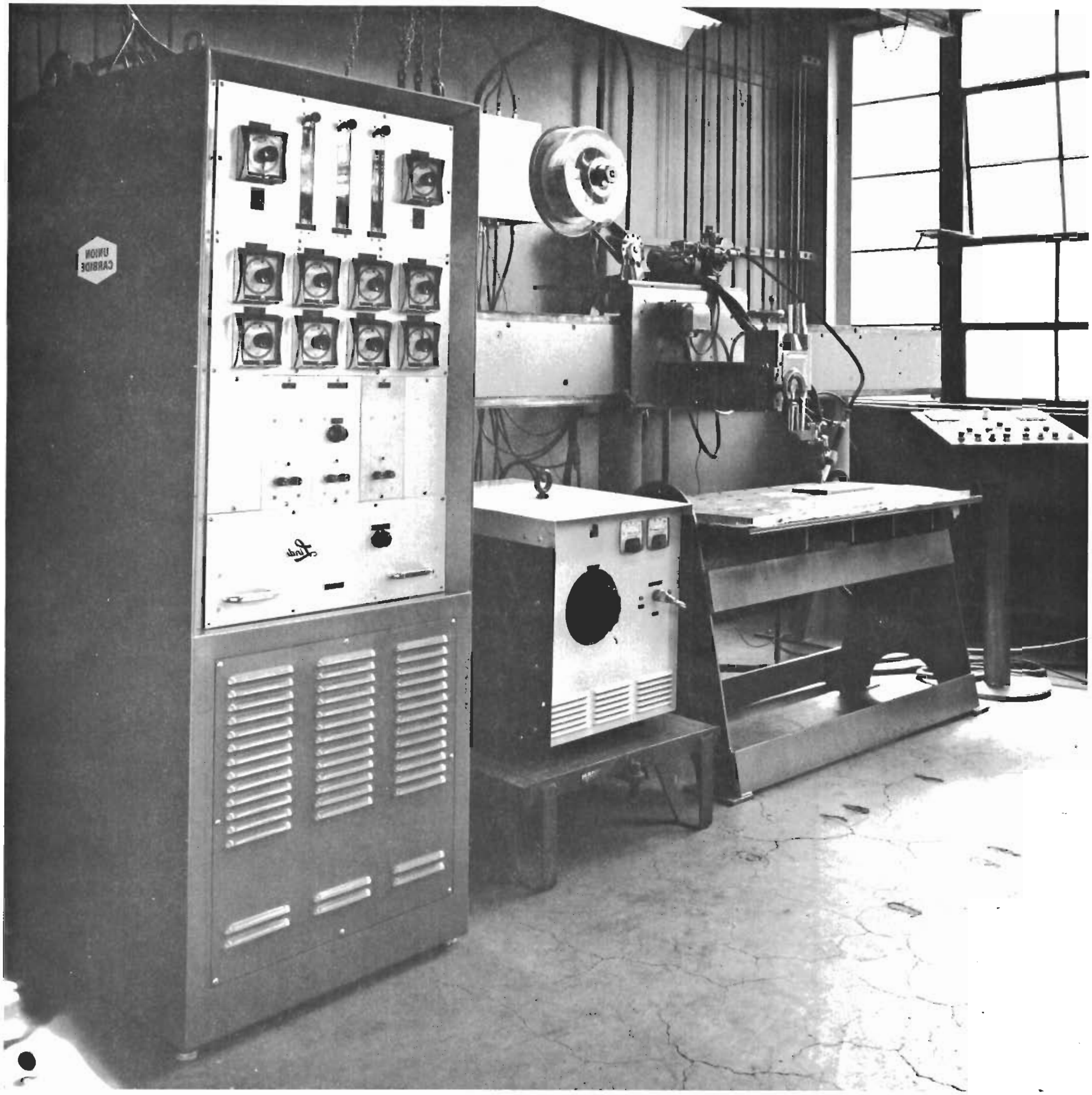


FIGURE 4

PROGRAM WELDING FACILITY

20862

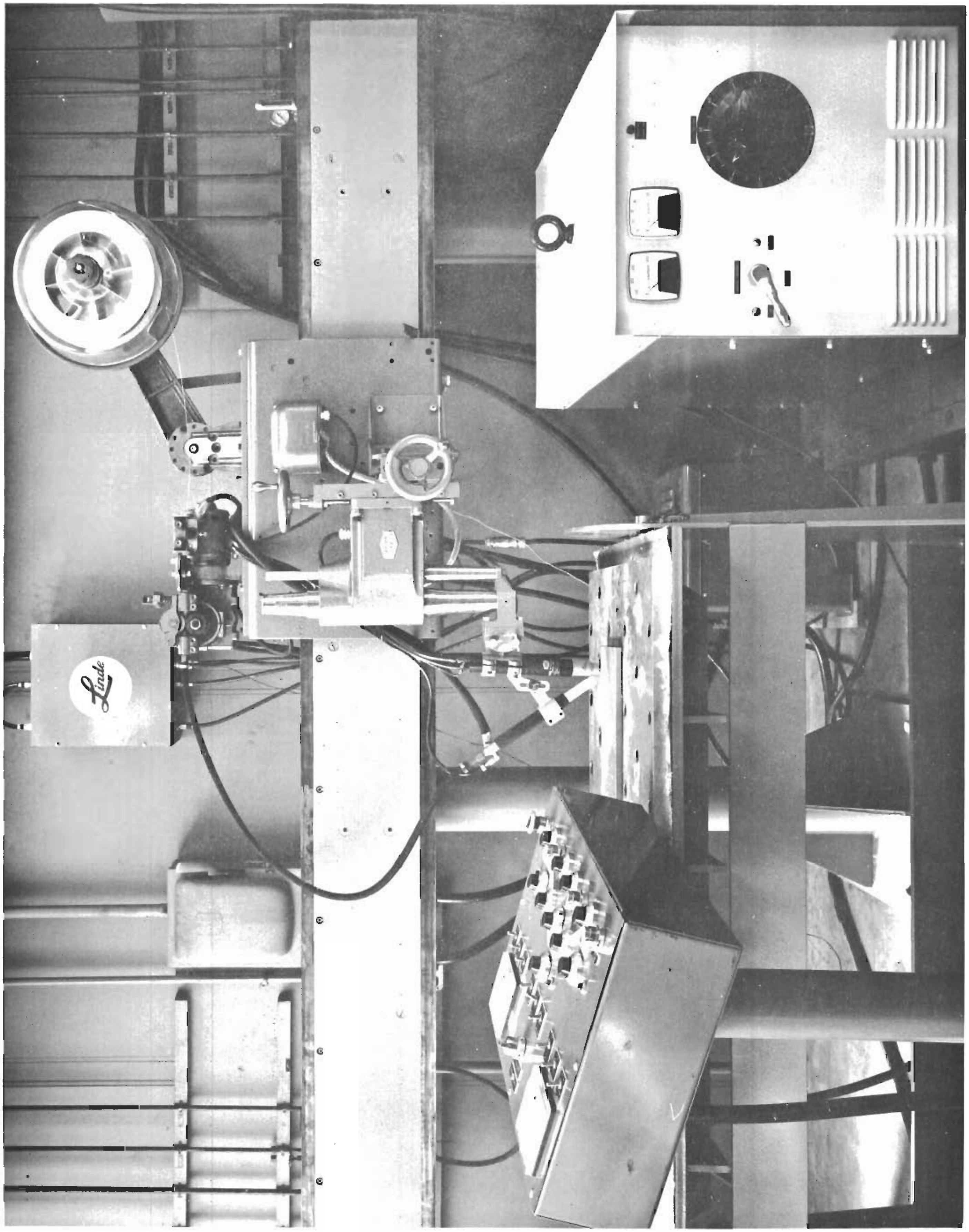


FIGURE 5

PROGRAM WELDING FACILITY

20863

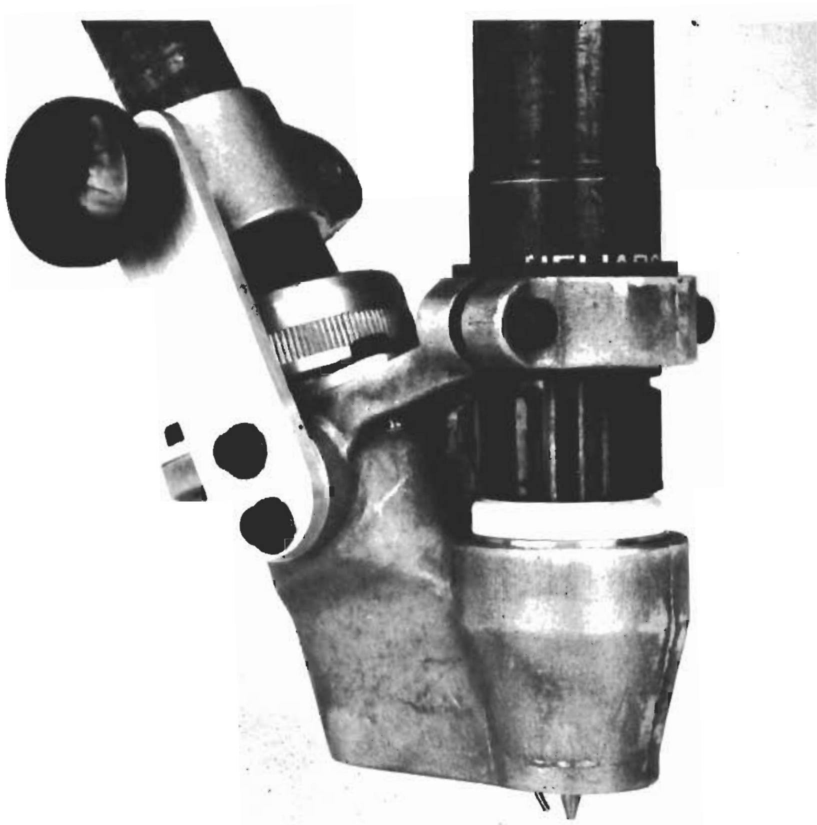


FIGURE 6

MECHANIZED TIG WELDING TORCH WITH HOT WIRE ATTACHMENT

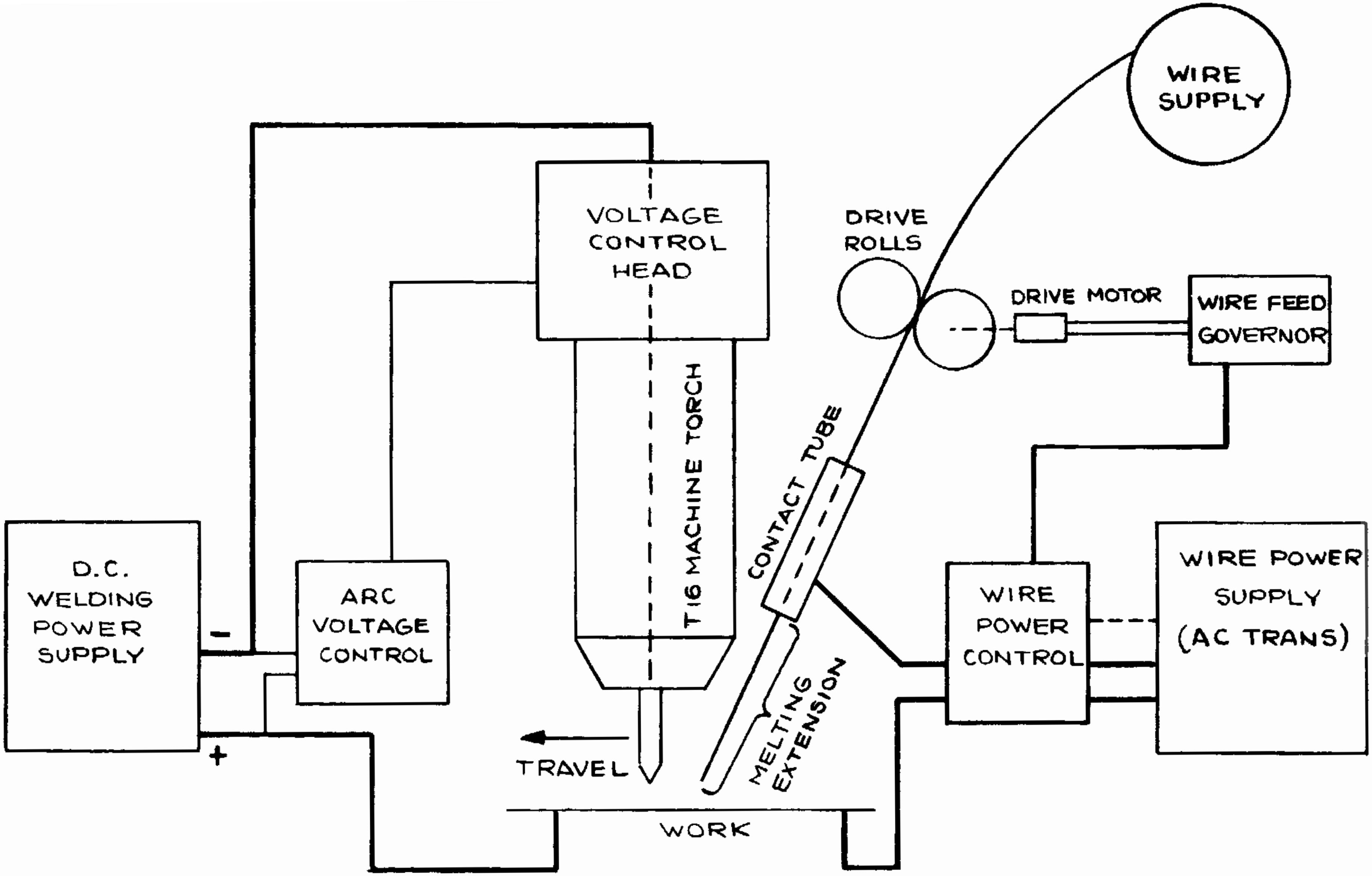
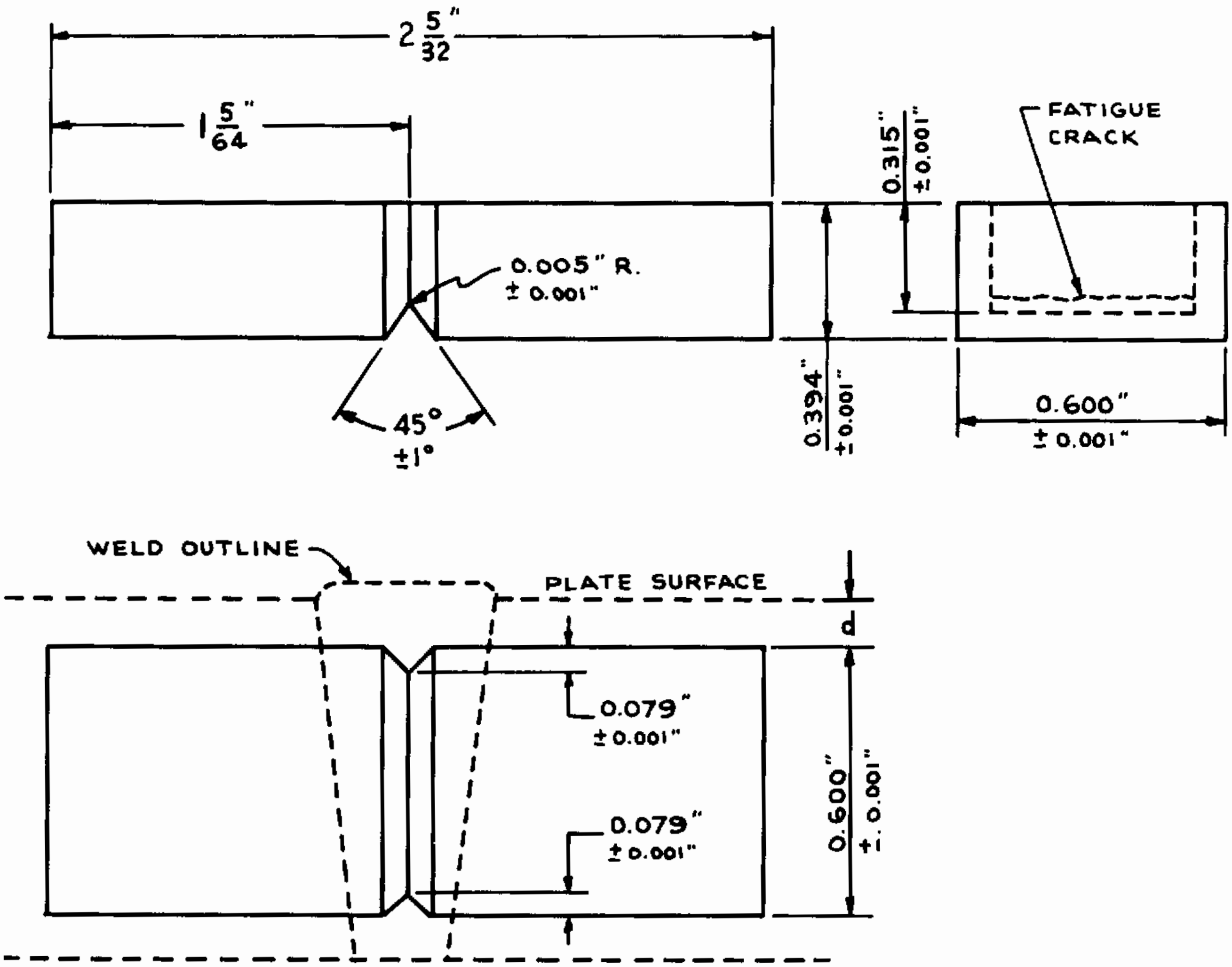


FIGURE 7

BLOCK DIAGRAM OF TIG-HOT WIRE WELDING SYSTEM



NOTES :

1. NOTCH TO RUN FROM TOP TO BOTTOM OF WELD ON WELD SPECIMEN.
2. DIMENSION d SHALL BE 1/8" UNLESS OTHERWISE SPECIFIED.

FIGURE 8

PRECRACKED CHARPY-VEE NOTCH IMPACT SPECIMEN

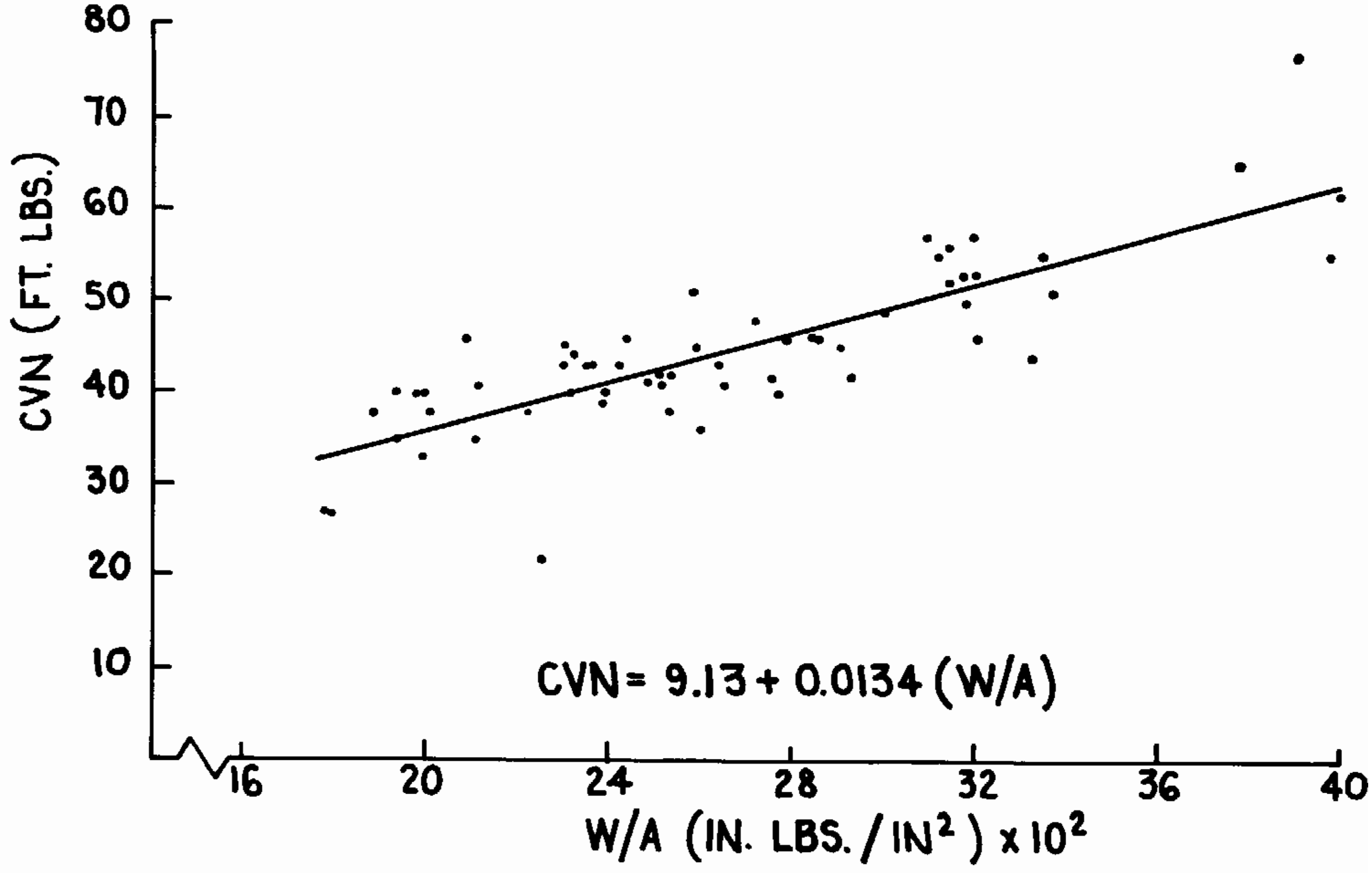
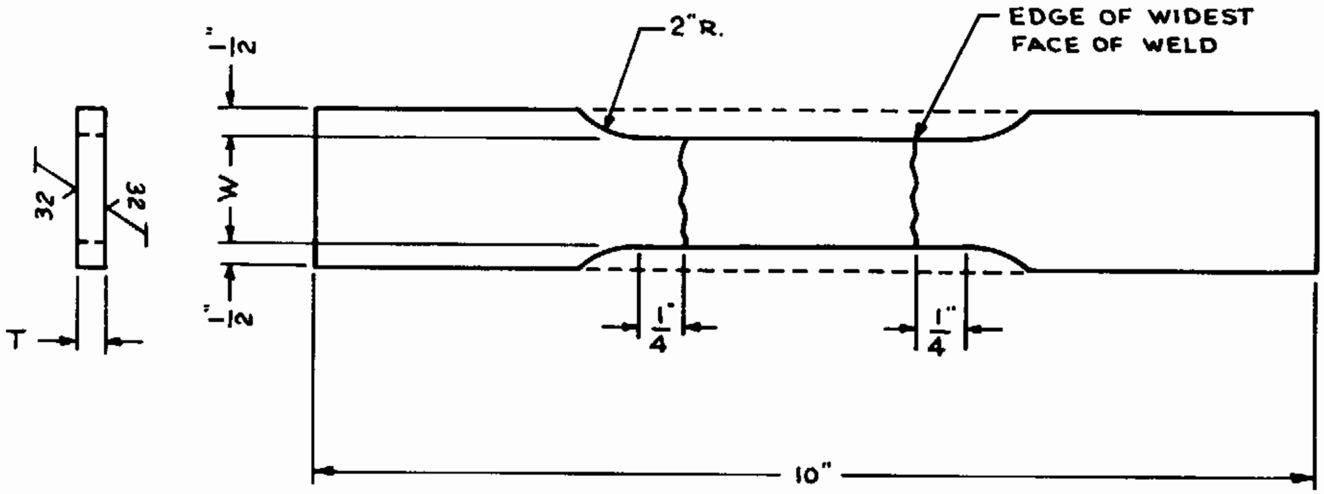


FIGURE 9

RELATIONSHIP BETWEEN ASTM & PRECRACKED CHARPY ENERGY ABSORPTION
HP 9 NI-4 CO-.20 C STEEL



NOTE : SPECIMEN TO BE LOCATED 1/8" FROM TOP OF WELD UNLESS OTHERWISE SPECIFIED

MATERIAL	W IN. (NOM.)	T IN. (NOM)
18% Ni & HP9-4	1	.5
D-6 AC	.5	.375

FIGURE 10

FLAT TRANSVERSE TENSILE SPECIMEN

CONVENTIONAL TIG PRACTICE - 3 LB./HR.

TIG-HOT WIRE WELDING - 8 LB./HR.

FIGURE 11

RADIOGRAPHS OF TIG-HOT WIRE AND TIG-COLD WIRE WELDS
MADE WITH MN-NI-MO-V FILLER METAL

21632
21633

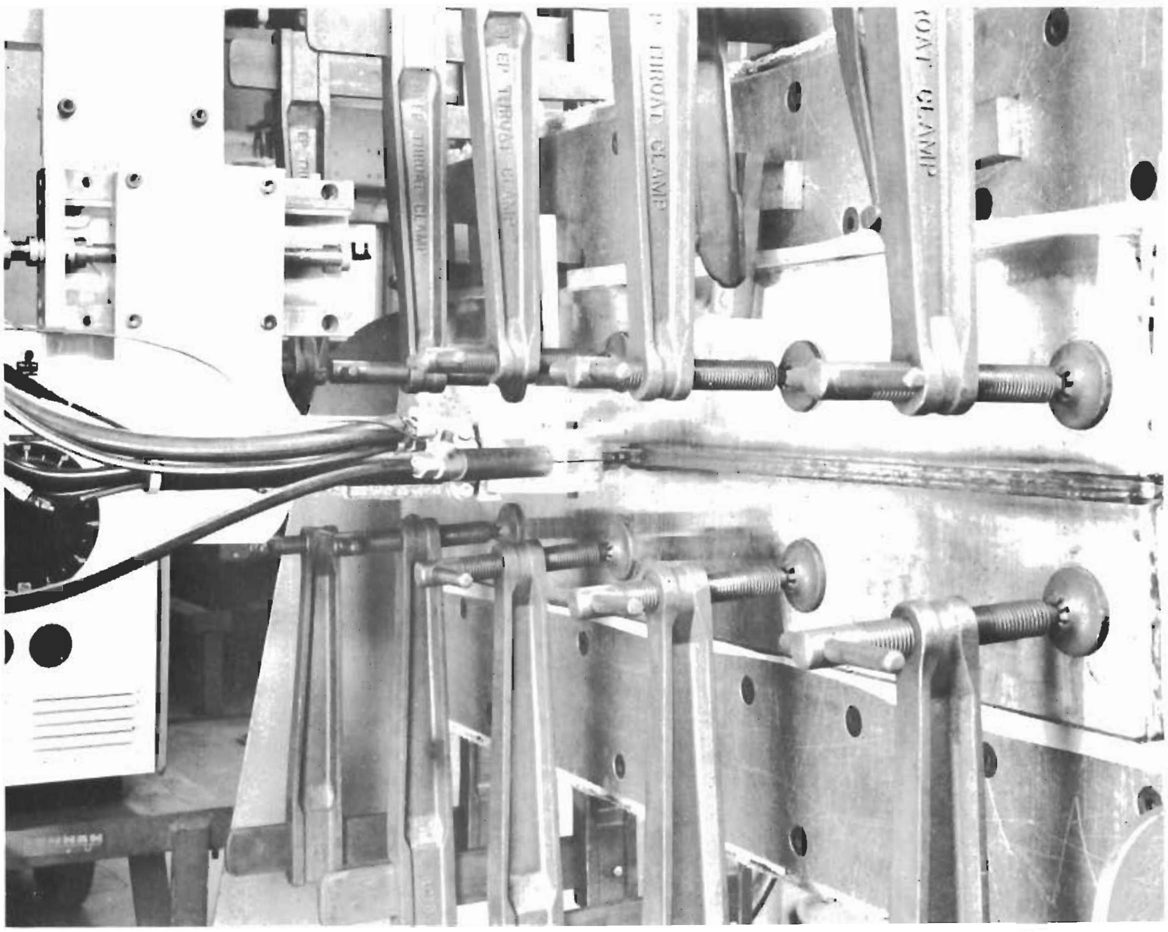


FIGURE 12

HORIZONTAL TIG-HOT WIRE WELD AND FIXTURE

 21705

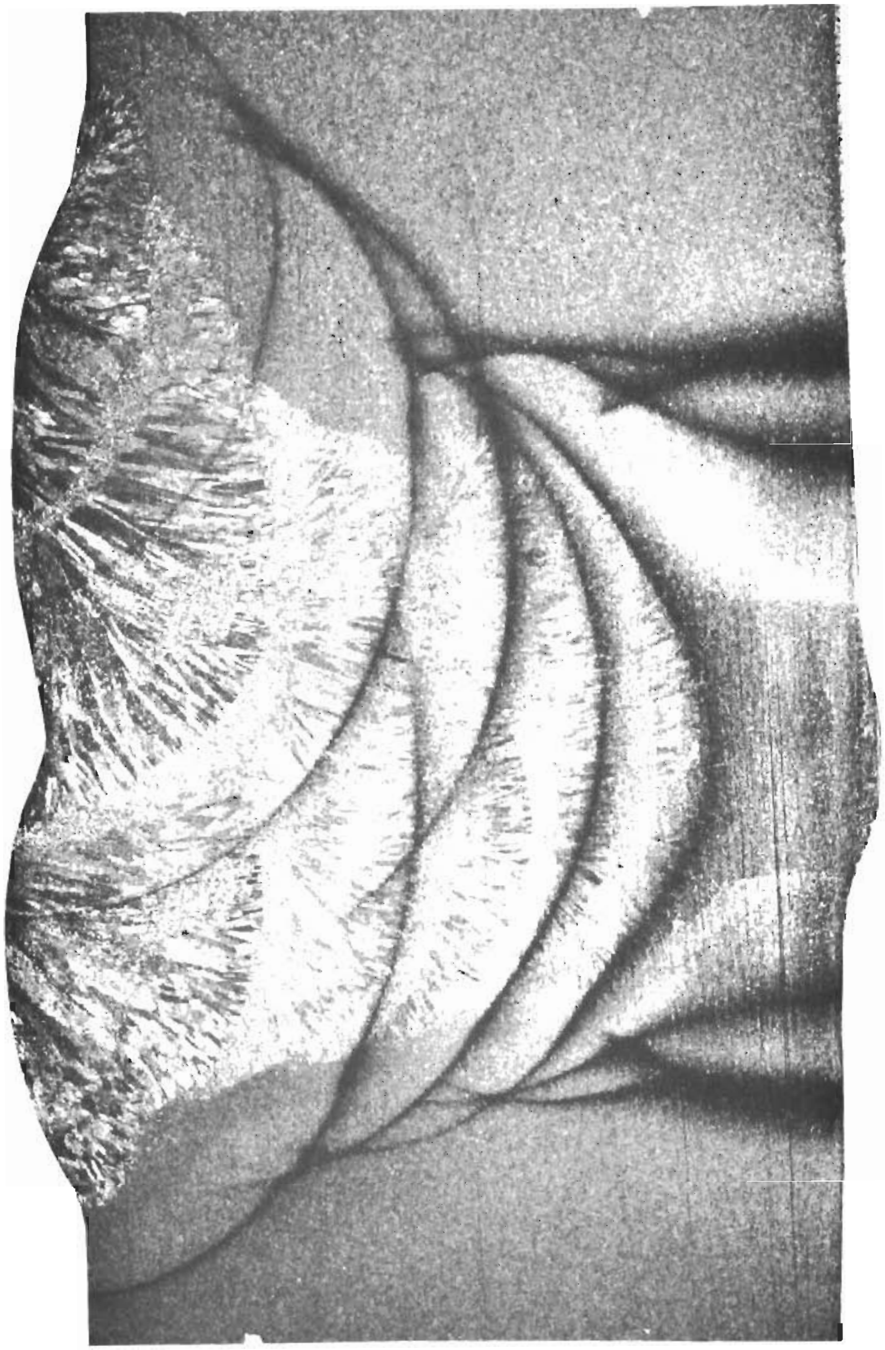


FIGURE 13

CROSS-SECTION OF HORIZONTAL TIG-HOT WIRE WELD 1187-99

21908

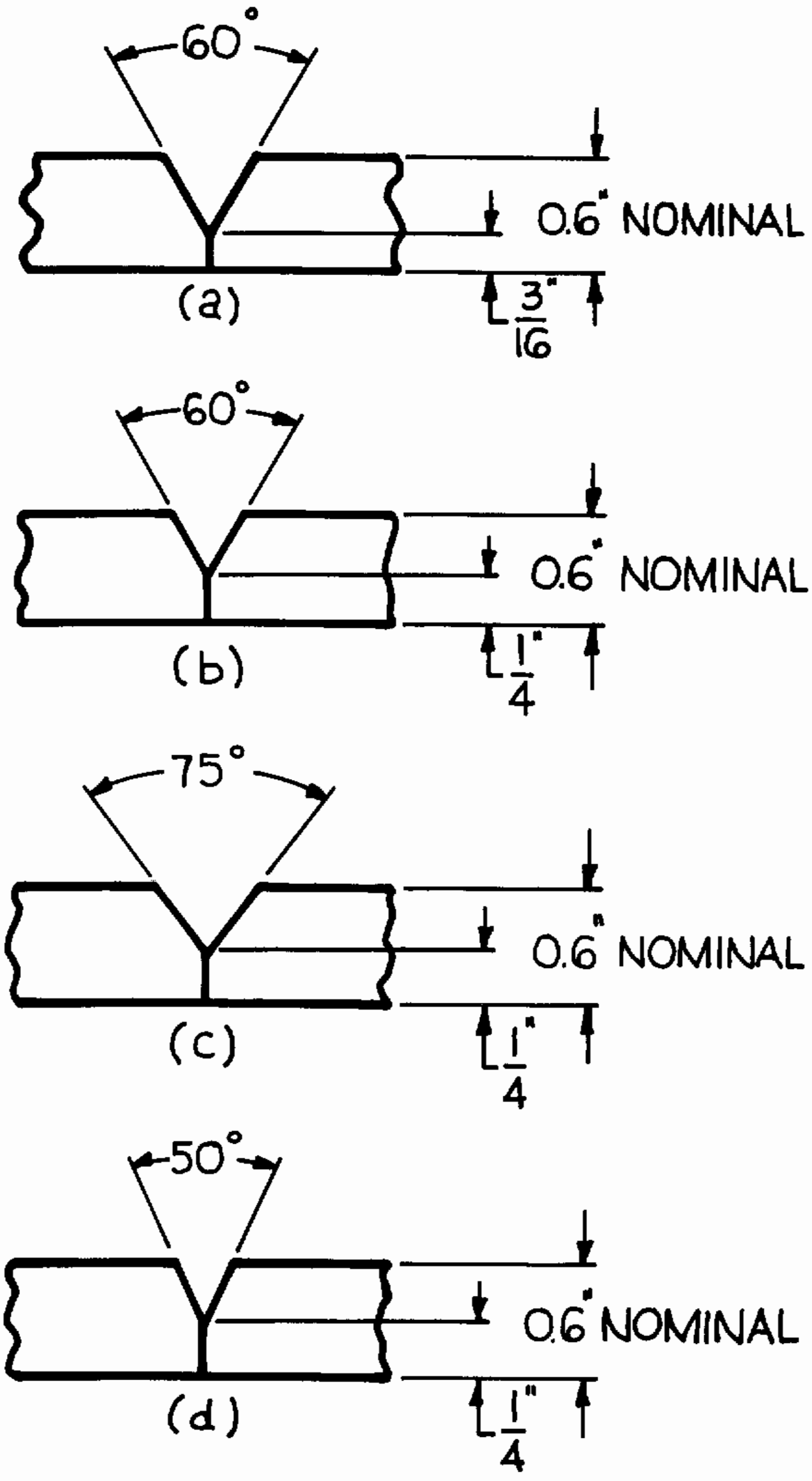
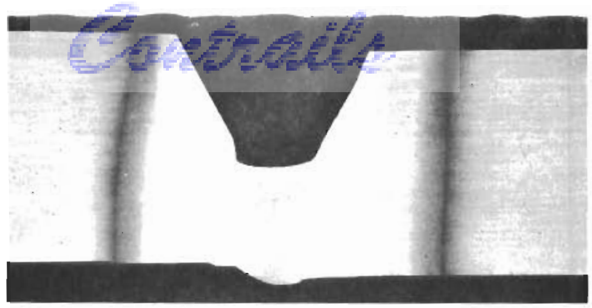


FIGURE 14

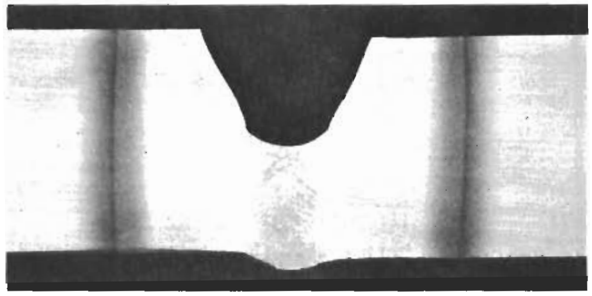
JOINT PREPARATIONS FOR PLASMA ARC WELDING

(a)



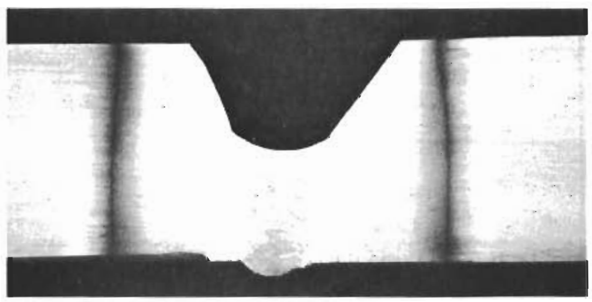
3/16-In. Root Face - 60° Included Angle Joint Preparation

(b)



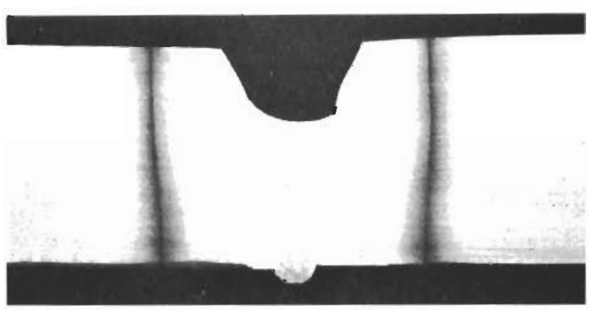
1/4-In. Root Face - 60° Included Angle Joint Preparation

(c)



1/4-In. Root Face - 75° Included Angle Joint Preparation

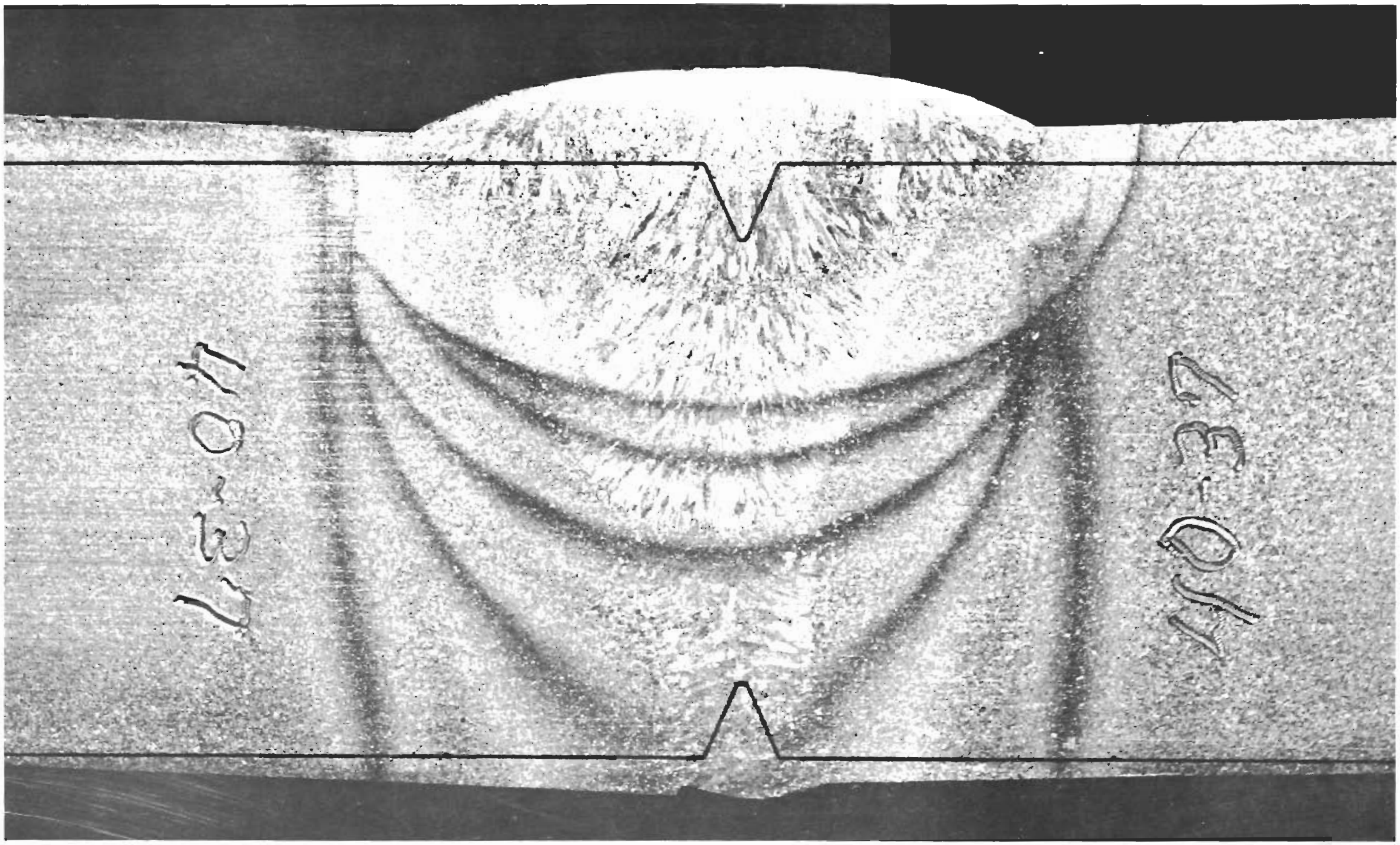
(d)



1/4-In. Root Face - 50° Included Angle Joint Preparation

FIGURE 15

CROSS-SECTIONS OF PLASMA ARC
ROOT PASS WELDS 0.6-IN. 18 NI STEEL



7 lb./hr. - 14 ipm 6X K^{*}_{IC} - 117 ksi $\sqrt{in.}$

FIGURE 16

CROSS-SECTION OF PLASMA ARC-HOT WIRE WELD 40-37

21930

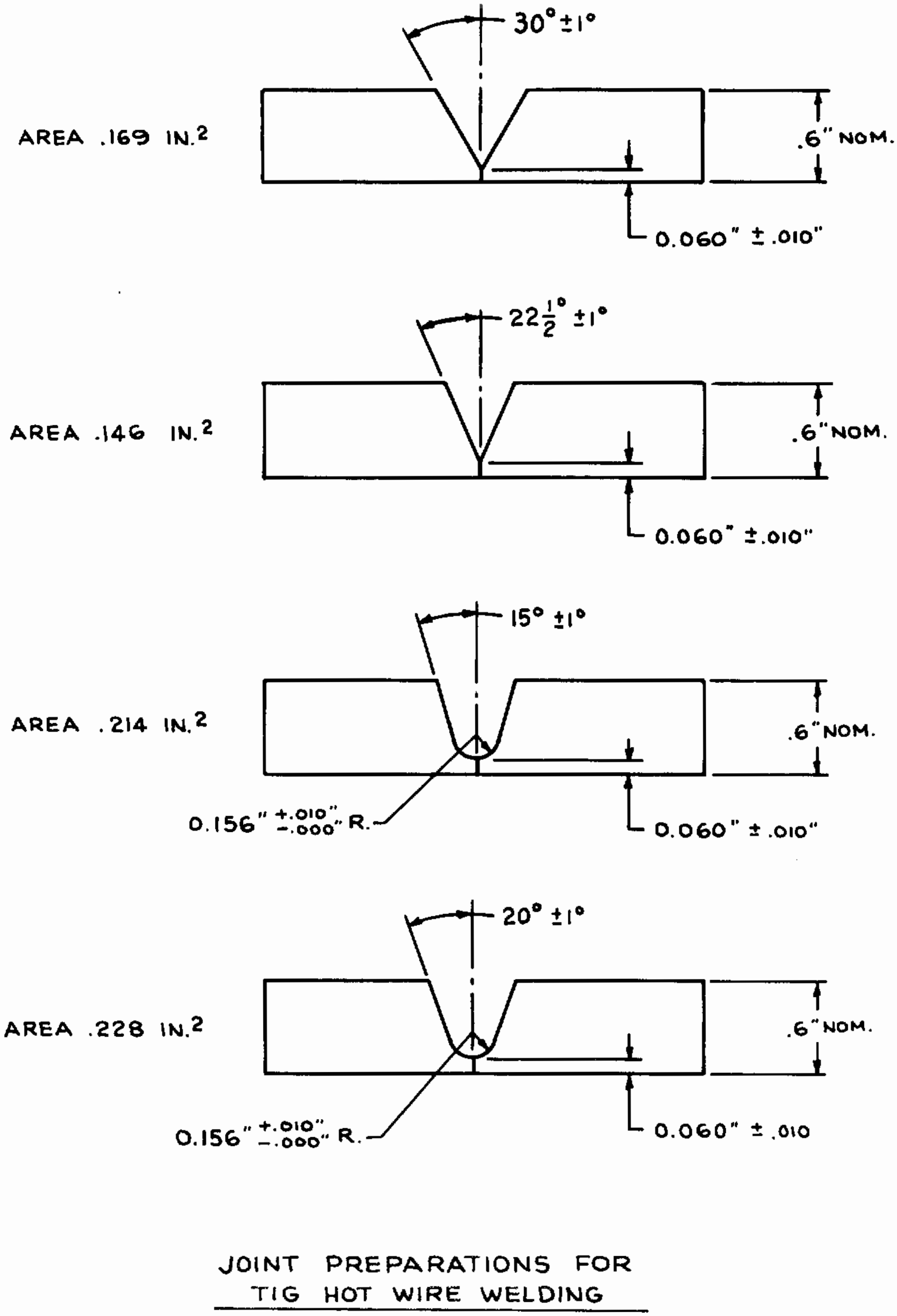


FIGURE 17

JOINT PREPARATIONS FOR TIG-HOT WIRE WELDING

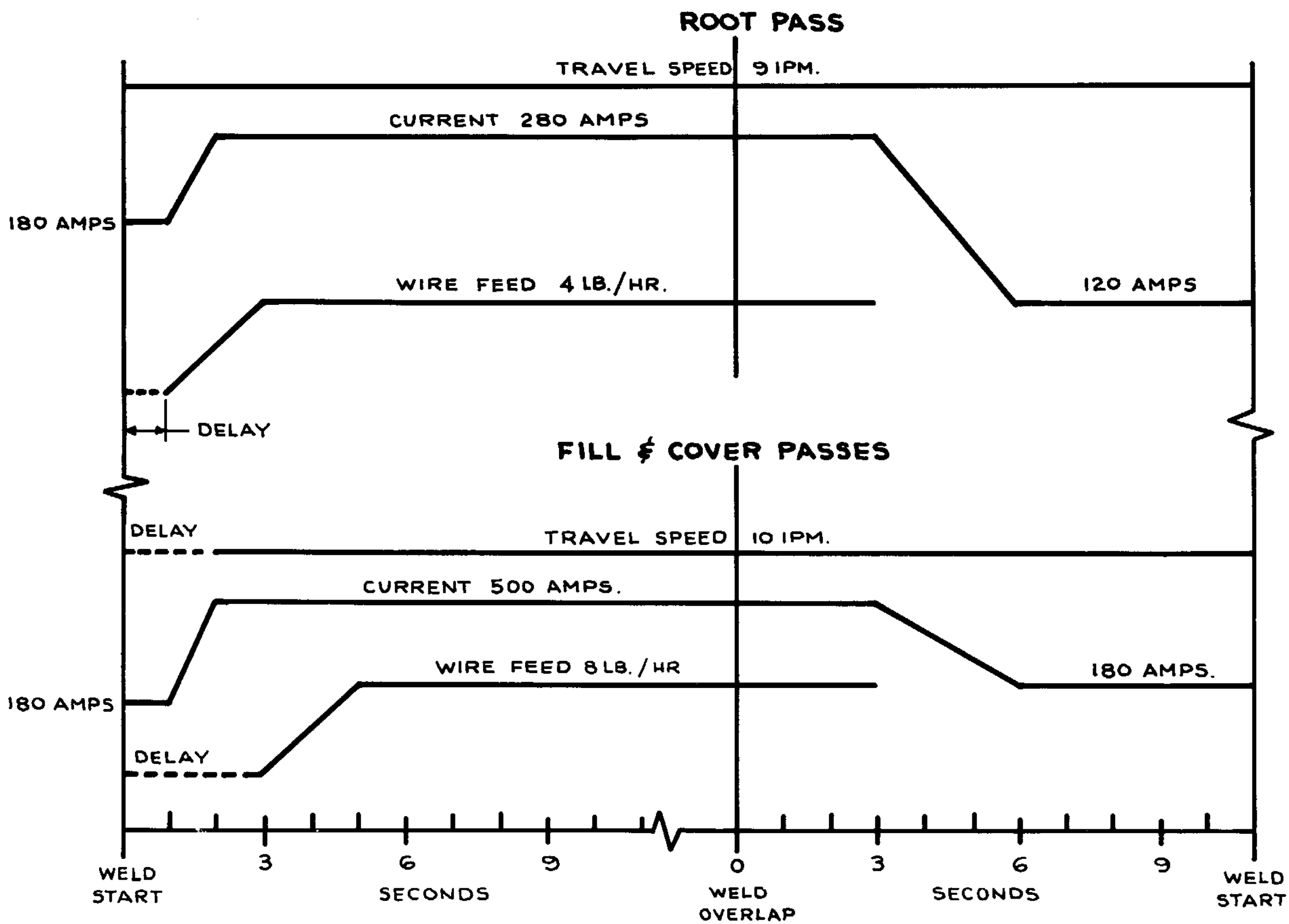
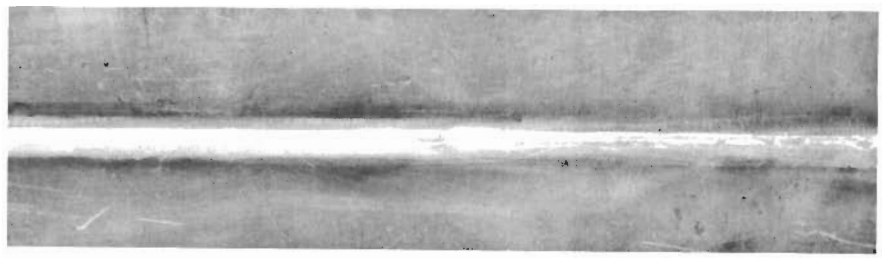
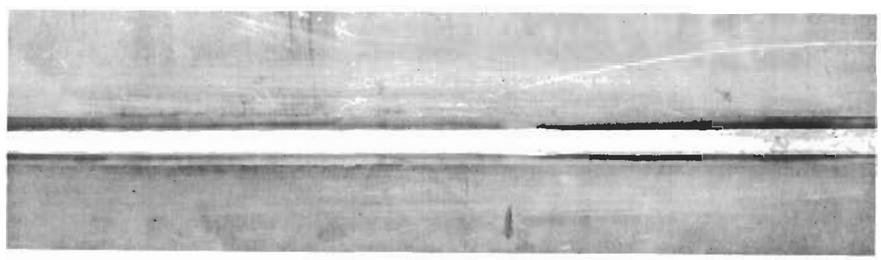


FIGURE 18

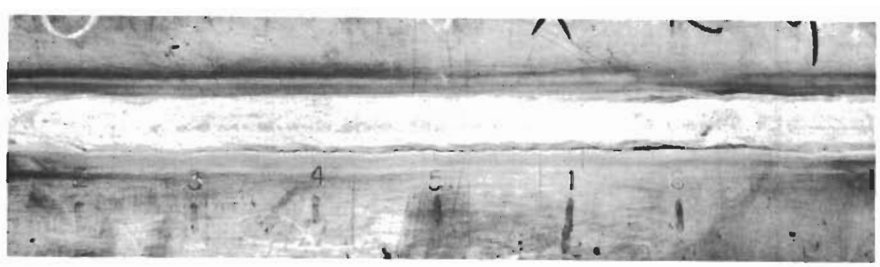
STARTING AND STOPPING SEQUENCE FOR
CIRCUMFERENTIAL TIG-HOT WIRE WELD



UNDERBEAD



SURFACE OF ROOT PASS



COVER PASS

FIGURE 19 21918

TIG-HOT WIRE WELD OVERLAPS 21919

21920

FIGURE 20

RADIOGRAPH OF TIG-HOT WIRE WELD OVERLAPS

21937

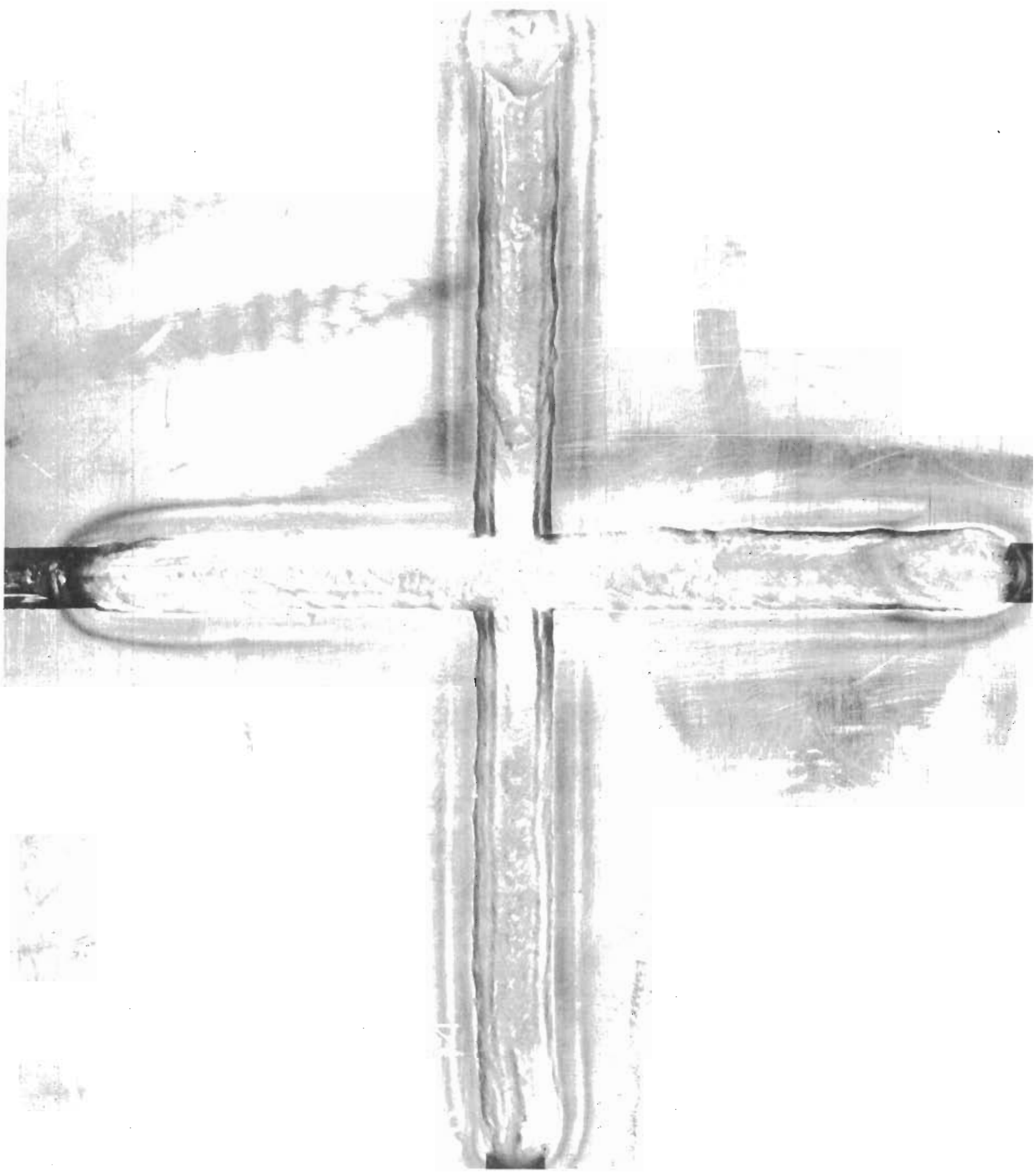


FIGURE 21

TIG-HOT WIRE WELD INTERSECT

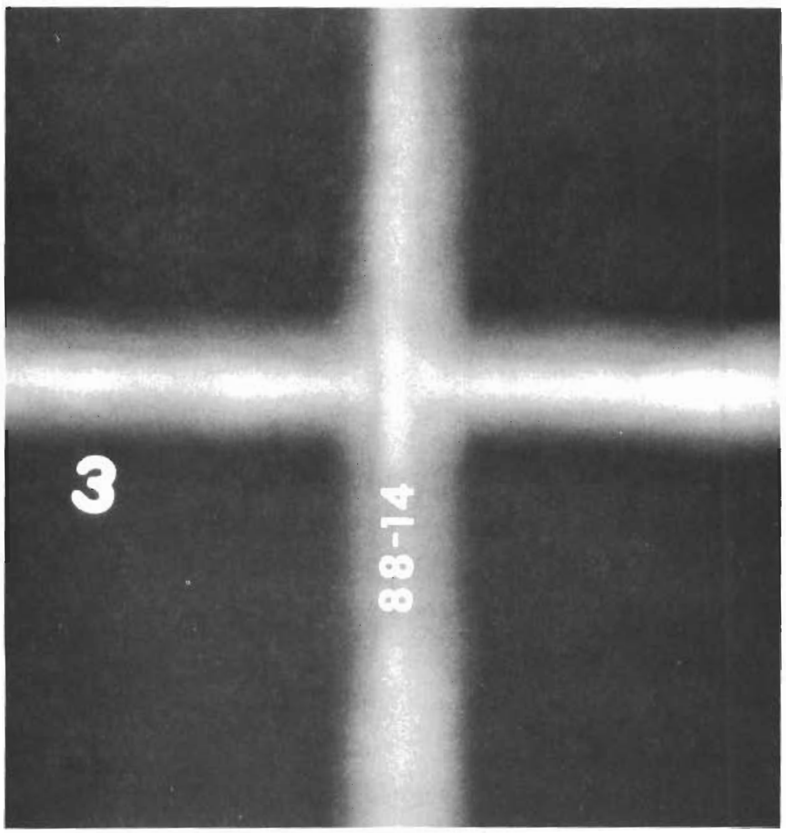


FIGURE 22

RADIOGRAPH OF TIG-HOT WIRE WELD INTERSECT

21938

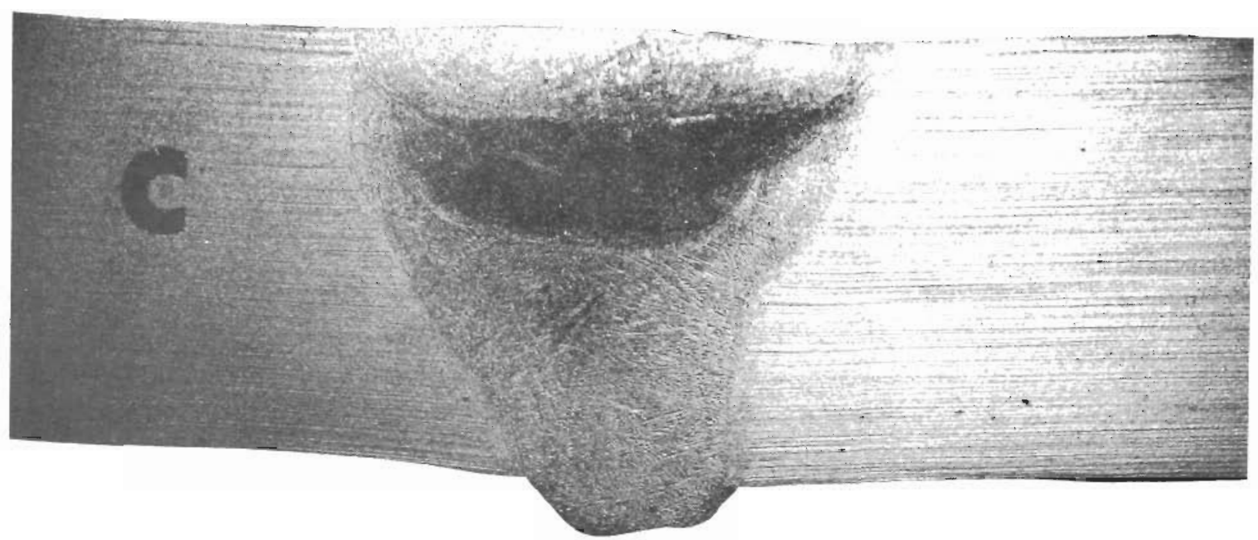


FIGURE 23

CROSS-SECTION OF TIG-COLD WIRE WELD
IN D-6ac STEEL - DEPOSITION RATE 2 LBS./HR.

22495

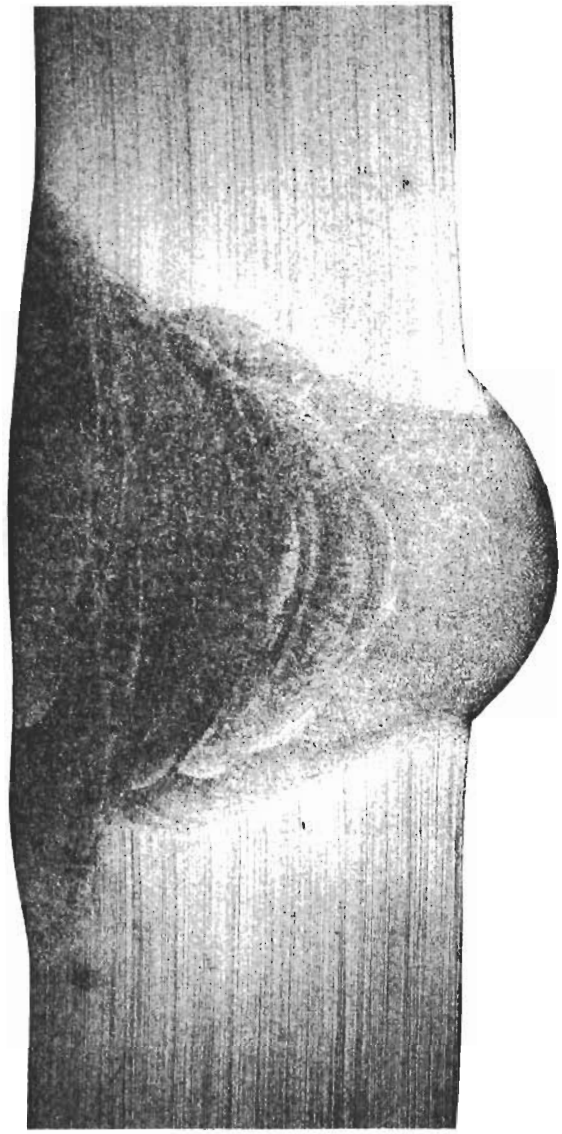


FIGURE 24

CROSS-SECTION OF TIG-HOT WIRE WELD
IN D-6ac STEEL - DEPOSITION RATE 2 LBS./HR.

22496

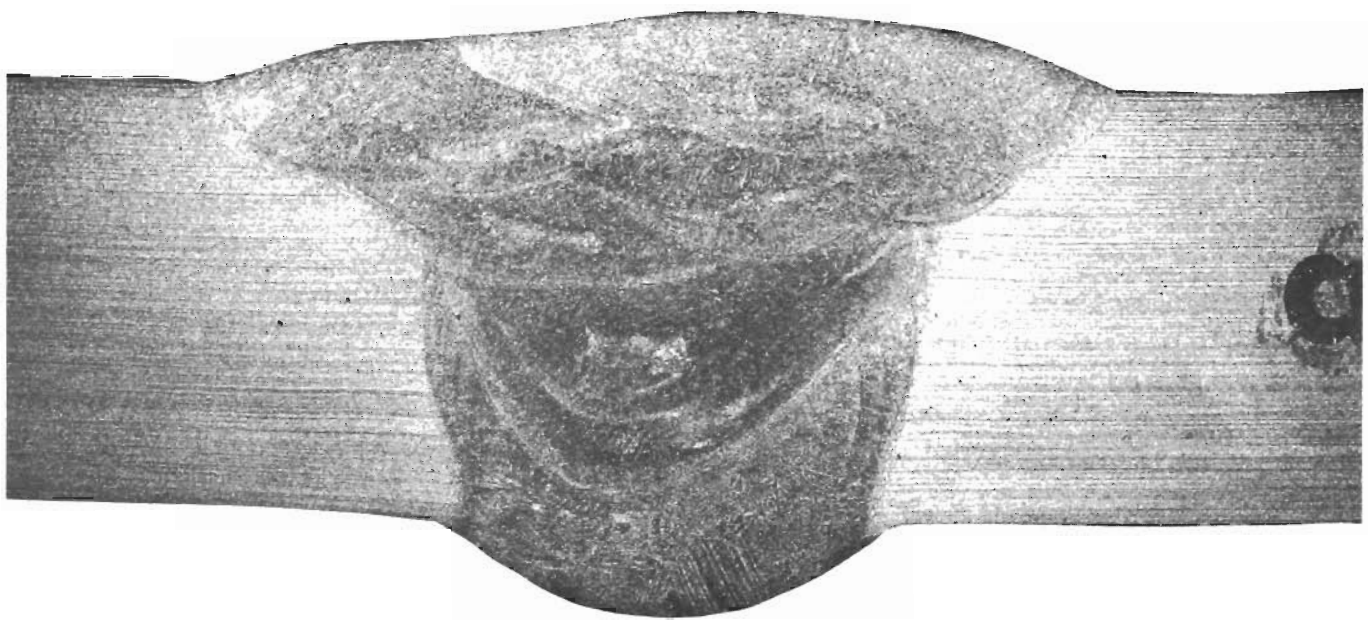


FIGURE 25

CROSS-SECTION OF TIG-HOT WIRE WELD
IN D-6ac STEEL - DEPOSITION RATE 5 LBS./HR.

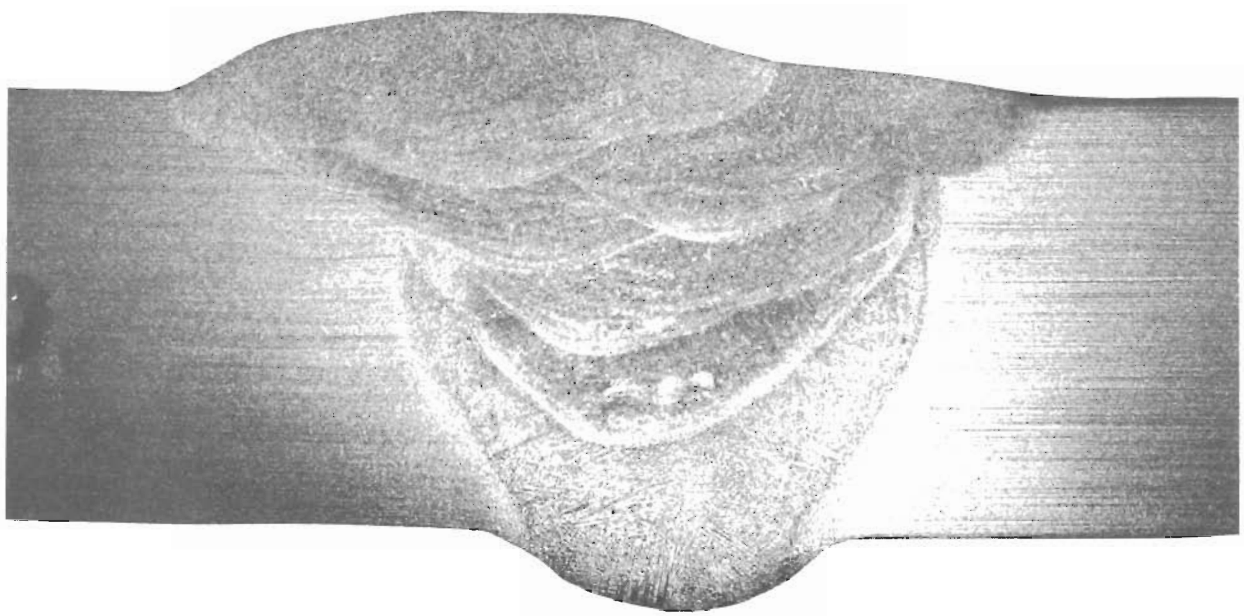


FIGURE 26

CROSS-SECTION OF TIG-HOT WIRE WELD
IN D-6ac STEEL - DEPOSITION RATE 8 LBS./HR.

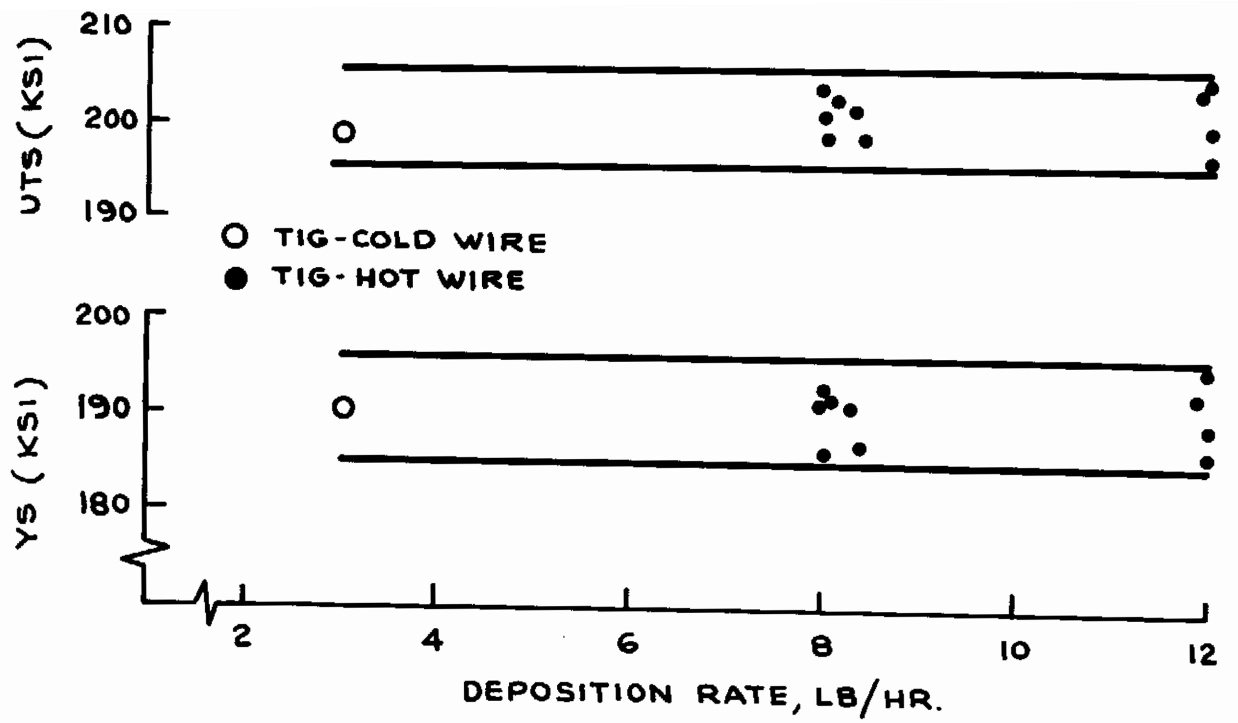


FIGURE 27

YIELD AND ULTIMATE TENSILE STRENGTH VS.
DEPOSITION RATE - TIG-HOT WIRE WELDS
IN 0.6-IN. 18 NI STEEL

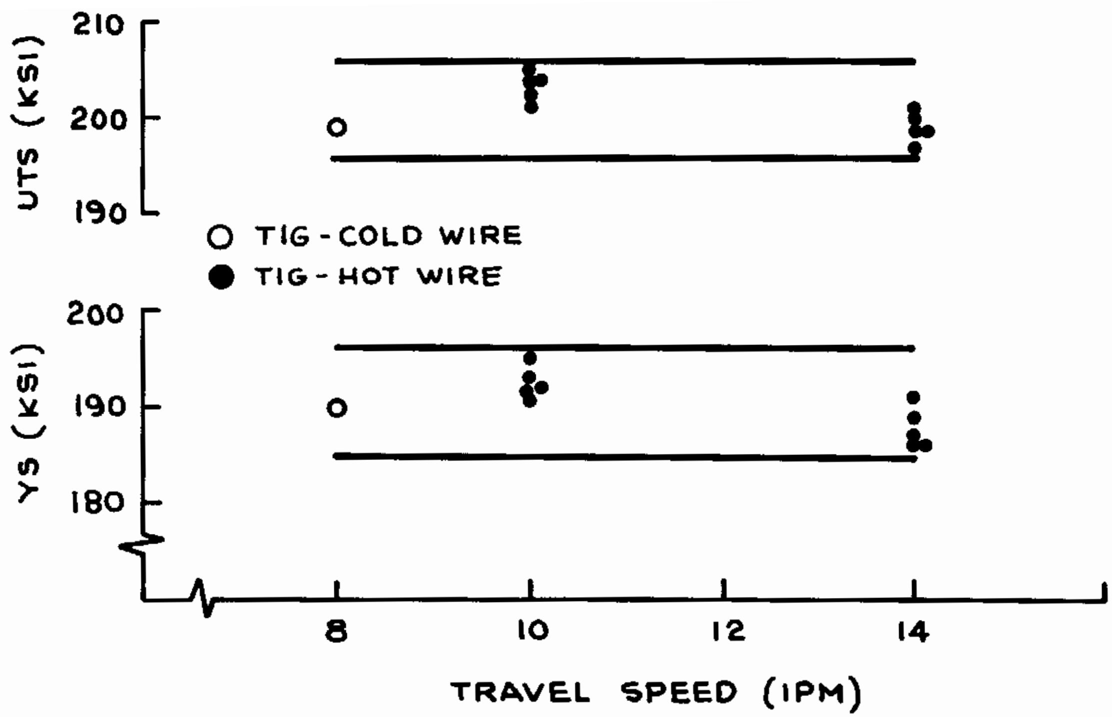


FIGURE 28

YIELD AND ULTIMATE TENSILE STRENGTH VS.
TRAVEL SPEED - TIG-HOT WIRE WELDS
IN 0.6-IN. 18 NI STEEL

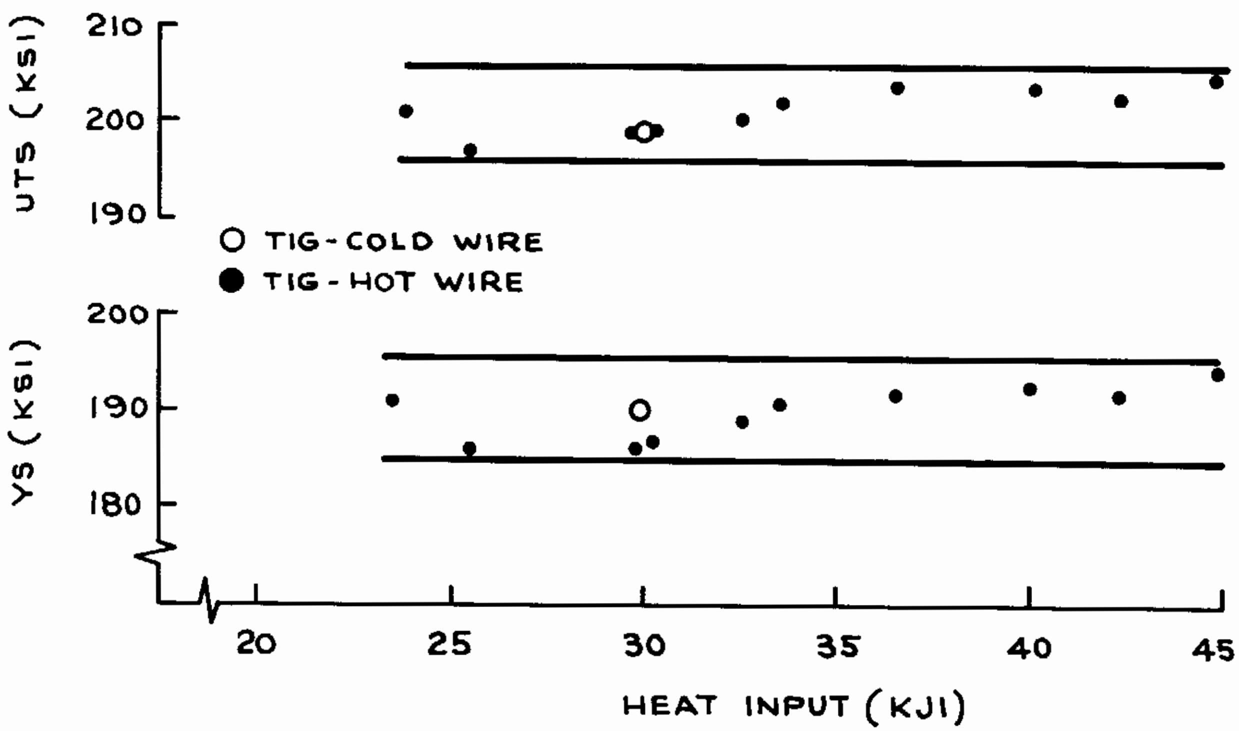


FIGURE 29

YIELD AND ULTIMATE TENSILE STRENGTH VS.
RATE OF HEAT INPUT (KJI)
TIG-HOT WIRE WELDS IN 0.6-IN. 18 NI STEEL

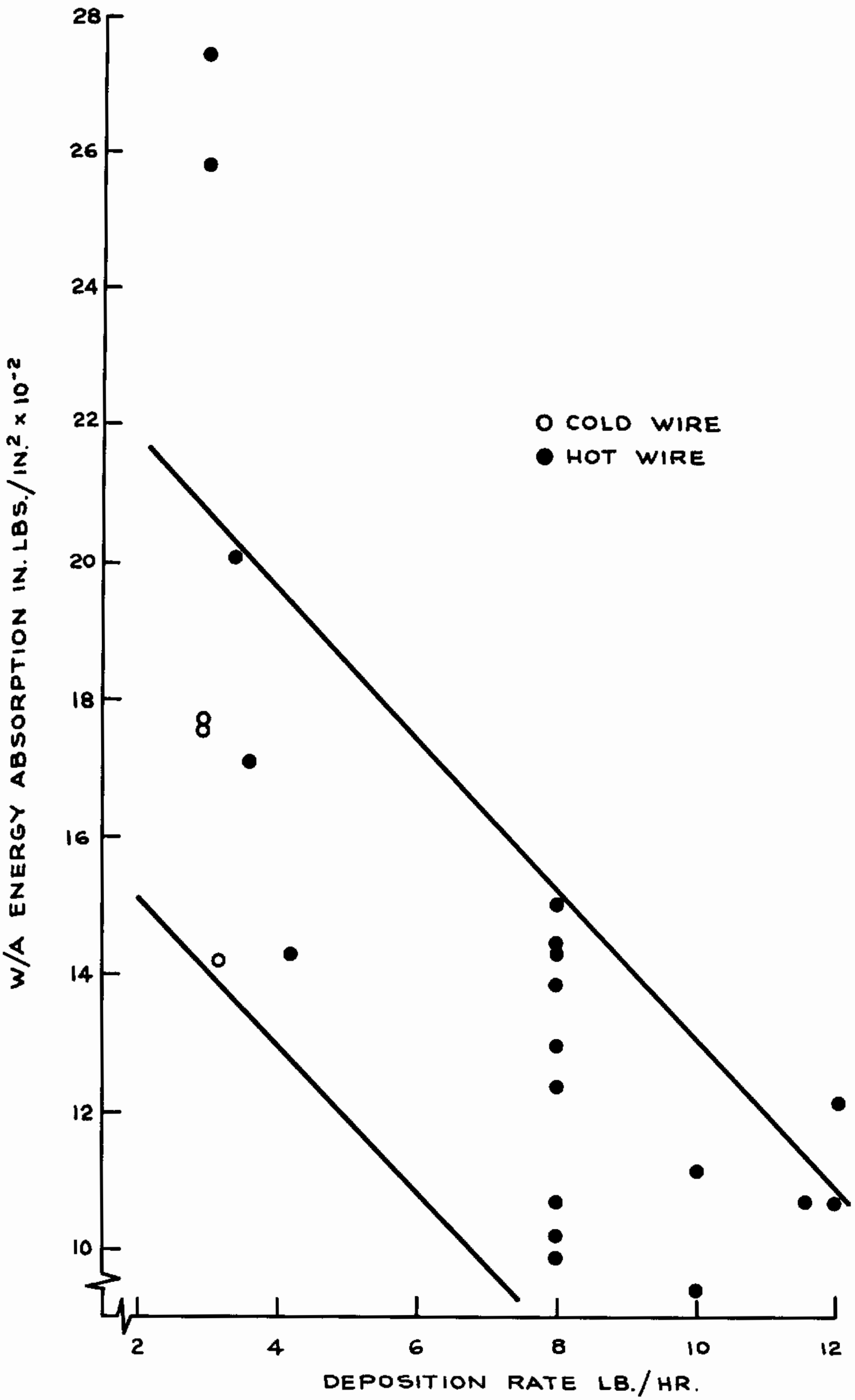


FIGURE 30

W/A ENERGY ABSORPTION VS.
DEPOSITION RATE TIG-HOT WIRE WELDS IN 18 NI STEEL

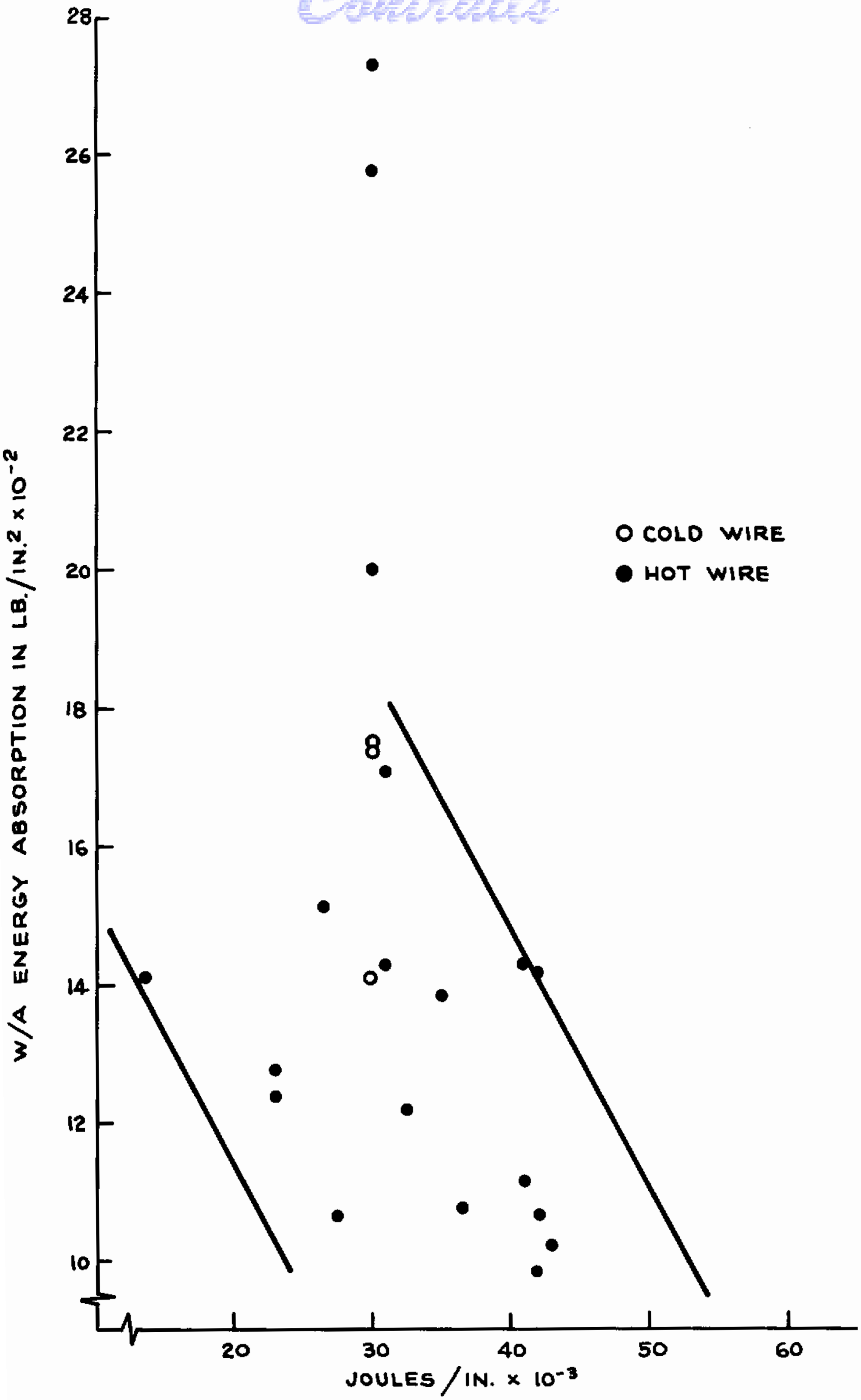
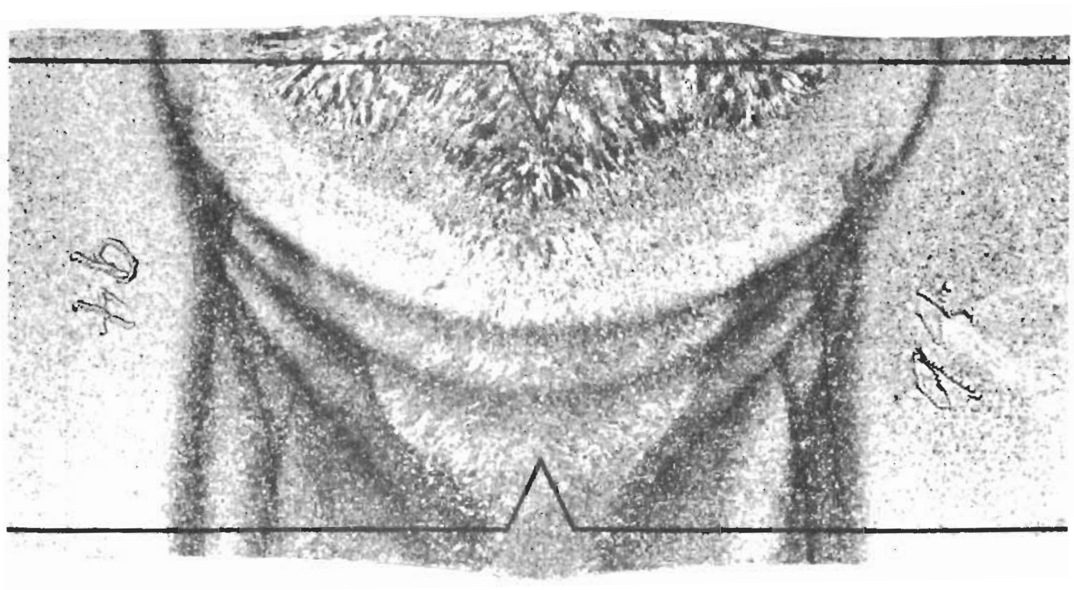
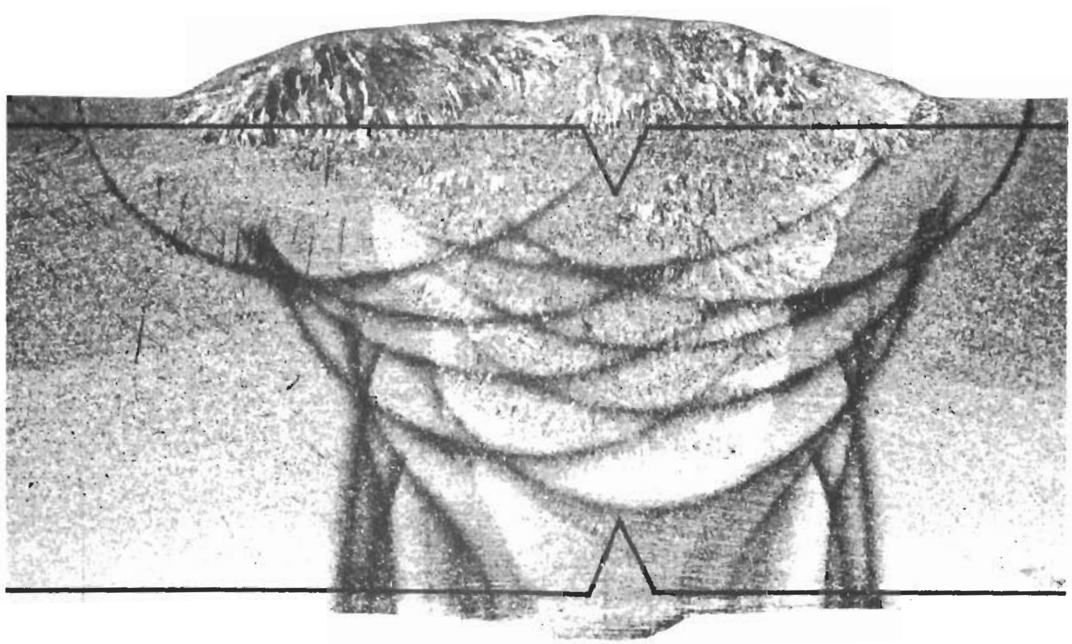


FIGURE 31

W/A ENERGY ABSORPTION VS. RATE OF HEAT INPUT (KJI)
TIG-HOT WIRE WELDS IN 18 NI STEEL



8 lb./hr. - 10 ipm W/A = 1078 in. lb./in.^{2}



3 lb./hr. - 8 ipm W/A = 2735 in. lb./in.^{2}

FIGURE 32

MACROSTRUCTURES OF TIG-HOT WIRE WELDS
HAVING HIGH AND LOW PRECRACKED CHARPY ENERGY ABSORPTIONS
0.6-IN. 18 NI STEEL

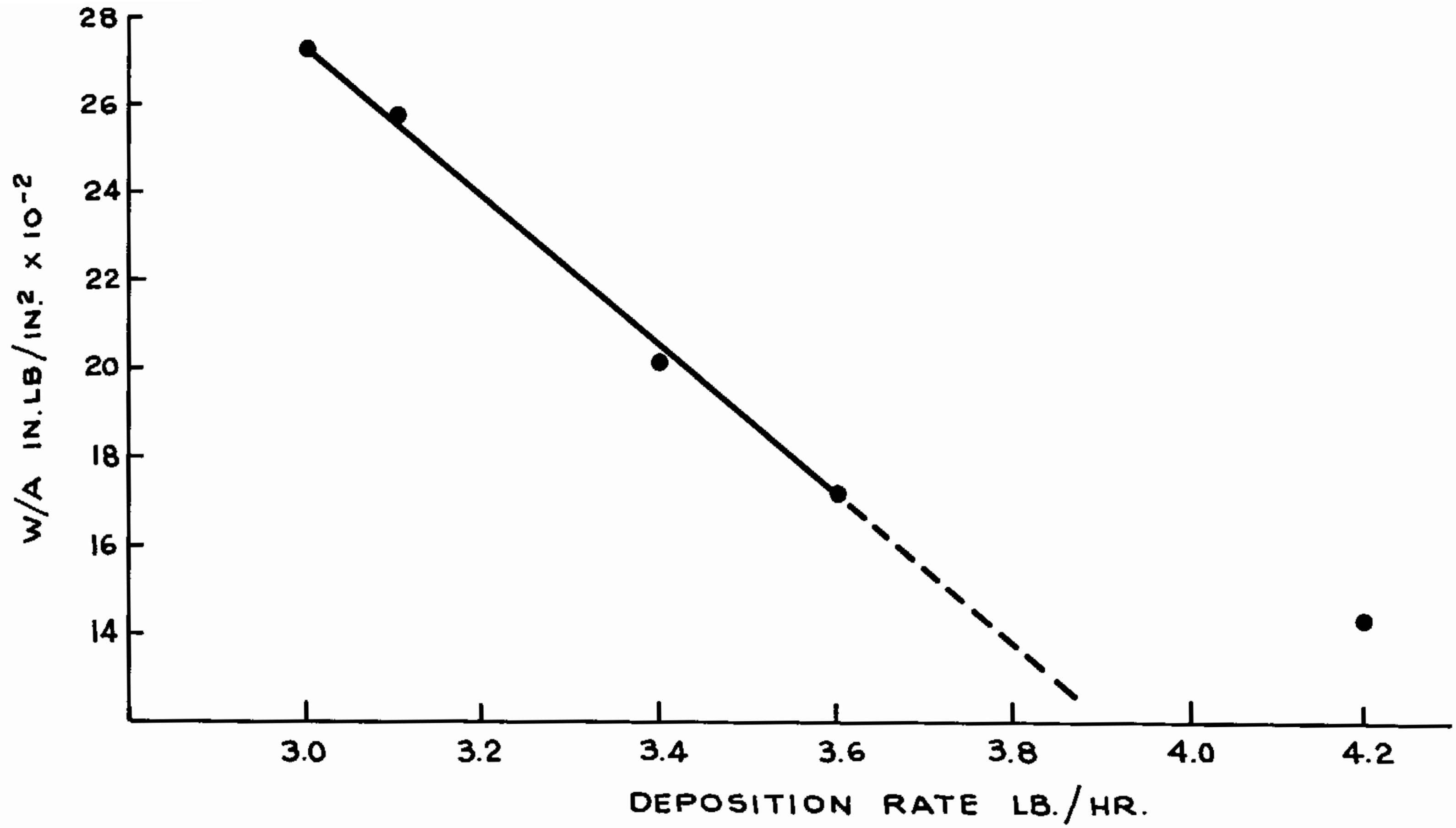
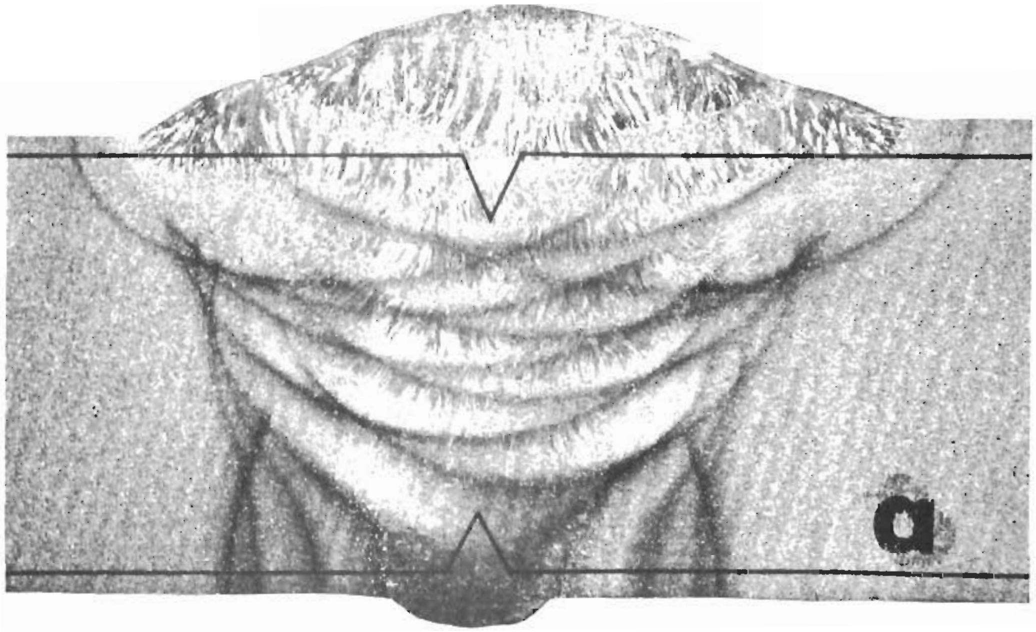
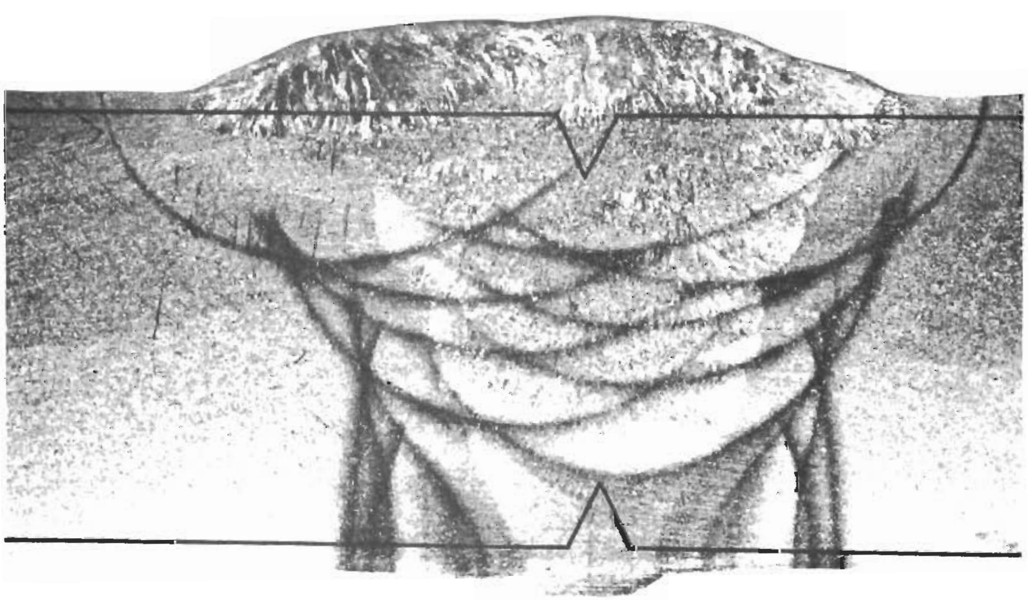


FIGURE 33

W/A ENERGY ABSORPTION VS. DEPOSITION RATE
OF LOW DEPOSITION RATE WELDS
0.6-IN. 18 NI STEEL



7.6 lb./hr. - 19 ipm   W/A = 2520 in. lb./in.^{2}



3 lb./hr. - 8 ipm   W/A = 2735 in. lb./in.^{2}

FIGURE 34

MACROSTRUCTURES OF HIGH AND LOW DEPOSITION RATE
STRINGER BEAD TYPE TIG-HOT WIRE WELDS
0.6-IN. 18 NI STEEL

23069

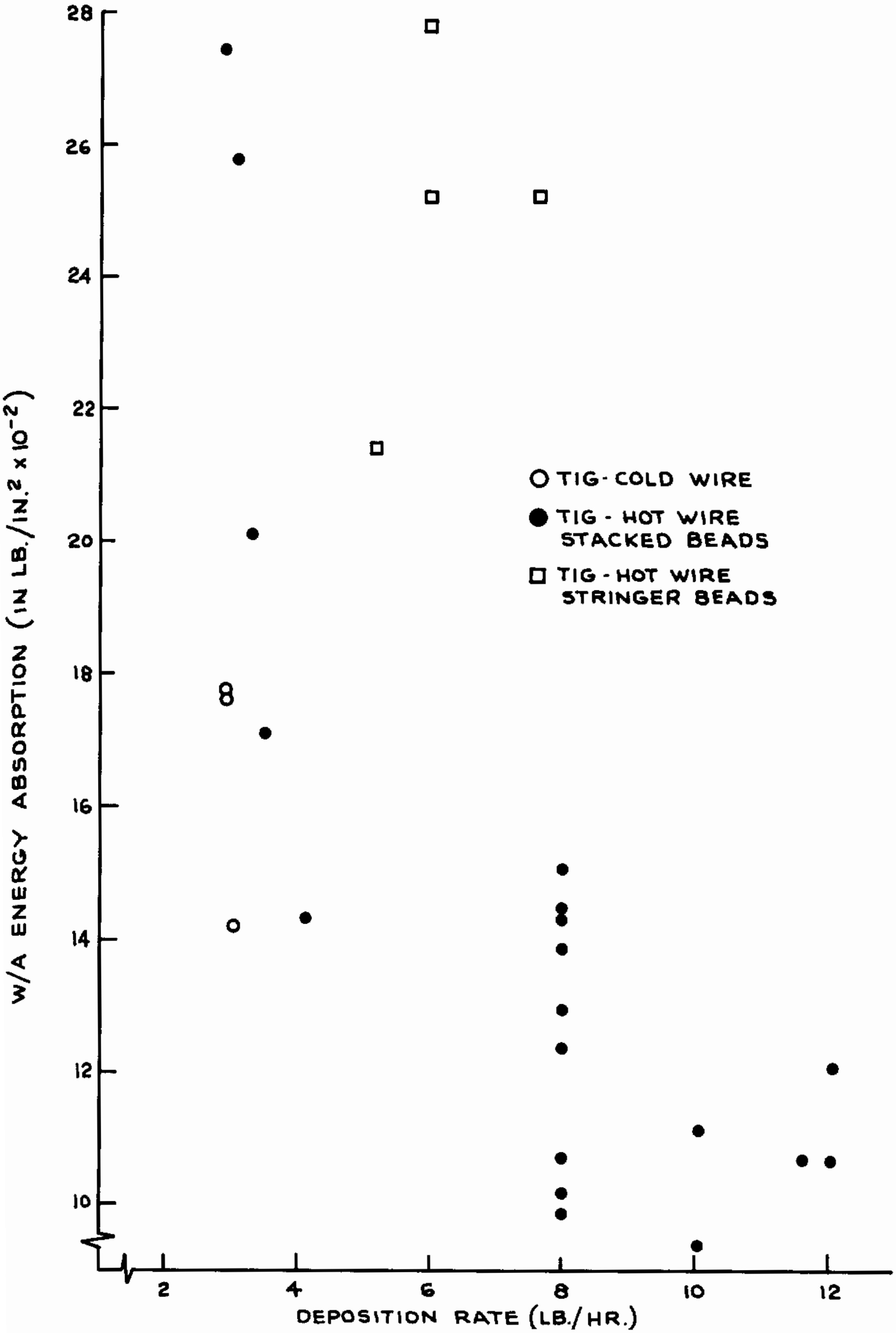
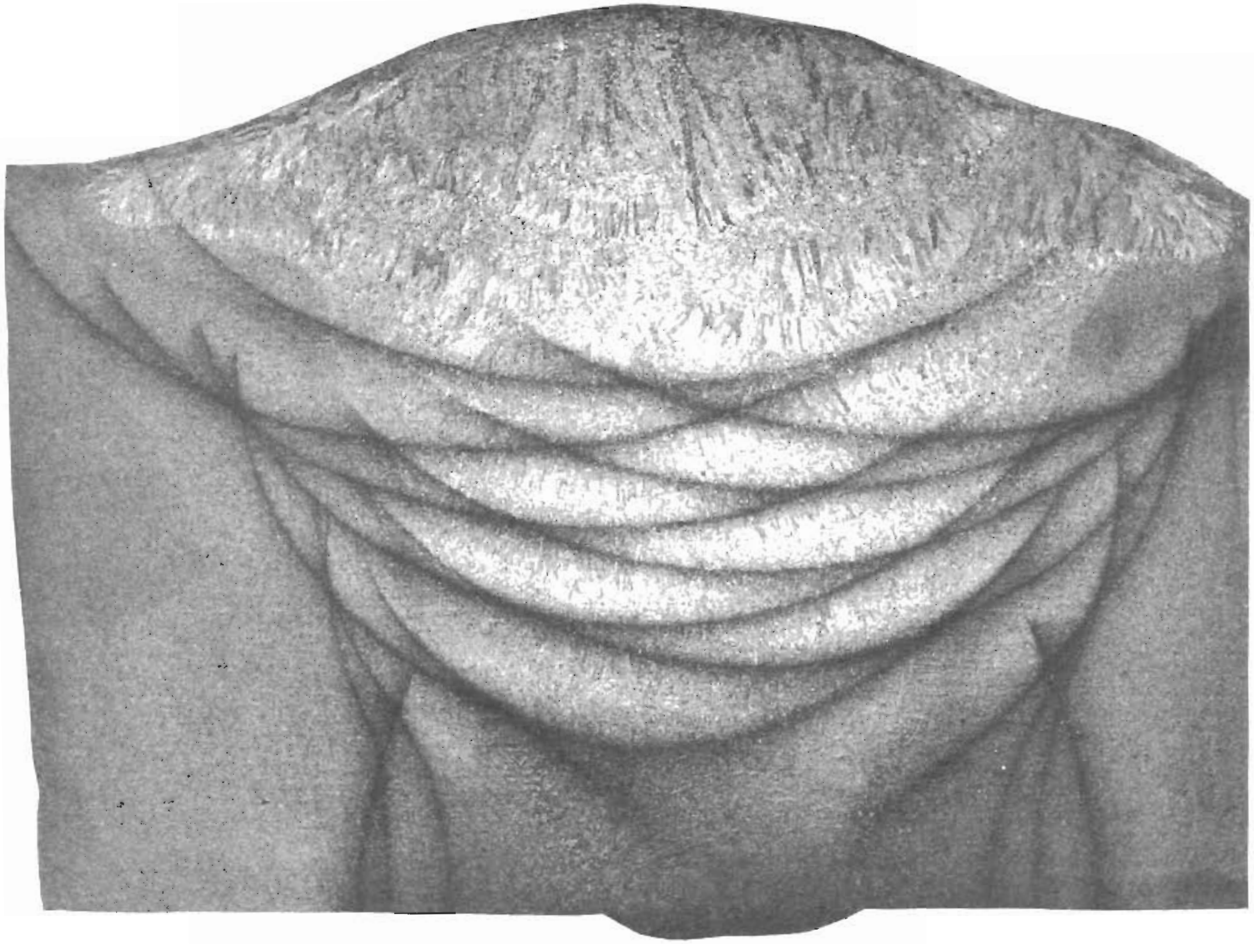


FIGURE 35

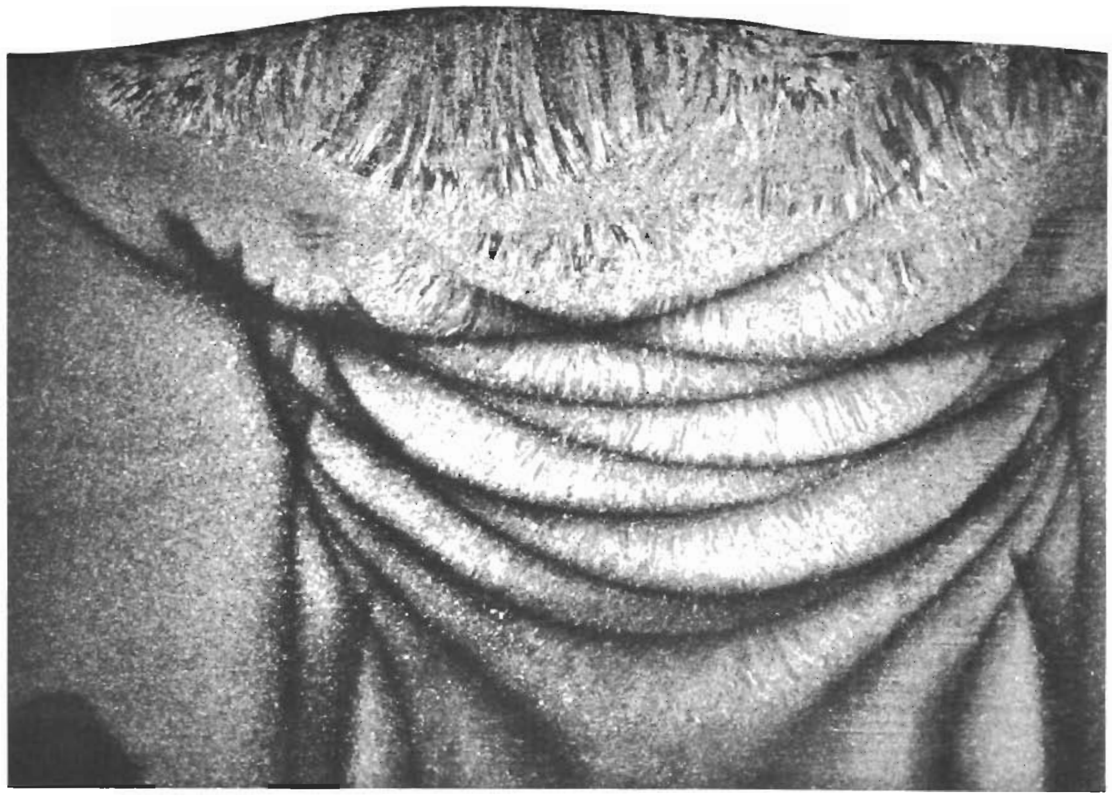
COMPARISON OF W/A ENERGY ABSORPTION OF STACKED AND STRINGER BEAD TYPE HIGH DEPOSITION RATE WELDS 0.6-IN. 18 NI STEEL



5 lbs./hr.   6X   W/A = 2523 in. lb./in.^{2}

FIGURE 36

HIGH DEPOSITION RATE WELD WITH GOOD BEAD INTERLACING
0.6-IN. 18 NI STEEL

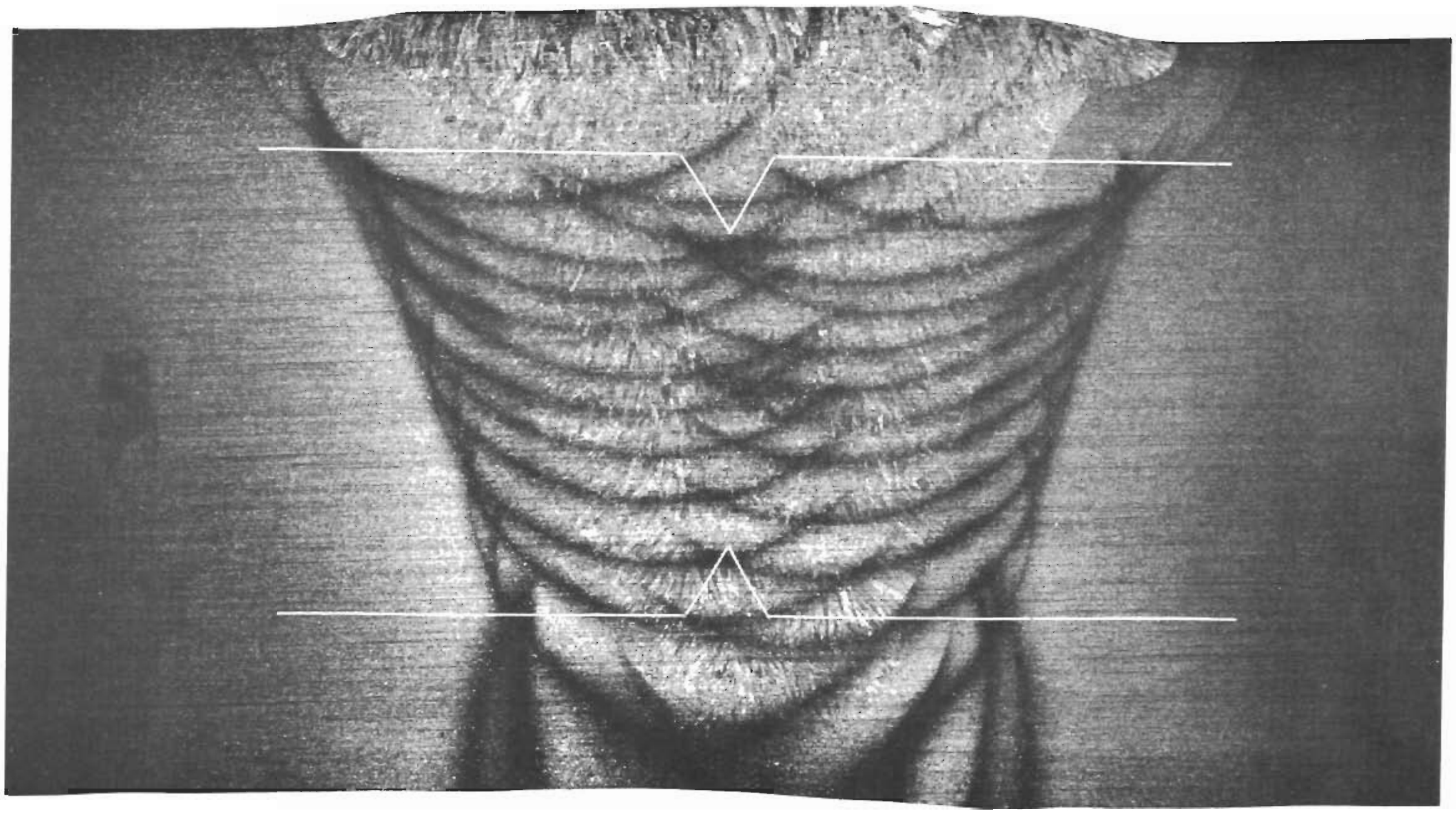


5 lbs./hr. 6X W/A = 1864 in. lb./in.^{2}

FIGURE 37

HIGH DEPOSITION RATE WELD WITH FAIR BEAD INTERLACING
0.6-IN. 18 NI STEEL

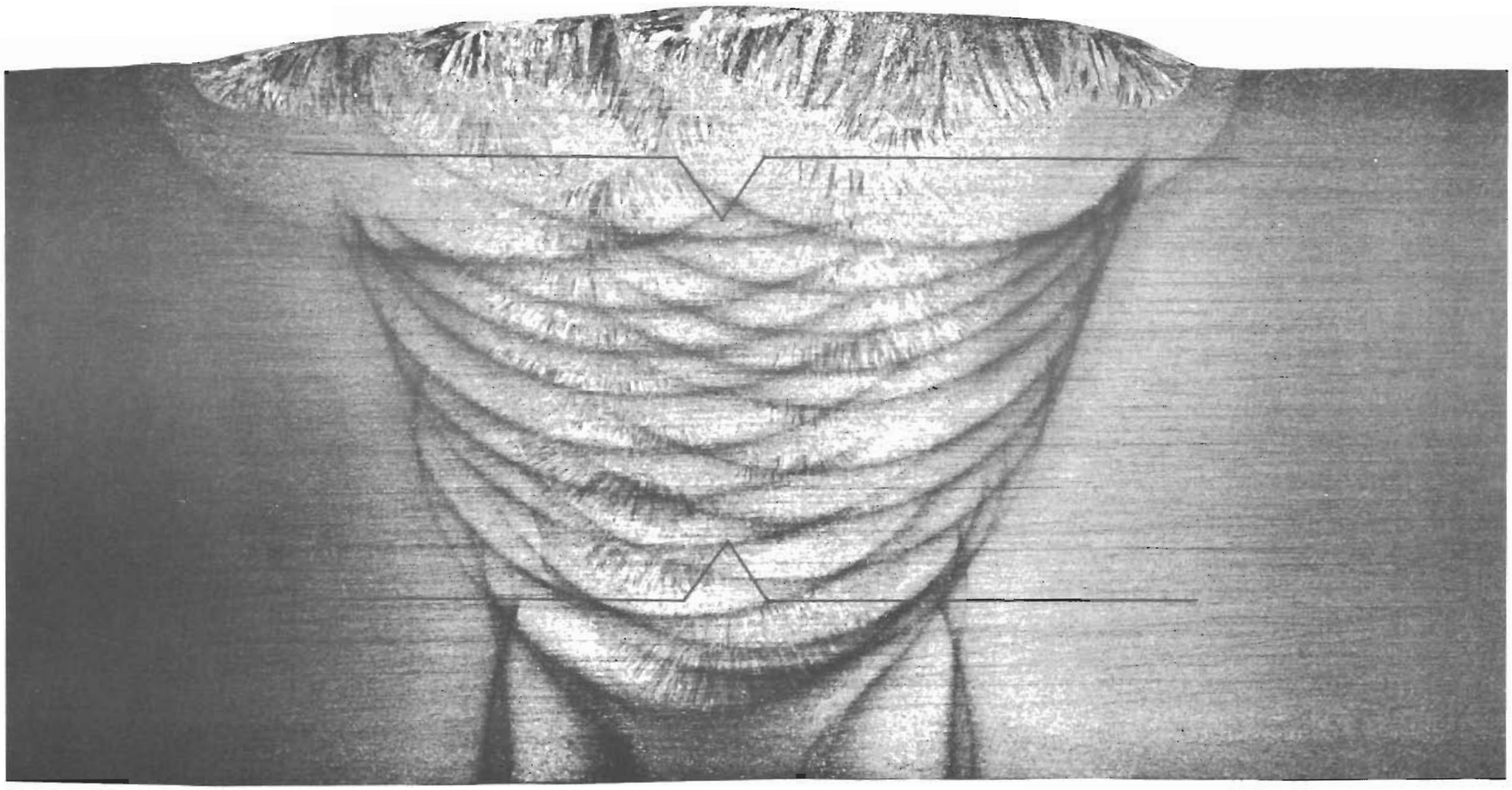
23242



3 lbs./hr. - 8 ipm   4X   W/A = 1989 in. lb./in.^{2}

FIGURE 38

CROSS-SECTION OF TIG-COLD WIRE WELD 88-92
IN 1-IN. 18 NI STEEL

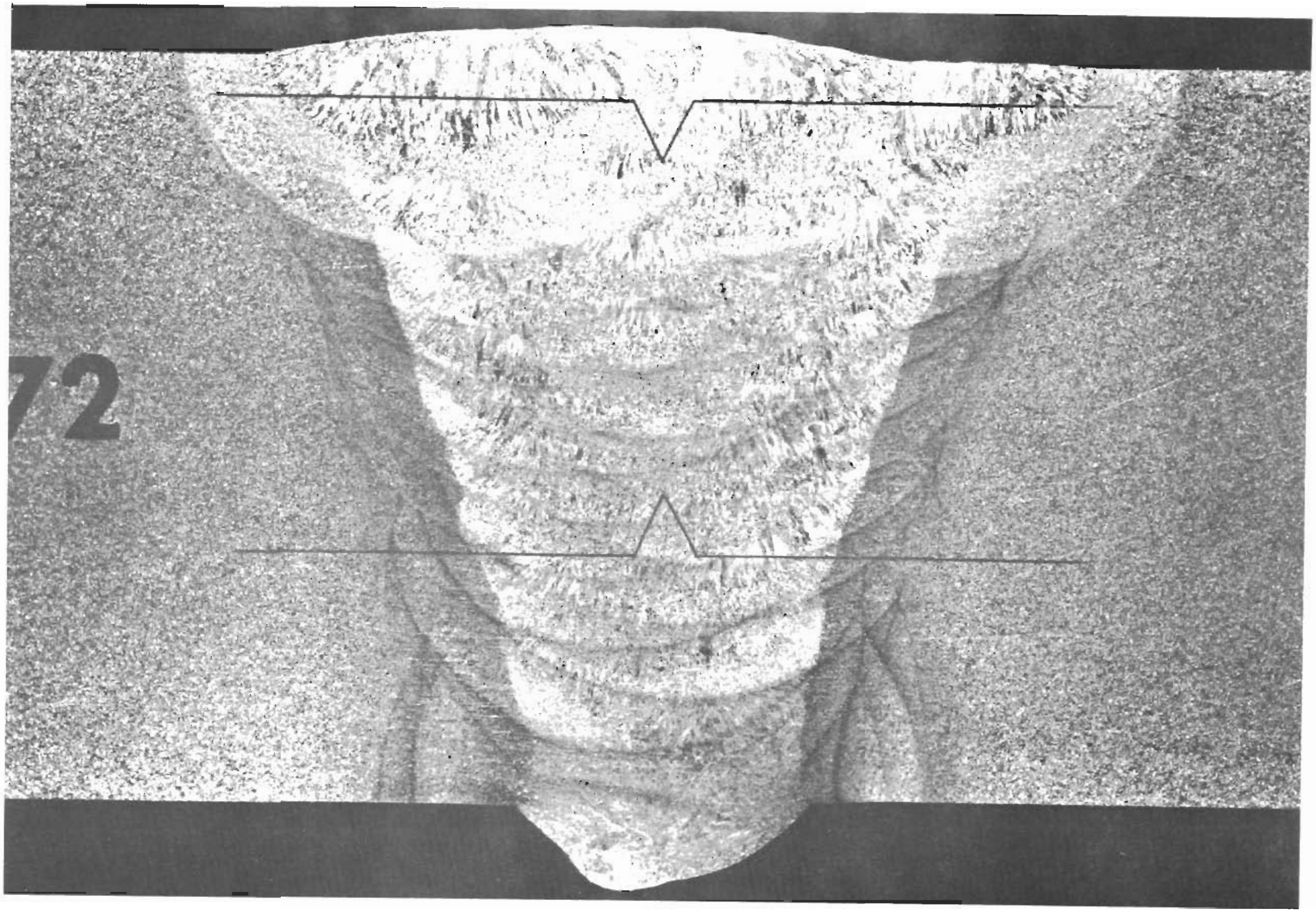


7.6 lbs./hr. - 19 ipm   4X   W/A = 1700 in. lb./in.^{2}

FIGURE 39

CROSS-SECTION OF TIG-HOT WIRE WELD 88-97
IN 1-IN. 18 NI STEEL

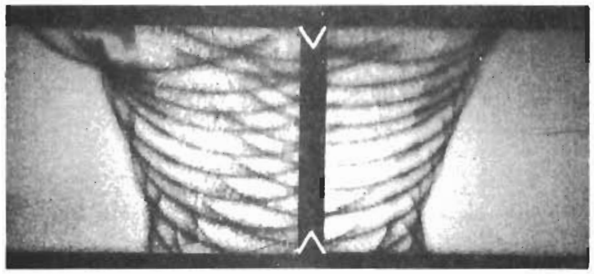
23130



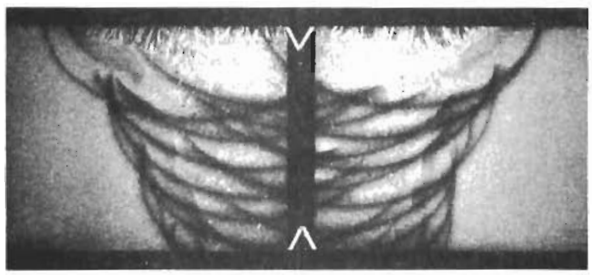
3 lbs./hr. - 8 ipm   4X   W/A = 1266 in. lb./in.^{2}

FIGURE 40

CROSS-SECTION OF TIG-COLD WIRE WELD 88-72
IN 1-IN. 18 NI STEEL

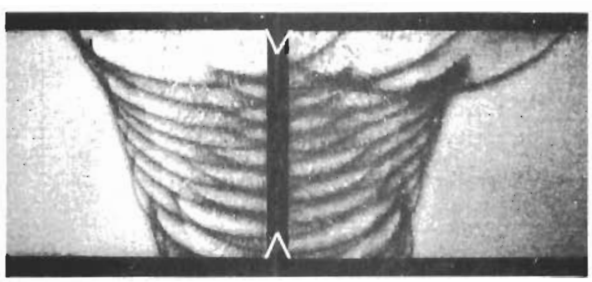


Weld No. 88-92
Specimen location
3/16 in. below top
W/A = 1989 in. lb./in.^{2}

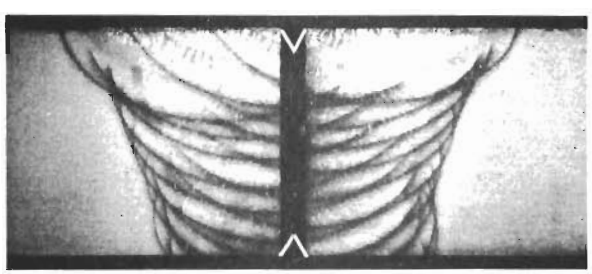


Weld No. 88-72
Specimen location
1/16 in. below top
W/A = 1266 in. lb./in.^{2}

TIG-COLD WIRE - 3 LBS./HR.



Weld No. 88-96
Specimen location
3/16 in. below top
W/A = 1800 in. lb./in.^{2}



Weld No. 88-86
Specimen location
1/16 in. below top
W/A = 1346 in. lb./in.^{2}

TIG-HOT WIRE - 5 LBS./HR.

FIGURE 41

MARAGED PRECRACKED CHARPY TEST SPECIMENS
1-IN. WELDS IN 18 NI STEEL

23235
23236
23238
23243

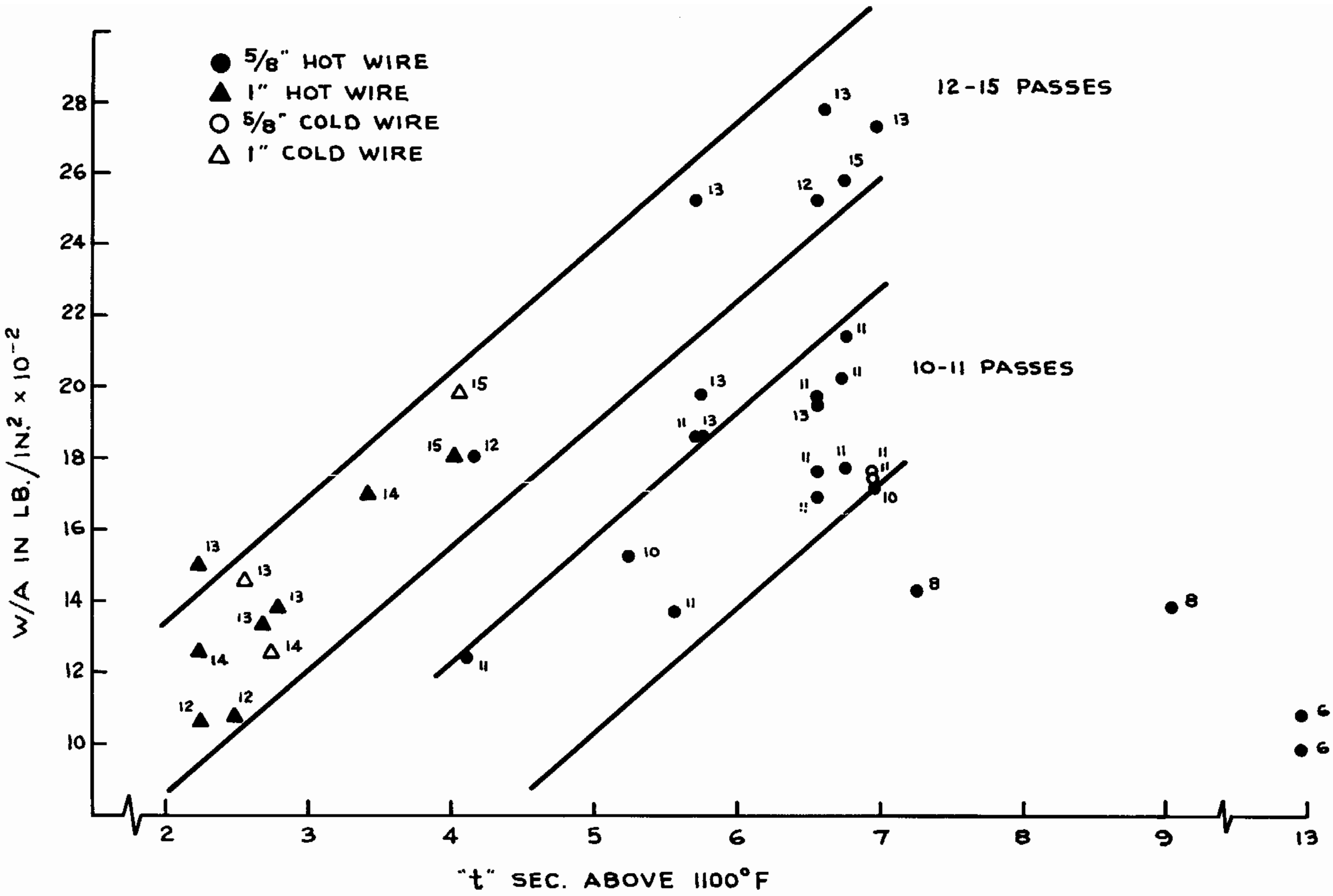


FIGURE 42

W/A ENERGY ABSORPTION VS. TIME ABOVE 1100° F.
AND NUMBER OF PASSES - 18 NI STEEL

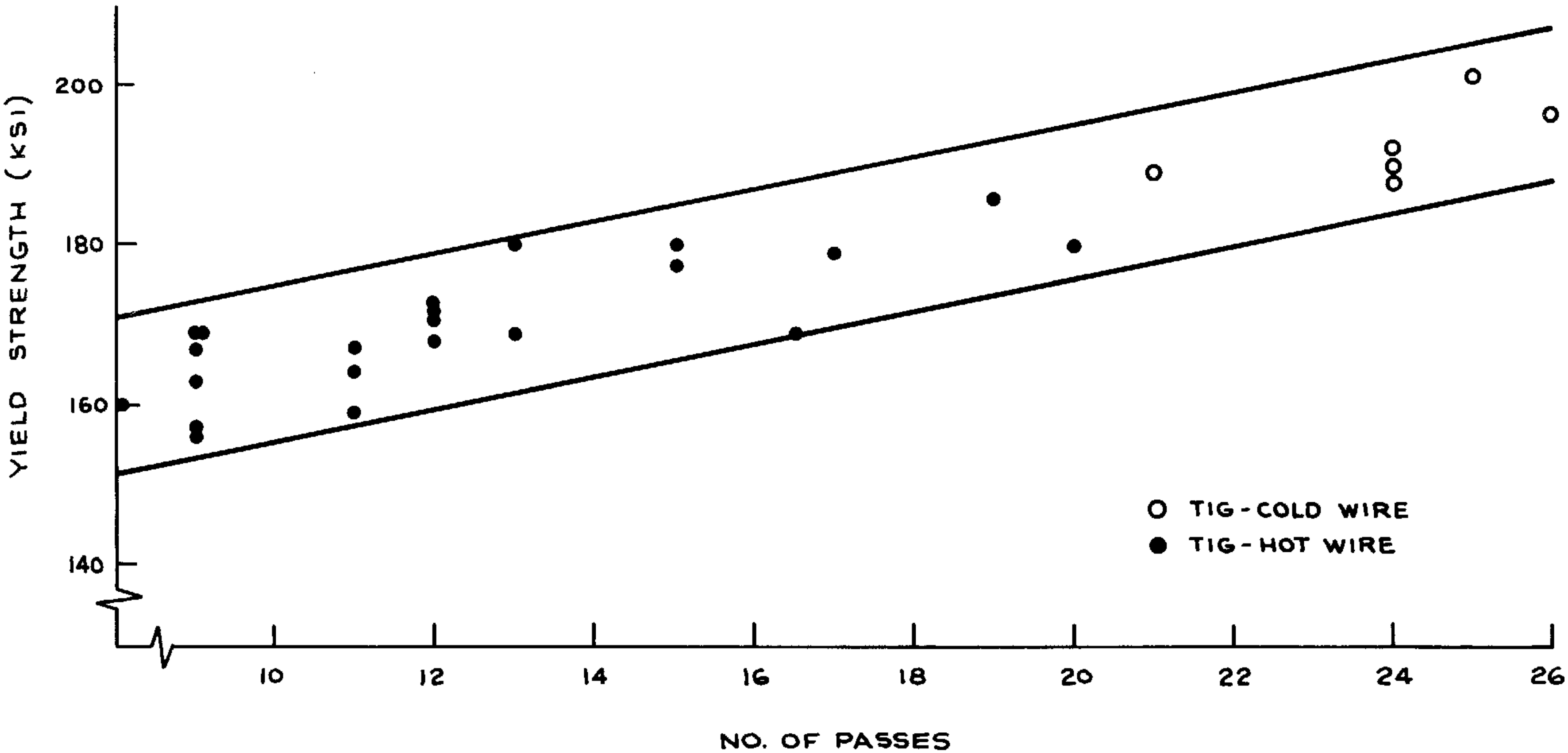


FIGURE 43

YIELD STRENGTH VS. NUMBER OF PASSES
0.6-IN. HP 9 NI-4 CO-.20 C STEEL

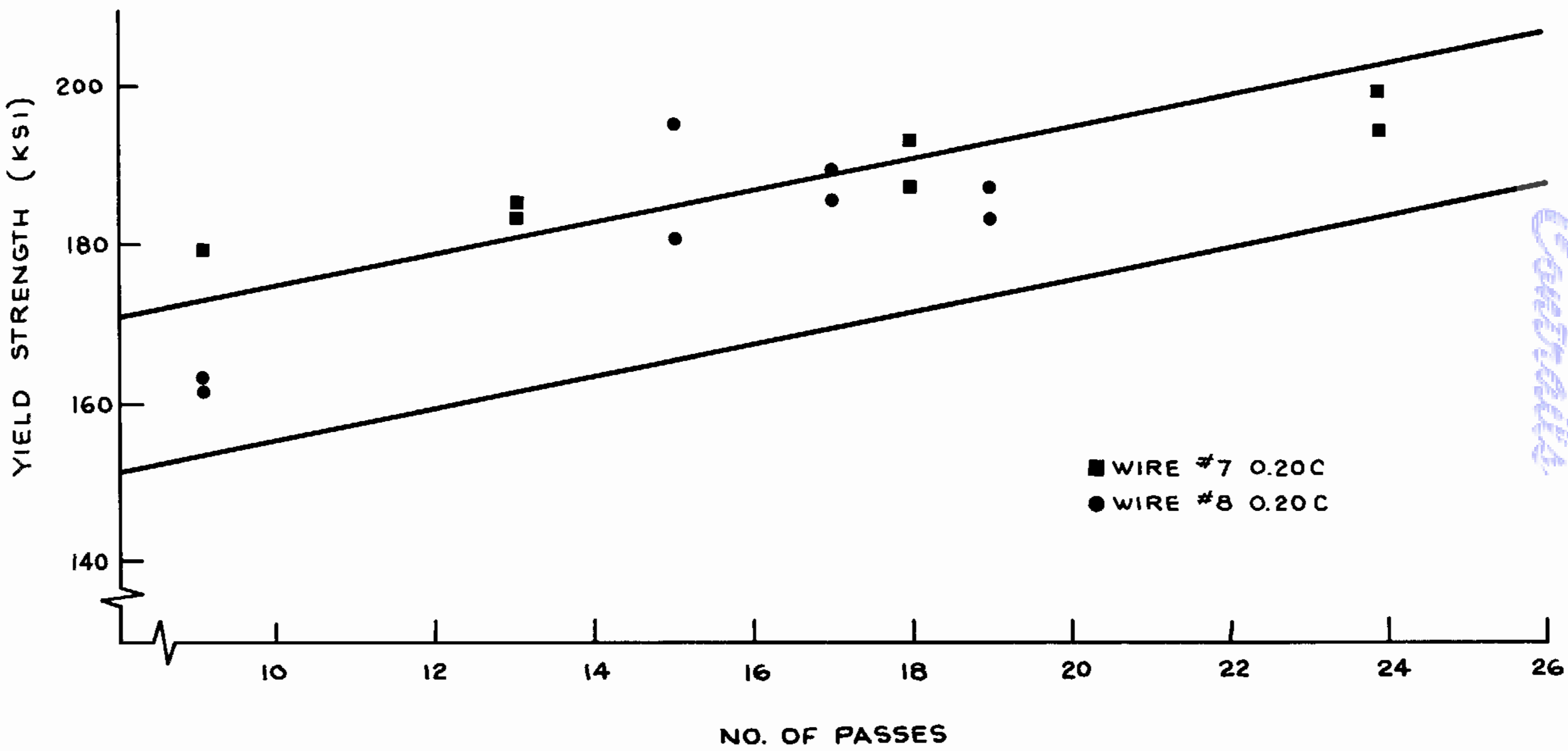


FIGURE 44

YIELD STRENGTH VS. NUMBER OF PASSES
0.5-IN. CONVENTIONAL TIG WELDS
(TRW DATA)

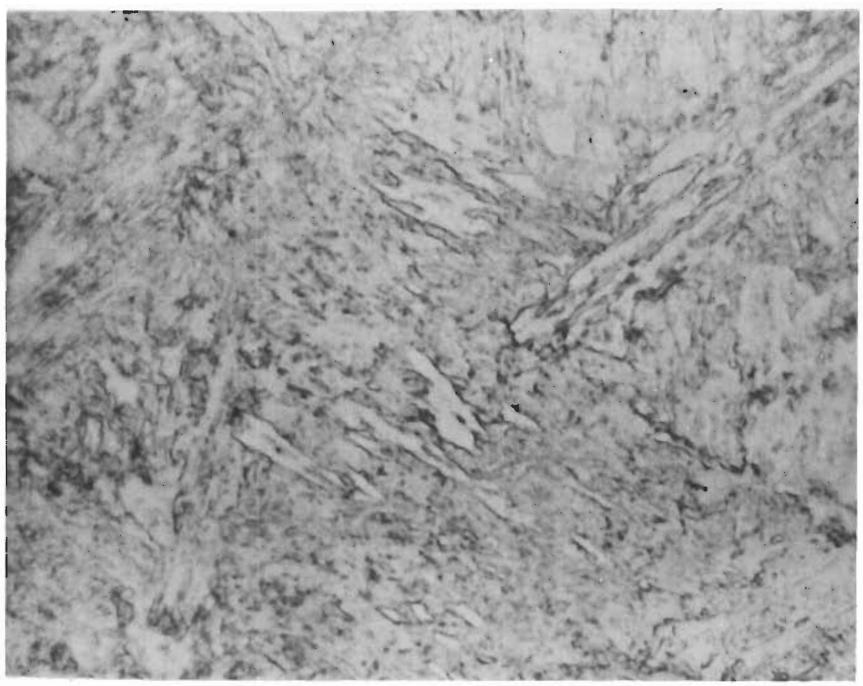


FIGURE 45

PHOTOMICROGRAPH (1500X) OF AS-DEPOSITED
COVER PASS MATERIAL IN WELD 88-84
HP 9 NI-4 CO-.20 C STEEL

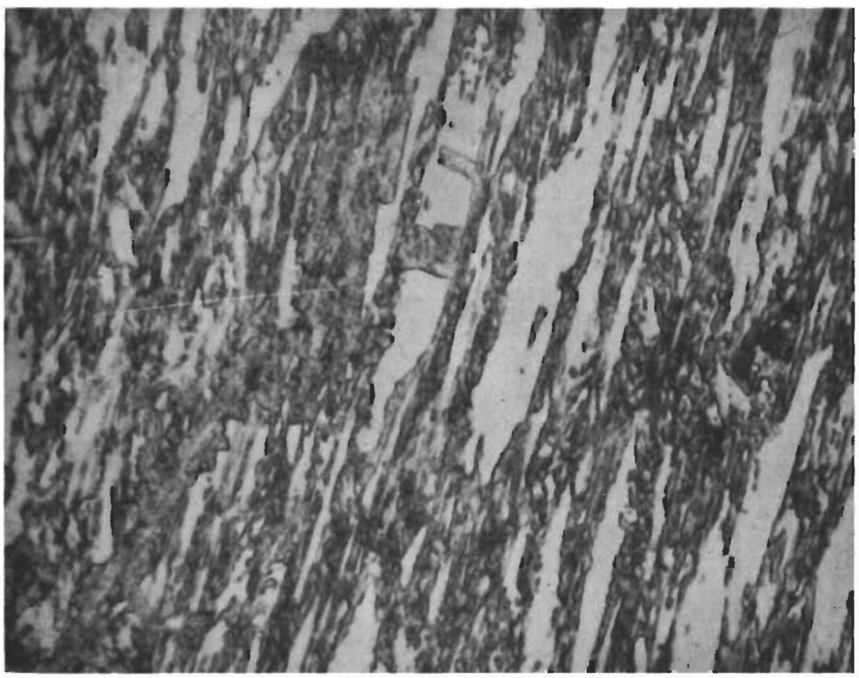


FIGURE 46

PHOTOMICROGRAPH (1500X) OF GRAIN COARSENED
REGION OF HOT WIRE WELD 88-84
HP 9 NI-4 CO-.20 C STEEL

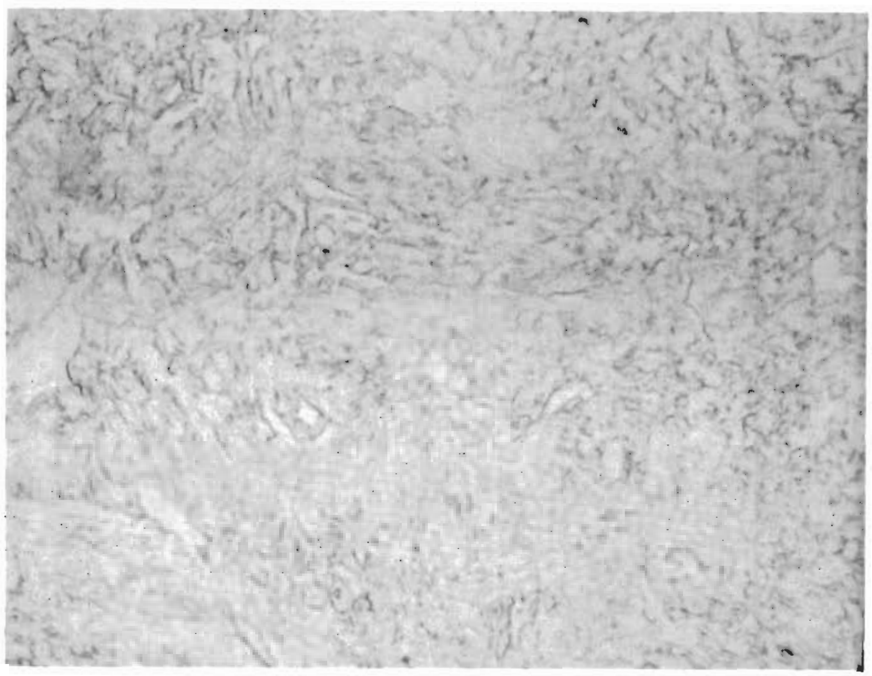
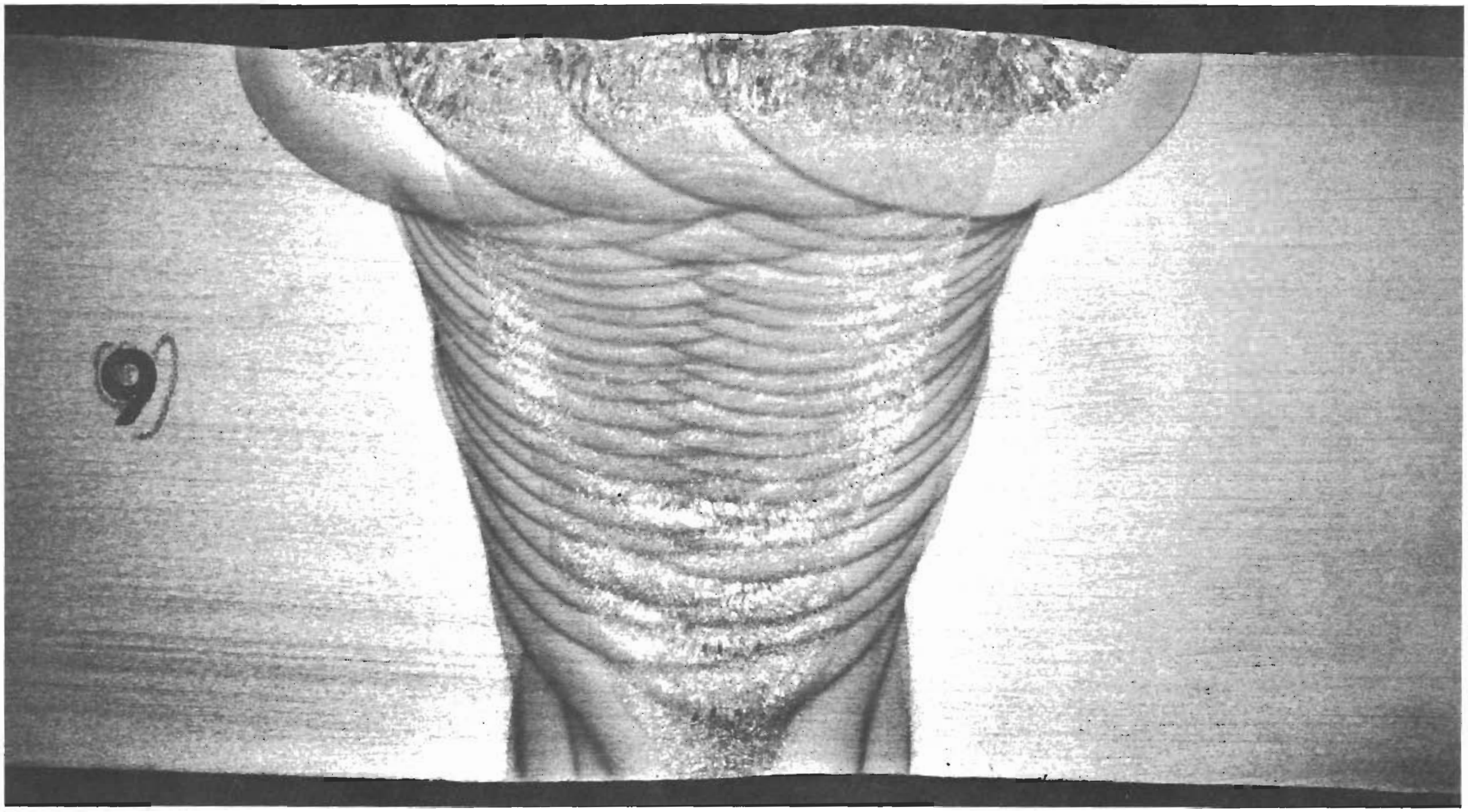


FIGURE 47

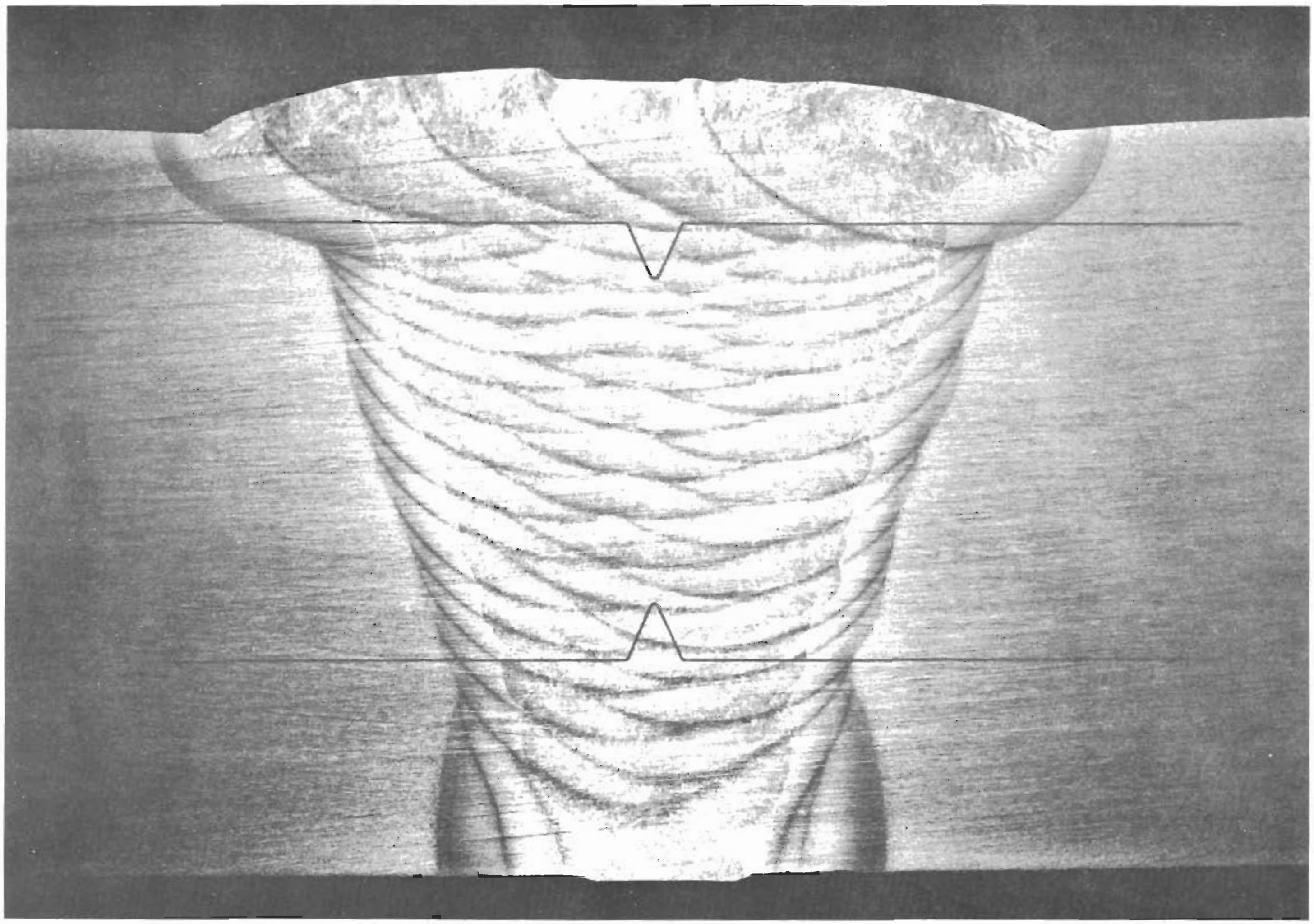
PHOTOMICROGRAPH (1500X) OF FINE GRAIN
REGION OF TIG WELD 186-53
HP 9 NI-4 CO-.20 C STEEL



1.6 lbs./hr. - 8 ipm   4X   YS = 201 ksi

FIGURE 48

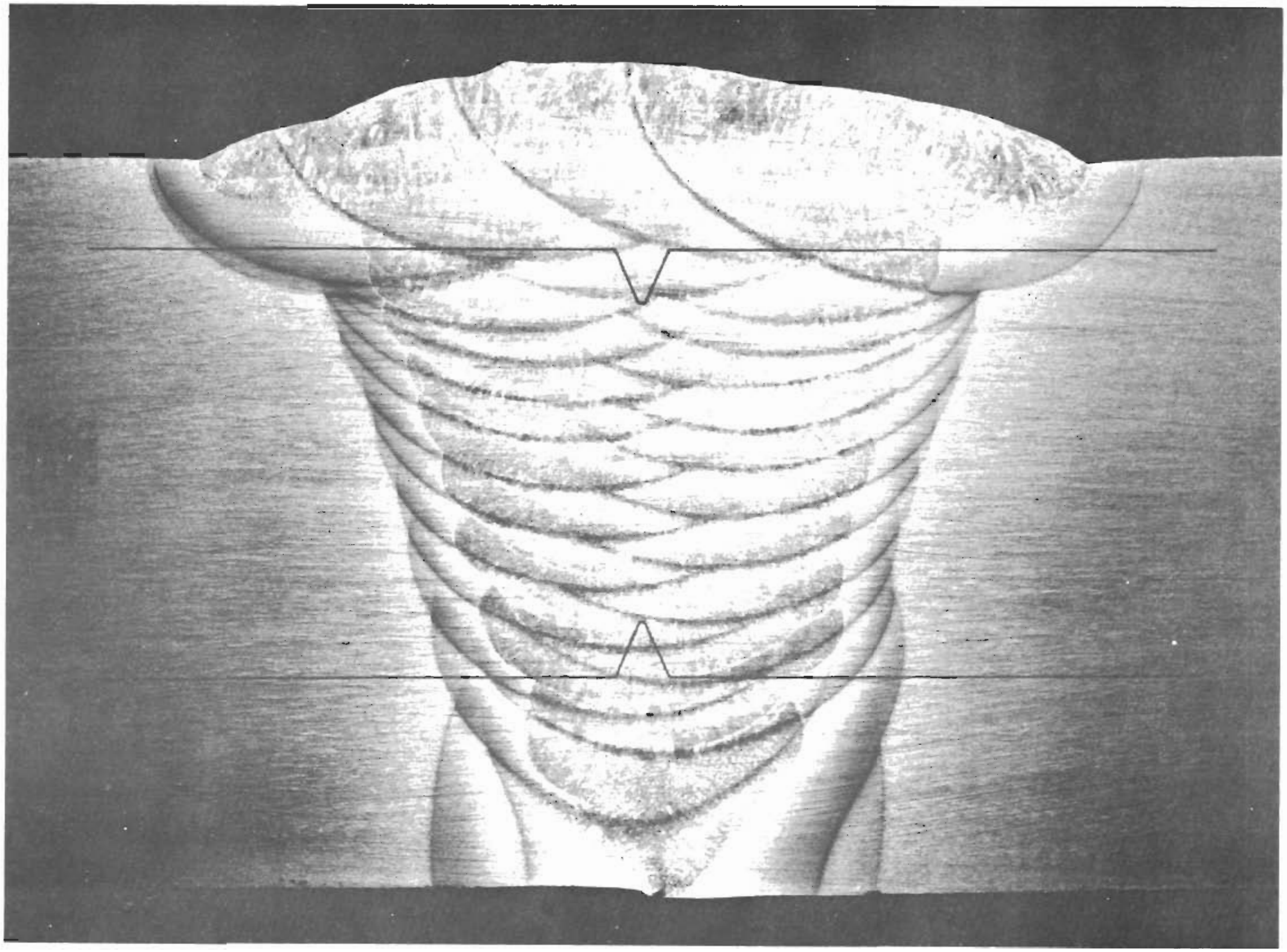
CROSS-SECTION OF TIG-COLD WIRE WELD 186-53
IN 1-IN. HP 9 NI-4 CO-.20 C STEEL



3.0 lbs./hr. - 8 ipm   4X   YS = 198 ksi

FIGURE 49

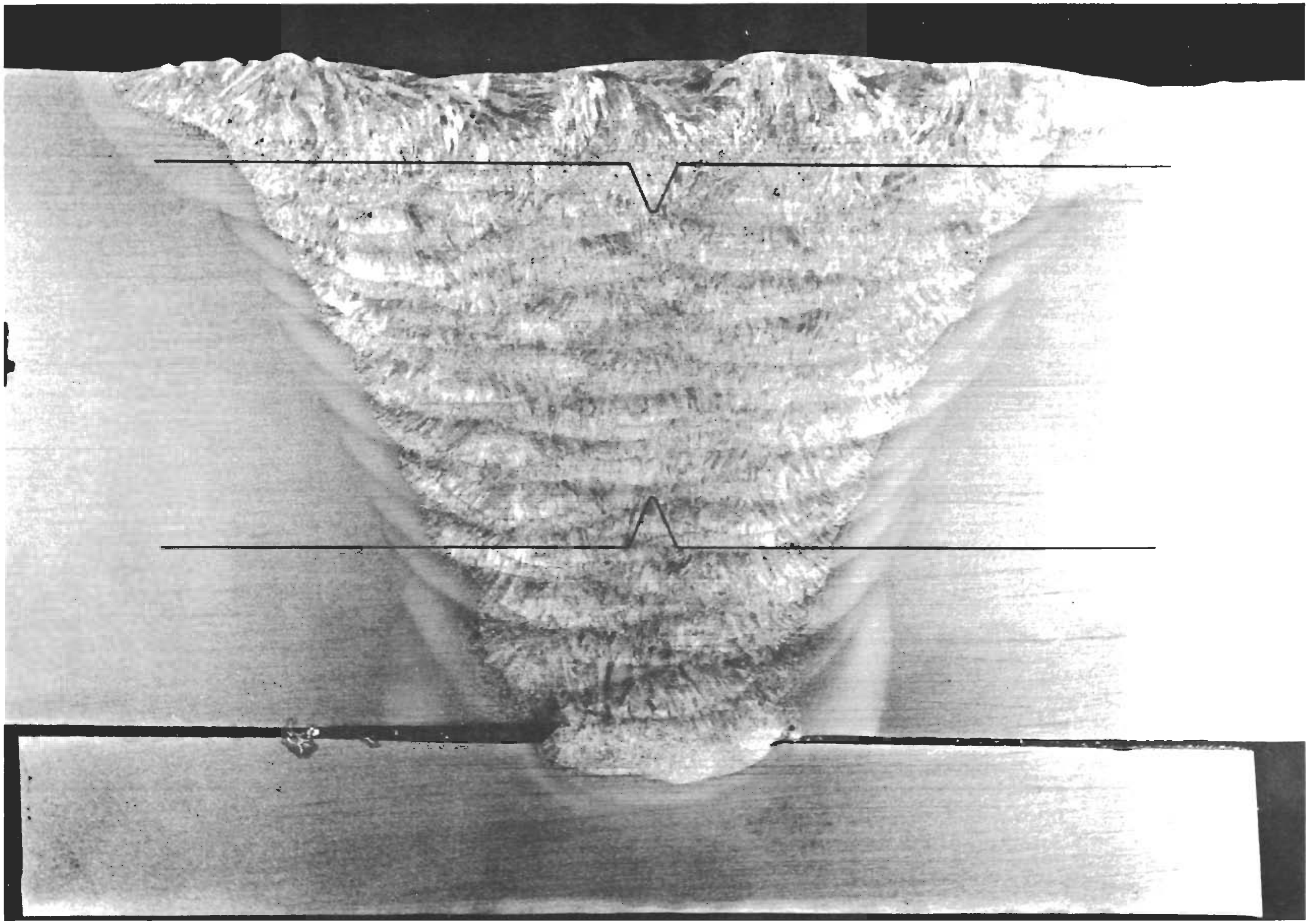
CROSS-SECTION OF TIG-HOT WIRE WELD 186-57
IN 1-IN. HP 9 NI-4 CO-.20 C STEEL



5.0 lbs./hr. - 12 ipm   4X   YS = 186 ksi

FIGURE 50

CROSS-SECTION OF TIG-HOT WIRE WELD 186-56
IN 1-IN. HP 9 NI-4 CO-.20 C STEEL



7.6 lbs./hr. - 16 ipm   4X   YS = 198 ksi

FIGURE 51

CROSS-SECTION OF TIG-HOT WIRE WELD 186-61
IN OPEN VEE JOINT PREPARATION - 1-IN. HP 9 NI-4 CO-.20 C STEEL

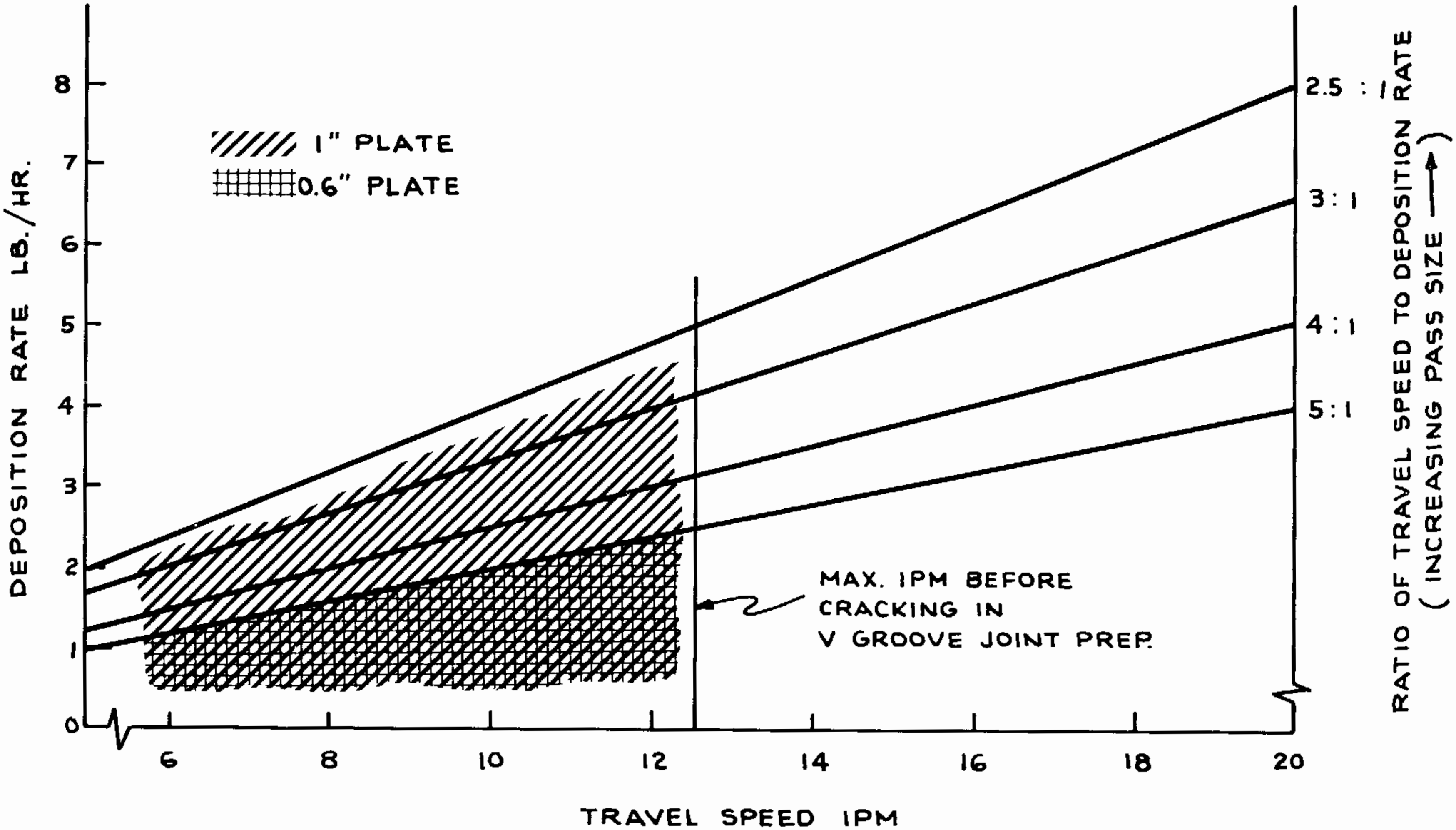


FIGURE 52

BOUNDARY LIMITS FOR TIG-HOT WIRE WELDING
OF HP 9 NI-4 CO-.20 C STEEL USING 40° INCLUDED ANGLE -
0.156-IN. RADIUS - 0.60-IN. ROOT FACE SINGLE U GROOVE JOINT PREPARATION

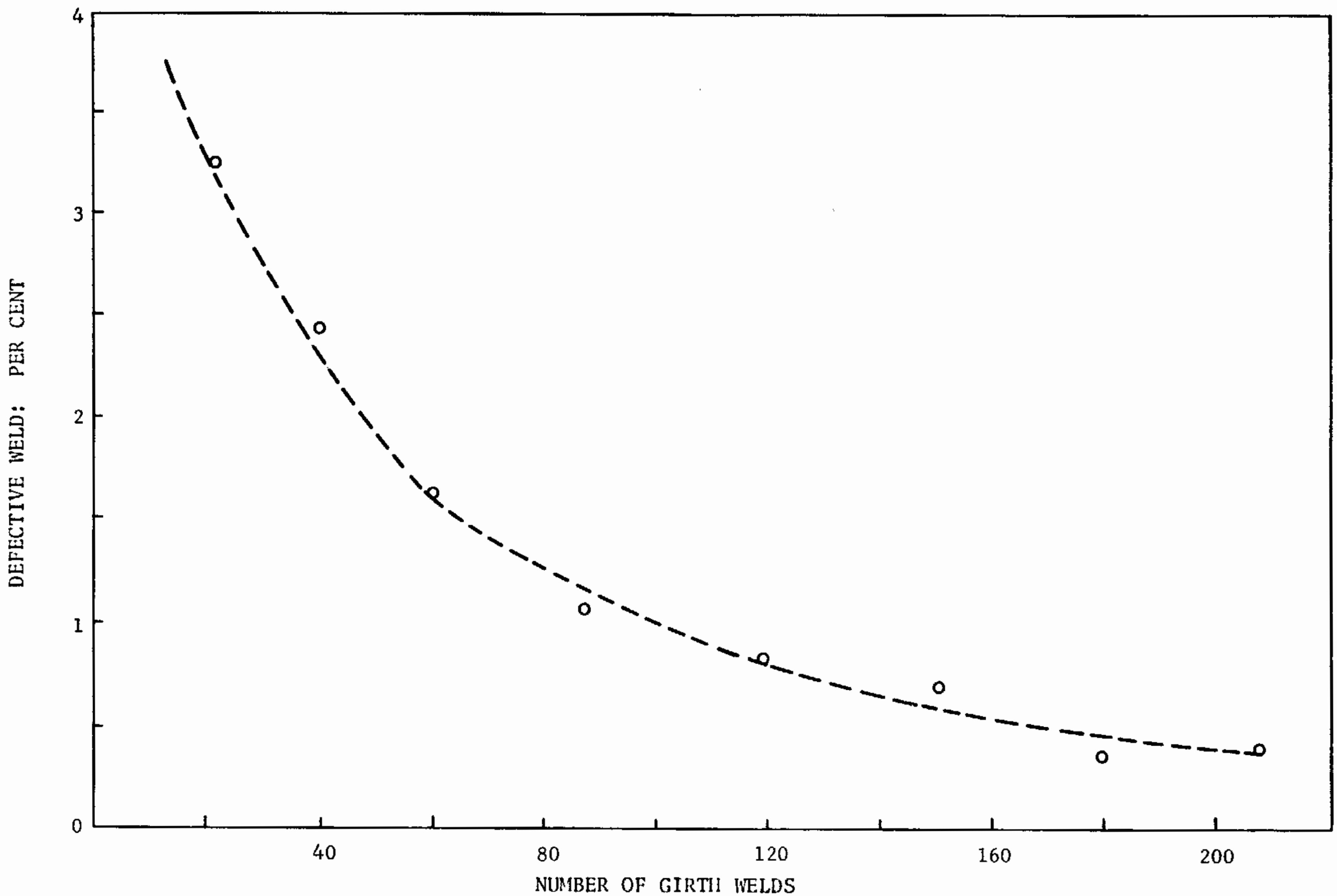


FIGURE 53

WELD DEFECTS VS. NUMBER OF TIG GIRTH WELDS
TITAN III C ROCKET MOTOR CASES

TABLE I

CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES
3/8-IN. (NOM.) D-6ac STEEL TEST PLATE
CAMERON IRON WORKS, HEAT NO. 50050

Chemical Analyses, %

	C	Mn	P	S	Si	Cr	Ni	Mo	V
Curtiss-Wright Specification	0.42/ 0.48	0.60/ 0.90	0.010 max.	0.010 max.	0.15/ 0.30	0.90/ 1.20	0.40/ 0.70	0.90/ 1.10	0.05/ 0.10
Mill Analysis	0.46	0.75	0.009	0.003	0.21	1.08	0.60	0.96	0.10
Linde Analysis	0.46	0.74	0.010	0.006	0.18	1.08	0.52	0.95	0.087

Mechanical Properties

	Yield Strength 0.2% Offset (ksi)	Ultimate Tensile Strength (ksi)	Elongation %	Reduction of Area %	Hardness R_c
Mill Data(1) Avg. Longitudinal	198.6	214.5	14.8	47.0	47
Avg. Transverse	198.6	219.6	14.0	42.0	47

Mill Data

Decarburization: 0.008-in. max.

Inclusion Rating: S/N 4301 - Type D: 1-H - All others 1 thin.

Ultrasonic Inspection: QS-NTP-31 - Satisfactory

(1)Heat Treat Cycle: Austenitize - 1650° F./2 hrs.
Salt Quench - 400° F./10 min.
Snap Temper - 400° F./2 hrs. and 600° F./2 hrs.
Final Temper- 1125° F./4 hrs.

TABLE II

CHEMICAL ANALYSIS AND GAS CONTENT
0.062-IN. DIAMETER D-6ac FILLER METAL, HT. NO. 41572

Chemical Analyses

	Element %									
	C	Mn	P	S	Si	Ni	Cr	V	Mo	P + S
Specification	0.26/ 0.32	0.60/ 0.90	0.010 max.	0.010 max.	0.15/ 0.30	0.40/ 0.70	0.90/ 1.20	0.05/ 0.10	0.90/ 1.10	0.015 max.
Mill	0.29	0.85	0.002	0.005	0.23	0.55	1.06	0.080	1.01	
Linde	0.31	0.85	0.01	0.002	0.23	0.55	1.12	0.080	0.94	

Gas Analyses

	Vacuum Fusion			Kjeldahl Nitrogen		
	O_2 (ppm)	H_2 (ppm)	N_2 (ppm)	% Sol	% Insol	% Total
Specification	25	15	50	-	-	-
Mill	10	<1	5	-	-	-
Linde	14	2	30	0.002	0.002	0.004

TABLE III

CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES
0.6-IN. (NOM.) 18 PER CENT NI (200) VAR MARAGING STEEL PLATE
CAMERON IRON WORKS HEAT NO. 50264

	Chemical Analyses, %										Additives, %		
	C	Mn	Si	S	P	Al	Ni	Co	Mo	Ti	B	Zr	Ca
Purchase Spec.	0.03 max.	0.10 max.	0.10 max.	0.01 max.	0.01 max.	0.05/ 0.15	17.5/ 19.0	7.0/ 8.0	4.0/ 4.5	0.05/ 0.25	0.003	0.02	0.06
Mill	0.002	0.05	0.05	0.005	0.005	0.12	18.0	7.38	4.28	0.11	0.003	0.02	0.06
Linde	0.031	0.04	0.09	0.006	0.004	0.11	18.0	7.45	4.35	0.09	0.003	0.015	-

MECHANICAL PROPERTIES

		Maraging Cycle	Yield Strength 0.2% Offset (ksi)	Ultimate Tensile Strength (ksi)	Elongation %	Reduction of Area %
Mill	Avg. Longitudinal	890° F. - 4 hrs.	216.0	222.9	14.6	55.5
	Avg. Transverse	Air Cooled	218.0	225.6	12.5	52.4
Linde (1)	Avg. Longitudinal	900° F. - 4 hrs.	218.7	225.7	11.5	58.9
	Avg. Transverse	Air Cooled	219.3	227.6	10.9	54.9
	Avg. Longitudinal	900° F. - 3 hrs.	212.3	219.0	12.5	58.2
	Avg. Transverse	Air Cooled	214.0	221.8	11.1	57.0

ROOM TEMPERATURE PRECRACKED CHARPY ENERGY ABSORPTION W/A (In. Lb./In.^{2})

Linde Data(2) - Avg. Longitudinal 1490
Avg. Transverse 1160
(Maraging Cycle - 900° F. - 3 hrs. - Air Cooled)

MILL DATA

Microcleanliness (ASTM-E-45) - All fields less than 1 thin.
Grain Size - 6
Ultrasonic Examination - Satisfactory
Magnaflux - Satisfactory
Plate solution annealed @ 1675° F. - 1 hr. - water quenched.

(1) Data obtained from 0.357-in. diameter tensile bars. Elongation gage length 1.4 in.
(2) Data obtained from 0.394-in. x 0.600-in. precracked and side-notched Charpy impact specimens.

TABLE IV

CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES
1-IN. (NOM.) 18 PER CENT NI (200) VAR MARAGING STEEL PLATE
CAMERON IRON WORKS HEAT NO. 50234

	Chemical Analyses, %										Additives, %		
	C	Mn	Si	S	P	Al	Ni	Co	Mo	Ti	B	Zr	Ca
Purchase Spec.	0.03 max.	0.10 max.	0.10 max.	0.01 max.	0.01 max.	0.05/ 0.15	17.5 19.0	7.0/ 8.0	4.0/ 4.5	0.05/ 0.25	0.003	0.02	0.06
Mill	0.02	0.05	0.06	0.007	0.006	0.08	18.22	7.36	4.25	0.16	0.003	0.02	0.06
Linde	-	0.06	0.11	-	0.005	0.06	18.00	7.30	4.35	0.20	-	0.01	-

MECHANICAL PROPERTIES

		Maraging Cycle	Yield Strength 0.2% Offset (ksi)	Ultimate Tensile Strength (ksi)	Elongation %	Reduction of Area %
Mill	Avg. Longitudinal	890° F. - 4 hrs.	219.6	226.9	12.5	55.5
	Avg. Transverse	Air Cooled	222.8	230.1	10.9	46.5
Linde(1)	Avg. Longitudinal	900° F. - 3 hrs.	203.0	214.0	10.0	49.7
	Avg. Transverse	Air Cooled	207.2	218.1	11.4	54.9

ROOM TEMPERATURE PRECRACKED CHARPY ENERGY ABSORPTION W/A (In. Lb./In.^{2})

Linde Data(3) - Avg. Longitudinal 1030
Avg. Transverse 793
(Maraging Cycle - 900° F. - 3 hrs. - Air Cooled)

MILL DATA

Microcleanliness (ASTM-E-45) - All fields less than 1 thin.
Grain Size - 7
Ultrasonic Examination - Satisfactory
Magnaflux - Satisfactory
Plate solution annealed @ 1650° F. - 1 hr. - water quenched

(1) Data obtained from 0.357-in. diameter tensile bars. Elongation gage length 1.4 in.
(2) Data obtained from 0.600 x 0.394-in. precracked and side-notched Charpy impact specimens.
(3) Date obtained from 0.394-in. x 0.600-in. precracked and side-notched Charpy impact specimens.

TABLE V

CHEMICAL ANALYSIS, GAS CONTENT AND TENSILE PROPERTIES
0.045-IN. DIAMETER 18 NI (200) VAR MARAGING STEEL FILLER METAL
HEAT NO. 02105

	Element %										
	C	Mn	Si	S	P	Al	Ca	Ni	Co	Mo	Ti
Specification	0.03 max.	0.10 max.	0.05 max.	0.01 max.	0.01 max.	0.10 added	0.05 added	17.5/ 18.5	7.5/ 8.0	3.6/ 3.8	0.26/ 0.30
Armetco	0.006	0.01	0.01	0.007	0.003	0.03	0.05 added	17.92	7.70	3.76	0.29
Linde	0.007	0.04	0.01	0.005	0.005	0.04	0.015	17.5	7.95	3.65	0.30

Gas Analyses

		O_2	H_2	N_2
Purchase Spec., ppm (max.)		20	2	35
Armetco Analysis, ppm		25	3	40
Linde Analyses, ppm	(1) as-received	51	5	38
	cleaned	49	2	28
	(2) as-received	68	9	68
	cleaned	53	5	32
	(3) as-received	45	5	26
	cleaned	43	3	26
	(4) as-received	57	10	54
	cleaned	45	5	33

Tensile Properties

Weld No.	Yield Strength 0.2% Offset (ksi)	Ultimate Strength (ksi)	Elongation 1-in. gage, %	Reduction of Area %
1187-47-1 (hot wire hog trough)	189	199	11.4	52

TABLE VI

TENSILE PROPERTIES - W/A ENERGY ABSORPTION - K^*_{IC} FRACTURE TOUGHNESS

TIG-COLD WIRE AND TIG-HOT WIRE CALIBRATION WELDS

Weld No.	Filler Metal	Yield Strength 0.2% Offset (ksi)	Ultimate Tensile Strength (ksi)	Elongation in 1.4 in. %	Reduction of Area %	W/A Energy Absorption in. lb./in.^{2}	K^*_{IC} ksi in. Weld	K^*_{IC} ksi in. HAZ
		Tig-Cold Wire Welds						
1187-31-1	Ht.09944	205	212	10.7	47.1	1238 (1)	138 124 (2)	147 144
1187-46-1	Ht.02105	190	199	12.1	57	1413	137	140
		Tig-Hot Wire Welds (Hog Trough Joint)						
1187-32-1	Ht.09944	202	215	10.4	49.7	875 (1)	114 106 (2)	136 119
1187-47-1	Ht.02105	189	199	11.4	52	1070	-	-

Maraging Cycle: 3 hrs. @ 900° F. except where noted:

(1) 4 hrs. @ 900° F.

(2) 8 hrs. @ 900° F.

W/A values obtained from 0.394 x 0.600 precracked and side-notched specimens.

Welding conditions were the same for similar type welds.

TABLE VII

CHEMICAL COMPOSITION AND TENSILE PROPERTIES REPUBLIC STEEL HP 9-4-.20C TEST PLATE, HT. 3951995

Chemical Composition

	Element %									
	C	Mn	P	S	Si	Ni	Cr	Mo	V	Co
Republic	0.18	0.30	0.004	0.007	0.01	8.98	0.75	1.02	0.09	4.40
Linde	0.18	0.38	0.004	0.008	0.03	8.65	0.83	1.07	0.12	4.83

Tensile Properties

		Plate Thickness	Yield Strength 0.2% Offset (ksi)	Ultimate Tensile Strength (ksi)	Elongation in 2 in. %	Reduction of Area, %	Hardness R_c
Republic		5/8 in.	183	202	16	61.9	42
Linde(1)	(L)	5/8 in.	173	200	18.3	68.3	43
	(T)	5/8 in.	177	202	17.1	61.6	-
Republic		1 in.	181	207	16	64.5	42
Linde(1)	(L)	1 in.	176	205	16.8	64.0	44
	(T)	1 in.	174	201	16.4	62.4	-

(1)Tensile data obtained from 0.357-in. diameter tensile specimens.

TABLE VIII

STANDARD AND PRECRACKED CHARPY ENERGY ABSORPTION
REPUBLIC STEEL HP 9-4-.20C PLATE, HT. 3951995

Standard Charpy Energy Absorption(1)

Plate Thickness	Test Temperature °F.	Energy Absorption ft. lbs. Longitudinal	Energy Absorption ft. lbs. Transverse
5/8 in.	Rm.	69	53
	0	51	47
	-60	48	39
1 in.	Rm.	45	51
	0	42	43
	-60	36	37

Precracked Charpy Energy Absorption(2)

Plate Thickness	W/A Energy Absorption in. lb./in.^{2} Longitudinal	W/A Energy Absorption in. lb./in.^{2} Transverse
5/8 in.	3235	2711
1 in.	1977	1897

(1) Data obtained from standard ASTM 0.394-in. square specimens.

(2) Data obtained from 0.394-in. x 0.600-in. precracked and side-notched specimens.

TABLE IX

CHEMICAL COMPOSITION, GAS CONTENT AND TENSILE PROPERTIES
REPUBLIC STEEL HP 9-4-.20C FILLER METAL, HT. 60320

Chemical Analyses, %

	C	Mn	P	S	Si	Ni	Cr	Mo	V	Co
Linde	0.16	0.79	0.004	0.008	0.23	6.90	0.52	0.88	0.084	3.28

Gas Analyses

Sample Identification		Vacuum Fusion O_2 ppm	Vacuum Fusion H_2 ppm	Vacuum Fusion N_2 ppm	Kjeldahl Nitrogen % Soluble	Kjeldahl Nitrogen % Insoluble	Kjeldahl Nitrogen % Total
Spool 1	As-Rec'd	34	2	23	0.004	0.000	0.004
	Cleaned	15	1	27	-	-	-
Spool 2	As-Rec'd	35	2	22	0.004	0.000	0.004
	Cleaned	22	1	19	-	-	-
Spool 3	As-Rec'd	36	2	18	0.003	0.001	0.004
	Cleaned	28	1	21	-	-	-
Spool 4	As-Rec'd	32	2	22	0.006	0.002	0.008
	Cleaned	30	1	22	-	-	-

All-Weld Metal Tensile Properties(1)

Yield Strength 0.2% Offset (ksi)	Ultimate Tensile Strength (ksi)	Elongation 1-in. gage %	Reduction of Area %
194	215	17.0	58.0

(1) Average of three Tig-cold wire welds - as-welded properties - 0.252-in. diameter tensile specimens.

TABLE X

COMPARISON OF H_2 CONTENTS OF "ARCLESS" HOT WIRE DEPOSITS AND ORIGINAL FILLER METAL

Wire Type	Hydrogen Content ppm	Hot Wire Deposit Hydrogen Content ppm
18 Ni, Ht. 02105		
Spool 15	9	1
	9	1
Spool 3	9	1
	9	1
18 Ni, Ht. 08950	6	1
	6	2
Cr-Mn-Ni-Mo	3	1
	3	1
Mn-Ni-Mo-V	14	2
	14	2
	14	2

TABLE XI

COMPARISON OF O_2 AND N_2 CONTENTS OF "ARCLESS" HOT WIRE DEPOSITS AND ORIGINAL FILLER METAL

WIRE TYPE	GAS CONTENTS			
	Oxygen (Vacuum Fusion)		Nitrogen (Kjeldahl)	
	ppm	% Sol.	% Insol.	% Total
18 Ni (Heat 02105)				
Wire (Spool 8)	23	0.005	0.001	0.006
Deposit	4	0.005	0.000	0.005
	10	0.005	0.000	0.005
Wire (Spool 14)	5	0.005	0.002	0.007
Deposit	2	0.004	0.000	0.004
	4	0.004	0.001	0.005
	2	0.004	0.001	0.005

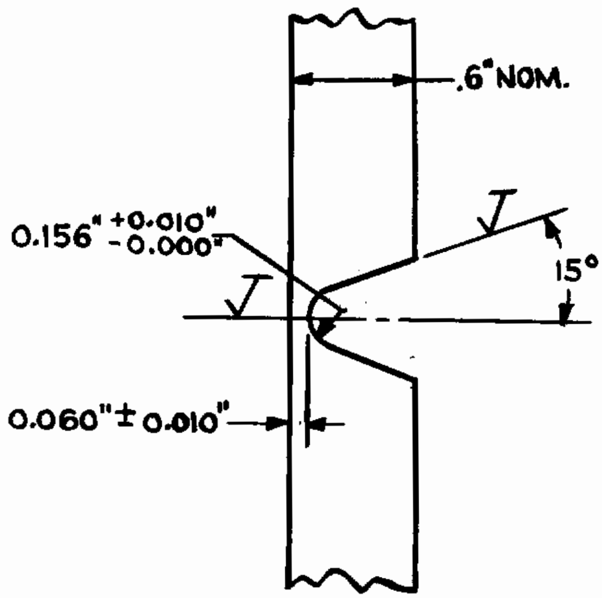
TABLE XII

ANALYSIS OF ALL WELD METAL DEPOSITS MADE WITH
TIG-HOT WIRE & CONVENTIONAL COLD WIRE TECHNIQUES

	Element %										
	C	Mn	Si	S	P	Al	Ca	Ni	Co	Mo	Ti
Filler Metal (ht. 02105)	0.007	0.04	0.01	0.005	0.005	0.04	0.015	17.5	7.95	3.65	0.30
Hot Wire Weld	0.008	0.02	0.01	0.005	0.004	0.02	-	18.5	7.80	3.60	0.30
Cold Wire Weld	0.005	0.02	0.01	0.004	0.005	0.02	-	17.8	7.80	3.60	0.29

TABLE XIII

JOINT PREPARATION AND WELDING CONDITIONS USED FOR HORIZONTAL TIG-HOT WIRE WELDING



JOINT PREPARATION

WELDING CONDITIONS

	Root Pass	Fill Pass
Arc Current, amperes	265	400
Arc Voltage, volts	11	11.5
Hot Wire Current, amperes	136	170
Hot Wire Voltage, volts	5.6	6
Travel Speed, ipm	9	14
Deposition Rate, lbs./hr.	5.5	8.5
Number of Passes	1	6

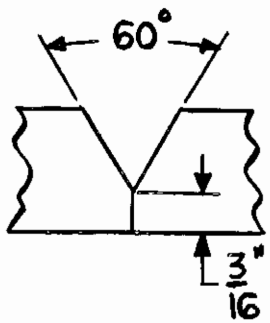
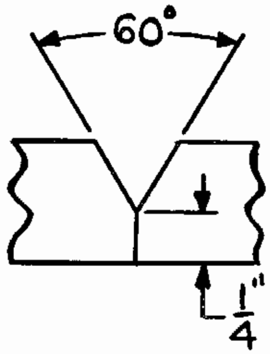
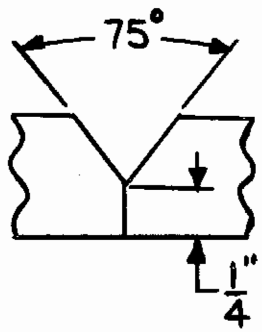
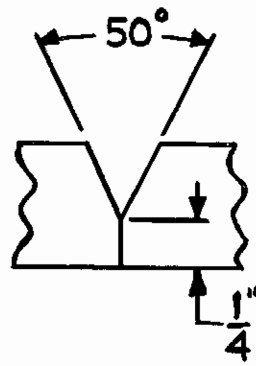
TABLE XIV

COMPARISON OF TENSILE PROPERTIES - W/A ENERGY ABSORPTION - K_{IC}^{*} FRACTURE TOUGHNESS DOWNHAND AND HORIZONTAL TIG-HOT WIRE WELDS

Weld No.	Description		Yield Strength 0.2% Offset ksi	Ultimate Tensile Strength ksi	Elongation in 1.4 in. %	Reduction of Area %	W/A Energy Absorption in. lb./in.^{2} Weld	W/A Energy Absorption in. lb./in.^{2} HAZ	K_{IC}^{*} ksi$\sqrt{in.}$ Weld	K_{IC}^{*} ksi$\sqrt{in.}$ HAZ
1187-94	Tig-Hot Wire Downhand Position 8 lbs./hr. - 10 ipm	(L) (T)	197 207	208 212	10.0 10.0	51 51	990	1796	124	134
1187-99	Tig-Hot Wire Horizontal Position 8 lbs./hr. - 14 ipm	(L) (T)	196 205	206 209	9.0 8.0	48 41	940	1923	125	142

TABLE XV

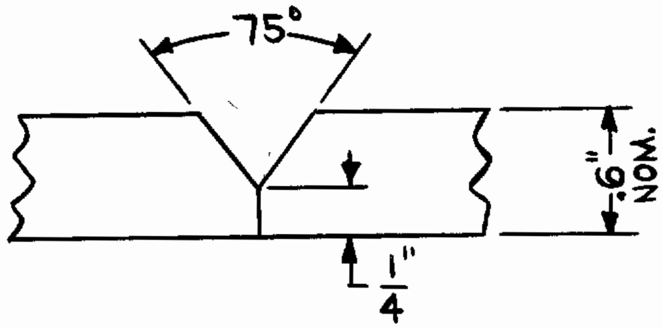
PLASMA ARC ROOT PASS WELDING CONDITIONS

Joint Preparation				
Welding Current, amp. DCSP	330	330	320	330
Voltage, volts	31	30	30	29
Travel Speed, ipm	5	4.5	5.0	4.6
Orifice Gas Flow Rate, cfh	Argon 17	Argon 16.5	Argon 18.0	Argon 13
Orifice Diameter, in.[1]	0.136	0.136	0.136	0.136
Electrode Setback, in.	0.070	0.070	0.070	0.070
Torch Standoff from Work, in.	1/8	1/8	1/8	1/8
Shielding Gas Flow Rate, cfh	Argon 100	Argon 100	Argon 100	Argon 100

[1]Multiport orifice design consisting of a center hole with (2) 0.040-in. diameter side ports spaced 0.187 in. on either side of main orifice.

TABLE XVI

JOINT PREPARATION AND WELDING CONDITIONS USED FOR
PLASMA ARC-HOT WIRE "FINAL" WELD PANEL



	Weld 40-37	
	Keyhole Root Pass	Hot Wire Fill Passes
Current, amp. DCSP	300	310
Voltage, volts	31	35
Travel Speed, ipm	5.5	14
Deposition Rate, lbs./hr.	-	7
Hot Wire Current, amp.	-	155
Hot Wire Voltage, volts	-	5.0
Heat Input, Kji	90[1]	46.5
Orifice Gas, cfh	18 Ar	25 He-75[2]
Shielding Gas, cfh	100 Ar	150 He-75[2]

Orifice Type: 136 C

Electrode Size: 5/32-in. diameter

Electrode Setback: 0.070 in.

Torch Standoff: 1/8 in.

[1]Value based on estimated 10 per cent heat loss to orifice.
[2]He-75: 75 per cent helium, 25 per cent argon mixture.

TABLE XVII

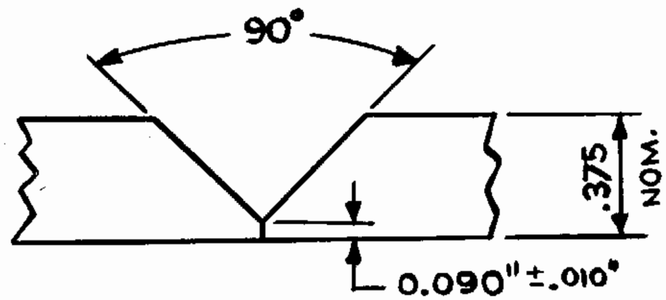
COMPARISON OF TENSILE PROPERTIES - W/A ENERGY ABSORPTION - K^*_{IC} FRACTURE TOUGHNESS OF CONVENTIONAL TIG, PLASMA ARC-HOT WIRE, AND TIG-HOT WIRE WELDS

Weld No.	Description		Yield Strength 0.2% Offset ksi	Ultimate Tensile Strength ksi	Elongation in 1.4 in. %	Reduction of Area %	W/A Energy Absorption in.lb./in.^{2} Weld	W/A Energy Absorption in.lb./in.^{2} HAZ	Average K^*_{IC} ksi in. Weld	Average K^*_{IC} ksi in. HAZ
1187-98	Conventional Tig	(L) (T)	198 206	208 212	10.1 10.0	51 50				
40-37	Plasma Arc-Hot Wire 7 lbs./hr. 14 ipm	(L) (T)	198 207	208 214	11.1 11.5	53 55	896	1838	117	155
1187-92	Tig-Hot Wire 8 lbs./hr. 10 ipm	(L) (T)	200 208	209 213	10.7 9.3	53 49	1078	1896	119	137
1187-94	Tig-Hot Wire 8 lbs./hr. 10 ipm	(L) (T)	197 207	208 212	10.0 10.0	51 51	990	1796	124	134

Maraging Cycle: 3 hrs. @ 900° F.

TABLE XVIII

WELDING CONDITIONS
FINAL TIG-HOT WIRE WELDS IN D-6ac STEEL



Weld No.	Type	Deposition Rate lbs./hr.	Travel Speed ipm	Tig Arc Current amp.	Tig Arc Volts volts	Hot Wire Current amp.	Hot Wire Volts volts	Shielding Gas cfh
88-56	Cold Wire	2	9	300	11	-	-	40 Ar
88-62	Hot Wire	2	13	290	11	80	2.8	50 He-75
88-61	Hot Wire	5	13	420	11	136	4.7	50 He-75
88-60	Hot Wire	8	18	450	11	200	5.5	80 He-75
All Root Passes		-	4.5	290	11	-	-	50 He-75

NOTES: Preheat & interpass temperature - 500-550° F.
Postweld heat treatment - 600-650° F./1 hr.

TABLE XIX

TENSILE PROPERTIES AND FRACTURE TOUGHNESS FINAL TIG-HOT WIRE WELDS IN D-6ac STEEL

Weld No.	Type	Deposition Rate lbs./hr.	Yield Strength 0.2% Offset, ksi	Ultimate Tensile Strength, ksi	Elongation in 2 in.,%	Reduction of Area,%	K_{IC} ksi in. Weld	HAZ
Base Plate (L)		-	192	207	14.0	52	107	
(T)		-	192	208	13.5	50		
88-56 (L)	Cold Wire	2	175	197	14.0	50	105	103
(T)			185	197	7.5	31		
88-62 (L)	Hot Wire	2	178	192	12.0	40	103	104
(T)			181	193	7.8	33		
88-61 (L)	Hot Wire	5	175	189	15.0	50	101	104
(T)			181	193	7.5	30		
88-60 (L)	Hot Wire	8	172	186	15.0	49	105	101
(T)			183	194	7.8	35		

NOTE: Longitudinal data from 0.252-in. diameter round tensile specimens.
Transverse data from 0.500-in. x 0.350-in. (nom.) flat tensile specimens.

Heat Treat Cycle:
- Austenitize - 1650° F./2 hrs.
- Salt Quench - 400° F./10 min.
- Snap Temper - 400° F./2 hrs. and 600° F./2 hrs.
- Final Temper - 1125° F./4 hrs.

TABLE XX

WELDING CONDITIONS AND TENSILE PROPERTIES
TIG-HOT WIRE WELDS IN 0.6-in. 18 NI STEEL

Weld No.	Dep. Rate lbs./hr.	Travel Speed ipm	Arc Current	Arc Volt.	Hot Wire Current	Hot Wire Volt.	Total Kji	YS 0.2% Offset ksi	UTS ksi	Elong. in 1.4-in. %	RA %
1187-47	3.0	8	370	11.0	Cold Wire		30.0	189	199	11.4	52.0
1187-50-1	8.0	10	490	12.0	180	5.6	41.1	193	204	11.8	59.6
1187-52-1	12.0	10	500	12.0	204	7.2	44.8	195	205	10.7	50.3
1187-53-1	8.1	10	495	12.2	172	5.7	42.2	192	203	11.1	55.5
1187-54-1	11.8	10	395	11.6	211	7.1	36.5	192	204	10.0	46.6
1187-55-1	8.3	10	395	11.6	165	5.9	33.3	191	202	10.7	51.7
1187-56-1	8.0	14	390	11.6	166	5.9	23.6	191	201	10.4	50.0
1187-60-1	8.4	14	500	12.0	178	5.7	30.1	187	199	12.1	58.0
1187-61-1	12.0	14	400	11.5	198	6.9	25.5	186	197	10.0	55.2
1187-62-1	8.0	14	500	12.0	168	5.9	29.9	186	199	12.8	55.2
1187-63-1	12.0	14	485	12.7	208	6.8	32.4	189	200	9.3	43.0

TABLE XXI

EFFECT OF COSMETIC PASSES ON TOUGHNESS OF HIGH DEPOSITION RATE WELDS

Weld No.	Deposition Rate lbs./hr.	Travel Speed ipm	Arc I Amp.	Arc E Volts	Hot Wire Amp.	Hot Wire Volts	Energy Absorption in. lb./in.^{2} Weld	Energy Absorption in. lb./in.^{2} HAZ	Apparent Fracture Toughness K_{IC} ksi$\sqrt{in.}$ Weld	Apparent Fracture Toughness K_{IC} ksi$\sqrt{in.}$ HAZ
1187-92	8	10	500	12	168	5.6	1078	1896	119	137
Cosmetic Pass	0	10	300	12.5	-	-	1154	1995	121	157
1187-94	8	10	500	12	176	5.3	990	1796	124	134
Cosmetic Pass	0	10	300	12.5	-	-	1115	1884	129	156

NOTES: Shielding Gas - 75% He - 25% Ar.

Cosmetic passes added to one-half of each weld.

TABLE XXII

WELDING CONDITIONS USED FOR VARIABLE DEPOSITION RATE WELD 88-2

	Pass Number								
	Root	1	2	3	4	5	6	7	8
Deposition Rate, lbs./hr.	5	5.4	6.5	8.4	9.5	10.8	11.8	5.4	-
Arc Current, amp. DCSP	280	430	480	580	605	650	650	470	350
Arc Voltage, volts	11	12	12	13	14	15	16	13	13
Hot Wire Current, amp.	140	144	160	176	188	208	220	136	-
Hot Wire Voltage, volts	5	5	5.1	5.8	5.9	6.6	7.1	5.5	-
Travel Speed, ipm	9	12	12	12	12	12	12	12	12
Total Heat Input, Kji	25	29	33	43	48	56	60	34	23

TABLE XXIII

WELDING CONDITIONS

TIG-HOT WIRE WELDS IN 18 NI STEEL

Weld No.	Arc I (amp.)	Arc E (volts)	Travel Speed (ipm)	Deposition Rate (lb./hr.)	Hot Wire I (amp.)	Hot Wire E (volts)	Total Heat Input (Kji)	No. Passes	W/A in.lb./in.
88-34	340	10.8	8	3.0	100	4.2	30.6	13	2735
1187-96	340	10.5	8	3.1	100	4.0	30.0	15	2579
88-26	340	10.5	8	3.4	100	4.2	29.9	11	2015
1187-64	340	10.5	8	3.6	108	4.4	31.2	10	1711
1187-80	350	10.5	8	4.2	116	4.2	31.0	8	1433

TABLE XXIV

LONGITUDINAL AND TRANSVERSE TENSILE PROPERTIES OF HIGH DEPOSITION RATE WELDS IN 5/8-IN. 18 NI STEEL

Weld No.	Type	Deposition Rate lbs./hr.		Yield Strength 0.2% Offset ksi	Ultimate Tensile Strength ksi	Elongation %	Reduction of Area %
	Base Metal	-	(L)	212	219	12.5	58
			(T)	214	221	11.1	57
1187-98	Cold Wire	3	(L)	198	208	10.1	51
			(T)	206	212	10.0	50
1187-96	Hot Wire	3	(L)	195	207	10.2	51
			(T)	207	212	10.0	50
1187-94	Hot Wire	5	(L)	197	209	11.6	55
			(T)	-	-	-	-
1187-95	Hot Wire	7.6	(L)	204	215	12.6	58
			(T)	210	216	13.3	45

NOTE: Longitudinal tensile data from ASTM 0.357 specimens.
Transverse tensile data from ASTM flat specimens.

TABLE XXV

LONGITUDINAL AND TRANSVERSE TENSILE PROPERTIES OF HIGH DEPOSITION RATE WELDS IN 1-IN. 18 NI STEEL

Weld No.	Type	Deposition Rate lbs./hr.		Yield Strength 0.2% Offset ksi	Ultimate Tensile Strength ksi	Elongation %	Reduction of Area %
	Base Metal	-	(L)	203	214	10.0	50
			(T)	207	218	11.4	55
88-65[1]	Cold Wire	3	(L)	193	204	12.1	56
88-64[1]	Hot Wire	3	(L)	194	206	12.8	57
88-66[1]	Hot Wire	5	(L)	195	207	12.1	56
88-69[1]	Hot Wire	7.6	(L)	194	207	12.1	57
88-92[2]	Cold Wire	3	(L)	198	206	11.8	50
			(T)	202	208	12.1	47
88-93[2]	Hot Wire	3	(L)	197	206	11.5	53
			(T)	201	208	12.0	48
88-96[2]	Hot Wire	5	(L)	197	208	11.0	51
			(T)	201	210	11.8	46
88-97[2]	Hot Wire	7.6	(L)	198	207	10.5	50
			(T)	203	211	12.0	47

[1]Double-U groove joint preparation.

[2]Single-U groove joint preparation.

NOTE: Longitudinal tensile data from ASTM 0.505 specimens.
Transverse tensile data from Mod. ASME flat specimens (1/2-in. x 1-in. section).

TABLE XXVI

PRECRACKED CHARPY ENERGY ABSORPTION AND APPARENT FRACTURE TOUGHNESS OF HIGH DEPOSITION RATE WELDS IN 5/8-IN. 18 NI STEEL

Weld No.	Type	Deposition Rate lbs./hr.		W/A in. lb./in.^{2}	K^*_{IC} ksi $\sqrt{in.}$ Weld	HAZ
	Base Plate	-	(L) (T)	1490 1160	147	
1187-98	Cold Wire	3		1775	137	140
1187-96	Hot Wire	3.1		2579	141	144
88-94	Hot Wire	5		1775	130	133
88-95	Hot Wire	7.6		1864	116	122

TABLE XXVII

PRECRACKED CHARPY ENERGY ABSORPTION AND APPARENT FRACTURE TOUGHNESS OF HIGH DEPOSITION RATE WELDS IN 1-IN. 18 NI STEEL

Weld No.	Type	Deposition Rate lbs./hr.	W/A in. lb./in.^{2}		K^*_{IC} ksi$\sqrt{in.}$ Weld	HAZ
	Base Plate	-	(L)	1030	125	
			(T)	793		
88-65[1]	Cold Wire	3		1450	146	-
88-64[1]	Hot Wire	3		1380	141	-
88-66[1]	Hot Wire	5		1084	133	-
88-69[1]	Hot Wire	7.6		1066	132	-
88-92	Cold Wire	3.1		1989[2]	142	143
88-96	Hot Wire	5		1800[2]	143	132
88-97	Hot Wire	7.6		1700[2]	148	140

[1]Double-U groove joint preparation

[2]Charpy specimen located 3/16-in. below top surface of plate

TABLE XXVIII

WELDING CONDITIONS - RATE OF HEAT INPUT - TIME ABOVE 1100° F. - W/A ENERGY ABSORPTION

TIG-COLD WIRE AND HOT WIRE WELDS IN 18 NI STEEL

Weld No.	Plate Thick. in.	Dep. Rate lbs./hr.	No. Passes (N)	Arc I Amp.	Arc E Volts	Hot Wire I Amp.	Hot Wire E Volts	Travel Speed ipm	Total Kji	Time Above 1100°F. (t) sec.	W/A in. lb./in.^{2}
1187-46	5/8	3.2	12	370	11.0	Cold	Wire	8	30.5	6.92	1413
1187-98	"	3.0	15	370	11.0	"	"	8	30.5	6.92	1755
88-27	"	3.1	11	370	11.0	"	"	8	30.5	6.92	1755
88-34	"	3.0	13	340	10.75	100	4.2	8	30.6	6.96	2735
1187-96	"	3.1	15	340	10.50	100	4.2	8	30.0	6.71	2579
88-26	"	3.4	11	340	10.50	100	4.2	8	30.0	6.71	2015
1187-64	"	3.6	10	340	10.50	108	4.4	8	30.4	6.92	1711
1187-80	"	4.2	8	350	10.50	116	4.2	8	31.3	7.26	1433
88-47	"	5.2	11	490	12.0	130	4.9	13	30.1	6.76	2140
88-68	"	5.0	11	490	11.25	128	4.9	13.5	27.3	5.55	1369
88-80	"	5.0	11	490	12.0	128	4.1	13	29.6	6.55	1971
88-81	"	5.0	13	490	12.0	128	4.1	13	29.6	6.55	1962
88-94	"	5.0	11	490	12.0	128	4.8	13	30.0	6.72	1775
186-25	"	5.0	11	490	12.0	128	4.1	13	29.6	6.55	1690
186-26	"	5.0	11	490	12.0	128	4.1	13	29.6	6.55	1760
186-27	"	5.0	11	490	12.0	128	4.1	13	29.6	6.55	1789
88-46	"	6.0	12	550	13.0	140	5.3	16	29.6	6.55	2520
88-48	"	6.0	13	550	13.0	145	5.3	16	29.7	6.60	2785
88-33	"	7.0	13	600	13.0	160	6.2	19	27.7	5.72	1980
88-45	"	7.6	12	600	13.0	160	6.0	19	27.6	5.68	2523
88-67	"	7.5	13	595	13.25	155	6.0	19	27.8	5.76	1857
88-95	"	7.6	11	600	13.0	160	6.1	19	27.6	5.68	1864
186-23	"	7.6	11	590	13.0	160	6.1	19	27.3	5.55	1865
186-62	"	7.6	12	500	13.0	160	6.1	19	23.6	4.15	1800
1187-92	"	8.0	6	500	12.0	168	5.6	10	41.6	12.95	1078
1187-94	"	8.0	6	500	12.0	176	5.3	10	41.6	12.95	990
88-41	"	8.0	8	500	12.0	160	6.4	12	35.1	9.02	1389
88-37	"	8.0	10	500	12.0	172	6.1	16	26.4	5.22	1515
88-36	"	8.0	11	500	12.0	168	6.2	18	23.5	4.11	1241

TABLE XXVIII CONT'D

Weld No.	Plate Thick. in.	Dep. Rate lbs./hr.	No. Passes (N)	Equiv. No. Passes	Arc I Amp.	Arc E Volts	Hot Wire I Amp.	Hot Wire E Volts	Travel Speed ipm	Total Kji	Time Above 1100° F. (t) sec.	W/A in.lb./in.^{2}
88-65	1	3.0	22	13	370	10.5	Cold Wire		8	29.2	2.53	1450
88-64	"	3.0	22	13	340	11.0	85	4.1	8	30.6	2.77	1380
88-66	"	5.0	20	12	480	12.0	115	4.7	13	29.1	2.50	1084
88-69	"	7.6	20	12	600	13.0	160	6.0	19	27.6	2.26	1066
88-92	13/16	3.1	26	15	370	11.0	Cold Wire		8	30.5	4.17	1989
88-96	"	5.0	25	15	490	12.0	128	4.8	13	30.0	4.05	1800
88-97	"	7.6	24	14	600	13.0	160	6.1	19	27.6	3.42	1700
88-72	1	3.0	25	14	370	11.0	Cold Wire		8	30.5	2.76	1266
88-73	"	7.6	22	13	600	13.0	160	5.9	19	27.6	2.26	1500
88-86	"	5.3	23	13	490	12.0	136	4.9	13	30.2	2.69	1346
186-24	"	7.6	25	14	600	13.0	160	6.1	19	27.6	2.26	1264

TABLE XXIX

WELDING CONDITIONS AND MECHANICAL PROPERTY DATA
0.6-IN. WELDS IN HP 9 NI-4 CO-.20 C STEEL

Weld No.	Description	D.R. Lb./Hr.	Travel Speed ipm	Arc I	Arc E	Hot Wire I	Hot Wire E	Cool. Rate °F/Sec.	No. Pass	YS (ksi)	W/A in. lb./in.^{2}	CVN ft./lb.
88-91	Cold Wire	1.0	8	350	11	-	-	60	26	196	3172	53
88-75	Cold Wire	1.6	8	340	12	-	-	54	21	189	2533	42
88-76	Cold Wire	1.6	8	300	12	-	-	65	24	192	3135	52
88-77	Cold Wire	1.6	8	400	12	-	-	38	24	190	2648	41
88-78	Cold Wire	1.6	8	350	15	-	-	36	25	201	2932	42
88-82	Hot Wire	2.4	8	350	12	80	3.6	43	19	186	2590	45
88-83	Hot Wire	2.4	8	350	15	80	4.1	33	17	179	2355	43
88-84	Hot Wire	5.0	8	350	13	128	4.6	33	9	156	2512	41
88-89	Hot Wire	5.0	13	490	12	128	4.6	57	11	159	2783	46
186-1	Hot Wire	5.0	8	350	12	128	4.6	38	9	167	2320	40
186-2	Hot Wire	5.0	8	300	12	128	4.6	45	9	169	2390	40
186-3	Hot Wire	5.0	8	400	12	128	4.6	29	9	157	1985	40
186-4	Hot Wire	5.0	8	450	12	128	4.6	23	9	163	1934	35
186-5	Hot Wire	5.0	8	500	12	128	4.6	18	9	169	2087	46
186-17	Hot Wire	5.0	16	360	12	128	4.6	150	15	180	1997	-
186-19	Hot Wire	5.0	16	550	13	128	4.6	58	13	180	2480	41
186-20	Hot Wire	5.0	8	595	13	128	4.6	10	8	160	1885	38
186-21	Hot Wire	5.0	12	600	13	128	4.6	28	11	167	2105	39
186-22	Hot Wire	5.0	20	600	13	128	4.6	82	15	177	2327	44
186-40	Hot Wire	3.0	8	330	12	100	3.0	50	12	173	2529	38
186-41	Hot Wire	3.0	8	300	12	100	3.0	60	11	164	2648	43
186-49	Hot Wire	7.6	16	380	12	160	6.1	120	12	173	2252	22
186-50	Hot Wire	5.0	12	300	12	128	4.1	120	13	169	2394	39
186-51	Hot Wire	3.0	12	300	12	100	3.0	130	17	169	2902	45

NOTE: Preheat and Interpass Temperature: 150° F.

TABLE XXX

WELDING CONDITIONS AND MECHANICAL PROPERTY DATA FOR
HIGH DEPOSITION RATE WELDS IN HP 9 NI-4 CO-.20 C STEEL

WELD NO.	DESCRIPTION	DEP. RATE #/HR.	TRAVEL SPEED IPM	ARC AMP.	ARC VOLTS	HOT WIRE AMP.	HOT WIRE VOLTS	COOL. RATE °F./SEC.	NO. PASS		YS KSI	UTS KSI	EL.[2] %	% R. A.	BREAK	IN.LB./IN.^{2}	CVN FT./LB.	K_{IC} KSI$\sqrt{IN.}$
186-54	COLD WIRE 5/8"	1.6	8	300	12.5	-	-	65	24	(L)	188	216	13.0	23.3		3145	52	-
										(T)	181	207	14.0	33.0	HAZ			
186-53	COLD WIRE 1"	1.6	8	300	12.5	-	-	95	49	(L)	201	212	14.5	43.1		3097	57	159
										(T)	197	213	17.0	21.0	W			
186-60	HOT WIRE 5/8"	3.0	12	300	12.0	100	3.0	130	20	(L)	181	196	17.0	60.6		3352	55	-
										(T)	165	198	15.0	26.3	HAZ			
186-57	HOT WIRE 1"	3.0	12	300	12.0	100	3.0	140	44	(L)	198	203	17.0	61.5		4030	62	192
										(T)	187	203	17.5	41.9	W			
186-59	HOT WIRE 5/8"	5.0	12	350	13.0	128	4.6	79	12	(L)	168	196	17.0	57.0		3187	50	-
										(T)	172	202	12.5	31.5	W			
186-56	HOT WIRE 1"	5.0	12	350	13.0	128	4.6	105	27	(L)	186	201	14.0	47.2		2714	48	170
										(T)	186	201	5.0	8.8	W			
186-58[1]	HOT WIRE 5/8"	7.6	16	380	13.0	160	6.1	105	12	(L)	172	195	16.5	60.1		3331	51	-
										(T)	169	202	9.0	21.2	W			
186-55[1]	HOT WIRE 1"	7.6	16	400	13.0	160	6.1	117	24	(L)	180	196	13.5	40.7		2265	40	158
										(T)	177	192	4.0	-	W			
186-61	HOT WIRE 1" SINGLE VEE WITH BACKING STRAP 60° INCL. ANGLE 1/4" ROOT OPENING	7.6	16	400	13.0	160	6.1	117	31	(L)	198	203	16.0	58.5		3734	58	-

[1] CRACKING IN FIRST 3 PASSES.

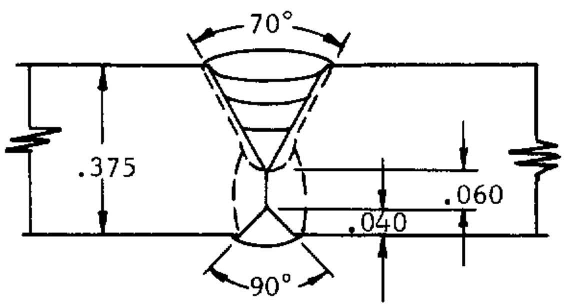
[2] GAGE LENGTH 1.4 IN. FOR 0.357" DIAMETER SPECIMENS - 2 IN. FOR 0.505" DIAMETER SPECIMENS.

PREHEAT & INTERPASS TEMPERATURE: 150° F.
SHIELDING GAS: 75% HE - 25% AR
5/8-IN. LONGITUDINAL TENSILE DATA FROM 0.357-IN. DIAMETER SPECIMENS
1-IN. LONGITUDINAL TENSILE DATA FROM 0.505-IN. DIAMETER SPECIMENS
ALL TRANSVERSE TENSILE DATA FROM 1.0 X 0.5-IN. (NOM.) FLAT SPECIMENS.

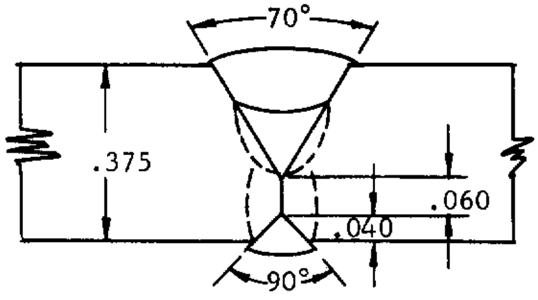
TABLE XXXI

RELATIVE WELDING DATA FOR 120-IN. DIAMETER GIRTH WELD
0.375 THICK D-6ac BUTT WELD, FLAT POSITION

TIG - Cold Wire



TIG - Hot Wire



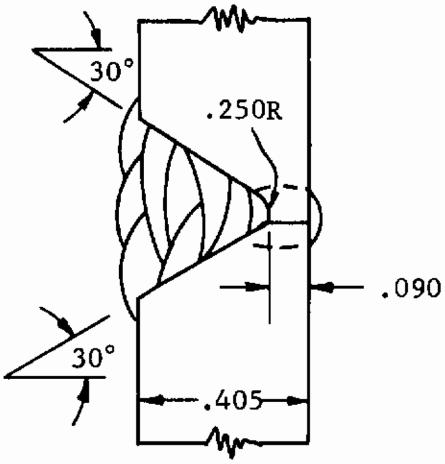
Deposition Rate Lbs/Hour (Cold Wire)	Travel Speed I.P.M. (Cold Wire)	Arc Time Minutes (Cold Wire)	Pass	Deposition Rate Lbs/Hour (Hot Wire)	Travel Speed I.P.M. (Hot Wire)	Arc Time Minutes (Hot Wire)
0	5	76	1	0	5	76
1.05	9	42	2	5.75	13	30
1.55	9	42	3	5.75	13	30
1.55	9	42	4	-	-	-
2.85	7	60	5	-	-	-

TIG - Cold Wire	TIG - Hot Wire
4.4 Arc Hours	2.25 Arc Hours
5.75 Lbs Total Deposit	5.75 Lbs Total Deposit
1.75 Lbs/Hours, Average Deposition Rate	5.75 Lbs/Hour, Deposition Rate

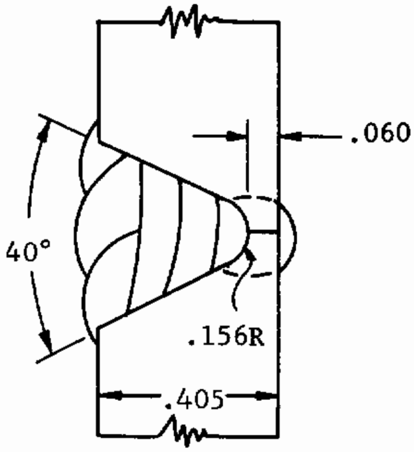
TABLE XXXII

COMPARATIVE WELDING DATA FOR 156-IN. DIAMETER GIRTH WELD
0.405 THICK BUTT, HORIZONTAL POSITION

TIG - Cold Wire



TIG - Hot Wire



Deposition Rate Lbs/Hour	Travel Speed I.P.M.	Arc Time Minutes	Pass	Deposition Rate Lb/Hour	Travel Speed I.P.M.	Arc Time Minutes
0.5	5	100	1	7	9	55
3.0	8	62	2	8	14	35
3.0	8	62	3	8	14	35
3.0	8	62	4	8	14	35
3.0	8	62	5	8	14	35
3.0	8	62	6	4	14	35
3.0	8	62	7	-	-	-
3.0	8	62	8	-	-	-
1-2	10	50	9	-	-	-

9.5 Arc Hours
25.5 lb Total Deposit
2.7 lb/hour, Average Deposition Rate

3.8 Arc Hours
26.5 lb Total Deposit
7 lb/hour, Average Deposition Rate

APPENDIX

FRACTURE TOUGHNESS TESTING

Prepared by

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Notch Slow Bend Test Procedure

Specimen Preparation

Sections from welded panels were received from the Linde Laboratory for evaluation. The sections were machined to the finished dimensions shown in Figure 1. Specimens were etched after machining to reveal the weld area in order to position the notch. On weld specimens, the notch was located in the center of the weld. On heat-affected zone specimens, the notch was located directly adjacent to the top pass fusion line. On some hot wire specimens, the top of the weld was considerably wider than that of the penetration side, making it difficult to confine the notch entirely within the heat-affected-zone. The notch was located to affect the maximum area of the heat-affected-zone.

Fatigue Crack Initiation

Fatigue cracking of notched specimens was accomplished with a 12,000 lb. capacity IVY fatigue Machine, Figure 2.

A special fixture was procured to hold the specimen and apply the bending load. A static cantilever load of 12,000 lb. and a vibratory load of 7,000 lb. were applied to produce a fatigue crack at the root of the machined notch. The calculated bending loads were below 50% of the yield strength. The specimens were vibrated until a 0.100 in. maximum crack length was visible emanating from the vertex of the machined notch.

Fatigue cracking of base metal specimens required approximately 8,000 cycles. In weld area, as high as 12,000 cycles were required. Development of the fatigue crack was observed through a 3X calibrated microscope. Neither liquids nor penetrants were used to accelerate or detect crack development.

Heat Treatment

The heat treatment performed on each bar is designated in Tables 1 to 6. One group of base metal specimens was solution annealed 1 hour at 1675°F and water quenched prior to machining. Aging was originally performed after fatigue cracking, however, to minimize strain age effect, the cycle was changed to age prior to cracking.

Notch-Slow-Bend Testing

Notch slow bend tests were performed on a 24,000 lb. Baldwin Testing Machine. A 4 point bending fixture was used (Figure 3) with the top (minor) span set at 2.5 in. 2 times specimen depth and the bottom (major) span set at .10 in. 8 times specimen depth. A tool jig was used to align the loading points and locate the specimen for test (Figure 3).

The bending load was applied at a rate of 2500 lbs. per minute controlled manually with a rate pacer. The test bar deflection was measured with a microformer type deflectometer and recorded with load on an X-Y recorder.

Acoustic crack detection was used to aid in determination of "pop-in" or crack propagation. The apparatus consisted of a piezo crystal attached directly to the specimen under test. The output from the crystal was amplified 60 Db. and recorded simultaneously with load data on a 2 channel tape recorder.

Calculation of Fracture Toughness

The critical stress intensity, K_{I_C}, expressed as ksi $\sqrt{In.}$ was calculated as follows:

$$K_{I_C} = \frac{PL}{\sqrt{1-V^2}\ \sqrt{B\ Bn}\ \ W\ 3/2}\left[34.7\left(\frac{a}{W}\right) - 55.2\left(\frac{a}{W}\right)^2 + 196\left(\frac{a}{W}\right)^3\right]^{1/2}$$

where
- P = Bending load in pounds
- L = 1/2 (major less minor span) in inches
- V = Poisson's ratio = .3
- B = Specimen width
- B_N = Net section width after side notching
- W = Specimen thickness
- a = Measured crack depth

The net section stress, σ_N, was determined from the formula:

$$\sigma_N = \frac{3\ PL}{\sqrt{B\ B_N}\ (W-a)^2} \quad \text{expressed in ksi}$$

The plastic zone size, r_y, was calculated as follows:

$$r_y = \frac{1}{2\pi} \left(\frac{K_{I_C}}{\sigma_y} \right)^2 \quad \text{expressed in inches}$$

where σ_y = the yield stress in pounds per in^2.

Verification of Test Results

Examination revealed that the fracture of some specimens was accompanied by the formation of shear lips on the specimen sides. The ductile fracture surfaces were more prevalent in welds fusion zones which had lower than 200 ksi yield strength. Acoustic detection of the crack front propagation and the corresponding correlation with the load-deflection curves further suggested that yielding might be preceding the pop-in in the testing of some of the specimens.

The load deflection curve of a moderately tough (K_{I_C} = 113 ksi $\sqrt{In.}$) weld sample is depicted in Figure 4. The specimen was smooth sided. Yielding is apparent at 8200 lb on the graph and pop-in at 8600 lb load. Final fracture occurred at 8840 lb after considerable yielding and crack propagation.

The load deflection test curve of a high toughness weld, K_{I_C} = 132 ksi $\sqrt{In.}$ is shown in Figure 5. The specimen was provided with side notches. The side notches were added after fatigue cracking in order to avoid propagation of the fatigue crack through the side notches. No cracking was detected acoustically before 9200 lb load when pop-in and complete fracture occurred. No yielding was evident from the load-deflection curve. Figure 6A shows the desired plane strain fracture of a side notched specimen. Figure 6B illustrates the shear lips prevalent in the fracture of smooth sided specimens of high fracture toughness.

A few tests of very high fracture toughness yielded slightly before pop-in, even though the specimens were side notched. Figure 7 illustrates the load-deflection curve of a test representative of this response. The test was on a weld specimen from TIG hot wire-low deposition rate weldment. K_{I_C} for this test was 142 ksi $\sqrt{In.}$

Acoustic detection of side notched specimens would begin to record minor crack events at approximately 85% of pop-in load. Several heat-affected-zone specimens with the notch partially in weld metal had threshold acoustic indications at a lower load, characteristic of weld metal.

A comparison of K_{I_C} values on TIG calibration specimens tested with (panel 1187-98) and without (panels 1187-45 and 1187-31-3) side notches revealed that the plasticity effects encountered had an influence on the test results. A difference of 7 ksi $\sqrt{In.}$ was observed in average K_{I_C} values, between the smooth and the side notched specimens (panels 2714 and 8-2714).

Surface Crack Tensile Testing

Specimen Geometry and Preparation

Specimen geometry was determined by available plate thickness and the following boundary conditions according to Stawley and Brown[1]:

Specimen Thickness	B = Nominal plate section
Width	$W \geq 6B$
Crack Depth	$a < B/2$
Crack Length	$2c < W/3$

Test specimens were finish machined with a minimum of stock removed from the test plate surfaces to insure flatness. Specimens were then heat treated according to schedules appropriate for the type of material. The weld area was polished and etched to locate an Elox slot in the desired weld structure. The Elox slot, 0.060 inch in depth and length and 0.020 inch wide was introduced as a crack starter. A fatigue crack was propagated from the Elox slot by flexing the specimen in an Ivy fatigue testing machine. Crack propagation was terminated when the crack length at the surface approached one-third of the specimen width as determined with a micrometer microscope. Width and thickness in the plane of the fatigue crack were measured prior to testing.

The large Mar-age material specimens (Figure 8) were tested in an 800,000 lb tensile testing machine. The smaller D6AC specimens (Figure 9) were tested in a 200,000 lb machine. All testing was augmented by acoustic crack detection apparatus. The acoustic transducer was attached to the specimen under test and the output tape recorded simultaneously with load increment signals. Initial crack growth (pop-in) was determined from the analysis of acoustic recordings and load-strain curves.

All 0.375" thick D6AC specimens gave pop-in indications and fractured immediately afterward at the ultimate load values.

When testing was attempted with the 0.625" thick Mar-age specimens, general yielding of the specimen would occur. The load would drop off and build up again. Fracture occurred in all instances after the initial drop-in load (yield point). Pop-in occurred a fraction of a second before complete fracture at substantially the ultimate load. As very little confidence could be placed upon test data from these specimens, further testing of Mar-age surface flaw tensile specimens was discontinued.

Calculation of Fracture Toughness

The plane strain fracture toughness parameter K_{1c} is calculated as follows:

$$K_{1c} = \sigma_o \left[\frac{3.77\ a}{\int_o^{\frac{\pi}{2}} \sqrt{1-\left(\frac{c^2-a^2}{c^2}\right)\sin\theta}\, d\theta \ -0.212 \left[\frac{\sigma_o}{\sigma_y}\right]^2} \right]^{1/2}$$

where σ = Gross fracture stress as ksi

a = Crack Depth in inches

$2c$ = Crack length in inches

σ_y = Yield stress as ksi

and K_{1c} is expressed as KSI $\sqrt{in.}$

Discussion

Fracture toughness testing was undertaken at the start of this project in line with accepted practices as recommended by ASTM. The problem associated with fracture toughness testing of very tough, high strength materials is to provide sufficient specimen size to avoid plastic flow in the specimen and maintain conditions of plane strain. The presence of large shear lips on the side of the slow bend tests (Figure 6B) led to a re-examination of testing procedures. In an effort to suppress the shear lips and maintain plane strain through the fracture path, side notches were added to the specimen (Figure 6A). Shear lips were virtually eliminated and pop-in was observed in the linear elastic portion of the load deflection curve. With refined welding procedures, the Linde Laboratories furnished weld tests with significantly improved fracture toughness and even side notched slow bend bars were occasionally observed to yield. It was necessary to side notch[2] after fatigue cracking in order to avoid a secondary fatigue crack protagating from the side notches.

A few experimental slow bend tests were fatigue cracked to half the specimen depth. While test performance is improved, many welded specimens will have an irregular fatigue crack due to the crack following variations in weld structure.

Valid fracture toughness tests depend upon a section thickness "B" relative to the material yield strength σ_y and plane strain stress intensity factor K_{1c} as follows:

$$B = 2.5 \left(\frac{K_{1c}}{\sigma_y} \right)^2$$

Thus for material yield stress of 180 ksi and K_{1c} of 140 ksi $\sqrt{in}$, the recommended section thickness is 1.5 inches. It is well established that toughness of a given material decreases with increasing section and the date reported for a section thickness valid for K_{1c} determination may not be meaningful for thinner section rocket motor cases.

The problems encountered in fracture toughness testing of very tough, high strength materials in this program were reviewed in March 1967 by Air Force, Linde and Curtiss-Wright engineers along with R. Stout of Lehigh University as a consultant. Since the primary objective of this work was to evaluate the TIG Hot Wire welding process, all subsequent fracture toughness testing would be confined to notch-slow-bend tests in one inch thick material. The latest recommended practices for fracture toughness testing were issued at this time by the ASTM. Testing procedures evolved at Curtiss-Wright are generally in conformance except for specimen thickness which is governed by plate section. In other respects Curtiss-Wright procedures incorporating side notches, and acoustic crack detection would provide more reliable data from specimen with less than optimum thickness.

Notch-Slow Bend specimens were prepared from 1" thick 9Ni-4Co panels welded by the Linde Laboratory. Fracture toughness, Klc of the base material was 154 KSI $\sqrt{in.}$ Although the net stress at fracture σ_n, was slightly greater than the yield strength σ_y, yielding was suppressed by 10% side notches in the specimen. All 1" thick side-notched specimens broke in the linear elastic portion of the load-deflection curve.

Tests from 9Ni - 4Co welds had moderately higher fracture toughness from 157 to 192 KSI $\sqrt{in.}$ All welded 9Ni - 4Co specimens had a tendency for the fatigue crack to propagate deeper in preferred weld passes. The minimum depth of the fatigue crack would be in those weld passes one-third of the section up from the weld root. In testing, fracture was considered to have started from the minimum depth of the crack as that area would be subjected to the highest stress. Fracture toughness calculations based on this assumption would result in the lowest values for Klc and are so reported.

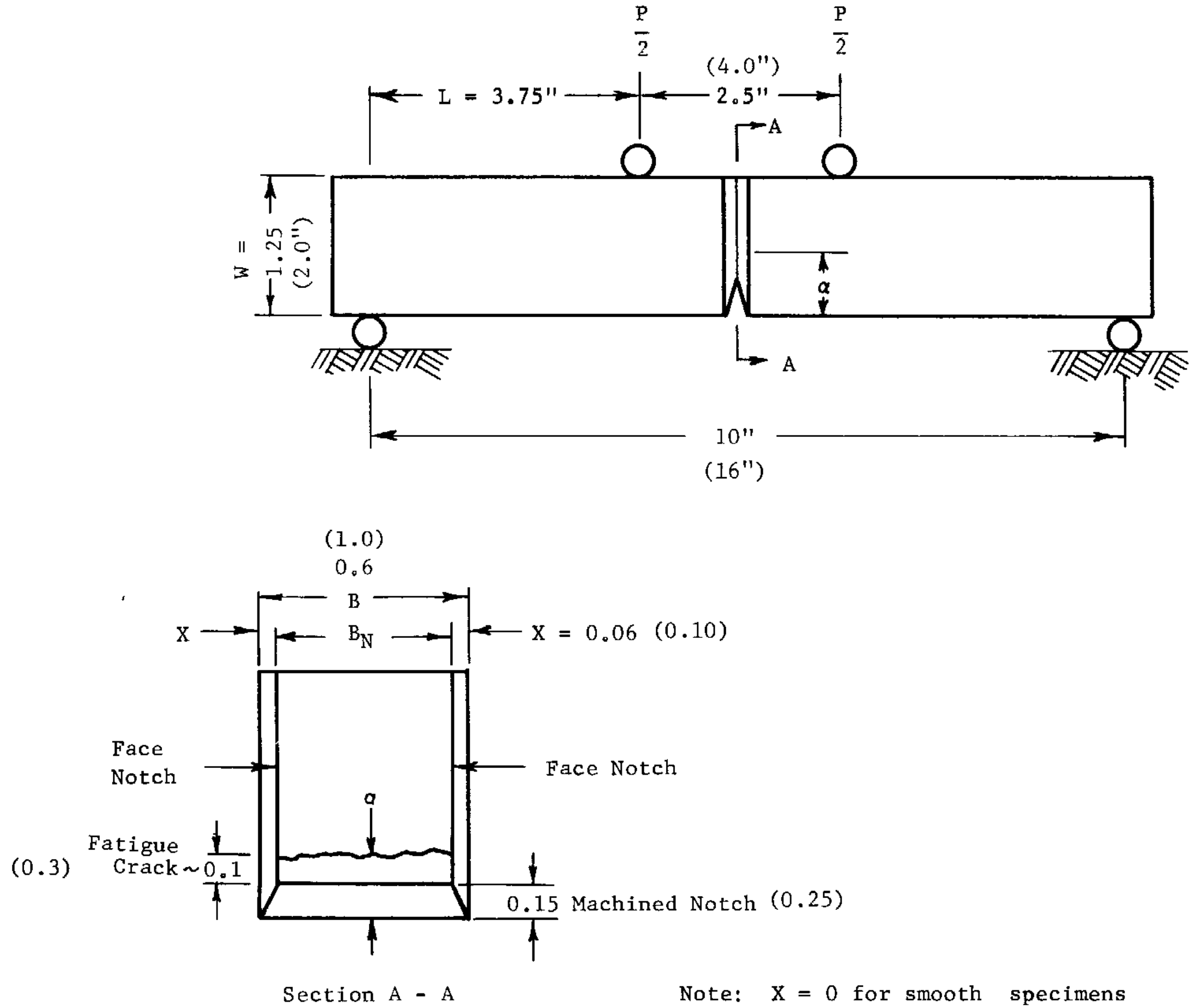
Companion tests in 9Ni - 4Co base material and 18 Ni mar-age welds prepared and tested at the same time and under identical conditions had normal fatigue cracks and fracture surfaces.

The fracture surface of all 9Ni - 4Co welded specimens were very rough and strongly influenced by effects of multi-pass welding, a typical example is shown in figure 10. The macro features of the fracture surface correspond to the dentritic structure in the weld.

References

1. "Fracture Toughness Testing". Srawley and Brown ASTM STP 381

2. "Effect of Face Notches on Slow-Bend K_{1c} Fracture Toughness Testing" No. 37.018-011 (1) Rolfe and Novak U.S. Steel Applied Research Lab.



Note: X = 0 for smooth specimens

Figures in Parentheses are for 1" Thick Specimens

FIGURE 1

K_{IC} SLOW-BEND TEST SPECIMEN

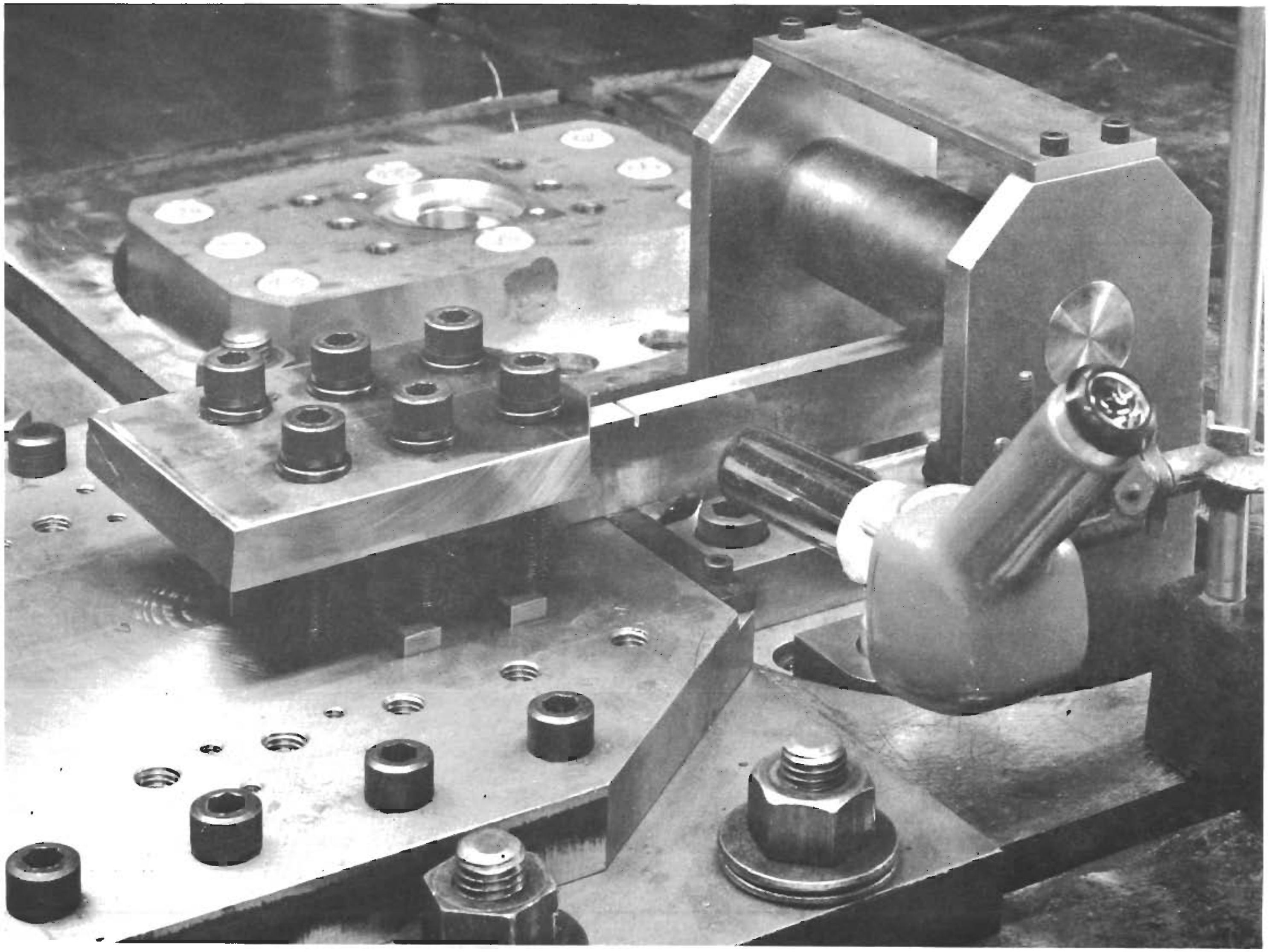


FIGURE 2

FATIGUE CRACK INITIATION FIXTURE

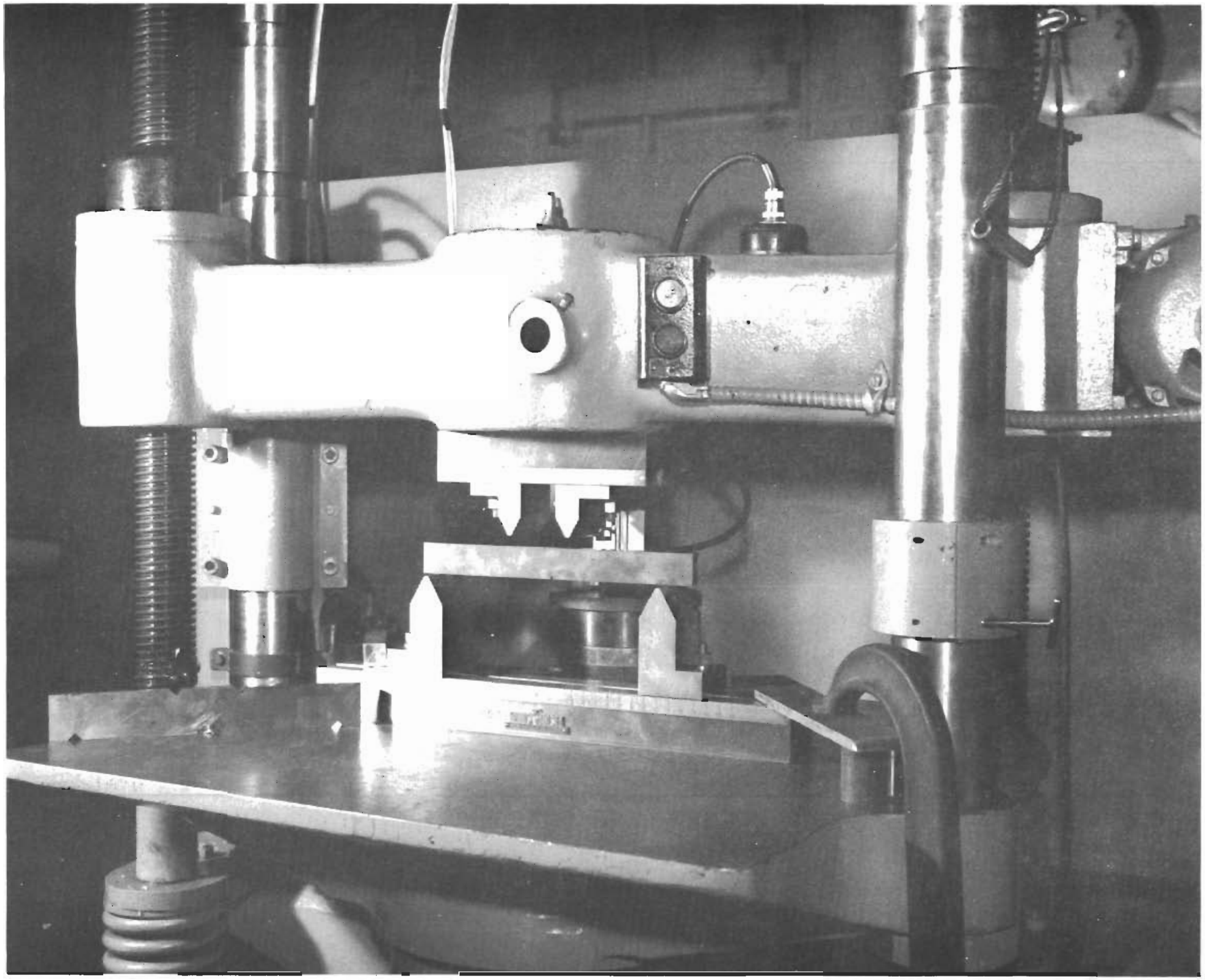


FIGURE 3

FRACTURE TOUGHNESS LOADING FIXTURE

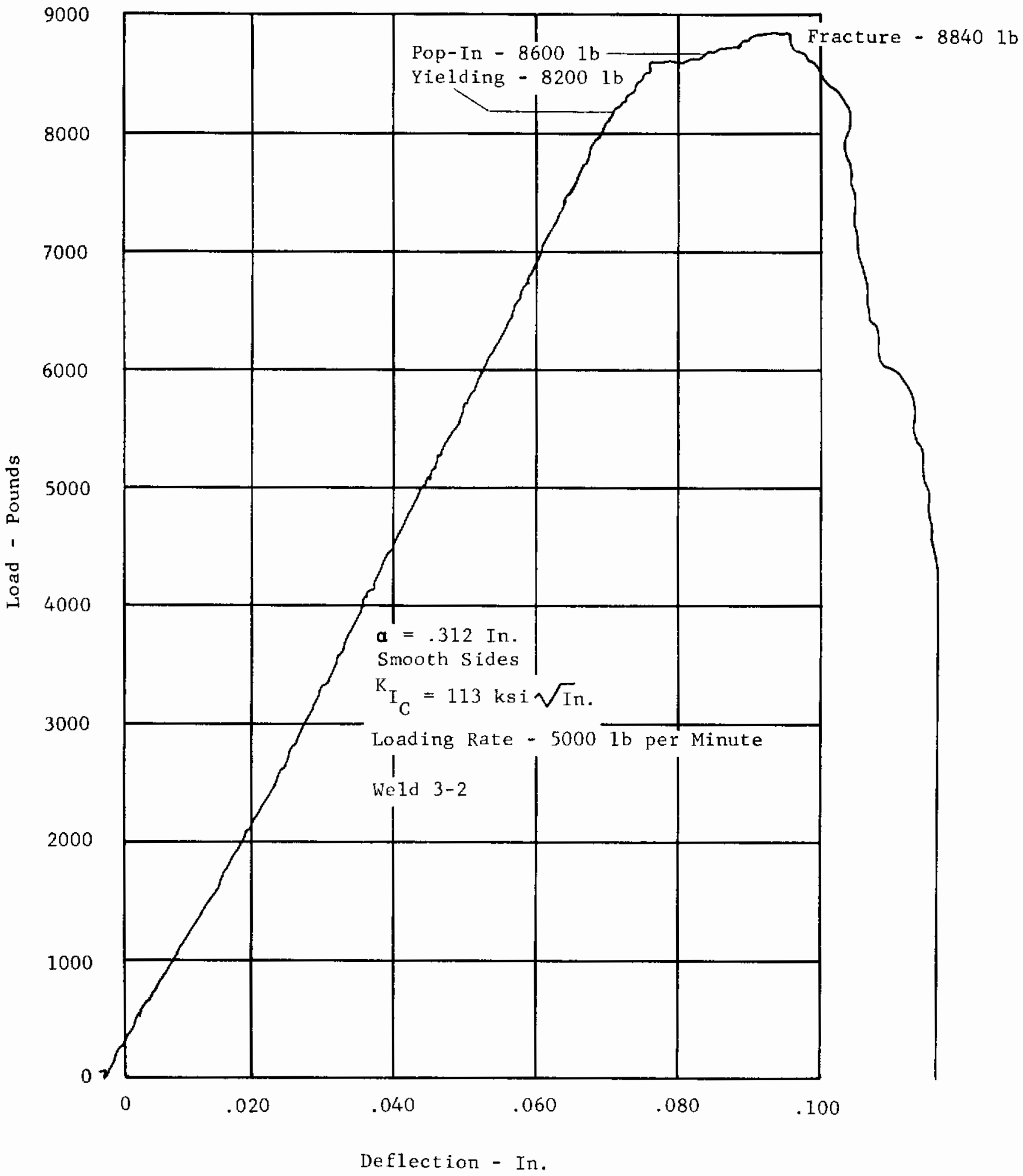


FIGURE 4

LOAD-DEFLECTION CURVE OF MODERATELY TOUGH WELD SPECIMEN, SMOOTH SIDES

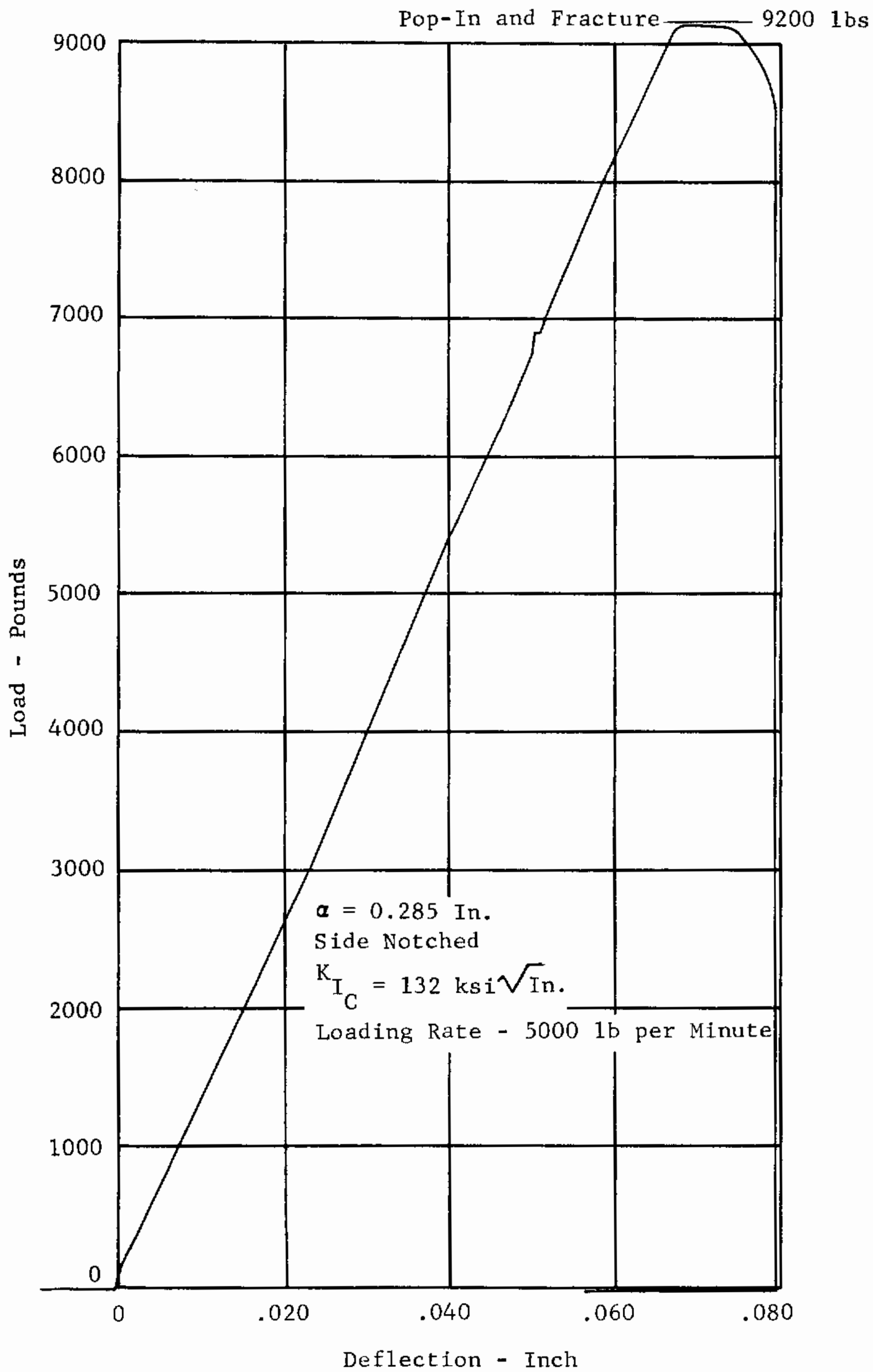


FIGURE 5

DEFLECTOMETER RECORD OF HIGH TOUGHNESS SIDE NOTCHED SPECIMEN

FIGURE 6

FRACTURE FACES OF SIDE NOTCHED AND SMOOTH NOTCH SLOW BEND FRACTURE TOUGHNESS SPECIMENS

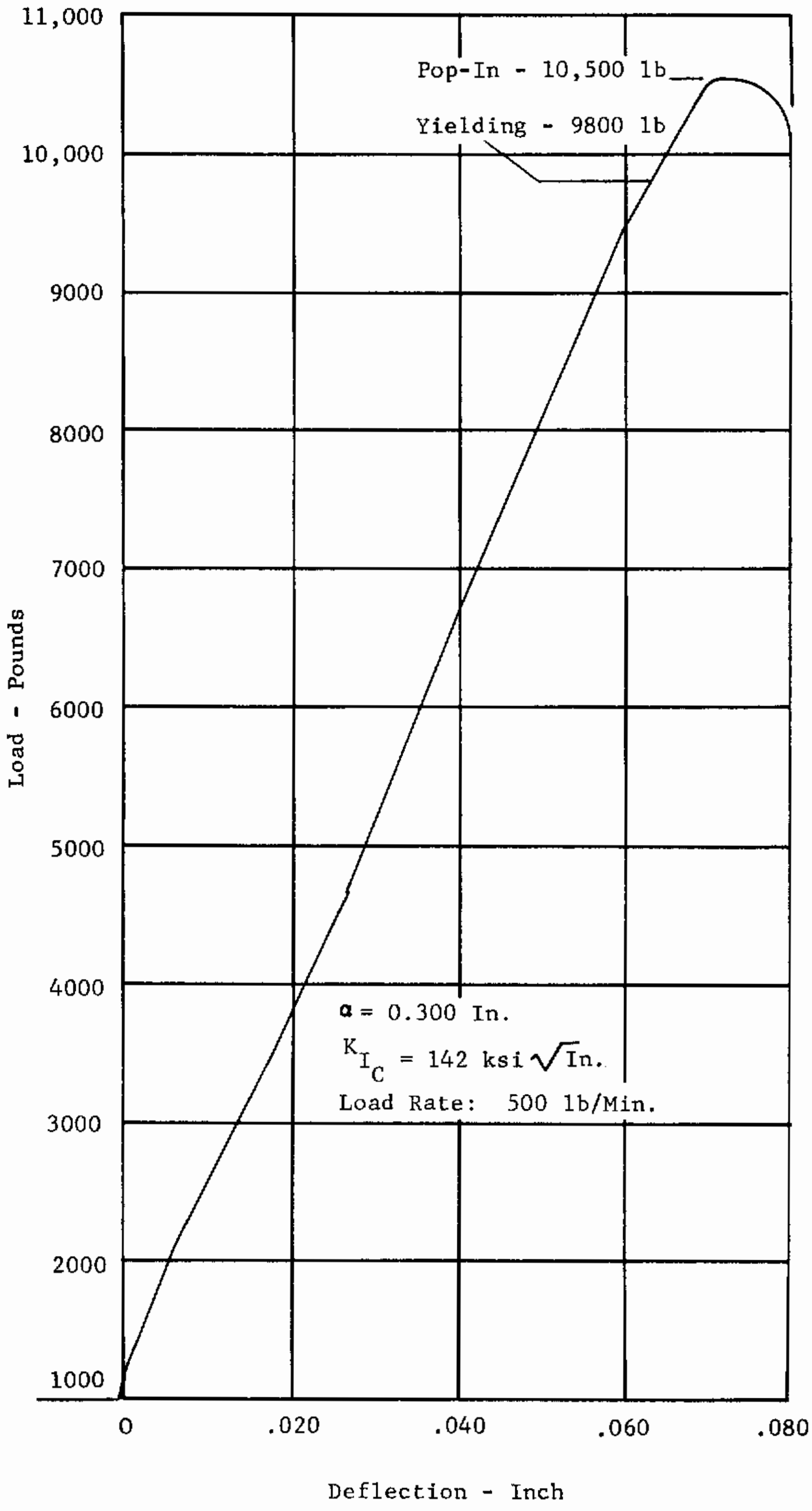
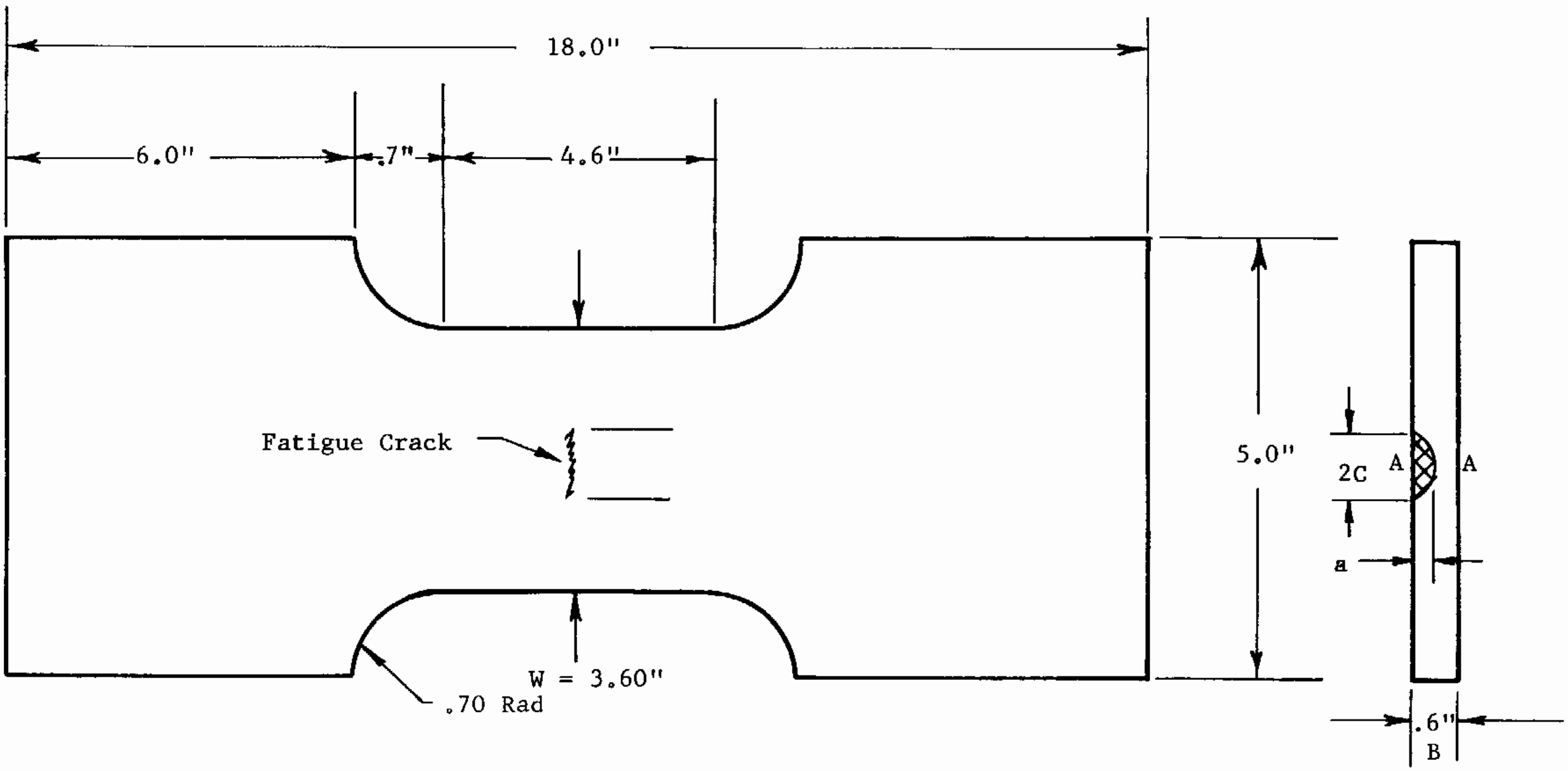


FIGURE 7

DEFLECTOMETER RECORD OF VERY TOUGH WELD SPECIMEN
WITH EVIDENCE OF YIELDING NOT SUPPRESSED BY SIDE NOTCHES



Note: 1. Flat surfaces to be machined to remove warping and/or weld metal.

2. All grinding on flat surfaces "A" to be parallel to centerline and gage section.

3. On weld specimens weld must be perpendicular to ℄ ± .005".

Tolerances = ± .01

FIGURE 8

SURFACE FLAW TENSILE SPECIMEN

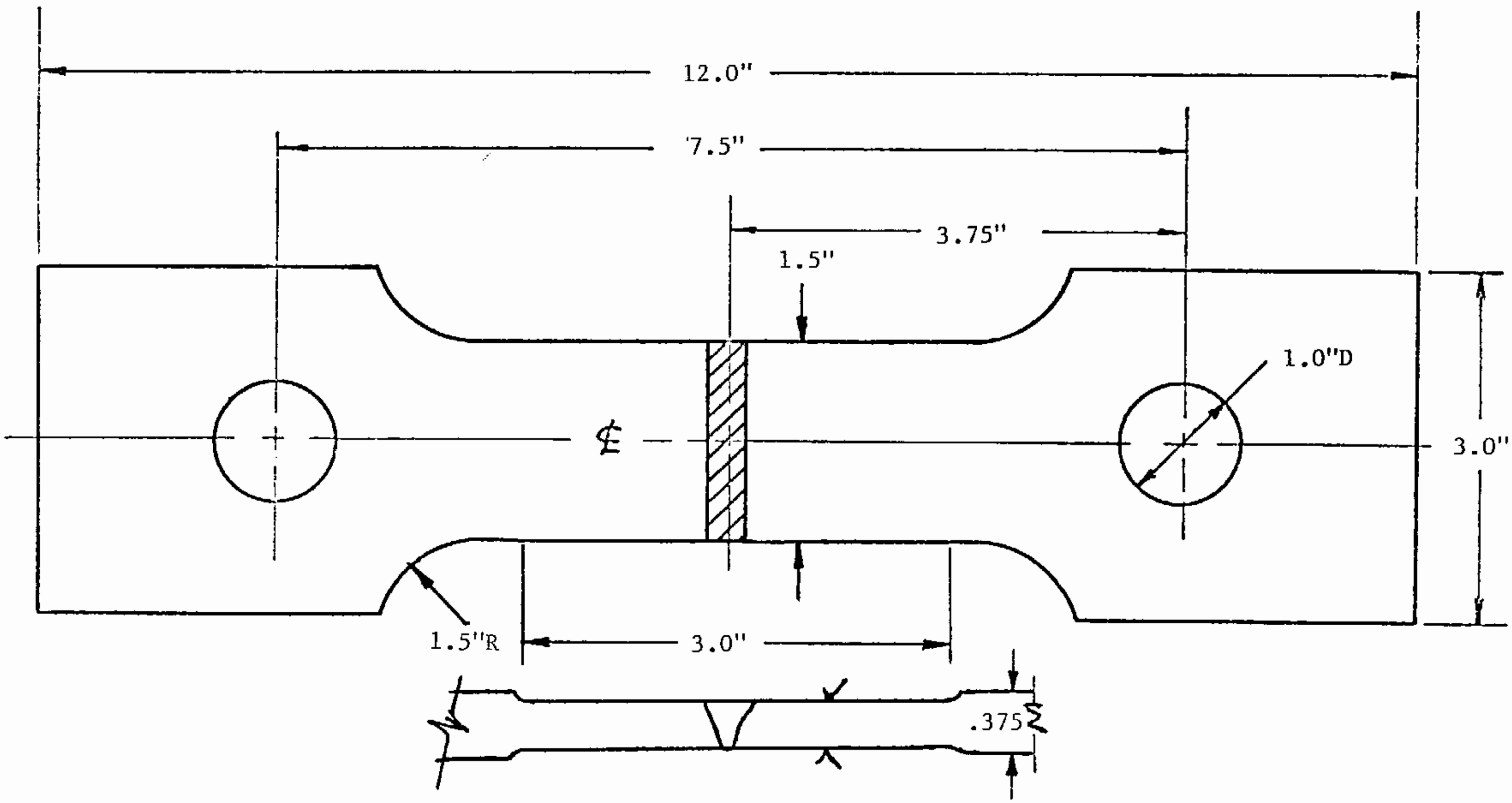


FIGURE 9

SURFACE FLAW TENSILE SPECIMEN

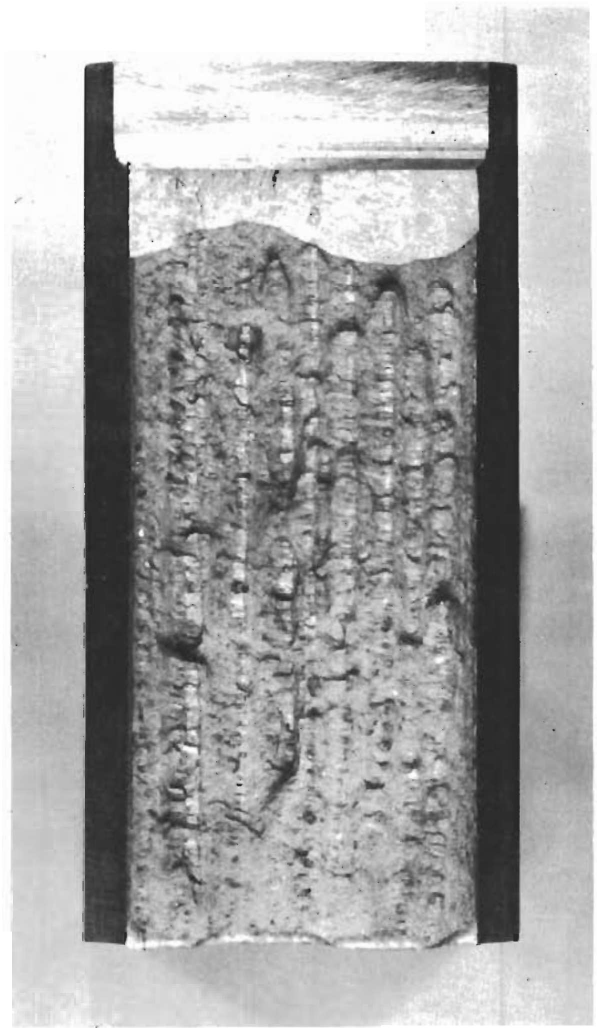


FIGURE 10

TYPICAL NOTCH SLOW BEND TEST IN 9 NI-4 CO WELD

TABLE I

NOTCH-SLOW BEND FRACTURE TESTS - PARENT METAL

Specimen Identification	Type Weld	Notch Location	Heat Treatment	B Inches	Bn Inches	a Inches	P Pounds	K_{I_C} ksi$\sqrt{In.}$	σ_n ksi	$\sigma n/\sigma y$	r_y Inches	y ksi	NOTES
2714 -1	None	Parent M.	3H-900°F	.6	.6	.297	11360	151	170	.78	.078	217	(1)
-2	None	Parent M.	3H-900°F	.6	.6	.273	11100	139	159	.73	.065	217	(1)
-3	None	Parent M.	3H-900°F	.6	.6	.275	10940	138	157	.72	.064	217	(1)
-4	None	Parent M.	3H-900°F	.6	.6	.275	10780	136	155	.71	.063	217	(1)
-5	None	Parent M.	3H-900°F	.6	.6	.275	11140	140	159	.73	.066	217	(1)
-6	None	Parent M.	3H-900°F	.6	.6	.281	10820	137	158	.73	.063	217	(1)
-7	None	Parent M.	3H-900°F	.6	.6	.278	10800	136	157	.72	.066	217	(1)
-8	None	Parent M.	3H-900°F	.6	.6	.277	11030	139/140	159	.73	.065	217	(1)
8-2714- -1	None	Parent M.	3H-900°F	.6	.480	.288	9340	144	154	.71	.070	217	(3)
-2	None	Parent M.	3H-900°F	.6	.480	.288	9560	147	159	.73	.073	217	(3)
-3	None	Parent M.	3H-900°F	.6	.480	.276	9690	146	156	.72	.072	217	(3)
-4	None	Parent M.	3H-900°F	.6	.480	.267	10215	151/147	154	.71	.077	217	(3)
6-2714-8 -1	None	Parent M.	8H-900°F	.6	.6	.278	11100	140	161				(1)
-2	None	Parent M.	8H-900°F	.6	.6	.274	10880	137	156				(1)
-3	None	Parent M.	8H-900°F	.6	.6	.281	10480	133/137	153				(1)
6-2714-8A-1	None	Parent M.	Ann. + 8H-900°F	.6	.6	.275	11140	140	159				(1)
-2	None	Parent M.	Ann. + 8H-900°F	.6	.6	.274	11140	140	160				(1)
-3	None	Parent M.	Ann. + 8H-900°F	.6	.6	.280	11200	141/140	162				(1)
6-2714-3A-1	None	Parent M.	Ann. + 3H-900°F	.6	.6	.275	11950	151	171				(1)
-2	None	Parent M.	Ann. ± 3H-900°F	.6	.6	.284	11830	153/152	173				(1)

TABLE II

NOTCH-SLOW BEND FRACTURE TOUGHNESS TESTS ON WELDMENTS

Specimen Identification	Type Weld	Notch Location	Heat Treatment	B Inches	Bn Inches	a Inches	P Pounds	K_{I_C} ksi$\sqrt{\text{In.}}$	σ_n ksi	σ_n/σ_y	r_y Inches	σ_y ksi	NOTES
1187-31-8-1	GTA	Weld	8H-900°F	.6	.6	.330	9100	129	145				(1)
-2	GTA	Weld	8H-900°F	.6	.6	.321	8720	119	141				(1)
								124					
1187-31-3-1	GTA	Weld	3H-900°F	.6	.6	.320	9950	136	161	.79	.070	205	(1)
-2	GTA	Weld	3H-900°F	.6	.6	.308	10,300	139	159	.78	.073	205	(1)
								138					
1187-31-8-1	GTA	HAZ	8H-900°F	.6	.6	.274	9450	141	(135)				(1)
-2	GTA	HAZ	8H-900°F	.6	.6	.298	11,200	147	169				(1)
								144					
1187-31-3-1	GTA	HAZ	3H-900°F	.6	.6	.303	10,750	147	164				(1)
1187-32-8-1	Hot Wire	Weld	8H-900°F	.6	.6	.329	7340	102	116				(1)
-2	Hog	Weld	8H-900°F	.6	.6	.315	8000	110	125				(1)
	Trough							106					
1187-32-3-1	Hot Wire	Weld	3H-900°F	.6	.6	.297	8830	115	134	.57	.052	202	(1)
-2	Hog	Weld	3H-900°F	.6	.6	.312	8300	113	128	.56	.049	202	(1)
	Trough							114					
1187-32-8-1	Hot Wire	HAZ	8H-900°F	.6	.6	.290	8840	114	130				(1)
-2	Hog	HAZ	8H-900°F	.6	.6	.296	9450	123	141				(1)
								119					
1187-32-3-1	Hot Wire	HAZ	3H-900°F	.6	.6	.300	10,370	137	156				(1)
-2	Hog	HAZ	3H-900°F	.6	.6	.307	10,030	134	159				(1)
	Trough							136					

TABLE II CONT'D

Specimen Identification	Type Weld	Notch Location	Heat Treatment	B Inches	Bn Inches	a Inches	P Pounds	K_{I_C} ksi$\sqrt{In.}$	σ_n ksi	σ_n/σ_y	r_y Inches	σ_y ksi	NOTES
1187-45-1 -A	GTA	Weld	3H-900°F	.6	.6	.291	10,570	138	156	.76	.071	205	(1), (2)
-B	GTA	Weld	3H-900°F	.6	.6	.306	10,100	135	156	.76	.069	205	(1), (2)
-C	GTA	Weld	3H-900°F	.6	.6	.300	9580	126	145	.71	.060	205	(2)
								133					
1187-45-1 -D	GTA	HAZ	3H-900°F	.6	.6	.303	10,250	136	156				(1), (2)
-E	GTA	HAZ	3H-900°F	.6	.6	.285	11,250	145	165				(1), (2)
-F	GTA	HAZ	3H-900°F	.6	.6	.294	11,650	152	174				(2)
								144					
1187-92-1 -D	Hot Wire	Weld	3H-900°F	.6	.480	.288	8180	119	136	.72	.082	189	(2), (3)
-E	Hot Wire	Weld	3H-900°F	.6	.480	.285	8460	122	139	.74	.086	189	(2), (3)
-F	Hot Wire	Weld	3H-900°F	.6	.480	.282	8080	117	133	.71	.079	189	(3)
								119					
1187-92-1 -A	Hot Wire	HAZ	3H-900°F	.6	.480	.297	9240	137	155				(2), (3)
-B	Hot Wire	HAZ	3H-900°F	.6	.480	.270	9220	(129)	(147)				(2), (6), (3)
-C	Hot Wire	HAZ	3H-900°F	.6	.480	.300	9200	137	156				(3)
								137					
1187-92-1C-A	Hot Wire	Weld Cosmetic	3H-900°F	.6	.480	.282	8310	120	136	.72	.065	189	(2), (3)
-C	Hot Wire	Weld Pass	3H-900°F	.6	.480	.300	8140	122	137	.73	.066	189	(2), (3)
-D	Hot Wire	Weld Added	3H-900°F	.6	.480	.285	8470	122	138	.73	.066	189	(2), (3)
								121					
1187-92-1C-B	Hot Wire	HAZ Cosmetic	3H-900°F	.6	.480	.285	10,560	153	173				(4), (3)
-E	Hot Wire	HAZ Pass	3H-900°F	.6	.480	.288	10,060	161	183				(4), (3)
-F	Hot Wire	HAZ Added	3H-900°F	.6	.480	.294	10,560	156	177				(4), (3)
								157					

TABLE II CONT'D

Specimen Identification		Type Weld	Notch Location		Heat Treatment	B Inches	Bn Inches	a Inches	P Pounds	K_{I_C} ksi$\sqrt{In.}$	σ_n ksi	$\sigma n/\sigma y$	r_y Inches	σy ksi	NOTES
1187-98-1-B		GTA	Weld		3H-900°F	.6	.480	.285	9120	132	150	.79	.078	189	(3)
-C		GTA	Weld		3H-900°F	.6	.480	.300	9640	143	161	.85	.091	189	(3)
-D		GTA	Weld		3H-900°F	.6	.480	.294	9300	137	156	.83	.084	189	(3)
										137					
1187-98-1-A		GTA	HAZ		3H-900°F	.6	.480	.294	9500	140	159	.73	.066	217	(5), (3)
1187-99	-D	Hot Wire	Weld		3H-900°F	.6	.480	.282	8340	121	137	.72	.065	189	(2), (3)
	-E	Horiz.	Weld		3H-900°F	.6	.480	.309	8100	124	141	.75	.068	189	
	-F	Pos.	Weld		3H-900°F	.6	.480	.300	8740	130	147	.78	.075	189	(2), (3)
										125					
1187-99	-A	Hot Wire	HAZ	Horiz.	3H-900°F	.6	.480	.300	9340	139	158	.73	.065	217	(5), (3)
	-B	Hot Wire	HAZ	Pos.	3H-900°F	.6	.480	.285	9710	140	159	.73	.066	217	(2), (5),(3)
	-C	Hot Wire	HAZ		3H-900°F	.6	.480	.294	9960	147	166	.76	.074	217	(4), (5),(3)
										142					
40-37	BB	Plasma	Weld		3H-900°F	.6	.480	.294	7800	115	131	.65	.052	201	(2), (3)
	D	Hot Wire	Weld		3H-900°F	.6	.480	.297	7980	118	133	.66	.054	201	(2), (3)
	C		Weld		3H-900°F	.6	.480	.300	7800	117	132	.66	.054	201	(2), (3)
										117					
40-37	AA	Plasma	HAZ		3H-900°F	.6	.480	.282	10,800	156	177	.81	.083	217	(5), (3)
	B	Hot Wire	HAZ		3H-900°F	.6	.480	.288	10,800	157	179	.82	.083	217	(3)
	A		HAZ		3H-900°F	.6	.480	.291	10,340	152	173	.80	.078	217	(3)
										155					

NOTES:
(1) Fatigue cracked before heat treatment.
(2) Acoustic detection apparatus used to determine pop-in.
(3) Side notched specimens.
(4) Yielding evident before pop-in.
(5) Yield stress estimated.
(6) Fracture diverted to weld porosity.

TABLE III

SURFACE FLAW TENSILE TESTS - 0.375-IN. THICK D-6ac STEEL

Specimen Identification	Type Weld	Crack Location	B Inches	W Inches	a Inches	2c Inches	P Pounds	σ_n ksi	σ_y ksi	K_{IC} ksi $\sqrt{In}$	NOTES
Base 1	None	Parent	.377	1.500	.150	.403	105.400	186.0	191.0	108	(8)
2	None	Parent	.383	1.500	.154	.395	105.900	183.8	191.0	106	
88-56-1	GTA Cold Wire	Weld Face	.350	1.500	.163	.482	91.000	173.5	175.0	109	(11)
-2	2 lbs/hr	Weld Face	.357	1.500	.163	.442	94.600	176.5	175.0	108	
88-56-1		Weld Root	.353	1.500	.138	.378	95.800	181.0	175.0	101	
-2		Weld Root	.357	1.495	.146	.412	94.600	177.5	175.0	104	
88-56-1		HAZ	.347	1.500	.158	.437	90.600	174.3	191.0	104	
-2		HAZ	.345	1.500	.150	.398	92.200	177.8	191.0	102	
88-60-1	TIG - Hot Wire	Weld Face	.351	1.505	.163	.429	92.000	174.2	172.0	105	
88-60-1	8 lbs/hr	Weld Root	.362	1.505	.150	.425	96.600	177.4	172.0	106	
-2		Weld Root	.364	1.507	.146	.399	98.000	178.4	172.0	104	
88-60-2		HAZ	.358	1.504	.146	.373	97.600	181.0	191.0	101	
88-61-1	TIG - Hot Wire	Weld Face	.356	1.508	.142	.378	94.000	175.2	175.0	101	
-2	5 lbs/hr	Weld Face	.360	1.501	.150	.403	94.700	175.2	175.0	102	
88-61-1		Weld Root	.360	1.503	.150	.398	95.400	176.2	175.0	101	(10) (11)
-2		Weld Root	.354	1.498	.163	.482	86.000	162.2	175.0	101	
88-61-1		HAZ	.341	1.505	.158	.463	89.300	174.0	191.0	106	
-2		HAZ	.352	1.505	.150	.386	95.000	179.2	191.0	102	(11)
88-62-1	TIG - Hot Wire	Weld Face	.347	1.503	.146	.386	92.600	177.5	178.0	104	
-2	2 lbs/hr	Weld Face	.340	1.501	.155	.412	90.800	178.0	178.0	104	
88-62-1		Weld Root	.348	1.508	.137	.374	95.100	181.0	178.0	102	
-2		Weld Root	.360	1.508	.150	.386	95.700	176.5	178.0	101	
88-62-1		HAZ	.354	1.507	.146	.395	96.800	182.0	191.0	104	
-2		HAZ	.357	1.507	.146	.403	96.300	179.0	191.0	104	

TABLE IV

NOTCH-SLOW BEND FRACTURE TOUGHNESS TESTS
1.0-IN. THICK 18 NI MARAGING STEEL

Specimen Identification	Type Weld	Notch Location	Heat Treatment	B Inches	Bn Inches	W Inches	a Inches	P Pounds	σ_n ksi	σ_y ksi	K_{IC} ksi $\sqrt{IN.}$	NOTES
HT No.	None	Parent	900° - 3H	.934	.734	2.005	.547	18300	153	203	125	(3)
50234	None	Parent	900° - 3H	.881	.672	2.002	.531	17550	157	203	126	(3)
88-64	Hot - Wire	Weld	900° - 3H	.954	.734	2.004	.547	20650	175	194	141	(3)
88-65	Hot - Wire	Weld	900° - 3H	.933	.723	2.006	.539	21800	184	192	146	(3)
88-66	Hot - Wire	Weld	900° - 3H	1.000	.805	1.992	.652	18500	172	195	133	(3)
88-69	Hot - Wire	Weld	900° - 3H	.918	.711	2.006	.422	23300	171	194	132	(3)
88-92	GTA Cold Wire	Weld	900° - 3H	.962	.762	2.005	.484	23350	176	195	142	(3)
88-92		Weld	900° - 3H	.980	.781	2.008	.578	21550	178	195	143	(3)
88-92		HAZ	900° - 3H	.954	.738	2.012	.567	20950	180	203	144	(3) (5)
88-92		HAZ	900° - 3H	.956	.766	2.008	.652	18900	180	203	142	(3) (5)
88-93	Hot - Wire	Weld	900° - 3H	.975	.766	2.000	.520	24800	206	196	157	(3)
88-93	3 lbs/hr	Weld	900° - 3H	.955	.758	2.000	.508	24400	206	196	155	(3)
88-93		HAZ	900° - 3H	.922	.719	2.006	.484	22100	176	203	142	(3) (5)
88-93		HAZ	900° - 3H	.955	.738	2.001	.527	22950	178	203	150	(3) (5)
88-96	Hot - Wire	Weld	900° - 3H	.903	.692	2.003	.609	18700	182	197	144	(3)
88-96	5 lbs/hr	Weld	900° - 3H	.900	.688	2.010	.586	18900	156	197	142	(3)
88-96		HAZ	900° - 3H	.925	.723	2.020	.453	22200	165	203	134	(3) (5)
88-96		HAZ		.950	.742	2.013	.496	21000	163	203	132	(3) (5)
88-97	TIG -	Weld	900° - 3H	.908	.715	2.005	.668	17950	178	198	146	(3)
88-97	Hot - Wire	Weld		.962	.759	2.010	.625	20650	188	198	150	(3)
88-97	7.6 lbs/hr	HAZ	900° - 3H	.965	.754	2.008	.488	23100	175	203	141	(3) (5)
88-97		HAZ	900° - 3H	.942	.742	2.008	.551	20750	175	203	140	(3) (5)

TABLE V

NOTCH-SLOW BEND FRACTURE TOUGHNESS TESTS 0.625-IN. THICK 18 NI MARAGING STEEL

Specimen Identification	Type Weld	Notch Location	Heat Treatment	B Inches	Bn Inches	W Inches	a Inches	P Pounds	σ_n ksi	σ_y ksi	K_{IC} ksi $\sqrt{in}$	NOTES
Base 1	None	Parent	900° - 3H	.646	.526	1.250	.672	4820	125	219	134	(3) (7) (9)
Base 2	None	Parent	900° - 3H	.650	.530	1.250	.688	4920	126	219	140	(3) (7) (9)
88-94	Hot-Wire	Weld	900° - 3H	.602	.488	1.200	.474	7500	183	197	128	(3)
88-94		Weld	900° - 3H	.600	.477	1.200	.366	8410	193	197	131	(3)
	5 lbs/hr											
88-94		HAZ	900° - 3H	.603	.489	1.198	.396	9080	209	219	133	(3)
88-94		HAZ	900° - 3H	.594	.474	1.200	.351	8740	201	219	134	(3)
88-95	Hot Wire	Weld	900° - 3H	.600	.489	1.200	.411	7520	176	204	114	(3)
88-95		Weld	900° - 3H	.600	.483	1.200	.387	8060	187	204	117	(3)
88-95	7.6 lbs/hr	HAZ	900° - 3H	.600	.489	1.200	.333	9540	217	219	123	(3)
88-95		HAZ	900° - 3H	.611	.503	1.179	.453	7620	181	219	122	(3)

TABLES 1 to 6

NOTES:

1. Fatigue Cracked Before Heat-Treatment
2. Acoustic Detection Apparatus Used To Determine Pop-In
3. Side Notched Specimen
4. Yielding Evident Before Pop-In
5. Yield Stress Estimated
6. Fracture Path Diverted by Weld Porosity
7. Deep Fatigue Crack
8. Curtiss-Wright Plate No. 4301
9. Specimen Transverse to Normal Test
10. Secondary Fatigue Crack in Specimen
11. Irregular Fatigue Crack

TABLE VI

NOTCH-SLOW BEND FRACTURE TOUGHNESS TESTS
1.0-IN. THICK 9 NI-4 CO STEEL

Specimen Identification	Type Weld	Notch Location	Heat Treatment	B Inches	Bn Inches	W Inches	a Inches	P Pounds	σ_n ksi	σ_y ksi	K_{IC} ksi$\sqrt{In}$	NOTES
Base	None	Parent	None	.997	.775	2.002	.474	21730	189	175	153	(3)
Base	None	Parent	None	.998	.808	2.000	.465	27100	191	175	154	(3)
186-53	GTA	Weld	None	.998	.815	1.990	.432	26725	202	202	157	(3) (11)
186-53	1.6 lbs/hr	Weld	None	1.002	.804	1.993	.447	24400	203	202	161	(3) (11)
186-55	TIG-Hot Wire	Weld	None	1.000	.784	2.002	.390	25800	202	180	160	(3) (11)
186-55	7.6 lbs/hr	Weld	None	1.000	.815	1.998	.405	25550	202	180	157	(3) (11)
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13. ABSTRACT Reliable procedures were established for high deposition Tig welding of three high strength steels. However, the selection of welding procedures is a function of the metallurgical behavior of each weld metal.

Because a postweld quench and temper heat treatment homogenizes most structural variations, the properties of welds made in D-6ac are virtually independent of welding parameters.

Although the postweld maraging heat treatment of welds made in 18 Ni (VAR) steel makes the tensile properties independent of welding procedures, the fracture toughness of such welds can vary. Toughness is a function of the amount of grain refinement and thermal cycling achieved in multipass welds. By balancing filler deposition rates and welding heat input, pass size can be adjusted so fracture toughness of welds will be equivalent or superior to conventional Tig welds.

The as-welded tensile and impact properties of welds made in HP 9 Ni-4 Co-.20 C steel are very sensitive to welding conditions. Grain refinement and self-tempering must be maximized; yet the amount of ferrite in the microstructure must be minimized. Despite these restraints, high deposition welding procedures will develop weld metal properties equivalent to Tig welding.

The high deposition rate Tig-hot wire process should offer significant cost savings to aerospace fabricators.

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