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Part II

DEVELOPMENT OF WELDING PROCEDURES AND FILLER MATERIALS FOR JOINING HIGH STRENGTH LOW ALLOY STEELS

J. M. Faulkner,
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and J. V. Peck of
TRW Inc.

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AIR FORCE MATERIALS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICES

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FOREWORD

This report was prepared by Materials and Processes Department, TRW Equipment Laboratories, TRW Inc., under Contract No. AF 33(657)-11229. The contract was initiated under Project No. 7351, "Metallic Materials", Task No. 735102, "Welding and Brazing of Metals". The work was administered under the direction of the Air Force Materials Laboratory, Research and Technology Division, with Mr. R. E. Bowman, Project Engineer.

This report covers work conducted from June, 1964 to June, 1965. The investigation was conducted by J. M. Faulkner, Research Metallurgist, G. L. Hanna, Metallurgist, and J. V. Peck, Metallurgist, under the direction of J. M. Gerken, Research Supervisor. Acknowledgment is given to E. A. Steigerwald, Research Supervisor, for his consultation and guidance with regard to the selection and heat treatment of the materials and testing and evaluation, and to S.J. Matas, Republic Steel Corporation, for his assistance and recommendations on the heat treatment and processing of the HP 9-4-20 alloys.

The manuscript was released by the authors in August, 1965, for publication as an RTD technical report.

This technical documentary report has been reviewed and is approved.

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ABSTRACT

The object of this program was to develop welding procedures and filler materials for joining martensitic and bainitic steels in the 180 to 200 ksi yield strength range.

The martensitic steels studied were HP 9-4-20, HP 9-4-25, AMS 6435, Vasco Jet X-2, and D6AC. The HP 9-4-XX steels could be successfully joined using the gas tungsten-arc (TIG) process without a subsequent post-heat. Manual TIG welding could also be similarly accomplished in the HP 9-4-20 material. Reduced porosity and improved mechanical properties were obtained in weldments in the HP 9-4-20 steel by making additions of Ti and Al to filler wires of base metal composition. The D6AC steel was capable of producing TIG weld joints of acceptable strength, but a definite lack of ductility was present and porosity in the weld deposits occurred often. The AMS 6435 and Vasco Jet X-2 steels could not be successfully joined without a post-heat during this program.

The bainitic steels examined consisted of HP 9-4-45 1/2-inch plate and 0.090-inch sheet and D6AC 1/2-inch plate. In no instance did welds in the HP 9-4-45 steel plate yield tensile properties comparable to that of the parent metal. However, it was calculated that a 25 percent material build-up at the joint could insure failure in the parent metal. Acceptable strength could be obtained in the sheet material, but low ductility was also invariably present. The D6AC steel could be TIG welded to produce acceptable properties in the weld deposit; however, the heat-affected zones were weak. Additional studies could possibly lead to successful welding techniques for this material.

Heat-affected zone strength and toughness characteristics of D6AC and HP 9-4-45 were studied using a synthetic weld thermal cycle technique. Specimens were exposed to peak temperatures between 1000 and 2400°F. The lowest strengths were associated with peak temperatures of 1200 and 1350°F. In the D6AC steel exposed to peak temperatures between 1450 and 1850°F, very low fracture toughness was produced.

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I INTRODUCTION

Present day requirements in the fabrication of large cases for solid rocket boosters (up to 260 inches in diameter) have created a demand for weldable structural materials having high strength-to-weight ratios. While materials such as these are available, they generally depend on post-weld heat treatment to meet the desirable strength levels. When these large cases are fabricated by welding, they soon become of such size that post-weld heat treatment is no longer practical or economical. Therefore, a need exists for a construction material that can be welded in the heat treated condition with a resultant yield strength of 180 to 200 ksi and adequate fracture toughness. The overall purpose of this program is to select suitable structural materials and to develop welding procedures and filler materials that will fulfill this need and also be suitable for field welding assemblies such as large solid rocket booster cases. The weld yield strength joint efficiency should be greater than 95 percent with ductility and fracture toughness equivalent to the base metal.

II BACKGROUND

This program was divided into three phases, the first two each requiring 12 months and the third requiring 13 months for completion. The first phase was devoted to establishing welding procedures for TIG and MIG welding a low carbon martensitic steel and a low alloy bainitic steel using commercially available filler materials. The second phase, which is the subject of this report, is concerned with a continued evaluation of welding procedures on materials examined in the first year's work, evaluation of additional steels as needed and modification of filler wires to achieve optimum properties.

The materials selected for the first year's work consisted of a relatively new steel with a nominal composition of 9% nickel, 4% cobalt and 0.20-0.25% carbon (designated Republic HP 9-4-20) and AMS 6435. The HP 9-4-20 alloy was chosen because it exhibited good toughness properties in the as-quenched condition. Furthermore, this steel offered the possibility of developing joining techniques requiring no pre- or post-weld heat treatments. The AMS 6435 was included in the program in order to evaluate the feasibility of welding bainitic high-strength steels. While it was recognized that the bainitic heat treatment would involve controlled low temperature pre- and post-weld heating, it was felt that the possible superior notch toughness would compensate for the increase in processing complexity.

The results of the first year's work, reported in ML-TDR-64-225(1)*, showed that the TIG welds made in the HP 9-4-20 plate and sheet material, with filler wire compositions essentially matching the plate, possessed good strength and ductility with fracture toughness comparable to the unwelded material. These properties were attained without pre- or post-weld heat treatments. MIG welds in the HP 9-4-20 plate failed to meet the basic program requirements. This was attributed to excessive loss in carbon during

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* Numbers in parenthesis pertain to references in the Bibliography.

welding which lowered the yield strength to below 180 ksi. In addition, both TIG and MIG welds contained some porosity. At the lower welding speeds, which were not conducive to good mechanical properties, the porosity level was tolerable while at the higher speeds, where better mechanical properties were attained, porosity increased and was excessive in some instances.

Porosity in welds is believed to be caused by a reaction between carbon and oxygen in the weld metal, forming CO or CO_2 bubbles which become entrapped. It was believed that porosity in the HP 9-4-20 welds could be controlled by the addition of deoxidizers such as aluminum and titanium to the filler wire. The levels of these elements in the wire composition can be controlled so that the remaining level of deoxidizers is insignificant.

The bainitic AMS 6435 weld joints failed to meet the basic yield strength requirements in all cases because of overtempering in the weld heat affected zones. In addition, the fracture toughness, K_{IC}, was considerably less than that of the HP 9-4-20 steel. For these reasons a recommendation was made to discontinue work on the bainitic AMS 6435 material.

In the third phase of the program additional materials will be investigated, and possible improvements in the procedures and filler wires for the materials previously used will be evaluated. The feasibility of repair welding the most promising materials will be studied. Small pressure vessels will be made from those materials whose weldments exhibit desirable properties and these will be pressure tested to destruction.

III MATERIALS

A. Base Metals

The martensite steels used in the performance of this phase of the program were: HP 9-4-20 1/2-inch plate, HP 9-4-25 1-inch plate, Vasco Jet X-2 1/2-inch plate and D6AC 1/2-inch plate and 0.090 inch sheet. The bainitic steels investigated included HP 9-4-45 1/2-inch plate and 0.090 inch sheet as well as a limited amount of D6AC 1/2-inch plate. These materials were furnished in the annealed condition from consumable electrode vacuum melt products.

1. Martensitic Steels

The composition and thickness of the martensitic materials are presented in Table 1. The HP 9-4-20 1/2-inch plate was on hand from the first year's work. The HP 9-4-25 1-inch plate was originally ordered as HP 9-4-20 material with the same composition as the 1/2-inch plate. However, upon ordering this material it was found that this composition was no longer available and that the commercially produced material was of the chemistry shown for the HP 9-4-25. The HP 9-4-25 steel has higher carbon and nickel contents and decreased amounts of chromium and molybdenum.

While the HP 9-4-20 alloy appears to meet all of the desired properties in the as-welded condition, it is moderately expensive and the question

TABLE 1

COMPOSITION OF STEELS

Material	Heat No.	Thickness (in.)	Source of Analysis	C	Mn	P	S	Si	Ni	Cr	Mo	V	Co	Al
AMS6435	3920562	0.500	TRW	0.37	0.93	0.018	0.004	0.67	1.93	0.88	0.39	0.24	-	-
AMS6435	3920562	0.500	Republic	0.38	0.72	0.010	0.004	0.50	1.91	0.81	0.39	0.20	-	-
AMS6435	3951099	0.500	TRW	0.35	0.84	0.010	0.007	0.40	1.75	0.80	0.35	0.25	-	-
AMS6435	3951099	0.500	Republic	0.38	0.64	0.005	0.004	0.42	1.79	0.84	0.34	0.21	-	-
HP9-4-20	3888665	0.500	TRW	0.23	0.26	-	-	0.11	7.12	0.90	0.90	0.11	3.86	-
HP9-4-20	3888665	0.500	Republic	0.23	0.19	0.005	0.007	0.06	7.08	1.10	0.91	0.09	4.05	-
HP9-4-20	3930774	0.500	Republic	0.25	0.32	0.004	0.007	0.01	7.19	1.01	1.03	0.09	3.90	-
HP9-4-20	3930774	0.500	TRW	0.23	0.35	0.010	0.008	0.01	7.17	1.17	1.00	0.10	3.82	-
HP9-4-25	3930961	1.000	TRW	0.27	0.28	0.003	0.009	0.03	8.51	0.39	0.50	0.05	3.77	-
HP9-4-25	3930961	1.000	Republic	0.25	0.26	0.004	0.009	0.01	8.19	0.39	0.45	0.07	3.90	-
Vasco Jet (X2)	08930	0.500	Van. Alloys	0.21	0.22	0.007	0.010	0.84	-	4.85	1.34	0.50	-	-
HP9-4-25	3920869	1.00	Republic	0.44	0.12	0.004	0.009	0.02	7.83	0.31	0.31	0.09	3.95	-
HP9-4-25	3920869	0.500	Republic	0.44	0.12	0.004	0.009	0.02	7.83	0.31	0.31	0.09	3.95	-
HP9-4-25	3920869	0.500	TRW	0.43	0.11	0.003	0.009	0.03	7.92	0.28	0.33	0.08	3.82	-
D6AC	3920915	0.500	Republic	0.47	0.70	0.007	0.004	0.21	0.55	1.03	1.03	0.10	-	0.09
D6AC	3920915	0.500	TRW	0.44	0.69	0.010	0.006	0.23	0.53	1.05	0.90	0.10	-	0.10
D6AC	3951290	0.500	Republic	0.48	0.64	0.008	0.003	0.19	0.56	1.10	0.99	0.10	-	0.05
D6AC	3951290	0.500	TRW	0.48	0.63	0.006	0.008	0.22	0.59	0.96	0.96	0.10	-	0.05
D6AC	3951129	0.090	Republic	0.46	0.68	0.005	0.004	0.22	0.55	1.06	1.00	0.10	-	0.07
D6AC	3951129	0.090	TRW	0.40	0.70	0.008	0.010	0.20	0.57	0.94	0.96	0.11	-	0.08
HP9-4-43	3950831		Republic	0.41	0.22			0.26	8.25	0.26	0.13	0.10	3.60	0.02

naturally arises as to whether a more economical steel could also be joined without pre- or post-weld heat treatment and provide the desired 180 to 200 ksi yield strength with adequate notch toughness.

The SAE 43XX steels appear to be capable of fulfilling this requirement. The combination of alloying elements used in these alloys has been proved to be good from a notch toughness standpoint and they have been successfully used in many landing gear and pressure vessel applications. The critical consideration in selecting a 43XX alloy for application in the as-welded condition is the carbon content. If the carbon is too high, cracking will occur during the weld operation. If the carbon is too low, the material will not be able to achieve the desired 180 ksi minimum yield strength. The SAE 4325 steel has a transformation comparable to the HP 9-4-20 alloy and does not violate the Cottrell cracking criterion(2). The smooth tensile properties of SAE 4325 steel, shown in Figure 1, indicate that a carbon content of 0.25 percent has the capability of providing the desired 180 to 200 ksi yield strength in the base metal as well as meeting the Cottrell cracking criterion. However, SAE 4325 steel was not found to be a standard steel and therefore was not immediately available. Preliminary studies were made on martensitic AMS 6435 to determine whether the transverse weld properties would meet the minimum 180 ksi yield strength requirement at the higher carbon level. If not, an examination of the SAE 4325 steel would not be necessary.

As an alternate material a 5%Cr-1.3%Mo-0.5%V-0.20%C (Vasco Jet X-2) steel was selected. This material was considered over the more commonly used low alloy carbon steels in an effort to gain improved weldability in the hardened condition and high ductility at the intermediate strength levels. It has extremely deep hardenability(4), and therefore, distortion, residual stresses and danger of cracking can be minimized by air cooling. As shown in Figure 2 (a), the Vasco Jet X-2 steel, tempered at 1075°F, provides the strength requirements of the program (180 to 200 ksi yield strength) together with good ductility.

Based on the smooth tensile results for as-deposited D6AC filler materials(1), D6AC 1/2-inch plate and 0.090 sheet was also included as a martensitic material during the eighth quarter.

2. Bainitic Steels

The composition and thicknesses of the bainitic materials are presented in Table I. It was recommended at the conclusion of the first phase of the program(1) that work on the bainitic AMS 6435 steel be discontinued and therefore other steels were considered as possible substitutions.

Data developed by the Republic Steel Research Laboratory(5) indicated that bainitic structures in the HP 9-4-XX alloys have good notch toughness properties. The impact energy of the bainites are shown as a function of yield strength in Figure 3. At high strength levels, the bainite is considerably better than the martensite of the same carbon content and slightly superior to the lower carbon HP 9-4-XX alloy in the martensite condition.

The influence of transformation temperature on the smooth tensile properties of the HP 9-4-43 bainite is illustrated in Figure 4. Yield

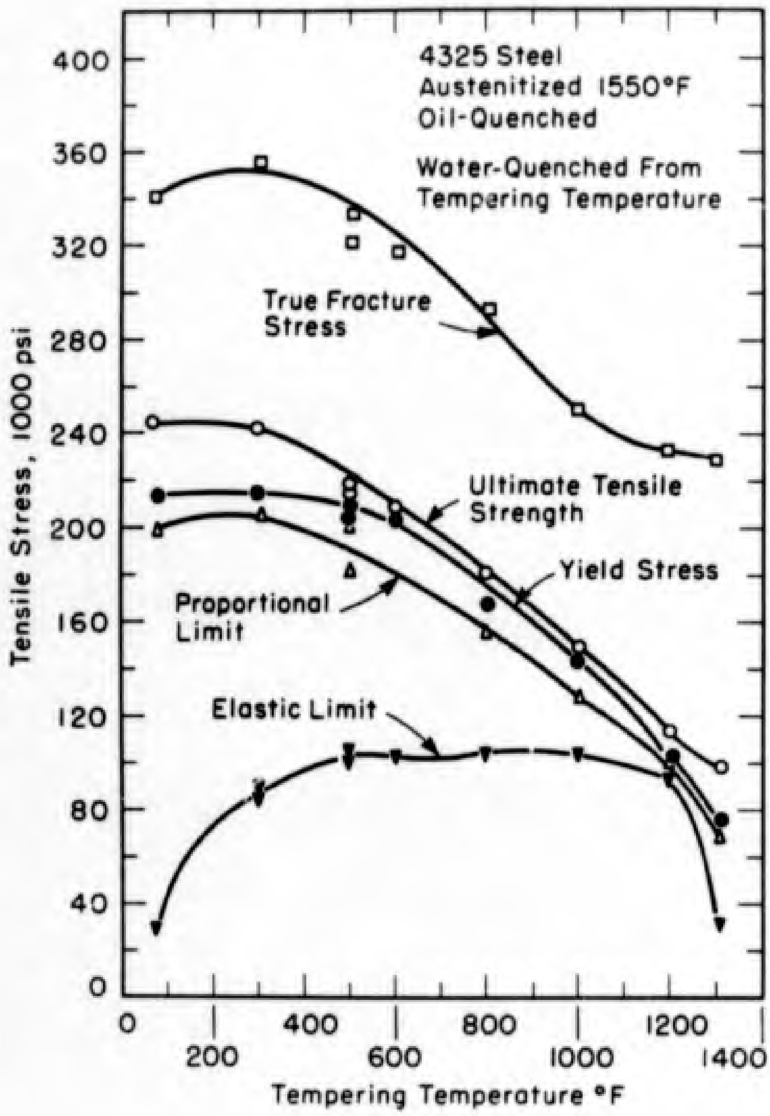
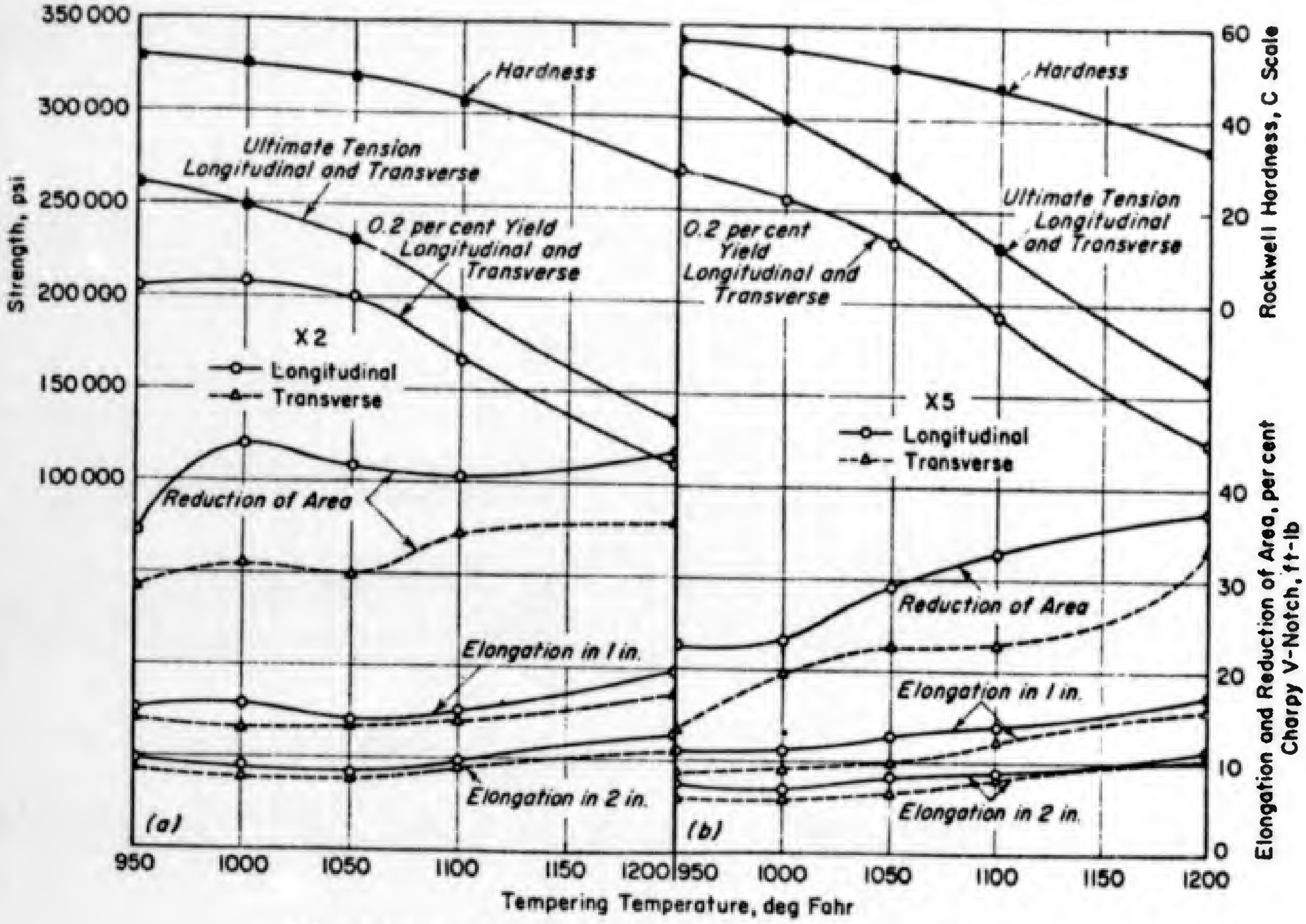


Figure 1. Tensile Properties of As-Quenched and Tempered Martensite for SAE 4325. (Ref. 3)



(a) 0.20 per cent carbon (b) 0.50 per cent carbon

Figure 2. Representative Sheet Tensile Properties of 5 Percent Chromium Steels 0.125 Inch Thick Sheet, Tested Both Parallel and Transversely to Its Long Dimension. (Ref. 4)

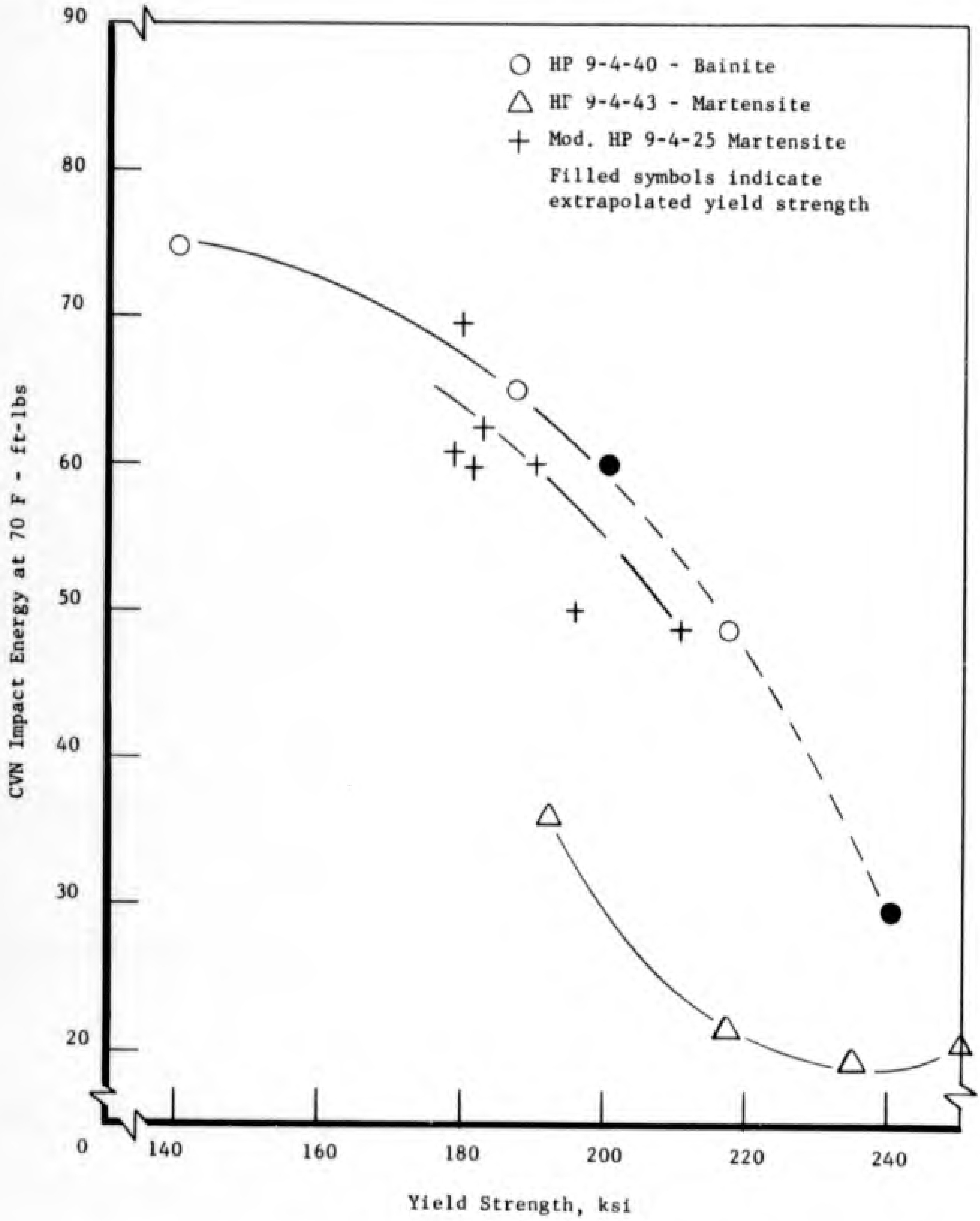


Figure 3. Impact Resistance of Tempered Martensitic and Bainitic Structures as Related to Yield Strength in HP 9-4-X Alloy Steels. (Ref. 5)

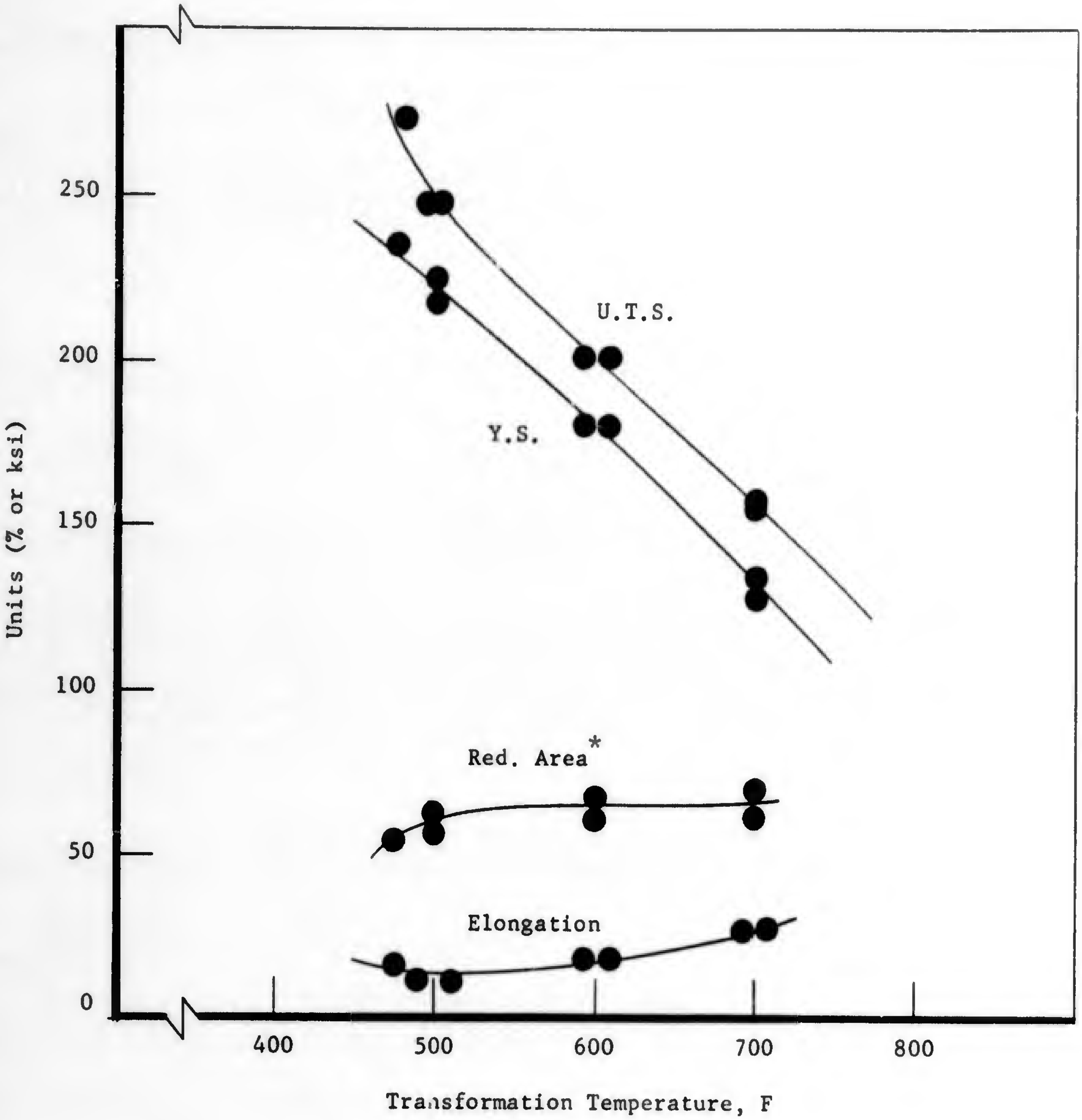


Figure 4. The Effect of Transformation Temperature on the Properties of Bainitic HP 9-4-43 Steel. (Heat 3950831) (Ref. 5)

*Red. Area is Usually Not Reported on Sheet Tensile Specimens.

strengths between 180 and 200 ksi can be obtained by transforming in the range of 525 to 575°F. Current results indicate that the exact time required to form 100 percent bainite can vary between 20 minutes and 3 hours depending on the particular heat and transformation temperature employed. The influence of transformation temperature on the notch impact properties are shown in Figure 5. As in the case of the martensitic steels, the impact energy progressively increases with decreasing strength level; i.e., increasing transformation temperature. Measurements of notch tensile properties indicate that bainitic HP-9-4-43 generally has better toughness than the martensitic material at intermediate strength levels[6]. This higher toughness is consistent with the high impact strengths obtained in Charpy tests. The high toughness obtained in the bainitic structures of the HP 9-4-XX alloys made it a logical choice for study in this program.

However, as previously stated the HP 9-4-XX steels are relatively expensive. Therefore, in conjunction with the work on the HP 9-4-45 bainite, a low alloy steel was also evaluated. The results presented in ML-TDR-64-255[1] showed that while transverse joint properties in AMS 6435 were poor due to over-tempering in the heat affected zone, the all weld metal properties of D6AC deposits transformed to bainite at 575°F, met the desired 180 ksi yield strength requirements. Thus D6AC steel was included in the program as a bainitic material.

B. Filler Wires

At the conclusion of the first year's work[1] it was determined that the HP 9-4-20 filler wires were capable of producing welds with desirable properties in the HP 9-4-20 material. However, it was thought that weld quality, in relation to porosity, could be improved by making either aluminum or titanium additions to the filler wires. Therefore, for this year's work four 15 pound heats of HP 9-4-20 steel with additions of aluminum or titanium and one base heat without additions were melted and forged to 2-1/4 inch square billets. These billets were subsequently drawn to 1/16 inch diameter weld wire. These wires were used to weld the HP 9-4-20 material in the martensitic condition. In addition, a spool of HP 9-4-25 wire with less chromium and molybdenum, than the previous HP 9-4-20 wires, was procured late in the program. This wire is commercially available and was developed by Republic Steel Corporation.

Other filler wires used for the various materials were D6AC high and low carbon and 1722AS for the martensitic steels and HP 9-4-45 and D6AC high carbon for the bainitic steels. The composition and diameter of the wires used during the performance of this program are presented in Table 2. It should be noted that each wire has been assigned a code number. These wires will be referred to by this number in subsequent sections of this report.

IV EXPERIMENTAL PROCEDURE

A. Materials Preparation

The base metals used in the performance of this program are classed into two catagories: 1) those heat treated by quenching and tempering to a martensitic

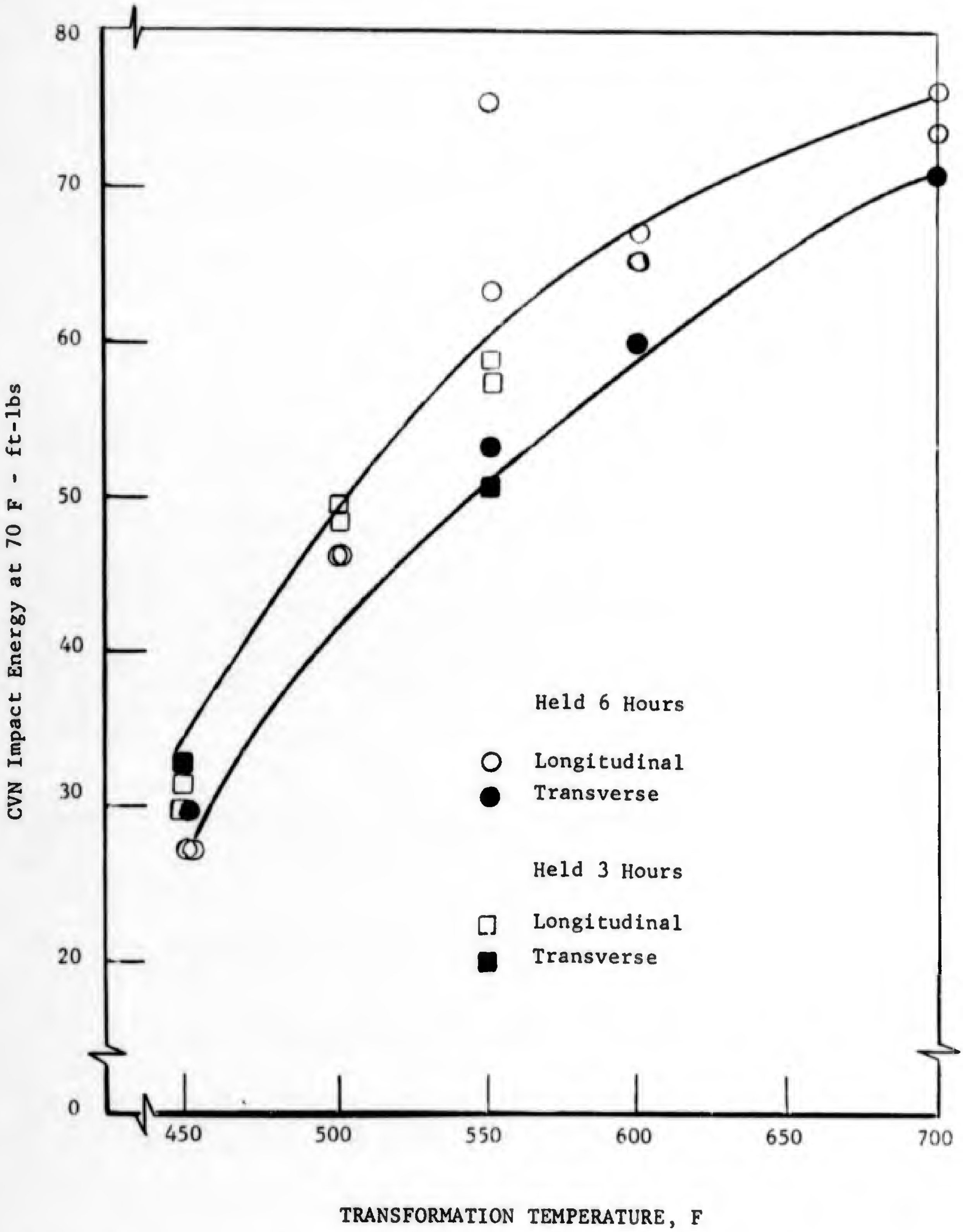


Figure 5. Impact Resistance as a Function of Bainitic Transformation Temperature of HP 9-4-43 Steel. (Heat 3950831) (Ref. 5)

TABLE 2

COMPOSITION OF FILLER WIRES

Code	Material	Heat No.	Diameter (inch)	Source of Analysis	C	Mn	P	S	Si	Ni	Cr	Mo	V	Co	Ti	Al
1	D6AC	07642	0.062	Armetco	0.26	0.66	0.006	0.005	0.26	0.60	1.09	0.95	0.09	-	-	-
1	D6AC	07642	0.062	TRW	0.30	0.59	0.010	0.011	0.46	0.54	1.08	1.26	0.08	-	-	-
5	D6AC(a)	3950899	0.062	Nat'l. Std.	0.45	0.86	0.007	0.006	0.25	0.94	1.05	1.00	-	-	-	-
5	D6AC(a)	3950899	0.062	TRW	0.48	0.76	0.011	0.011	0.53	0.51	1.00	1.32	-	-	-	-
9	7.5Ni-4Co(a)	3888650	0.045	TRW	0.24	0.50	0.013	0.019	0.58	6.72	1.48	1.09	0.04	3.46	-	-
10	7.5Ni-4Co(a)	3888651	0.045	TRW	0.27	0.45	0.013	0.033	0.57	6.69	0.75	1.04	0.04	3.45	-	-
11	HP 9-4-20(b)	V297	0.062	Republic	0.26	0.52	0.011	0.010	0.56	6.98	1.00	0.99	0.065	3.37	-	-
11	HP 9-4-20(b)	V297	0.062	TRW	0.24	0.64	0.007	0.014	0.55	7.13	0.85	1.08	0.11	3.38	-	-
12	HP 9-4-20(b)	V298	0.062	Republic	0.26	0.51	0.010	0.010	0.51	6.92	1.00	1.01	0.09	3.36	0.05	-
12	HP 9-4-20(b)	V298	0.062	TRW	0.25	0.64	0.007	0.010	0.52	7.11	0.85	1.07	0.11	3.37	0.03	-
13	HP 9-4-20(b)	V299	0.062	Republic	0.26	0.52	0.010	0.010	0.53	7.02	1.01	0.98	[illegible].065	3.32	0.20	-
13	HP 9-4-20(b)	V299	0.062	TRW	0.24	0.58	0.007	-	0.51	7.12	0.87	1.08	0.13	3.39	0.20	-
14	HP 9-4-20(b)	V300	0.062	Republic	0.26	0.54	0.010	0.010	0.60	6.88	1.00	1.00	0.08	3.34	-	0.06
14	HP 9-4-20(b)	V300	0.062	TRW	0.24	0.63	0.007	-	0.54	7.02	0.87	1.05	0.12	3.39	-	0.07
15	HP 9-4-20(b)	V301	0.062	Republic	0.27	0.53	0.010	0.010	0.53	6.94	1.01	1.01	0.07	3.36	-	0.12
15	HP 9-4-20(b)	V301	0.062	TRW	0.24	0.61	0.007	-	0.56	7.08	0.87	1.10	0.11	3.39	-	0.15
17	HP 9-4-45	3888702	0.062	Republic	0.42	0.46	0.005	0.006	0.25	8.11	0.34	0.32	0.12	4.30	-	-
17	HP 9-4-45	3888702	0.062	TRW	0.38	0.62	0.007	0.004	0.26	8.04	0.26	0.30	0.12	3.98	-	-
18	Vasco Jet X2	06346	0.062	Armetco	0.25	0.23	0.010	0.005	0.93	-	4.91	1.20	0.51	-	-	-
18	Vasco Jet X2	06346	0.062	TRW	0.25	0.23	0.006	0.003	0.78	-	5.02	1.26	0.53	-	-	-
19	HP 9-4-25	3931006	0.062	Republic	0.26	0.40	0.003	0.006	0.23	8.05	0.55	0.52	0.08	3.90	-	-
19	HP 9-4-25	3931006	0.062	TRW	0.26	0.40	0.007	0.014	1.18	7.77	0.50	0.53	0.02	3.60	-	-
3	1722AS	6840T-517	0.062	Arcos	0.31	0.53	0.005	0.004	0.61	-	1.25	0.53	0.25	-	-	-
3	1722AS	6840T-517	0.062	TRW	0.33	0.53	0.009	0.015	0.68	-	1.22	0.68	0.21	-	-	-
6	D6AC	C56353	0.062	Arcos	0.48	0.80	0.010	0.006	0.24	0.59	0.94	0.95	0.13	-	-	-
6	D6AC	C56353	0.062	TRW	0.43	0.77	0.010	0.016	0.47	0.58	0.90	1.10	0.09	-	-	-

(a) Copper coated.

(b) Modified HP 9-4-20 wire.

structure, and 2) those heat treated by isothermal transformation to a bainitic structure. The materials preparation consisted of heat treating to obtain the appropriate structure and properties, cleaning and machining the weld joint design on each plate.

1. Heat Treatment of Martensitic Materials

Heat treatment for the HP 9-4-20 material was experimentally determined during the first year's investigation(1). The 1-inch HP 9-4-25 plate was heat treated in the same manner. The material was austenitized in salt at 1550°F for 1 hour, oil quenched and double tempered at 950°F for 2 hours each. Plates of AMS 6435 1/2-inch material were heat treated by austenitizing at 1550°F for 30 minutes and oil quenching. Pairs of plates were then tempered, in preparation for welding, at various temperatures ranging from 450 to 800°F. The Vasco Jet X-2 material was heat treated by austenitizing at 1825°F for 30 minutes, air cooling and triple tempering at 1075°F for 2 hours each. The D6AC 1/2-inch plate was heat treated by austenitizing at 1650°F for 1 hour quenching to 375°F in salt, holding for 10 minutes, air cooling then double tempering at 1050°F for 2 hours each. The D6AC 0.090 inch sheet was heat treated by normalizing at 1650°F for 15 minutes, air cooling, austenitizing at 1550°F for 15 minutes, oil quenching then double tempering at 950°F for 2 hours each.

2. Heat Treatment of Bainitic Materials

The HP 9-4-45 sheet and plate were transformed to lower bainite by normalizing at 1600°F for 1 hour, air cooling, austenitizing at 1500°F for 1 hour, quenching directly to 550°F and holding for 7 hours. The D6AC material was transformed to bainite by austenitizing at 1650°F for 1 hour and austempering various plates at 575, 625, 650 or 725°F.

3. Weld Joint and Surface Preparation

Weld joints in all sheet and plate thicknesses were made between two 4-inch x 12-inch pieces butted along the 12 inch edge. Joints in 0.090 inch sheet were ground square and straight.

The weld joints for 1/2-inch plate were prepared by machining a 12 inch edge of each of the two joint members with a standard single V or U groove or a double V groove configuration. A schematic of these joint designs is presented in Figure 6. The single V groove joint design with a 70° included angle was used for the majority of welding throughout the program. This particular joint was selected to allow tensile specimens to be made consisting entirely of weld metal. The single U and double V groove designs were used to determine the effect of joint design on the mechanical properties of the weldment.

The weld joint designs used for the 1-inch plate are shown in Figure 7. The U groove configuration was selected for the thicker material in preference to the V groove design since with the V groove configuration there is a tendency for the side walls at the base of the V to melt and run down into the bottom of the joint making complete penetration difficult to obtain. In addition, the V groove design has a tendency to cause centerline cracking in

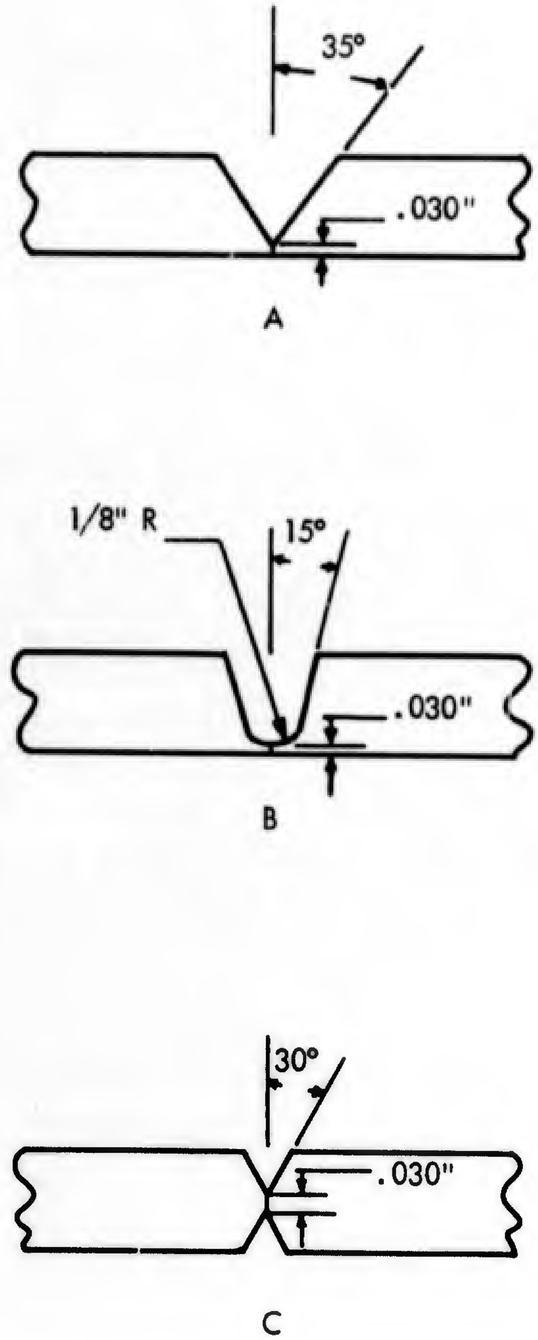


Figure 6. Weld Joint Designs for 1/2 Inch Plate.

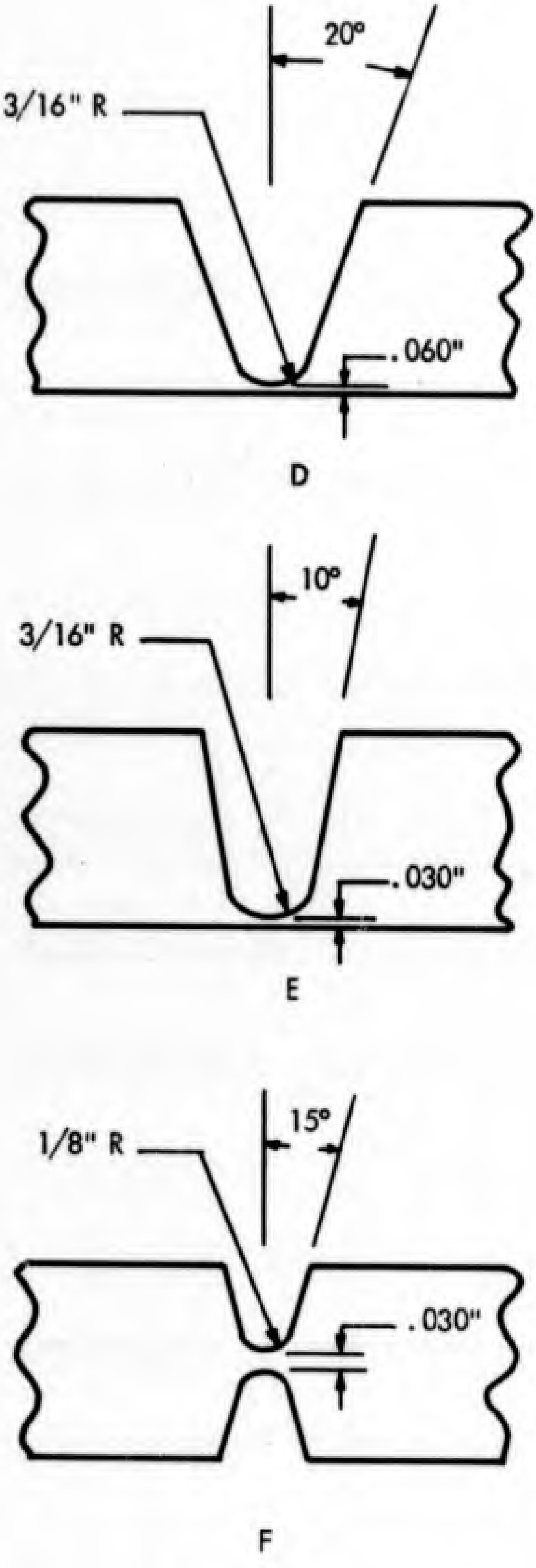


Figure 7. Weld Joint Designs for 1 Inch Plate.

thick plate weldments. The joint design presented in Figure 7(D) was used to evaluate the various filler wires and welding parameters. Designs (E) and (F) were used for the horizontal and vertical welding studies as well as for flat position welding.

Prior to welding, each plate was mechanically cleaned with a grinding wheel to approximately 1/2-inch back from each side of the weld joint. The plates were then tack welded together and cleaned with acetone before and after assembly in the weld fixture.

B. Welding Procedure

The automatic and manual gas tungsten arc and automatic gas metal arc welding processes were used during the performance of this program. Gas tungsten arc welding was done by means of an electronically controlled TIG welding head capable of maintaining a preset arc voltage of 0.1 volt. A 400 amp rectifier was used to furnish DC straight polarity. Manual welding was accomplished by a conventional manual welding torch and a 400 amp DC rectifier. Spray-transfer gas metal arc welding was done by a conventional MIG welding head. The DC reverse polarity was furnished by a 400 amp rectifier fitted with a constant potential adaptor unit. Short arc welding employed a conventional MIG welding head and DC reverse polarity was furnished by a constant potential DC welder with continuously variable slope.

To afford maximum constraint during welding each of the plates were bolted down under steel clamping jaws. A photograph of the welding fixture and heliarc torch is presented in Figure 8. The fixture is fitted with a grooved perforated copper backing bar to allow inert gas shielding to be supplied to the root side of the weld bead. In addition, the fixture is equipped with eighteen 550 watt cromolox immersion heaters which are capable of providing the pre-heat temperature ranges designated for this program (700°F maximum). Interpass and post weld temperatures were measured by a chromel-alumel thermocouple attached near each end of the plate to be welded. The arc current and voltage for each weld pass were recorded on Esterline Angus strip chart meters while welding speed and filler wire feed rates were timed with a stop watch. Oxides were removed from multipass welds by wire brushing or grinding between passes.

C. Evaluation

Welds and base material were evaluated for metallographic structure, quality, hardness, tensile properties and fracture toughness. Weld quality was determined by dye penetrant and radiographic inspection.

The smooth tensile properties of both weld and parent metal were determined using the test specimen configurations illustrated in Figures 9 and 10. The specimen types shown in Figures 9(a) and (b) were used to examine the parent metal and weld metal deposits in 1/2-inch and 1-inch plate respectively. Specimens of the geometry shown in Figure 10(a) and (b) were used to determine transverse joint properties. Since parent metal, the heat affected zones and the weld deposit all are included within its gage length, the zone in which failure occurred could be assumed to be the weakest. The specimen geometry

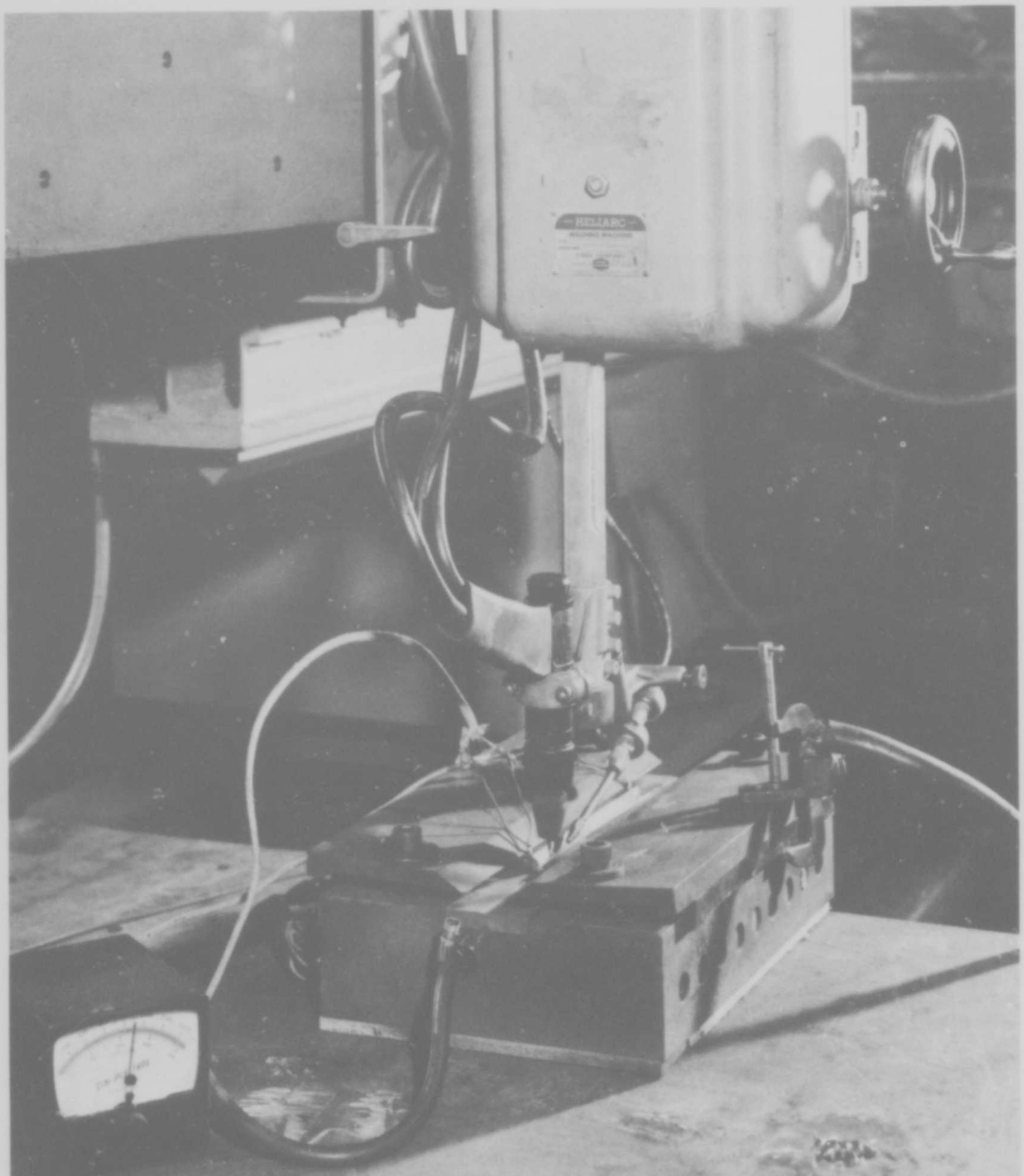


Figure 8 Welding Fixture and Heliarc Torch

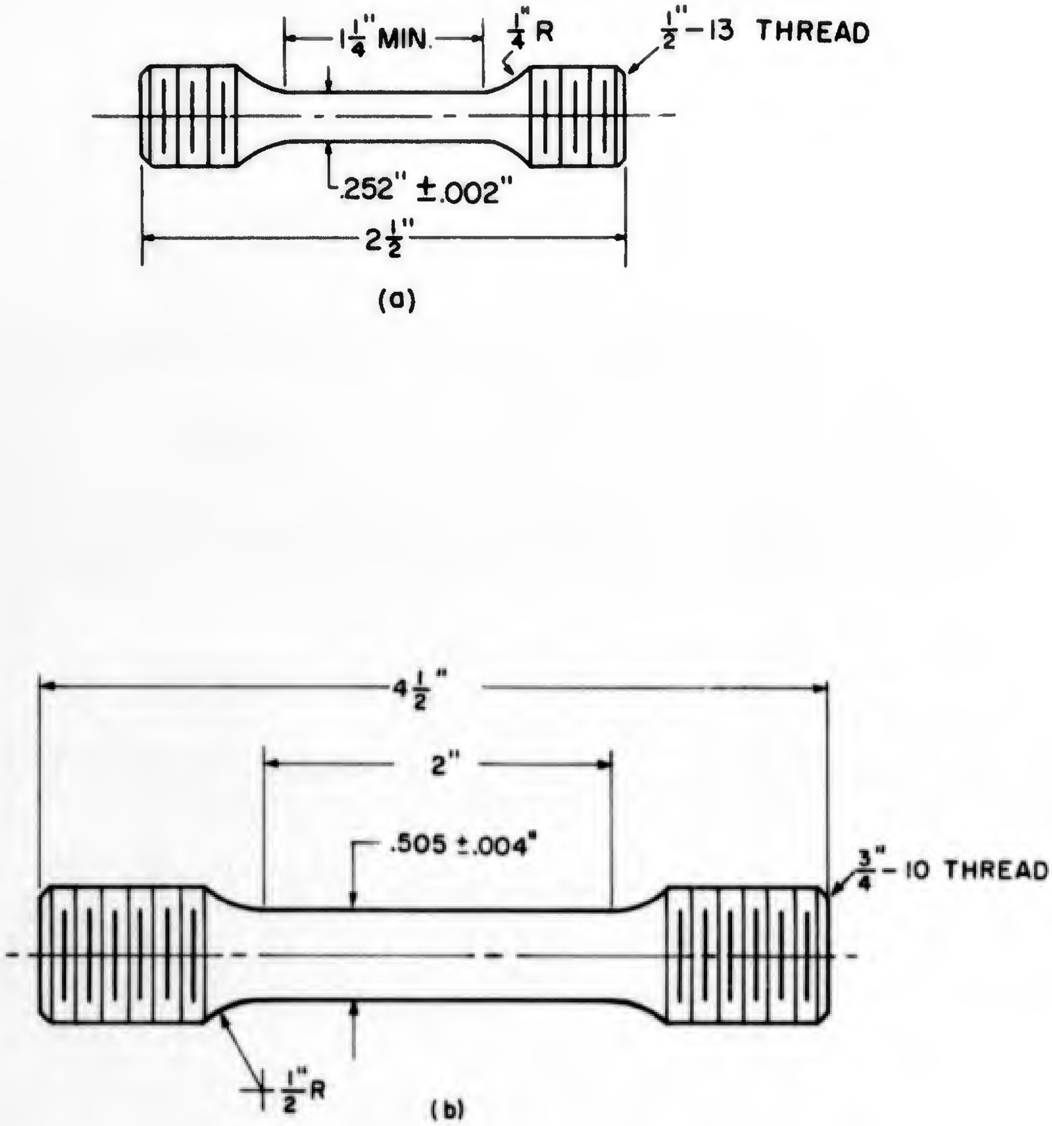


Figure 9. Smooth Tensile Specimen Geometries.

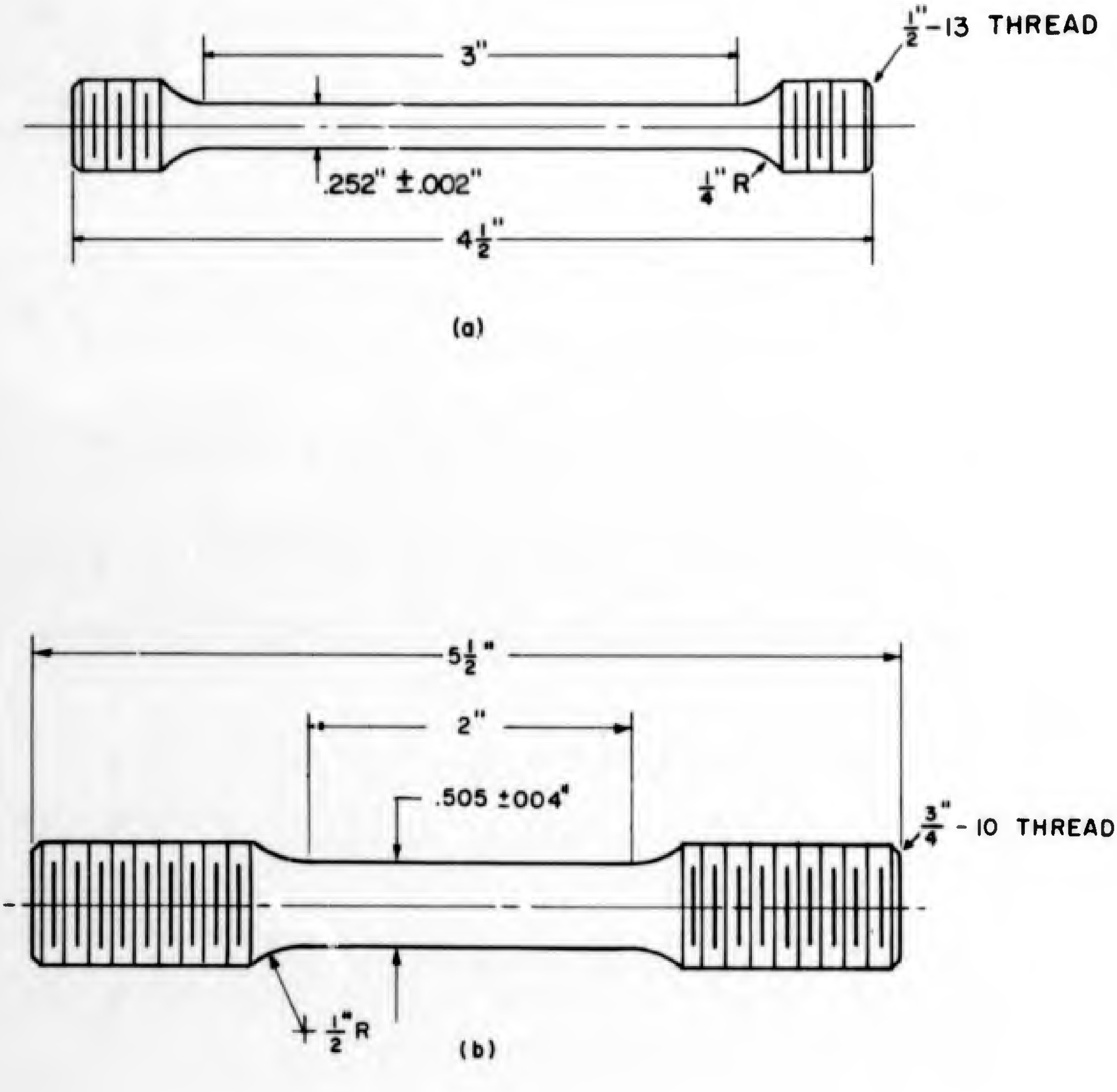


Figure 10. Smooth Tensile Specimen Geometries Used to Determine Transverse Joint Properties.

shown in Figure 11 was used to experimentally confirm the calculated thickness increase or build-up in the weld joint to give a 100 percent joint efficiency. It was intended that this specimen should cause fracture to take place in the parent metal rather than in the heat affected zone or fusion zone of weldments with low strength. The specimen design shown in Figure 12 was used to determine the smooth properties of the 0.090 inch sheet parent metal and to examine weld joint efficiencies. All smooth tensile properties were determined at room temperature at a strain rate of 0.001 in/in/min.

Plane strain fracture toughness, K_{IC}, determinations were made on the base materials and those weldments which exhibited good smooth tensile properties. Both notch bend and surface-cracked specimen types were employed (see Figures 13 and 14). The notch bend specimen was generally used to obtain comparative fracture toughness values since it is the more economical of the two. Surface-cracked specimens were used only to determine the K_{IC} of the parent metals and those weldments believed to have the most desirable properties.

Fatigue precracking was accomplished using a fixture which held the specimens as a cantilever beam and applied the load in a tension-tension cycle with the maximum stress less than 0.3 of the yield strength.

Notch bend specimens were tested under both three and four point loading. Three-point loading was used in the early phases of the program. However, it has recently been found that four-point loading produces load deflection curves which are more easily interpreted as to the point at which crack growth initiates and also yields less scatter in the resultant K_{IC} values[7]. The fracture toughness values were calculated from the currently available calibration curves[8] in the case of the notch bend specimens and from Irwin's analysis[9] for surface-cracked specimens. The formulae are presented in Figure 15 along with schematics of the specimen types and loading conditions.

Displacement gages were used to determine the load-deflection curves in all tests. Whenever the initiation of crack propagation was revealed by an observable discontinuity in the load-displacement curve (pop-in), the load at that point could be used directly to calculate plane-strain fracture toughness, K_{IC}. However, when a distinct pop-in was not observed the fracture toughness was measured by using the load at the point where the load-deflection curve first showed an observable deviation from linearity. An example of each of the three general classifications of load-deflection curves are shown in Figure 16. It can be seen that when a Type 1 curve is obtained, the deviation from linearity is not well defined and considerable difficulty can be encountered in determining the load at which initiation of crack growth occurred. However, Type 2 curves which have only one straight line portion and undergo at least a 10 percent change in slope at a load 5 percent greater than the point at which deviation from linearity first occurred (see Figure 17) have been found to yield comparable fracture toughness values to those determined from Type 3 curves (pop-in)[7].

The presently accepted conditions for which K_{IC} determinations[8] are that a pop-in be observed and that

$$\sigma_{nom}/\sigma_{ys} \leq 0.8$$

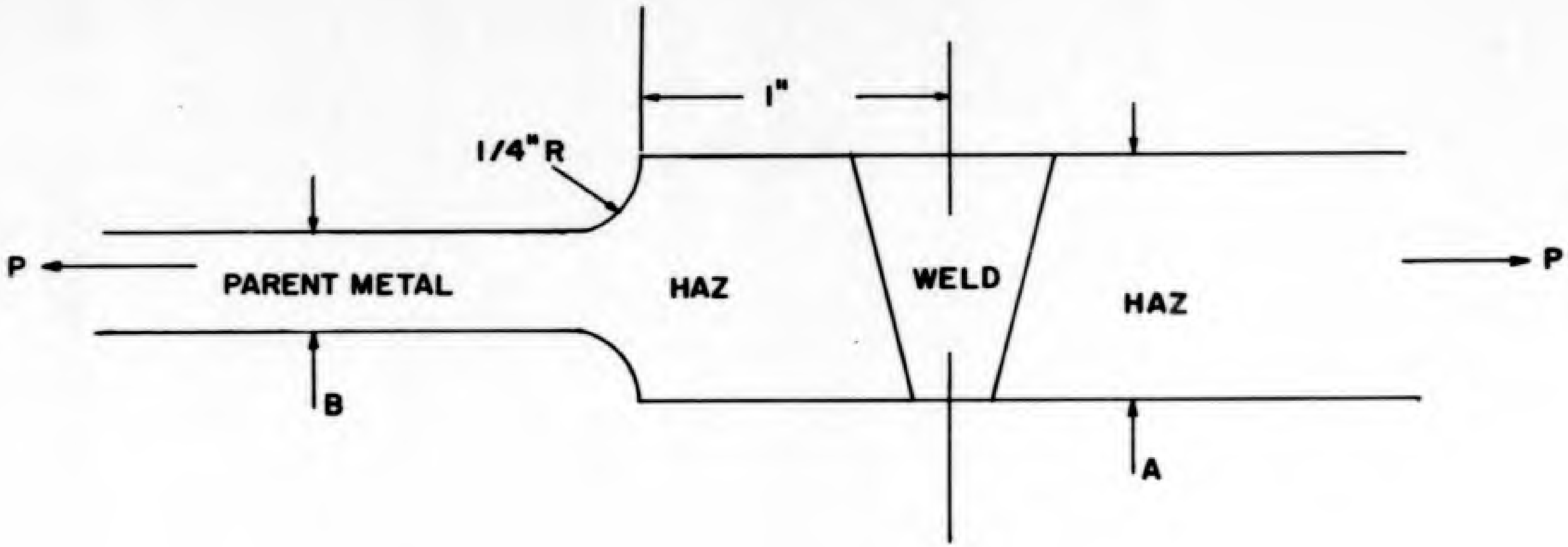


Figure 11. Joint Efficiency Tensile Specimen Geometry.

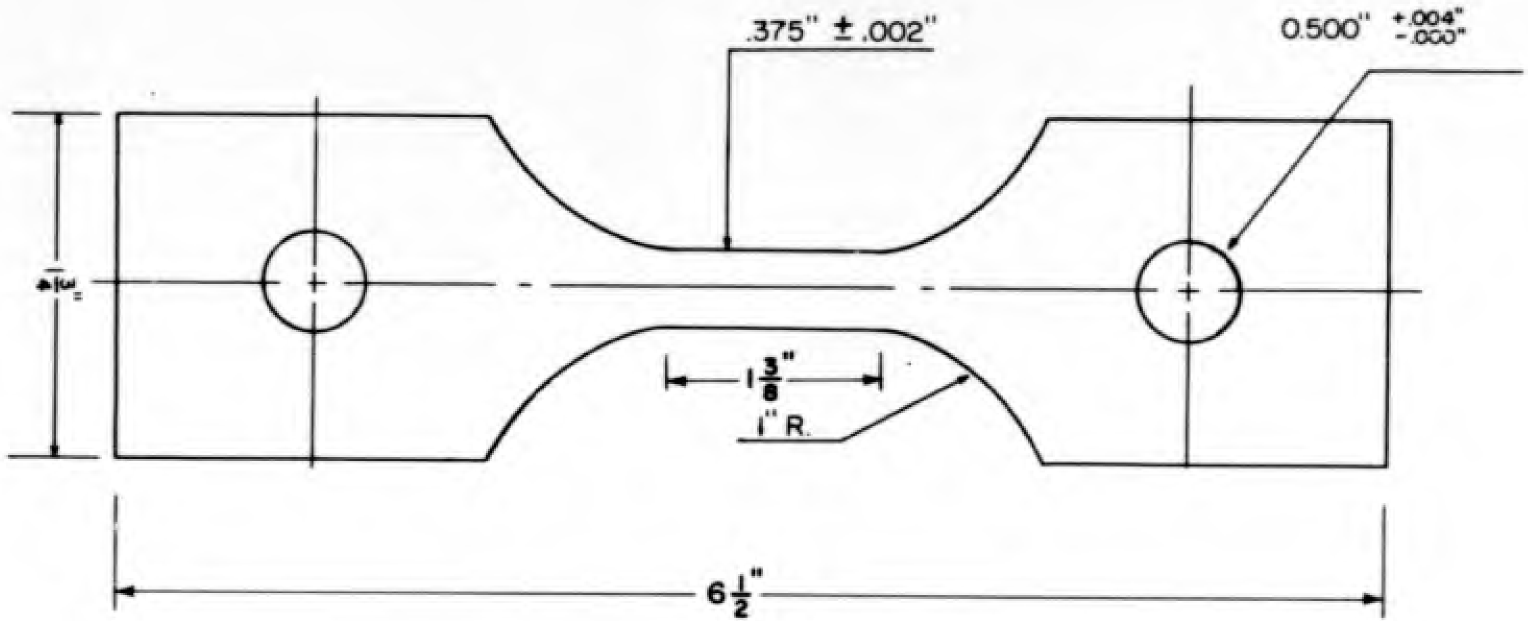


Figure 12. Smooth Sheet Tensile Specimen Geometry.

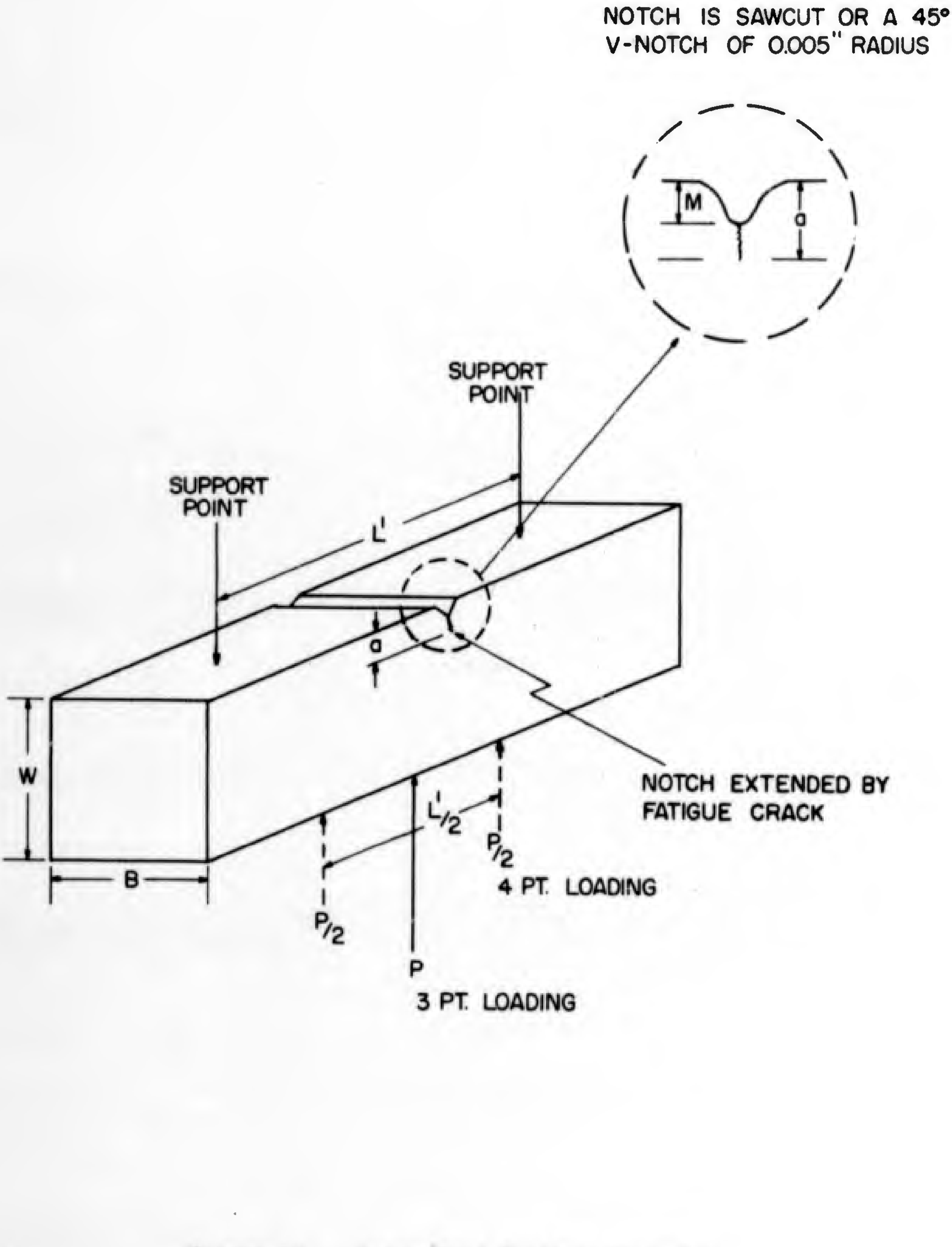
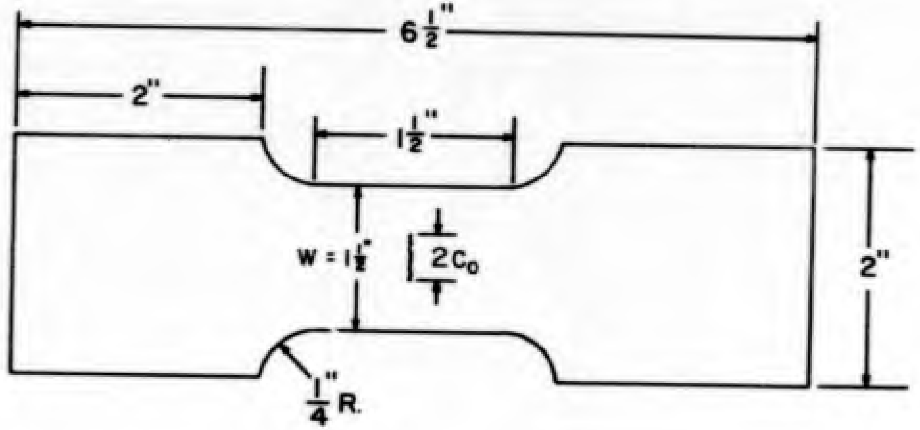


Figure 13. Notch Bend Specimen Geometry.

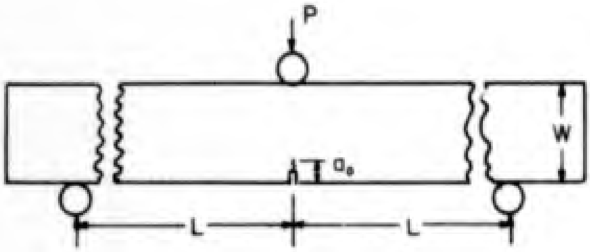


$B = \frac{1}{4}$ INCH

a = CRACK DEPTH = 0.100 INCH

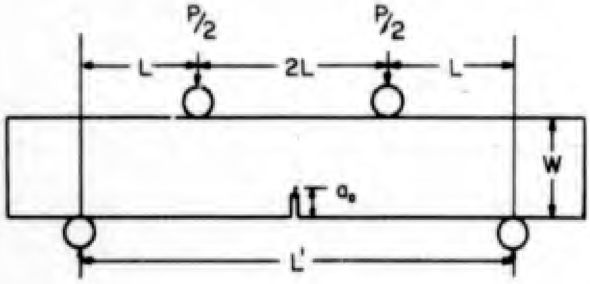
$2C_o$ = 0.500 INCH

Figure 14. Surface-Cracked Specimen Geometry.



$$K_{IC}^2 = \left[\frac{1}{1-\nu^2}\right]\left(\frac{P}{B}\right)^2 \frac{L^2}{W^3}\left[31.7\,\frac{a}{W} - 64.8\left(\frac{a}{W}\right)^2 + 211\left(\frac{a}{W}\right)^3\right]$$

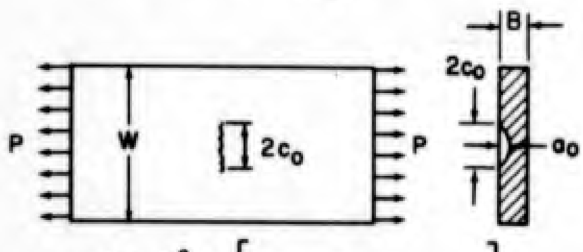
NOTCH BEND TEST (THREE POINT LOADING)



$$K_{IC}^2 = \left[\frac{1}{1-\nu^2}\right]\left(\frac{P}{B}\right)^2 \frac{L^2}{W^3}\left[34.7\,\frac{a}{W} - 55.2\left(\frac{a}{W}\right)^2 + 196\left(\frac{a}{W}\right)^3\right]$$

NOTCH BEND TEST (FOUR POINT LOADING)

$$a = a_0 + \frac{K^2}{6\pi\sigma_{YS}^2} \quad \text{IN BOTH CASES}$$



$$K_{Ic}^2 = \frac{1.2\pi P^2 a_0}{W^2\,B^2}\left[\frac{1}{\Phi^2 - 0.2\left(\frac{P^2}{W^2 B^2 \sigma_{YS}^2}\right)}\right]$$

$$\Phi = \int_0^{\pi/2}\sqrt{\frac{c_0^2 \quad a_0^2}{c_0^2}\sin^2\theta}\;d\theta$$

Surface cracked plate.

Figure 15. Formulae Used to Compute K_{IC} Values.

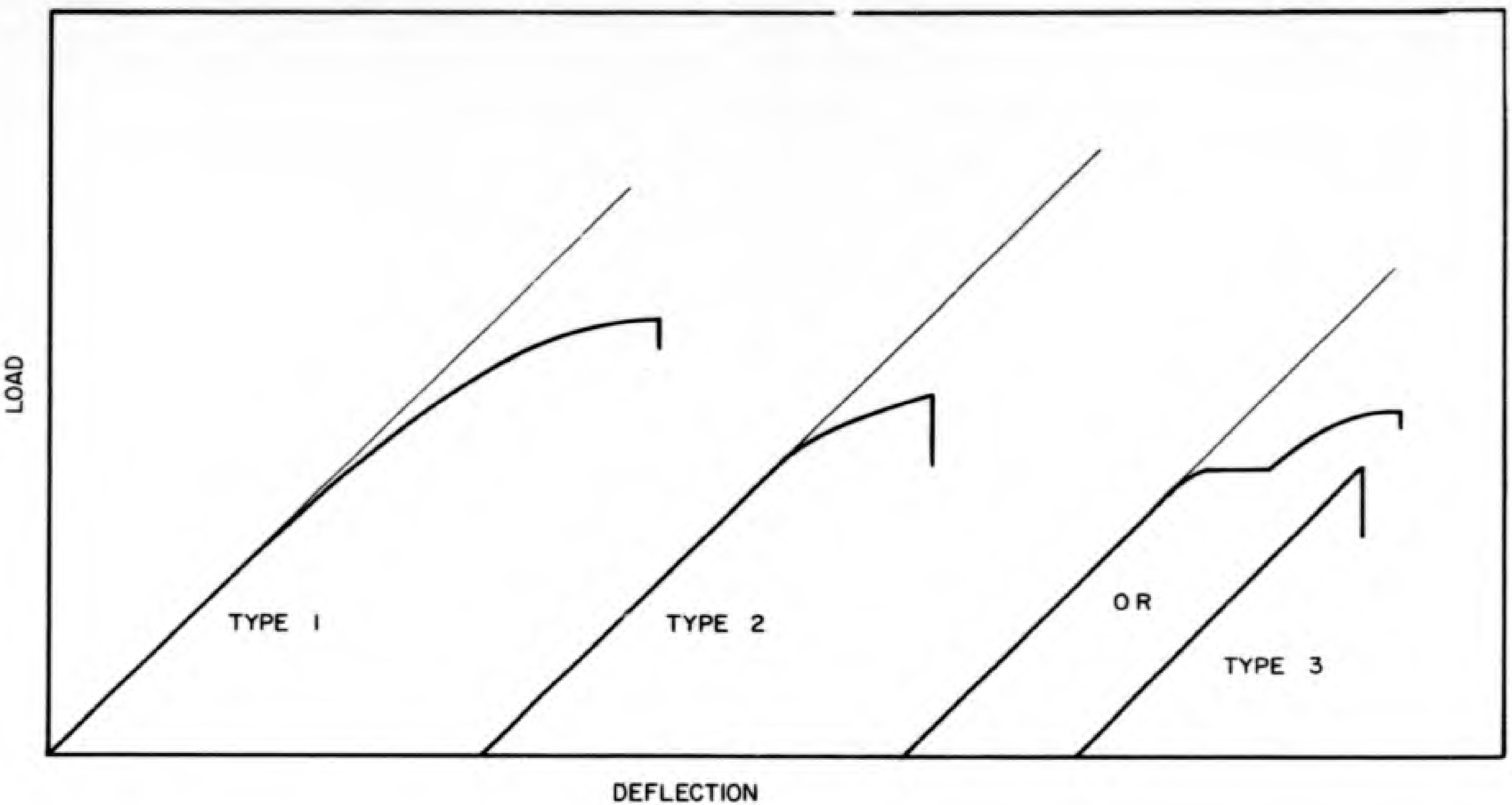


Figure 16. Classification of Types of Load-Deflection Curves Observed in Notch Bend Tests.

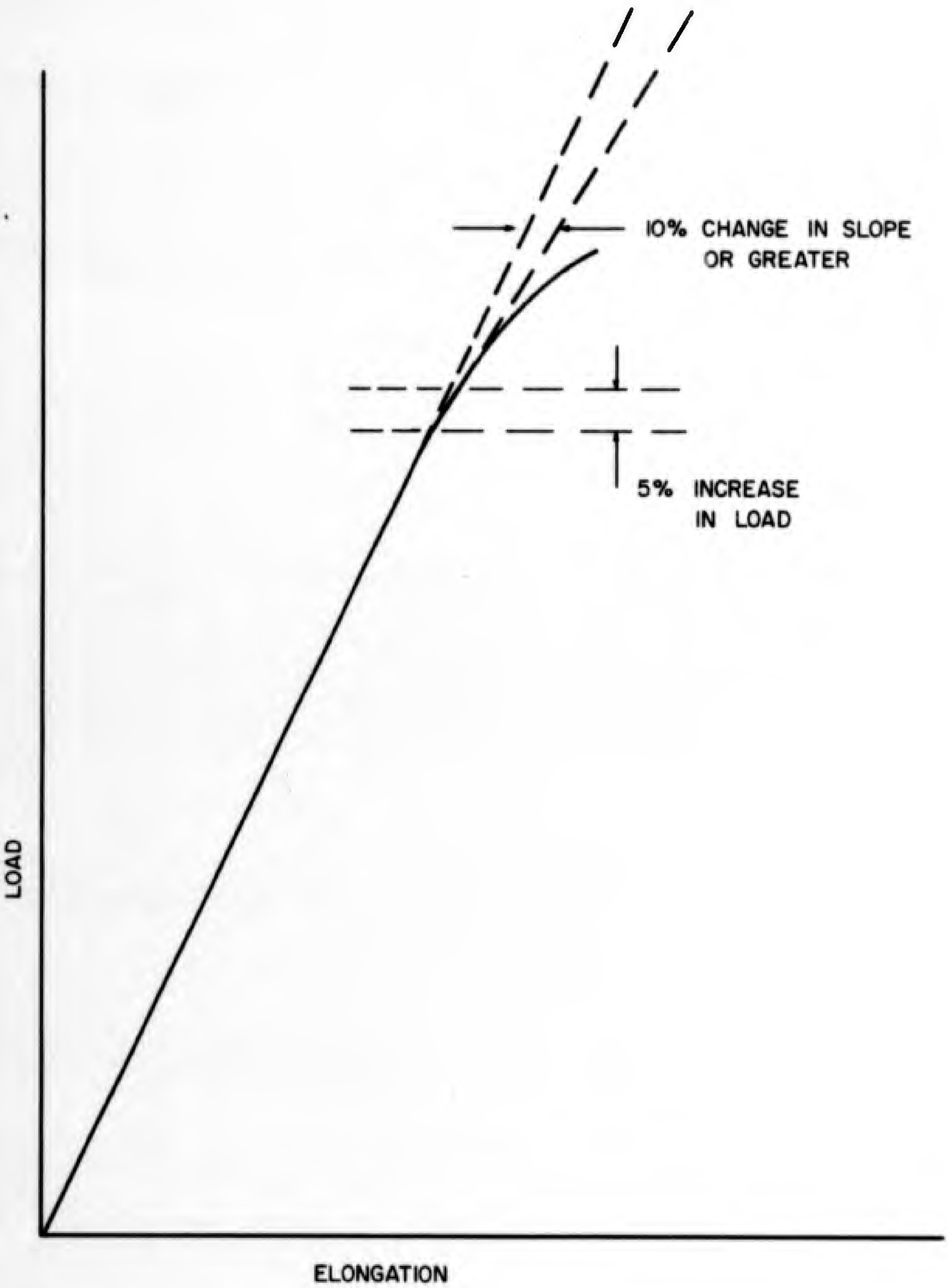


Figure 17. Schematic Illustration of Criterion for Type 2 Crack Extension Curve.

where: σ_{nom} = nominal stress at crack tip at initiation of crack growth, and

σ_{ys} = 0.2% offset yield strength

When either or both criteria were violated the fracture toughness value is indicated as the calculated fracture toughness K_{IC}^{*}.

The center notch fatigue precracked sheet specimen shown in Figure 18 was used to determine the fracture toughness of welds made in the 0.090 inch sheet. This specimen design corresponds to the recommendations of the ASTM Committee on Fracture Testing of High Strength Materials[10]. The K_{IC} parameter was determined using a compliance gage to detect initiation of crack growth. Notches were placed in the weld deposit, heat affected zone or parent metal to determine their comparative toughness.

Charpy impact properties were determined for the parent metals and for those welds found to be representative of the most satisfactory filler wires and parameters. Tests were conducted at room temperature, 0, -100 and -320°F. The Charpy specimen used for these studies is presented in Figure 19.

Hot and cold cracking tendencies of the welds and heat affected zones were evaluated by means of the circular patch specimen shown in Figure 20. In these tests Ø was 90°, d was 5 inches, t was 1/2-inch and L and W were 12 inches each.

D. <u>Determination of Properties of the Heat Affected Zone</u>

Microstructures representing a particular point in a HAZ were reproduced in tensile and fracture toughness specimens by means of a time temperature controller ("Gleeble"). Bars of each material 0.42 inch square by 3-1/2 inch long were exposed to thermal cycles having peak temperatures ranging from 1000 to 2400°F. These thermal cycles were based on energy input levels of 25 and 50 K-joules per inch with no pre-heat for the D6AC steel and with a 525°F preheat for the HP 9-4-45 steel. The D6AC specimens were run for a total period of about 6 minutes; i.e., the approximate time for cooling from the peak temperature to room temperature. The HP 9-4-45 specimens were run for a total time of 3 hours to permit transformation to bainite.

The tensile specimen used to study the properties produced by the synthetic weld thermal cycles is shown in Figure 21. The radius is placed in the gage length so that the minimum diameter is positioned at the point where the central thermocouple was attached during the thermal cycle. This insured an accurate determination of the properties at the point of temperature measurement and control and not of an adjoining region. Of course, this specimen type cannot yield the commonly used 0.2 percent offset yield strength and the proportional limit must be used as the yielding criterion. Typical slow notch bend specimens (see Figure 13) were used to determine the relative toughnesses produced by the various cycles.

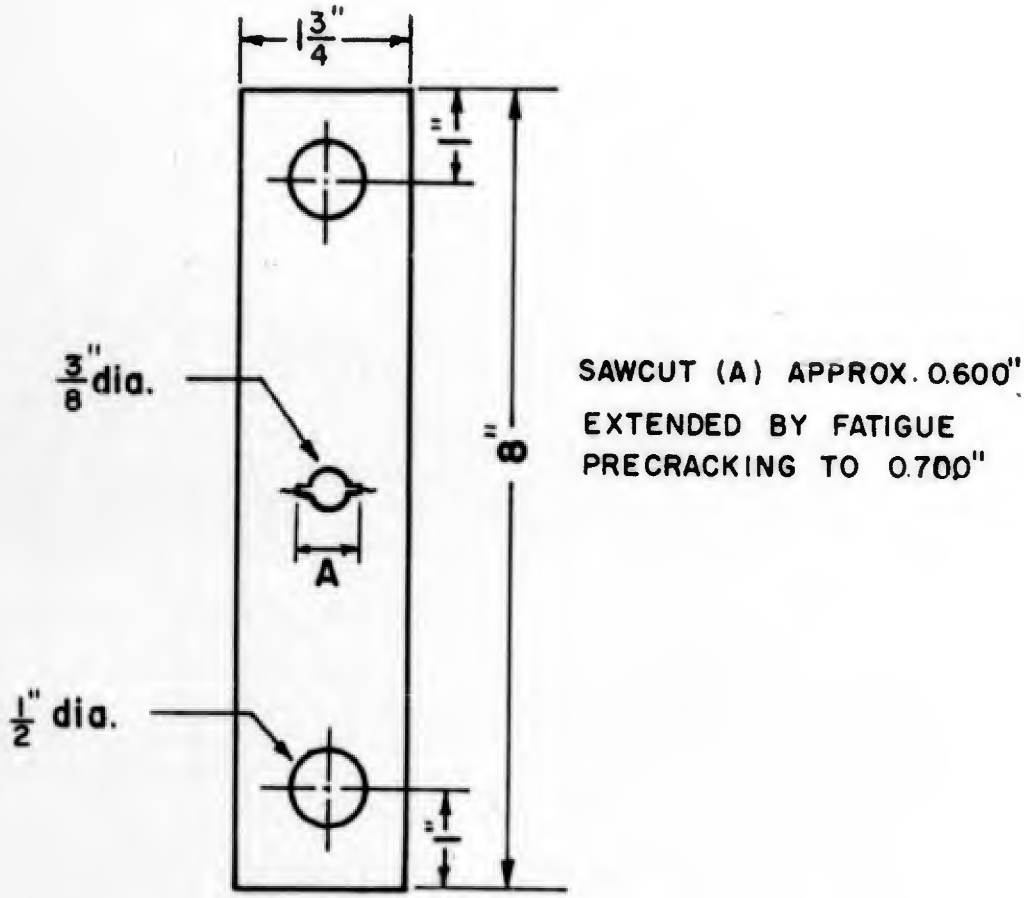


Figure 18. Center Notch Tensile Specimen Geometry.

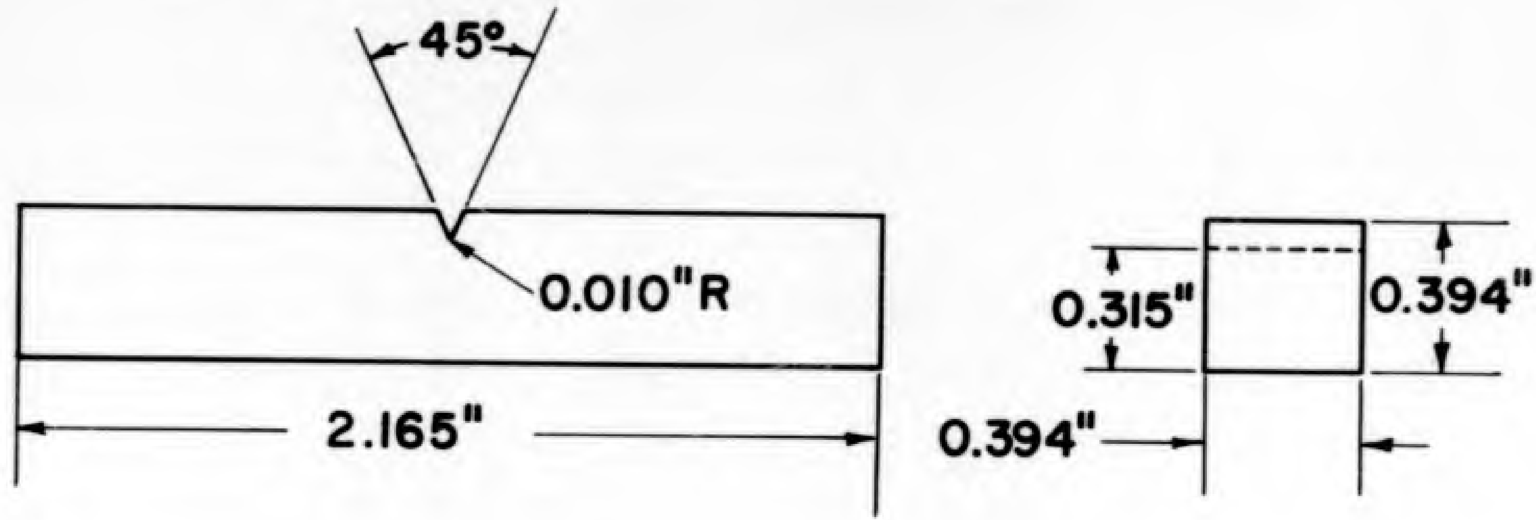
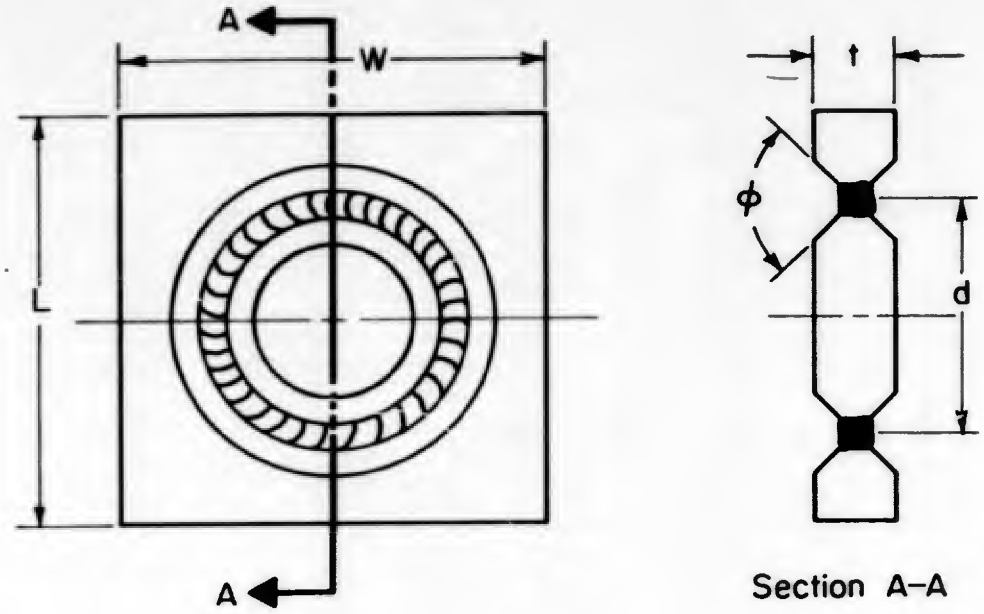


Figure 19. Charpy V Notch Impact Specimen (ASTM E-23-56T).

CRACK-SUSCEPTIBILITY SPECIMEN - CIRCULAR PATCH



Dimensions, inches				
L	W	φ	d	t
12	12	90°	Var.	Var.
5	5	0°	2	0.076

Figure 20. Circular Patch Weld Restraint Snecimen (Ref. 11).

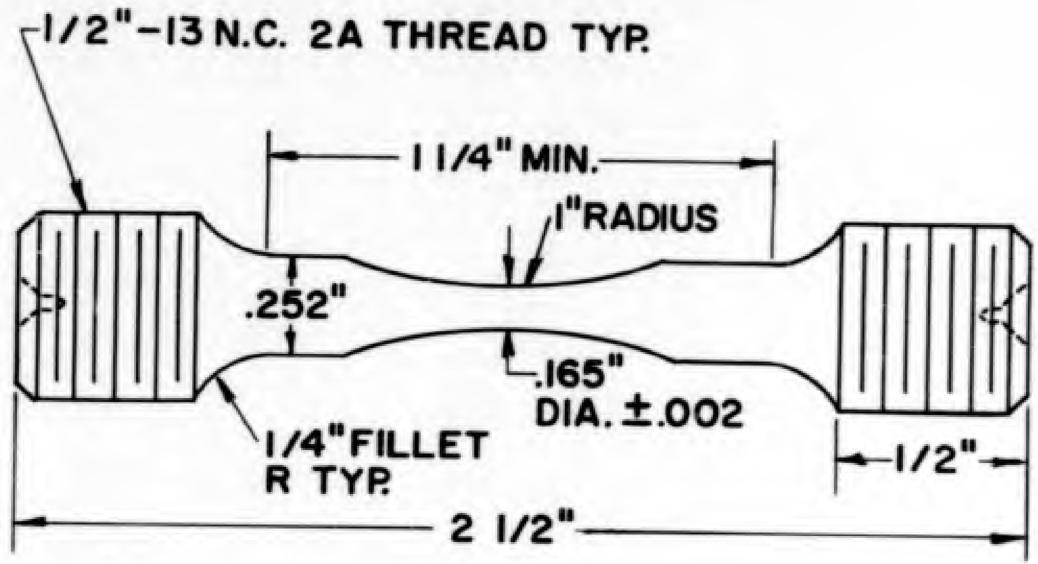


Figure 21. Synthetic Weld Thermal Cycle Tensile Specimen Geometry.

V RESULTS AND DISCUSSION

A. Martensitic Steels

A total of five martensitic steels were incorporated into the program for this year including two low carbon 9%Ni-4%Co steels (HP 9-4-20 1/2-inch plate and HP 9-4-25 1-inch plate), a low alloy steel (AMS 6435 1/2-inch plate) and two hot-work die steels (Vasco Jet X-2 1/2-inch plate and D6AC 1/2-inch plate and 0.090-inch sheet).

1. HP 9-4-20 Steel (1/2-Inch Plate)

a. Base Metal Evaluation

The heat treatment of the HP 9-4-20 steel was identical to that used in the first year's work[1], i.e., austenitized at 1550°F for 30 minutes, oil quench and double temper at 950°F for 2 hour cycles. The smooth tensile properties of plate given this heat treatment are shown in Table 3. The plane strain fracture toughness, K_{IC}, of the material using surface cracked specimens was found to be about 86 ksi $\sqrt{in.}$ Photomicrographs of unetched HP 9-4-20 plate, shown in Figure 22, indicate that the inclusion content of this material is low. The microstructure of heat treated plate, Figure 23, consists of fine grained tempered martensite. The Charpy V-notch impact properties at several temperatures of the HP 9-4-20 steel were determined previously and are presented in Table 4 and Figure 24.

b. Evaluation of TIG Welds in HP 9-4-20 1/2-Inch Plate

Automatic gas tungsten arc welds were made in HP 9-4-20 material at the parameter selected as the most satisfactory at the conclusion of the first year's work[1]. These welds were made at a welding speed of 10 inches per minute (ipm) using helium gas shielding with the five specially prepared modified filler wires. HP 9-4-20 with 0.05%Ti, 0.20%Ti, 0.06%Al, 0.12%Al and a control wire with no Ti or Al. Manual gas tungsten arc welds were also made in HP 9-4-20 material to develop procedures for manual welding. These welds were made using a mixture of 30 cubic feet per hour (cfh) helium and 5 cfh of argon flowing through the torch and 5 cfh of helium flowing through the backup bar. Both the weave bead and stringer bead techniques were used. In making weave beads, the operator oscillated the torch from side to side while making the weld. The stringer beads were made without oscillating the torch from side to side. Weave beads are usually much wider than stringer beads. These welds were made using filler wire No. 15 (HP 9-4-20 with 0.12%Al). Fusion welding parameters for the second through the final pass of these welds are presented in Table 5. It should be noted that the first or root pass of most welds is made with a slightly different wire feed rate, amperage and voltage to allow complete penetration and prevent cracking. The welding parameters for the root pass are presented in Table 6.

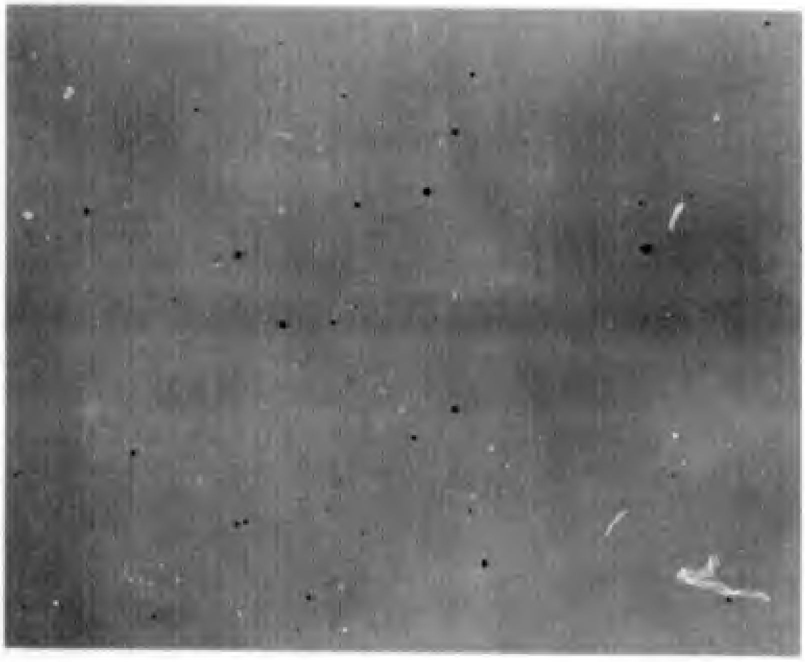
(1) Weld Quality

The results of radiographic evaluation are presented in the comments column of Table 5. The weld made with modified HP 9-4-20 filler wire

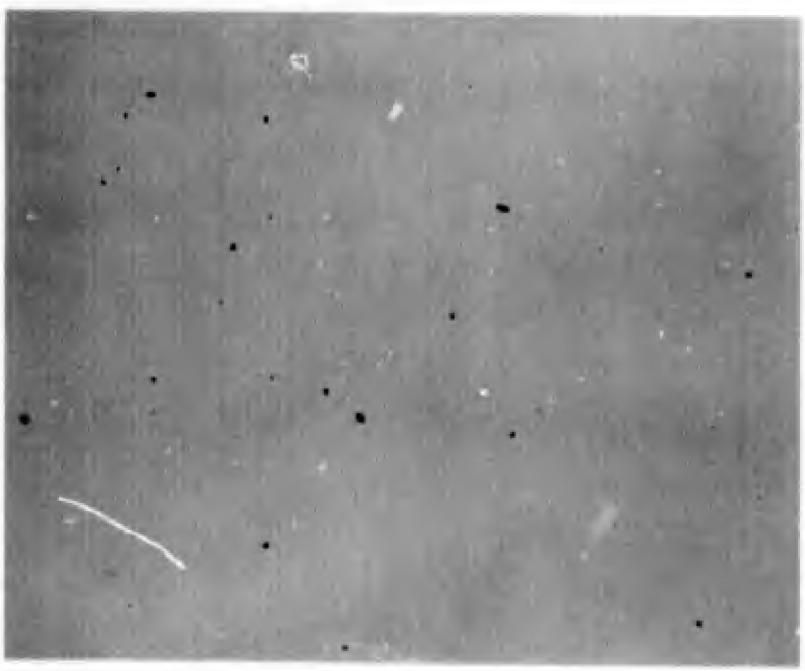
TABLE 3

SMOOTH TENSILE PROPERTIES OF HP 9-4-20 PLATE

Heat No.	Thickness (in.)	Test Direction	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elongation (%-1")	R.A. (%)
3930774 (Code H)	0.500	Longitudinal	192.5	216.6	20.0	59.7
		Longitudinal	190.9	216.9	19.0	57.7
		Transverse	191.3	215.9	18.5	59.2
		Transverse	191.9	217.1	18.0	55.6

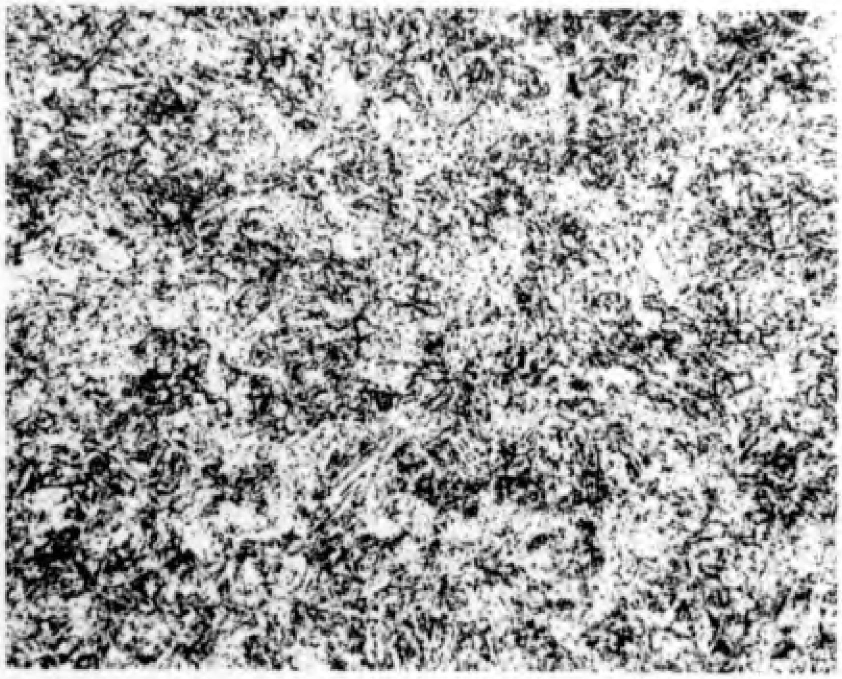


(a) Parallel to Rolling Direction



(b) Perpendicular to Rolling Direction

Figure 22. Unetched HP 9-4-20 1/2-Inch Plate Material Showing Inclusion Levels. 100X



Heat No. 3930774 500X

Figure 23. Microstructure (Tempered Martensite) of 1/2-Inch HP 9-4-20 Plate Austenitized at 1550°F/30 Minutes Plus a Double Temper at 950°F for 2 Hours. Etch: 2% Nital

TABLE 4

CHARPY V-NOTCH IMPACT STRENGTH OF 1/2 INCH
HP 9-4-20 PLATE MATERIAL

Temp. (°F)	Impact Energy (Ft. lbs)	% Fibrous Fracture	Lateral Expansion (Mils)*
0	28.0	100	15
-50	25.0	100	15
-80	24.5	100	15
-120	24.0	100	10
-150	23.0	100	9

* Expansion measured at base of fracture

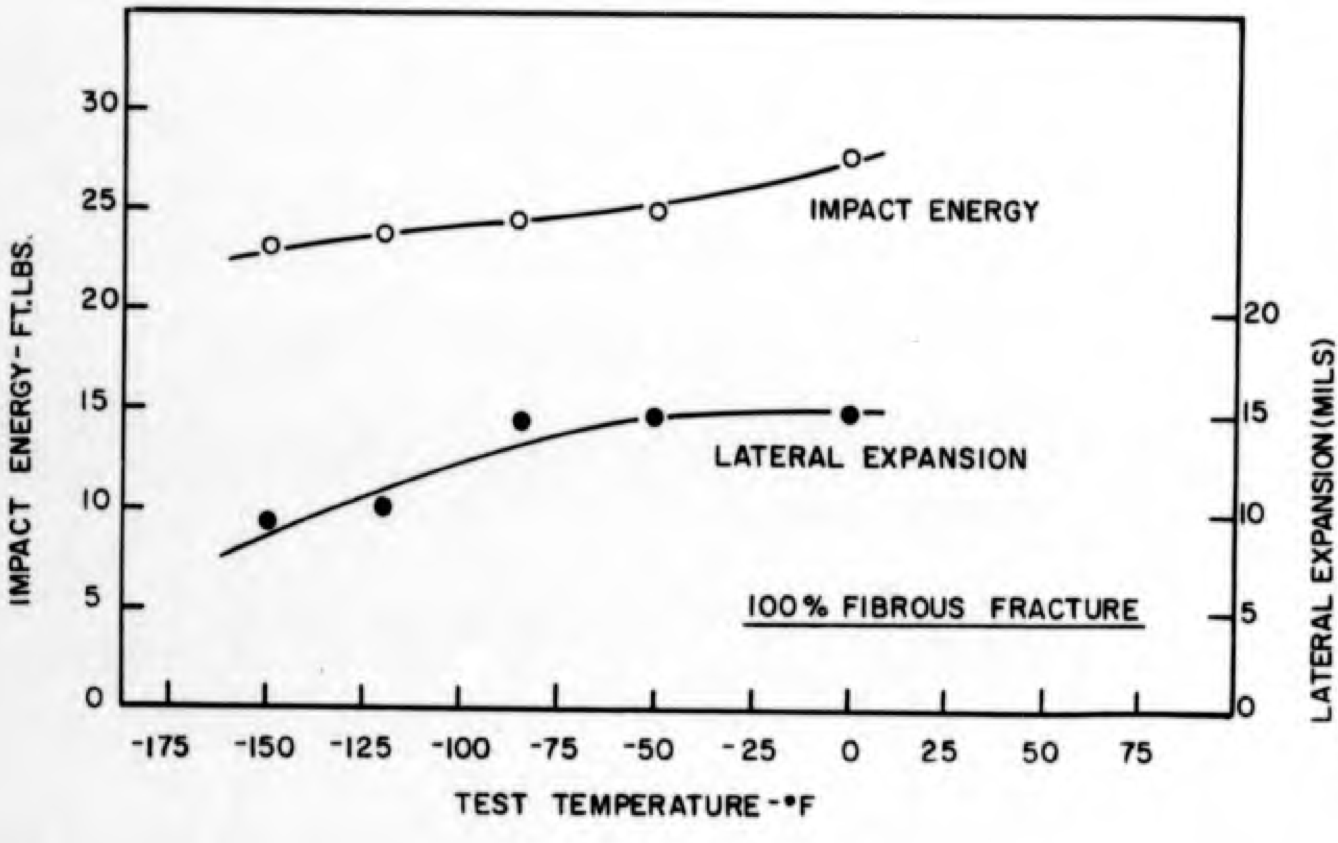


Figure 24. Charpy V-Notch Impact Transition Curve for HP 9-4-20 1/2-Inch Plate Material.

TABLE 5

FUSION WELDING PARAMETERS FOR
TIG WELDS MADE IN HP 9-4-20 1/2 INCH PLATE

Weld No.	Filler Wire Dia. (in.)	Wire(a) Composition	Pre- and Post Heat °F	No Passes	W/S ipm	Wire Speed (ipm)	amps	Volts	Gas (cfh) Torch	Gas (cfh) Backup	Comments(c)
H247	0.062	11	None	13	10	48(b)	230	18	50He	4He	2 spots porosity
H248	"	12	"	13	10	44(b)	"	"	"	"	Scattered porosity
H249	"	13	"	13	10	44(b)	"	"	"	"	
H250	"	14	"	13	10	44(b)	"	"	"	"	Slight scattered porosity
H251	"	15	"	13	10	44(b)	"	"	"	"	Three small spots porosity
H258	"	15	"	9	Man	-	130	16	30He 5A	5He	Weld made with weave beads
H259	"	15	"	15	Man	-	"	"	30He 5A	"	Weld made with stringer beads
H283	"	15	"	12	10	-	-	-	50He	5He	These welds discussed under crack
H284	"	13	"	11	10	-	-	-	"	"	Susceptibility section
H288	"	14	"	11	10	44(b)	230	18	50He	5He	
H289	"	15	"	11	10	44(b)	230	"	"	"	

(a) Wire composition is presented in Table 2.

(b) The wire speed, amperage and voltage are for the second pass through the final pass. Parameters for the first pass are presented in Table 6.

(c) Weld quality comments based upon radiographic inspection.

TABLE 6

FUSION WELDING PARAMETERS OF FIRST PASS FOR
TIG WELDS MADE IN HP 9-4-20 1/2 INCH PLATE

Weld No.[(a)]	Wire Speed (ipm)	amps	Volts
H247	36	220	17
H248	36	230	17
H249	44	230	16
H250	12	230	16
H251	12	230	17

(a) Wire composition, welding speed and shielding gas were the same as those shown in Table 5.

without additions of either Ti or Al (weld No. H247) contained two small spots of porosity near the end of the weld. Welds made with filler wires containing 0.05%Ti and 0.06%Al (welds No. H248 and H250, respectively) both contained appreciable porosity. The weld made with 0.20%Ti filler wire (weld No. H249) was completely free from porosity, while the weld made with the 0.12%Al filler wire (weld No. H251) had only three very small spots. Welds made with filler wires containing Ti had a tendency to form a tenacious surface oxide on the weld puddle. This oxide could only be removed by grinding each weld pass prior to making subsequent passes. Welds made with the Al bearing wires were clean at the completion of the welding operation and required only a light wire brushing. In addition, it was quite noticeable that the weld puddle was much more fluid when using wire containing both levels of aluminum. The manual welds were found to be sound and free from porosity.

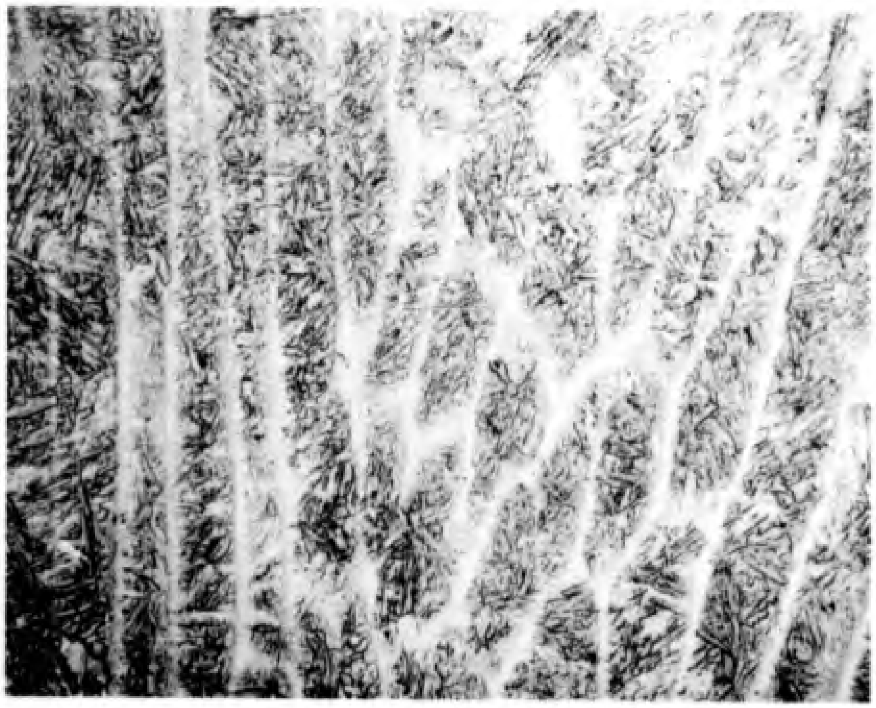
(2) <u>Weld Microstructure</u>

The microstructure of TIG welds made in HP 9-4-20 plate with modified HP 9-4-20 filler wires are presented in Figures 25 to 27. These welds were made with wire of the basic HP 9-4-20 composition (wire No. 11), the basic composition with a 0.20%Ti addition (wire No. 13) and the basic composition with a 0.12%Al added (wire No. 15) respectively. The microstructure for weld No. H247 made with the wire of basic composition (Figure 25) is typical of welds made in HP 9-4-20 material. Evidence of coring is present in the top of the fusion zone and grain refinement has taken place in the center of the fusion zone. The microstructure for weld No. H249 made with wire containing 0.20%Ti, Figure 26, shows evidence of titanium oxide or carbides being present in the top of the fusion zone. The microstructure of weld No. H251 made with wire containing 0.12%Al (Figure 27) shows a significant amount of aluminum oxide in the center of the fusion zone, but only small amounts present in the top of the fusion zone.

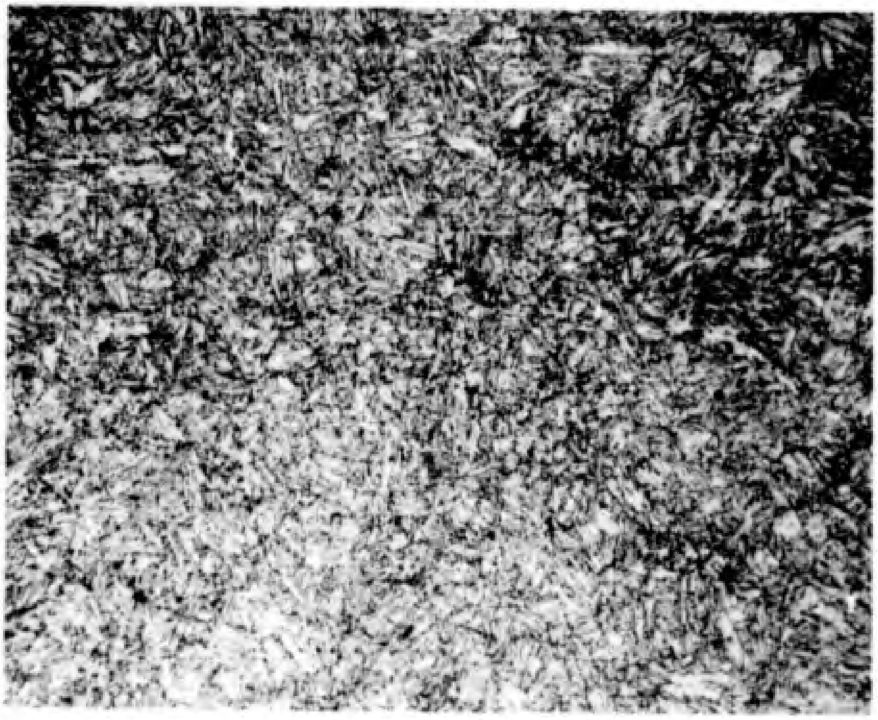
The microstructure of manual TIG welds made in HP 9-4-20 material using filler wire No. 15 (0.12%Al addition) are presented in Figures 28 and 29. Although the microstructures of the top of the fusion zones of both welds are similar and coring and segregation have occurred, close observation indicates that the dendritic spacings are greater in weld No. H258 made with the weave bead technique, Figure 28. This is the result of a greater energy input into the weld at the slower travel speed required to make a weave type bead. It was determined during the first year's work[1] that welds with fairly wide dendritic spacings usually have lower strengths than desired for this program. However, it was possible to reduce these spacings by decreasing the energy input into the weld. The microstructures of the center of the fusion zone indicate that a more homogeneous structure resulted from the weave beads. This occurred as a result of the higher temperatures, longer times at temperature, and slower cooling rates in previously deposited weld metal caused by the reheat cycle from subsequent weave pattern weld passes.

(3) <u>Weld Hardness Surveys</u>

Hardness surveys of welds made in HP 9-4-20 plate with each of the modified HP 9-4-20 filler wires are presented in Figures 30 to 34. The hardness of the weld and heat-affected zones are in general higher than those for the base metal. No appreciable difference in hardness of the fusion zones

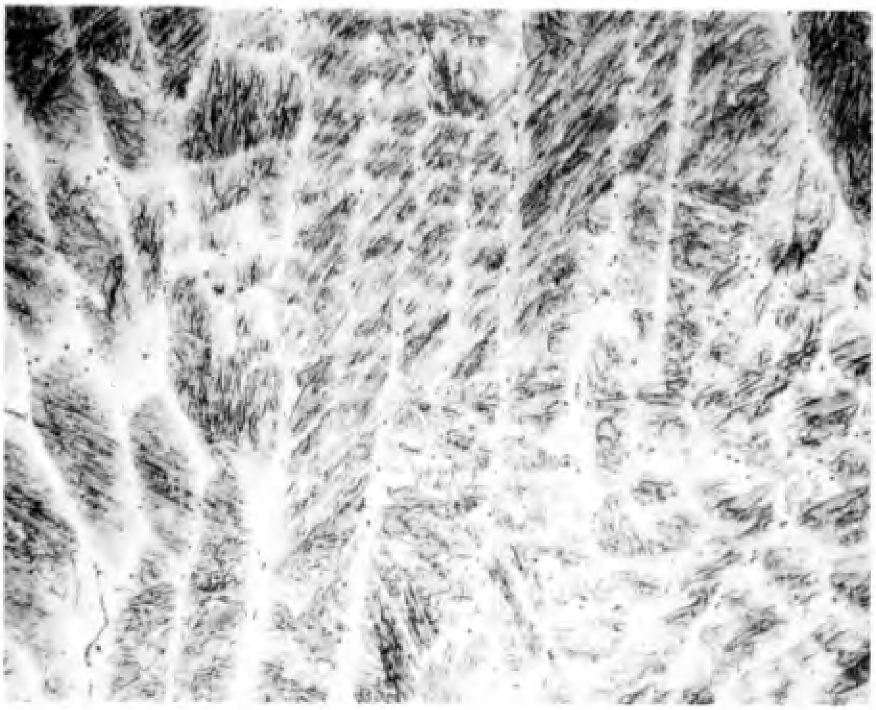


Top of Fusion Zone 500X

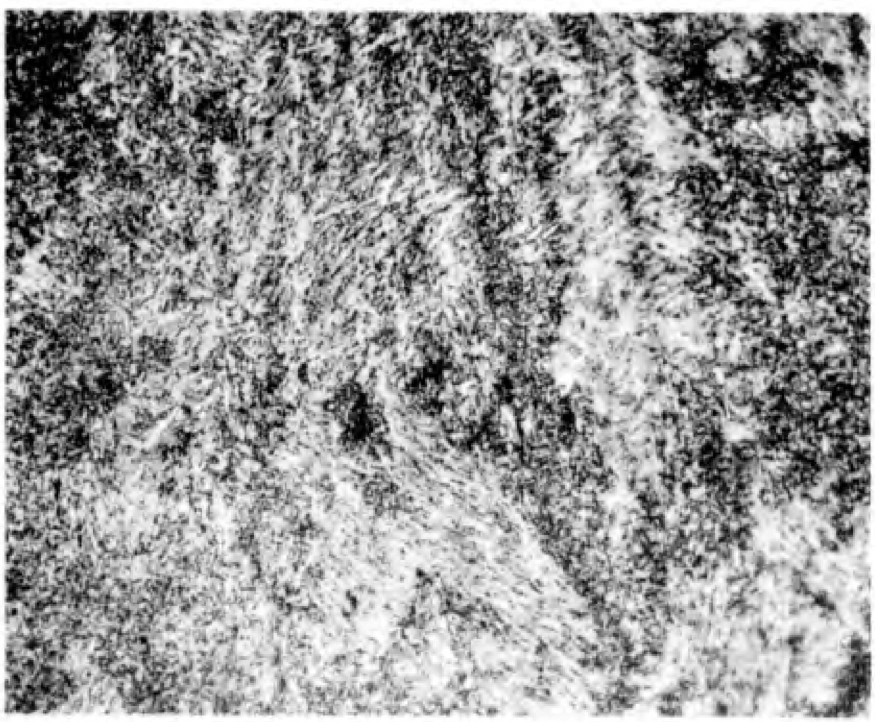


Center of Fusion Zone 500X

Figure 25. Microstructure (Martensite) of the Top and Center of the Fusion Zone of TIG Weld No. H247 Made in HP 9-4-20 Plate Using Filler Wire No. 11. Etch: 2% Nital

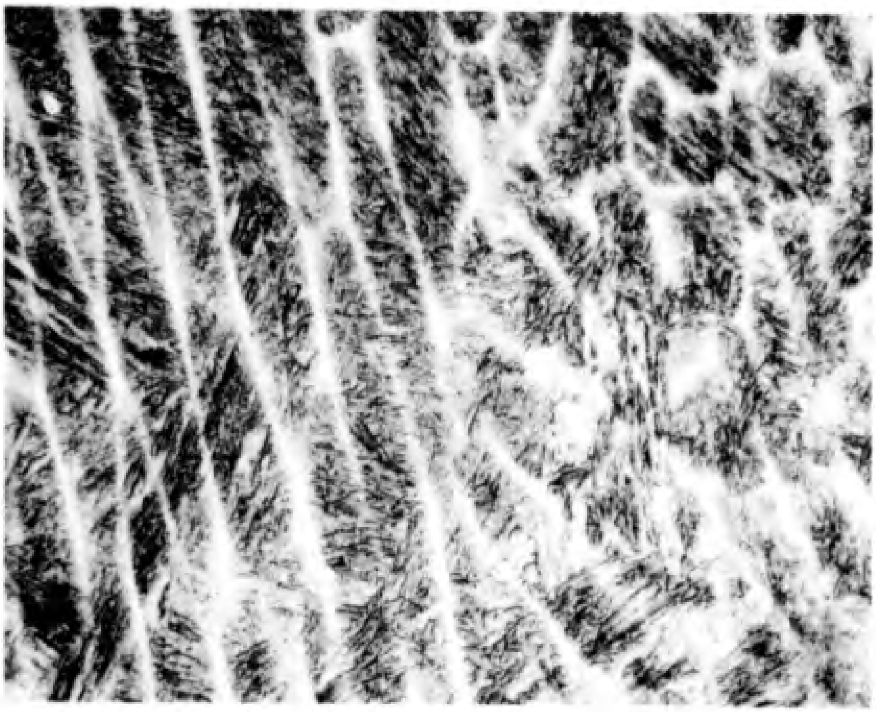


Top of Fusion Zone 500X

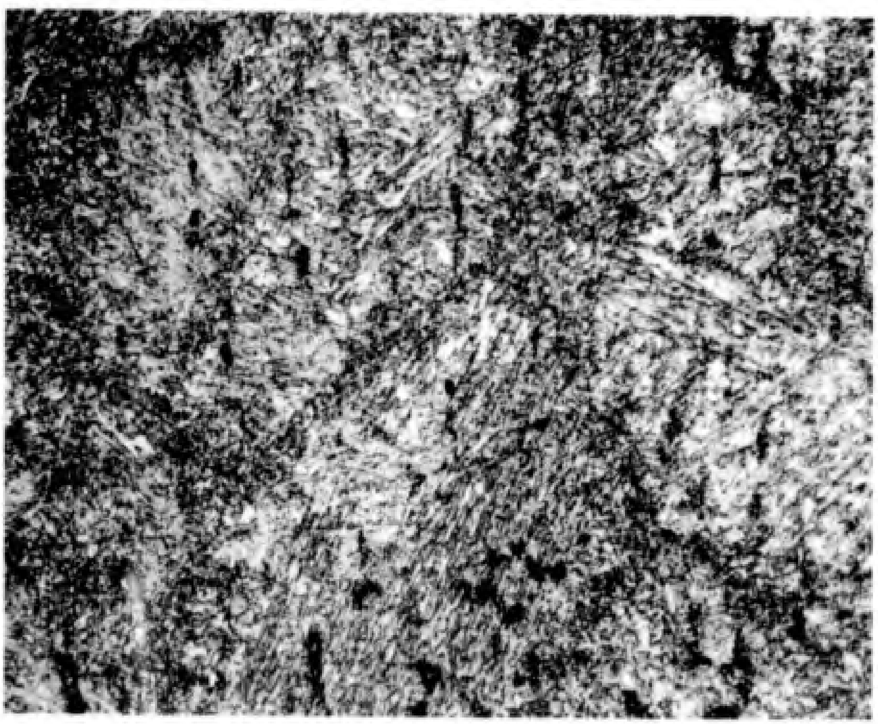


Center of Fusion Zone 500X

Figure 26. Microstructure (Martensite) of the Top and Center of the Fusion Zone of TIG Weld No. H249 Made in HP 9-4-20 Plate Using Filler Wire No. 13. Etch: 2% Nital



Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 27. Microstructure (Martensite) of the Top and Center of the Fusion Zone of TIG Weld No. H251 Made in HP 9-4-20 Plate Using Filler Wire No. 15. Etch: 2% Nital

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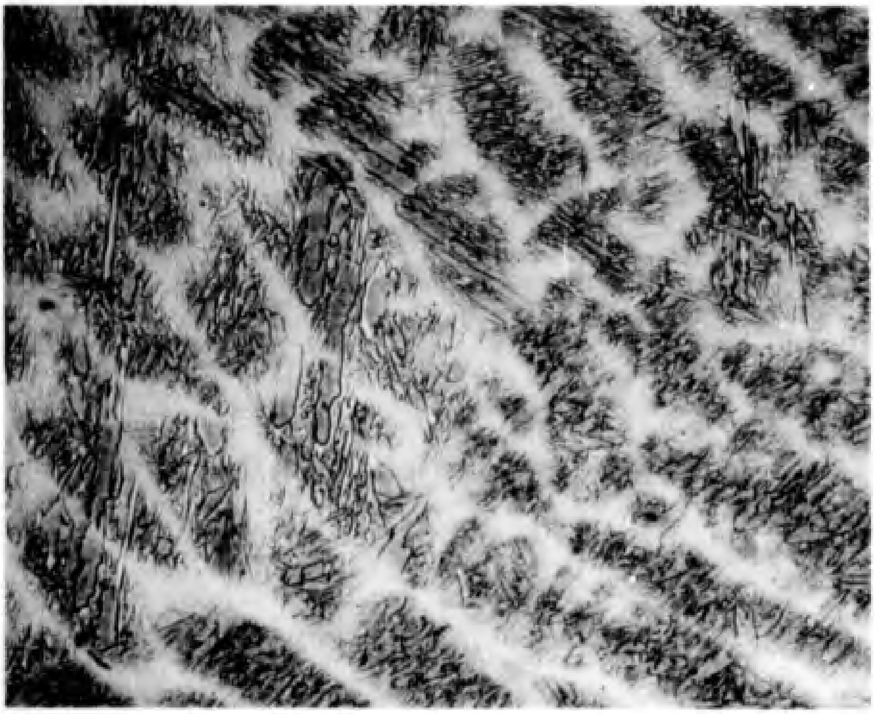
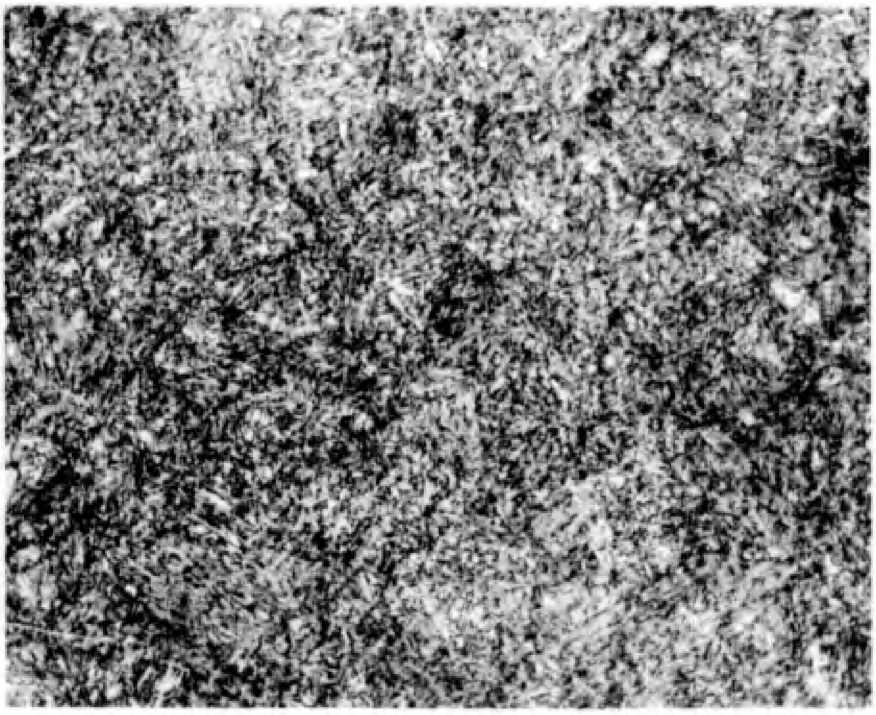


Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 28. Microstructure of Multipass Manual Tungsten Inert Gas Weld No. H258 Made in 1/2-Inch HP 9-4-20 Plate Using Filler Wire No. 15. Weld Was Made with Weave Bead Technique. Etch: 2% Nital

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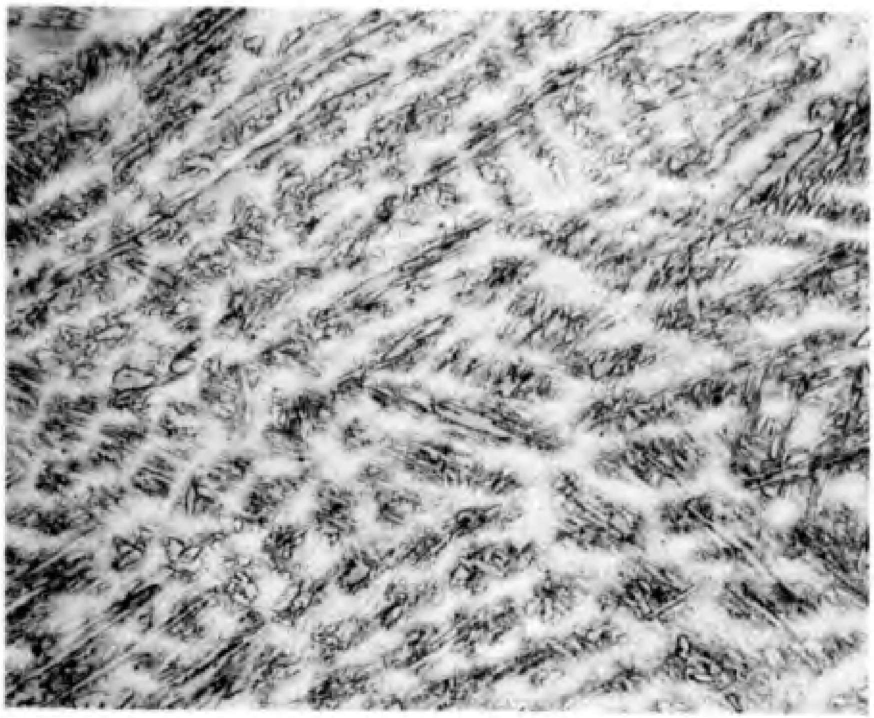
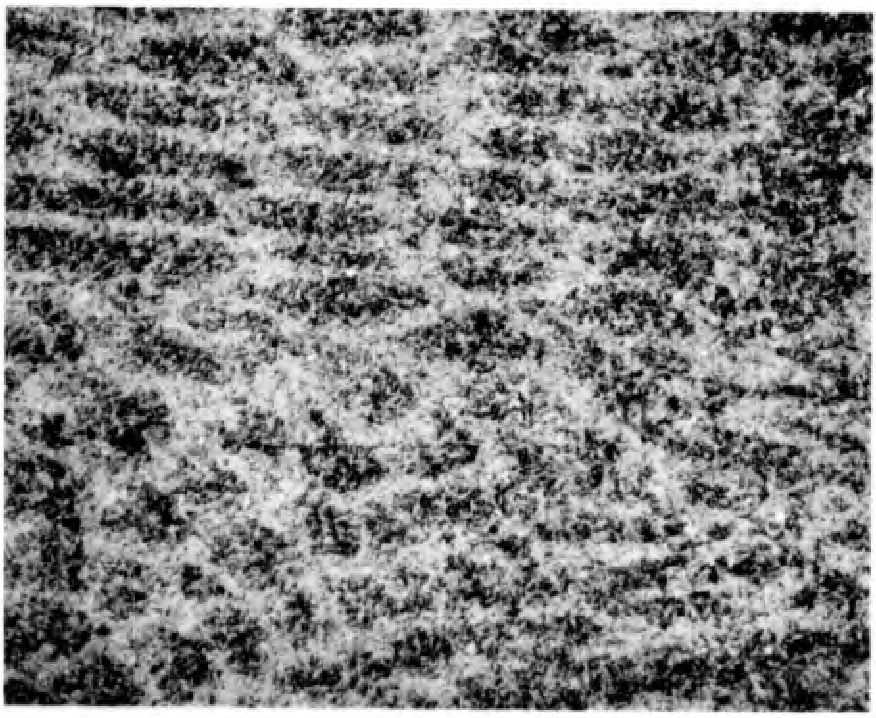


Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 29. Microstructure of Multipass Manual Tungsten Inert Gas Weld No. H259 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 15. Weld Was Made with Stringer Bead Technique. Etch: 2% Nital

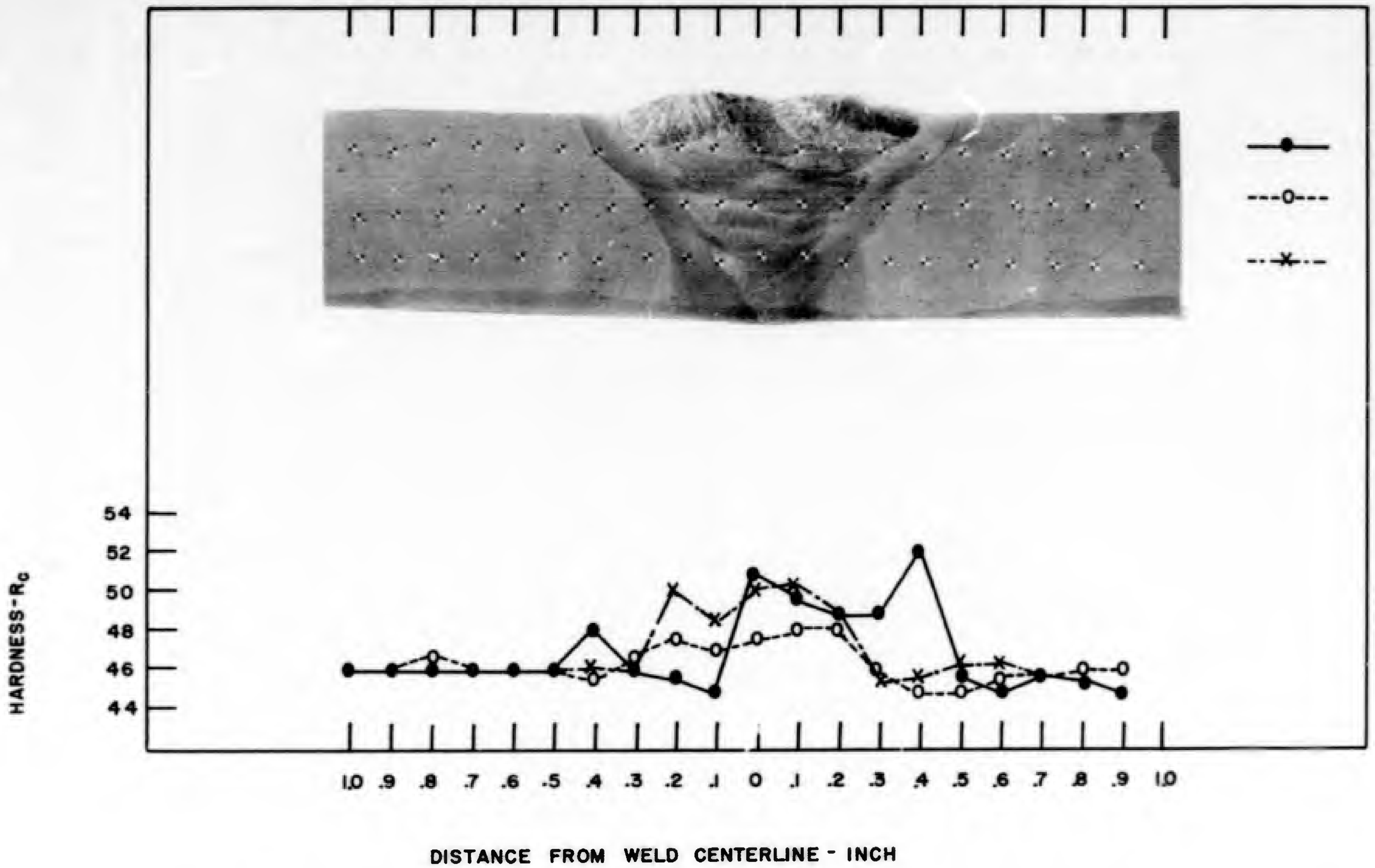


Figure 30. Hardness Survey of TIG Weld No. H247 Made in HP 9-4-20 Plate Using Filler Wire No. 11. (Unmodified HP 9-4-20)

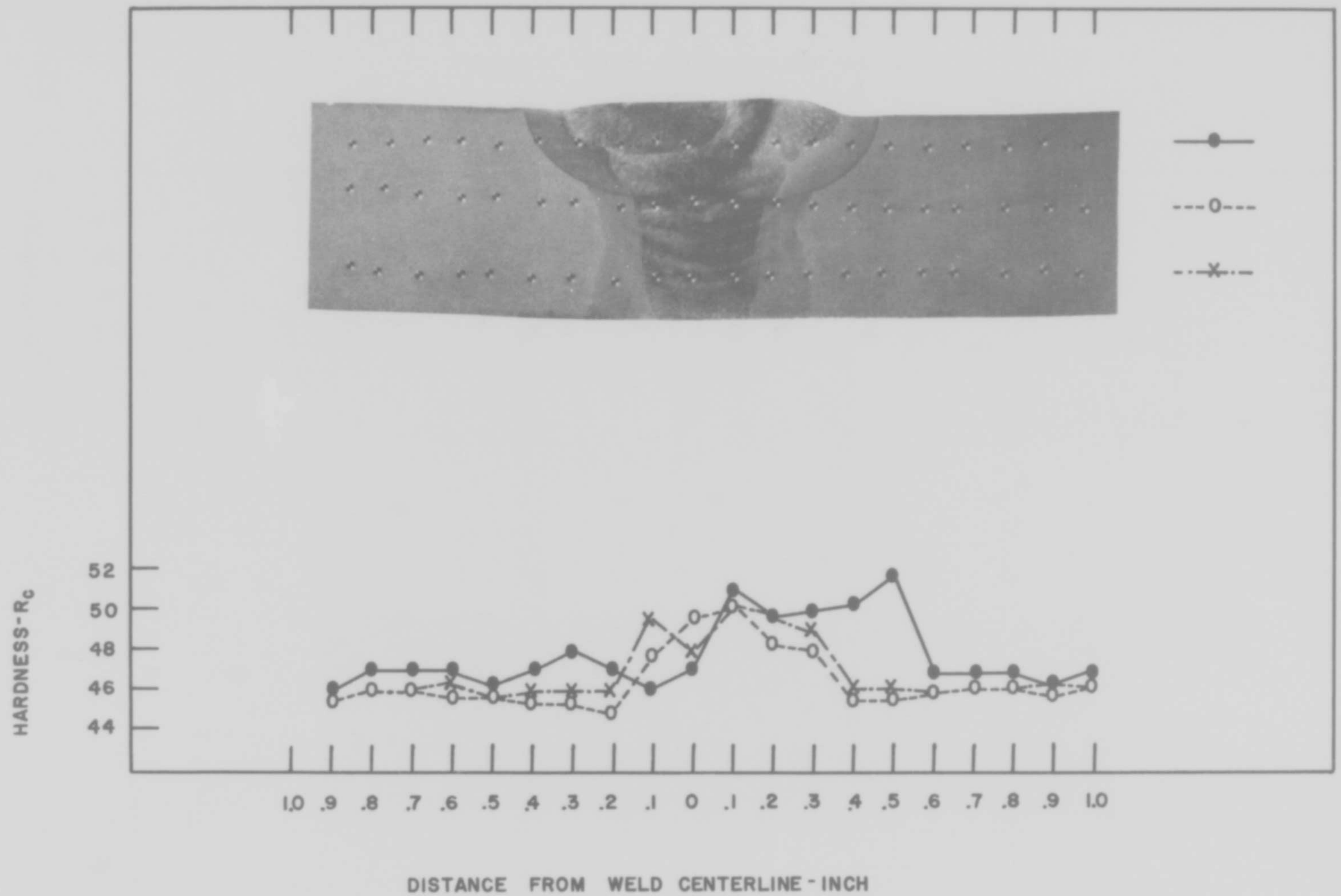


Figure 31. Hardness Survey of TIG Weld No. H248 Made in HP 9-4-20 Plate Using Filler Wire No. 12 (HP 9-4-20 Modified with 0.05% Ti).

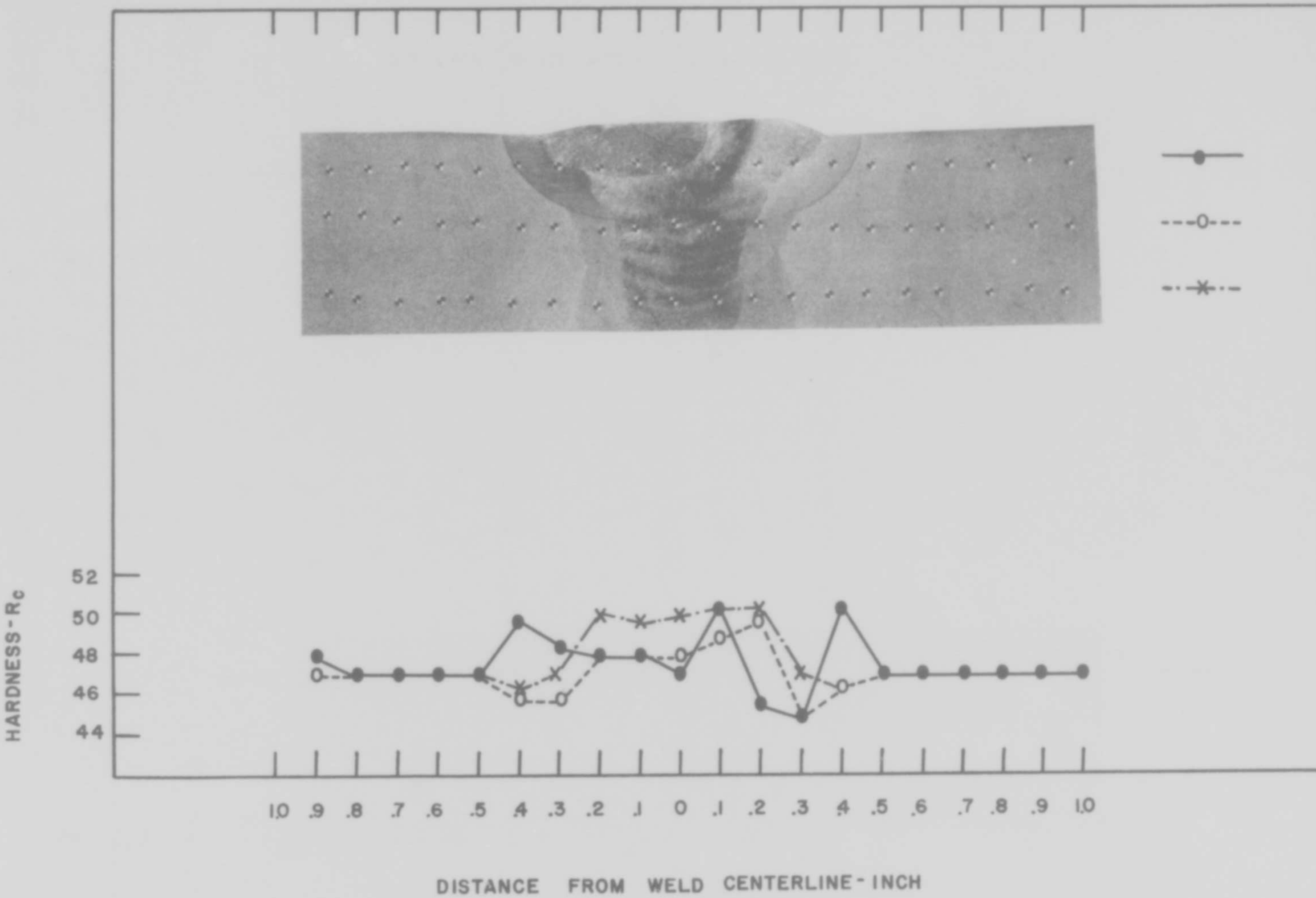


Figure 32. Hardness Survey of TIG Weld H249 Made in HP 9-4-20 Plate Using Filler Wire No. 13 (HP 9-4-20 Modified with 0.20%Ti).

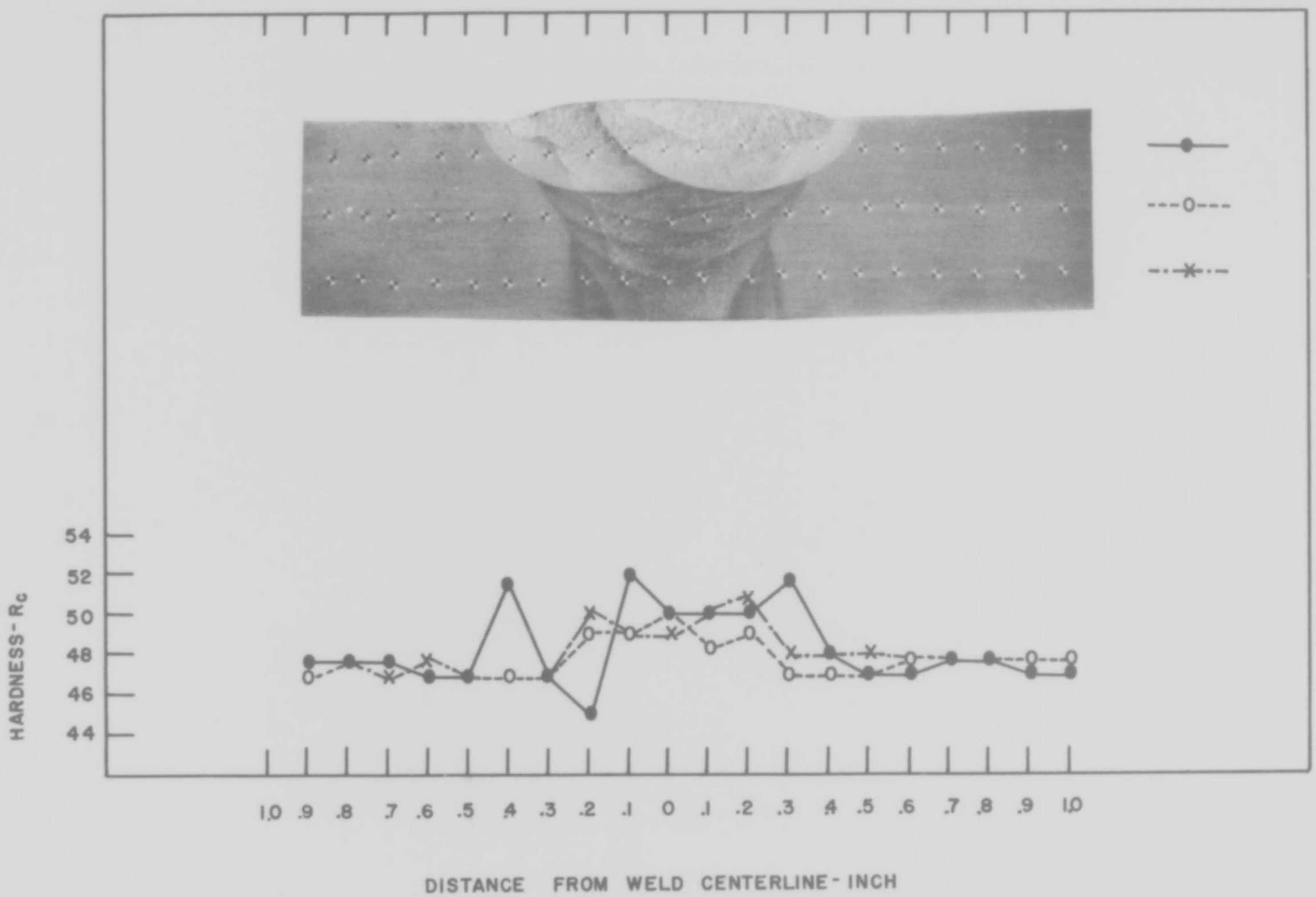


Figure 33. Hardness Survey of TIG Weld No. H250 Made in HP 9-4-20 Plate Using Filler Wire No. 14 (HP 9-4-20 Modified with 0.06%Al).

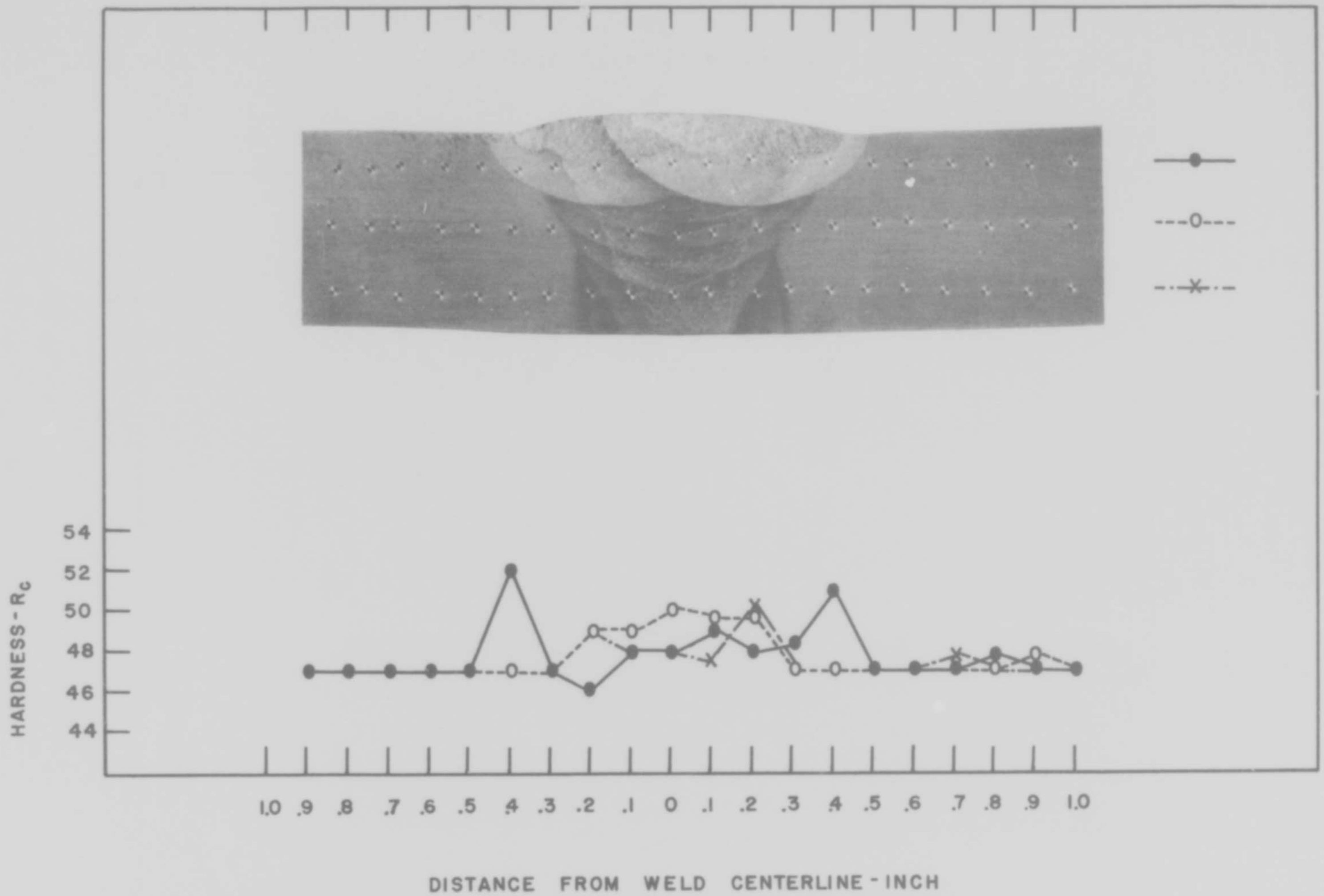


Figure 34. Hardness Survey of TIG Weld No. H251 Made in HP 9-4-20 Plate Using Filler Wire No. 15 (HP 9-4-20 Modified with 0.12%Al).

of the various welds is evident. This indicates that the elements, either Ti or Al, added for deoxidation should not have an adverse effect upon the mechanical properties of the weldments.

Hardness surveys of manual welds made in HP 9-4-20 1/2-inch plate are presented in Figures 35 and 36. Although there are low hardness readings in each of the welds, the hardnesses of the weld made with weave beads (weld No. H258) are generally lower than those for the weld made with stringer beads (weld No. H259). Nevertheless, the majority of the hardness readings for each weld indicate that the mechanical properties should meet the criteria for the program. However, as will be discussed in the next section, the weld with the weave beads, Figure 35, did not have adequate yield strength in either longitudinal or transverse specimens.

(4) Tensile Properties

The smooth tensile results for automatic welds made in HP 9-4-20 1/2-inch plate are presented in Table 7. These welds, made with each of the five modified HP 9-4-20 filler wires (Table 2), have desirable properties with yield strengths exceeding 180 ksi and both yield strength and ultimate strength joint efficiencies greater than 99 percent. The smooth tensile results for the weave and stringer bead manual welds indicate that the weld made with stringer beads possessed the desirable properties with yield strengths in excess of 180 ksi and yield strength and ultimate strength joint efficiencies greater than 97 percent. These results substantiate the findings of previous work[1] that low energy inputs are beneficial in welding this material. Each of these welds was made at the same amperage and voltage, the only variable being travel speed which was obviously slower for the weld made with weave beads. Based upon these results, it can be concluded that the required mechanical properties can be obtained in manual welds in HP 9-4-20 1/2-inch plate if stringer beads and a relatively low energy input are used.

(5) Fracture Toughness

The fracture toughness values for automatic TIG welds made in HP 9-4-20 material using each of the five modified filler wires are presented in Table 8. It appears that an addition of 0.03%Ti (wire No. 12) to the base composition wire (No. 11) caused a slight reduction in the fracture toughness of the weld. An addition of 0.20%Ti (wire No. 13) to the base composition did not appear to change the fracture toughness significantly as might be expected. However, additions of aluminum (wires No. 14 and No. 15) resulted in increased fracture toughness values for the weld. These values compare favorably with those determined during the first year's work[1] for filler wires 9 and 10 using surface crack specimens (83.5 to 89.4 ksi $\sqrt{\text{inch}}$).

It was noted that whenever a Type 2 curve was obtained under a 3 point loading a K_{IC}^* value of greater than 100 ksi $\sqrt{\text{inch}}$ was measured. Four point loading of notch bend specimens from duplicate welds (see Table 8) showed an increased consistency in K_{IC}^* values between 110 and 120 ksi $\sqrt{\text{inch}}$, although Type 2 and 3 load deflection curves were not obtained as expected. Surface-cracked specimens were also tested of welds H288 and H289 made with the aluminum bearing filler wires No. 14 and 15. As shown in Table 8(a), K_{IC} values comparable to those obtained on the parent metal in last year's work were obtained.

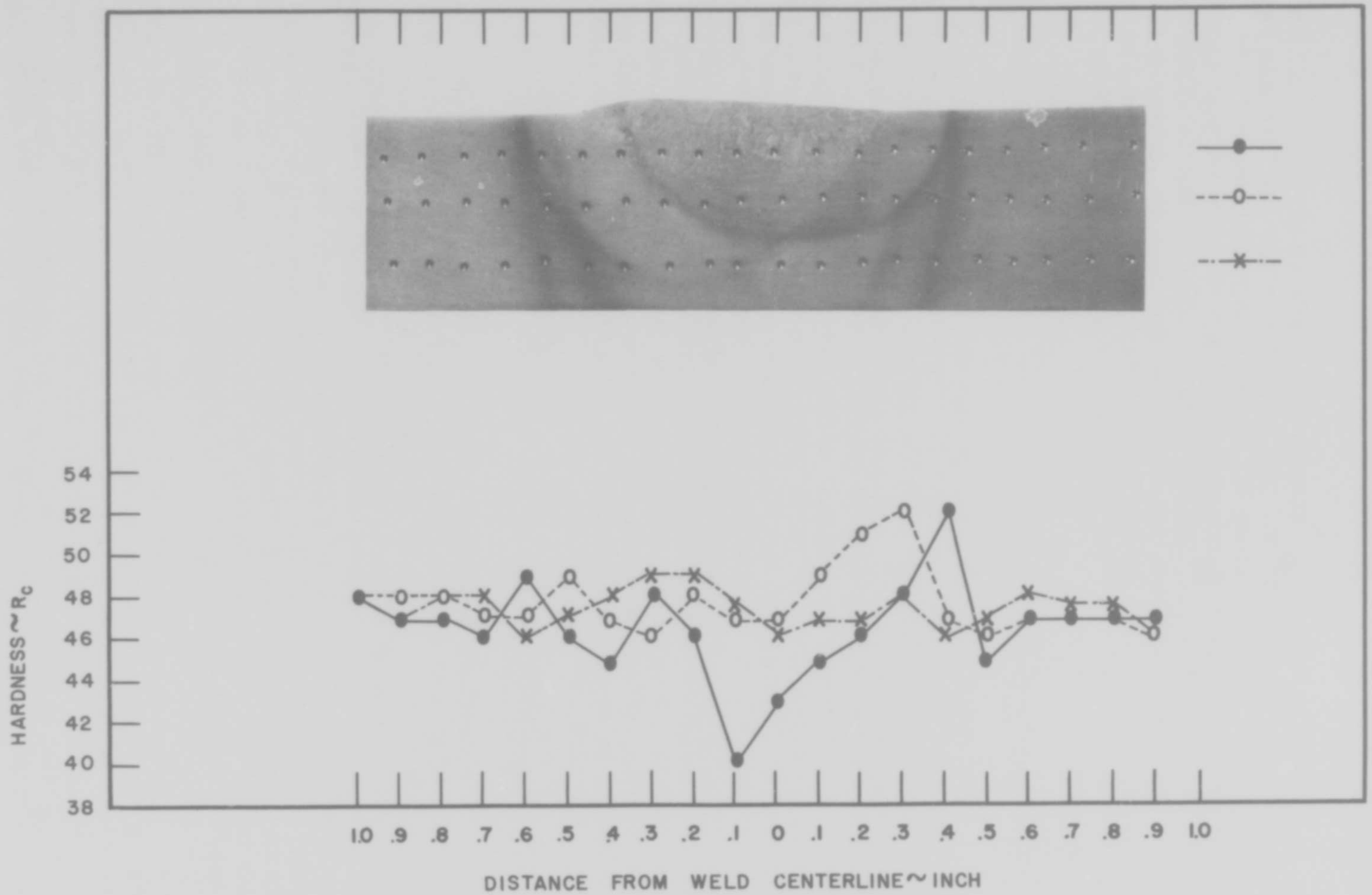


Figure 35. Hardness Survey of Manual TIG Weld No. H258 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 15. Weld was Made with Weave Beads.

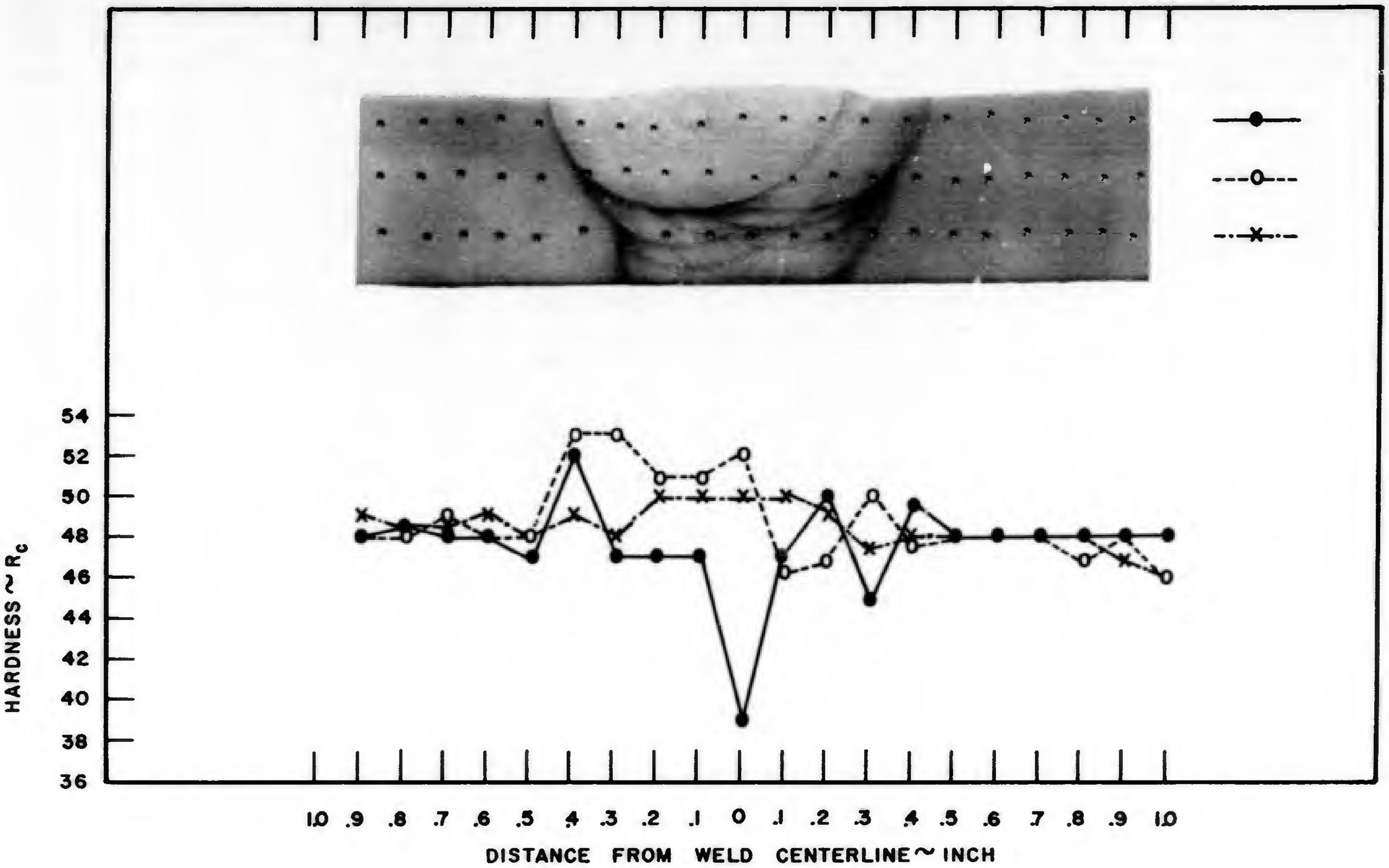


Figure 36. Hardness Survey of Manual TIG Weld No. H259 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 15. Weld was Made with Stringer Beads.

TABLE 7

TENSILE PROPERTIES OF TIG WELDS MADE IN HP 9-4-20 1/2 INCH PLATE

Weld No.	Test(a) Direction	Filler Wire(b)	Welding Speed (ipm)	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elong. %(c)	R.A. (%)	Energy Input KJ/in/pass	% Joint Efficiency(d) Y.S.	U.T.S.	Comments
H247	L	11	10	190.3	241.4	18.0	55.0	24.8	-	-	-
"	L	11	10	193.5	237.2	19.0	54.5	24.8	-	-	-
"	T	11	10	189.8	216.8	10.0	61.5	24.8	99.4	100.0	g
"	T	11	10	193.4	216.5	8.5	59.2	24.8	100.0	100.0	g
H248	L	12	10	202.5	242.6	13.5	32.9	24.8	-	-	--
"	L	12	10	200.3	247.2	15.0	39.5	24.8	-	-	-
"	T	12	10	191.9	219.5	10.0	61.3	24.8	100.0	100.0	g
"	T	12	10	191.1	220.3	10.0	59.8	24.8	100.0	100.0	g
H249	L	13	10	210.6	229.8	14.0	31.3	24.8	-	-	-
"	L	13	10	210.5	230.9	14.0	35.4	24.8	-	-	-
"	T	13	10	191.3	217.3	10.5	62.4	24.8	100.0	100.0	g
"	T	13	10	191.4	217.1	10.0	62.4	24.8	100.0	100.0	g
H250	L	14	10	198.4	238.8	17.0	56.1	24.8	-	-	-
"	L	14	10	197.7	237.1	15.0	44.5	24.8	-	-	-
"	T	14	10	190.6	220.3	10.5	58.7	24.8	99.0	100.0	g
"	T	14	10	192.1	220.5	10.5	58.7	24.8	100.0	100.0	g
H251	L	15	10	203.5	235.7	18.5	55.4	24.8	-	-	-
"	L	15	10	200.1	233.2	15.5	26.5	24.8	-	-	-
"	T	15	10	190.9	219.5	10.5	59.7	24.8	99.9	100.0	g
"	T	15	10	193.3	219.9	10.0	50.8	24.8	100.0	100.0	g
H258	L	15	Manual	164.2	231.1	15.0	49.0	-	-	-	-
"	L	15	Manual	162.2	224.3	14.0	43.2	-	-	-	-
"	T	15	Manual	176.2	212.7	6.5	49.6	-	92.3	98.6	f
"	T	15	Manual	176.6	213.1	6.6	49.0	-	92.5	98.8	e
H259	L	15	Manual	193.3	242.0	15.0	51.9	-	-	-	-
"	L	15	Manual	180.6	246.4	17.0	54.5	-	-	-	-
"	T	15	Manual	187.6	219.7	7.5	42.3	-	98.2	100.0	e
"	T	15	Manual	185.8	218.5	7.5	49.6	-	97.2	100.0	e

TABLE 7 (CONTINUED)

TENSILE PROPERTIES OF TIG WELDS MADE IN HP 9-4-20 1/2 INCH PLATE

(a) (L) specimens were taken parallel with the weld and consisted entirely of weld deposit.
(T) specimens were taken transverse to the weld and included weld, heat affected zones and parent metal.

(b) Filler wire composition is presented in Table 2.

(c) (T) specimens had a gage length of two inches. (L) specimens had a gage length of one inch.

(d) Joint efficiency based on 191 and 216 ksi parent metal yield and ultimate strengths, respectively.

(e) Fracture occurred in heat affected zone approximately 1/4 inch from the fusion line.

(f) Fracture occurred in heat affected zone approximately 1/8 inch from the fusion line.

(g) Fracture occurred in parent metal.

TABLE 8

CALCULATED FRACTURE TOUGHNESS, K_{IC}^*, OF TIG WELDS MADE IN 1/2 INCH HP 9-4-20 PLATE AT A WELDING SPEED OF 10 IPM USING HELIUM SHIELDING

Specimen Identity	Filler Wire(a)	Notch Position	Width, W (inch)	Thickness, B (inch)	Crack Depth, a (inch)	Major Span Length, L' (inches)	Curve Type(b)	Load (lbs.)	Relative Plastic Zone Size r_y/B(c)	σ_{nom}/σ_{ys}(d)	Calculated Fracture Toughness, K_{IC}^* (ksi $\sqrt{inch}$)
3-Point Loading											
H247	11	Weld	0.425	0.501	0.123	4.0	1		0.012	2.02	69.8
	11	Weld	0.425	0.501	0.092	4.0	1		0.014	1.92	75.0
	11	HAZ	0.445	0.500	0.076	4.0	1		0.006	0.77	51.9
	11	HAZ	0.445	0.500	0.069	4.0	1		0.014	1.09	73.9
H248	12	Weld	0.428	0.501	0.067	4.0	1		0.008	0.85	56.0
	12	Weld	0.428	0.501	0.083	4.0	1		0.010	0.92	61.8
	12	HAZ	0.418	0.500	0.083	4.0	1		0.020	1.37	94.7
	12	HAZ	0.418	0.500	0.090	4.0	1		0.014	1.10	74.8
H249-3	13	Weld	0.414	0.498	0.097	4.5	1	1590	0.010	0.97	71.3
-4	13	Weld	0.423	0.496	0.115	4.5	1	1340	0.009	0.91	67.8
H250-3	14	Weld	0.392	0.497	0.128	4.5	1	1385	0.018	1.33	91.5
-4	14	Weld	0.414	0.498	0.115	4.5	1	1630	0.017	1.25	88.4
-5	14	Weld	0.414	0.487	0.123	4.5	1	1635	0.021	1.35	96.3
H251-3	15	Weld	0.427	0.497	0.111	4.5	1	1585	0.013	1.07	77.3
-4	15	Weld	0.427	0.497	0.128	4.5	1	1660	0.018	1.25	91.3
-5	15	Weld	0.427	0.487	0.147	4.5	1	1600	0.022	1.40	102.1
4-Point Loading											
H288-1	14	Weld	0.438	0.498	0.093	5.0	1	4505	0.030	1.49	116.6
-2	14	Weld	0.438	0.498	0.085	5.0	1	4480	0.027	1.41	109.3
-3	14	Weld	0.438	0.499	0.107	5.0	1	4110	0.029	1.47	115.3
H289-1	15	Weld	0.438	0.498	0.094	5.0	1	4580	0.031	1.52	119.7
-2	15	Weld	0.438	0.498	0.093	5.0	1	4490	0.029	1.48	116.0
-3	15	Weld	0.438	0.498	0.085	5.0	1	4845	0.031	1.52	119.8

Notes:
(a) Filler wire compositions given in Table 2.
(b) Curve types are defined in Figure 16.
(c) Plastic zone size, r_y, equals the difference between the effective crack length a^* and the measured crack length a ($a^* = a + E\theta/6\pi\sigma_{ys}^2$).
(d) σ_{nom}/σ_{ys} = nominal stress at crack initiation divided by 0.2% yield strength.

TABLE 8A

PLANE STRAIN FRACTURE TOUGHNESS OF TIG WELDS MADE IN HP 9-4-20 STEEL
1/2-INCH PLATE AT 10 IPM USING HELIUM SHIELDING

(Surface-Cracked Specimens)

Specimen Identity	Filler Wire(a)	Notch Position	Width, W (inch)	Thickness, B (inch)	Crack Size $2c_o$ (inch)	Crack Size a_o (inch)	Gross Failure Stress (ksi)	Plane Strain Fracture Toughness, K_{IC} (ksi $\sqrt{\text{inch}}$)
H288-1	14	HAZ	1.499	0.250	0.309	0.062	189.2	86.8
H288-2	14	Weld	1.499	0.250	0.260	0.086	209.2	98.2
H289-1	15	HAZ	1.499	0.250	0.184	0.052	223.5	87.7
H289-2	15	HAZ	1.499	0.250	0.260	0.077	206.3	95.3
H289-3	15	Weld	1.499	0.250	0.360	0.001	191.2	101.9

Note: (a) Filler wire composition given in Table 2.

(6) Charpy Impact Properties

The Charpy V-notch impact data for TIG welds H288 and H289 made in HP 9-4-20 1/2-inch plate using filler wires No. 14 and 15 (Table 2) are presented in Table 9, and shown graphically in Figure 37. The impact energies indicate that these welds have substantial toughness at temperatures from -320°F to room temperature considering the high strength levels. The fracture ductility represented by the lateral expansion at the base of the notch is somewhat low at -320°F but adequate at -100°F. At -100°F and up, the fractures were characterized by generous shear lips and a fibrous fracture texture. At -320°F, the shear lips were small and the fracture appeared brittle. Filler wire No. 15 seems to possess slightly better impact properties, but the differences may be considered insignificant.

(7) Crack Susceptibility Test

Circular patch weld restraint specimens, Figure 20, were made in HP 9-4-20 1/2-inch plate at 10 ipm using helium gas shielding. Two tests were made, one using filler wire 15 and one using filler wire 13. The procedure included first tack welding the patch in place, then depositing the root pass on one side of the plate. The plate was then turned over and the joint completely filled on the second side. In the first test made, using filler wire No. 15, the root pass was made at 230 amps using 16 volts and 28 inches of wire per minute. This pass was dye penetrant checked and found to be free from surface cracks. However, upon turning the plate over for the weld on the second side, it was found that full penetration was not achieved and that each of the tacks had cracked. In welding components that require tacking, this is not an uncommon occurrence. The stresses built up by welding generally cause the tacks to crack just prior to the weld puddle passing their location. These cracks were ground out and the parent metal ground out to meet the weld bead on the first side. The second weld pass was put in using the same parameter as the first pass and was found to contain several visible centerline longitudinal cracks and to be unusually concave. This pass was completely ground out and another pass made in its place at the same amperage and voltage, but with an increase in the wire feed rate from 22 to 66 inches per minute. This weld pass and the remaining passes required to fill both sides of the joint were free from additional cracking, as determined by radiographic examination.

The second test made using filler wire No. 13 employed a fusion root pass in which no wire was used. Examination of this fusion pass by visual and by dye penetrant inspection indicated that there were three longitudinal cracks approximately 0.100 inch long in the weld. These were ground out and manually repaired. The second pass was made at 230 amps 17 volts and 66 inches of wire per minute at 10 ipm travel speed using helium gas shielding. One small crack appeared in this weld at a location corresponding to one of the fusion root pass cracks. This crack was ground out and repaired manually. The joints on both sides of the plate were filled completely without a reoccurrence of cracking. Radiographic and dye penetrant inspection indicated that the weld was sound and free from further cracking.

TABLE 9

CHARPY V-NOTCH IMPACT PROPERTIES OF HP 9-4-20
TIG WELD METAL

Identification	Filler Wire	Test Temp. (°F)	Impact Energy (ft. lbs)	Lateral Expansion (Mils)
H-288-1	14	Room	31.0	11.5
H-288-2	"	0	28.0	11.5
H-288-3	"	-100	26.0	9.0
H-288-4	"	-100	26.0	9.5
H-288-5	"	-320	21.0	3.5
H-289-1	15	Room	33.0	15.5
H-289-2	"	0	30.0	13.0
H-289-3	"	-100	26.5	9.5
H-289-4	"	-100	27.0	10.0
H-289-5	"	-320	20.0	7.5

Note: Lateral expansion measured at base of fracture.

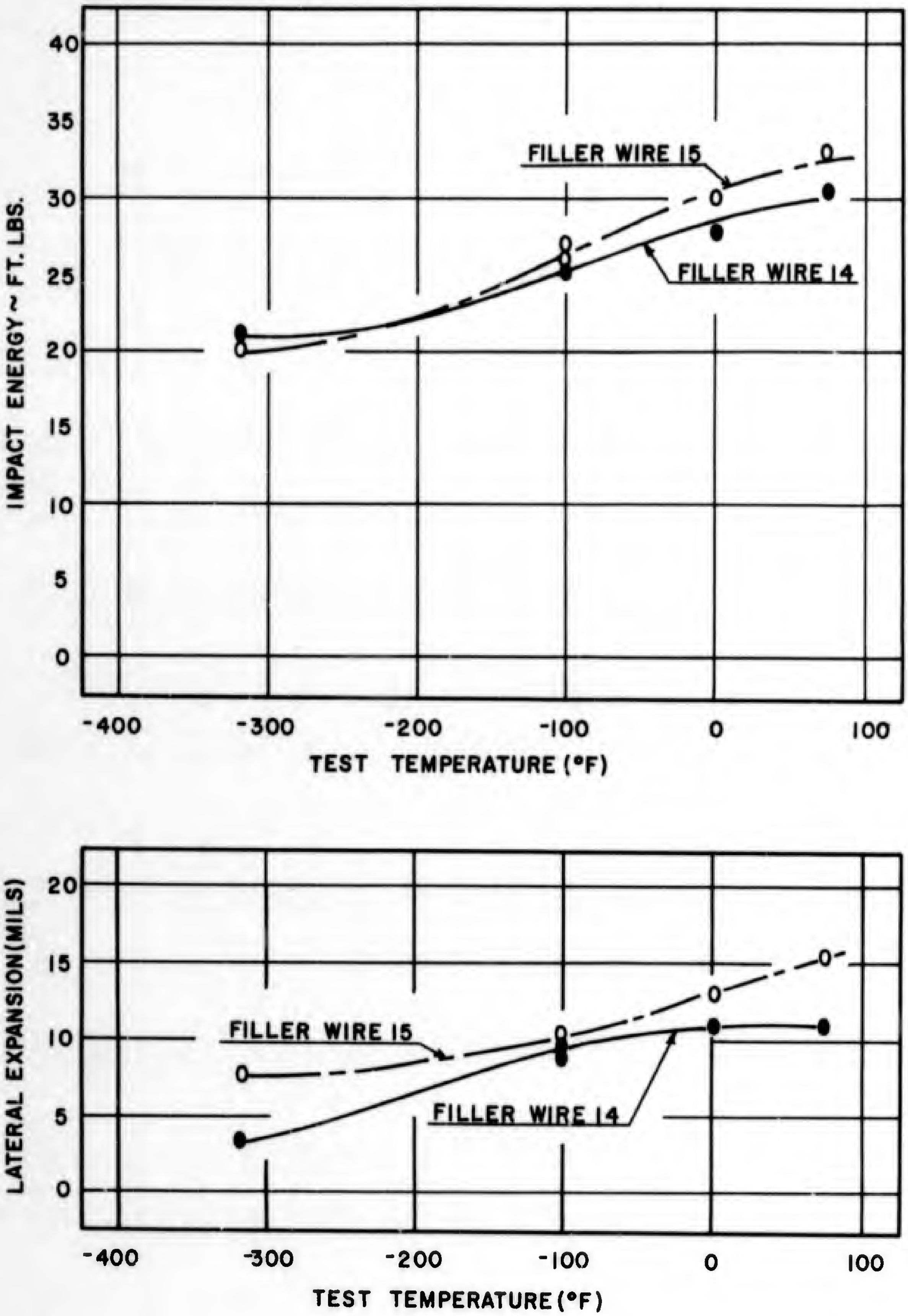


Figure 37. Charpy V-Notch Impact Properties of Martensitic HP 9-4-20 TIG Weld Metal.

c. Evaluation of MIG Welds in HP 9-4-20 1/2-Inch Plate

Gas metal arc welds were made in HP 9-4-20 1/2-inch plate employing high, medium and low energy inputs using the MIG spray transfer process. In addition, parameters were established for short-circuiting arc MIG welds. These welds were evaluated for quality, microstructure, hardness and smooth tensile properties. Fusion welding parameters for these welds are presented in Table 10.

(1) Weld Quality

The results of radiographic examination are presented in the comments column, Table 10. Initially, welds were made without gas backing to determine the efficiency of the modified filler wires in eliminating porosity. It was observed that MIG spray transfer welds made using argon-2% oxygen (Welds No. H254 and H256) or pure argon shielding (weld No. H257) through the torch and HP 9-4-20 filler wire modified with an addition of titanium (filler wire No. 13) contained appreciable porosity. However, weld H255 made with wire modified with an aluminum addition (filler wire No. 15) was fairly sound, containing only 4 small spots of porosity. Additional welds (H269 and H270) made using an argon-2% oxygen mixture through the torch and helium gas backing indicated again that filler wire No. 15 was most efficient in eliminating porosity. However, the bead contour of the weld made in argon-2% oxygen using this wire resulted in cold shuts in the weld or incomplete side wall fusion. In addition, welds were made using a helium and argon mixture through the torch and filler wires 13, 14, 15, and 17. Weld H281, made with filler wire 13 (0.2%Ti), contained large scattered porosity throughout the weld, while the welds (H286 and H280) made with the wires containing aluminum additions (wires 14 and 15) were fairly sound with only a few spots of porosity. Weld H285, made with the wire containing a higher carbon content (No. 17), had several large transverse cracks spaced approximately 1-1/2 inches apart throughout its entire length. In addition, it was observed that when using an argon-helium gas shield and the parameters selected, a complete spray transfer in the arc was not achieved and a tendency for globular transfer was present. Weld H268, made with the short-circuiting arc process, using filler wire No. 15 and an argon-carbon dioxide gas mixture, was found to be relatively sound with only one small spot of porosity in the weld. However, due to the low energy input used to make the weld, the joint was not completely penetrated.

(2) Weld Microstructure

The microstructures of MIG spray transfer welds (H255 and H269), made using filler wire No. 15 with both high (43.2 K-joules/inch) and medium (28.8 K-joules/inch) energy inputs, are presented in Figures 38 and 39, respectively. Although these structures are similar, the dendritic spacings (top of the fusion zone) are slightly narrower for the weld made with the lower energy input, Figure 39. The microstructures of MIG spray transfer welds (H256 and H270), using high and medium energy inputs and filler wire No. 13, are

TABLE 10

FUSION WELDING PARAMETERS FOR
MIG WELDS MADE IN HP 9-4-20 1/2 INCH PLATE

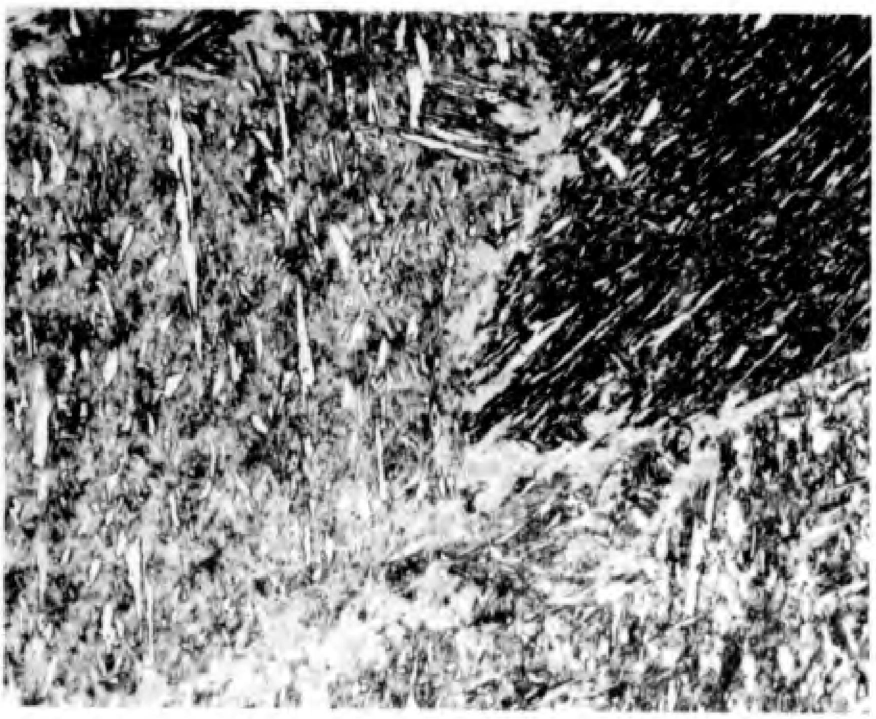
Weld No.	Filler Wire Dia. (in.)	Wire[a] Composition	No. Passes	W/S (ipm)	amps	Volts	Gas (cfh) Torch	Backup	Comments[b]
H254	0.062	13	4	10	320	24	$35AO_2$	None	Excessive porosity weld not evaluated
H255	0.062	15	4	10	300	24	$35AO_2$	"	Four small spots porosity
H256	0.062	13	4	10	330	23	$35AO_2$	"	Large scattered porosity
H257	0.062	13	2	10	335	25	35A	"	15 spots large scattered porosity
H267	0.062	15	8	8	180	19	$35A+CO_2$	"	Large scattered porosity
H268	0.062	15	15	20	180	19	$35ACO_2$	5He	One small spot porosity Incomplete penetration
H269*	0.062	15	5	15	300	24	$35AO_2$	5He	4 spots porosity incomplete penetration
H270	0.062	13	6	15	300	24	$35AO_2$	5He	Large scattered porosity
H280*	0.062	15	7	15	200	24	37.5 He 12.5A	5He	One spot of porosity
H281*	0.062	13	8	25	300	24	37.5 He 12.5A	5He	Large scattered porosity
H285*	0.062	17	7	17.4	300	24	37.5 He 12.5A	5He	Severe transverse weld cracking
H286*	0.062	14	7	17.4	300	24	37.5 He 12.5A	5He	Few spots porosity

* Metal transfer across the arc was globular.

(a) Wire composition is presented in Table 2.

(b) Weld quality comments based upon radiographic inspection.

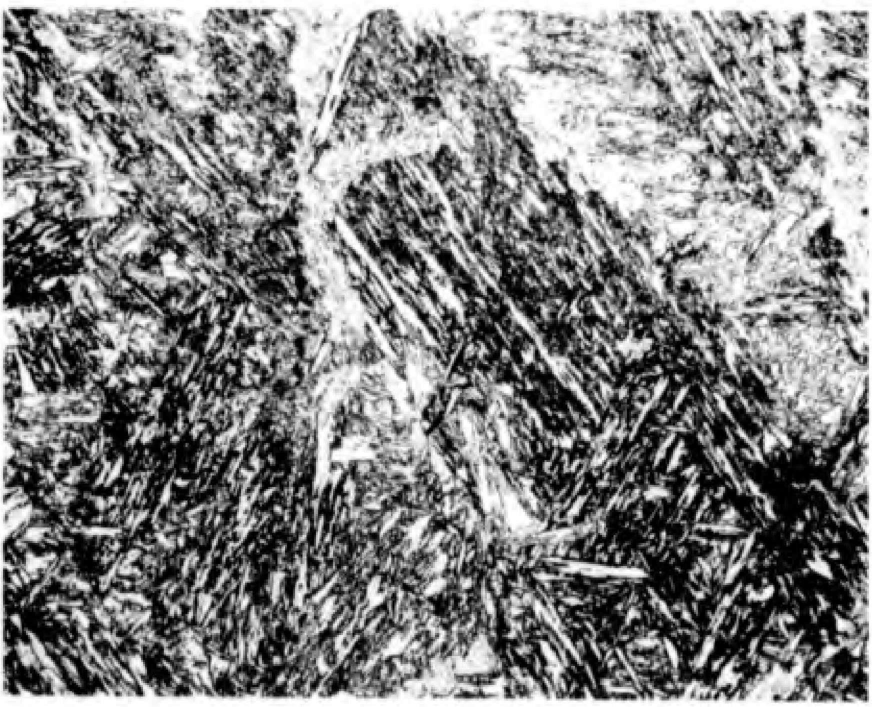
Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 38. Microstructure of Multipass MIG Weld No. H255 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 15. Weld Was Made with an Energy Input of 43.2 K-Joules/Inch.

Top of Fusion Zone 500X



Center of Fusion Zone 500X

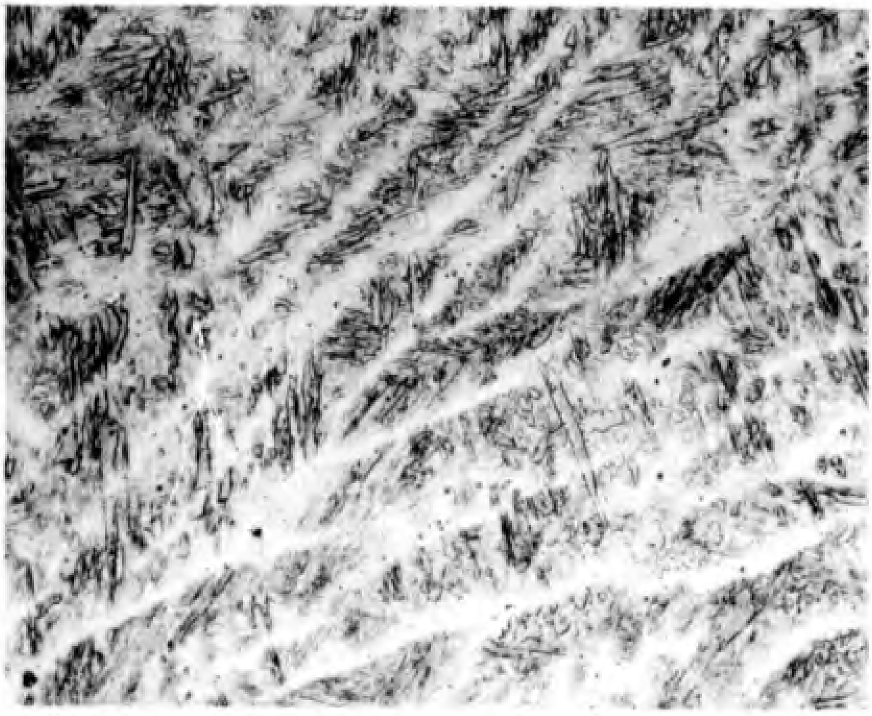
Figure 39. Microstructure of Multipass MIG Weld No. H269 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 15. Weld Was Made with an Energy Input of 28.8 K-Joules/Inch.

presented in Figures 40 and 41, respectively. As in the case of the welds made with the aluminum bearing wire (filler wire No. 15), the dendritic spacings for the lower energy input weld, Figure 41, are slightly narrower. It was noted that a more uniform structure was produced in the center of the fusion zone under the same welding conditions when the titanium bearing wire was used (filler wire No. 13) than for the aluminum bearing wire (No. 15). The microstructure (Figures 40 and 41) for these welds shows evidence of titanium carbide or oxides present in the top of the fusion zone. The microstructure for a short-circuiting arc weld (H268) is presented in Figure 42. This microstructure shows the influence of a decreased energy input into a weld. The dendritic spacings are narrow and coring and segregation are minimized.

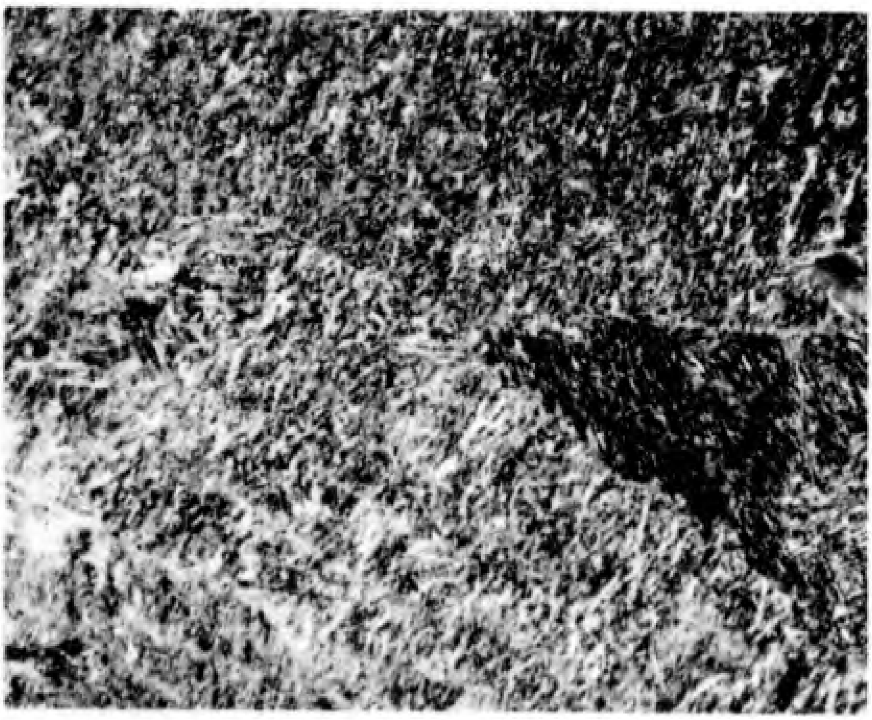
(3) Weld Hardness Surveys

Hardness surveys for MIG welds (H255 and H256), made by the spray transfer method using HP 9-4-20 filler wires modified with titanium (No. 13) and aluminum (No. 15) and argon-2% oxygen shielding, are presented in Figures 43 and 44, respectively. The hardness surveys of these welds, which were made at a relatively high energy input (43.2 to 46.0 K-joules/inch/pass), indicate that the top areas of the fusion zone of each weld were relatively soft. However, the hardnesses of the heat-affected zones and the bottom passes were generally in the range considered desirable. The hardness survey of weld H257, made using pure argon shielding and filler wire No. 13, is presented in Figure 45. This weld, made in two passes as a result of the increased deposit build-up using pure argon, has a hardness transverse pattern similar to automatic TIG welds and indicates that all the hardnesses are within a desirable range. The hardness traverse for medium energy MIG spray transfer welds (H269 and H270), made using aluminum and titanium bearing filler wires and argon-2% oxygen shielding, are presented in Figures 46 and 47, respectively. In general, these hardness readings are within a desirable range. The soft areas in the fusion zone of the lower passes are also in the heat-affected zone of the last pass. The hardness surveys for each weld are quite similar, even though different wires were used.

Hardness surveys for welds (H281, H286, and H280), made at a low and medium energy input using filler wires 13, 14, and 15, respectively, and helium-argon gas mixture through the torch, are presented in Figures 48, 49, and 50. The soft area in the center traverse of the fusion zone of welds made with wires No. 14 and 15 are due to the traverse being taken in the over-tempered region of the heat-affected zone of the top pass. The hardness survey for a short-circuiting arc weld (H268) made at a very low energy input (10.3 K-joules/inch/pass) using HP 9-4-20 filler wire containing aluminum, is presented in Figure 51. The hardness of the heat-affected zone at the top of the weld was higher than that for the base metal or fusion zones. This indicated the presence of slightly tempered martensite. This is to be expected in the top portion of a martensitic weldment since there are no subsequent weld passes to cause significant tempering of the fresh martensite formed during welding.



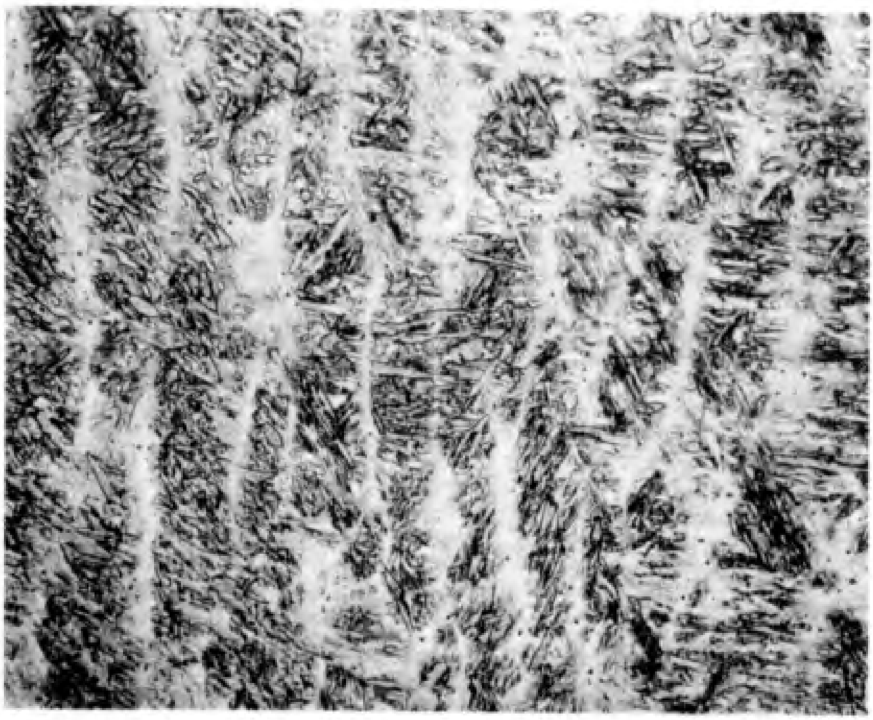
Top of Fusion Zone 500X



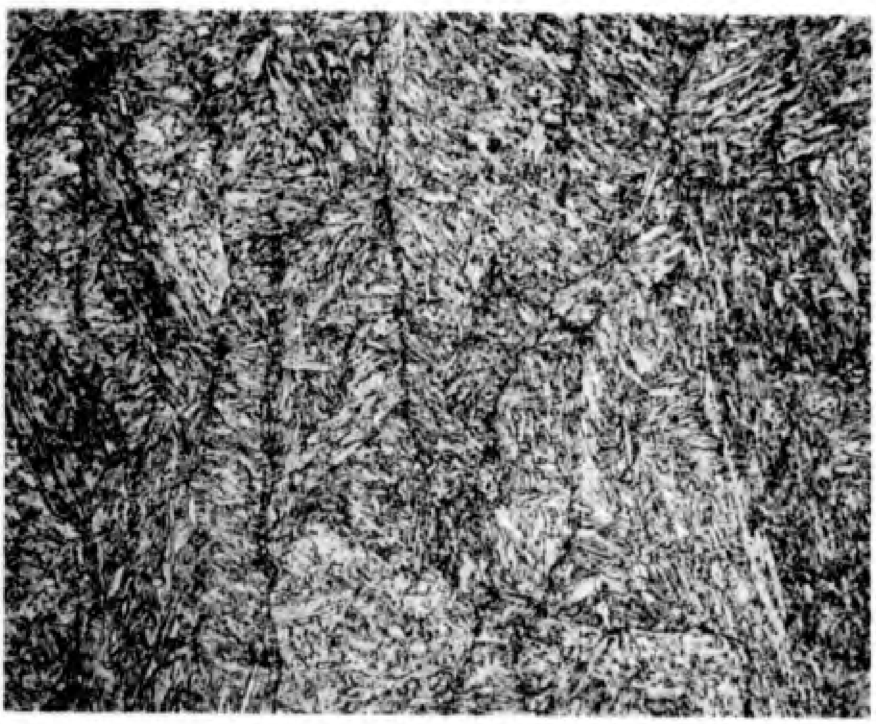
Center of Fusion Zone 500X

Figure 40. Microstructure of Multipass MIG Weld No. H256 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 13. Weld Was Made with an Energy Input of 46 K-Joules/Inch.

7975

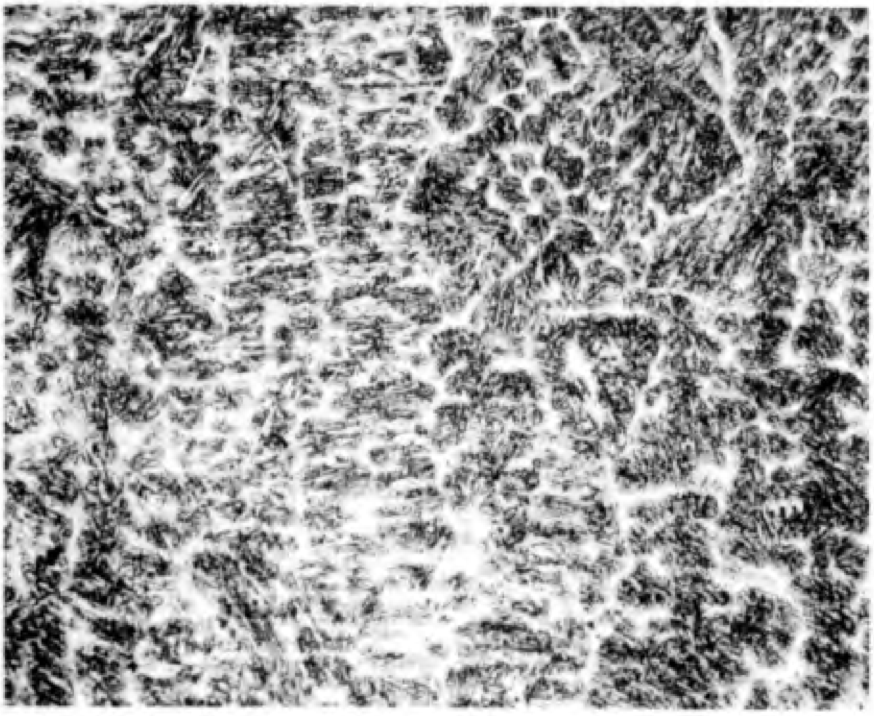


Top of Fusion Zone 500X

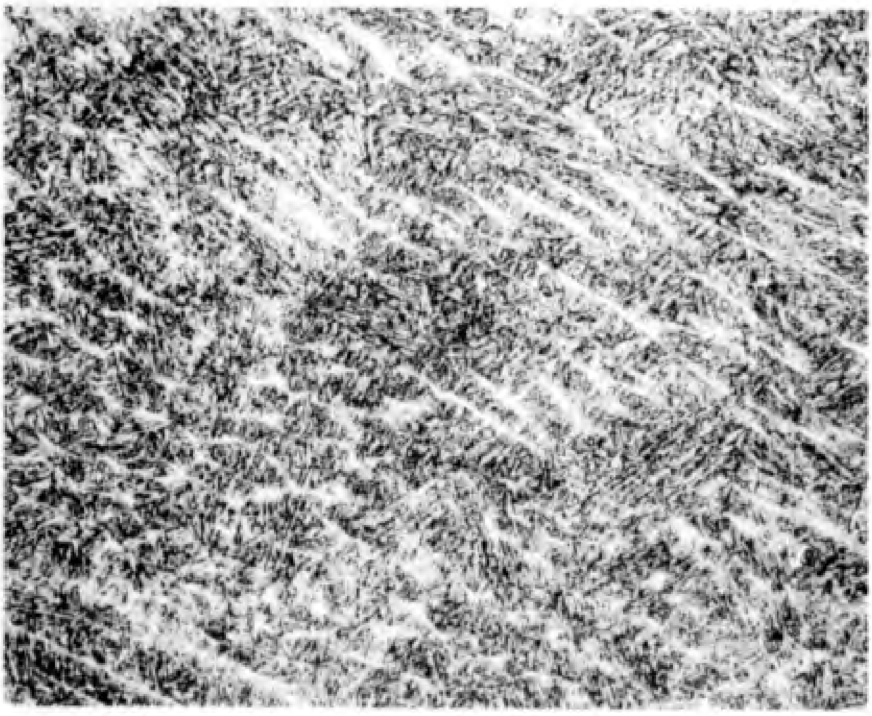


Center of Fusion Zone 500X

Figure 41. Microstructure of Multipass MIG Weld No. H270 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 13. Weld Was Made with an Energy Input of 28.8 K-Joules/Inch.



Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 42. Microstructure of Short-Circuiting Arc Weld No. H268 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 15. Weld Was Made Using an Energy Input of 10.3 K-Joules/Inch.

7978

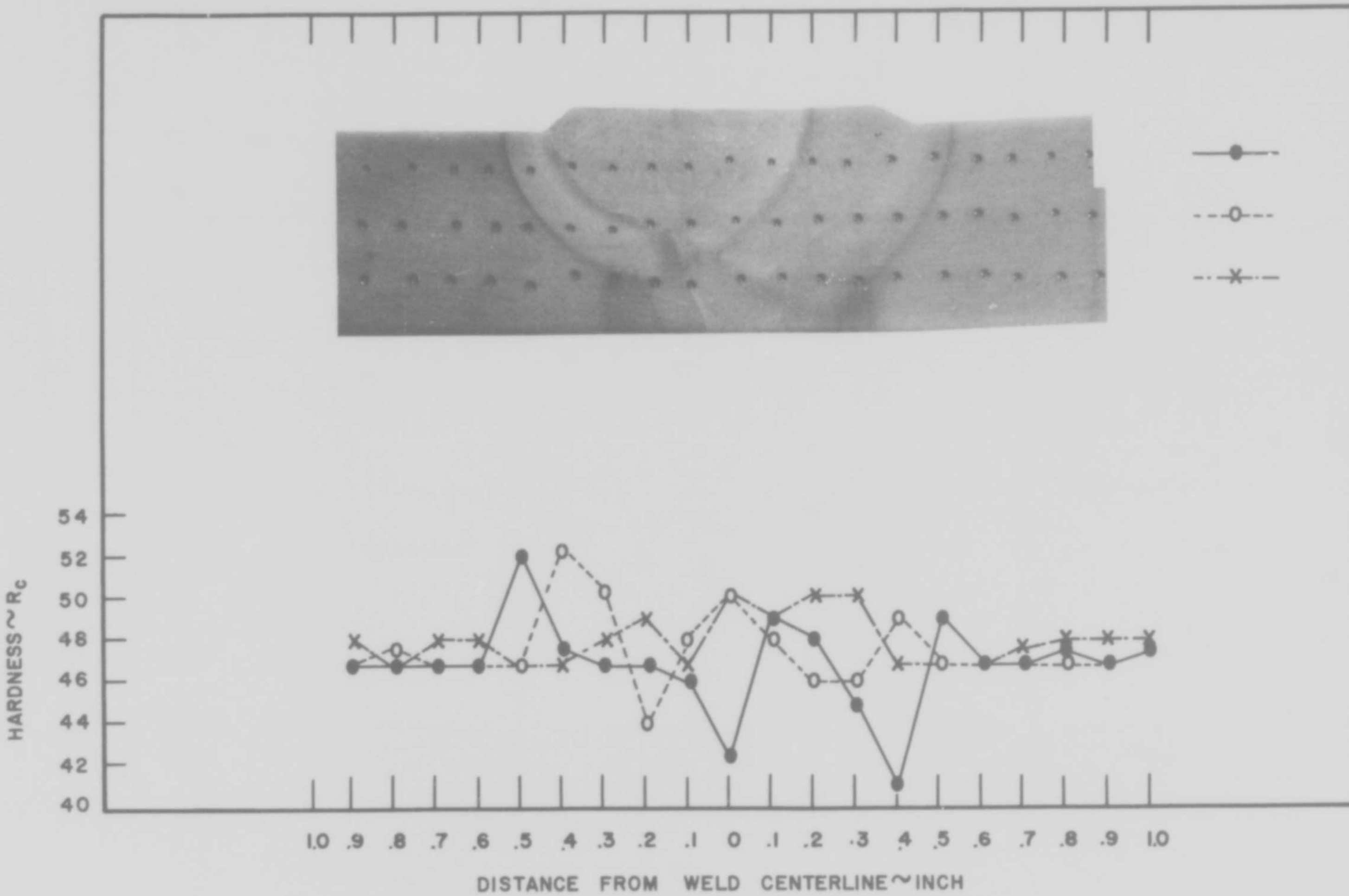


Figure 43. Hardness Survey of MIG Weld No. H256 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 13, an Argon-2% Oxygen Gas Mixture, and a High Energy Input.

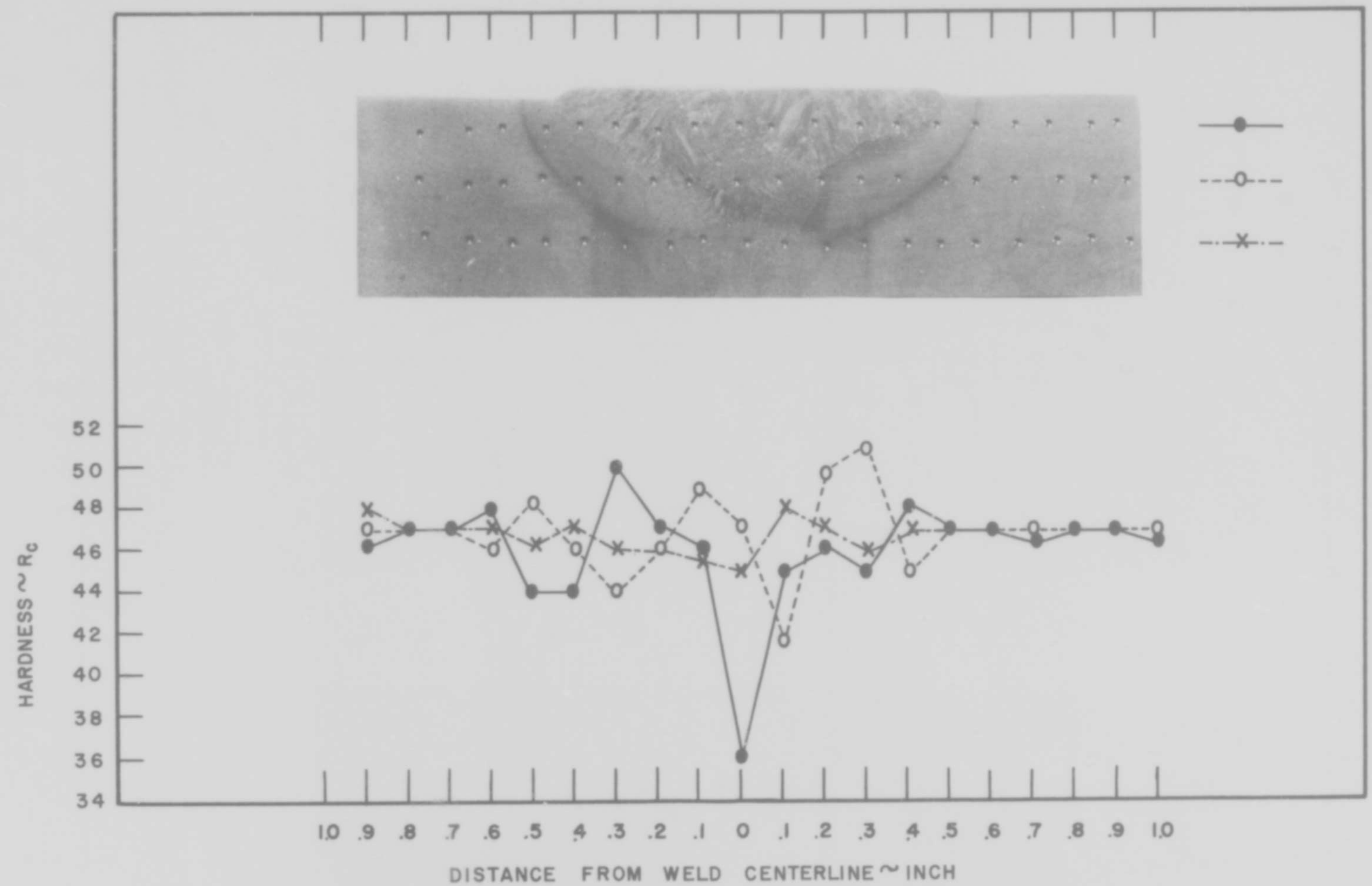


Figure 44. Hardness Survey of MIG Weld No. H255 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 15, an Argon-2% Oxygen Gas Mixture, and a High Energy Input.

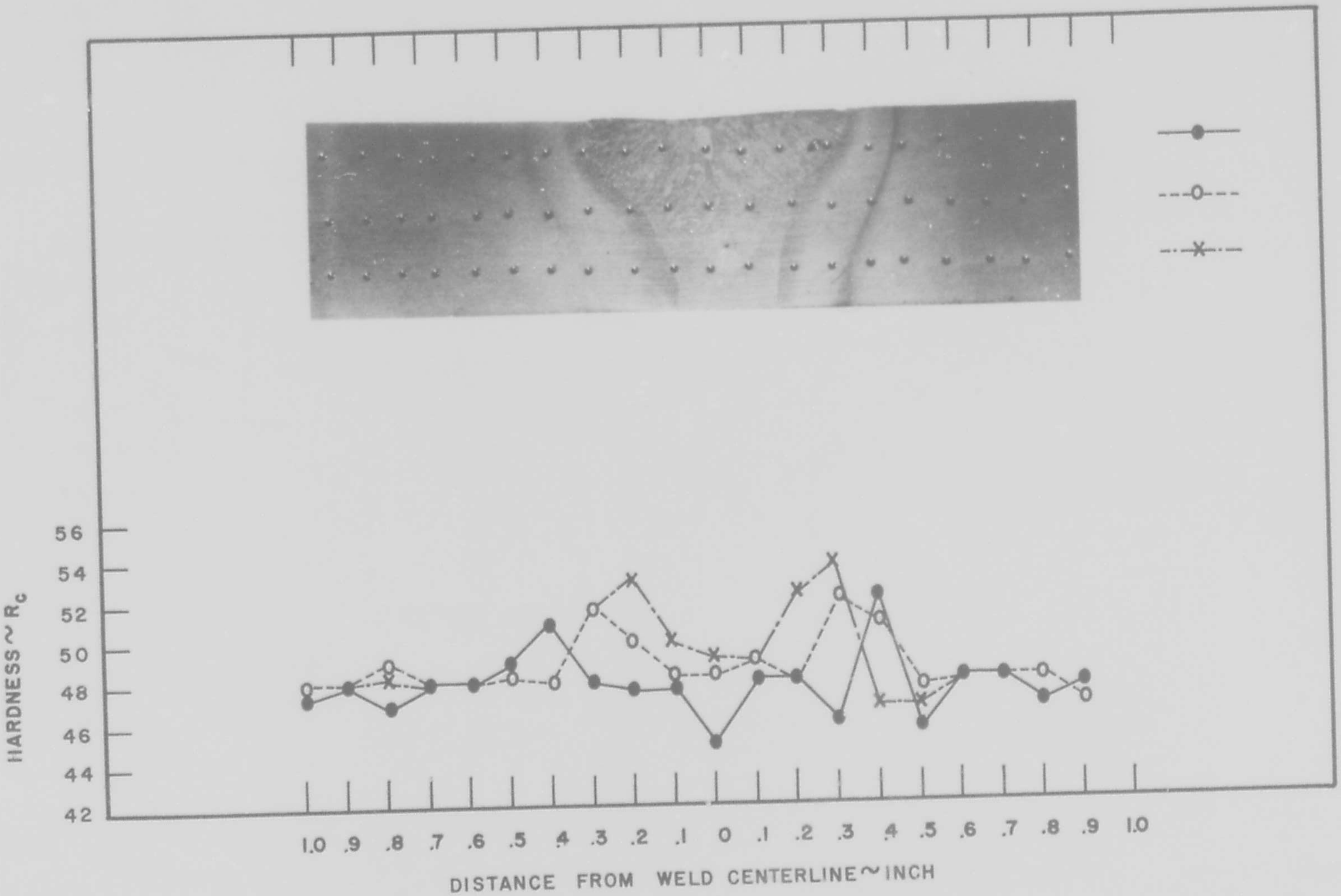


Figure 45. Hardness Survey of MIG Weld No. H257 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 13, Pure Argon Gas, and a High Energy Input.

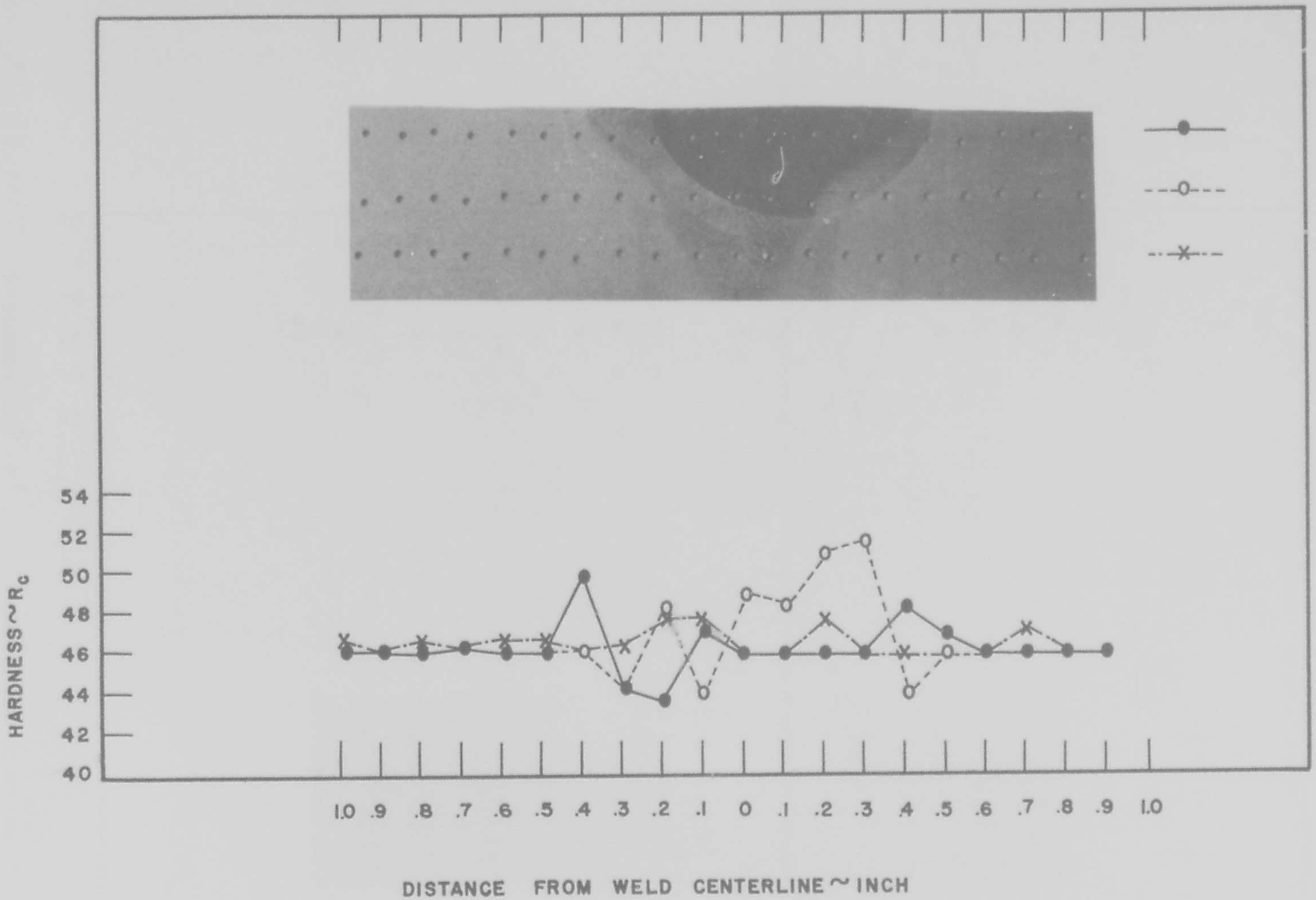


Figure 46. Hardness Survey of MIG Weld No. H269 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 15. Weld Was Made Using a Medium Energy Input and an Argon-2% Oxygen Gas Mixture.

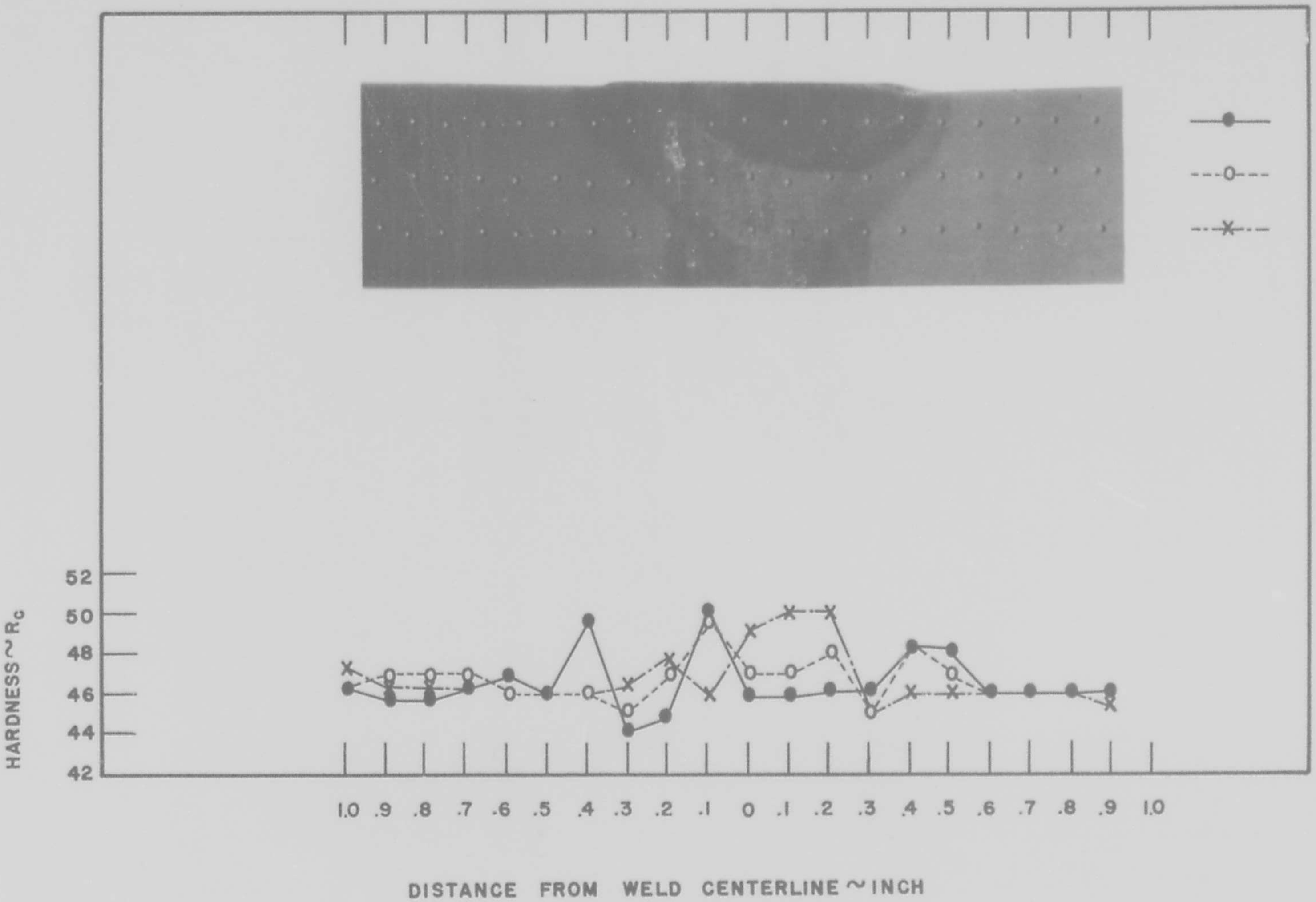


Figure 47. Hardness Survey of MIG Weld No. H270 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 13. Weld Was Made Using a Medium Energy Input and an Argon-2% Oxygen Gas Mixture.

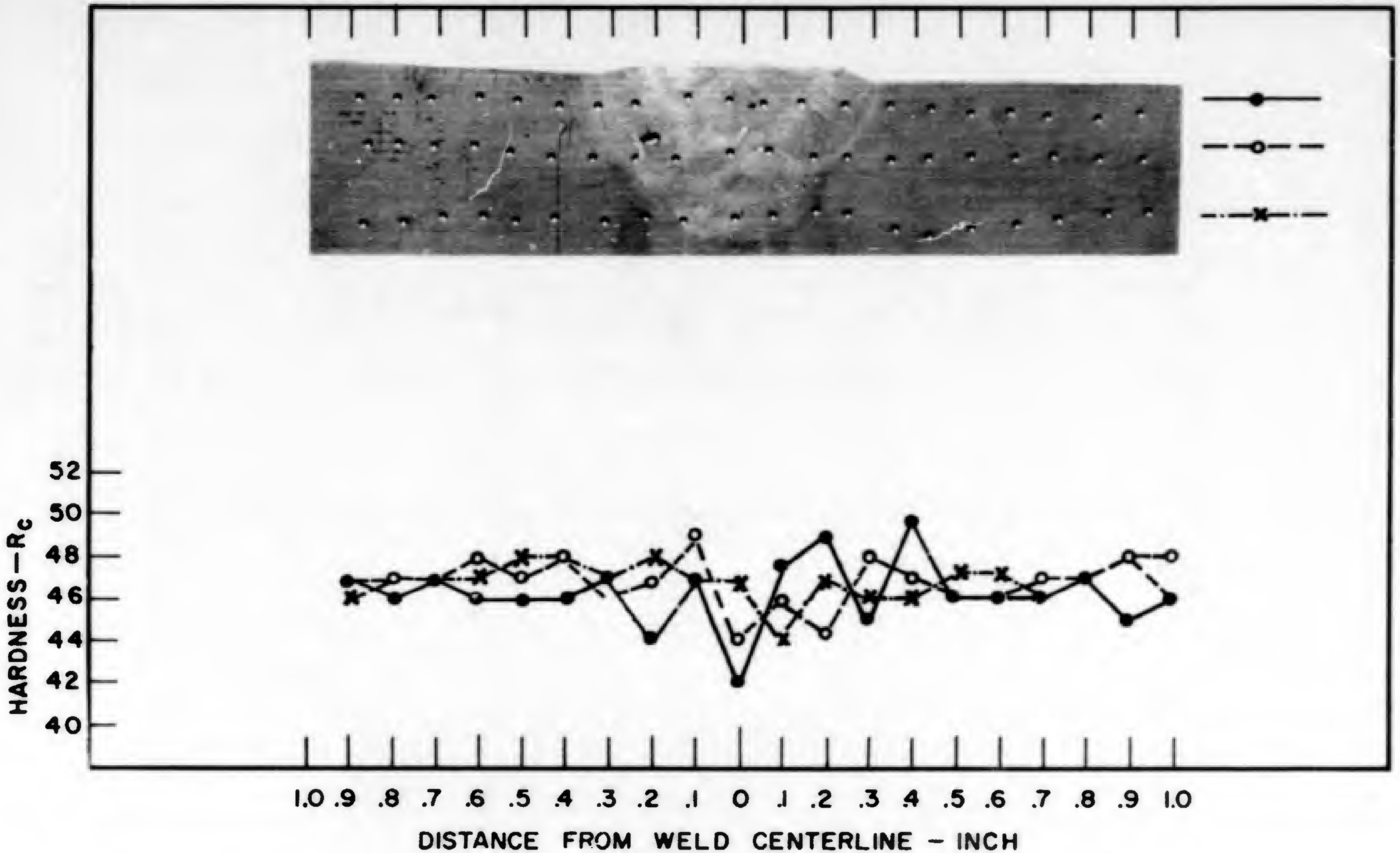


Figure 48. Hardness Survey of MIG Weld No. H281 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 13, a Helium-Argon Gas Mixture, and a Low Energy Input.

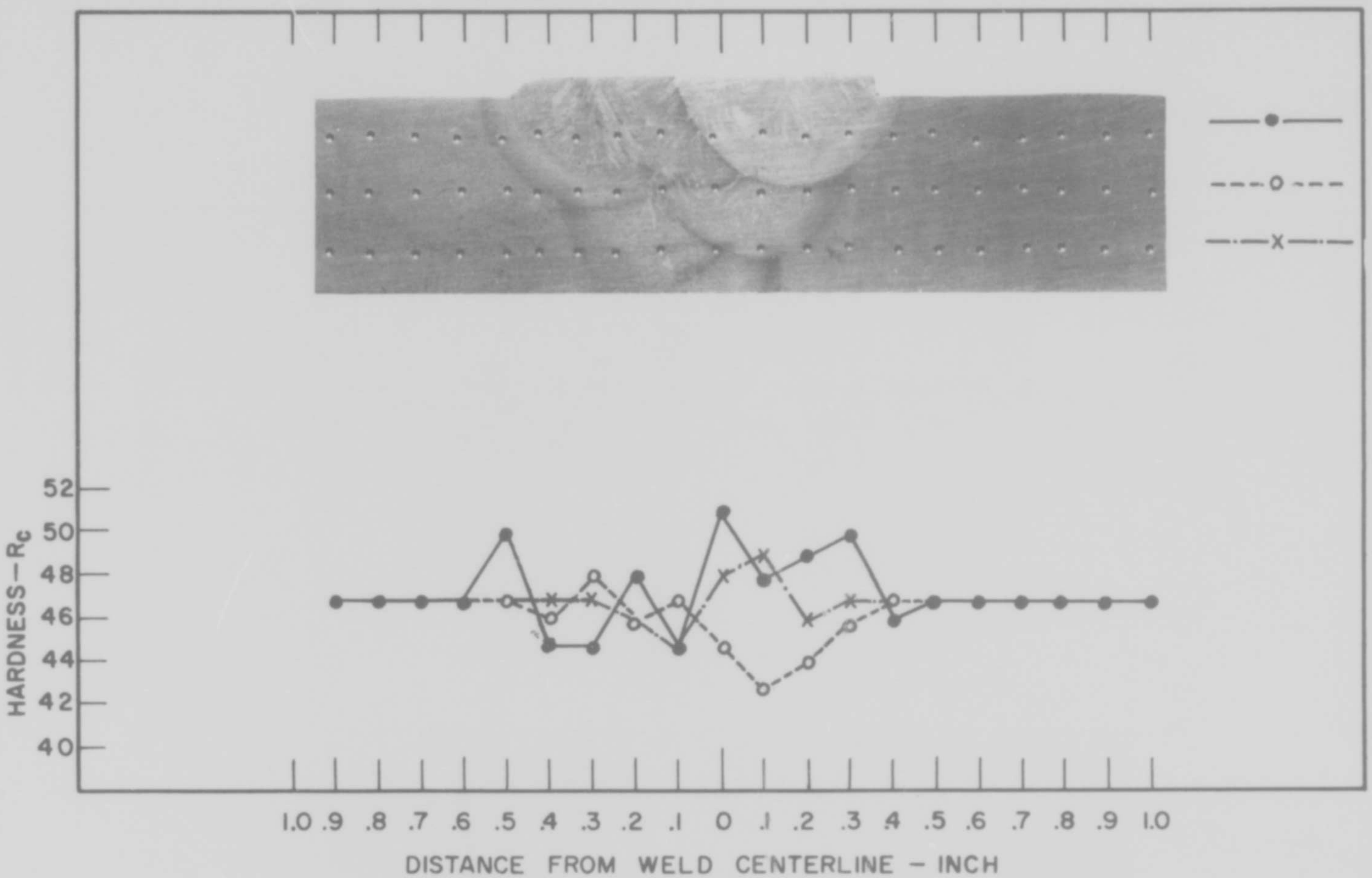


Figure 49. Hardness Survey of MIG Weld H286 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 14, a Helium-Argon Gas Mixture, and a Medium Energy Input.

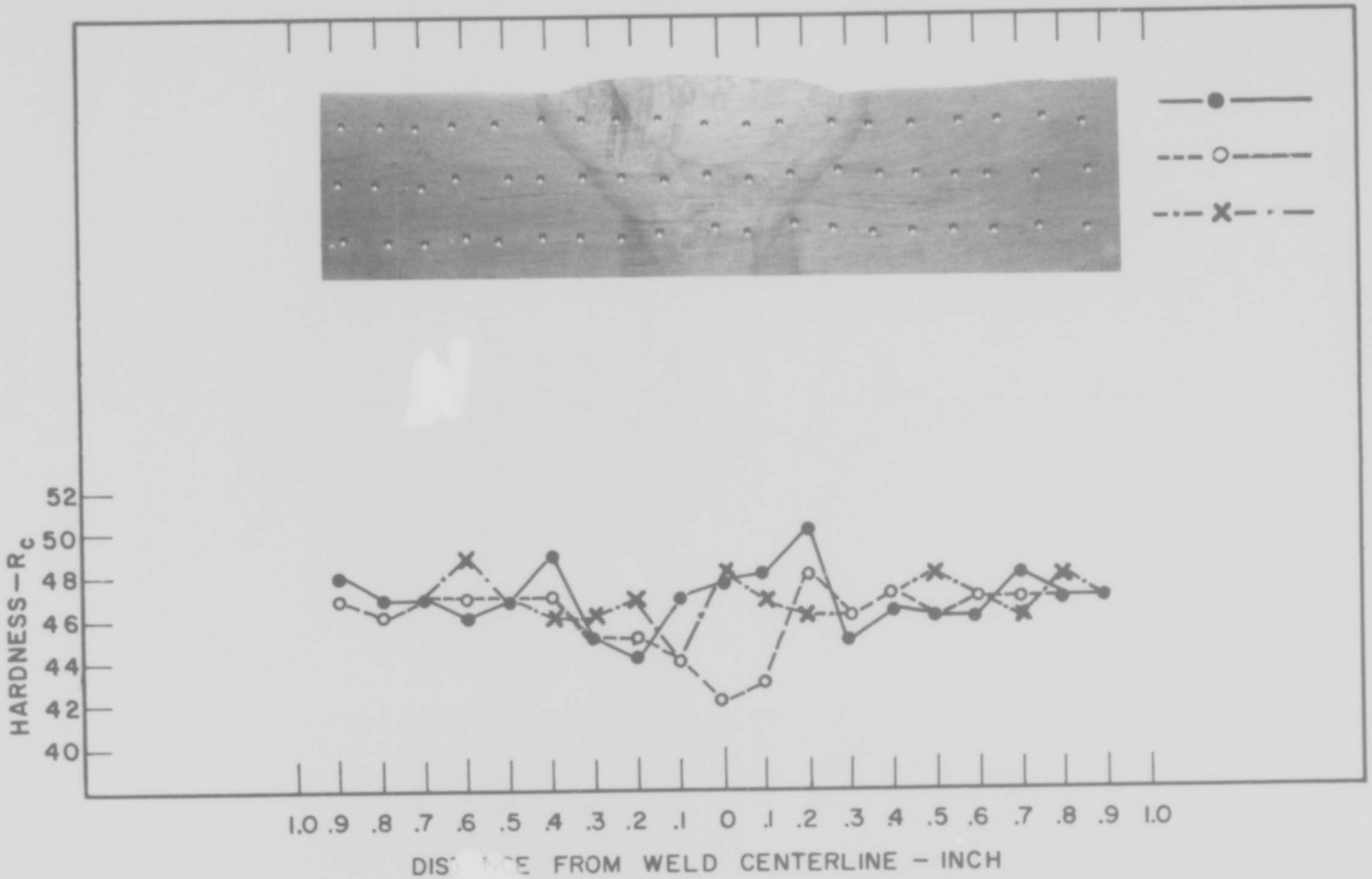


Figure 50. Hardness Survey of MIG Weld No. H280 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 15, a Helium-Argon Gas Mixture, and a Low Energy Input.

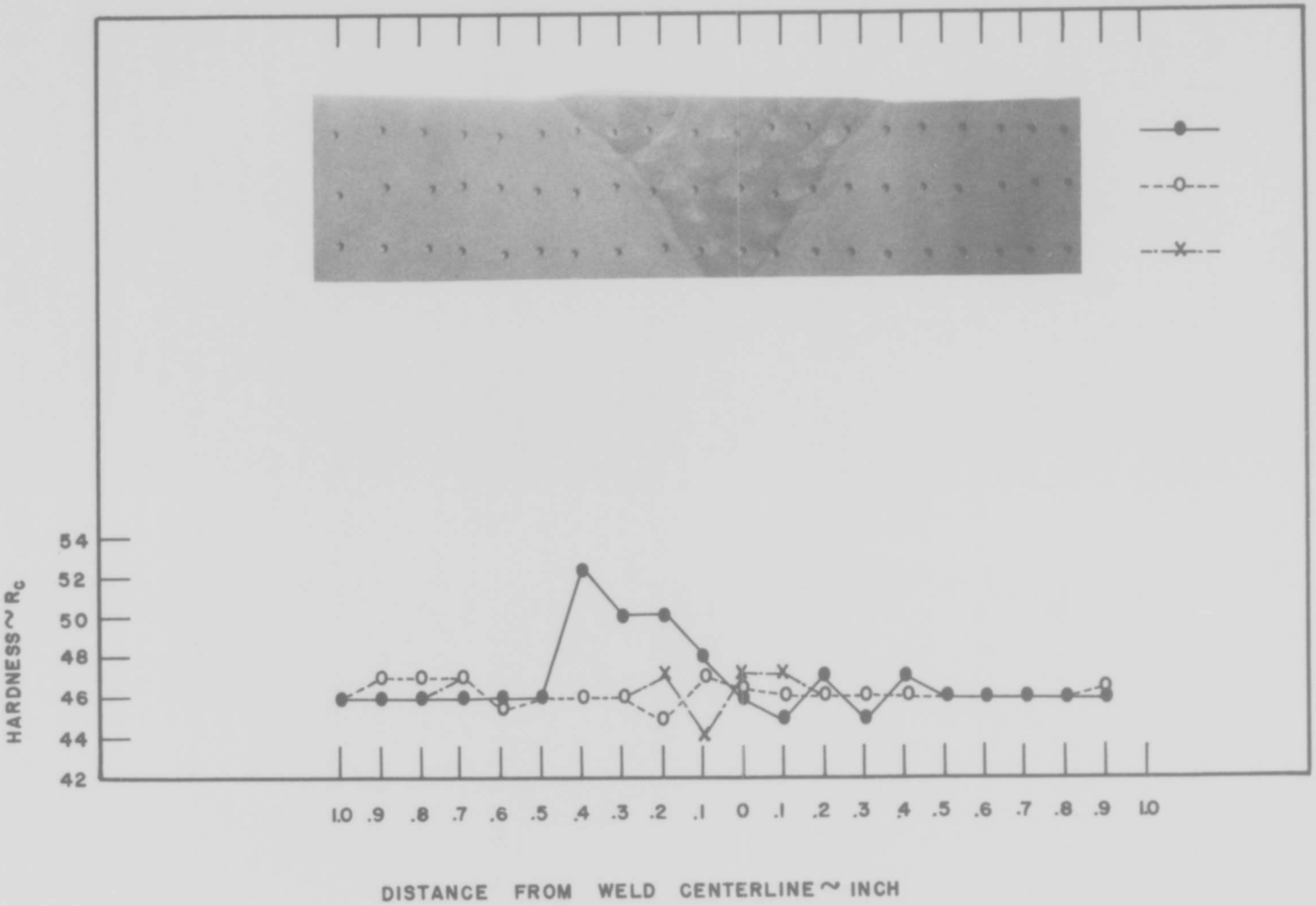


Figure 51. Hardness Survey of a Short-Circuiting Arc Weld No. H268 Made in HP 9-4-20 1/2-Inch Plate Using Filler Wire No. 15 and an Argon-Carbon Dioxide Gas Mixture.

(4) Tensile Properties

The smooth tensile properties for low, medium, and high energy input MIG welds and for a low energy input short arc weld are presented in Table 11. These welds were made with HP 9-4-20 filler wire modified with additions of aluminum (wires 14 and 15) and titanium (wire No. 13). Although some of the welds exhibited acceptable transverse tensile properties, the longitudinal yield strength of all welds was low. Ductility of MIG welds was generally substantially lower than that for TIG welds in this material made with the same filler wires and essentially the same energy input levels.

Welds made at the lowest energy input levels, weld H268 at 10.3 K-joules/inch and weld H280 at 12.5 K-joules/inch, did not exhibit the best strength properties as might be expected from TIG weld results. In addition to being low in strength, the transverse ductility of these welds was exceptionally low. Hardness surveys of these welds (Figures 50 and 51) do not reveal any unusually soft areas. The low strength and ductility of these welds are believed to be caused by microcracking in the fusion zone or heat-affected zone, as suggested by the low strength and ductility.

Microcracking is more likely to occur in MIG welds than in TIG welds because the filler wire is added at a faster rate and there is less time for adsorbed gases and surface oxides to be removed during heating in the arc. This will introduce a larger amount of oxygen and nitrogen into the weld puddle. Upon solidification, the shrinkage stresses can cause microcracks to form in the low ductility material. Another factor which may contribute to the formation of microcracks is the reduced amount of interpass tempering which occurs during the rapid cooling associated with low energy input levels. This would result in lower ductility in the heat-affected zone and fusion zone and a tendency to form microcracks under shrinkage stresses. The greater amount of impurities in MIG welds in general is believed to be the major cause of poorer weld mechanical properties compared to TIG welds.

d. General Discussion

The results of two years' work indicate that weldments with yield strengths in excess of 180 ksi, adequate ductility, and plane strain fracture toughness comparable to parent metal with weld joint efficiencies greater than 95 percent can be produced in HP 9-4-20 1/2-inch plate without the use of pre-heat or post-heat. These properties can be obtained by either the automatic or manual gas tungsten arc welding processes provided low energy inputs (24.8 K-joules/inch/pass) are used for the automatic process and the stringer bead technique is used for the manual process. Small additions of Al or Ti to HP 9-4-20 wire resulted in improved radiographic quality, strength, and fracture toughness. Welds made by the MIG process failed to meet the criteria of the program. This was attributed to microcracking in the weld.

TABLE 11

TENSILE PROPERTIES OF MIG WELDS MADE IN HP 9-4-20 1/2 INCH PLATE

Weld No.	Test(a) Direction	Filler Wire(b)	Welding Speed (ipm)	0.2% Y.S. (ksi)	UT.S. (ksi)	Elong. %(c)	R.A. (%)	Energy Input K J/in/pass	% Joint Efficiency(d) Y.S.	U.T.S.	Comments
H255	L	15	10	155.2	247.4	13.0	38.7	43.2	-	-	Spray Transfer
"	L	15	10	156.4	243.4	12.0	40.7	43.2	-	-	"
"	T	15	10	175.1	220.0	8.0	49.4	43.2	91.6	100.0	" (e)
"	T	15	10	176.7	214.0	2.5	8.2	43.2	92.4	99.0	" (f)
H256	L	13	10	167.4	211.5	2.5	6.3	46.0	-	-	"
"	L	13	10	162.5	223.0	7.0	11.3	46.0	-	-	"
"	T	13	10	176.6	216.3	6.0	36.4	46.0	92.4	100.0	" (f)
"	T	13	10	180.2	217.1	3.0	7.8	46.0	94.2	100.0	" (g)
H257	L	13	10	140.1	214.4	4.0	7.4	46.0-56.0	-	-	"
"	L	13	10	143.6	216.0	4.0	7.8	46.0-56.0	-	-	"
"	T	13	10	173.1	219.3	10.0	57.6	46.0-56.0	90.8	100.0	" (h)
"	T	13	10	183.4	219.8	10.0	59.0	46.0-56.0	96.0	100.0	" (h)
H268	L	15	20	177.6	205.1	8.0	10.8	10.3	-	-	Short Arc
"	L	15	20	174.6	205.9	10.0	13.1	10.3	-	-	"
"	T	15	20	175.0	190.7	1.0	5.5	10.3	91.7	88.2	" (g)
"	T	15	20	181.0	190.7	1.0	3.1	10.3	94.8	88.2	" (g)
H270	L	13	15	161.4	228.3	5.0	8.1	28.8	-	-	Spray Transfer
"	L	13	15	164.5	227.2	4.0	4.7	28.8	-	-	"
"	T	13	15	181.0	212.7	10.0	60.2	28.8	94.1	98.5	" (i)
"	T	13	15	181.4	212.9	11.0	61.5	28.8	94.4	98.6	" (i)
H280	L	15	15	159.9	221.4	14.0	36.2	12.5	-	-	Globular Transfer
"	L	15	15	159.9	216.6	11.0	16.6	12.5	-	-	"
"	T	15	15	186.7	218.7	4.0	5.1	12.5	97.7	100.0	" (f)
"	T	15	15	185.8	218.3	3.0	7.8	12.5	97.2	100.0	" (f)
H286	L	14	17.4	166.8	211.4	11.5	27.7	24.8	-	-	"
"	L	14	17.4	167.8	209.9	13.5	29.5	24.8	-	-	"
"	T	14	17.4	183.3	216.6	5.5	33.3	24.8	96.0	100.0	" (h)
"	T	14	17.4	184.0	218.1	6.5	38.9	24.8	96.3	100.0	" (h)

(Continued)

TABLE 11 (CONTINUED)

TENSILE PROPERTIES OF MIG WELDS MADE IN HP 9-4-20 1/2 INCH PLATE

(a) (L) specimens were taken parallel with the weld and consisted entirely of weld deposit.
(T) specimens were taken transverse to the weld and included weld, heat affected zone, and parent metal.

(b) Filler wire composition is presented in Table 2.

(c) (T) specimens had a gage length of two inches. (L) specimens had a gage length of one inch.

(d) Joint efficiencies were based on parent metal ultimate strength and yield strength of 216 and 191 ksi, respectively.

(e) Fracture occurred 5/32 inch from the fusion heat-affected zone line.

(f) Fracture occurred at the fusion heat-affected zone line.

(g) Fracture occurred in the weld.

(h) Fracture occurred 5/16 inch from the fusion heat-affected zone line.

(i) Fracture occurred in parent metal.

2. HP 9-4-25 Steel (1-Inch Plate)

a. Base Metal Evaluation

Since only slight differences in chemistry exist between the HP 9-4-20 and HP 9-4-25 steels, identical heat treatments were given the two steels (i.e., austenitized at 1550°F for 30 minutes, oil quenched and double tempered at 950°F for 2 hour cycles). Therefore, the welding parameters established for the 1/2-inch HP 9-4-20 plate during the last year's work could be reproduced on the 1-inch HP 9-4-25 plate to study the influence of thickness.

Photomicrographs presented in Figures 52 and 53 show the inclusion level and typical microstructure of the HP 9-4-25 plate, respectively. It can be seen that both the inclusion level and microstructure are very similar to that of the HP 9-4-20 plate (Figures 22 and 23).

The smooth tensile properties of the HP 9-4-25 plate are presented in Table 12, along with the tensile properties of the HP 9-4-20 plate, for comparative purposes. As indicated, the two materials had very similar 0.2% yield strengths and ductility; however, the ultimate strength of the HP 9-4-25 was lower than that of the 0.20% carbon steel (200 ksi compared to 215 ksi).

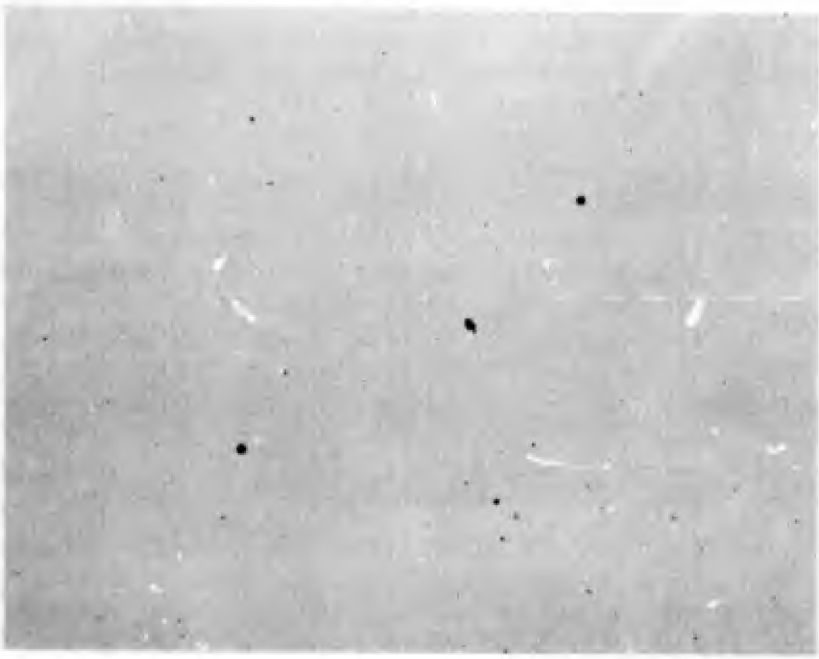
The fracture toughness, K_{IC}, of the HP 9-4-25 steel was determined testing notch bend specimens (1" x 1" x 9") under 3-point loading. Type 3 load deflection curves were obtained and an average K_{IC} of 135.8 ksi $\sqrt{\text{inch}}$ was established (see Table 13). This increase in toughness over that of the HP 9-4-20 material is believed to be in part the result of the lower Cr and Mo contents of the 0.25% carbon steel.

The Charpy V-notch impact properties of the 1-inch HP 9-4-25 plate are given in Table 14. The impact energy at -100°F and above is considered satisfactory for a material of the 180 - 200 ksi strength level. The fracture ductility is adequate as characterized by a lateral expansion of 10 mils or greater, large shear lips, and essentially 100 percent fibrous fracture. At -320°F, the energy absorption is lower, but satisfactory; however, the fracture ductility is low and the fracture surfaces showed partial signs of brittle failure.

b. Evaluation of TIG Welds in 1-Inch HP 9-4-25 Plate

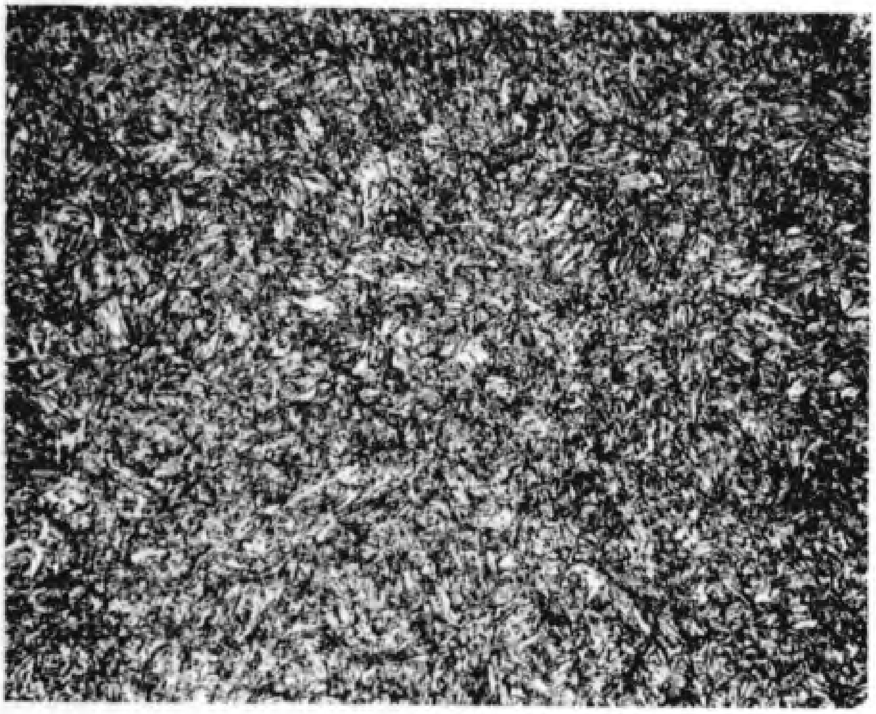
Gas tungsten arc welds were made in 1-inch HP 9-4-25 plate and compared to weldments in 1/2-inch HP 9-4-20 material to establish the influence of thickness on the mechanical properties of welds made in this type of material. Both single U and double U groove joints were employed. In addition, automatic horizontal and manual vertical welds were made. Filler wire Nos. 14, 15, and 19 were used in making these welds. No pre- or post-heat treatment was used and a weld interpass temperature of 80°F was maintained. Fusion welding parameters are presented in Tables 15 and 16.

(a) Parallel to Rolling Direction 100X



(b) Perpendicular to Rolling Direction 100X

Figure 52. Unetched HP 9-4-25 1-Inch Plate Showing Inclusion Levels.



500X

Figure 53. Microstructure (Tempered Martensite) of 1-Inch HP 9-4-25 Plate Austenitized at 1550°F/1 Hour Plus a Double Temper at 950°F for 2 Hours. Etch: 2% Nital; Average Hardness: R_c 44.6.

TABLE 12

SMOOTH TENSILE PROPERTIES OF HP 9-4-25 and HP 9-4-20 PLATE

Heat No.	Test[(a)] Direction	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elongation (%-1")	R.A. (%)
A. HP 9-4-25 1 Inch Plate					
3930961	L	190.1	200.4	25.0	59.5
(Code M)	L	188.4	199.6	27.0	64.4
	T	189.5	200.3	22.0	50.3
	T	189.1	202.3	22.0	52.1
B. HP 9-4-20 1/2 Inch Plate					
3930774	L	192.5	216.6	20.0	59.7
(Code H)	L	190.9	216.9	19.0	57.7
	T	191.3	215.9	18.5	59.2
	T	191.9	217.1	18.0	55.6

(a) Test direction relative to the rolling direction.

TABLE 13

CALCULATED FRACTURE TOUGHNESS, K^*_{IC}, OF 1 INCH HP 9-4-25 PLATE[a]

(3 POINT LOADED)

Specimen Identity	Width, W (inch)	Thickness, B (inch)	Crack Depth, a (inch)	Major Span, L' (inch)	Curve Type[b]	Load (lbs)	Relative Plastic Zone Size, r_y/B [c]	$\frac{\sigma_{nom}}{\sigma_{ys}}$ [d]	Calculated Fracture Toughness, K^*_{IC} (ksi $\sqrt{in}$)
M9-3	0.971	0.886	0.218	8.0	2	10,400	0.025	1.31	136.8
M9-5	0.971	0.886	0.206	8.0	2	10,620	0.024	1.30	134.9

Notes: (a) Material was austenitized at 1550°F 1 hour; OQ; and tempered at 950°F (2 hrs. + 2 hrs.).

(b) Curve types are defined in Figure 16.

(c) Plastic zone size, r_y, equals the difference between the effective crack length a^* and the measured crack length, a ($a^* = a + eG/6\pi\sigma_{ys}^2$).

(d) σ_{nom}/σ_{ys} = nominal stress at crack initiation divided by 0.2% yield strength.

TABLE 14

CHARPY V-NOTCH IMPACT PROPERTIES OF 1 INCH HP 9-4-25 PLATE HEAT TREATED TO MARTENSITE (HEAT NO. 3930961)

Identification	Test Temp. (°F)	Impact Energy Input (ft. lbs)	Lateral Expansion (Mils)
M-17-1	Room	33.0	15.5
M-17-2	"	35.0	15.5
M-17-3	0	30.0	14.5
M-17-4	"	37.0	17.0
M-17-5	-100	26.0	11.0
M-17-6	"	32.5	16.0
M-17-7	-320	20.5	4.5
M-17-8	"	17.5	2.5

Note: Lateral expansion measured at base of fracture.

TABLE 15

FUSION WELDING PARAMETERS FOR
TIG WELDS MADE IN HP 9-4-25 1 INCH PLATE

Weld No.	Filler Wire Dia. (in.)	Wire[a] Composition	No. Passes	W/S (ipm)	Wire Speed (ipm)	amps	Volts	Gas (cfh) Torch	Gas (cfh) Backup	Comments[c]
M276	0.062	15	31	10	66[b]	240	17.5	50He	5He	Joint Design D
M282	0.062	15	18	10	66[b]	235	17.5	50He	5He	Joint Design F[d]
M291	0.062	19	29	10	66[b]	240	17.5	50He	5He	Joint Design D
M294	0.062	14	23	10	-	-	-	-	-	Joint Design F[e]
M302	0.062	17	36	3	Manual	130	16.0	30He 5A	5He	Joint Design F[f]
M303	0.062	19	16	10	66[b]	240	17.5	50He	5He	Joint Design E

(a) Wire composition is presented in Table 2.

(b) The wire speed, amperage and voltage are for the second through the final pass except where noted below.

(c) Weld quality comments based upon radiographic inspection.

(d) Parameters for third through final pass. Weld was made in double U-joint design and centerline cracking occurred. Discussion is in text.

(e) Discussion of this parameter in text. Horizontal weld in double U-groove joint design.

(f) Parameter for fourth through final pass. Vertical weld in double U-groove joint design.

TABLE 16

FUSION WELDING PARAMETERS OF FIRST PASS
FOR TIG WELDS MADE IN HP 9-4-25 1 INCH PLATE

Weld No.	Wire Speed (ipm)	amps	Volts
M276	66	240	17.5
M282	66	235	17.5
M291	66	240	17.5
M302*	Manual	110	14.0
M303	66	240	17.5

* Parameters for first through third pass.

(1) Weld Quality

In general, each of the welds made in 1-inch HP 9-4-25 material was clean and free from porosity. However, some centerline cracking occurred in the root passes of welds made with the double U groove configuration. Weld No. M282 was made in the flat position. The first weld pass made at 235 amps, 17-1/2 volts, a wire feed rate of 66 ipm, and a welding speed of 10 ipm cracked in the center along the entire 12 inch length. The crack was ground out, the piece was turned over, and a second pass was made at 300 amps, 19 volts, a wire feed rate of 100 ipm, and a welding speed of 10 ipm. Two cracks were observed in this pass. One crack 0.300 inch long occurred 1-1/2 inches from the end of the weld, and the other crack 0.100 inch long occurred 1/2 inch from the end of the weld. These cracks were ground out, manually repaired and the remaining passes made at 235 amps, 17-1/2 volts, a wire feed rate of 66 ipm, and a welding speed of 10 ipm did not show signs of cracking.

Weld No. M294 was made in the horizontal position. A photograph of the torch and fixture in this position is presented in Figure 54. Although the photograph shows the torch at a slight angle to the plate, the final welding was accomplished with the torch normal to the plate surface. The first pass for this weld was made at 130 amps, 15.5 volts, a wire feed rate of 20 ipm, and a welding speed of 4 ipm. No cracking occurred in this pass. The plate was turned around and the second pass made at the same parameter. Again, no cracking was observed. However, the second pass had a ropy appearance and did not tie into the side walls properly. Rather than place one pass down the center of the joint, two beads staggered on either side of the joint would have been more acceptable. The third through theeleventh pass, on this side of the joint, were made at 240 amps, 17 volts, a wire feed rate of 66 ipm, and a welding speed of 10 ipm. To prevent excessive undercutting of the top plate, the amperage and voltage for the twelfth pass were reduced to 195 amps and 16 volts. These settings allowed this pass to fill properly without undercutting. The plate was then turned over and dye checked on this side. Up to this point, no cracking had occurred in the weld. The thirteenth pass made at 240 amps, 17 volts, a wire feed rate of 66 ipm, and a welding speed of 10 ipm cracked in the center. The crack was ground out and the pass remade at 130 amps, 15 volts, a wire feed rate of 20 ipm, and a welding speed of 4 ipm. This pass did not crack; however, the weld bead was again ropy. This rope effect was ground down and the fourteenth through the twenty-third passes were made at 240 amps, 17 volts, a wire feed rate of 66 ipm, and a welding speed of 10 ipm. No further cracking was observed.

Weld No. M302 was a vertical up weld made by the manual TIG process. This weld, made in the double U-groove joint design, did not have any cracking. However, to allow acceptable side wall melting, it was necessary to use the following parameters.

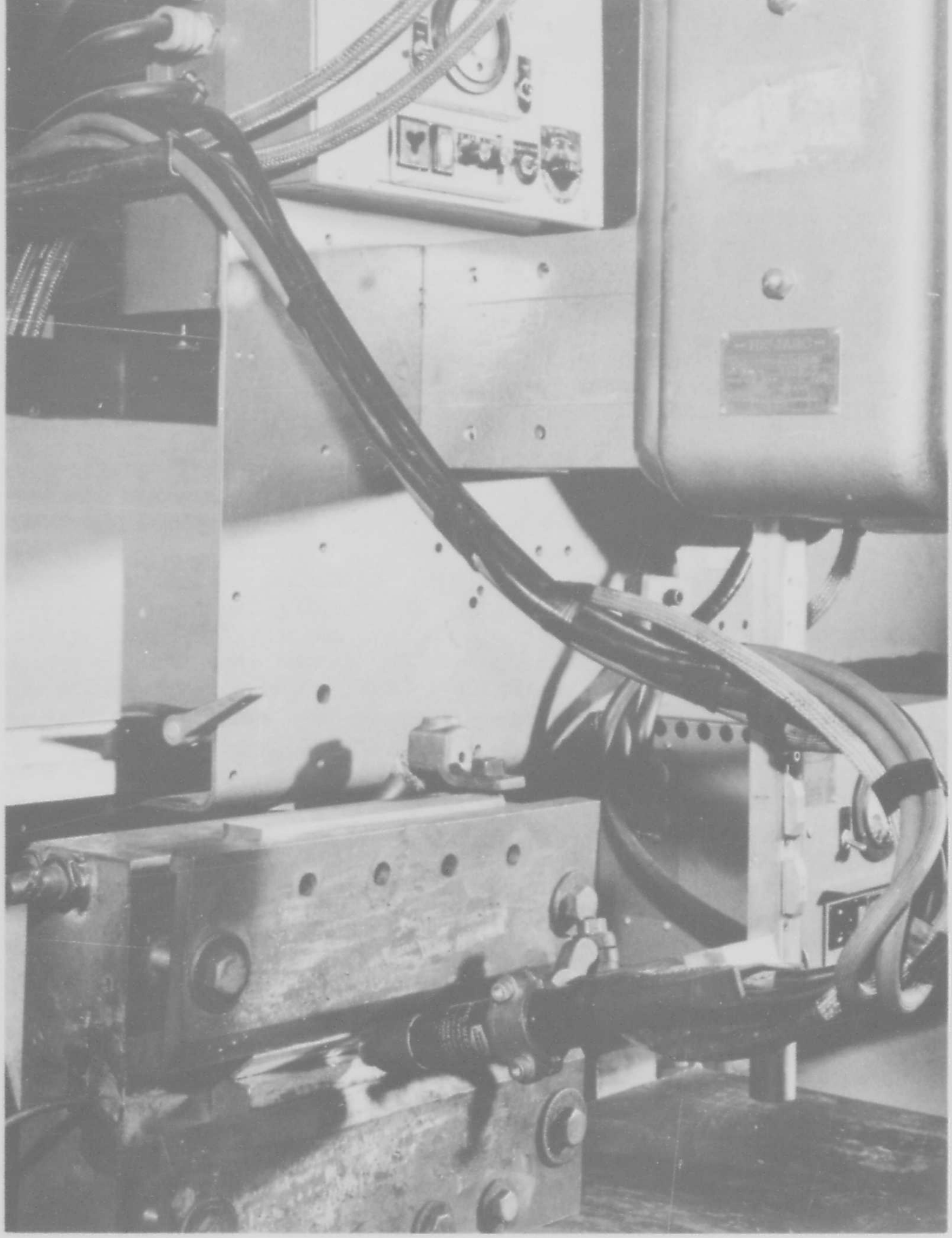


Figure 54. Heliarc Torch in Position for Horizontal Welding.

1st pass - 100 amps - 14 volts

2nd pass - 110 amps - 14 volts
(opposite side)

3rd pass - 110 amps - 14 volts

4th pass through the 13th pass
130 amps - 16 volts

18th pass through the 36th pass
160 amps - 16 volts

These passes were put in by alternating three passes on each side of the plate.

(2) Weld Microstructures

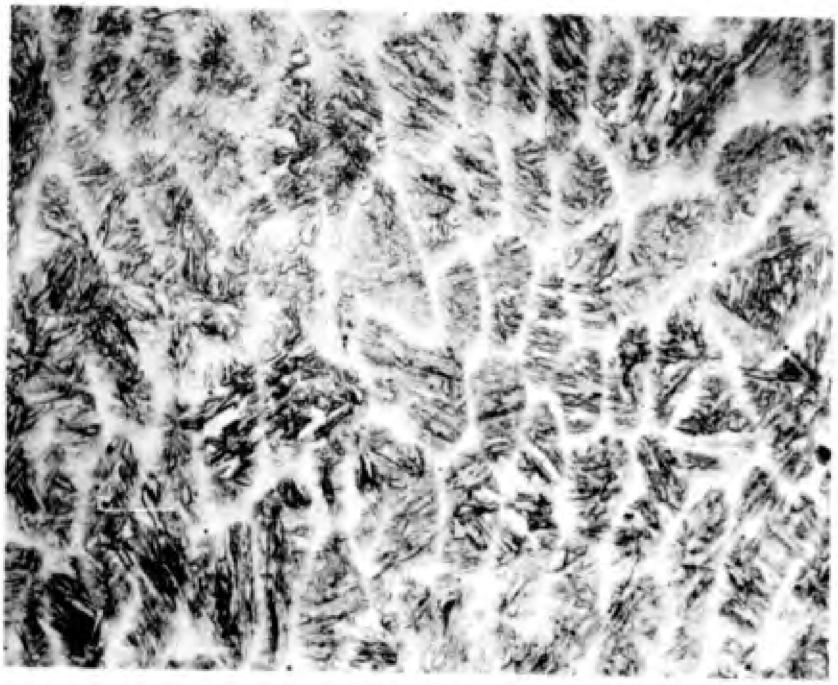
The microstructure of welds made in 1-inch HP 9-4-25 plate using filler wires Nos. 15 and 19 are presented in Figures 55 to 57. As in the case of the welds made in HP 9-4-20 1/2-inch plate, these microstructures show evidence of coring at the top of the fusion zone and refinement in the center of the fusion zone. These microstructures consist essentially of fresh and tempered martensite. The aluminum oxide found in the 1/2-inch plate welds using filler wire No. 15 was not evident in these welds.

(3) Weld Hardness Surveys

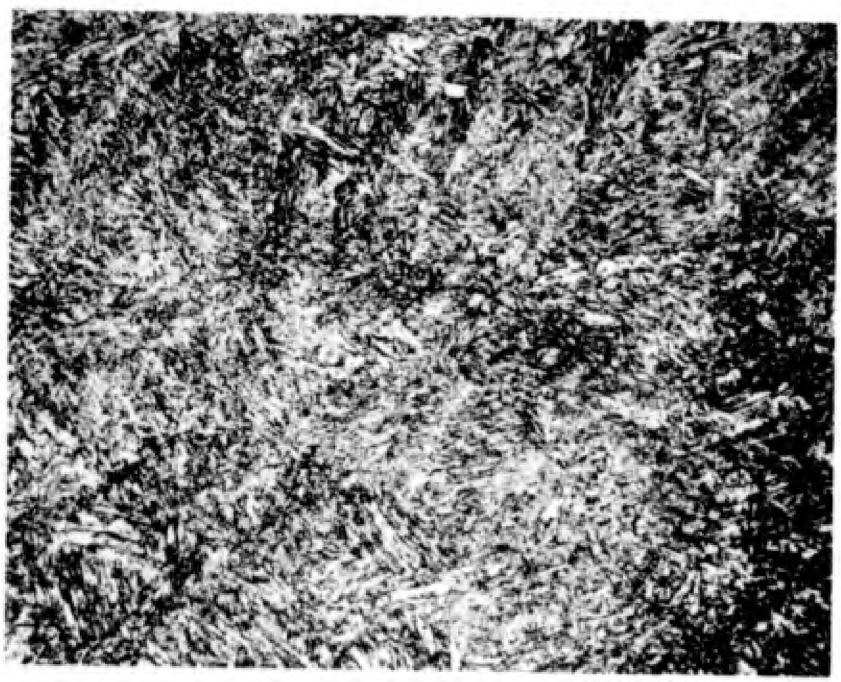
Hardness surveys for multipass TIG welds made in HP 9-4-25 1-inch plate are presented in Figures 58 to 60. Weld No. M276, made in the single U-groove joint design using filler wire No. 15 (Figure 58), in general has higher hardness readings in the fusion zone than weld No. M282, made in the double U-groove joint design (Figure 59). The energy inputs into these welds was essentially the same, 25.2 and 24.7 K-joules/inch/pass, respectively. The lower hardness readings in the center of the weld using the double U-groove joint design reflect the additional energy input into the root passes of this weld. However, they are not significantly different from areas in the top two passes and each side of the plate. In general, the hardness traverse of weld No. M291, made using filler wire No. 19 (Figure 60), is more consistent in all three areas, with only a slight increase in hardness in the fusion zone.

(4) Tensile Properties

The smooth tensile properties for TIG welds made in 1-inch HP 9-4-25 material are summarized in Table 17. All welds produced 100% yield and ultimate strength joint efficiencies, even though one transverse specimen of weld M282 (wire No. 15, double U-joint) failed in the weld metal. The ductilities obtained were also comparable to that of the parent metal excepting the single weld metal failure which only exhibited 4% elongation and 7.4%

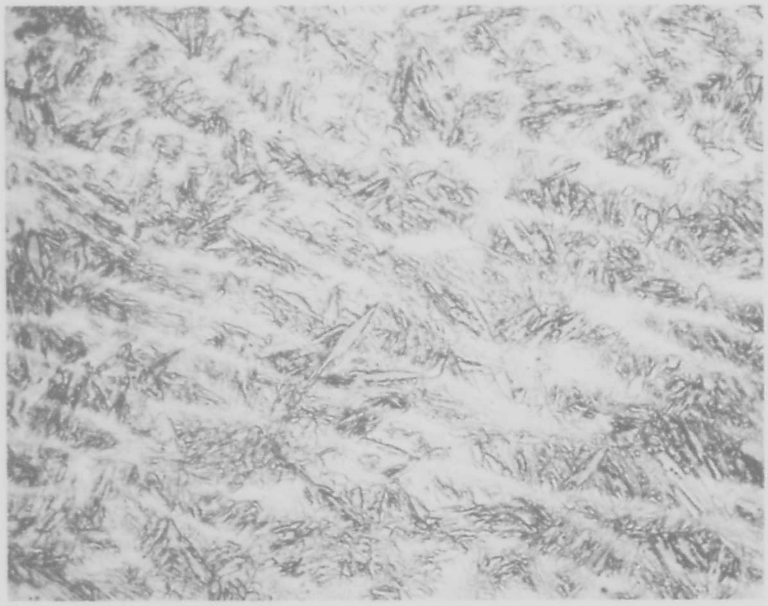


Top of Fusion Zone 500X

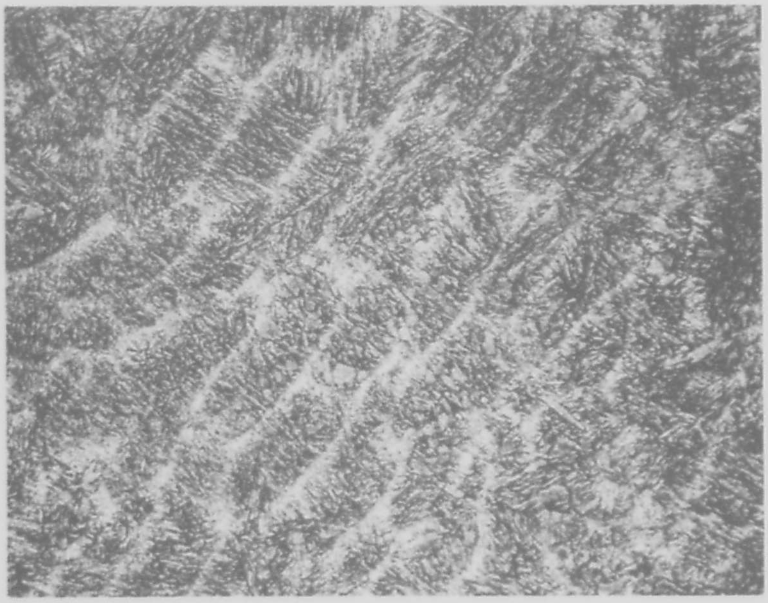


Center of Fusion Zone 500X

Figure 55. Microstructure of Multipass TIG Weld No. M276 Made in HP 9-4-25 1-Inch Plate. Weld was Made in Helium at a Welding Speed of 10 ipm Using Filler Wire No. 15 and a Single U-Groove Joint Design.



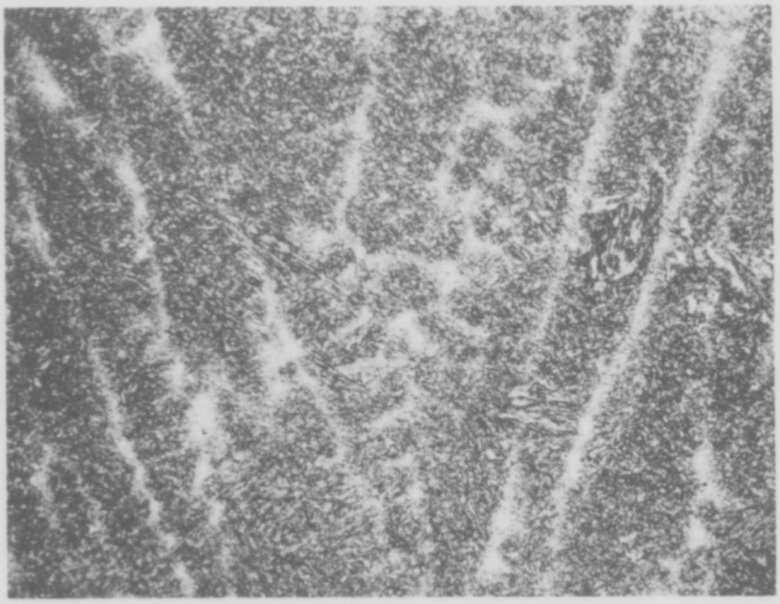
Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 56. Microstructure of TIG Weld No. M282 Made in HP 9-4-25 1-Inch Plate. Weld was Made in Helium at a Welding Speed of 10 ipm Using Filler Wire No. 15 and a Double U-Groove Joint Design.

Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 57. Microstructure of Multipass TIG Weld No. M291 Made in HP 9-4-25 1-Inch Plate. Weld was Made in Helium at a Welding Speed of 10 ipm Using Filler Wire No. 19 and a Single U-Groove Joint Design.

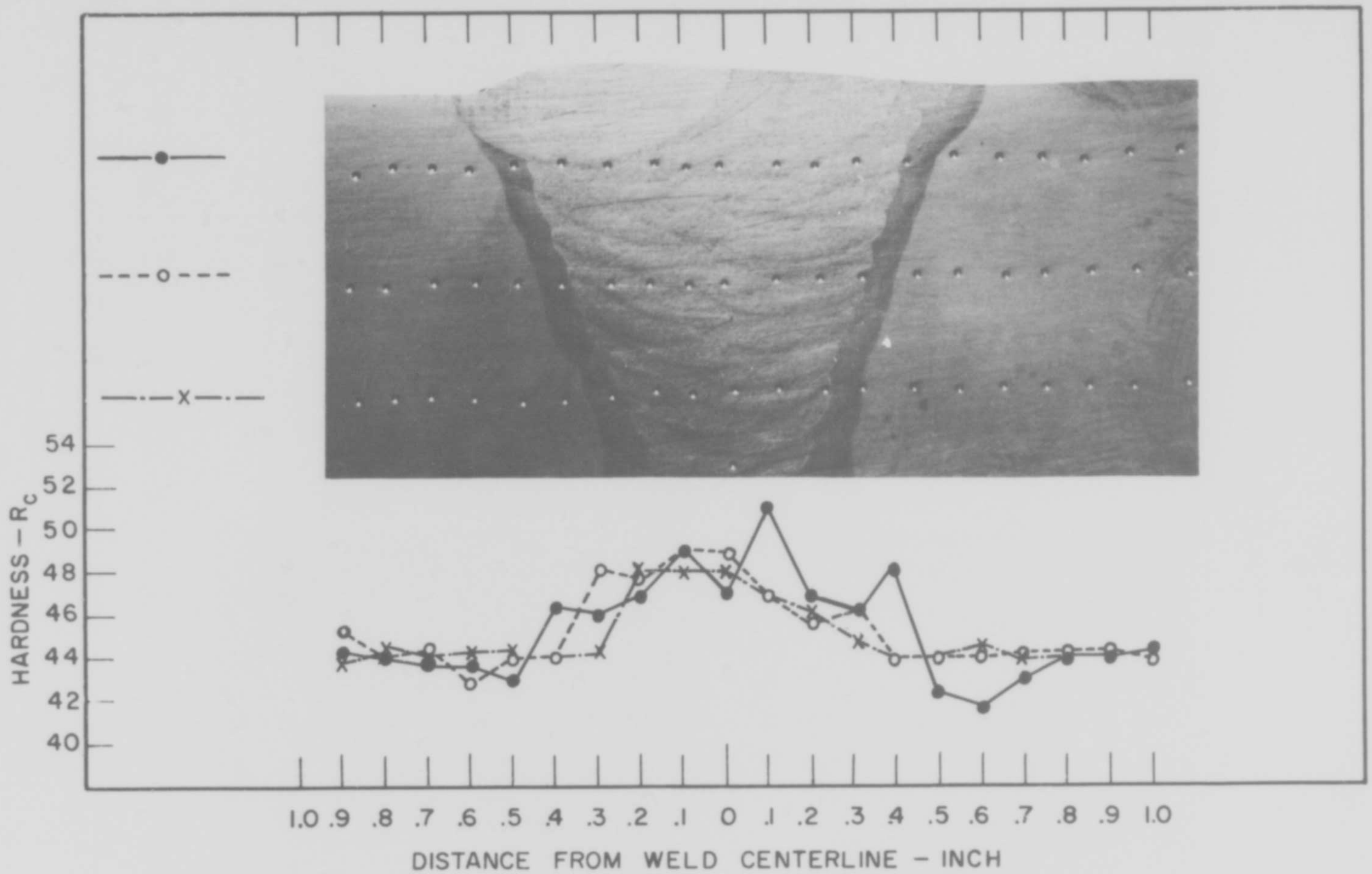


Figure 58. Hardness Survey of Multipass TIG Weld No. M276 Made in HP 9-4-25 1-Inch Plate. Weld was Made in Helium at a Welding Speed of 10 ipm Using Filler Wire No. 15 and a Single U-Groove Joint Design.

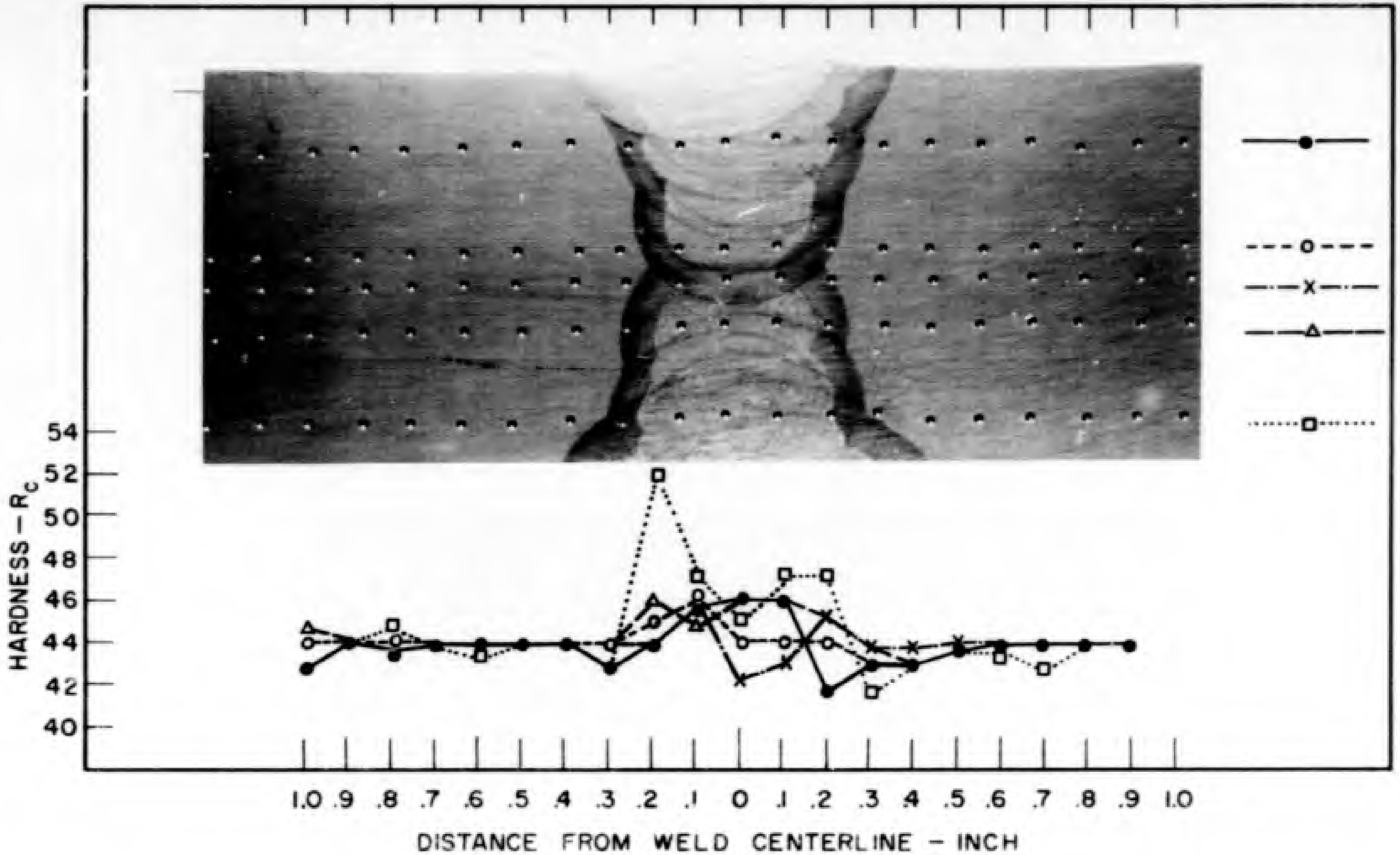


Figure 59. Hardness Survey of Multipass TIG Weld No. M282 Made in HP 9-4-25 1-Inch Plate. Weld was Made in Helium at a Welding Speed of 10 ipm Using Filler Wire No. 15 and a Double U-Groove Joint Design.

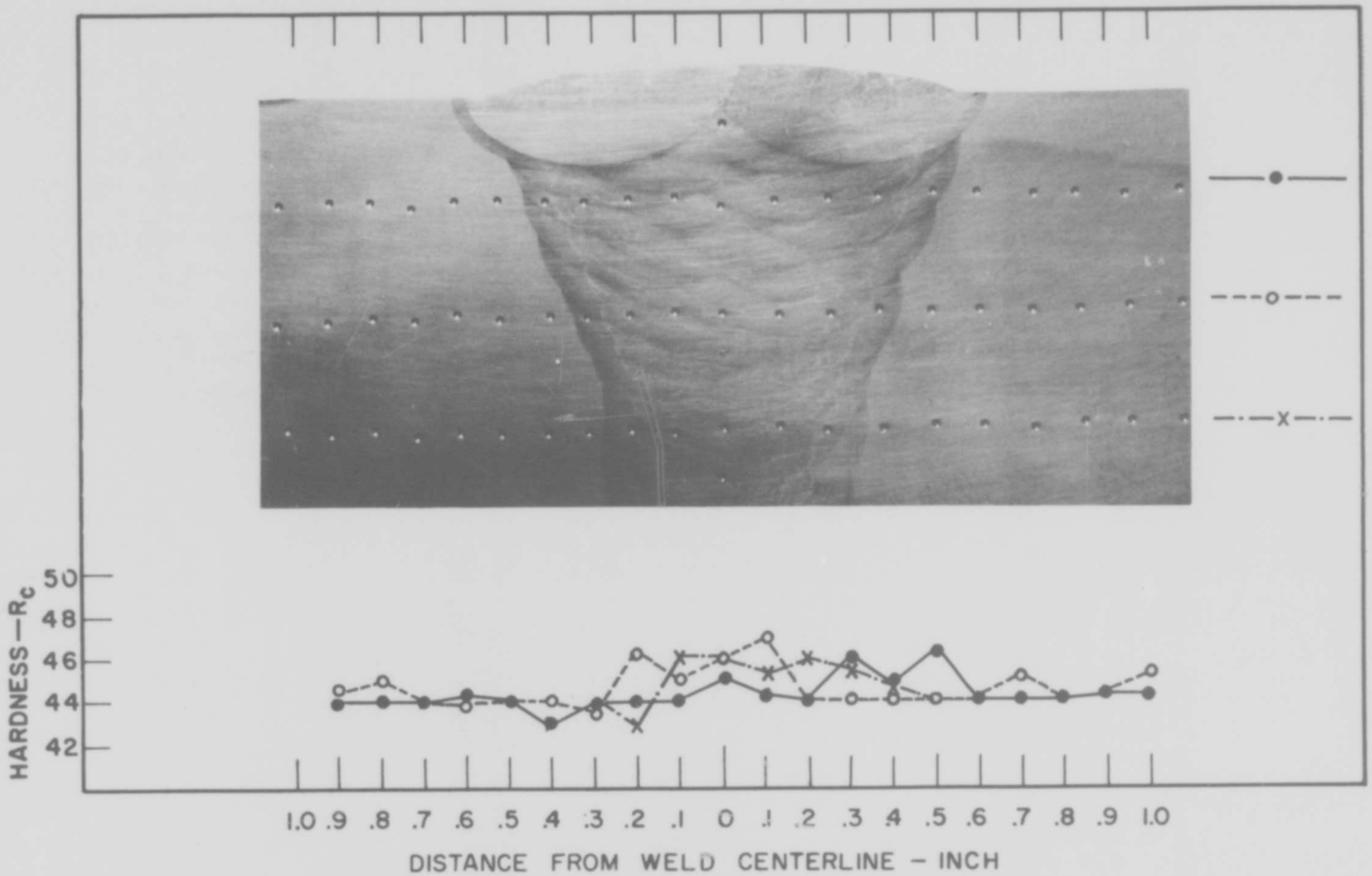


Figure 60. Hardness Survey of Multipass TIG Weld No. M291 Made in HP 9-4-25 1-Inch Plate. Weld was Made in Helium at 10 ipm Using Filler Wire No. 19 and a Single U-Groove Joint Design.

TABLE 17

TENSILE PROPERTIES OF TIG WELDS MADE IN HP 9-4-25 1 INCH PLATE

Weld No.	Test Direction(a)	Filler Wire(b)	Welding Speed (ipm)	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elongation %(c)	R.A. (%)	Energy Input K-J/in./pass	% Joint Efficiency(d) Y.S.	U.T.S.	Comments
M276	Longitudinal	15	10	210.2	225.9	14.0	38.8	25.2			
	Transverse	15	10	192.1	203.0	14.0	59.7	25.2	100.0	100.0	(e)
	Transverse	15	10	192.2	202.4	13.5	58.3	25.2	100.0	100.0	(e)
M282	Transverse	15	10	190.7	200.9	15.0	61.2	24.7	100.0	100.0	(e)
	Transverse	15	10	188.7	199.4	4.0	7.4	24.7	99.6	99.9	(f)
M291	Longitudinal	19	10	201.9	210.4	17.5	55.2	25.2			
	Transverse	19	10	191.4	202.0	15.0	62.0	25.2	100.0	100.0	(g)
	Transverse	19	10	187.0	201.3	14.0	61.1	25.2	98.8	100.0	(g)
M294	Transverse	14	10	190.3	201.1	15.5	60.6	--	100.0	100.0	(e) Horizontal Weld
	Transverse	14	10	189.3	201.4	16.5	58.5	--	100.0	100.0	(e) Horizontal Weld
M302	Transverse	19	Manual	191.4	201.8	15.5	59.2	--	100.0	100.0	(g) Vertical Weld
	Transverse	19	Manual	190.7	201.8	15.0	58.7	--	100.0	100.0	(g) Vertical Weld
M303	Transverse	19	10	184.6	201.5	15.5	59.8	25.2	97.5	100.0	(g) Joint Design E
	Transverse	19	10	189.4	201.7	16.0	62.2	25.2	100.0	100.0	(g) Joint Design E

Notes:

(a) (L) specimens were taken parallel with the weld and consisted entirely of weld deposit.

(T) specimens were taken transverse to the weld and included, weld, heat affected zone, and parent metal.

(b) Filler wire composition is presented in Table 2.

(c) (T) specimens had a gage length of 2 inches. (L) specimens had a gage length of 1 inch.

(d) Joint efficiency based upon 189.3 and 199.5 ksi parent metal yield and ultimate strengths, respectively.

(e) Fracture occurred in parent metal 1/2 inch from the fusion line.

(f) Fracture occurred in the weld.

(g) Fracture occurred in parent metal 3/8 inch from the fusion line.

reduction in area. However, observation of this specimen indicated that either a crack was present in the weld (M282) or that the weld was not properly fused in the center. In addition, these results indicate that desirable properties were obtained from horizontal and vertical welds made using filler wires No. 14 and 19, respectively. Reducing the number of weld passes by using a narrower joint design (design E, weld M303) did not appreciably improve the tensile properties. Joint efficiencies greater than 97.5% were obtained in all weldments in this material.

(5) Fracture Toughness

The fracture toughness of the HP 9-4-25 weldments was determined using notch bend specimens. As shown in Table 18, both 3- and 4-point loading conditions were employed. However, in only two instances were Type 2 curves (Figure 16) obtained, even under 4-point loading. The three welds examined (M276, M282, and M291) for fracture toughness all exhibited similar properties. The K_{IC} values generally ranged in the 130 ksi $\sqrt{\text{inch}}$ range, excepting the two specimens notched in a heat-affected zone of weld M282 which had a K_{IC} of about 120 ksi $\sqrt{\text{inch}}$. These values were considered excellent since they compared favorably to that of the parent metal. One remarkable finding was the degree of toughness of weld M282, even though incomplete penetration existed in the plane of the notch.

(6) Charpy Impact Properties

The Charpy V-notch impact properties of TIG Weld No. M303 made in HP 9-4-25 plate using filler wire No. 19 are given in Table 19. These results are also plotted in Figure 61, together with the plate data previously presented. The impact energy absorbed by the weld metal is somewhat lower than the plate at temperatures below 0°F and essentially the same as the plate at 0°F and room temperature. The heat-affected zone impact energy falls between the weld and plate metal at temperatures below about -50°F. At temperatures above -50°F the HAZ absorbs less energy than either plate or weld. While there is some variation in the impact energy of the joint components, the fracture ductility as measured by lateral expansion of plate, weld, and HAZ are essentially the same.

c. General Discussion

Desirable tensile properties (in excess of 184.6 ksi) yield strength and 199.4 ultimate strength) with adequate ductility and fracture toughness comparable to parent metal can be obtained in 1-inch thick HP 9-4-25 material. In addition, automatic horizontal and manual vertical welding can be successfully accomplished. However, welds in double U-groove joint designs appear to be susceptible to centerline cracking.

3. AMS 6435 Steel (1/2-Inch Plate)

a. Base Metal Evaluation

The AMS 6435 material was subjected to various tempers ranging from 450°F to 1200°F to determine the tempering temperatures that would result

TABLE 18

CALCULATED FRACTURE TOUGHNESS, K^*_{IC}, OF TIG WELDS MADE IN 1 INCH HP 9-4-25 PLATE AT A WELDING SPEED OF 10 IPM USING HELIUM SHIELDING

(4 POINT LOADED)

Specimen Identity	Filler Wire(a)	Notch(b) Position	Width, W (inch)	Thickness, B (inch)	Crack Depth, a (inch)	Major Span, L' (inch)	Curve Type(c)	Load (lbs)	Relative Plastic Zone Size, r_y/B(d)	σ_{nom}/σ_{ys}(e)	Calculated Fracture Toughness, K^*_{IC} (ksi $\sqrt{in}$)
M276x	15	Weld	0.938	1.000	0.283	7.5	1	10,300	0.025	1.43	147.2
"	15	Weld	0.938	1.001	0.289	7.5	1	9,200	0.021	1.30	131.9
M282-1	15	HAZ	0.939	0.992	0.257	6.5	1	20,400	0.019	1.14	124.1
M282-2	15	HAZ	0.939	0.992	0.217	6.5	1	21,850	0.017	1.09	118.5
M282-3	15	Weld	0.937	0.992	0.196	6.5	1	26,550	0.023	1.25	138.3(f)
M282-4	15	Weld	0.939	0.992	0.308	6.5	2	19,350	0.022	1.26	136.1(f)
M282-5	15	HAZ	0.939	0.992	0.213	6.5	1	24,850	0.022	1.22	134.9
M282-6	15	Weld	0.939	0.992	0.171	6.5	1	31,850	0.027	1.40	155.8(f)
M291-1	19	HAZ	0.935	0.992	0.124	6.5	2	33,200	0.022	1.31	138.4
M291-2	19	Weld	0.939	0.992	0.240	6.5	1	25,700	0.027	1.37	152.7

Notes: x - 3 Point loaded.

(a) Filler wire compositions given in Table 2.
(b) HAZ - Heat affected zone.
(c) Curve types are defined in Figure 16.
(d) Plastic zone size, r_y, equals the difference between the effective crack length a^* and the measured crack length, a $(a^* = a + EG/6\pi\sigma_{ys}^2)$.
(e) σ_{nom}/σ_{ys} = nominal stress at crack initiation divided by 0.2% yield strength.
(f) Incomplete weld penetration.

TABLE 19

CHARPY V-NOTCH IMPACT PROPERTIES OF A TIG WELD
MADE IN HP 9-4-25 1-INCH PLATE

Identification	Notch Location	Test Temp. (°F)	Impact Energy (ft. lbs)	Lateral Expansion (Mils)
M303-1	Weld	Room	35.5	17.0
M303-2	"	0	33.5	13.5
M303-3	"	-100	26.5	10.5
M303-4	"	"	26.5	13.5
M303-5	"	-320	13.5	1.5
M303H-1	HAZ	Room	31.0	15.5
M303H-2	"	0	30.0	12.5
M303H-3	"	-100	27.0	10.0
M303H-4	"	"	32.0	13.0
M303H-5	"	-320	16.5	1.5

Note: Lateral expansion measured at base of fracture.

*Weld was made with filler wire No. 19 (see Table 2).

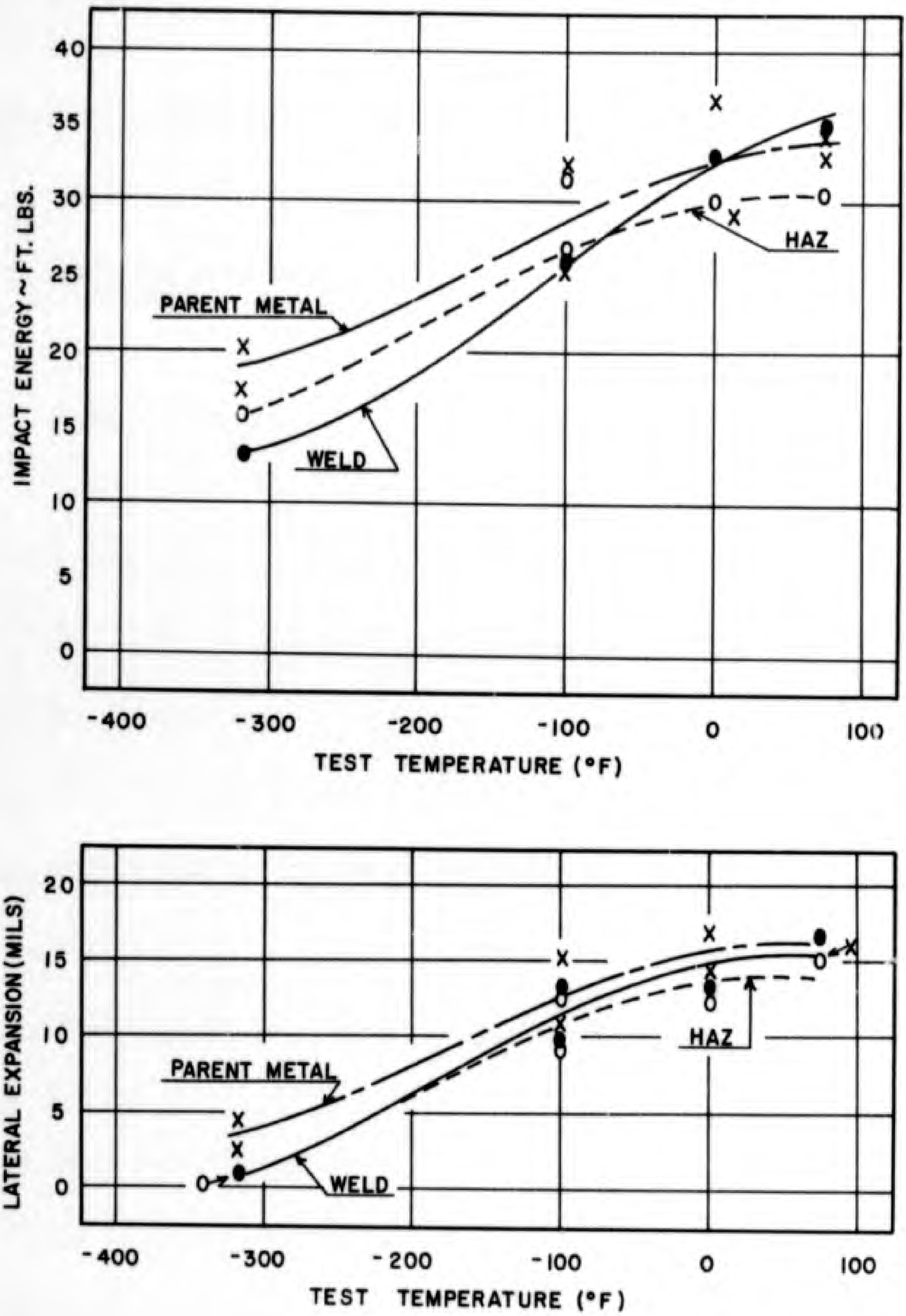


Figure 61. Charpy V-Notch Impact Properties of TIG Weld No. M303 Made in HP 9-4-25 1-Inch Plate at 10 ipm in Helium Using Filler Wire No. 19.

in the desired 180 to 200 ksi yield strength. Hardness surveys were made to determine tempering temperatures which would yield hardnesses greater than R_c 45, corresponding to the 180 ksi yield strength. The results of this survey are summarized in Figure 62. It was indicated that tempering temperatures of 800°F and below could be used, and tempering temperatures of 450, 550, 700, and 800°F for 2 hours were therefore employed.

The inclusion content of the as-received material is shown in Figure 63 for both the longitudinal and transverse directions. Typical microstructures produced by the four tempering cycles are presented in Figure 64.

The influence of tempering temperature on the smooth tensile properties of AMS 6435 plate is summarized in Table 20. All tempers examined produced yield strengths above the 180 ksi minimum for the program and also yielded good ductilities. The fracture toughness of AMS 6435 steel in the tempered conditions examined on this program has been determined previously(12) and ranged from 50 ksi $\sqrt{\text{inch}}$ for the 400°F temper to 70 ksi $\sqrt{\text{inch}}$ for the 800°F temper.

b. Evaluation of TIG Welds in AMS 6435 1/2-Inch Plate

Gas tungsten arc welds were made in 1/2-inch plates of AMS 6435 material that had been tempered at 450, 500, 700 and 800°F for 2 hours. Welds were made at 4 and 10 ipm in plates tempered at 700°F and at 10 ipm in plates tempered at each of the other temperatures. Both high and low carbon D6AC, 1722 AS, and HP 9-4-20 filler wires were used. These welds were evaluated for quality, metallographic structure, hardness, and smooth tensile properties. Fusion welding parameters for these welds are presented in Tables 21 and 22.

(1) Weld Quality

Each weld made in AMS 6435 material was free from porosity; however, some cracking did occur in the weld metal. Welds (D227 and D226, respectively), made at 10 ipm with high carbon D6AC filler wires No. 5 and No. 6 (see Table 2), cracked in the crater at the end of the weld. These cracks continued propagating through each subsequent pass and were visible to the naked eye. The cracks were about 1/2-inch long and were confined to the very end of the weld. This cracking could have been eliminated by using run-off tabs; however, it is an indication that high carbon filler wires could pose a problem under highly restrained conditions with no pre- or post-weld treatment.

In addition, metallographic examination revealed fine root cracks in initial welds where complete penetration was not accomplished. This occurred regardless of the filler wire used. Insufficient penetration was the result of both excessive land thickness and low energy input into the weld. For subsequent work with low energy inputs, the land thickness on the weld joint was decreased from 0.060 to 0.030 inch.

(2) Weld Microstructure

The fusion zone microstructures of welds made at 4 and 10 ipm are presented in Figures 65 to 67. Although these welds all exhibit coring in the top of the fusion zone, it is interesting to note that in welds A232 and

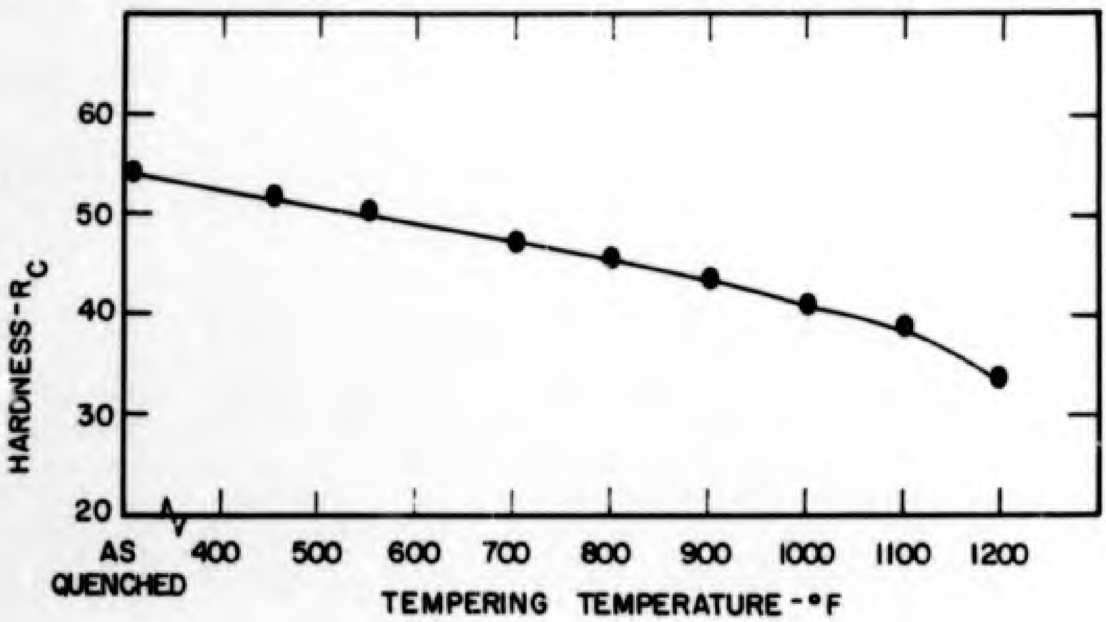


Figure 62. Effect of Tempering Temperature on Hardness of AMS 6435 Steel.

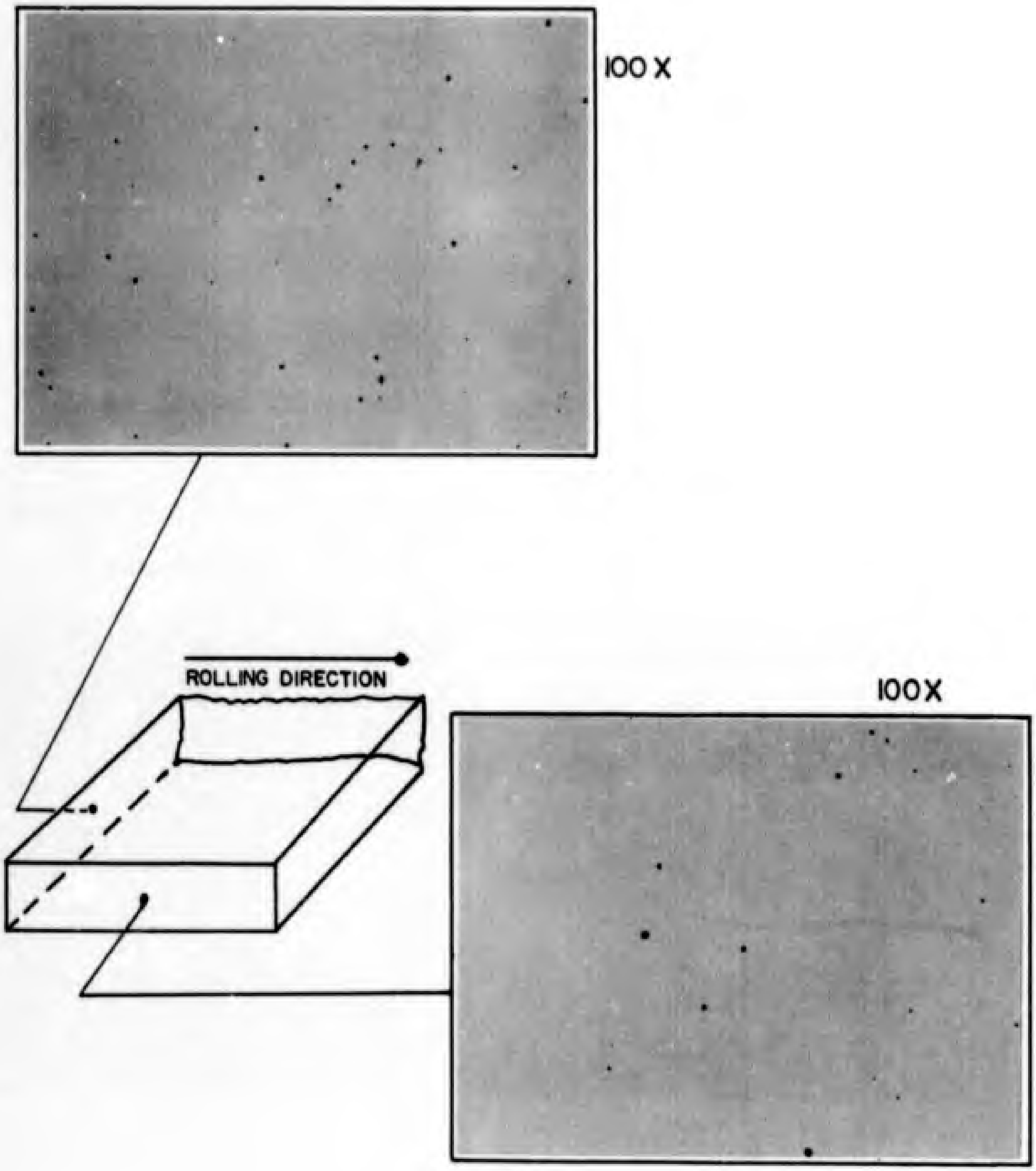
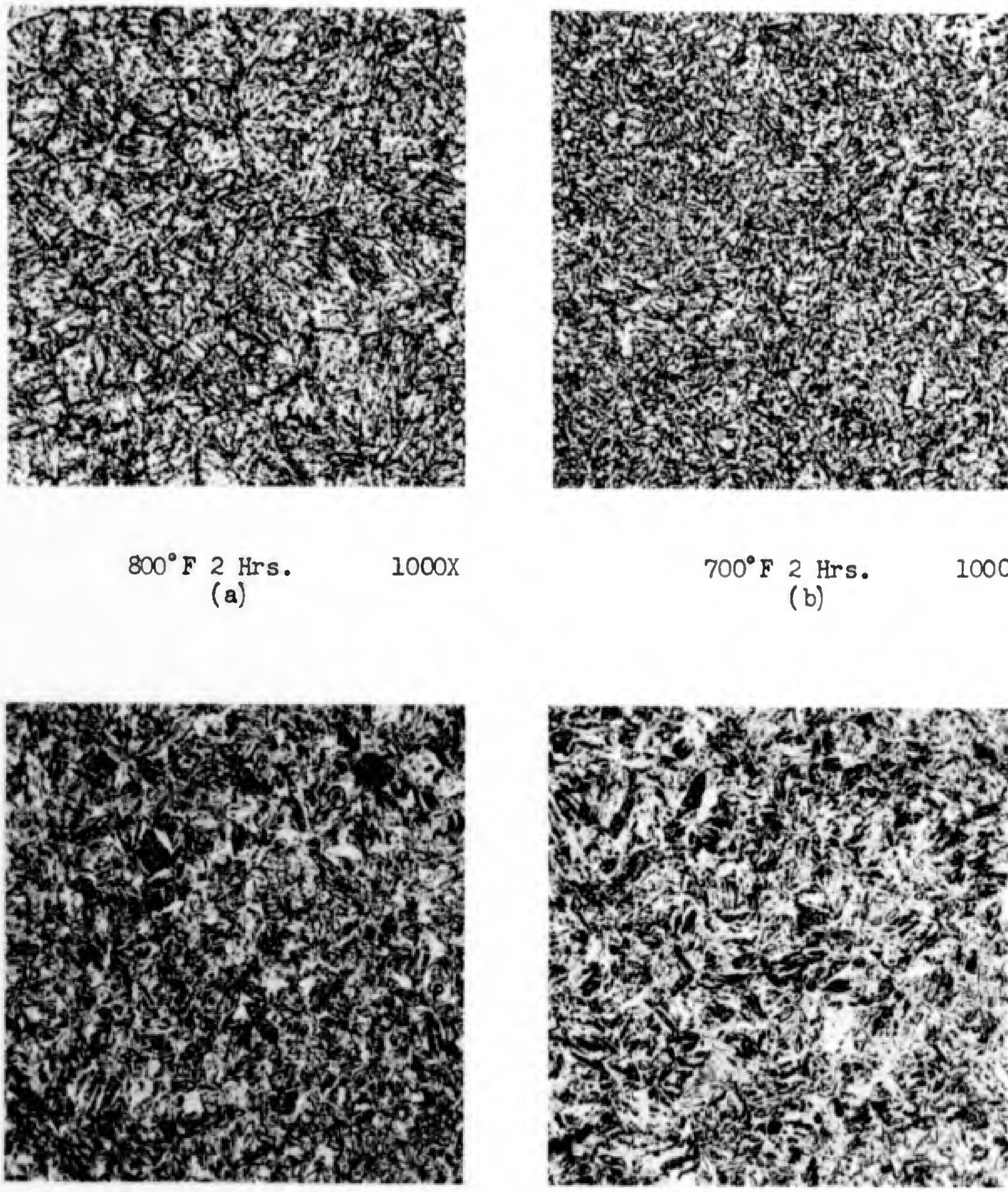


Figure 63. Inclusions In AMS 6435 Hot Rolled-Annealed And Pickled Plate, Unetched



800°F 2 Hrs. (a) 1000X

700°F 2 Hrs. (b) 1000X

550°F 2 Hrs. 1000X

450°F 2 Hrs. 1000X

Figure 64. Microstructure of AMS 6435 Steel Austenitized at 1550°F, 30 Minutes Oil Quenched and tempered for 2 Hours at the Designated Temperatures. Etch: 2% Nital

TABLE 20

EFFECT OF TEMPERING TEMPERATURE ON PROPERTIES OF AMS 6435 1/2 INCH PLATE

Tempering Temp. (°F)	Test(a) Direction	0.2% Yield Strength (ksi)	Ultimate Strength (ksi)	Elongation (%-1")	R.A. (%)
450	L	220.6	271.3	14.0	50.5
"	L	221.4	267.4	13.5	47.4
550	L	233.6	263.3	13.5	51.9
"	L	236.1	263.4	12.5	48.8
700	T	196.1	220.0	11.5	42.3
"	T	199.7	223.1	10.0	38.3
"	L	212.1	229.1	13.0	48.4
"	L	211.2	229.1	12.0	48.4

(a) Test direction relative to rolling direction.

TABLE 21

FUSION WELDING PARAMETERS FOR
TIG WELDS MADE IN AMS 6435 1/2 INCH PLATE

Weld No.	Filler Wire Dia. (in.)	Wire(a) Composition	Pre- and Post-Heat °F	No. Passes	W/S (ipm)	Wire Speed (ipm)	amps	Volts	Gas (cfh) Torch	Gas (cfh) Backup	Comments(c)
D226	0.062	6	None	10	10	48(b)	220	18	50He	4He	(d)
D227	"	5	"	10	10	48(b)	220	18	"	"	(d)
A232	"	1	"	9	4	20(b)	175	14	"	5He	-
A233	"	3	"	11	4	20(b)	175	14	"	"	-
D234	"	3	"	13	10	26(b)	235	16	"	"	-
D235	"	1	"	14	10	26(b)	235	16	"	"	-
A236	"	1	"	18	10	26(b)	230	17	"	"	-
D237	"	9	"	14	10	26(b)	230	17	"	"	-
A238	"	9	"	15	10	26(b)	230	17	"	"	-
A239	"	1	"	18	10	26(b)	230	17	"	"	-

(a) Filler wire compositions presented in Table 2.

(b) The wire speed, amperage and voltage are for the second pass through the final pass. Parameters for the first pass are presented in Table 22.

(c) Weld quality comments based on radiographic inspection.

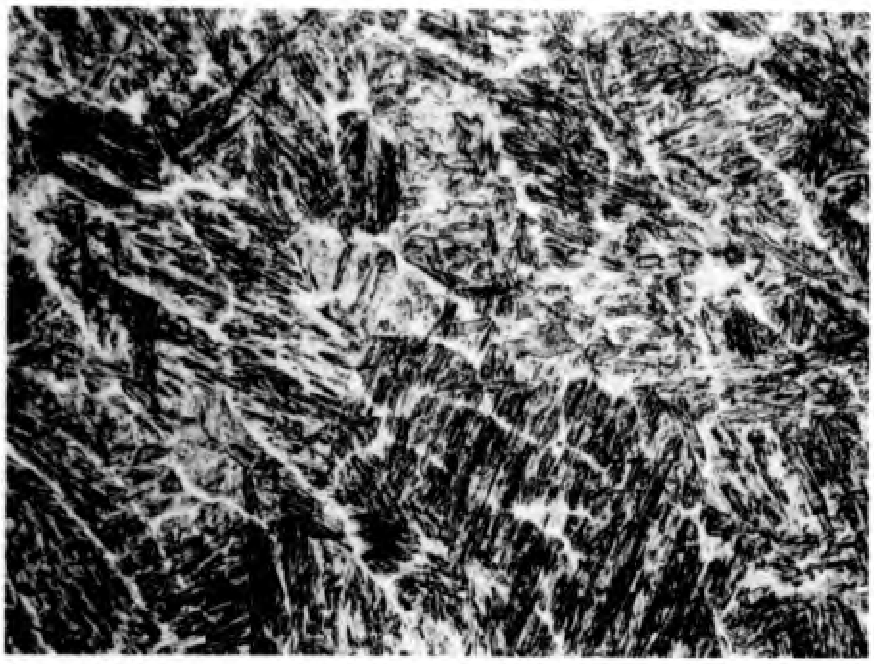
(d) Crater cracking observed at end of weld.

TABLE 22

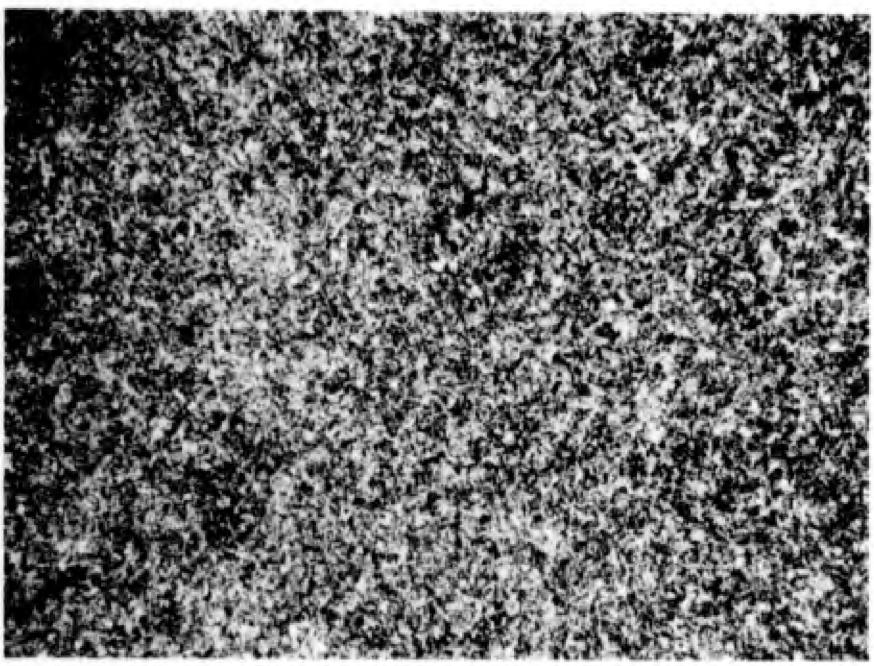
FUSION WELDING PARAMETERS OF FIRST PASS FOR
TIG WELDS MADE IN AMS 6435 1/2 INCH PLATE

Weld No.	Wire Speed (ipm)	amps	Volts
D226	None	220	18.0
D227	"	220	18.0
A232	"	175	14.0
A233	"	175	14.0
D234	"	235	16.0
D235	"	230	16.0
A236	"	230	17.0
D237	"	230	17.0
A238	"	230	17.0
A239	"	230	17.0

Note: Wire composition, welding speed and gas were the same as those listed in Table 21.

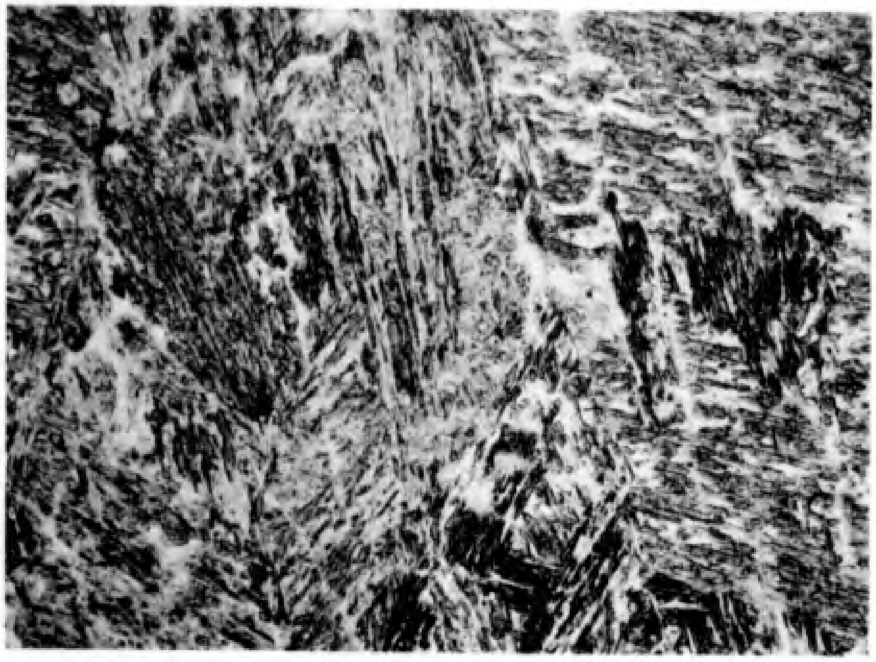


Top of Fusion Zone 500X

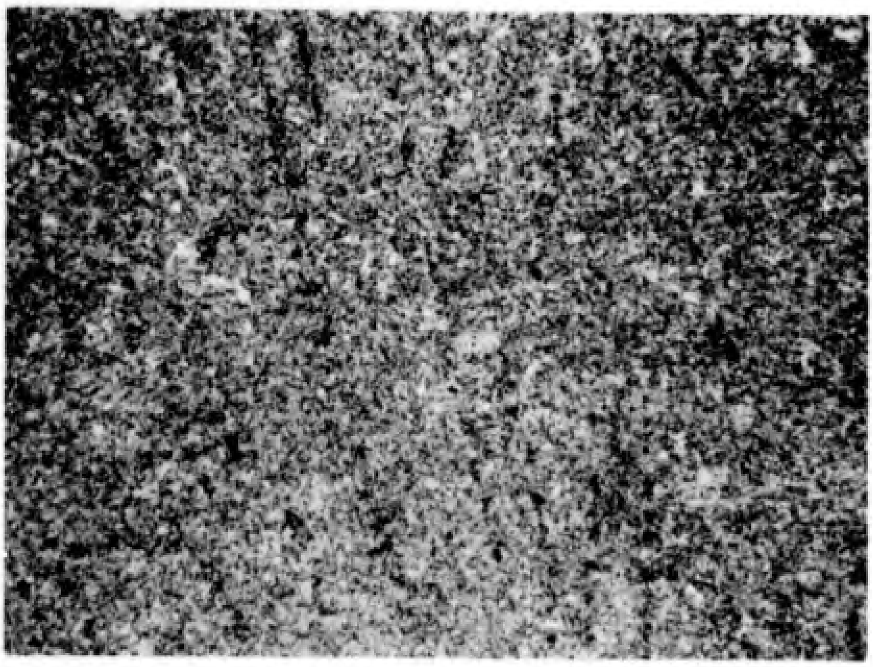


Center of Fusion Zone 500X

Figure 65. Microstructure (Martensite) of the Top and Center of the Fusion Zone of Multipass TIG Weld No. A232 Made In AMS 6435 1/2-Inch Plate at 4 ipm in Helium Using Filler Wire No. 1. Etch: 2% Nital

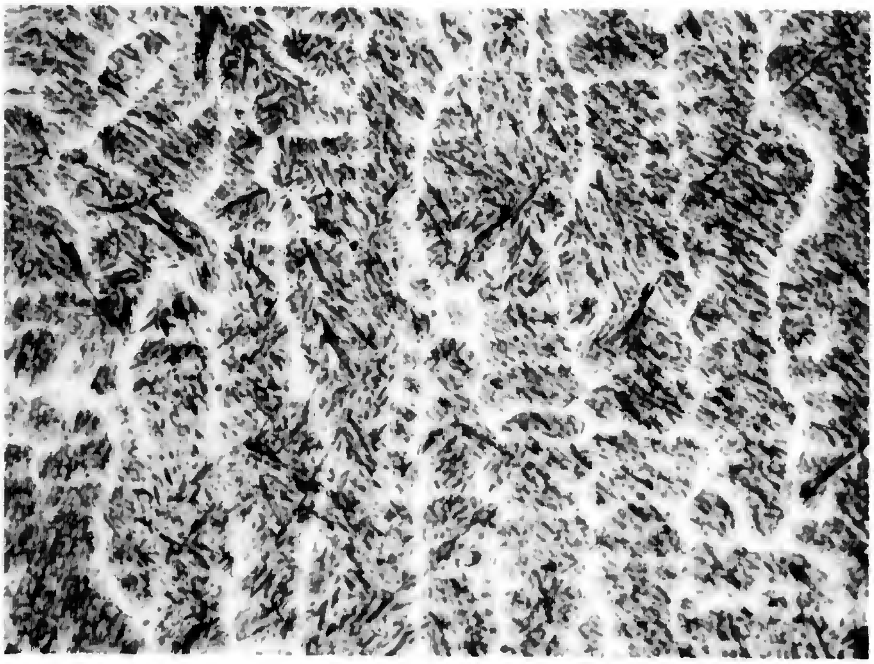


Top Of Fusion Zone 500X

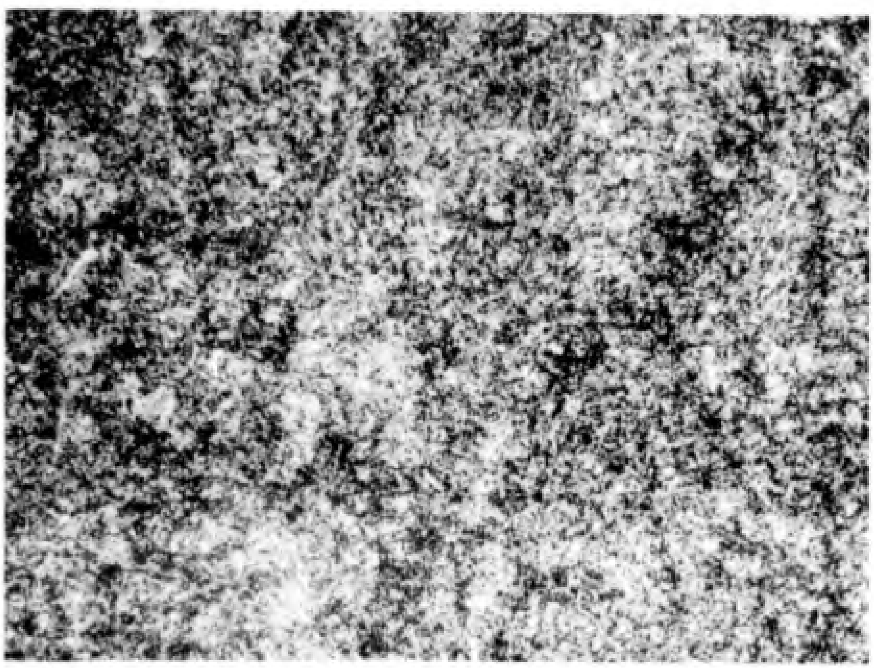


Center of Fusion Zone 500X

Figure 66. Microstructure (Martensite) of the Top and Center of the Fusion Zone of Multipass TIG Weld No. D235 Made in AMS 6435 1/2-Inch Plate at 10 ipm in Helium Using Filler Wire No. 1. Etch: 2% Nital



Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 67. Microstructure (Martensite) of the Top and Center of the Fusion Zone of Multipass TIG Weld No. D227 Made in AMS 6435 1/2-Inch Plate at 10 ipm in Helium Using Filler Wire No. 5. Etch: 2% Nital

and D235 where low alloy filler wire was used (Figures 65 and 66, center of fusion zone) subsequent weld passes have heat treated the deposited metal, resulting in a more homogeneous structure.

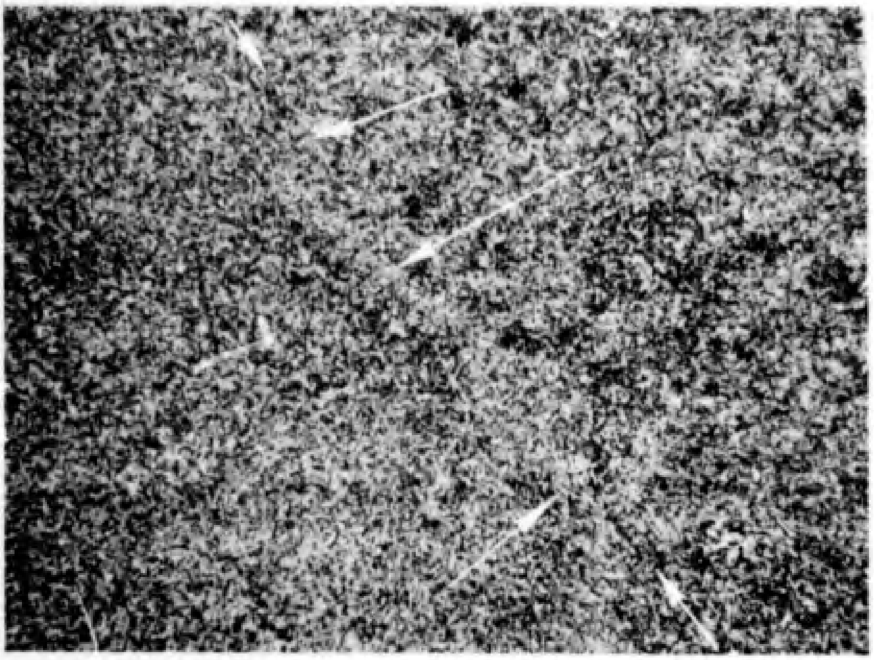
In addition, the slower welding speed and higher energy input into weld A232 has resulted in almost complete elimination of the coring effect in the center of the fusion zone, Figure 65. The light etching regions between the dendrites is believed to be untempered martensite. The microstructure of the fusion zone heat-affected zone interface for welds A232 and D235 made at 4 and 10 ipm, respectively, are presented in Figure 68. These microstructures are quite similar to those of parent metal. Grain coarsening, although not apparent in Figure 68, was observed in the heat-affected zone adjacent to the fusion line.

(3) Weld Hardness Surveys

Hardness surveys of welds made in AMS 6435 1/2-inch plate are presented in Figures 69 to 73. These surveys represent welds made in material that had been tempered at temperatures ranging from 450 to 800°F prior to welding. All welds exhibit a substantial decrease in hardness in the heat affected zone about 0.1 inch away from the fusion zone. In this region, the metal is exposed to tempering temperatures just below the A_1 temperature. The time that this region was exposed to a high tempering temperature appears sufficient to cause softening. Regardless of the tempering temperature of the base plate prior to welding, this area tends to soften to about the same degree in welds made with the same energy input. It can be noticed by comparing welds A232 and D235, Figures 71 and 72, that this region is somewhat softer when welded at a slower speed and a higher energy input (approximately 36.8 K-joules/inch as compared to 23 K-joules/inch). The hardnesses show considerable variation from the top to bottom of the joint. This is attributed to various degrees of tempering resulting from subsequent weld pass thermal cycles.

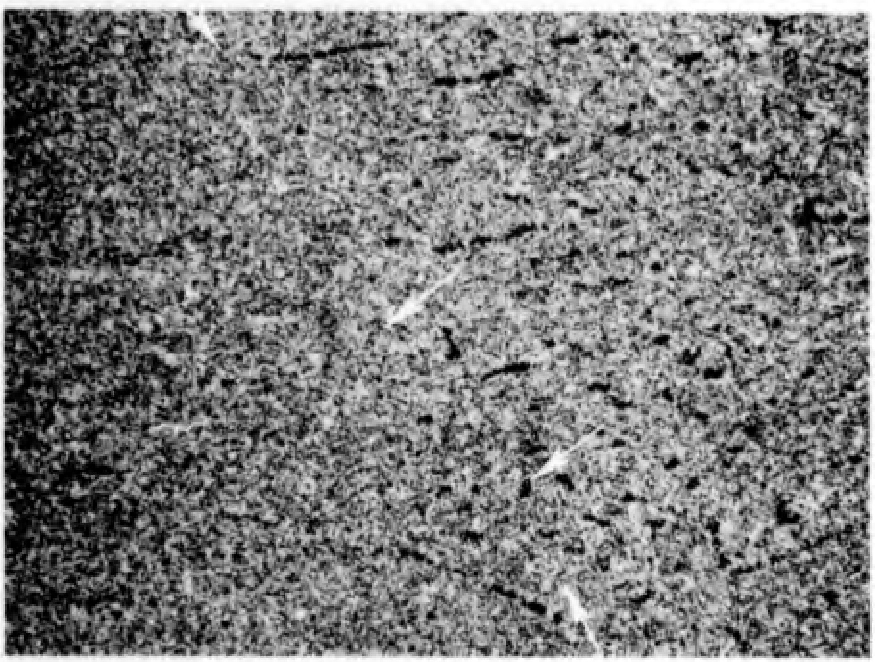
(4) Tensile Properties

The smooth tensile properties of welds made in AMS 6435 plate material are presented in Table 23. These welds were made in material heat treated by tempering at 450, 550, 700 and 800°F prior to welding. These results indicate that the original tempering temperature of the plate material had little effect on the strengths obtained after welding. This similarity in properties can be expected because the welding procedure and energy input into welds were the same and the resulting thermal cycles to which the heat-affected zone was subjected were the same. Therefore, if the resulting heat-affected zone is the weakest mechanically, all specimens would fail in the same general area as did occur. Each of the transverse specimens failed at the heat-affected zone fusion zone interface. This is further substantiated by the fact that the 4 ipm welds made with a higher energy input than the 10 ipm welds resulted in lower yield strengths. All transverse specimens exhibited relatively low elongation and reduction of area values. Adequate strength and ductility was obtained in all-weld metal deposits made with low carbon filler wires. However, weld metal deposits made with high carbon D6AC wires exhibited low ductility. Since adequate ductility could not be produced in AMS 6435 steel weldments, no fracture toughness or Charpy tests were made.



500X

4 ipm TIG Weld. Plate Tempered at 700°F
Before Welding. Weld No. A232



10 ipm TIG Weld. Plate Tempered at 700°F 500X
Before Welding. Weld No. D235

Figure 68. Microstructure (Martensite) of Fusion Zone-Heat Afftected Zone of TIG Multipass Welds Made in AMS 6435 1/2 Inch Plate at 4 and 10 ipm in Helium Using Filler Wire No. 1 Etch: 2% Nital

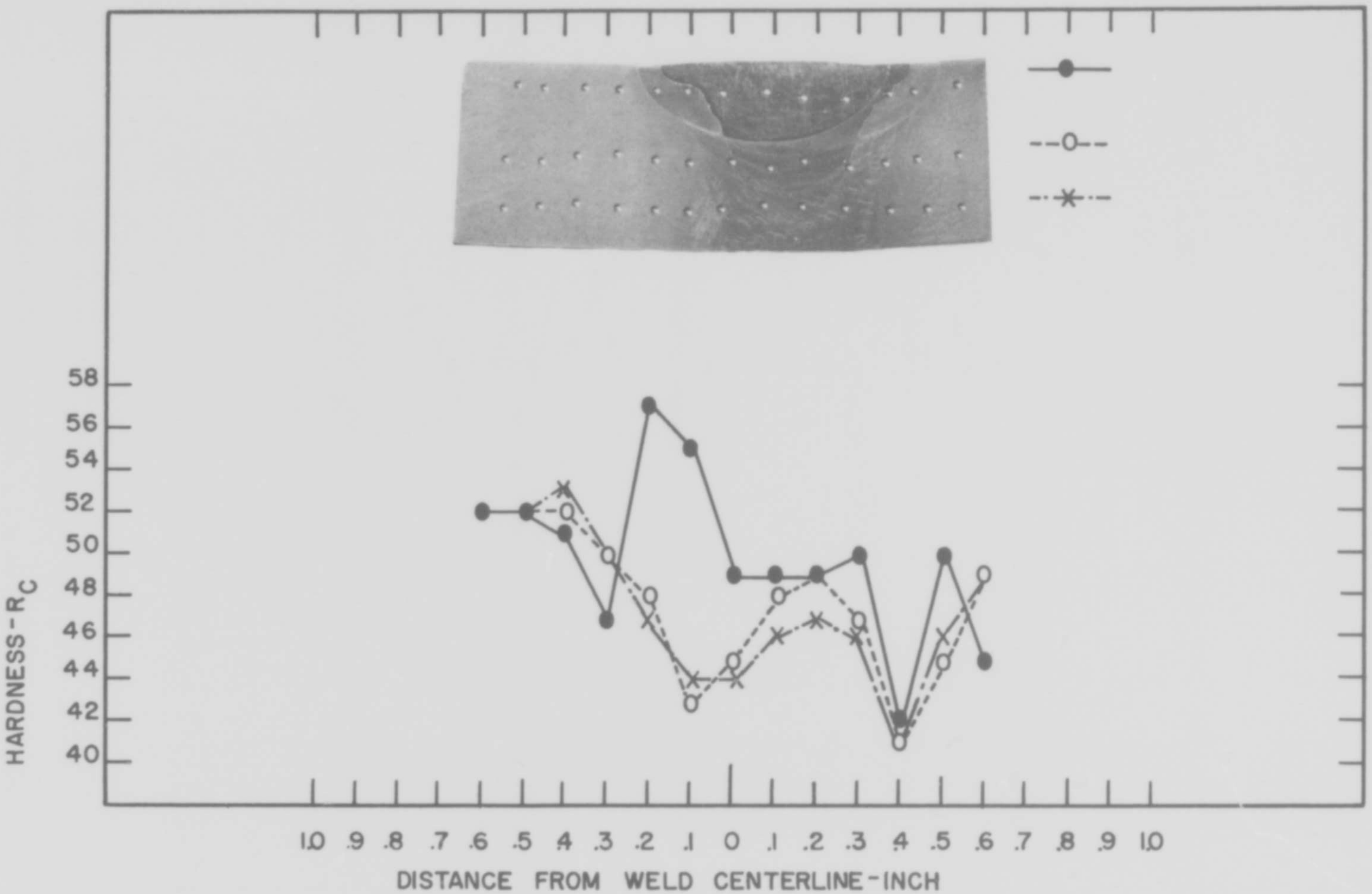


Figure 69. Hardness Survey of TIG Weld No. D237 Made in AMS 6435 Plate Material Tempered at 450°F at a Welding Speed of 10 ipm Using Filler Wire No. 9.

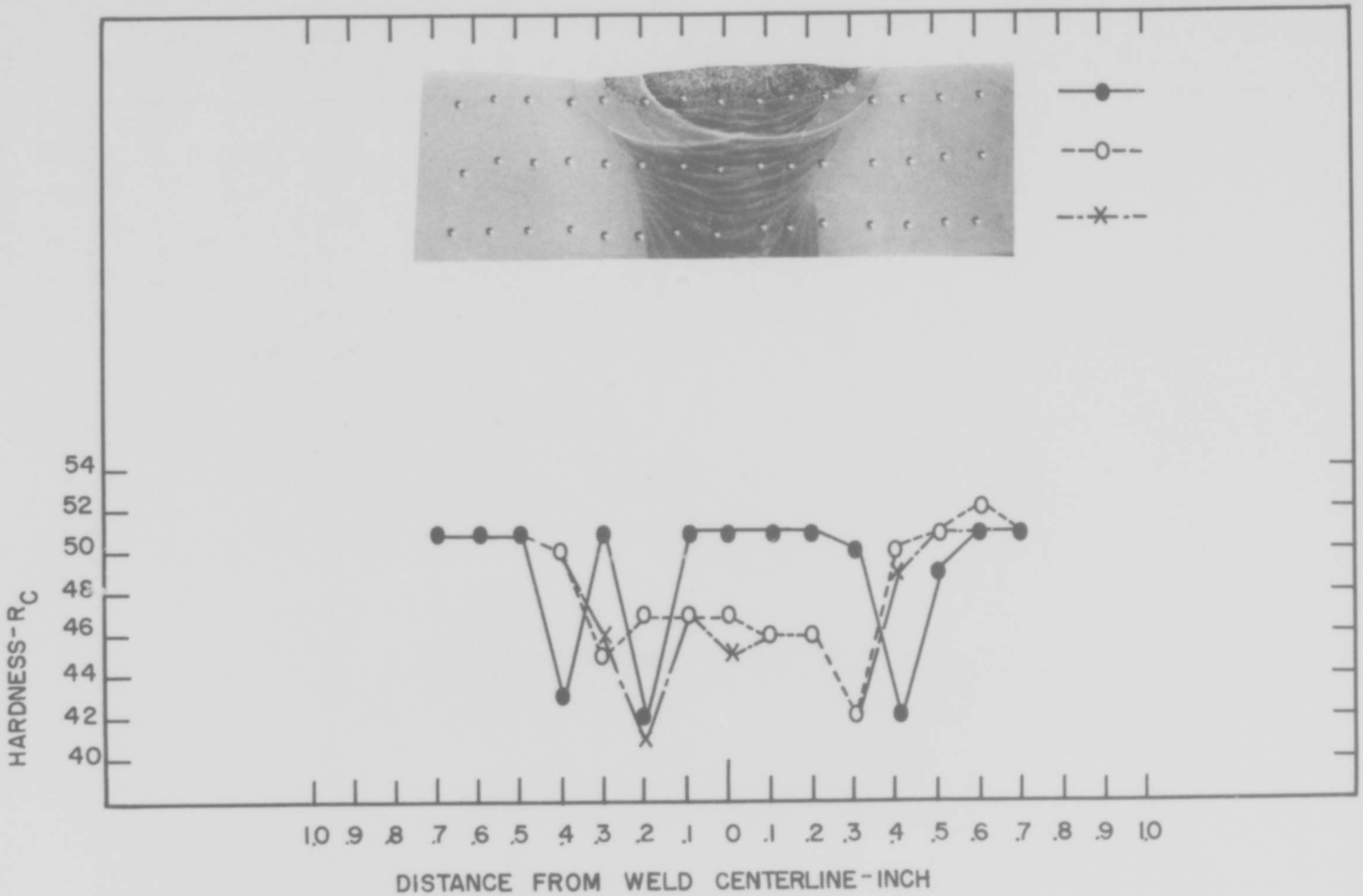


Figure 70. Hardness Survey of TIG Weld No. A239 Made in AMS 6435 Plate Material Tempered at 550°F at a Welding Speed of 10 ipm Using Filler Wire No. 1.

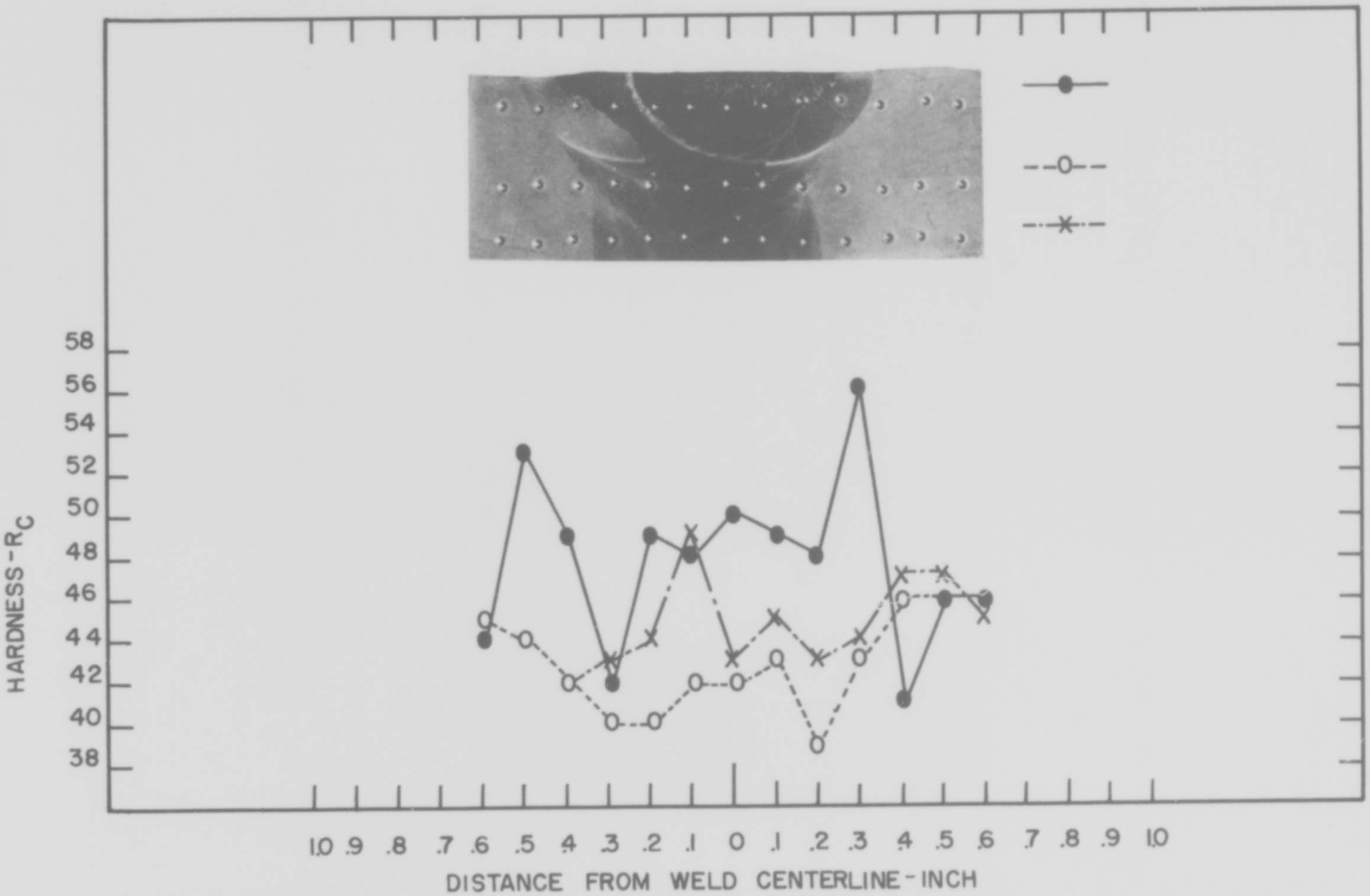


Figure 71. Hardness Survey of TIG Weld No. A232 Made in AMS 6435 Plate Material Tempered at 700°F at a Welding Speed of 4 ipm Using Filler Wire No. 1.

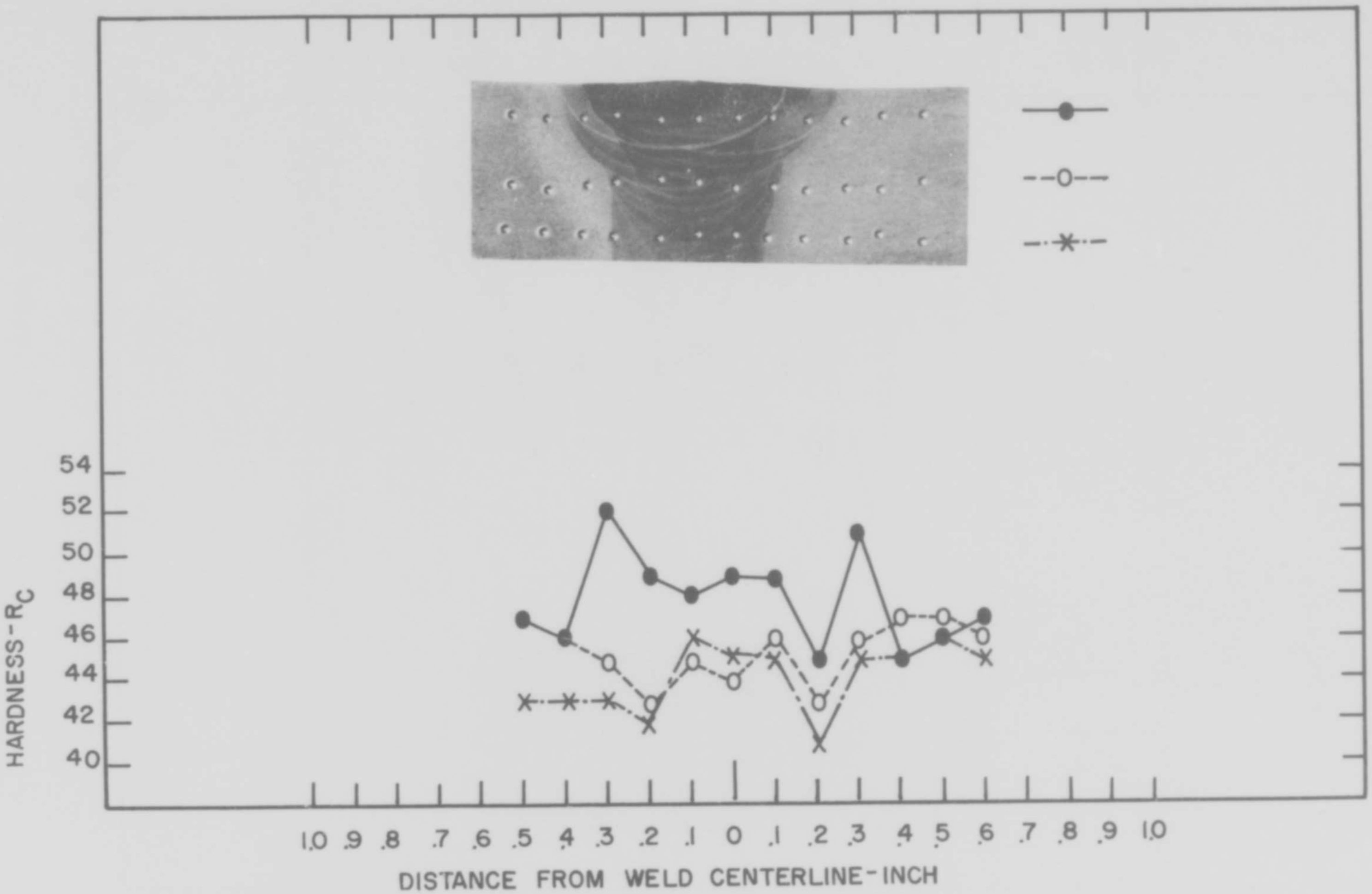


Figure 72. Hardness Survey of TIG Weld No. D235 Made in AMS 6435 Plate Material Tempered at 700°F at a Welding Speed of 10 ipm Using Filler Wire No. 1.

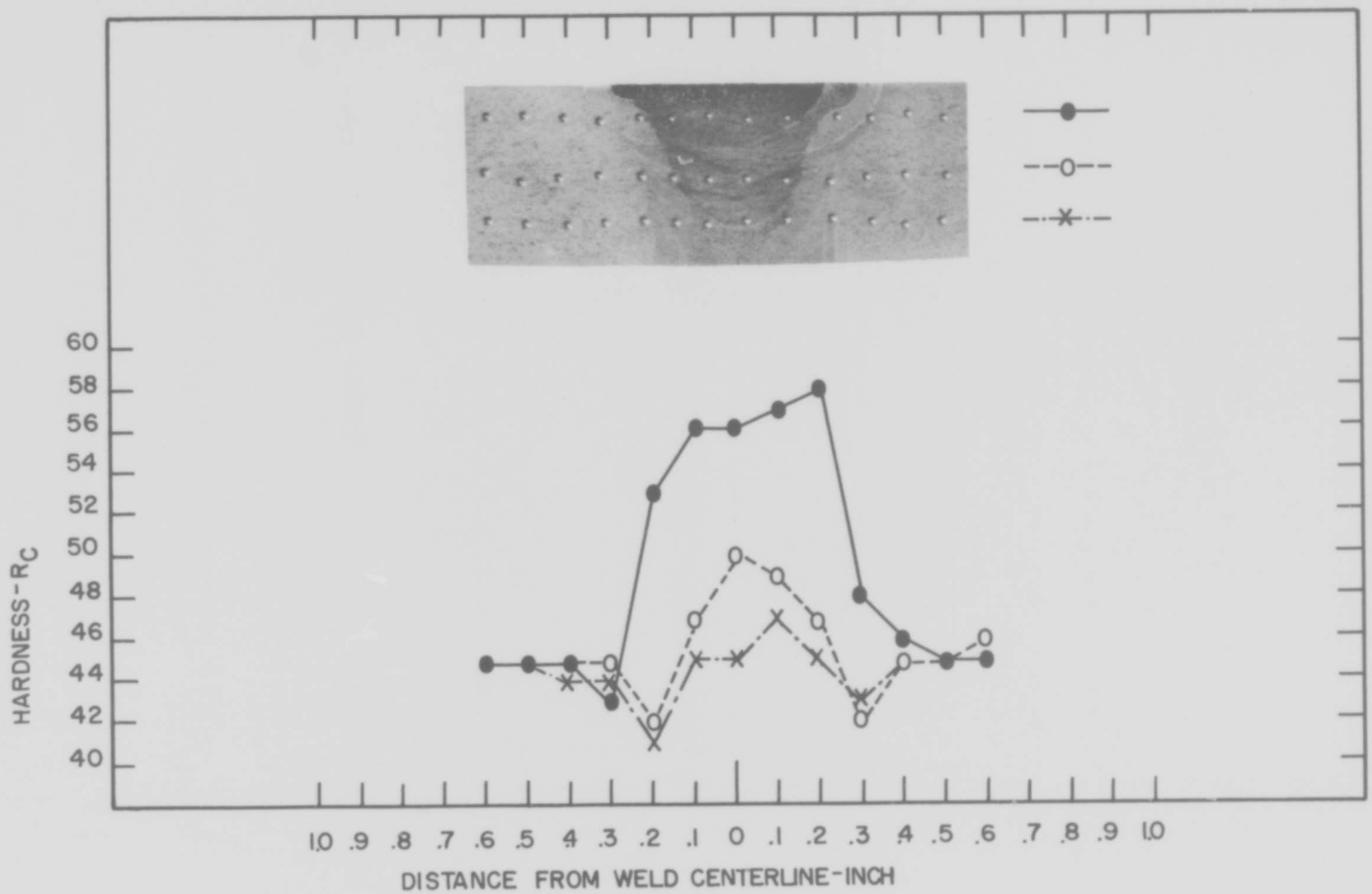


Figure 73. Hardness Survey of TIG Weld No. D227 Made in AMS 6435 Plate Material Tempered at 800°F at a Welding Speed of 10 ipm Using Filler Wire No. 5.

TABLE 23

SMOOTH TENSILE PROPERTIES OF TIG WELDS MADE IN AMS 6435 1/2-INCH PLATE

Weld No.	Test(a) Direction	Base Metal Temper °F	Filler Wire (b)	Welding Speed (ipm)	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elong. (% 1")	R.A. (%)	Energy Input KJ/in.	No. Weld Passes	Comments
D226	T	800	6	10	193.1	203.5	2.5	21.3	23.76	10	(c)
"	T	"	6	10	194.9	203.5	3.5	29.1	"	10	(c)
"	L	"	6	10	197.5	225.0	2.5	8.5	"	10	-
D227	T	"	5	10	191.0	203.1	2.0	15.9	"	10	(c)
"	T	"	5	10	191.5	203.1	2.5	17.4	"	10	(c)
"	L	"	5	10	201.3	228.3	3.0	4.3	"	10	-
"	L	"	5	10	211.5	232.9	4.0	4.7	"	10	-
A232	T	700	1	4	181.8	202.5	2.5	17.1	36.75	9	(c)
"	T	"	1	4	184.8	202.9	2.0	12.4	"	9	(c)
A233	T	"	3	4	185.9	200.3	2.0	10.1	"	11	(c)
"	T	"	3	4	184.6	201.1	2.5	11.5	"	11	(c)
D234	T	"	3	10	191.8	205.9	2.5	14.4	22.56	13	(c)
"	T	"	3	10	190.0	206.7	2.5	19.1	"	13	(c)
D235	T	"	1	10	189.8	203.5	2.0	16.2	"	14	(c)
"	T	"	1	10	189.2	203.9	2.5	15.9	"	14	(c)
A238	T	550	9	10	183.1	209.2	2.0	6.3	23.46	15	(c)
"	T	"	9	10	187.8	207.2	2.5	13.1	"	15	(c)
"	L	"	9	10	192.6	232.4	15.5	46.3	"	15	-
"	L	"	9	10	193.7	239.6	15.0	46.1	"	15	-
A239	T	"	1	10	190.4	206.5	2.0	11.6	"	18	(c)
"	T	"	1	10	191.2	207.4	2.0	10.1	"	18	(c)
"	L	"	1	10	201.3	213.1	15.5	50.7	"	18	-
"	L	"	1	10	-	212.1	15.8	45.4	"	18	-

TABLE 23 (CONTINUED)

SMOOTH TENSILE PROPERTIES OF TIG WELDS MADE IN AMS 6435 1/2-INCH PLATE

Weld No.	Test(a) Direction	Base Metal Temper °F	Filler Wire (b)	Welding Speed (ipm)	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elong. (% 1")	R.A. (%)	Energy Input KJ/in.	No. Weld Passes	Comments
A236	T	450	1	10	181.1	205.5	2.5	9.3	23.46	18	(c)
"	T	"	1	10	179.5	206.1	2.5	6.6	"	18	(c)
"	L	"	1	10	197.3	212.0	15.5	48.8	"	18	-
"	L	"	1	10	197.9	217.1	15.5	43.2	"	18	-
D237	T	"	9	10	184.7	201.5	2.0	16.0	"	14	(c)
"	T	"	9	10	186.0	203.9	2.0	16.8	"	14	(c)
"	L	"	9	10	199.5	232.9	11.0	38.0	"	14	-
"	L	"	9	10	191.3	232.0	10.0	20.3	"	14	-

(a) (T) specimens were taken transverse to the weld and included weld heat affected zone and parent metal.
(L) specimens were take parallel with the weld and consisted entirely of weld deposit.

(b) Filler wire compositions are presented in Table 2.

(c) Fracture occurred at the fusion-heat affected zone line.

c. General Discussion

Although the parent metal quenched and tempered between 450 and 800°F resulted in yield strengths well within the desired 180 to 200 ksi range, relatively low ductility was obtained in transverse weld specimens, regardless of parent metal heat treatment or weld parameter. Adequate strength and ductility was obtained in each weld deposit (all-weld metal specimen) consisting of low carbon D6AC, 1722 AS, and HP 9-4-20 wires. Based upon these results and the fact that SAE 4325 steel is not a commercially available grade, it was recommended that materials other than the low alloy carbon steels should be considered for the martensite material.

4. Vasco Jet X-2 Steel (1/2-Inch Plate)

a. Base Metal Evaluation

The heat treatment selection for the Vasco Jet steel was based on work done by Hamaker and Vater[4]. As shown in Figure 74 (Figure 2 duplicated for reader convenience), triple tempering at 1075°F for 2 hour cycles after austenitizing at 1825°F for 20 minutes and air cooling produces the desired tensile properties.

The inclusion content of the material is shown in Figure 75, and a photomicrograph revealing the microstructure of the heat treated material is presented in Figure 76.

The smooth tensile properties of the Vasco Jet X-2 plate are presented in Table 24A, and the fracture toughness is shown in Table 24B. The low strength of the one longitudinal specimen was caused by a defect in the material. The plane strain fracture toughness, K_{IC}, of the material was found to be extremely low (42 ksi $\sqrt{\text{inch}}$) in comparison to the other program materials. Only a single data point could be obtained because of difficulty in stopping a fatigue precrack once it initiated.

b. Evaluation of TIG Welds in Vasco Jet X-2 1/2-Inch Plate

Gas tungsten arc welds were made in the Vasco Jet X-2 steel at welding speeds of 4, 10, and 15 ipm using helium gas shielding. A filler wire of similar composition was used in making these welds. In addition, welds were made at 10 ipm in helium using HP 9-4-20 and D6AC low carbon filler wires. All welds were made without a pre- or post-heat; and the weld interpass temperature was maintained at room temperature. Fusion welding parameters for these welds are presented in Tables 25 and 26. These welds were examined for quality, microstructure, and hardness in addition to tensile properties and fracture toughness values.

(1) Weld Quality

The results of radiographic evaluation for welds made in the Vasco Jet X-2 material are presented in the comments column, Table 25. Although some porosity was found in each of the welds made in the Vasco Jet material at welding speeds of 4 and 10 ipm using filler wire No. 18, it was not excessive. No porosity was found in the weld made at 15 ipm using Vasco

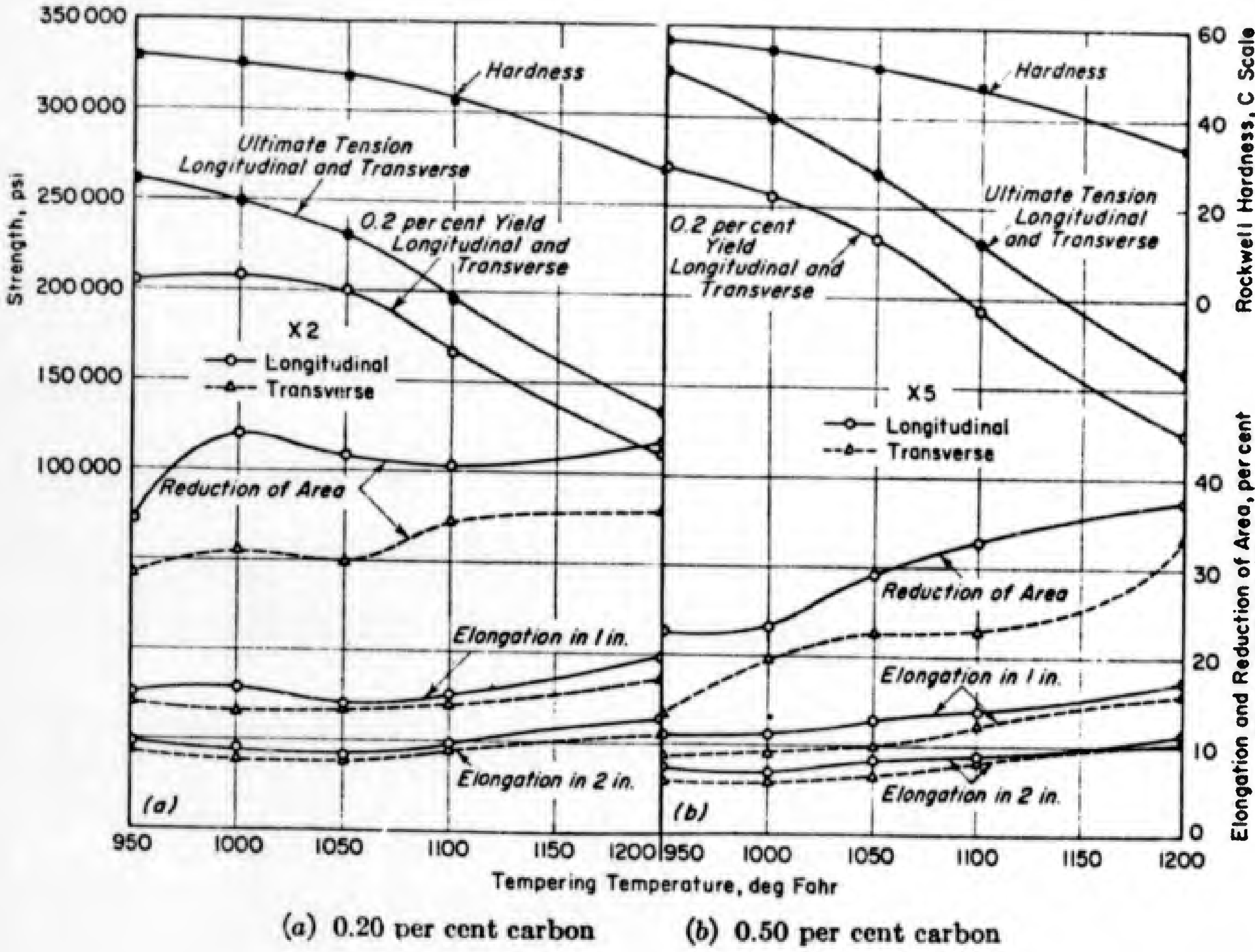
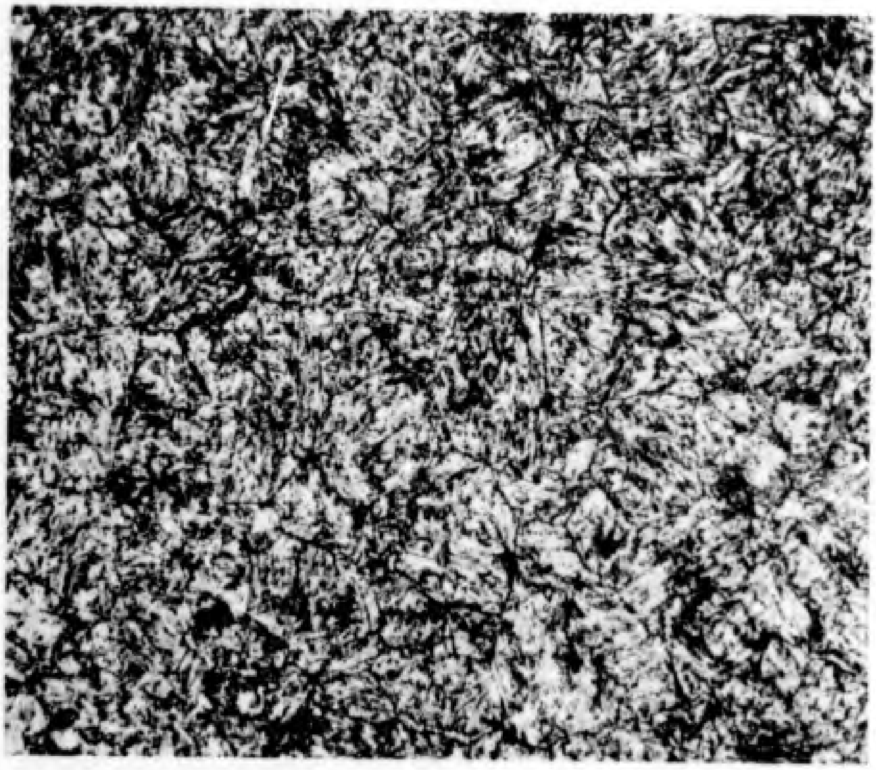


Figure 74. Representative Sheet Tensile Properties of 5 Percent Chromium Steels 0.125 inch Thick Sheet, Tested Both Parallel and Transversely to Its Long Dimension. (Ref. 4)

(a) Parallel to Rolling Direction 100X

(b) Perpendicular to Rolling Direction 100X

Figure 75. Unetched Vasco Jet 1/2-Inch Plate Showing Inclusion Levels.



500X

Figure 76. Microstructure of Heat Treated Vasco Jet 1/2-Inch Plate. Etch: Modified Fry's.

TABLE 24

A. SMOOTH TENSILE PROPERTIES OF VASCO JET 1/2 INCH PLATE

Heat No.	Test[(a)] Direction	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elong. (% 1")	R.A. (%)
089230	L	144.5	172.6	2.5	7.0
(Code X)	L	189.3	213.7	20.0	63.1
	T	186.4	215.5	16.0	57.7
	T	191.3	215.5	16.0	58.4

(a) Test direction relative to the rolling direction.

B. PLANE STRAIN FRACTURE TOUGHNESS, K_{IC}, OF 1/2 INCH VASCO JET X2 PLATE[(a)]

(3 POINT LOADED)

Specimen Identity	Width, W (in.)	Thickness, B (in.)	Crack Depth, a (in.)	Major Span, L' (in.)	Curve Type[(b)]	Load (lb)	Relative Plastic Zone Size, r_y/B[(c)]	σ_{nom}/σ_{ys}[(d)]	Plane Strain Fracture Toughness, K_{IC} (ksi $\sqrt{in.}$)
X2-1	0.475	0.497	0.128	4.5	3	965	0.019	1.23	41.7

(a) Material was austenitized at 1825°F for 30 min.; A.C. and tempered at 1075°F (2 hrs. + 2 hrs. + 2 hrs.).
(b) Curve types are defined in Figure 16.
(c) Plastic zone size, r_y, equals the difference between the effective crack length a* and the measured crack length, a ($A^* = a + EG/6\pi\sigma_{ys}^2$).
(d) σ_{nom}/σ_{ys} = nominal stress at crack initiation divided by 0.2% yield strength.

TABLE 25

FUSION WELDING PARAMETERS FOR
TIG WELDS MADE IN VASCO JET X2 1/2 INCH PLATE

Weld No.	Filler Wire Dia. (in.)	Wire[a] Compositions	Pre-and Post-Heat (°F)	No. Passes	W/S (ipm)	Wire Spe d (ipm)	amps	Volts	Gas (cfh) Torch	Backup	Comments[c]
X244	0.062	18	None	11	10	48[b]	220	18	50He	4He	Slight porosity, incomplete penetration
X245	0.062	18	"	14	15	48[b]	270	19	"	"	Incomplete penetration
X246	0.062	18	"	13	4	16[b]	115	15	"	"	Two spots porosity
X253	0.045	9	"	13	10	78[b]	220	18	"	"	One small spot porosity
X266	0.062	1	"	25	10	20[b]	170	15	"	"	

(a) Wire compositions are presented in Table 2.

(b) The wire speed, amperage and voltage are for the second through the final pass. Parameters for the first pass are presented in Table 26.

(c) Weld quality comments based on radiographic inspection.

TABLE 26

FUSION WELDING PARAMETERS OF FIRST PASS FOR TIG WELDS MADE IN VASCO JET X2 1/2 INCH PLATE

Weld No.	Wire Speed (ipm)	amps	Volts
X244	30	220	17.0
X245	48	270	19.0
X246	12	115	14.0
X253	18	220	17.0
X266	20	170	15.0

Note: Wire composition, welding speed and gas were the same as those listed in Table 25.

Jet filler wire. Filler wires No. 1 and No. 9 (D6AC and HP 9-4-20) generally produced sound welds. As in the case of the Al bearing HP 9-4-20 filler wires, the Vasco Jet filler material (No. 18) made a clean fluid weld puddle with excellent side wall wetting. However, radiographic examination revealed some incomplete fusion in the root pass of welds X255 and X245. This can be compensated for by an adjustment in the root pass parameters.

(2) Weld Microstructure

The microstructures of TIG welds (X246 and X245, respectively) made in the Vasco Jet X-2 material at 4 and 15 ipm are presented in Figures 77 and 78, respectively. Some coring is present, and the 4 ipm weld appeared to have produced a more homogeneous microstructure. Figure 79 illustrates a crack propagating from an area of incomplete penetration in weld No. X244 made at 10 ipm in Vasco Jet material. This indicates that the material could possibly be crack sensitive and have poor fracture toughness when welded with filler wire of a matching composition.

The microstructures of TIG welds X253 and X266 made using HP 9-4-20 and D6AC low carbon filler wires are presented in Figures 80 and 81, respectively. The weld shown in Figure 80 was made with a much higher energy input than the one made with low carbon D6AC filler wire (Figure 81). As in the case of the HP 9-4-20 welds, the center of the fusion zone for the weld made with the higher energy input was more homogeneous, and a greater amount of tempering had occurred.

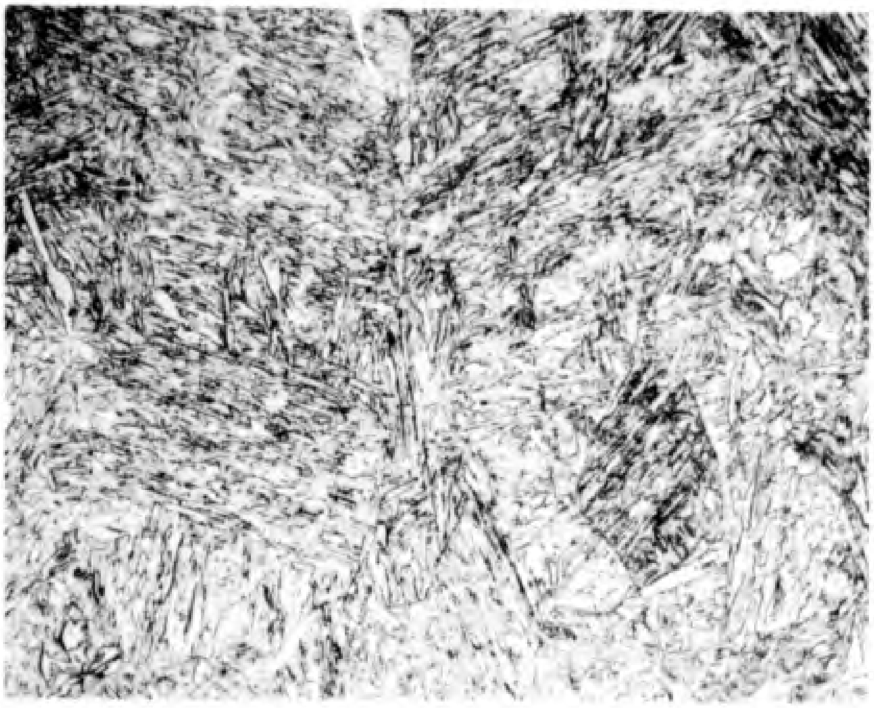
(3) Weld Hardness Surveys

Hardness surveys of welds (X246, X244, and X245) made at 4, 10, and 15 ipm, respectively, using filler wire No. 18 in Vasco Jet 1/2-inch plate, are presented in Figures 82 to 84. The hardness of the heat-affected zones and weld deposits for the top weld passes are higher than the base material. The hardnesses for the center and bottom passes are quite low with respect to the base material. This indicates that overtempering has occurred in these passes and the welds made with the Vasco Jet filler wire probably would not meet the strength criteria of the program.

Hardness surveys of welds X253 and X266 made in Vasco Jet X-2 material using HP 9-4-20 and D6AC filler wires are presented in Figures 85 and 86, respectively. Although the weld made with D6AC filler wire was made at a significantly lower energy input than the one made with HP 9-4-20 filler wire (15.3 as compared to 23.8 K-joules/inch/pass), each weld showed appreciable softening in the heat-affected zone, as well as soft areas in the fusion zone. The soft areas in the fusion zone apparently resulted from dilution with the base metal. The fact that low hardness values are obtained through the plate thickness in a given area is a good indication that the tensile strength of these welds will be below the required level.

(4) Tensile Properties

The smooth tensile properties for welds made in Vasco Jet X-2 plate are presented in Table 27. Although the HP 9-4-20 and D6AC filler wires met the requirements of the program, a weak area existed in the heat-

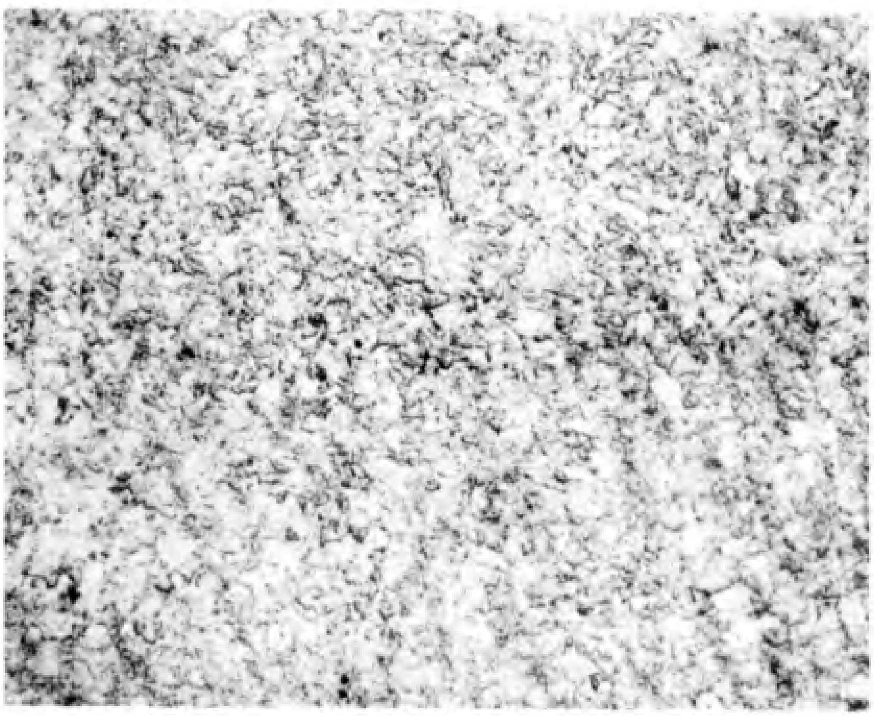


Top of Fusion Zone 500X

Center of Fusion Zone 500X

Figure 77. Microstructure (Martensite) of Multipass TIG Weld No. X246 Made In Vasco Jet 1/2-Inch Plate at 4 ipm Using Vasco Jet Filler Wire No. 18. Etch: Modified Fry's.

Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 78. Microstructure (Martensite) of Multipass TIG Weld No. X245 Made in Vasco Jet 1/2-Inch Plate at 15 ipm Using Vasco Jet Filler Wire No. 18. Etch: Modified Fry's.

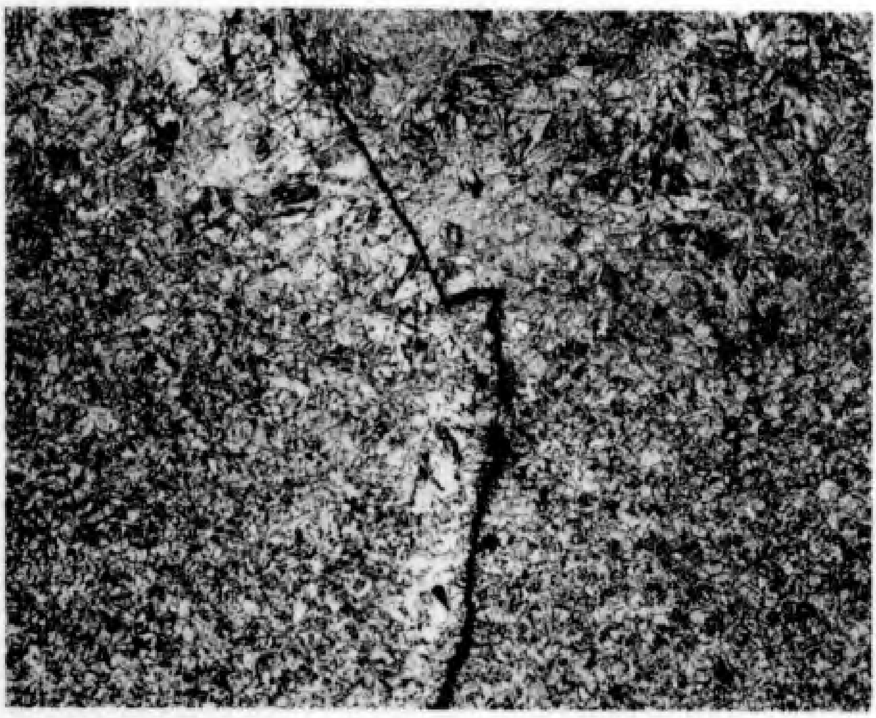
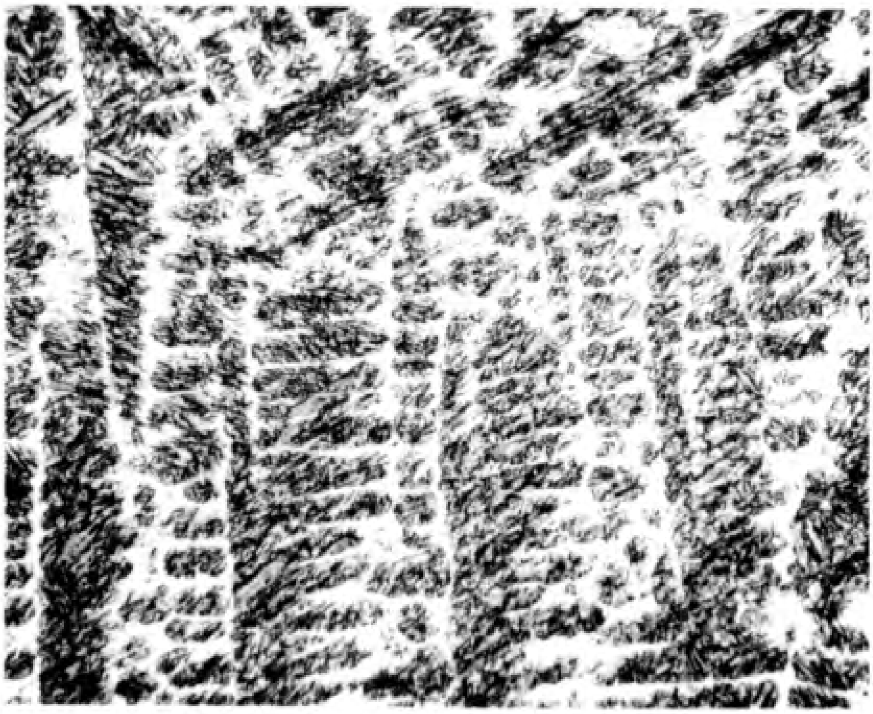
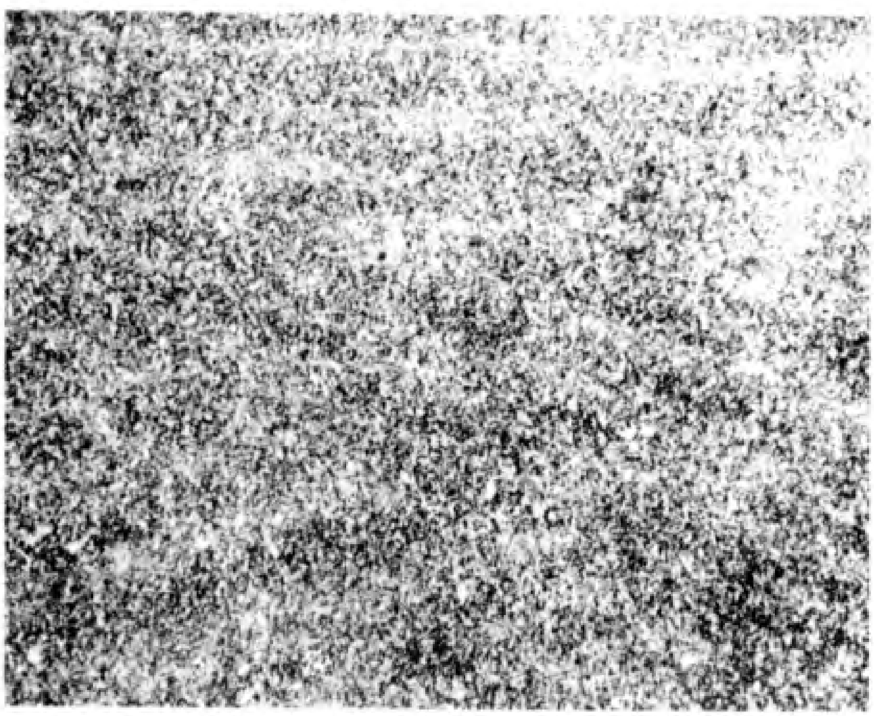


Figure 79. Photomicrograph Showing Root Crack in Multipass TIG Weld No. X244 Made in Vasco Jet 1/2-Inch Plate at 10 ipm Using Vasco Jet Filler Wire No. 18. Etch: Modified Fry's.

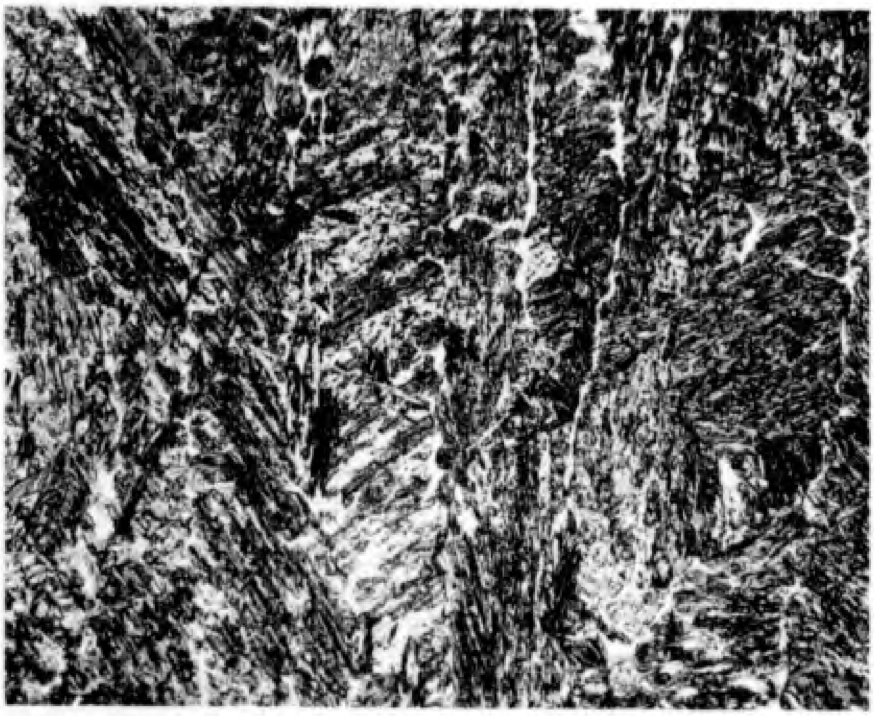


Top of Fusion Zone 500X

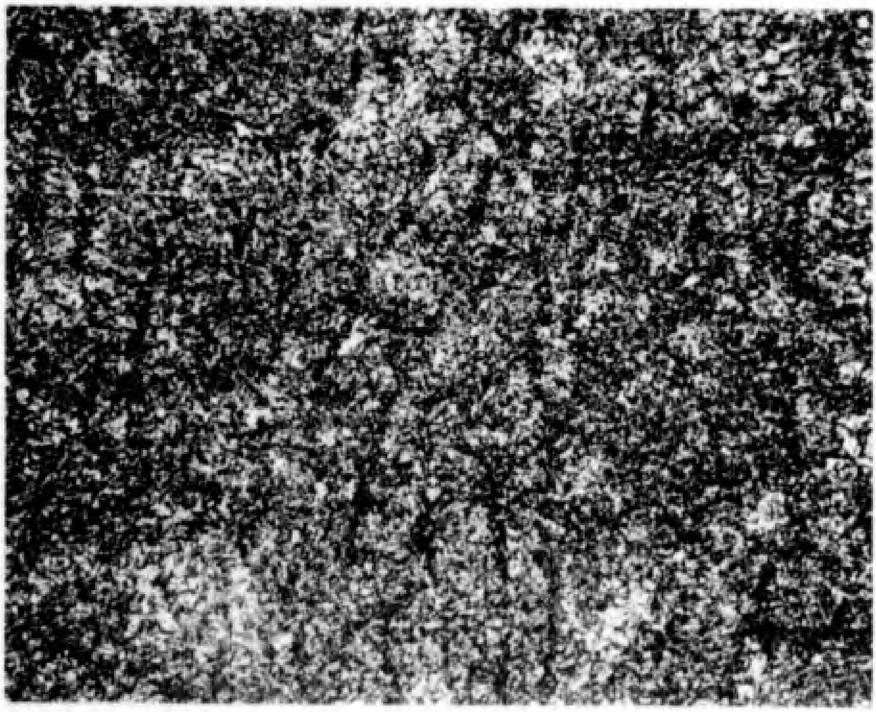


Center of Fusion Zone 500X

Figure 80. Microstructure (Martensite) of Multipass TIG Weld No. X253 Made in Vasco Jet 1/2-Inch Plate Using HP 9-4-20 Filler Wire No. 9. Etch: 2% Nital



Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 81. Microstructure (Martensite) of Multipass TIG Weld X266 Made in Vasco Jet X-2 1/2-Inch Plate Using D6AC Low Carbon Filler Wire No. 1. Etch: 2% Nital

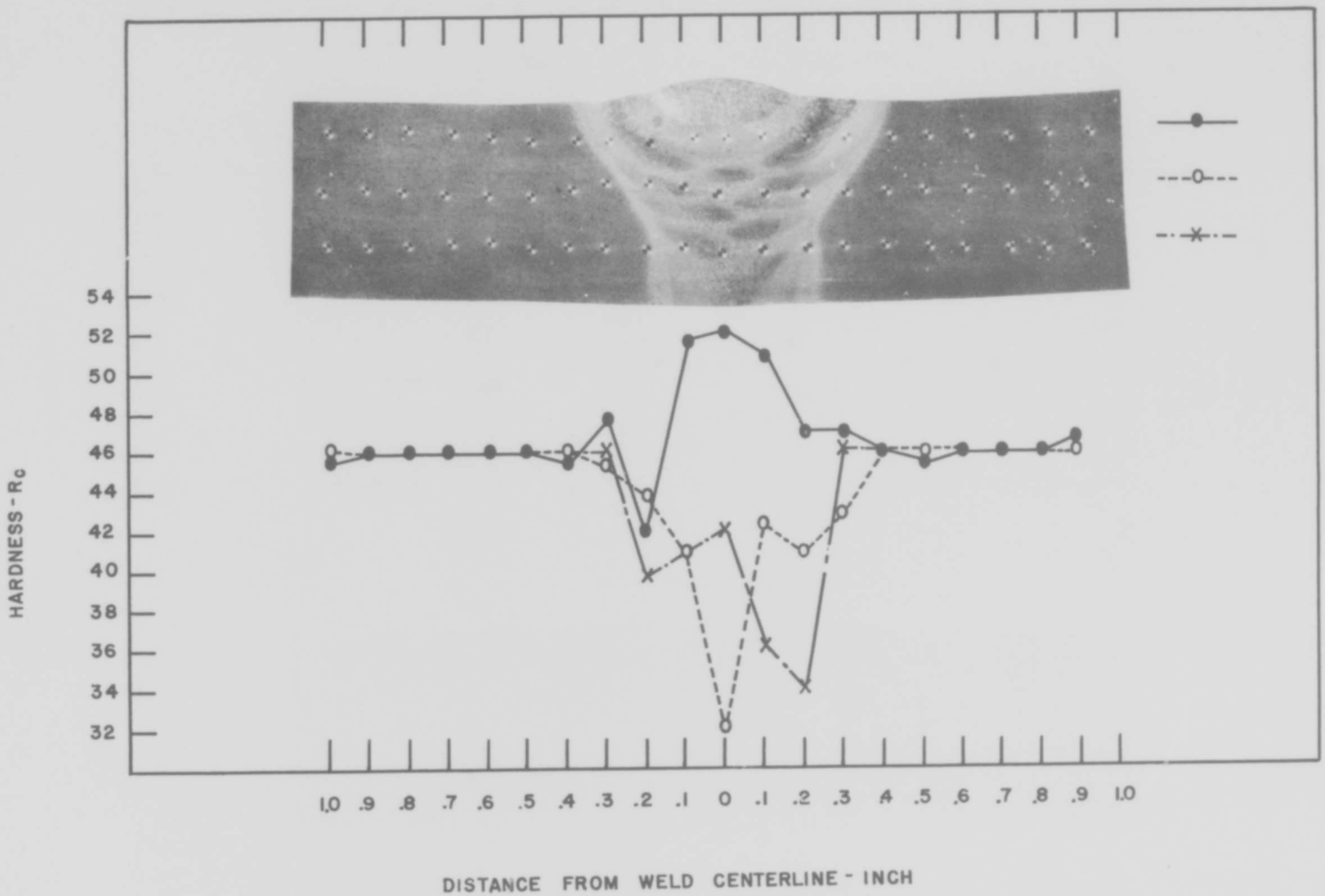


Figure 82. Hardness Survey of TIG Weld No. X246 Made in Vasco Jet Plate at 4 ipm Using Vasco Jet Filler Wire No. 18.

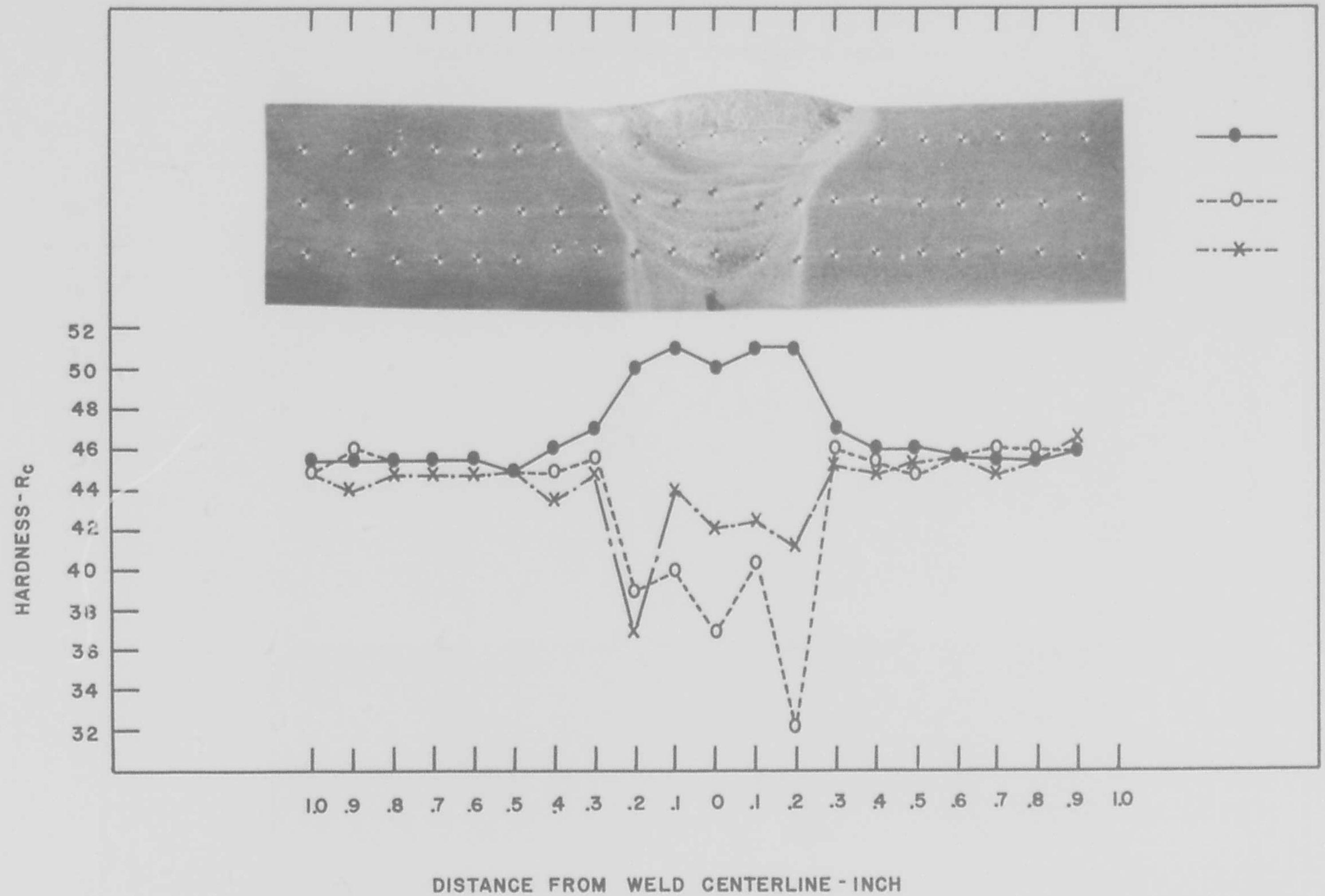


Figure 83. Hardness Survey of TIG Weld No. X244 Made in Vasco Jet Plate at 10 ipm Using Vasco Jet Filler Wire No. 18.

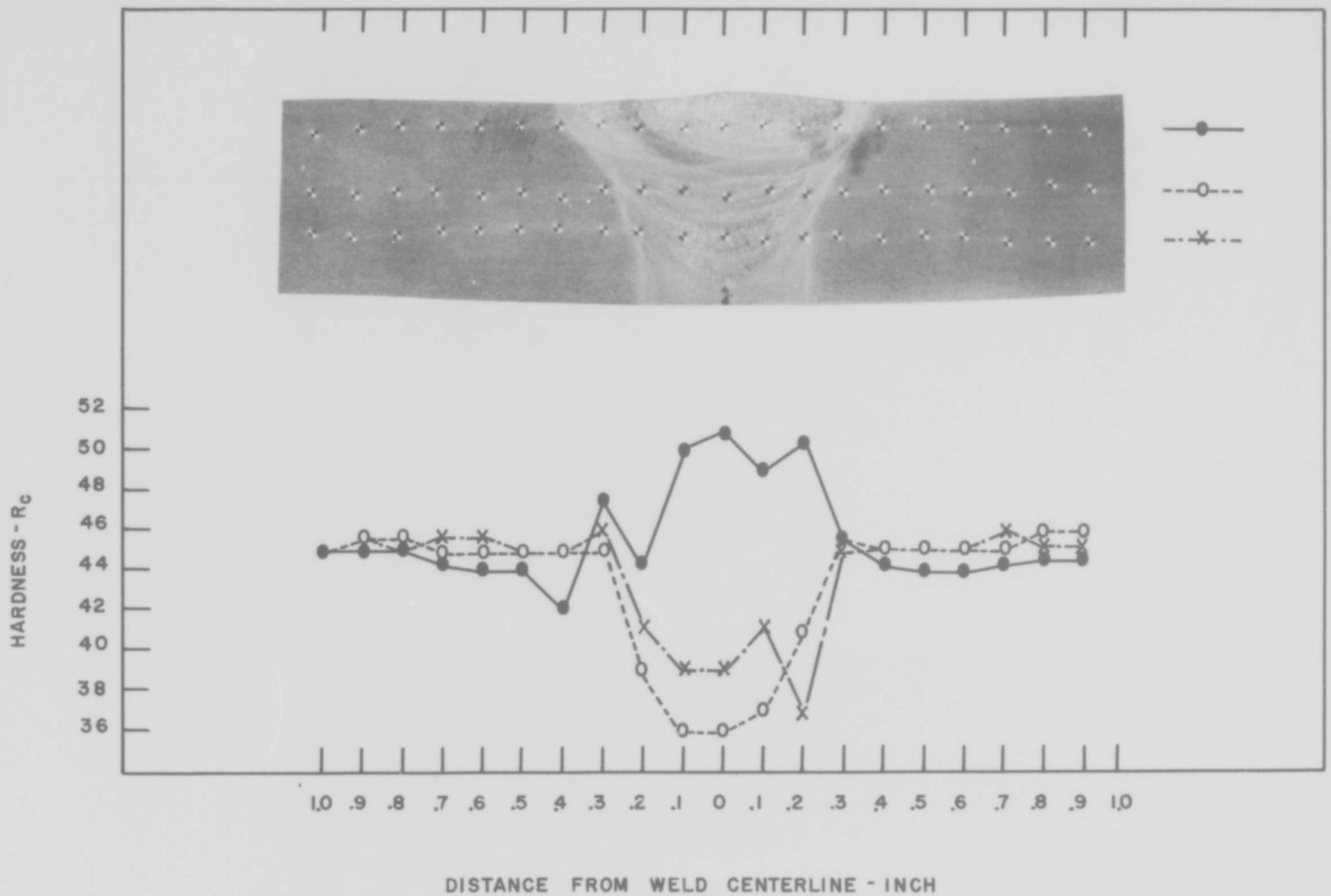


Figure 84. Hardness Survey of TIG Weld No. X245 Made in Vasco Jet Plate at 15 ipm Using Vasco Jet Filler Wire No. 18.

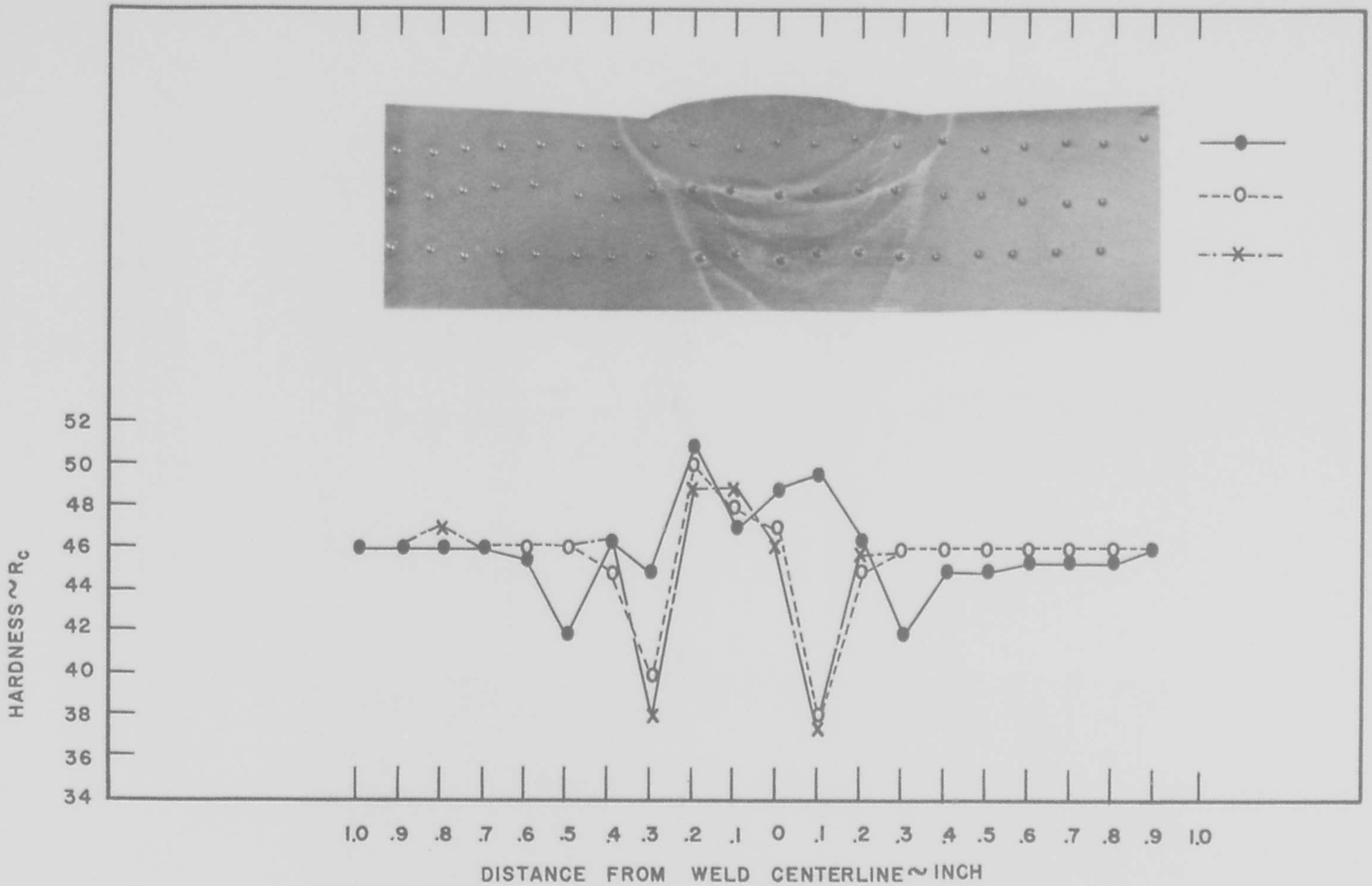


Figure 85. Hardness Survey of TIG Weld No. X253 Made in Vasco Jet X-2 1/2-Inch Plate at 10 ipm Using Filler Wire No. 9.

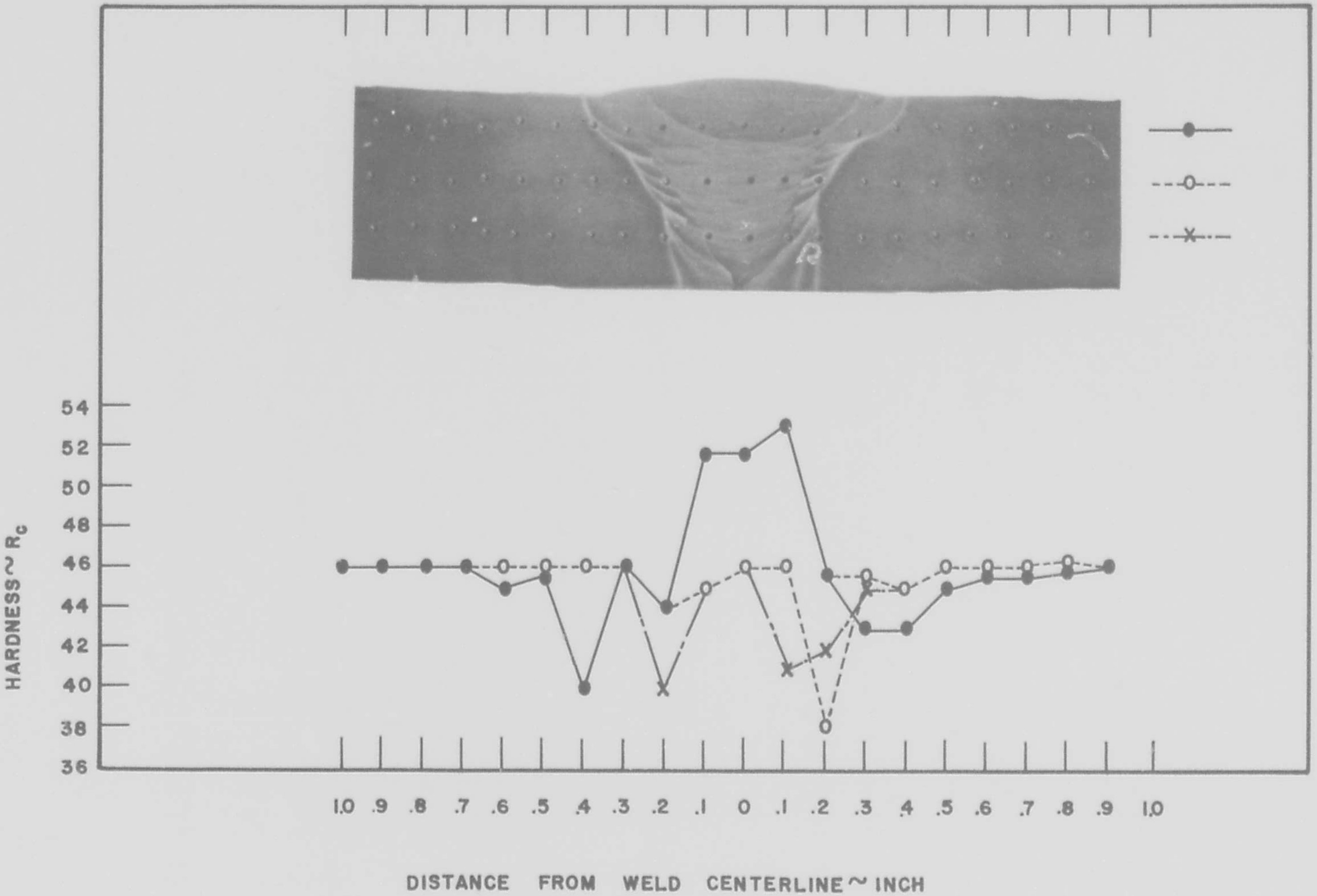


Figure 86. Hardness Survey of TIG Weld No. X266 Made in Vasco Jet X-2 1/2-Inch Plate at 10 ipm Using Filler Wire No. 1.

TABLE 27

TENSILE PROPERTIES OF TIG WELDS MADE IN VASCO JET X2 1/2 INCH PLATE

Weld No.	Test Direction(a)	Filler Wire(b)	Welding Speed (ipm)	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elong. % (c)	R.A. (%)	Energy Input K J/in/pass	% Joint Efficiency(d) Y.S.	% Joint Efficiency(d) U.T.S.	Comments
X253	T	9	10	168.5	184.2	1.0	3.5	23.8	89.0	86.1	(e)
"	T	9	10	167.5	185.9	1.5	3.9	23.8	88.4	86.9	(e)
X266	L	1	10	202.3	202.3	19.0	61.2	15.3	-	-	-
"	L	1	10	201.7	204.3	14.5	35.1	15.3	-	-	-
"	T	1	10	171.0	188.9	1.5	8.5	15.3	90.3	88.3	(e)
"	T	1	10	172.4	187.9	2.0	8.5	15.3	91.0	87.9	(e)
X246	L	18	4	158.6	179.9	20.0	66.8	25.9	-	-	-
"	L	18	4	162.7	185.3	20.0	61.4	25.9	-	-	-
"	T	18	4	157.2	173.0	1.0	4.7	25.9	83.0	81.0	(e)
"	T	18	4	152.7	171.1	1.5	6.5	25.9	80.6	80.4	(e)
X244	L	18	10	166.9	182.0	18.5	59.8	23.8	-	-	-
"	L	18	10	164.7	184.4	19.5	62.5	23.8	-	-	-
"	T	18	10	152.8	160.4	3.0	13.4	23.8	80.7	75.1	(f)
""	T	18	10	167.0	184.0	2.0	11.5	23.8	88.3	86.2	(e)
X245	L	18	15	159.8	176.8	22.0	65.6	20.6	-	-	-
"	L	18	15	161.9	177.8	21.0	64.4	20.6	-	-	-
"	T	18	15	165.1	184.0	2.5	15.2	20.6	87.3	86.2	(e)
"	T	18	15	167.1	181.2	1.5	5.9	20.6	88.3	85.0	(e)

(a) (L) specimens were taken parallel with the weld and consisted entirely of weld deposit.
(T) specimens were taken transverse to the weld and included weld, heat affected zone, and parent metal.
(b) Filler wire composition is presented in Table 2.
(c) (T) specimens had a gage length of two inches. (L) specimens had a gage length of one inch.
(d) Joint efficiencies were based upon parent metal ultimate and yield strengths of 213.7 and 189.3 ksi, respectively.
(e) Fracture occurred at the fusion heat affected zone line.
(f) Fracture occurred in the weld.

affected zone of these weldments. An attempt to improve the heat affected zone properties by decreasing the energy input (weld X266) resulted in only a slight improvement in the ultimate strength, yield strength and ductility.

(5) Fracture Toughness

The fracture toughness of certain welds made in the Vasco Jet X-2 steel were determined using notch bend specimens under 3-point loading. As shown in Table 28, the weld deposits (all wire No. 18) had a calculated fracture toughness, K_{IC}^*, higher than the parent metal (K_{IC} = 40 ksi $\sqrt{\text{inch}}$). The weld deposits of welds X245 and X246 (welding speed of 15 and 4 ipm respectively) both had good toughness while X244 (welding speed of 10 ipm) had only a slightly better K_{IC}^* value than the parent metal. However, the significant finding of this examination was the very low toughness of the heat affected zones. Most specimens failed during the precracking operation due to their inability to stop the propagation of a crack once it had initiated. Only the one specimen from weld X244 was successfully precracked and it exhibited a K_{IC}^* of only 34.7 ksi $\sqrt{\text{inch}}$ (see Table 28).

c. General Discussion

Although desirable tensile properties were obtained in Vasco Jet X-2 1/2-inch plate, the fracture toughness properties in this material were low. In addition, the ductility and fracture toughness of welds in this material were poor. Therefore, Vasco Jet X-2 was considered as not acceptable with respect to the program requirements and further work on it was discontinued.

5. D6AC Steel (1/2-Inch Plate)

a. Base Metal Evaluation

The D6AC steel was austenitized at 1650°F for 1 hour and quenched into salt at 375°F for 10 minutes to prevent quench cracking then air cooled to room temperature. The plate was subsequently double tempered at 1050°F for 2 hour cycles resulting in a hardness level of R_c 48.

Photomicrographs, Figure 87, of the as received material, indicate the inclusion content in the direction parallel to the rolling direction is relatively high in comparison to the other program materials. However, they were generally spheroidal in shape and no significant stringers were seen. The microstructure of the heat treated D6AC is shown in Figure 88.

The plate was evaluated for both smooth tensile and plane strain fracture toughness. The tensile results, presented in Table 29, show that somewhat higher strengths than expected were obtained using the 1050°F temper, i.e., about 220 ksi 0.2% yield strength and 240 ksi ultimate strength. These high strengths may have been due to a higher than average carbon level in the steel.

The fracture toughness of the D6AC plate was determined using both notch bend and surface-cracked specimens. The results of notch bend tests conducted on both heats of the material are summarized in Table 30. It can be seen that heat "K" had a slightly higher K_{IC}^* (85.6 ksi $\sqrt{\text{inch}}$) than did heat "S"

TABLE 28

FRACTURE TOUGHNESS, K_{IC}^{*}, OF TIG WELDS MADE IN 1/2 INCH VASCO JET X2 PLATE USING HELIUM SHIELDING

(3 POINT LOADING)

Specimen Identity	Filler Wire[a]	Notch Position	Width, W (in.)	Thickness, B (in.)	Crack Depth, a (in.)	Major Span, L' (in.)	Curve Type[b]	Load (lbs)	Relative Plastic Zone Size r_y/B[c]	$\frac{\sigma_{nom}}{\sigma_{ys}}$[d]	Calculated Fracture Toughness, K_{IC}^{*} (ksi $\sqrt{in.}$)
X244	18	HAZ	0.424	0.500	0.084	4.0	3	975	0.002	0.53	34.7
"	18	Weld	0.428	0.501	0.085	4.0	1	1445	0.003	0.78	51.3
"	18	Weld	0.428	0.501	0.065	4.0	1	1650	0.003	0.79	50.1
X245	18	Weld	0.425	0.501	0.086	4.0	1	1940	0.006	1.07	71.7
"	18	Weld	0.425	0.501	0.082	4.0	1	1895	0.006	1.02	68.0
X246	18	Weld	0.418	0.500	0.109	4.0	1	1540	0.006	1.02	68.4
"	18	Weld	0.418	0.500	0.126	4.0	1	1560	0.007	1.16	78.0

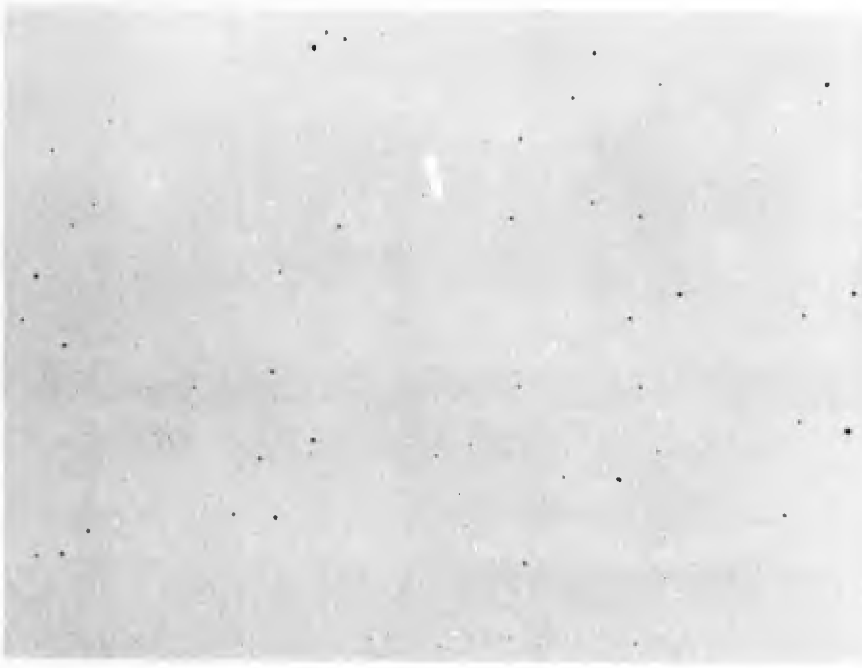
(a) Filler wire compositions given in Table 2.

(b) Curve types are defined in Figure 16.

(c) Plastic zone size, r_y, equals the difference between the effective crack length a^* and the measured crack length, a ($a^* = a + EG/6\sigma_{ys}$).

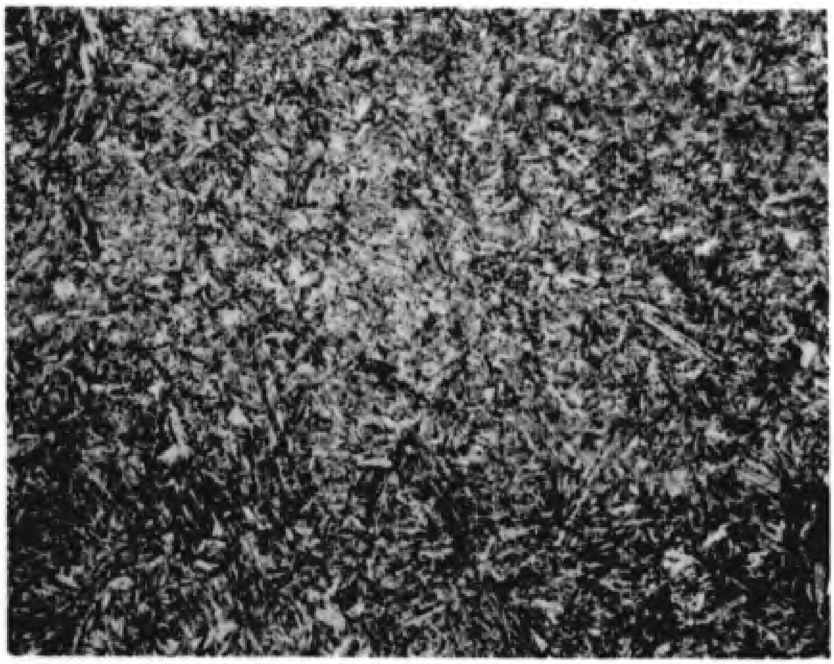
(d) σ_{nom}/σ_{ys} = nominal stress at crack initiation divided by 0.2% yield strength.

(a) Parallel to Rolling Direction 100X



(b) Perpendicular to Rolling Direction 100X

Figure 87. Unetched D6AC 1/2 Inch Plate Showing Inclusion Levels.



Hardness R_c 48 500X

Figure 88. Microstructure of D6AC 1/2 Inch Plate Austenitized at 1650°F/1 Hr. Quenched to 375°F/10 Minutes and Double Tempered at 1050°F 2 Hours Each. Etch: 2% Nital.

TABLE 29

SMOOTH TENSILE PROPERTIES OF D6AC STEEL 1/2 INCH PLATE

Heat No.	Test Direction[a]	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elongation (% - 1")	R.A. (%)
3951290	L	219.9	241.7	16.0	47.5
	L	217.8	238.5	16.0	43.3
	T	214.5	235.6	15.0	41.3
	T	216.6	236.9	15.0	42.1

Note: (a) Test direction relative to the rolling direction.

TABLE 30

FRACTURE TOUGHNESS OF D6AC STEEL 1/2 INCH PLATE (1050°F TEMPER)

(4 POINT LOADED)

A. Notch Bend Specimens

Specimen Identity	Width, W (in.)	Thickness, B (in.)	Crack Depth, a (in.)	Major Span, L' (in.)	Curve Type(b)	Load (lbs)	Relative Plastic Zone Size r_y/B(c)	σ_{nom}/σ_{ys}(d)	Calculated Fracture Toughness, K^*_{IC} (ksi $\sqrt{in.}$)
K17-1	0.500	0.495	0.159	4.0	3	3450	0.014	0.97	82.6
K17-2	0.500	0.495	0.130	4.0	2	4165	0.016	1.00	86.8
K17-3	0.500	0.495	0.106	4.0	2	4780	0.016	1.01	87.3
S9-1	0.505	0.500	0.113	5.25	2	3735	0.012	0.89	79.4
S9-2	0.505	0.500	0.108	5.25	2	3625	0.011	0.84	74.7
S9-3	0.504	0.500	0.109	5.25	2	3570	0.011	0.84	74.3

(a) Material was austenitized at 1650°F for 1 hour; quenched in salt to 375°F for 10 minutes; A.C. and tempered at 1050°F (2 hrs. + 2 hrs).

(b) Curve types are defined in Figure 16.

(c) Plastic zone size, ry, equals the difference between the effective crack length a* and the measured crack length, a $(a^* = a + EG/6\pi\sigma^2_{ys})$.

(d) σ_{nom}/σ_{ys} = nominal stress at crack initiation divided by 0.2% yield strength.

B. Surface Crack Specimens

Specimen Identity	Width, W (in.)	Thickness, B (in.)	Crack Size $2c_o$ (inch)	Crack Size a_o (inch)	Gross Failure Stress (ksi)	Plane Strain Fracture Toughness, K_{IC} (ksi $\sqrt{In.}$)
1	1.496	0.251	0.308	0.094	185.1	90.6
2	1.496	0.252	0.354	0.089	185.9	93.4

(76.1 ksi $\sqrt{\text{inch}}$). The average K_{IC} value obtained from the surface-cracked specimens was 92.0 ksi $\sqrt{\text{inch}}$ (see Table 30) indicating the K_{IC}* value obtained using notch bend tests was a valid plane strain fracture toughness value.

The results of Charpy V-notch impact tests on D6AC plate heat treated to a martensitic microstructure are presented in Table 31. The impact energy absorption was low - 14.5 foot/pounds at room temperature, lateral expansion was only 4.5 mils at room temperature, and the fractures possessed little or no shear lips.

b. Evaluation of Welds Made in D6AC 1/2-Inch Plate

TIG welds were made in the martensitic D6AC steel at 4, 10, and 15 ipm in helium or argon shielding. High and low energy inputs were used in making welds without a pre- and post-heat, as well as with a pre-heat and interpass temperature of 400°F with no post-heat. Based on the results obtained for martensitic welds in AMS 6435 material, wire No. 1 was selected for making TIG welds in this material. In addition, a MIG weld was made using filler wire No. 5 and a helium-argon gas mixture. Fusion welding parameters for welds made in martensitic D6AC 1/2-inch plate are presented in Tables 32 and 33.

(1) Weld Quality

The results of radiographic examination are presented in the comments column, Table 32. The welds made in either argon or helium at a welding speed of 4 ipm were in all cases clean and free from porosity. However, one weld made in argon at 4 ipm (weld No. S297) was not completely penetrated in the root pass. Welds made at 10 ipm in argon and helium (welds K292 and K293, respectively) contained very fine porosity throughout the joint. Additional welds made at 10 ipm in argon (welds S295, S304, and S305) were clear and free from porosity. Welds made at 15 ipm in either argon or helium were generally free from porosity. However, the weld made in helium contained a few spots of porosity and the weld made in argon contained several high density inclusions. The MIG weld (S301) contained three spots of porosity.

(2) Weld Microstructure

The microstructure of TIG welds K287 and K290, made in D6AC 1/2-inch plate at 4 ipm using filler wire No. 1 and helium gas shielding, are presented in Figures 89 and 90. Weld K287 was made without a preheat and the weld interpass temperature was maintained at room temperature (Figure 89). The other weld, K290, (Figure 90) was made with a 400°F preheat and the weld interpass temperature was maintained at 400°F. This weld was removed from the fixture immediately after welding and air cooled. The only significant difference in the microstructure of these two welds is the width of the dendritic spacings in the top of the fusion zone where the weld made with the 400°F preheat and interpass temperature has a wider dendritic spacing. These two welds were made at the same parameter with the exception of the preheat and interpass temperature. The preheat would cause a slower cooling rate and wider dendritic spacing the same as would a higher energy input to the weld. The microstructure for the center of the fusion zone for each of these welds does not differ appreciably. Where the martensite is apparent in the top of the fusion zone, the center is

TABLE 31

CHARPY V-NOTCH IMPACT PROPERTIES OF 1/2 INCH D6AC PLATE HEAT TREATED TO MARTENSITE (HEAT NO. 3951290)

Identification	Test Temp. (°F)	Impact Energy (Ft. lbs)	Lateral Expansion (Mils)
S91-1	Room	14.0	5.5
S91-2	"	15.0	3.5
S91-3	0	12.5	3.0
S91-4	"	12.5	2.5
S91-5	-100	11.5	8.0
S91-6	"	10.5	2.0
S91-7	-320	3.5	0.5
S91-8	"	3.5	0.5

Note: Lateral expansion measured at base of fracture.

TABLE 32

FUSION WELDING PARAMETERS FOR
TIG WELDS MADE IN D6AC 1/2 INCH PLATE

Weld No.	Filler Wire Dia. (in.)	Wire(a) Compositions	Pre-and Post-Heat (°F)	No. Passes	W/S (ipm)	Wire Speed (ipm)	amps	Volts	Gas (cfh) Torch	Gas (cfh) Backup	Comments(b)
K287	0.062	1	None	12	4	14	160	17.0	50He	5He	-
K290	"	1	400	11	4	14	160	17.0	"	"	-
K292	"	1	None	9	10	66	230	18.0	"	"	Fine porosity
K293	"	1	400	12	10	36	280	14.0	35A	5A	Fine porosity
S295	"	1	400	12	10	36	280	14.0	"	"	-
S292	"	1	None	9	10	48	230	18.0	50He	5He	Incomplete penetration, fine porosity
S297	"	1	None	10	4	24	205	13.5	35A	5A	Incomplete penetration
S298	"	1	None	25	15	42	280	14.0	"	"	High density inclusions
S299	"	1	None	14	15	60	270	19.0	50He	5He	Incomplete penetration, few spots porosity
S304	"	1	400	11	10	36	280	14.0	35A	5A	Single U-groove
S305	"	1	400	11	10	36	280	14.0	35A	5A	Double U-groove
S301*	"	5	400	8	18.3	-	300	24.0	37.5He12.5A	5He	Three spots porosity

(a) Wire composition presented in Table 2.

(b) Weld quality comments based on radiographic and visual inspection.

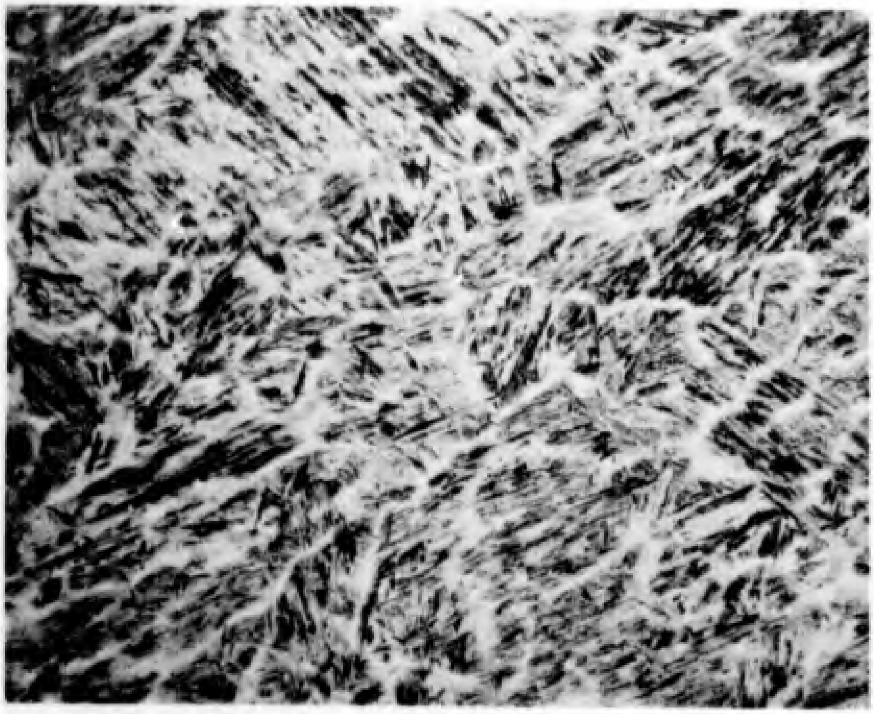
* Weld was made by the MIG process.

TABLE 33

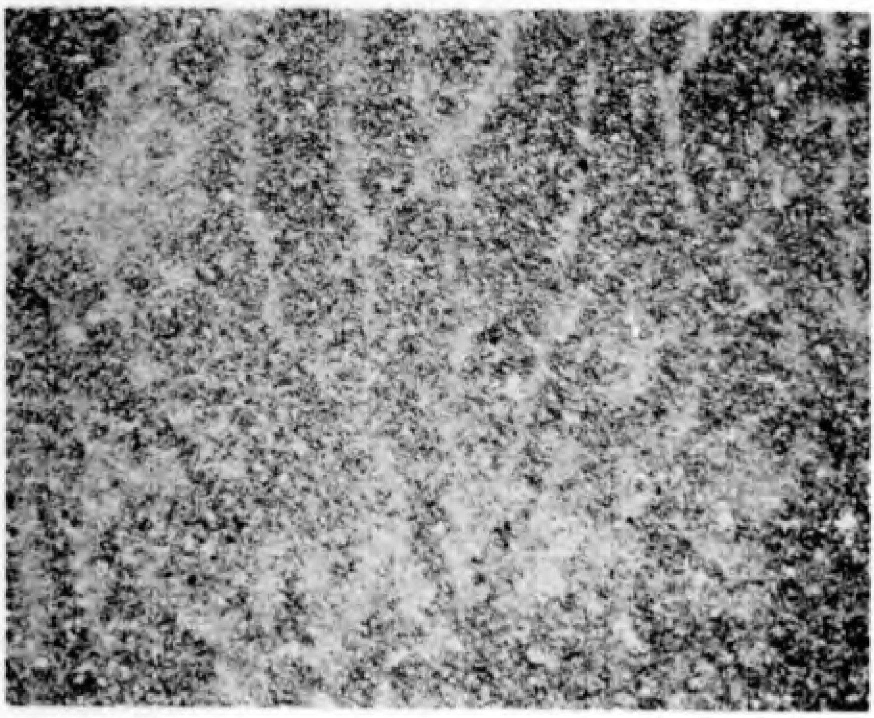
FUSION WELDING PARAMETERS OF FIRST PASS FOR
TIG WELDS MADE IN D6AC 1/2 INCH PLATE

Weld No.	Wire Speed (ipm)	amps	Volts
K287	None	160	17.0
K290	"	160	17.0
K292	36	230	18.0
K293	36	280	14.0
S295	36	280	14.0
S292	36	230	18.0
S297	24	205	13.5
S298	42	280	14.0
S299	42	270	19.0
S304	36	265	14.0
S305	36	275	11.5
S301	-	300	24.0

Note: Wire composition, welding speed and gas were the same as those listed in Table 32.

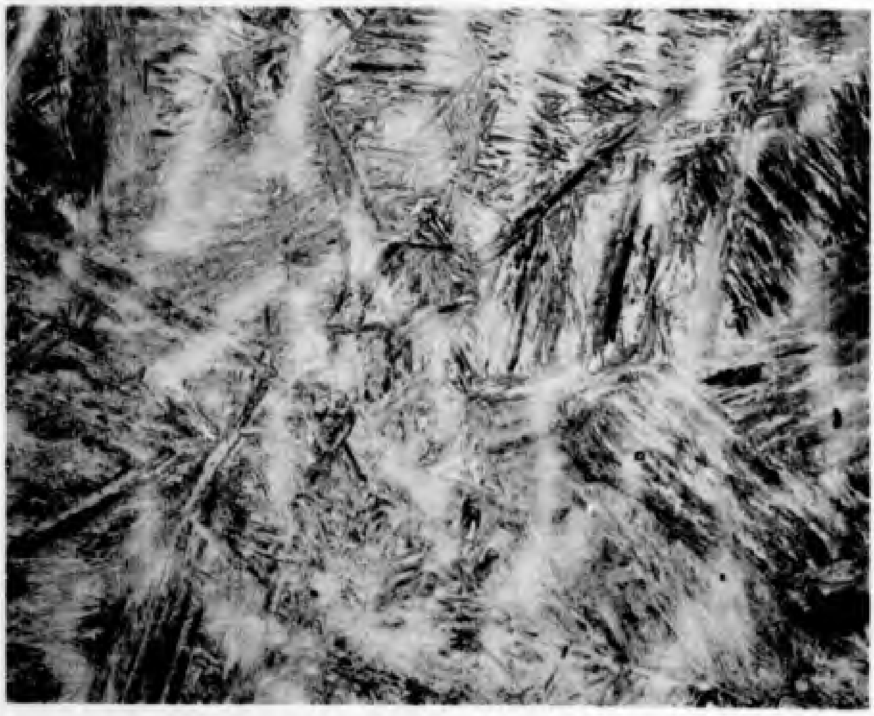


Top of Fusion Zone 500X

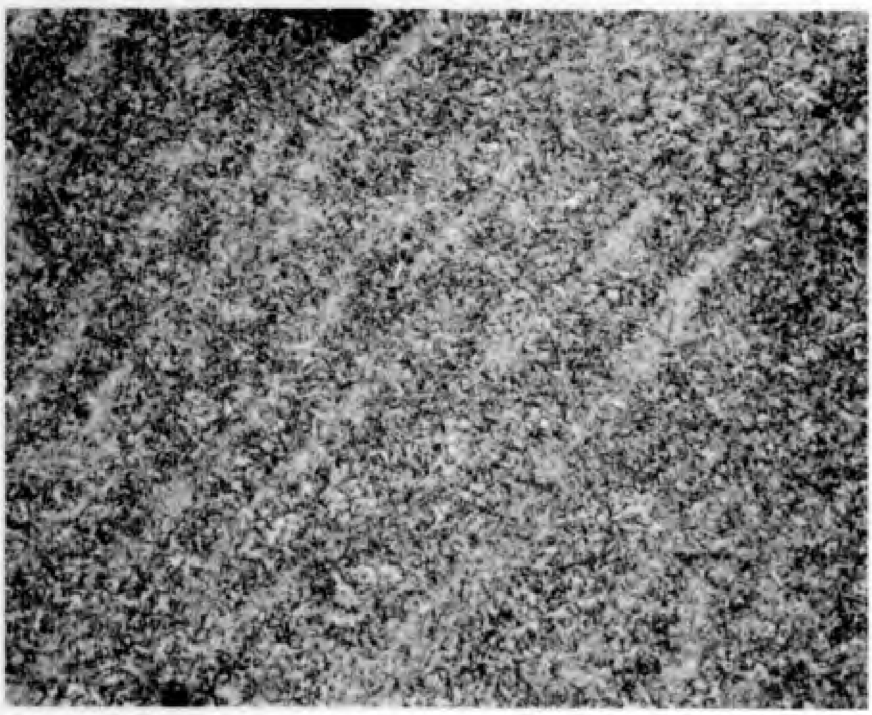


Center of Fusion Zone 500X

Figure 89. Microstructure (Martensite) of the Top and Center of the Fusion Zone of Multipass TIG Weld No. K287 Made in D6AC 1/2-Inch Plate. Weld Was Made in Helium at 4 ipm Using Filler Wire No. 1 and No Preheat. Etch: 2% Nital.



Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 90. Microstructure (Martensite) of the Top and Center of the Fusion Zone of Multipass TIG Weld No. K290 Made in D6AC 1/2-Inch Plate. Weld Was Made in Helium at 4 ipm Using Filler Wire No. 1 and a 400°F Preheat and Interpass Temperature. Etch: 2% Nital.

fine grained and more homogeneous as a result of the tempering effect of the thermal cycles of the additional weld passes. In addition, the center of the fusion zone for the weld made with the 400°F preheat appears to be slightly more homogeneous. The porosity evident in the top of the fusion zone, Figure 90, was not found in the radiograph for this weld.

The microstructure for welds K293 and S299 made at 10 ipm in argon and at 15 ipm in helium are presented in Figures 91 and 92, respectively. The weld made with the greater energy input, Figure 91, has wider dendritic spacings in the top of the fusion zone.

(3) Weld Hardness Surveys

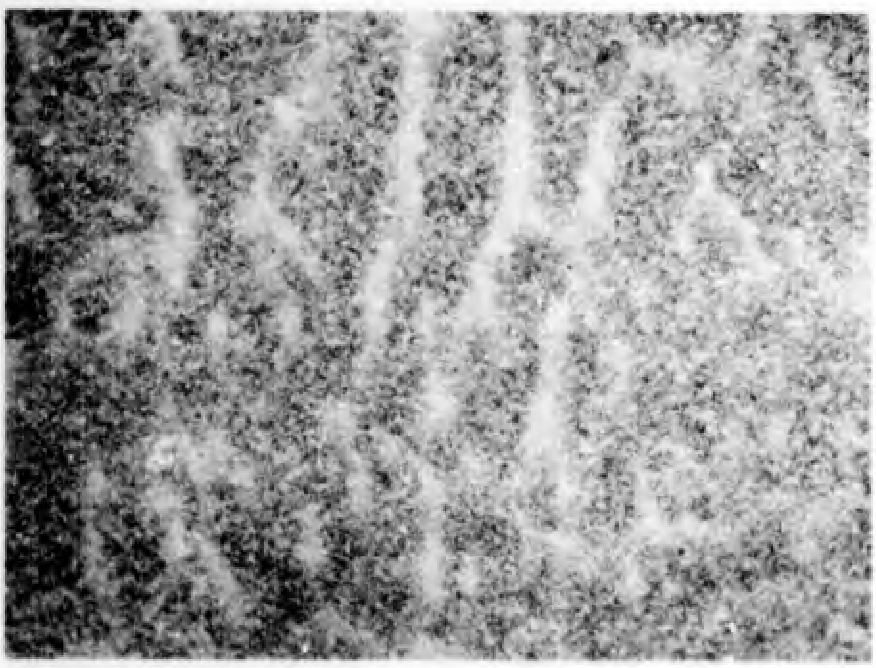
The hardness survey for TIG weld No. K287 made in D6AC plate at 4 ipm in helium without a preheat and with the interpass temperature maintained at room temperature is presented in Figure 93. Extremely high readings were observed in the heat-affected zones and top pass in the fusion zone of the weld (R_c 42 to 60). These readings indicate that fresh martensite has formed in these areas. In addition, the traverse of the bottom passes indicates that these have hardnesses comparable to parent metal and, in areas, higher than those of the parent metal. The traverse of the center of the weld shows lower readings in the heat-affected and fusion zones. These readings reflect tempering and the low carbon content of the filler wire. In Figure 94 is a hardness survey of weld No. K290 made at the same parameter as the one shown in Figure 93 with the exception that a 400°F preheat and interbead temperature was maintained throughout the welding operation. The significant difference in the hardness survey of this weld is that the hardnesses of the lower passes appear to be lower in this weld. However, the position in which these surveys are taken has a great affect upon the resultant readings, and the most that can be obtained are general trends. One point that should be mentioned is that in using filler wire of a lower carbon content than the base metal in a V-groove joint design, the very bottom passes have a higher carbon content than the metal in the center of the fusion zone farther up in the joint. This results from the composition of the weld puddle being made up of a combination of the filler wire composition and the base metal composition.

Hardness surveys for welds S299, K293, and K297, made at 10 ipm in helium or argon, are presented in Figures 95 to 97, respectively. These welds, made at a lower energy input than the 4 ipm welds, do not differ significantly in the hardness pattern from those made at 4 ipm. These surveys each indicate that areas with weld deposit have lower hardnesses than the parent metal, and therefore failure in this area would possibly occur under transverse loading. The hardness survey for MIG weld No. S307 is presented in Figure 98. The asymmetrical curve obtained from the traverse made in the upper part of the fusion zone can be correlated with the last weld pass made in which fresh martensite causes the high hardness. The adjacent previous top pass was tempered by the thermal cycle from the last pass.

(4) Tensile Properties

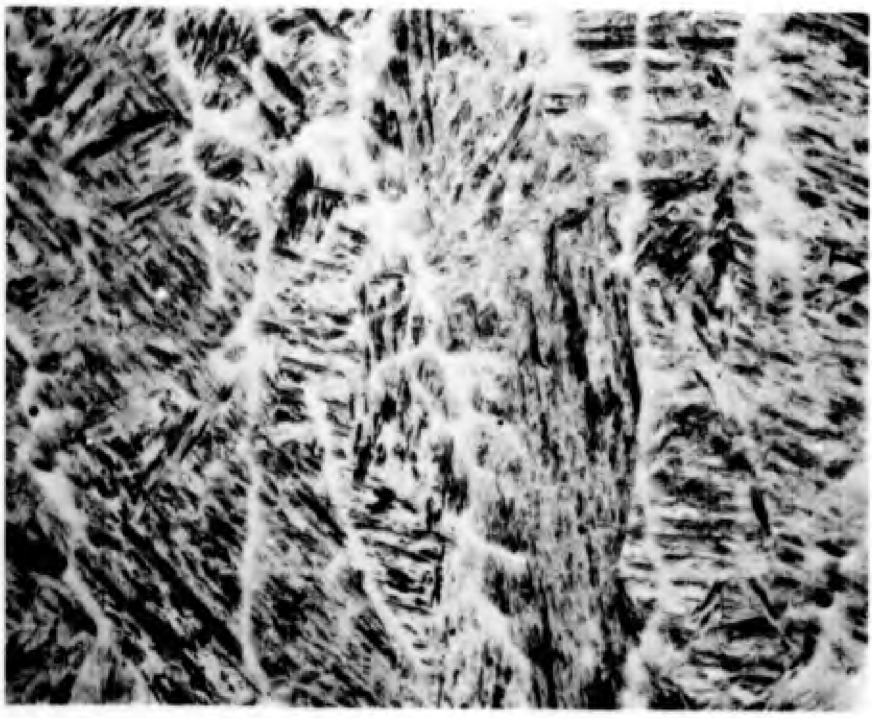
The tensile properties for welds made in D6AC material are presented in Table 34. Although the yield strengths of each of the TIG welds

Top of Fusion Zone 500X

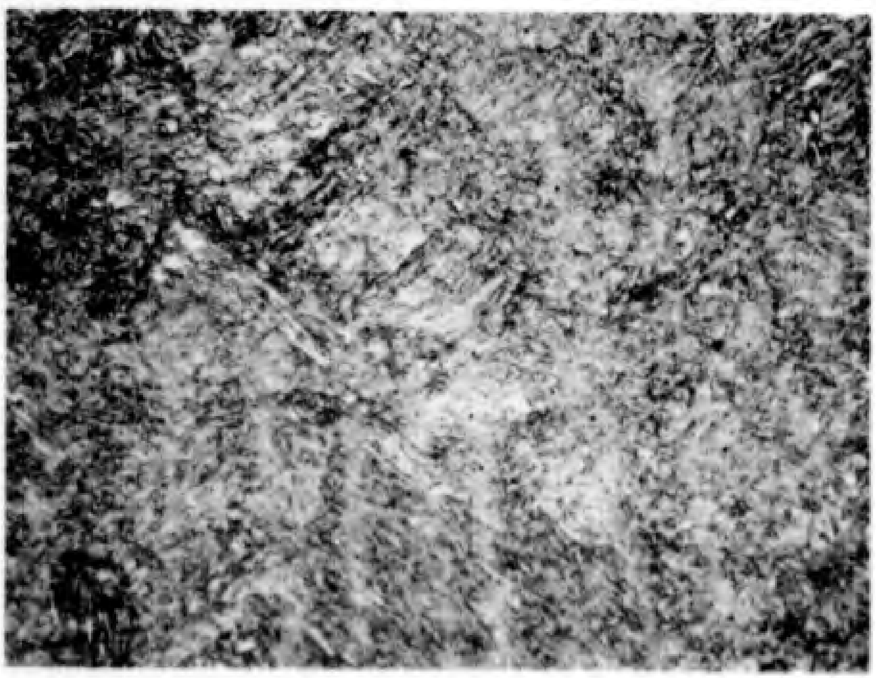


Center of Fusion Zone 500X

Figure 91. Microstructure (Martensite) of the Top and Center of the Fusion Zone of Multipass TIG Weld No. K293 Made in D6AC 1/2-Inch Plate. Weld Was Made in Argon at 10 ipm Using Filler Wire No. 1 and a 400°F Preheat and Interpass Temperature. Etch: 2% Nital.



Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 92. Microstructure of the Top and Center of the Fusion Zone of Multipass TIG Weld No. S299 Made in D6AC 1/2-Inch Plate. Weld Was Made in Helium at 15 ipm Using Filler Wire No. 1 and No Preheat. Etch: 2% Nital.

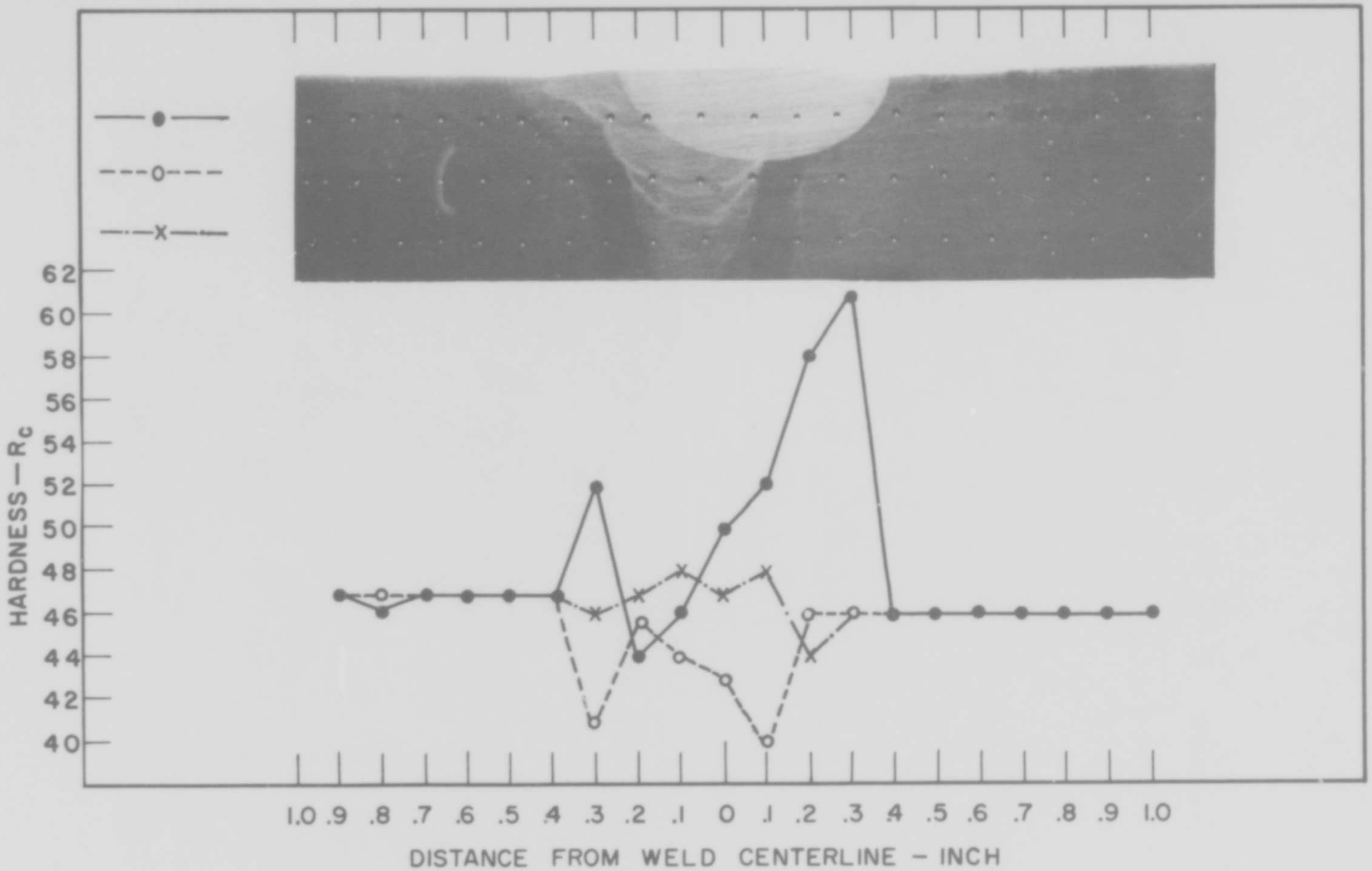


Figure 93. Hardness Survey of TIG Weld No. K287 Made in D6AC Plate at 4 ipm Using Helium Shielding, Filler Wire No. 1, and No Preheat.

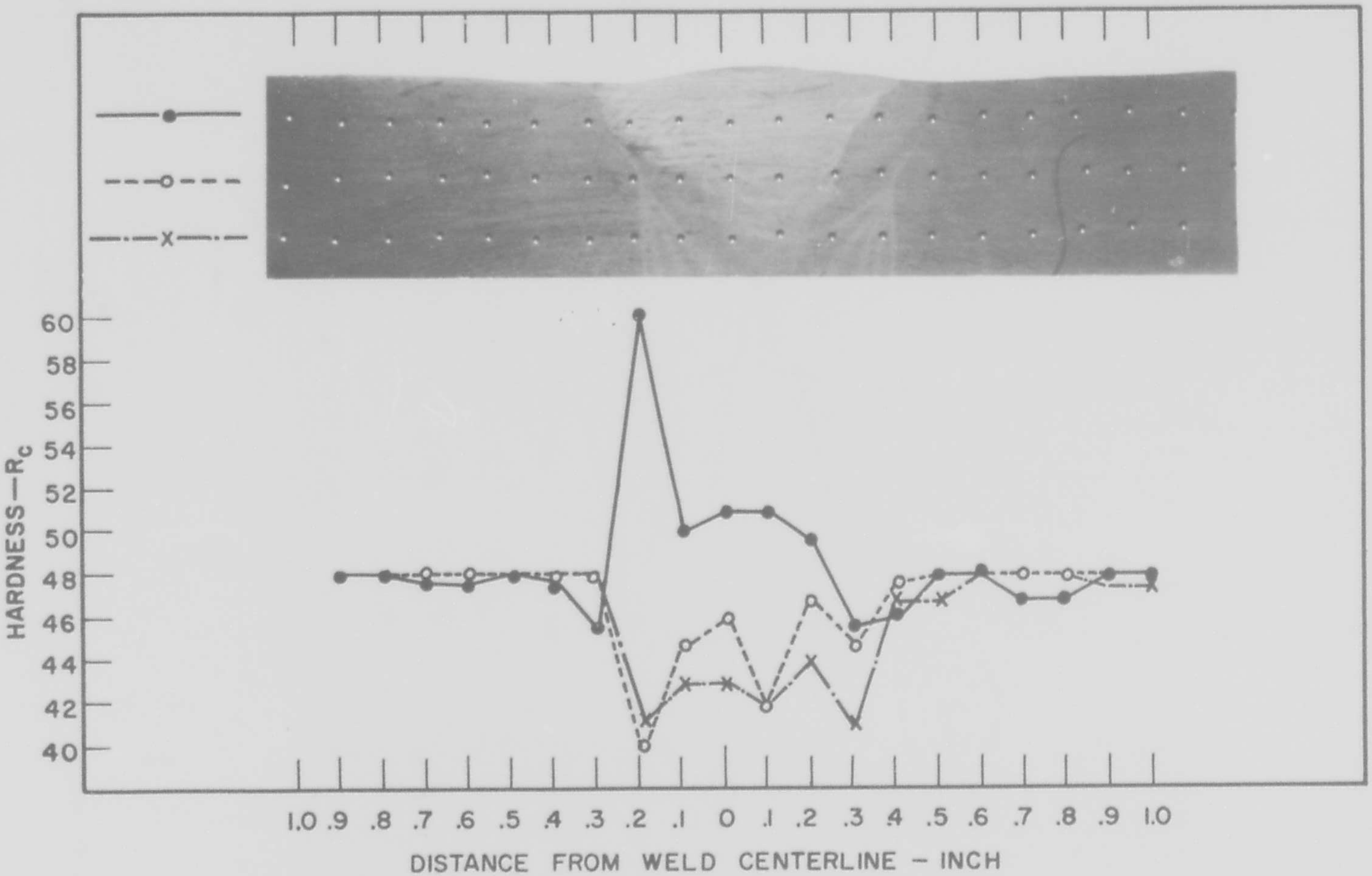


Figure 94. Hardness Survey of TIG Weld No. K290 Made in D6AC Plate at 4 ipm Using Helium Shielding, Filler Wire No. 1, and a 400°F Preheat and Interbead Temperature.

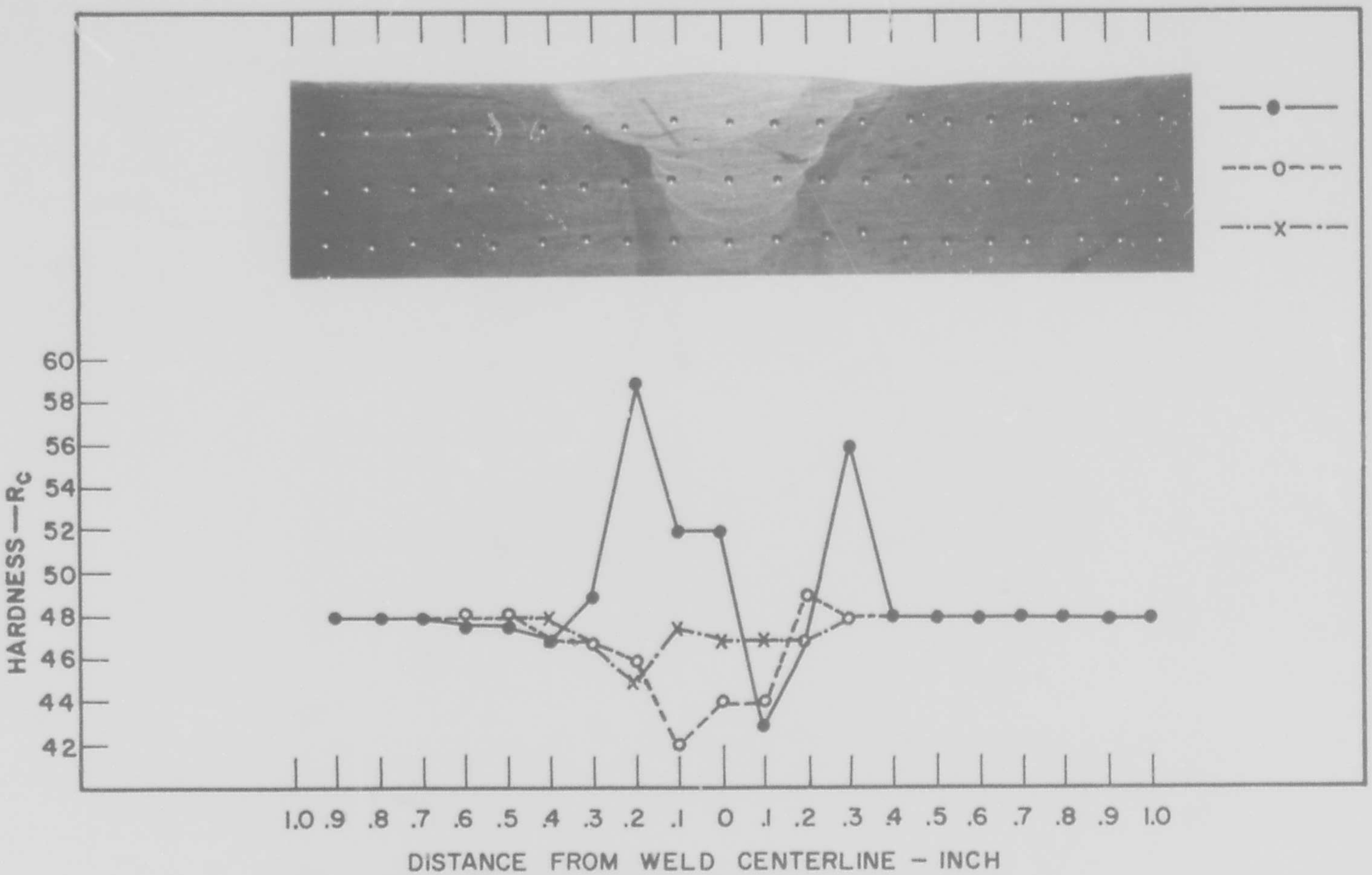


Figure 95. Hardness Survey of TIG Weld No. S299 Made in D6AC Plate at 10 ipm Using Helium Shielding, Filler Wire No. 1, and No Preheat.

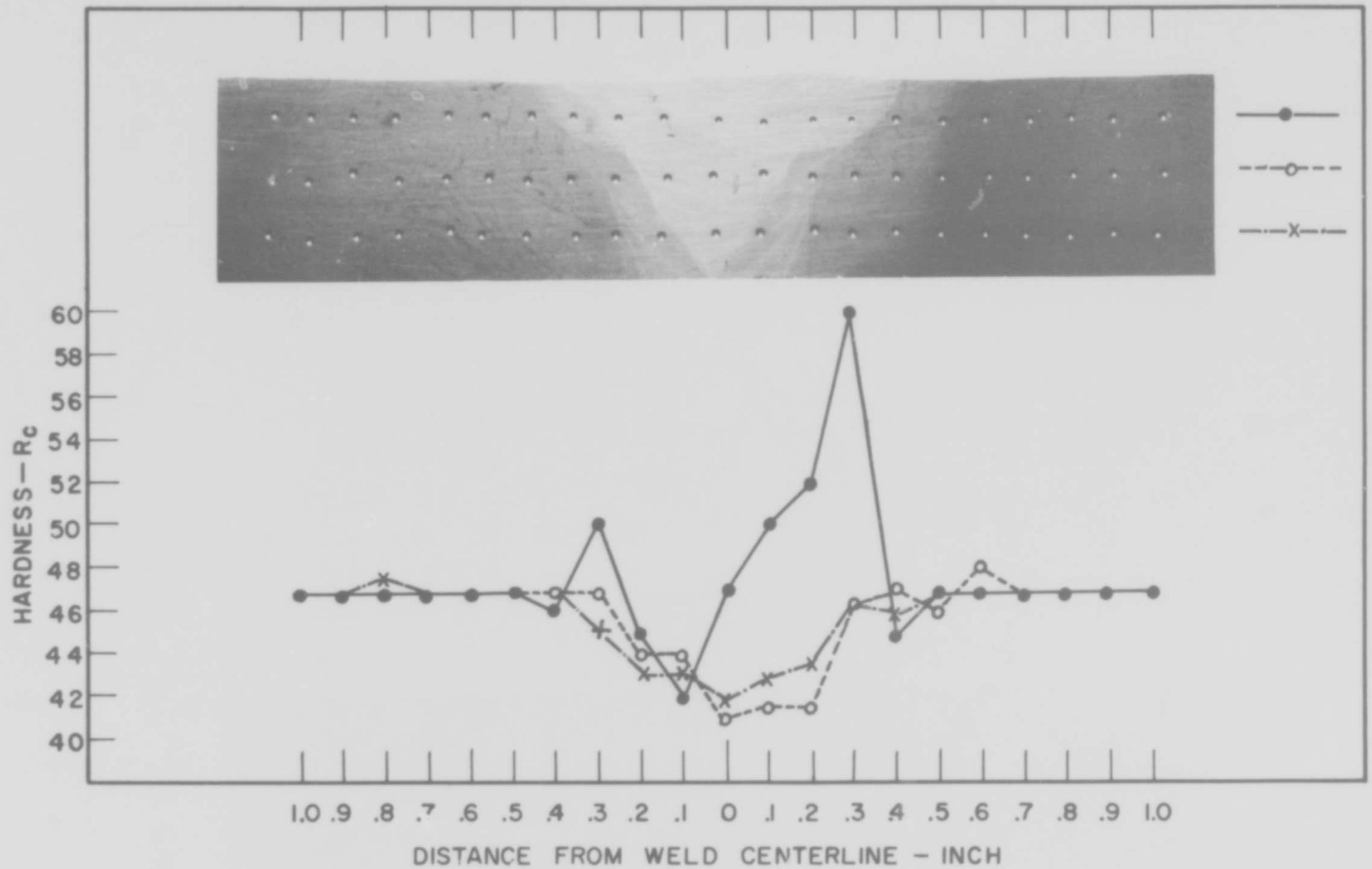


Figure 96. Hardness Survey of TIG Weld No. K293 Made in D6AC Plate at 10 ipm Using Argon Shielding, Filler Wire No. 1, and a 400°F Preheat and Interbead Temperature.

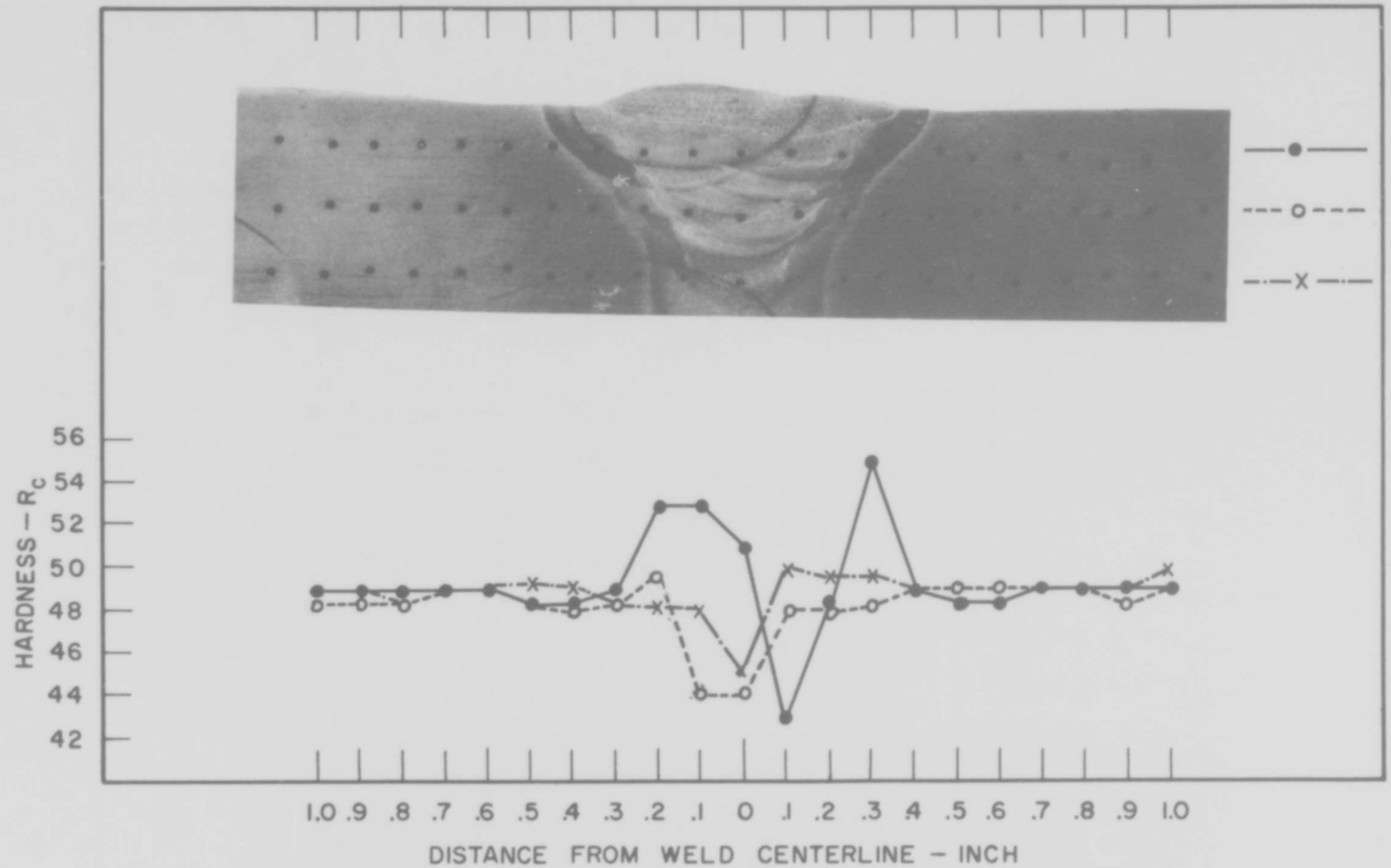


Figure 97. Hardness Survey of TIG Weld No. K297 Made in D6AC Plate at 10 ipm Using Argon Shielding, Filler Wire No. 1, and No Preheat.

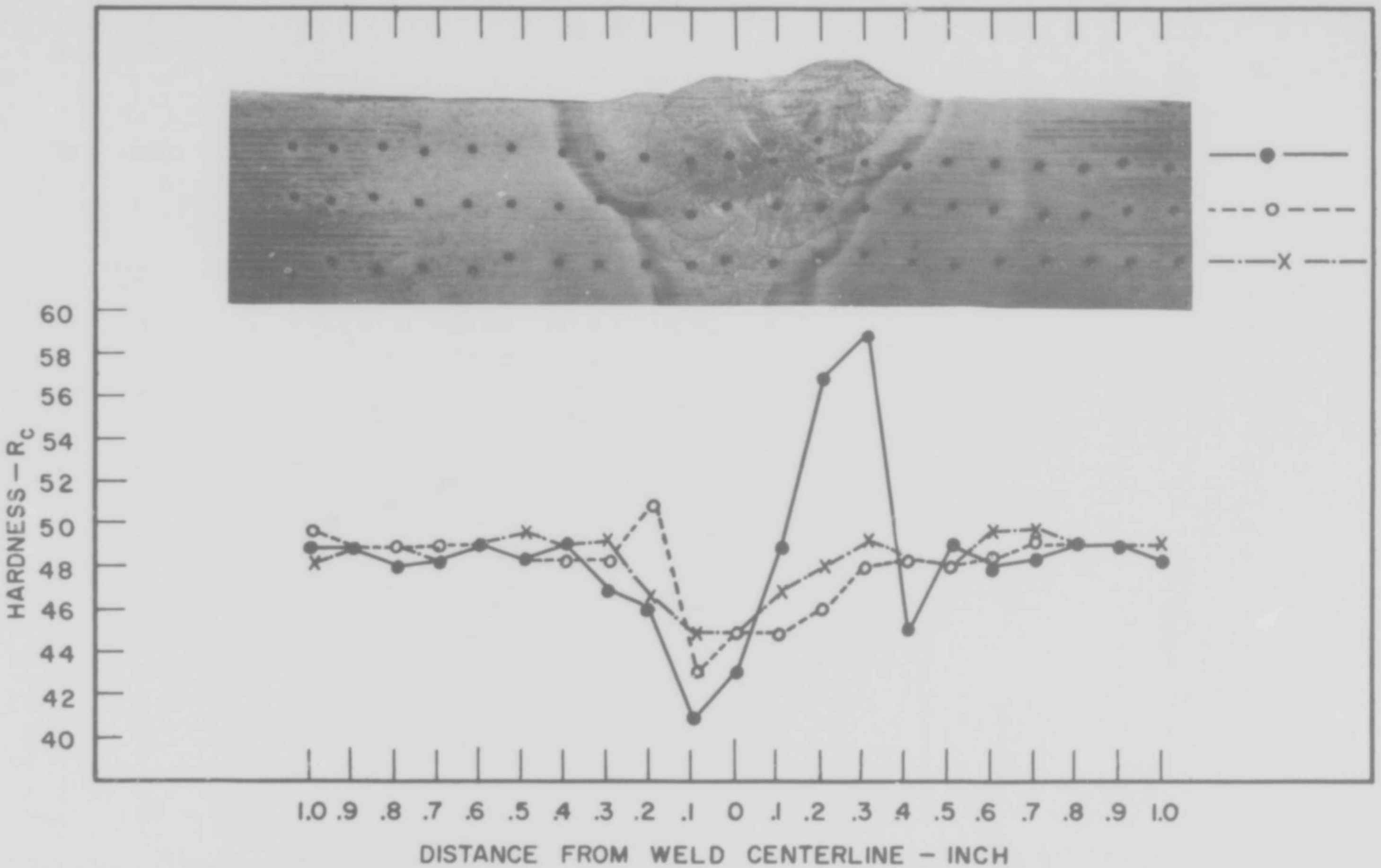


Figure 98. Hardness Survey of MIG Weld No. S301 Made in D6AC Plate.

TABLE 34

TENSILE PROPERTIES OF TIG AND MIG WELDS MADE IN D6AC 1/2-INCH PLATE

Weld No.	Test(a) Direction	Filler Wire(b)	Welding Speed (ipm)	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elong. (%)(c)	R.A. (%)	Energy Input KJ/in/pass	% Joint Efficiency(d) Y.S.	U.T.S.	Comments
K287	L	1	4	196.2	216.2	14.0	45.0	40.8	-	-	(i)
"	L	1	4	191.3	217.9	13.5	44.0	40.8	-	-	(i)
"	T	1	4	198.3	210.7	2.5	9.2	40.8	90.6	87.8	(i)
"	T	1	4	199.9	212.7	2.5	11.1	40.8	91.3	88.8	(i)
K290	L	1	4	180.8	227.1	13.5	41.3	40.8	-	-	(h)(i)
"	L	1	4	177.6	235.0	14.0	42.0	40.8	-	-	(h)(i)
"	T	1	4	185.6	206.3	3.0	21.0	40.8	84.8	85.9	(f)(h)(i)
"	T	1	4	185.2	205.5	2.5	17.4	40.8	84.6	85.6	(f)(h)(i)
K292	T	1	10	207.2	216.0	4.5	42.0	24.8	94.7	90.0	(j)(e)(i)
"	T	1	10	206.9	216.0	4.0	39.6	24.8	94.5	90.0	(j)(e)(i)
"	L	1	10	192.5	218.5	7.5	11.2	24.8	-	-	(j)(i)
"	L	1	10	202.7	209.2	13.5	28.2	24.8	-	-	(j)(i)
K293	L	1	10	184.5	199.9	11.5	20.4	23.5	-	--	(j)(g)(h)
"	L	1	10	185.7	201.1	18.0	55.5	23.5	-	-	(j) (g)(h)
"	T	1	10	192.7	207.1	4.0	24.5	23.5	88.0	86.3	(f)(g)(h)
"	T	1	10	191.7	205.9	5.0	32.8	23.5	87.6	85.8	(f)(g)(h)
S295	L	1	10	193.8	204.3	14.0	42.2	23.5	-	-	(g)(j)
"	L	1	10	195.0	206.0	14.0	34.3	23.5	-	-	(j)(g)
"	T	1	10	200.3	210.3	4.0	35.1	23.5	91.5	87.6	(j)(g)(e)
"	T	1	10	200.7	211.1	4.5	36.1	23.5	91.7	87.9	(j)(g)(e)

(Continued)

TABLE 34

TENSILE PROPERTIES OF TIG AND MIG WELDS MADE IN D6AC 1/2-INCH PLATE

Weld No.	Test(a) Direction	Filler Wire(b)	Welding Speed (ipm)	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elong. (%)(c)	R.A. (%)	Energy Input KJ/in/pass	% Joint Efficiency(d) Y.S.	% Joint Efficiency(d) U.T.S.	Comments
S297	L	1	4	187.0	223.5	13.0	37.4	41.5	-	-	(g)(j)
"	L	1	4	197.6	211.1	16.0	55.9	41.5	-	-	(g)(j)
"	T	1	4	203.1	213.5	4.0	33.8	41.5	92.8	88.9	(e)(g)(j)
S298	L	1	15	199.2	204.7	14.5	46.0	15.6	-	-	(j)(g)
"	L	1	15	198.1	202.6	15.0	46.2	15.6	-	-	(j)(g)
"	T	1	15	201.0	205.1	4.0	36.4	15.6	91.8	85.4	(e)(g)
"	T	1	15	201.2	205.1	4.0	33.8	15.6	91.9	85.4	(e)(g)
S299	L	1	15	189.0	208.9	10.5	14.4	20.5	-	-	(j)(i)
"	L	1	15	192.7	209.1	9.0	18.1	20.5	-	-	(j)(i)
"	T	1	15	203.9	214.3	5.5	32.9	20.5	93.1	89.3	(e)(j)(i)
"	T	1	15	202.5	212.1	4.5	33.8	20.5	92.5	88.3	(e)(j)(i)
S304	T	1	10	193.3	212.7	3.5	32.9	23.5	88.3	88.6	(f)(g)(h)(l)
"	T	1	10	193.7	214.7	4.5	22.4	23.5	88.5	89.4	(f)(g)(h)(l)
S305	T	1	10	199.3	219.4	3.0	18.8	23.5	91.0	91.4	(f)(g)(k)(h)
"	T	1	10	200.7	204.3	3.0	18.1	23.5	91.7	85.1	(f)(g)(k)(h)
S301*	L	5	18.3	144.6	177.3	2.5	5.1	23.6	-	-	Fibrous (h)
"	L	5	18.3	142.0	172.1	1.5	3.9	23.6	-	-	Fibrous (h)
"	T	5	18.3	206.8	219.9	4.0	30.6	23.6	94.5	91.6	(f)(h)
"	T	5	18.3	191.9	222.9	1.5	8.2	23.6	87.7	92.8	(e)(h)

(Continued)

TABLE 34

TENSILE PROPERTIES OF TIG AND MIG WELDS MADE IN D6AC 1/2-INCH PLATE

(a) (L) specimens were taken parallel with the weld and consisted entirely of weld deposit.

(T) specimens were taken transverse to the weld and included weld, heat affected zones, and parent metal.

(b) Filler wire composition is presented in Table 2.

(c) (T) specimens had a gage length of two inches. (L) specimens had a gage length of 1 inch.

(d) Joint efficiency based on 218.9 and 240.1 ksi parent metal yield and ultimate strengths, respectively.

(e) Fracture occurred in the weld.

(f) Fracture occurred at the fusion line.

(g) Weld was made in argon.

(h) Weld was made with a 400°F preheat and interbead temperature.

(i) Weld made in helium. All others in argon.

(j) Porosity observed in fractured specimens.

(k) Weld made in double U-groove joint design.

(l) Weld made in single U-groove joint design.

* Weld was made by the MIG process.

made in this material are in excess of 180 ksi the transverse ductility of these welds is quite low with regard to that desired regardless of welding parameter or shielding gas. As was indicated by the hardness traverses, a good percentage of the transverse specimens fractured in the weld with low ductility. The low ductility could be a function of local yielding only in the weld area. In general, the welds made with a preheat and interbead temperature of 400°F fractured at the fusion heat-affected zone line, while those made with no preheat and an interbead temperature of 75°F fractured in the weld. No improvement was realized by single U- and double V-groove joint designs for welds in this material.

The tensile properties for MIG weld No. S301 made in this material indicate that the low carbon weld metal will not meet the desired properties. In addition, as in the case of TIG welds, the transverse ductility is low.

(5) Fracture Toughness

Only one weldment of the D6AC steel plate was evaluated for fracture toughness since the welding parameters examined produced a generally low ductility in the transverse direction. The weld chosen for fracture toughness evaluation (S304) employed a single U-groove joint configuration and was made at 10 ipm using argon shielding and filler wire No. 1. The resultant transverse tensile properties were presented in Table 34. Notch bend tests were conducted under 4-point loading with notches placed in the weld deposit and heat-affected zone. Replica tests were made for each notch position, and the results are summarized in Table 35. Both the weld deposit and heat-affected zones possessed good fracture toughness (K_{IC}^* = 81.4 and 83.0 ksi $\sqrt{\text{inch}}$, respectively), although they are slightly lower than that of the base metal K_{IC} of 93.2 ksi $\sqrt{\text{inch}}$.

(6) Charpy Impact Properties

The Charpy V-notch impact properties of D6AC weld metal and heat-affected zones for TIG weld No. S304 are presented in Table 36. These results are also presented in Figure 99, together with the properties of the parent metal. As shown in Figure 99, the impact strength of the weld was below that of the plate at temperatures below about 75°F. At 75°F (room temperature) the weld has somewhat better impact strength than the plate. The fracture ductility of the weld was significantly greater than the plate at temperatures above -100°F.

The heat-affected zone exhibited considerably greater impact strength and fracture ductility than either plate or weld metal. This is apparently the result of previously reported overtempering in the heat-affected zones which also reduced tensile strength and increased ductility.

(7) Crack Susceptibility Test

Circular patch weld restraint specimens similar to those made for the HP 9-4-20 material were made in D6AC 1/2-inch plate using filler wire No. 1. The first attempt to weld this specimen without a preheat resulted in severe center bead cracking. Radiographic and dye penetrant inspection, of the second specimen made with a 400°F preheat and interbead temperature, did not reveal any cracking

TABLE 35

CALCULATED FRACTURE TOUGHNESS, K_{IC}^*, OF TIG WELD MADE IN D6AC STEEL 1/2 INCH PLATE

(4-Point Loading)

Specimen Identity	Notch Position	Width, W (inch)	Thickness, B (inch)	Crack Depth, a (inch)	Major Span, L' (inches)	Curve Type(a)	Load (lbs.)	Relative Plastic Zone Size r_y/B(b)	σ_{nom}/σ_{ys}(c)	Calculated Fracture Toughness, K_{IC}^* (ksi $\sqrt{\text{inch}}$)
S304-2	HAZ	0.464	0.499	0.093	7.0	1	2875	0.015	1.02	87.9
S304-3	HAZ	0.464	0.500	0.109	7.0	1	2350	0.012	0.91	78.1
S304-5	Weld	0.464	0.500	0.116	7.0	1	2540	0.018	1.13	89.4
S304-6	Weld	0.464	0.499	0.095	7.0	1	2385	0.013	0.95	73.3

Notes:

(a) Curve types are defined in Figure 16.

(b) Plastic zone size, r_y, equals the difference between the effective crack length a* and the measured crack length a ($a^* = a + E\,G/6\pi\sigma_{ys}^2$).

(c) σ_{nom}/σ_{ys} = nominal stress at crack initiation divided by 0.2% yield strength.

TABLE 36

CHARPY V-NOTCH IMPACT PROPERTIES OF D6AC MARTENSITIC WELD METAL AND HEAT AFFECTED ZONES FOR TIG WELD NO. S304

Identification	Notch Location	Test Temp. (°F)	Impact Energy (Ft.Lbs.)	Lateral Expansion (Mils)
S 304-1	Weld	Room	20.0	10.0
-2	"	0	12.0	8.5
-3	"	-100	4.0	9.5
-4	"	"	26.5	2.0
-5	"	-320	2.0	1.0
S 304H-1	HAZ	Room	38.5	20.0
-2	"	0	32.0	16.0
-3	"	-100	17.5	5.0
-4	"	"	20.0	6.0
-5	"	-320	12.5	1.5

Note: Lateral Expansion Measured at Base of Fracture.

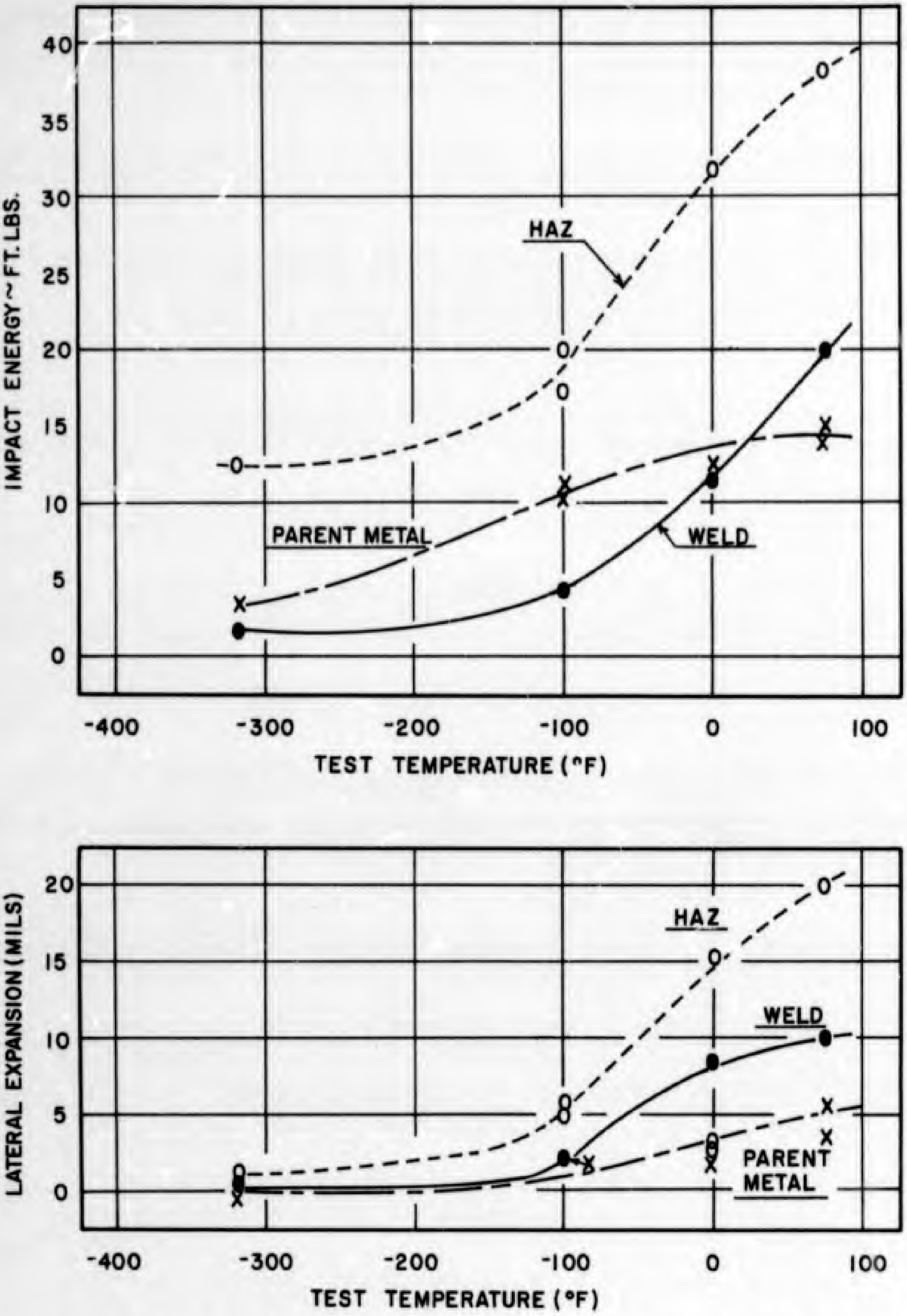


Figure 99. Charpy V-Notch Impact Properties of Martensitic D6AC Weld Metal and Heat Affected Zones for TIG Weld No. S304.

6. D6AC Steel 0.090-Inch Sheet

a. Base Metal Evaluation

As a result of the lower carbon content of the sheet material compared to the 1/2-inch plate, a lower tempering temperature of 950°F was necessary to obtain properties similar to those of the plate. The same 1650 and 1550°F normalizing and austenitizing temperatures were used, but for only 15 minute cycles followed by the double temper at 950°F (2 hours + 2 hours). The inclusion content and resultant microstructure are shown in Figures 100 and 101, respectively. Although the inclusion content was relatively low, stringers were revealed parallel to the rolling direction. In addition, the inclusions are not all spherical in shape and a low ductility could therefore be expected in the transverse direction.

The smooth tensile properties of the sheet are summarized in Table 37. These strengths were well within the desired ranges for the program, and the elongation was considered good, even though stringers and non-spheroidal inclusions were present in the material. The calculated fracture toughness of the sheet was determined using 3 x 12 inch center notch specimens, and K_{IC}^* was found to be 80.5 ksi $\sqrt{\text{inch}}$ (see Table 38).

b. Evaluation of TIG Welds in 0.090-Inch Sheet

Gas tungsten arc welds were made in D6AC 0.090-inch sheet at 4, 10, and 15 ipm using helium or argon gas shielding, filler wire No. 1, and no pre- or post-heat. These welds were subsequently evaluated for quality, microstructure, smooth tensile and fracture toughness. The fusion welding parameters for these welds are presented in Table 39.

(1) Weld Quality

Welds made at each of the parameters with the exception of one were radiographically sound. Weld No. T313 made in helium at 15 ipm contained one spot of porosity.

(2) Weld Microstructure

The microstructures for welds T309 and T308, made at 10 ipm in helium and argon, respectively, are shown in Figure 102. Although these microstructures are believed to consist primarily of martensite, a second phase is evident in the grain boundaries.

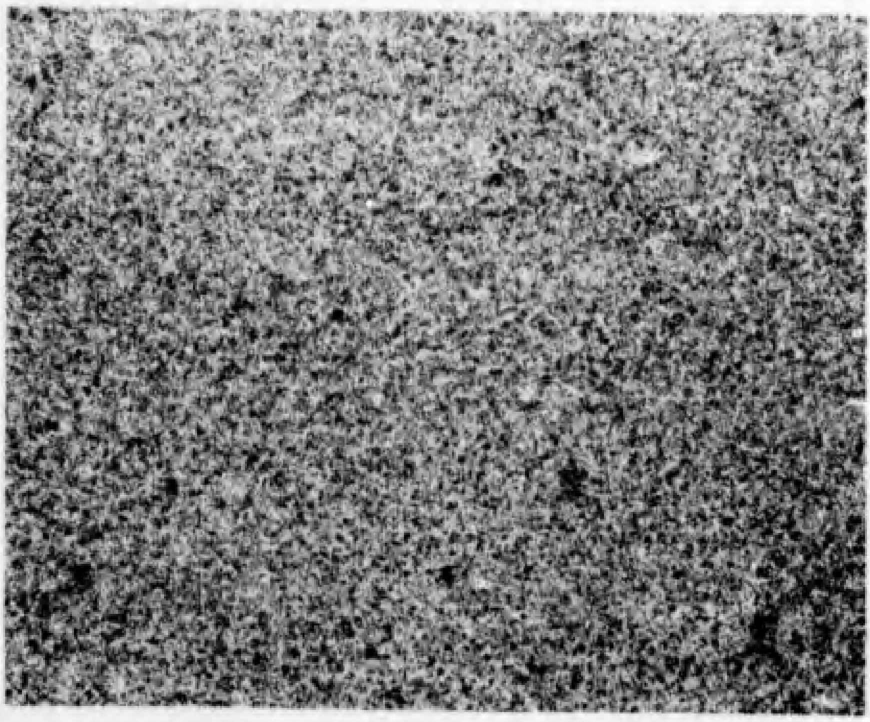
(3) Tensile Properties

The resultant smooth tensile properties are presented in Table 40. Although all welds except T312 made at 15 ipm using argon shielding had good strengths, the ductility decreased as the welding speed increased. The best overall properties resulted from using a welding speed of 4 ipm and argon shielding (weld No. T311). One of the two specimens from weld T310 made at 4 ipm in helium shielding also had good tensile properties. Some specimens from the welds made at higher speeds did not have enough ductility to allow calculation of a 0.2% offset yield strength (see Table 40).

(a) Parallel to Rolling Direction 100X

(b) Perpendicular to Rolling Direction 100X

Figure 100. Unetched D6AC 0.090 Inch Sheet Showing Inclusion Levels.



100X

Figure 101. Microstructure of Heat Treated D6AC 0.090 Inch Sheet.

TABLE 37

SMOOTH TENSILE PROPERTIES
OF D6AC 0.090 INCH SHEET

Specimen No.	0.2% Y.S. (ksi)	U.T.S. (ksi)	% Elong. (%-1")
1	195.1	208.6	13.0
2	193.1	210.5	7.0
3	192.3	210.0	7.0

TABLE 38

PLANE STRAIN FRACTURE TOUGHNESS OF D6AC STEEL
0.090 INCH SHEET

Specimen Identity	Test[(a)] Direction	Width, W (in.)	Thickness, B (in.)	Crack Length, 2a (in.)	Curve Type[(b)]	Load (lbs)	σ_y / σ_{ys}	Plane Strain Fracture Toughness, K_{IC} (ksi $\sqrt{in.}$)
1	T	3.042	0.089	0.930	1	15,200	0.29	79.0
2	T	3.046	0.089	1.021	1	15,000	0.28	82.0

(a) Test direction relative to rolling direction.

(b) Curve types described in Figure 16.

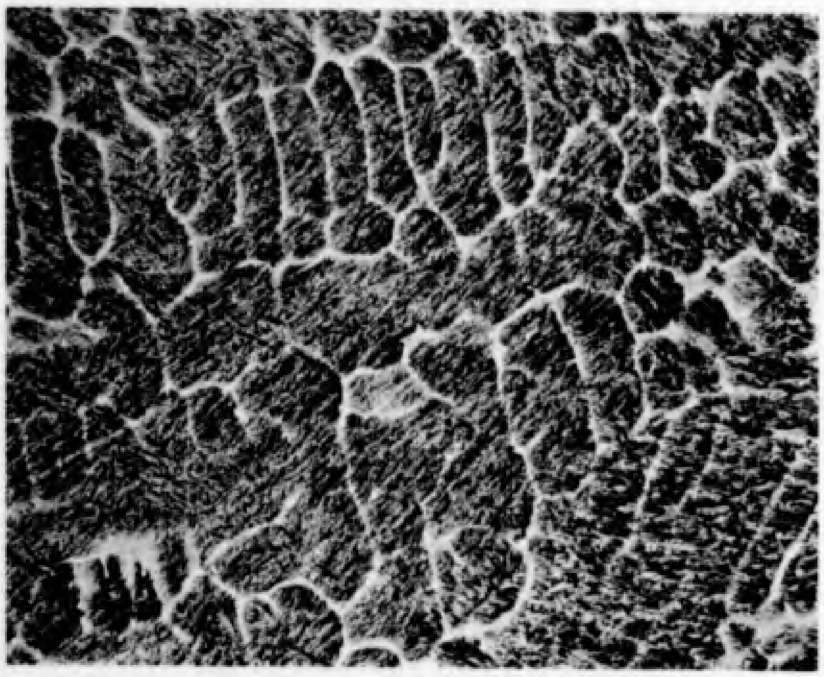
TABLE 39

FUSION WELDING PARAMETERS FOR
TIG WELDS MADE IN 0.090 INCH D6AC SHEET

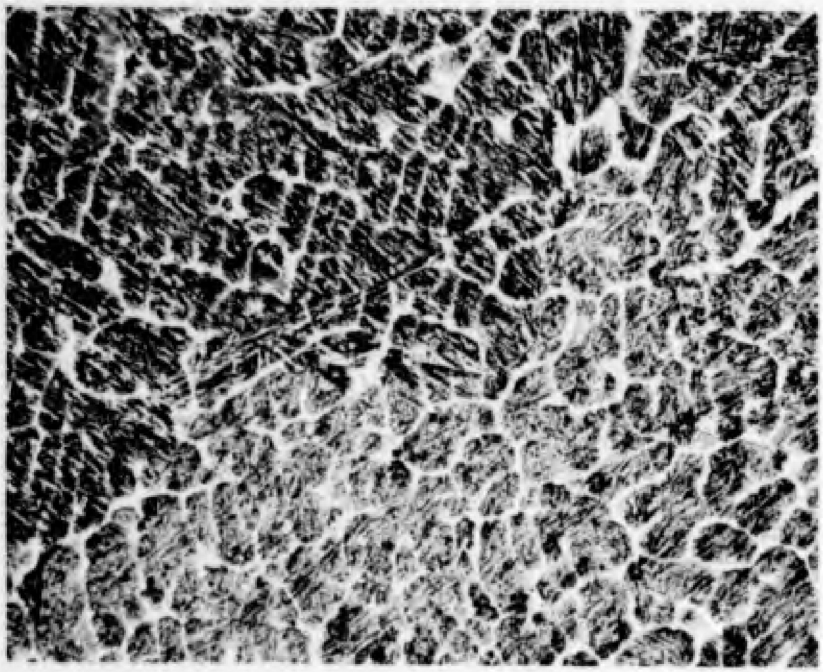
Weld No.	Filler Wire Dia. (In.)	Wire[a] Composition	No. Passes	W/S (ipm)	Wire Speed (ipm)	amps	Volts	Gas (cfh) Torch	Backup	Comments[b]
T308	0.062	1	1	10	6.8	105	13.5	50He	5He	
T309	"	1	1	10	6.6	150	10.0	35A	5A	
T310	"	1	1	4	4.0	55	13.0	50He	5A	
T311	"	1	1	4	4.0	90	8.0	35A	5A	
T312	"	1	1	15	20.0	220	11.0	35A	5A	
T313	"	1	1	15	20.0	160	13.0	50He	5He	One spot of porosity

(a) Filler wire composition is presented in Table 2.

(b) Weld quality comments based upon radiographic inspection.



Weld No. T309 Argon Shield 500X



Weld No. T308 Helium Shield 500X

Figure 102. Microstructure for Single Pass TIG Welds Made at 10 ipm in 0.090-Inch D6AC Sheet.

TABLE 40

TRANSVERSE TENSILE PROPERTIES OF TIG WELDS MADE IN 0.090 INCH D6AC STEEL SHEET[(a)]

Weld No.	Filler Wire[(b)]	Shielding Gas	Welding Speed (ipm)	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elong. (% 1")	% Joint Efficiency[(d)] Y.S.	% Joint Efficiency[(d)] U.T.S.	Comments
T310	1	He	4	194.9	205.5	2.0	99.9	98.3	(e)
"				192.3	210.0	7.0	98.5	100.0	(f)
T311	1	A	4	190.5	208.2	7.0	97.5	99.9	(f)
				193.1	210.5	6.0	99.0	100.0	(f)
T308	1	He	10	187.0	206.5	2.5	95.7	99.0	(g)
				(c)	182.4	1.0	-	88.5	(g)
T309	1	A	10	189.7	202.0	1.0	97.3	97.1	(g)
T313	1	He	15	190.8	211.0	3.0	97.6	100.0	(e)
				190.5	206.9	3.0	97.7	99.4	(e)
T312	1	A	15	(c)	172.1	0	-	82.4	(g)
				(c)	171.3	0.5	-	82.2	(g)

(a) Normalized at 1650°F for 15 minutes, A.C., austenitized at 1550°F for 15 minutes; O.Q; tempered at 950°F (2 hrs. + 2 hrs).
(b) Filler wire composition is presented in Table 2.
(c) 0.2% offset was not reached before failure.
(d) Joint efficiencies were based upon parent metal ultimate and 0.2% yield strengths of 208.6 ksi and 195.1 ksi, respectively.
(e) Fracture occurred in weld deposit.
(f) Fracture occurred in parent metal.
(g) Fracture occurred in heat affected zone.

(4) Fracture Toughness

Center-notched tensile specimens were used to evaluate the plane strain fracture toughness of the TIG weld. As shown in Table 41, the welding speed and shielding gas appeared to have no measurable influence on the calculated toughness value. The heat affected zones generally had a slightly higher toughness than the weld deposits. This is probably due to the heat affected zones being more heavily tempered by the welding passes. The criteria that $\sigma_{lg} / \sigma_{ys} \leq 0.8$ was met in all instances, however in only a few cases were Type 3 load-extension curves obtained. Both Type 1 and 3 curves obtained on similar specimens yielded similar K_{IC} values indicating that a good approximation of the material's toughness was obtained from Type 1 curves in this instance.

c. General Discussion

Although the parent metal smooth tensile properties were acceptable, the fracture toughness was lower than that for the HP 9-4-25 material. In addition, the Charpy V-notch impact properties for this material were low. This coupled with the low ductility values obtained in transverse specimens from weldments and the frequent failures of these specimens in the weld indicate that this high carbon material possibly should not be investigated further as a martensitic material. However, D6AC material with a lower carbon level would possibly perform with better properties in the weldments.

B. Bainitic Steels

This section of the report is concerned with a discussion of the welding of HP 9-4-45 steel, 1/2-inch plate and 0.090-inch sheet, and D6AC steel, 1/2-inch plate all in the bainitic condition.

1. HP 9-4-45 Steel, 1/2-Inch Plate

Investigation of the HP 9-4-45 1/2-inch plate during this year's work consisted of base metal evaluation and the evaluation of TIG and MIG welds made in this material.

a. Base Metal Evaluation

The base material, received in the annealed condition, was isothermally transformed to a structure of lower bainite. The heat treated material was evaluated metallographically and for smooth tensile, fracture toughness and Charpy impact properties.

Selection of the austempering heat treatment for the HP 9-4-45 material was made on the basis of information supplied by Republic Steel[13]. This information is presented graphically in Figures 103 and 104. From this information, tensile blanks were heat treated by austempering at 575°F and 550°F. These tests indicated that a 550°F austemper for 7 hours, subsequent to normalizing 1 hour at 1600°F, air cooling and austenitizing in salt at 1500°F for 1 hour provided the desirable properties. Although the transformation time of 7 hours was recommended[13], the TTT diagram (Figure 105) developed

TABLE 41

CALCULATED PLANE STRAIN FRACTURE TOUGHNESS OF TIG WELDS MADE IN D6AC STEEL
0.090 INCH SHEET USING FILLER WIRE NO. 1

(Center Notched Tensile Specimens)

Specimen Identity	Welding Speed (ipm)	Shielding Gas	Notch Position	Width, W (in.)	Thickness, B (in.)	Crack Length, 2a (in.)	Curve Type	Load (lbs)	$\frac{\sigma_y}{\sigma_{ys}}$	Calculated Plane Strain Fracture Toughness (ksi $\sqrt{in.}$)
T310-4	4	He	Weld	2.044	0.076	0.729	1	8400	0.28	68.8
T310-5	4	He	HAZ	2.037	0.077	0.764	1	8370	0.28	70.2
T311-3	4	A	Weld	2.046	0.072	0.807	1	6300	0.22	56.9
T311-4	4	A	Weld	2.031	0.072	0.668	3	6400	0.23	58.7
T311-5	4	A	HAZ	2.052	0.072	0.882	1	6600	0.23	64.2
T308-5	10	He	Weld	2.032	0.074	0.714	1	7750	0.28	64.6
T309-5	10	A	HAZ	2.045	0.062	0.764	1	5200	0.22	66.2
T313-3	15	He	Weld	2.039	0.066	0.536	1	6650	0.26	59.7
T313-4	15	He	Weld	2.037	0.068	0.697	1	7150	0.27	63.2
T313-5	15	He	HAZ	2.036	0.068	0.705	3	6640	0.25	58.6
T312-3	15	A	Weld	2.041	0.072	0.756	1	6400	0.25	56.2
T312-5	15	A	HAZ	2.033	0.071	0.542	3	7400	0.30	66.3

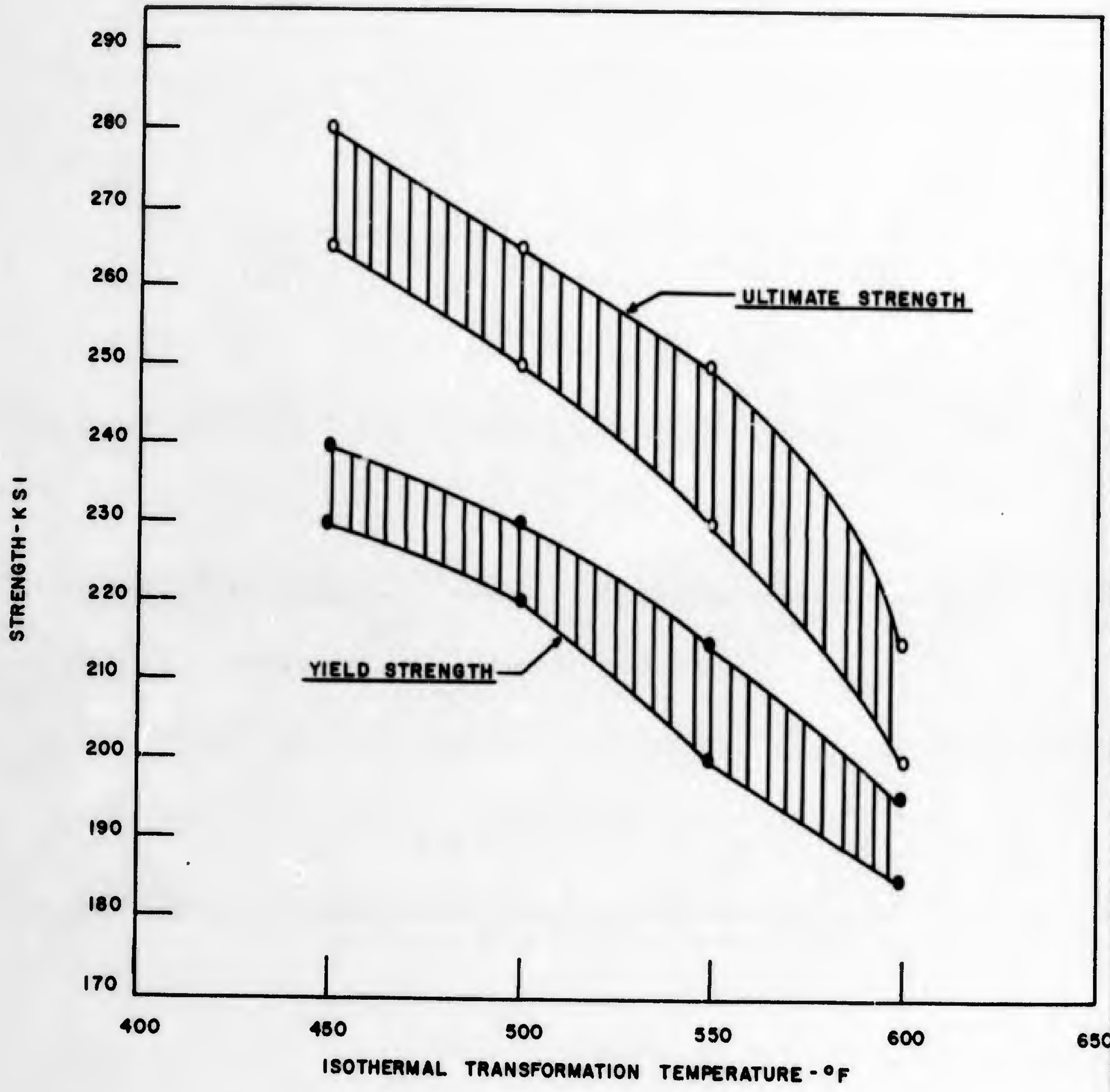


Figure 103. The Effect of Transformation Temperature on the Ultimate and Yield Strengths of HP 9-4-45 Steel.

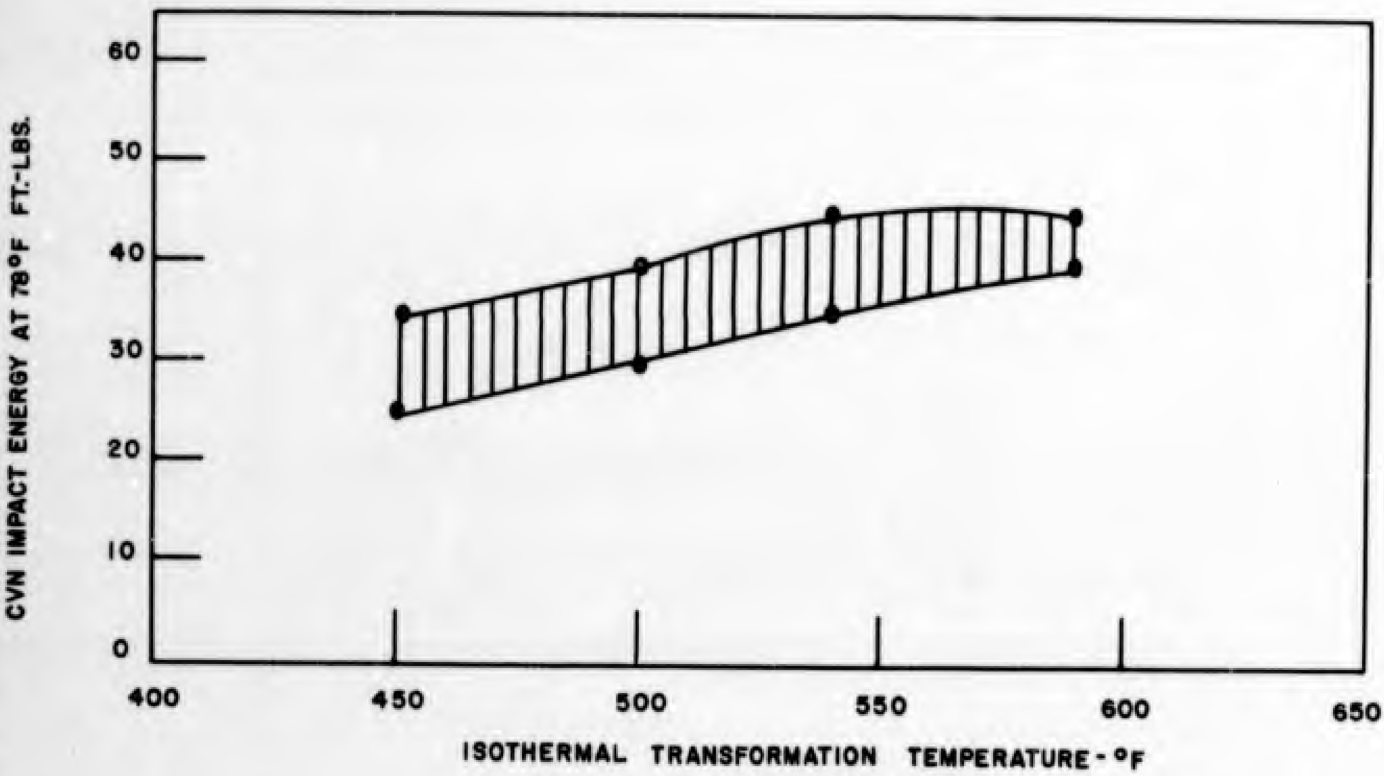


Figure 104. The Effect of Transformation Temperature on the Impact Toughness of HP 9-4-45 Steel.

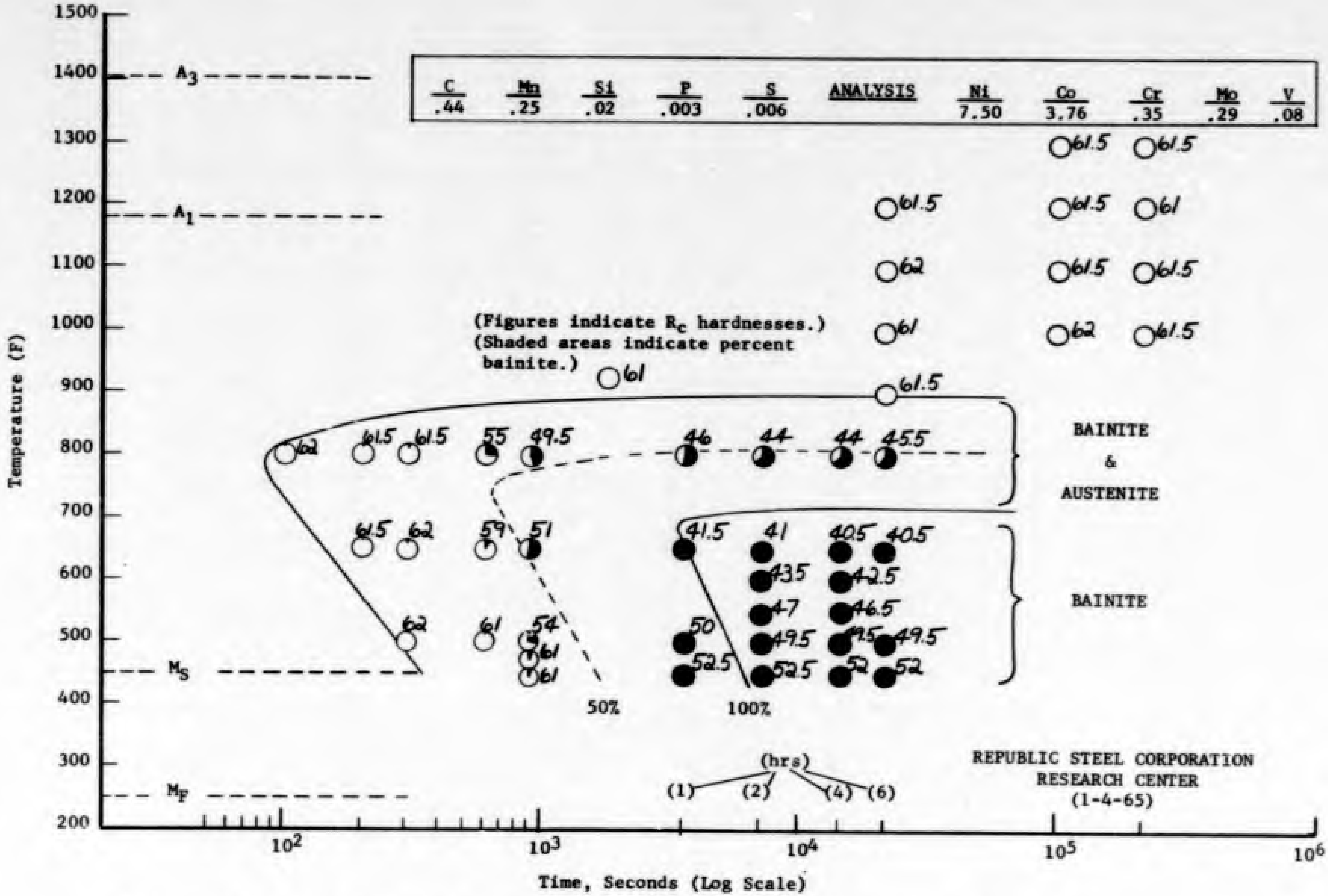


Figure 105. TTT Diagram for HP 9-4-45 Steel Heat No. 3930805 (Ref. 13).

at a later date by Republic Steel for an HP 9-4-45 steel, Heat No. 393085[13], indicated that the structure would consist of 100 percent bainite after only 2 hours at 550°F. The hardnesses, shown in Figure 105, for a 550°F transformation temperature (R_c 46.5 to R_c 47) correlated with the hardness obtained for the program material transformed at 550°F for 7 hours.

Photomicrographs of unetched as-received HP 9-4-45 plate are presented in Figure 106. The inclusion levels indicated by these photographs did not appear to be excessive and were spherical in shape. The microstructure of HP 9-4-45 1/2-inch plate commercially heat treated by austempering at 550°F for 7 hours is presented in Figure 107. The microstructure consists of lower bainite.

The smooth tensile properties for HP 9-4-45 material are presented in Table 42. Although the tensile properties for the 575°F laboratory heat treatment were within the required range, the 550°F laboratory heat treatment produced strengths closer to the center of the required range and would allow for greater latitude in commercial heat treatment. The tensile results for the commercial heat treatment (550°F austemper) were well within the 180 to 200 ksi yield strength range desired for the program. In addition, the HP 9-4-45 material in the bainitic condition has good elongation and reduction of area.

The plane strain fracture toughness of HP 9-4-45 plate was determined using both 4-point loaded notch bend and surface cracked specimens. The results, summarized in Tables 43 and 44 respectively, indicate the material had good toughness with average values of 98.8 and 94.4 ksi $\sqrt{\text{inch}}$ for the notch bend and surface cracked tests respectively.

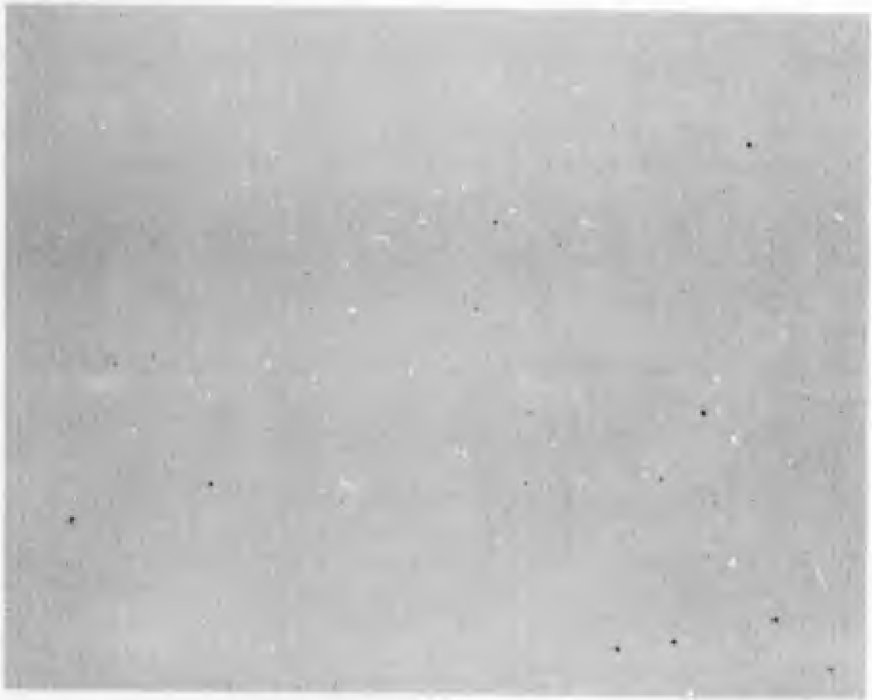
The Charpy V-notch impact properties of 1/2-inch HP 9-4-45 bainitic plate are given in Table 45. The impact strength (absorbed energy) above -320°F is considered satisfactory for this material. However, the lateral expansion, a measure of fracture ductility, is poor. This combination of relatively high impact energy and low ductility suggests that the greater portion of the impact energy was absorbed during crack initiation. The fracture surfaces showed no indications of brittle failure, and the shear lips of the specimens tested above -100°F were comparable with those normally obtained with a ductile failure.

b. Evaluation of Welds Made in 1/2-Inch HP 9-4-45 Plate

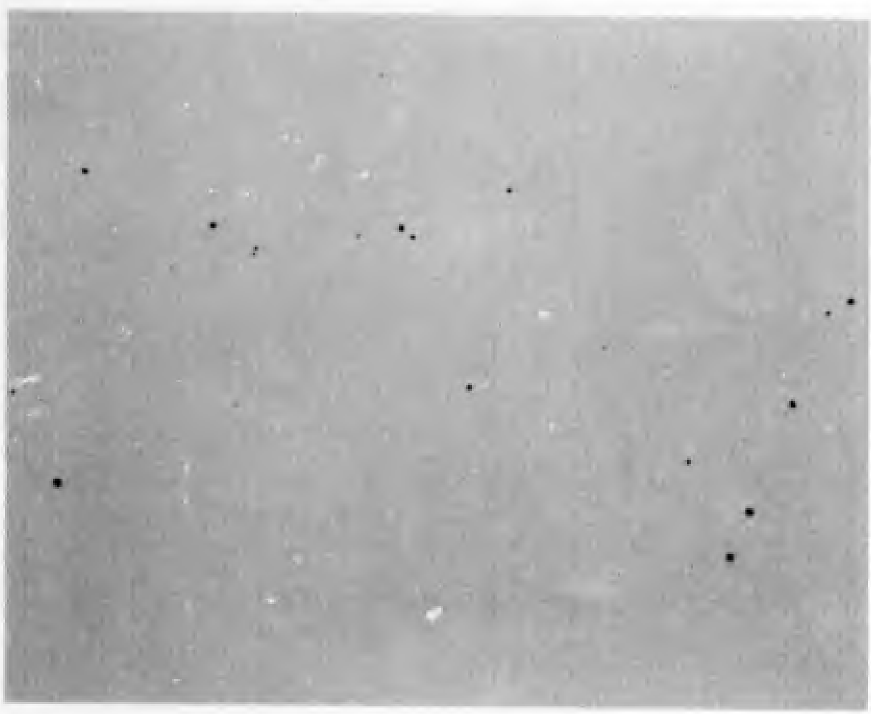
Gas tungsten arc welds were made in HP 9-4-45 1/2-inch plate at pre- and post-heat and interbead temperatures ranging from 75 to 575°F. These welds were subsequently evaluated for quality, metallographic structure, hardness and tensile values. Fusion welding parameters for these welds are presented in Table 46.

(1) Weld Quality

The results of radiographic inspection are presented in the comments column, Table 46. Initial welds in this material contained some porosity (welds 0242 and 0243). It was noticed during the welding operation that this porosity had a tendency to form in the lower weld passes. In addition, attempts to make a fusion root pass without filler wire resulted in

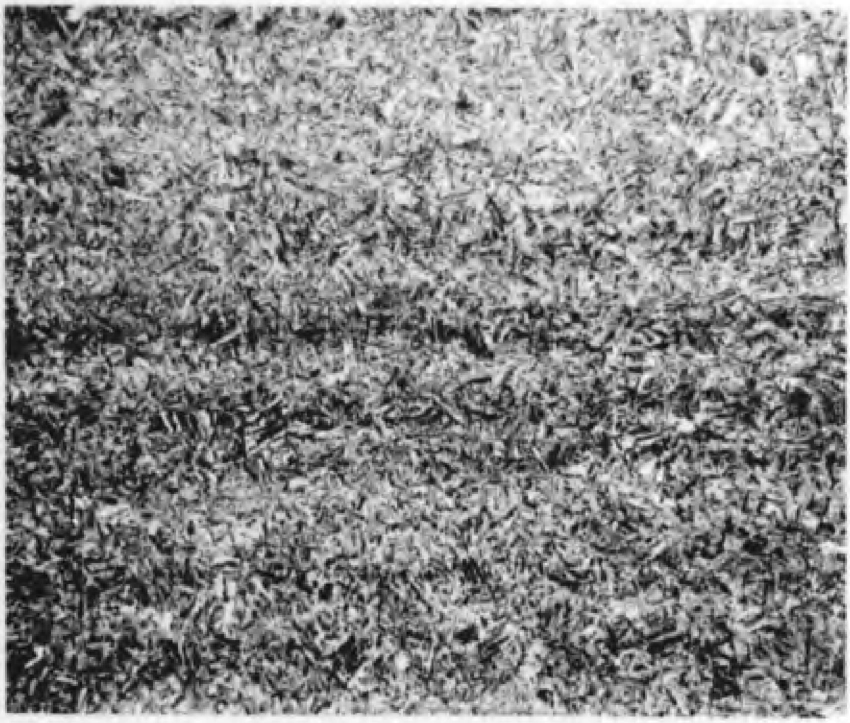


(a) Parallel to Rolling Direction 100X

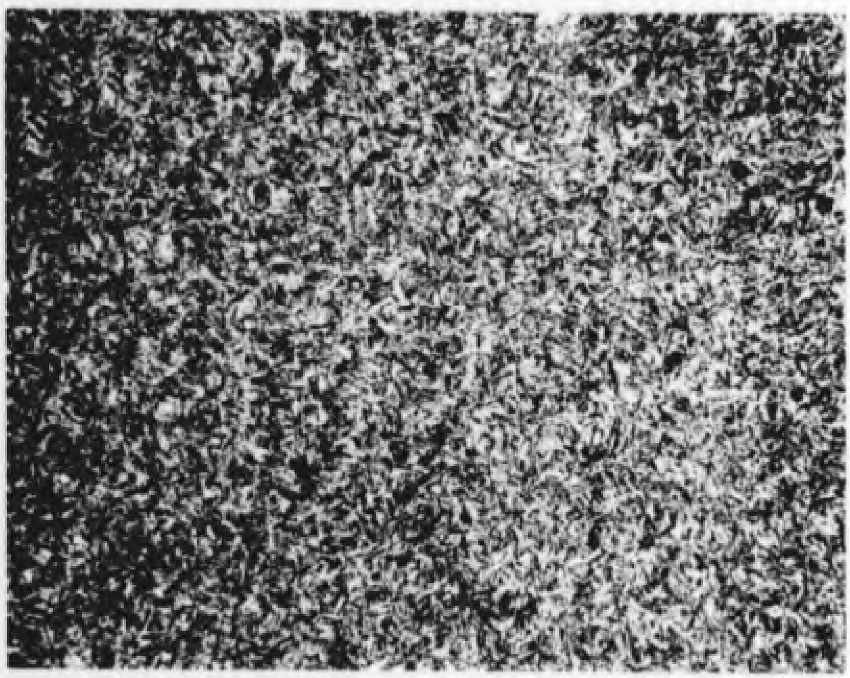


(b) Perpendicular to Rolling Direction 100X

Figure 106. Unetched HP 9-4-45 1/2 Inch Plate Showing Inclusion Levels.



(a) Austempered 550°F 7 Hours 500X



(b) Austempered 550°F 3 Hours 500X

Figure 107. Microstructure (Bainite) of HP 9-4-45 1/2 Inch Plate Austempered at 550°F for the Designated Times. Hardness: R_c 46.5-47 Etch: 2% Nital.

TABLE 42

SMOOTH TENSILE PROPERTIES OF HP 9-4-45

Heat No.	Thickness (in.)	Test[(a)] Direction	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elongation (% 1")	R.A. (%)	Austempering Temperature and Time
3920869	0.500	L	194.3	224.3	15.5	59.7	550°F-7 hrs. Lab. Heat treated
(Code 0)	"	L	-	224.3	16.5	60.2	"
	"	T	191.1	222.7	14.0	49.6	"
	"	T	191.3	222.7	15.0	53.9	"
3920869	"	L	187.0	214.4	17.0	61.5	575°F-7 hrs. Lab. Heat treated
(Code 0)	"	L	187.4	214.2	16.5	62.0	"
3920869	"	L	192.6	224.2	15.0	61.5	550°F-7 hrs. Commercial heat treated
	"	L	192.9	223.4	15.0	61.9	550°F-7 hrs. Commercial heat treated
	"	T	187.7	220.1	15.0	52.9	550°F-7 hrs. Commercial heat treated
	"	T	187.4	220.3	13.5	52.3	550°F-7 hrs. Commercial heat treated

(a) Test direction relative to rolling direction.

TABLE 43

CALCULATED FRACTURE TOUGHNESS, K^*_{IC}, OF 1/2 INCH HP 9-4-45 PLATE[(a)]

(4 POINT LOADED)

Specimen Identity	Width, W (in.)	Thickness, B (in.)	Crack Depth, a (in.)	Major Span, L' (in.)	Curve Type[(b)]	Load (lbs)	Relative Plastic Zone Size r_y/B[(c)]	σ_{nom}/σ_{ys}	Calculated Fracture Toughness, K^*_{IC} (ksi $\sqrt{in.}$)
051-1	0.500	0.500	0.099	5.0	2	4850	0.022	1.21	95.5
051-2	0.492	0.500	0.096	5.0	2	5150	0.025	1.28	102.1

(a) Material was austenitized at 1560°F for 1 hour; **austempered at 550°F** 7 hours and A.C.

(b) Curve types are defined in Figure 16.

(c) Plastic zone size, r_y, equals the difference between the effective crack length a* and the measured crack length, a ($a^* = a + E\,G/6\pi\sigma^2_{ys}$).

(d) σ_{nom}/σ_{ys} = nominal stress at crack initiation divided by 0.2% yield strength.

TABLE 44

PLANE STRAIN FRACTURE TOUGHNESS OF HP 9-4-45 STEEL 1/2-INCH PLATE

(Surface-Cracked Specimens)

Specimen Identity	Width, W (inch)	Thickness, B (inch)	Crack Size $2c_o$ (inch)	Crack Size a_o (inch)	Gross Failure Stress (ksi)	Plane Strain Fracture Toughness, K_{IC} (ksi $\sqrt{\text{inch}}$)
1	1.496	0.252	0.278	0.082	199.2	94.9
2	1.496	0.252	0.300	0.090	189.9	93.5
3	1.496	0.251	0.316	0.082	191.9	94.9

TABLE 45

CHARPY V-NOTCH IMPACT PROPERTIES OF 1/2 INCH HP 9-4-45
PLATE HEAT TREATED TO BAINITE (HEAT NO. 3920869)

Identification	Test Temp. (°F)	Impact Energy (Ft.lbs)	Lateral Expansion (Mils)
031-1	75	30.5	4.0
031-2	"	30.0	4.5
031-3	0	27.5	2.5
031-4	"	26.5	4.5
031-5	-100	20.0	5.0
031-6	"	20.0	5.0
031-7	-320	10.0	2.0
031-8	"	9.0	1.5

Note: Lateral expansion measured at base of fracture.

TABLE 46

FUSION WELDING PARAMETERS FOR TIG AND MIG WELDS MADE IN HP 9-4-45 1/2-INCH PLATE

Weld No.	Filler Wire Diameter (inch)	Wire Composition(a)	Pre- and Post-Heat (°F)	No. Passes	W/S (ipm)	Wire Speed (ipm)	Amps	Volts	GAS (cfh) Torch	Backup	Comments(d)
0242	0.062	17	575	9	10	66(c)	220	19	50 He	5 He	Centerline Cracking, Porosity
0243	0.062	17	575	14	4	18	115	15	50 He	3 He	Porosity
0260	0.062	17	500	9	10	66	230	18	50 He	5 He	
0261	0.062	17	475	9	10	66	230	17	50 He	5 He	
0264	0.062	17	475	9	10	66	230	17	50 He	5 He	
0271	0.062	17	440	9	10	66	225	18	50 He	5 He	5 Medium Sized Spots Porosity
0272	0.062	17	None	10	10	66	230	18	50 He	5 He	
0273	0.062	17	400	10	10	66	230	18	50 He	5 He	One Small Crack at End of Weld
0274	0.062	17	375	10	10	66	230	18	50 He	5 He	
0275	0.062	17	525	10	10	66	230	18	50 He	5 He	
0277	0.062	17	500	10	10	66	230	18	50 He	5 He	
0279	0.062	17	300	7	4	28	220	13.5	35 A	5 A	Incomplete Penetration
0296	0.062	17	525	9	10	66	230	18	50 He	5 He	3 Spots of Porosity
0306	0.062	17	525	8	10	66(c)	230	18	50 He	5 He	Single U Groove Joint
0307	0.062	17	525	8	10	66(c)	230	18	50 He	5 He	Double V Groove Joint -5 Spots Por.
0300	0.062	17	525		17.4	--	300	24	375 He 126 A	5 He	MIG Weld

Notes:
(a) Wire composition is presented in Table 2.

(b) Welds 0242 and 0243 were post-heated 6 hours at the indicated temperature. Welds 0296 through 0307 were post-heated 3 hours at the indicated temperature. The rest of the welds were post-heated 7 hours.

(c) Parameter is for second through final pass.
Weld 0242 first pass was fusion pass.
Weld 0306 first pass 150 amps, 14 volts, wire feed 36 inches per minute.
Weld 0307 first pass 170 amps, 15 volts, wire feed 66 inches per minute.

(d) Weld quality commends based upon radiographic inspection.

centerbead cracking (weld 0242). However, filler wire addition to the root pass eliminated this condition. In general, the welds made in this material were sound with minimum porosity evidenced in the radiographs.

(2) Weld Microstructure

The microstructure for welds 0243 and 0242 made at 4 and 10 ipm in helium are presented in Figures 108 and 109, respectively. Although these welds each exhibited coring in the top and center of the fusion zone, the weld made at 10 ipm (Figure 109) shows a slight decrease in this respect. In addition, the fusion zone heat-affected zone of the 4 ipm weld shows a greater grain coarsening than the weld made at 10 ipm. These welds were each made with a post-heat of 575°F for 6 hours.

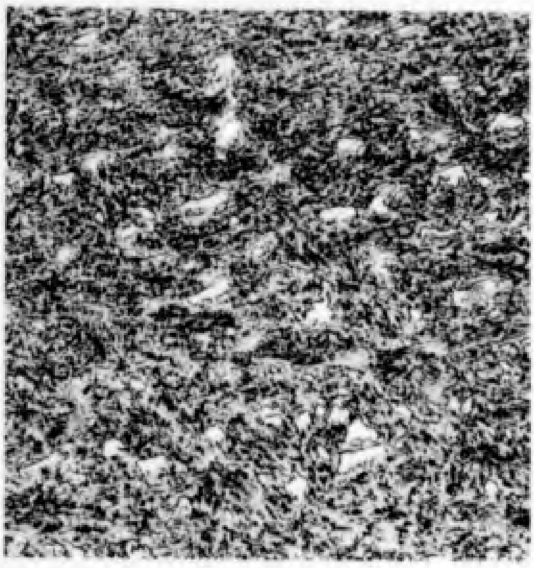
The microstructure for welds 0260, 0264, and 0271 post-heated at temperatures of 500, 475, and 440°F are presented in Figures 110 to 112, respectively. The microstructure for welds pre- and post-heated at 475 and 500°F are typical of welds in HP 9-4-45 alloys. Evidence of coring is present. However, these microstructures are believed to consist primarily of bainite. The microstructure of weld 0271 pre- and post-heated at 440°F, Figure 112, differs from those post-heated at 475 and 500°F in that it does not show distinct evidence of coring. In addition, evidence of a second phase can be observed. X-ray diffraction studies conducted to determine the possibility that it consisted of retained austenite in the primary structure of bainite indicated that less than 3 percent retained austenite was present. The microstructure of welds 0296 and 0275 post-heated at 525°F for 3 and 7 hours are presented in Figures 113 and 114, respectively. These microstructures are essentially the same and indicate that a post-heat time greater than 3 hours has little effect on the transformation to bainite. The microstructure for weld 0272 made with no pre- or post-heat and a room temperature weld bead interpass temperature is presented in Figure 115. This structure is essentially martensite.

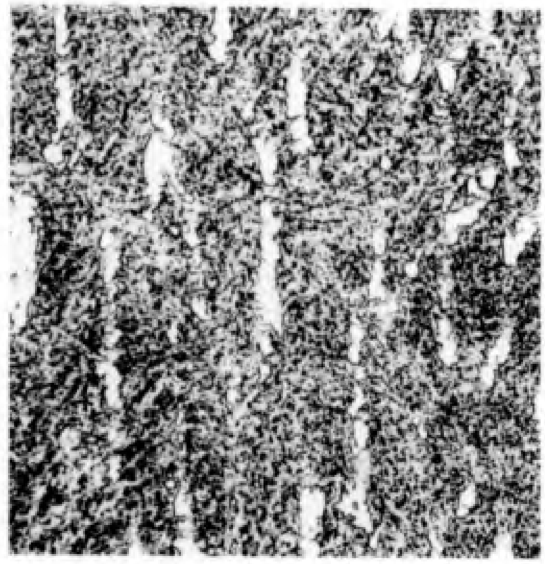
(3) Weld Hardness Surveys

Hardness surveys were made of the TIG weldments made with pre- and post-heats ranging from room temperature to 575°F. The hardness traverse of weld 0272 made with no pre- or post-heat, Figure 116, indicates uniform hardness in the parent metal and low readings in the heat-affected zone.

In the hardness traverse of weld 0279 post-heated at 300°F, Figure 117, the heat-affected zone is broad and hardness decreases gradually toward the fusion zone. The hardness of the fusion zone was generally higher than the parent metal. The 300°F post-heat temperature was considerably below the M_s temperature for the material and probably resulted in a mixture of bainite and martensite.

The hardness surveys for the rest of the welds made with higher post-heats (Figures 118 through 125) are generally similar; however, the hardness of the center and top of the fusion zone was higher for the weld post-heated at 300°F. These surveys indicate that this material in the bainitic



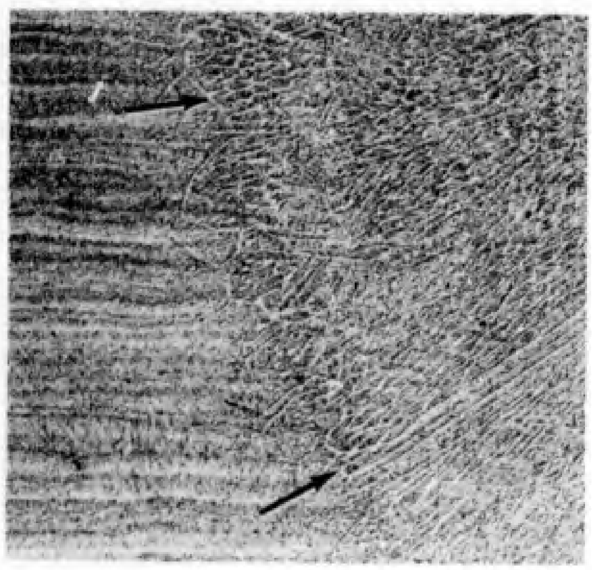


(a) 500X

Top of Fusion Zone

(b) 500X

Center of Fusion Zone



(c) 100X

Fusion Zone Heat Affected Zone

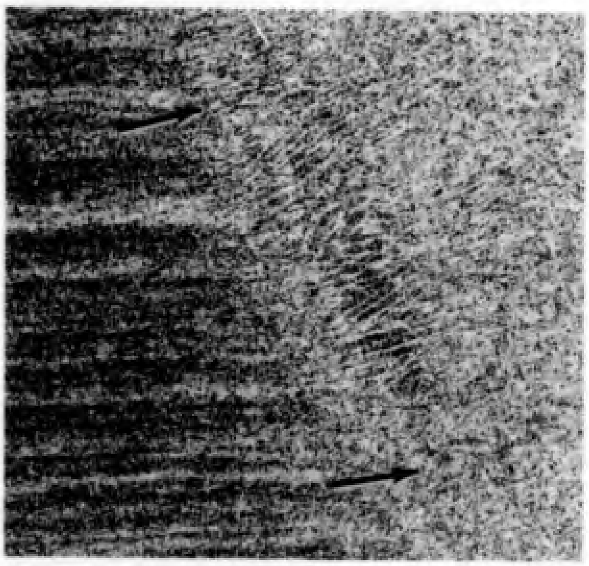
Figure 108. Microstructure of the Fusion Zone and Heat-Affected Zone of TIG Weld No. 0243 Made in HP 9-4-45 Plate. Weld Was Made at 4 ipm in Helium and Was Post-Heated (6 Hours) at 575°F. Etch: 2% Nital.

(a) 500X

Top of Fusion Zone

(b) 500X

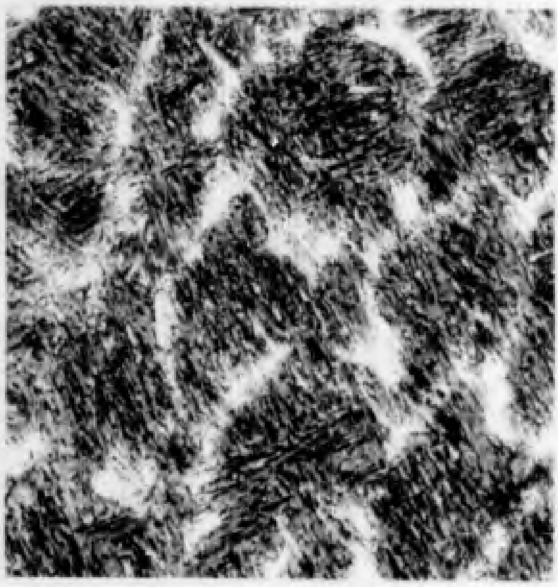
Center of Fusion Zone



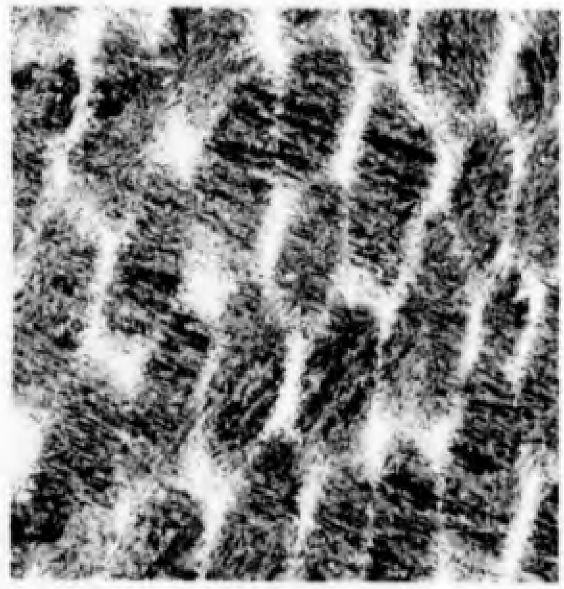
(c) 100X

Fusion Zone Heat Affected Zone

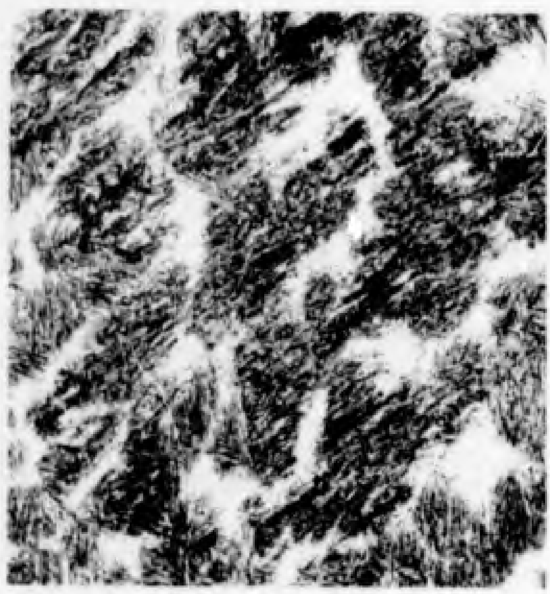
Figure 109. Microstructure of the Fusion Zone and Heat-Affected Zone of TIG Weld No. 0242 Made in HP 9-4-45 Plate. Weld Was Made at 10 ipm in Helium and Was Post-Heated (6 Hours) at 575°F. Etch: 2% Nital.



Top of Fusion Zone 500X

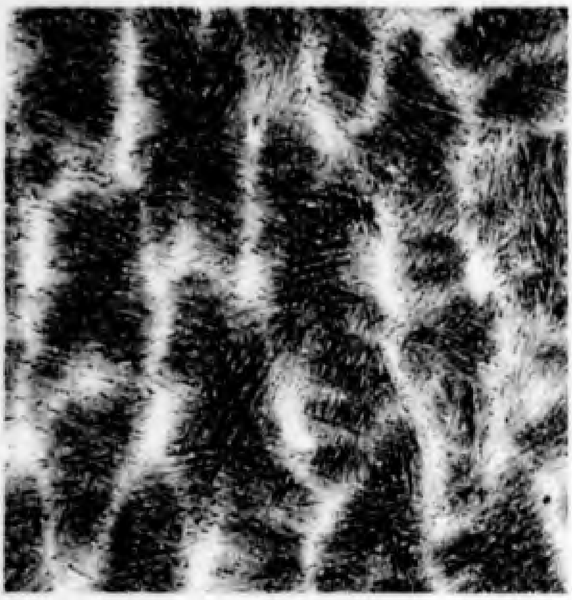


Center of Fusion Zone 500X

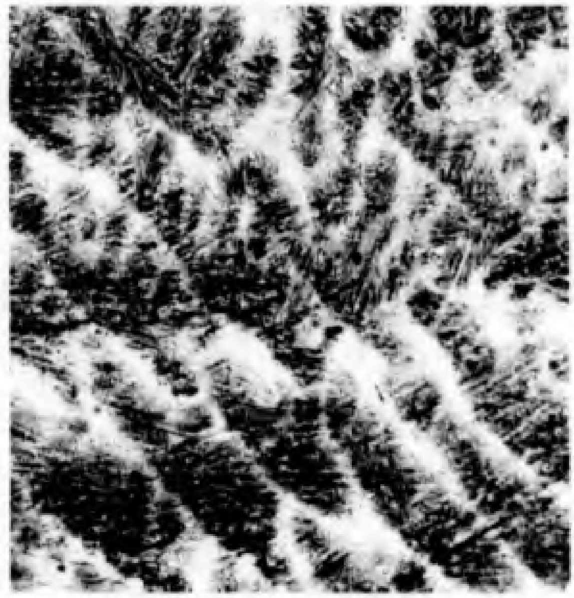


Bottom of Fusion Zone 500X

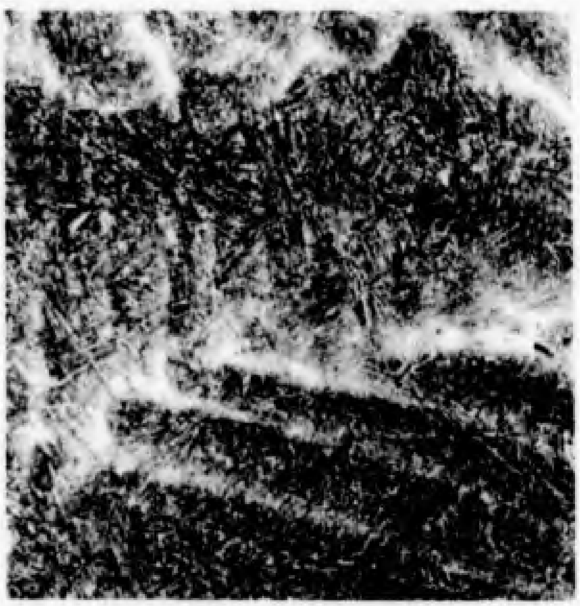
Figure 110. Microstructure of the Fusion Zone of TIG Weld No. 0260 Made in HP 9-4-45 1/2-Inch Plate Using a 500°F Pre- and Post-Heat. Post-Heat Was Held for 7 Hours. Etch: 2% Nital.



Top of Fusion Zone 500X

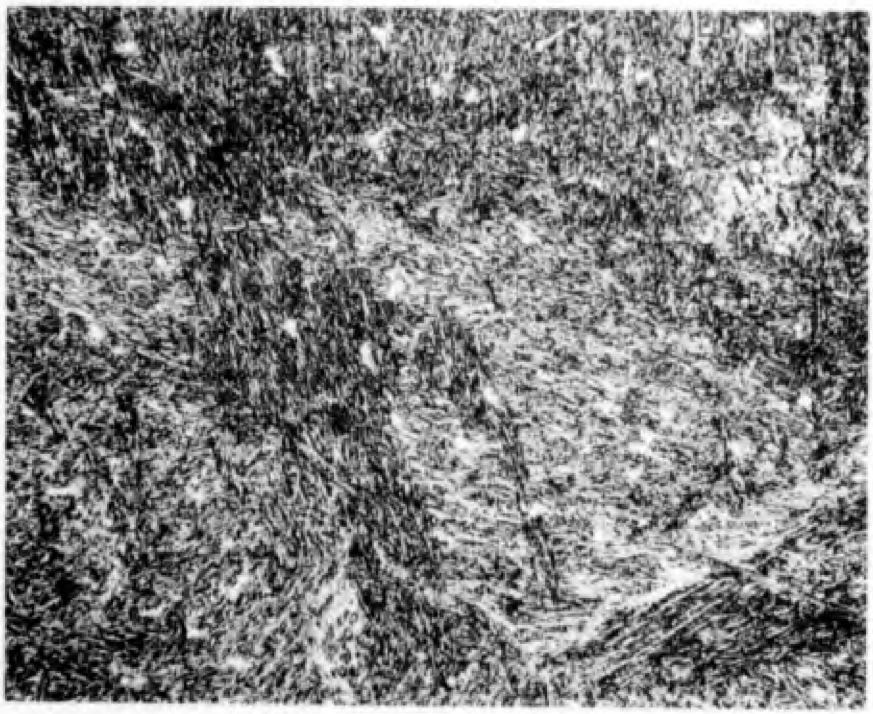


Center of Fusion Zone 500X



Bottom of Fusion Zone 500X

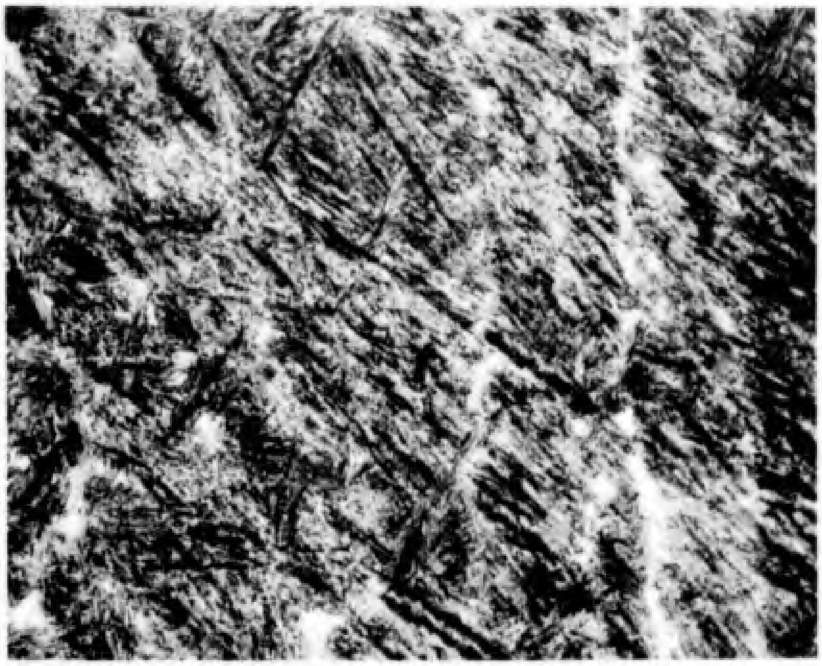
Figure 111. Microstructure of the Fusion Zone of TIG Weld No. 0264 Made in HP 9-4-45 1/2-Inch Plate Using a 475°F Pre- and Post-Heat. Post-Heat was Held for 7 Hours. Etch: 2% Nital.



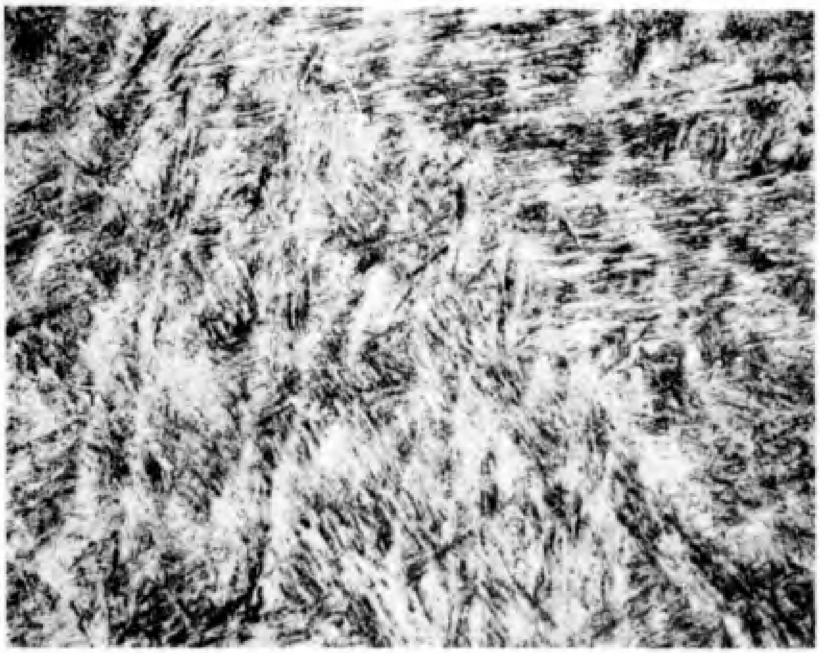
Top of Fusion Zone 500X

Center of Fusion Zone 500X

Figure 112. Microstructure of the Fusion Zone of TIG Weld No. 0271 Made in HP 9-4-45 1/2-Inch Plate Using a 440°F Pre- and Post-Heat. Post-Heat Was Held for 7 Hours. Etch: 2% Nital.



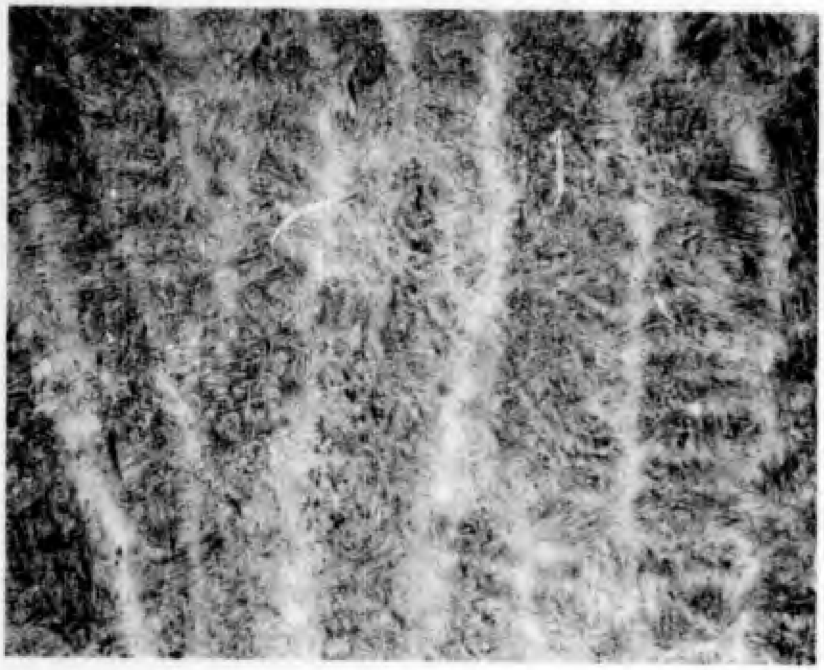
Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 113. Microstructure of the Top and Center of the Fusion Zone of Multipass TIG Weld No. 0296 Made in HP 9-4-45 1/2-Inch Plate. Weld Was Made at 10 ipm in Helium and Was Post-Heated at 525°F for 3 Hours. Etch: 2% Nital.

Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 114. Microstructure of the Top and Center of the Fusion Zone of Multipass TIG Weld No. 0275 Made in HP 9-4-45 1/2-Inch Plate. Weld Was Made at 10 ipm in Helium and Was Post-Heated at 525°F for 7 Hours. Etch: 2% Nital.

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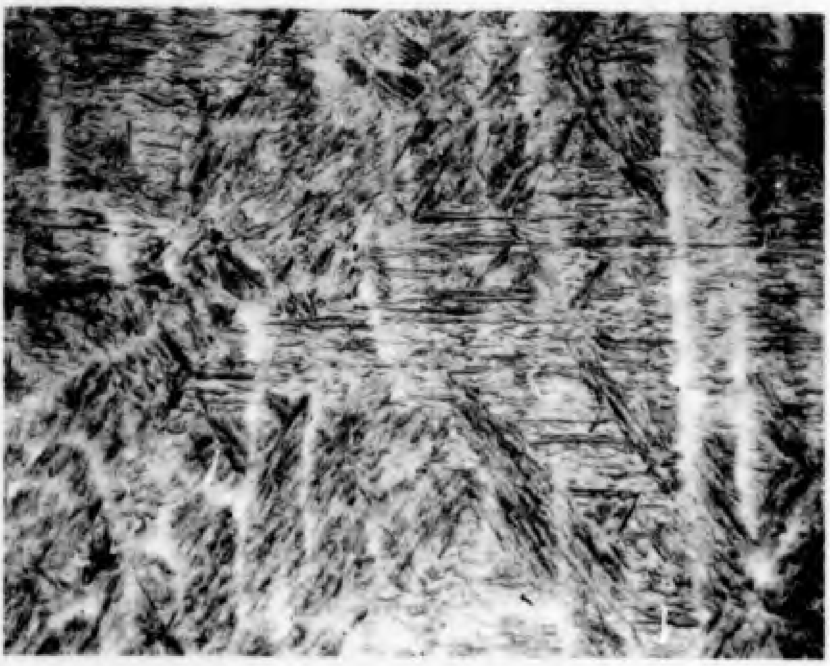
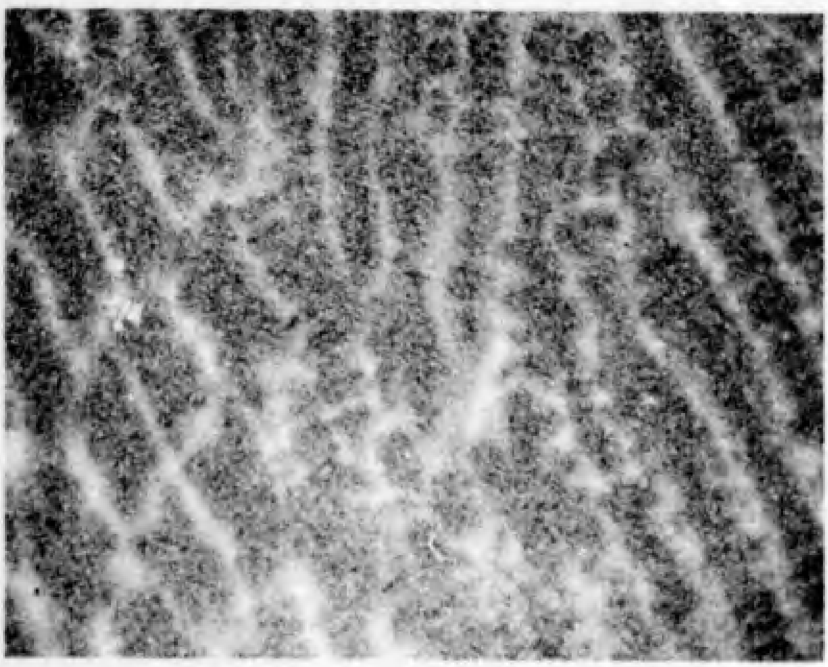


Top of Fusion Zone 500X



Center of Fusion Zone 500X

Figure 115. Microstructure (Martensite) of the Top and Center of the Fusion Zone of Multipass TIG Weld No. 0272 Made in HP 9-4-45 1/2-Inch Plate at 10 ipm in Helium. Weld Was Made with No Pre- or Post-Heat. Etch: 2% Nital.

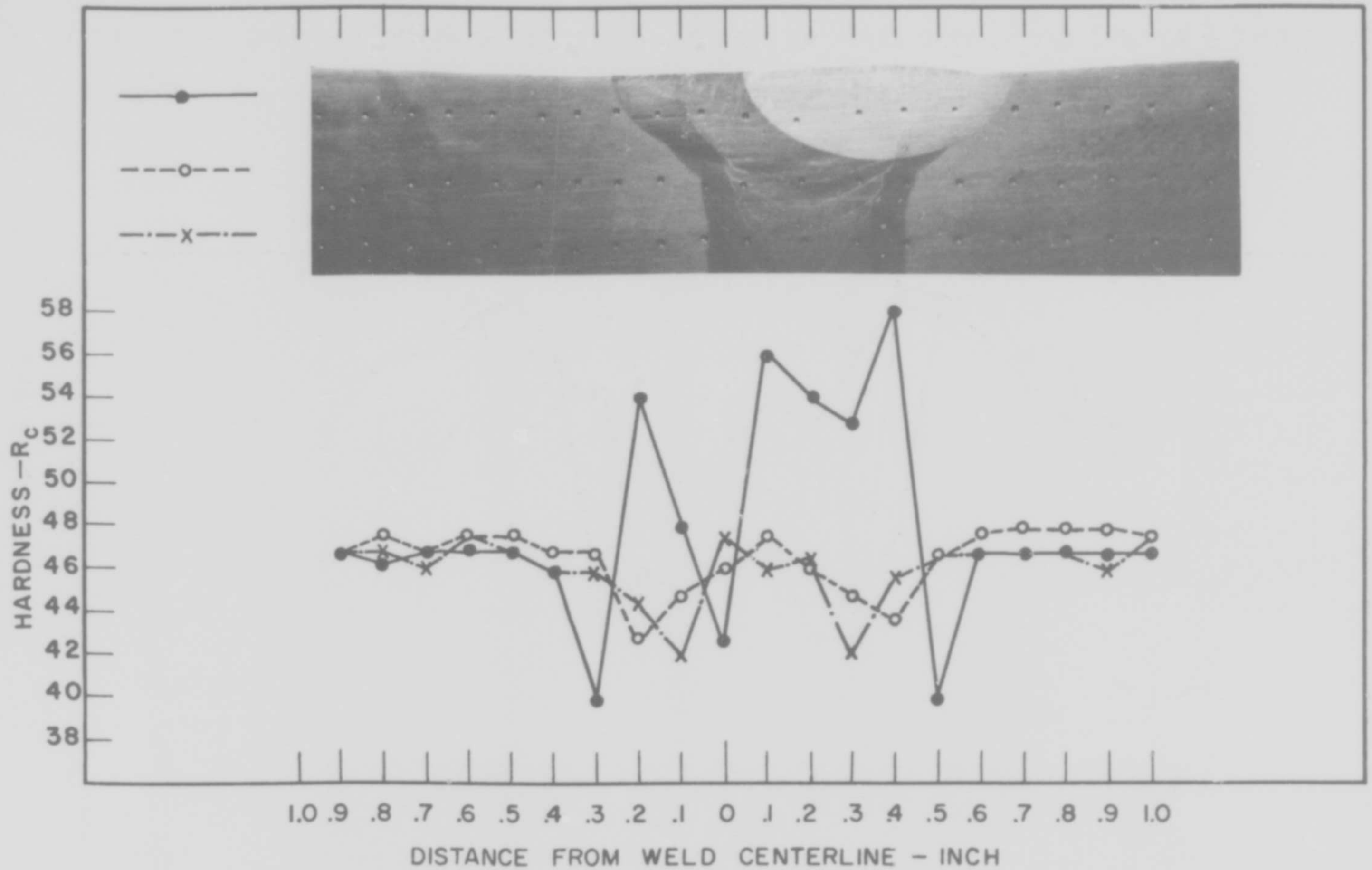


Figure 116. Hardness Survey of Multipass TIG Weld No. 0272 Made in 1/2-Inch HP 9-4-45 Plate Without a Pre- or Post-Heat.

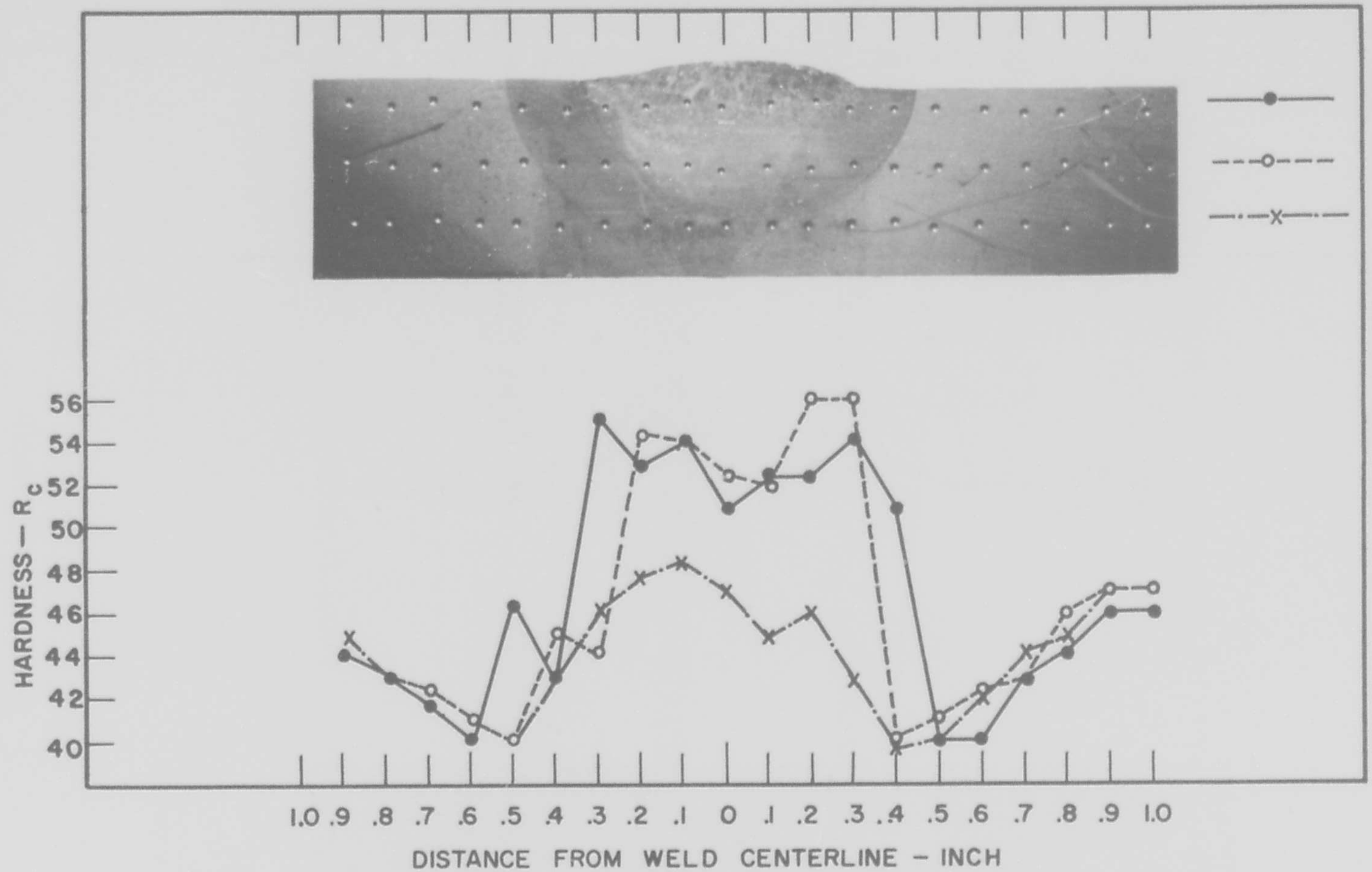


Figure 117. Hardness Survey of Multipass TIG Weld No. 0279 Made in 1/2-Inch HP 9-4-45 Plate Using a 300°F Pre- and Post-Heat.

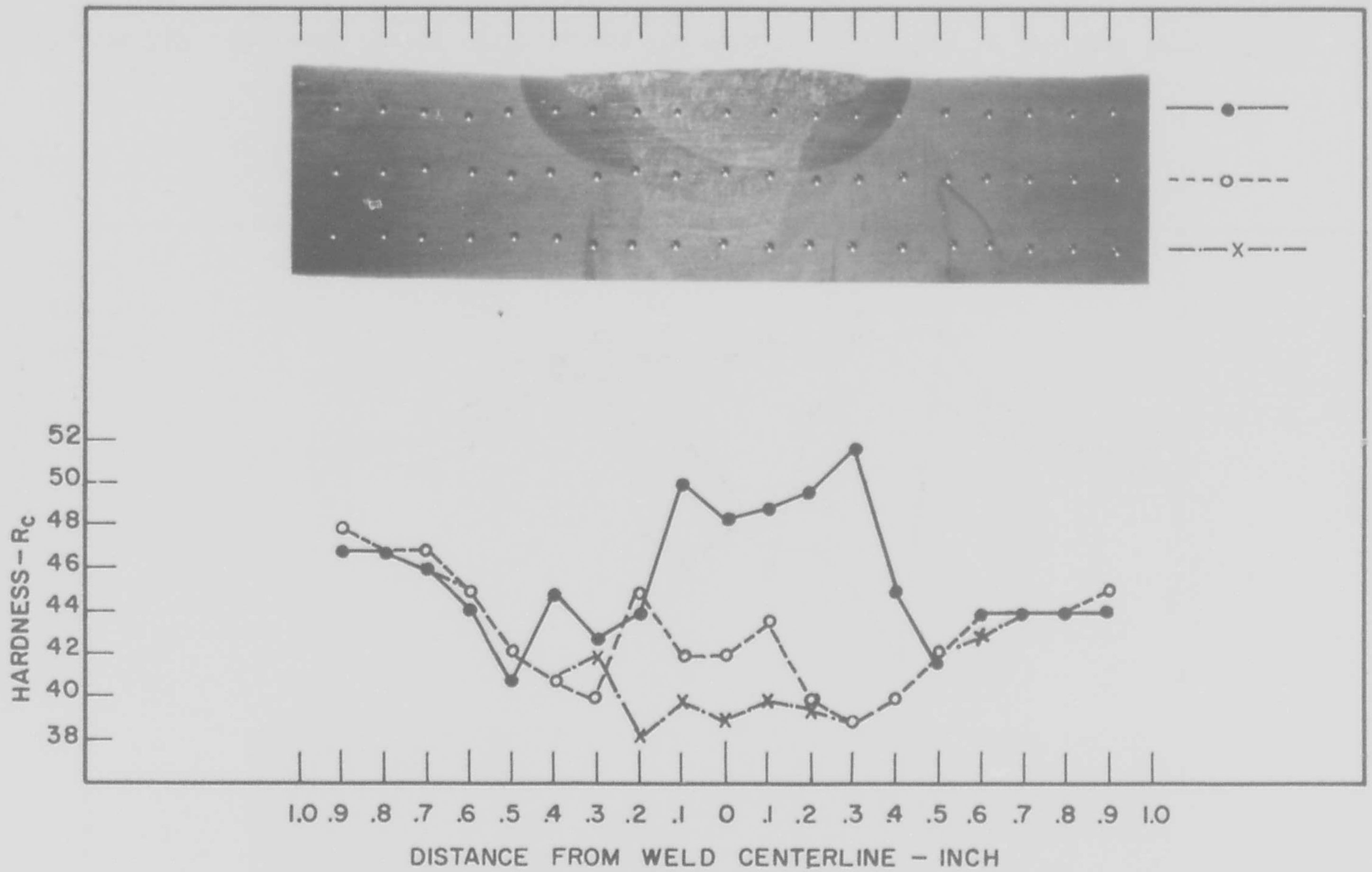


Figure 118. Hardness Survey of Multipass TIG Weld No. 0274 Made in 1/2-Inch HP 9-4-45 Plate Using a 375°F Pre- and Post-Heat.

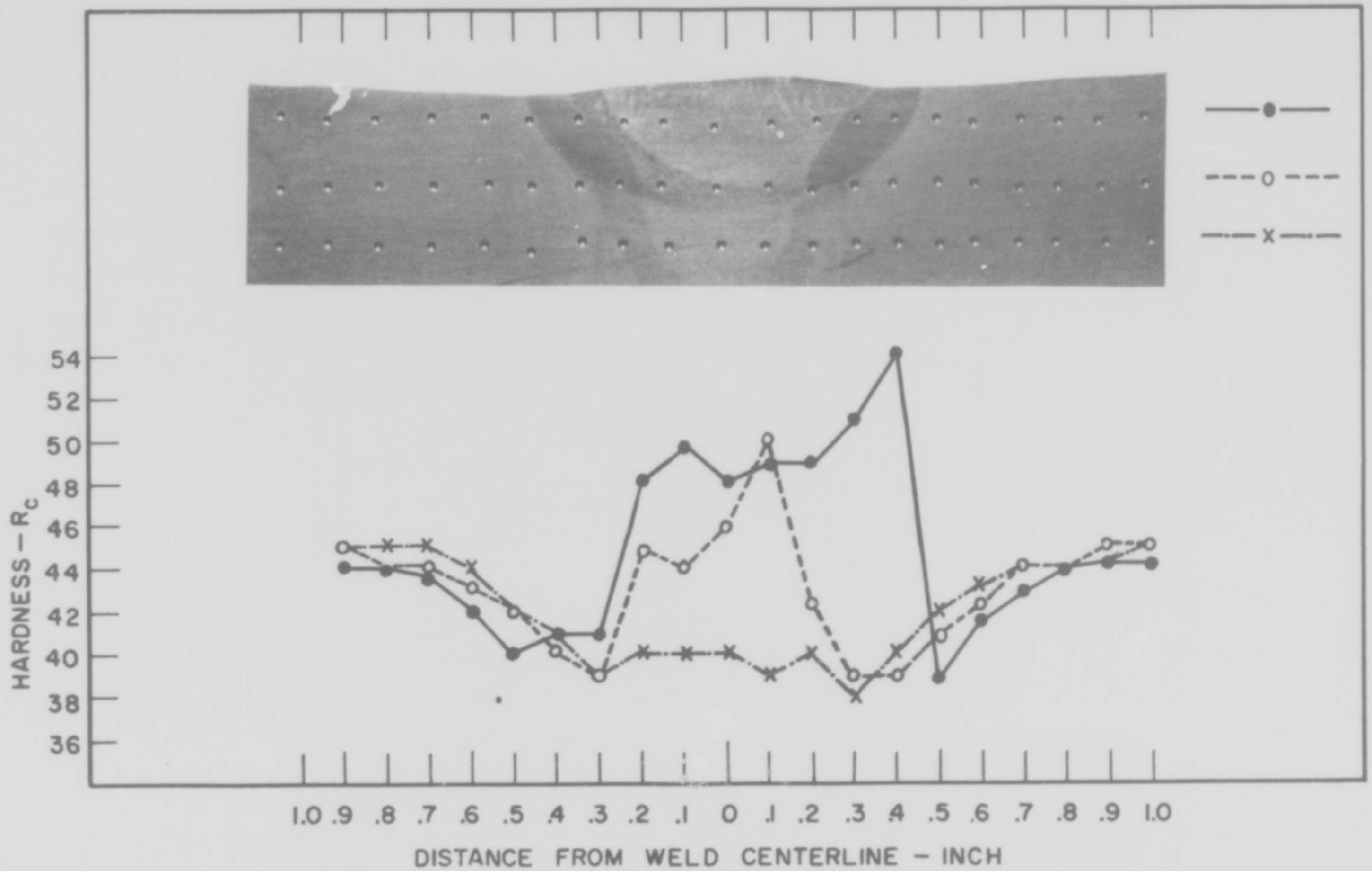


Figure 119. Hardness Survey of Multipass TIG Weld No. 0273 Made in 1/2-Inch HP 9-4-45 Plate Using a 400°F Pre- and Post-Heat.

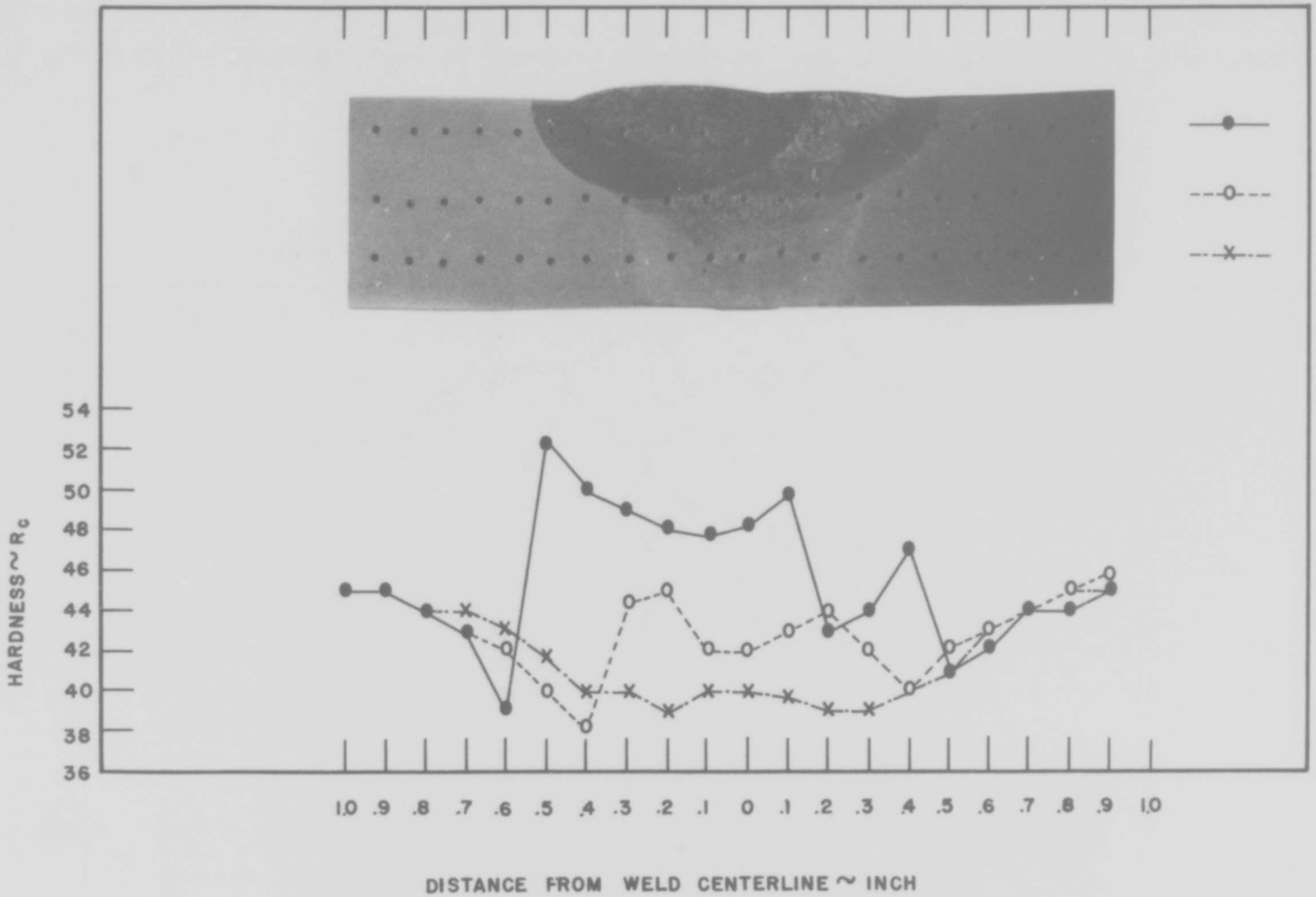


Figure 120. Hardness Survey of Multipass TIG Weld No. 0271 Made in HP 9-4-45 1/2-Inch Plate Using a 440°F Pre- and Post-Heat.

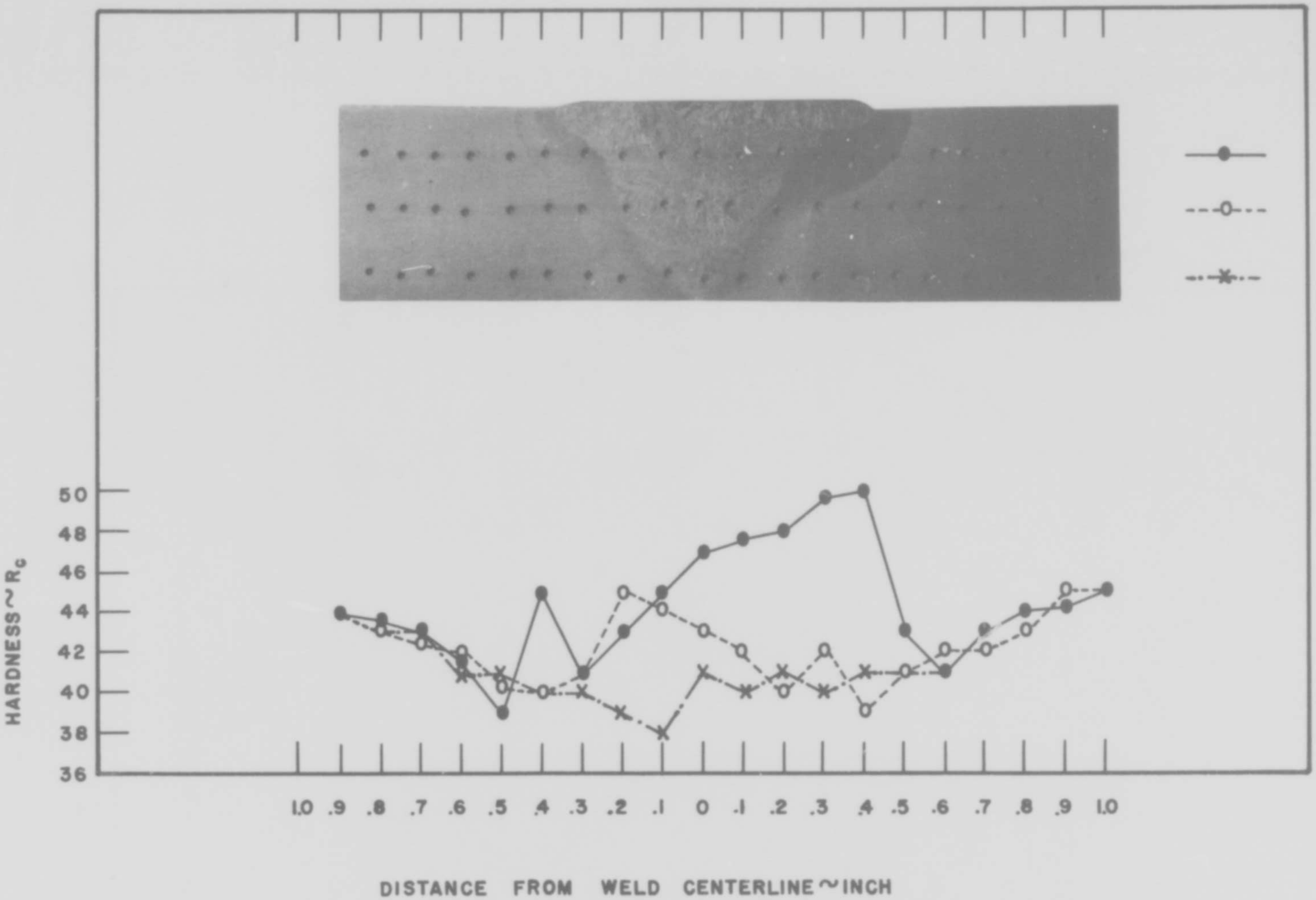


Figure 121. Hardness Survey of Multipass TIG Weld No. 0264 Made in HP 9-4-45 1/2-Inch Plate Using a 475°F Pre- and Post-Heat.

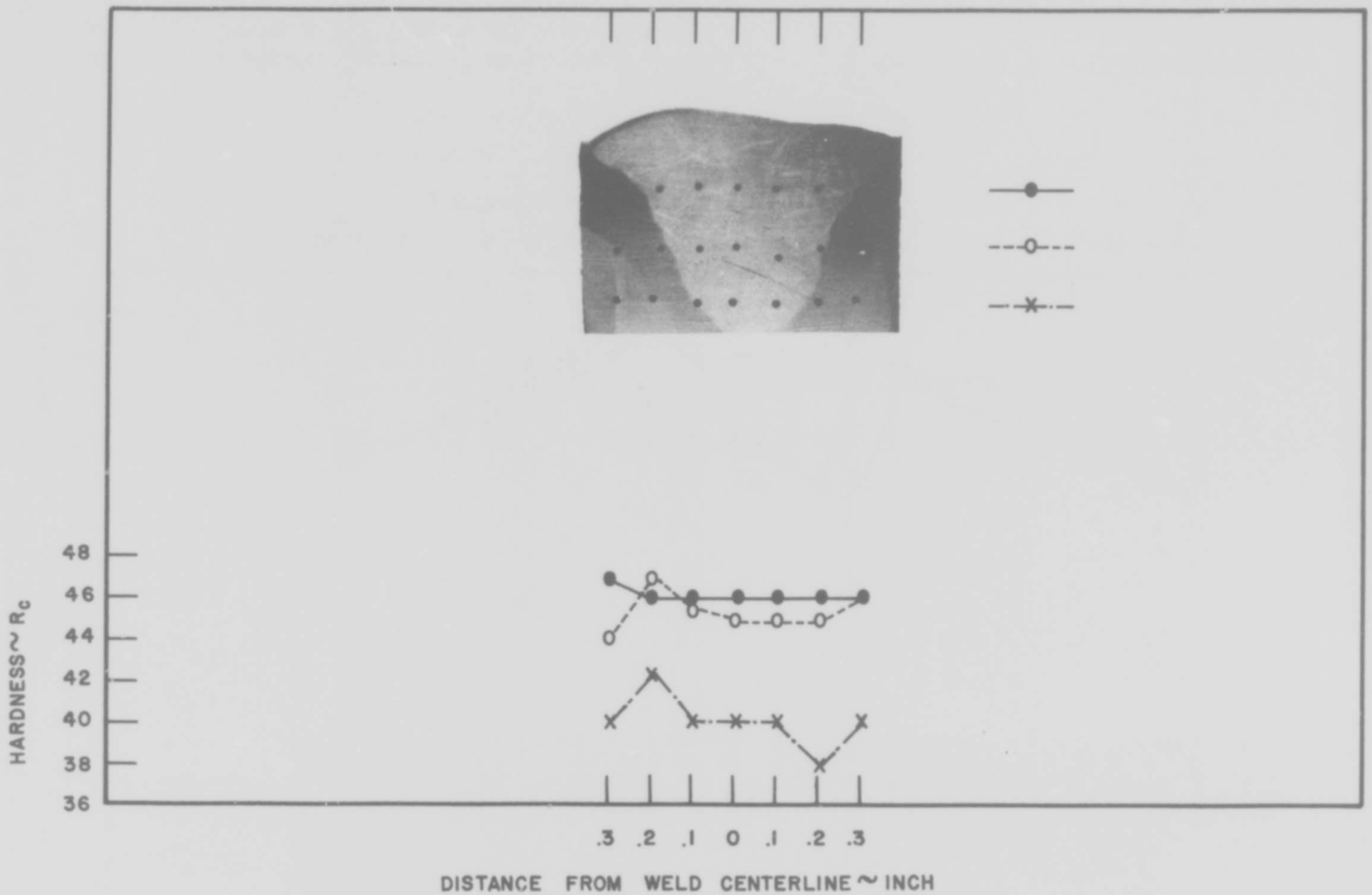


Figure 122. Hardness Survey of Multipass TIG Weld No. 0260 Made in HP 9-4-45 1/2-Inch Plate Using a Pre- and Post-Heat of 500°F.

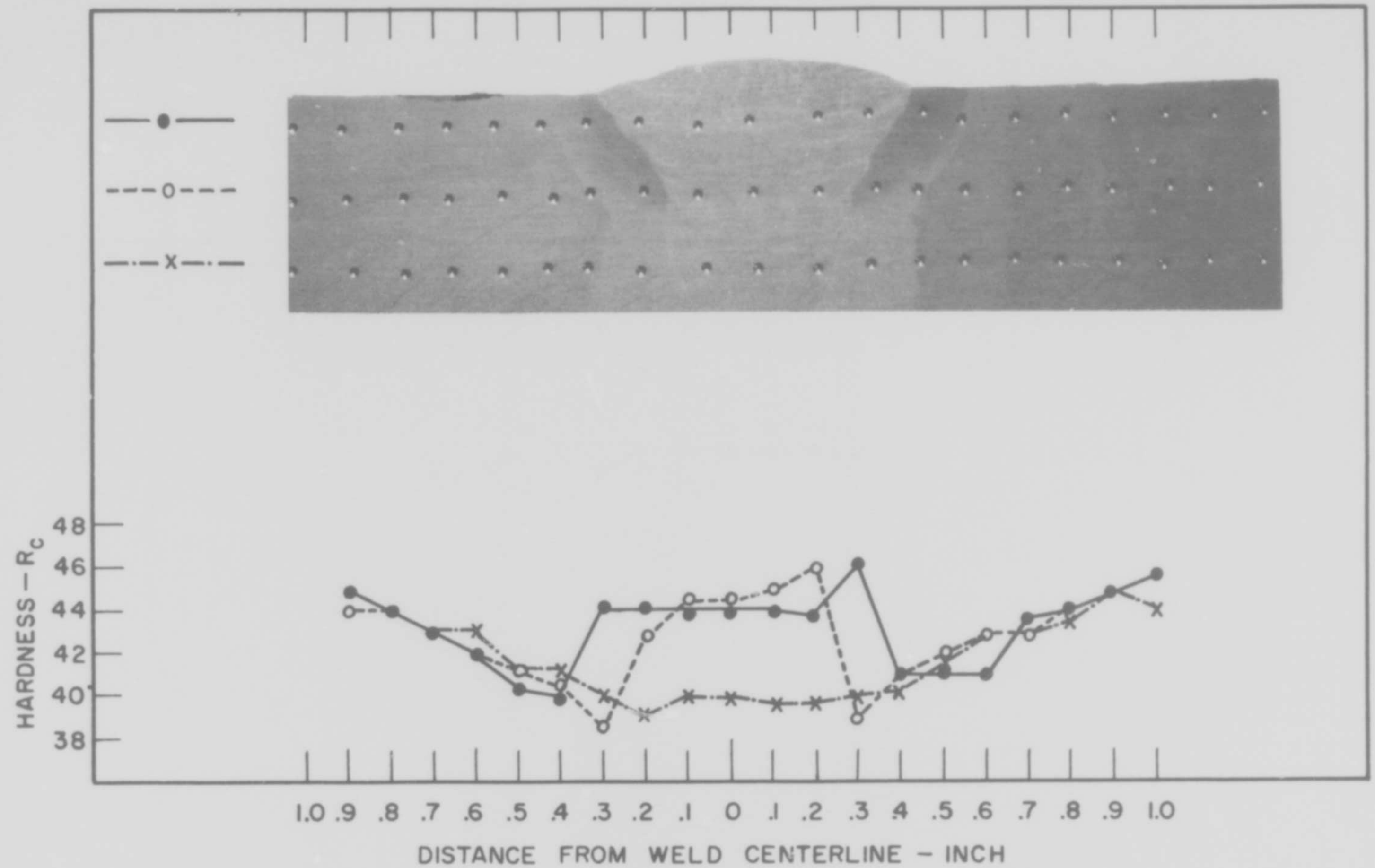


Figure 123. Hardness Survey of Multipass TIG Weld No. 0275 Made in HP 9-4-45 1/2-Inch Plate Using a 525°F Pre- and Post-Heat.

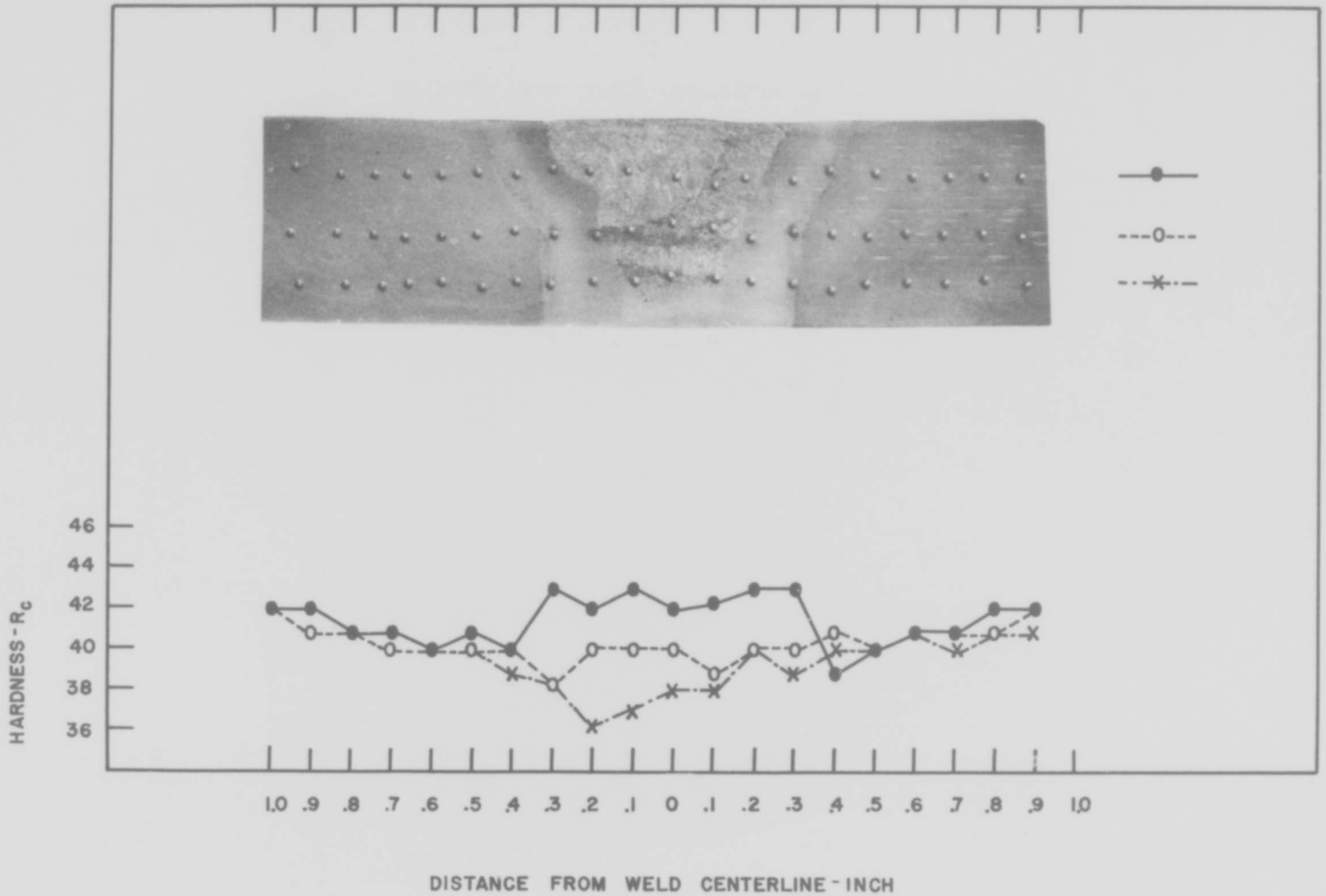


Figure 124. Hardness Survey of Multipass TIG Weld No. 0243 Made at 4 ipm in HP 9-4-45 Plate Using a 575°F Pre- and Post-Heat.

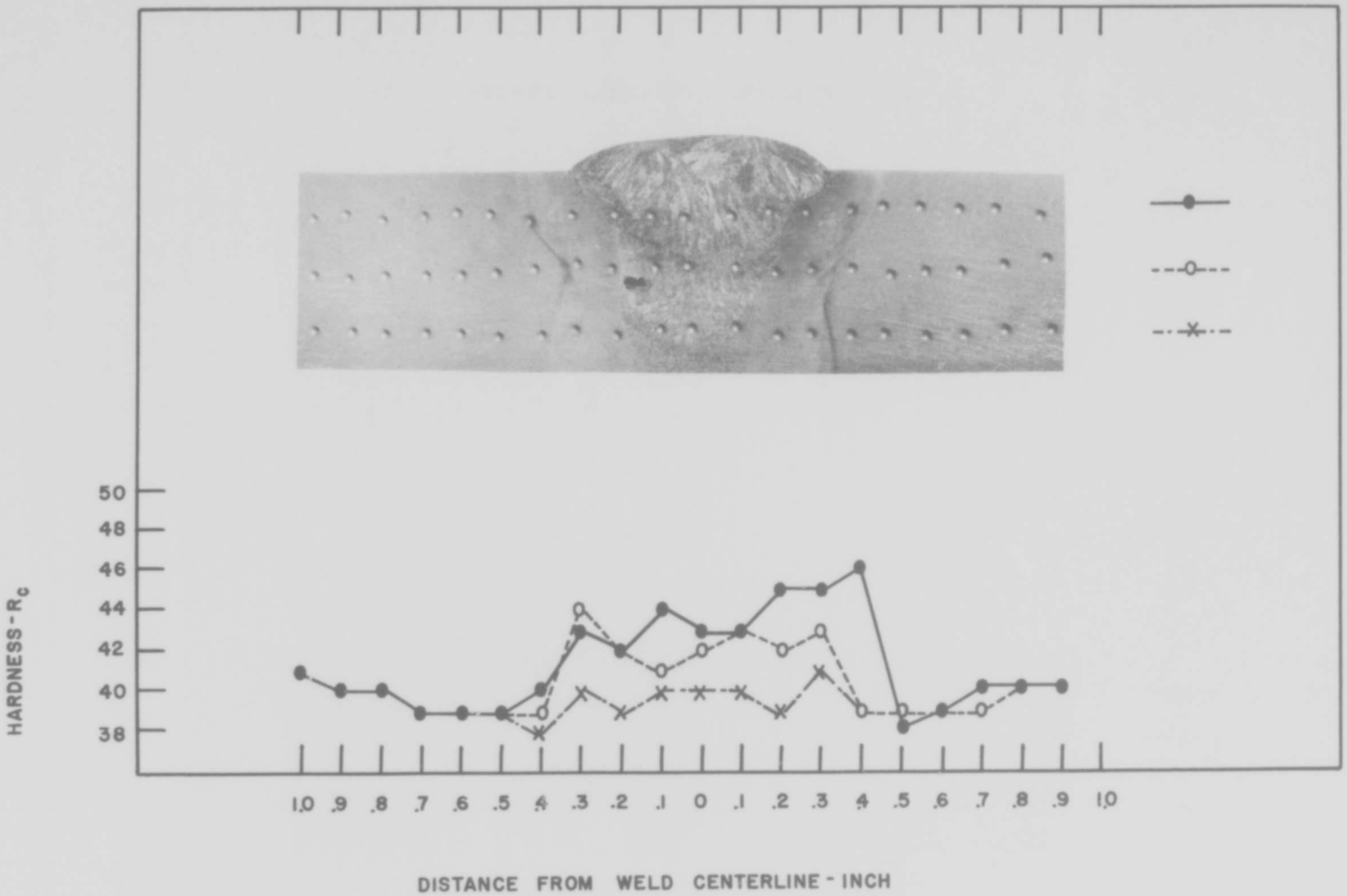


Figure 125. Hardness Survey of Multipass TIG Weld No. 0242 Made at 10 ipm in HP 9-4-45 Plate Using a 575°F Pre- and Post-Heat.

condition has low resistance to overtempering, as shown by the consistently low hardness in the heat-affected zones. In order to substantiate the overtempering tendency, 1/2-inch cubes of bainitic and martensitic HP 9-4-45 material of essentially the same hardness (R_c 46 and R_c 45, respectively) were held in a salt bath at 1200°F for times of 1 second, 30 seconds, 90 seconds, 900 seconds, and 10,800 seconds. The results of these tempering treatments are presented in Figure 126. From this graph, it is obvious that the bainitic structure softens at a more rapid rate than the martensite during the early stages of tempering (up to one minute). This is approximately the time interval that the heat-affected zone of a weld would remain in the tempering temperature range. However, for long times, the martensitic and bainitic structures approach the same hardness. This indicates that low energy inputs and extremely fast welding speeds would be essential to weld the bainitic material without heat-affected zone softening.

(4) Smooth Tensile Properties

The smooth tensile properties for welds made in bainitic HP 9-4-45 1/2-inch plate are presented in Table 47. The majority of these welds were made in an effort to determine the pre- and post-heat temperature which would result in the most desirable properties. Desirable yield, ultimate strength, and joint efficiency were obtained only from weld No. 0272. However, this weld was made with no pre- or post-heat and with weld interpass temperature maintained at room temperature. Therefore, an untempered martensitic weld deposit existed and the transverse ductility of this weld was quite low. None of the welds made using a pre- and post-heat treatment had desirable ultimate strength, yield strength, or joint efficiency. These results indicated that regardless of the post-heat used the average ultimate strength or yield strength joint efficiency did not differ significantly. Referring to Figure 126, where Rockwell C hardness is plotted against time at 1200°F, it can be predicted that regardless of welding parameter or pre- or post-heat temperatures, some point in the heat-affected zone would be exposed to the 1200°F temperature for sufficient time for softening to occur.

Based upon the mechanical properties shown, Table 47, a pre- and post-heat of 525°F was selected for making single U and double V joint welds in the HP 9-4-45 material. These results, shown for welds 306 and 307, respectively, indicate that the double U joint design resulted in slightly improved yield strengths, as shown by the yield strength joint efficiency of 92.6%. The results for a MIG weld made in this material are shown for weld No. 0300. The weld metal has low properties, 134.4 to 140.0 ksi yield strength. The transverse properties are similar to those observed for TIG welds.

In addition, specimens of the configuration shown in Figure 11 were machined from weld 0275. In these specimens, the parent metal B dimension was 0.252 inch square, and the weld heat-affected zone A dimension was 0.280 inch square. These dimensions represent a 23 percent increase in cross sectional area for the weld heat-affected zone area or an increase in thickness of approximately 1/8-inch over 1/2-inch thick parent metal. Thus, results of these specimens, designed to determine the amount of increase in section thickness for 100 percent joint efficiency, are presented in Table 48. Although each specimen fractured in parent metal, the average ultimate strength joint efficiency was only 96.96 percent, while the yield strength joint efficiency was 100 percent. It is not known whether the length of time the material was held

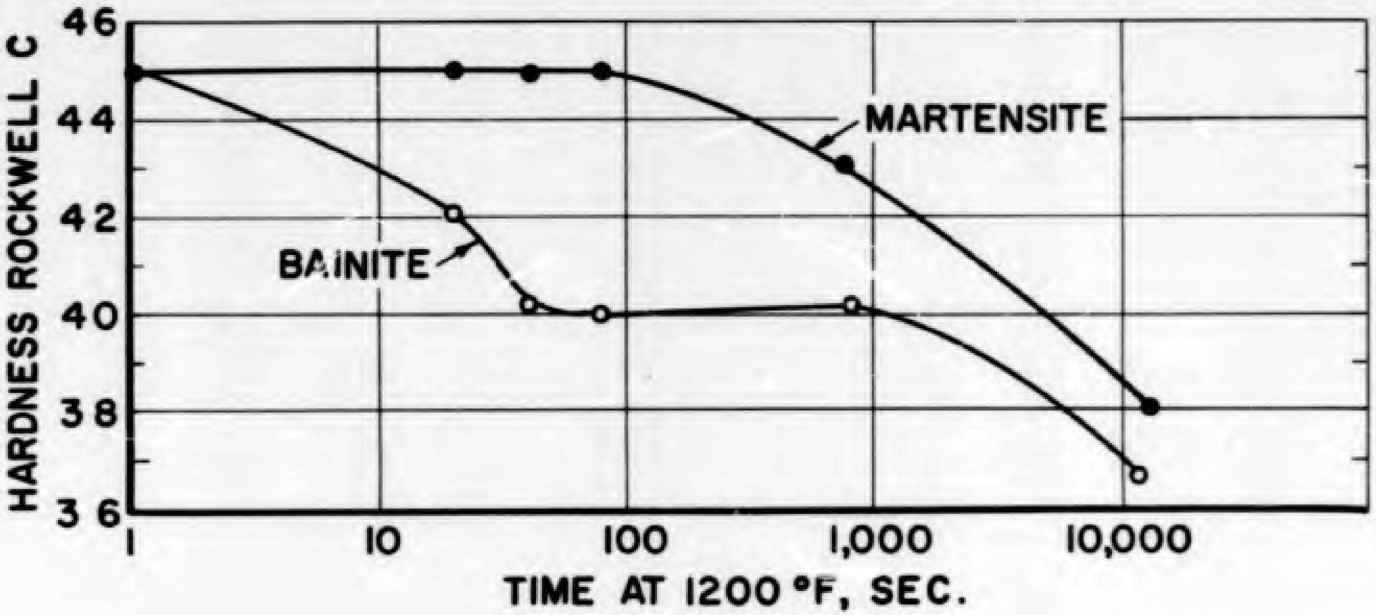


Figure 126. Softening With Increasing Time Interval at 1200°F of the Martensitic and Bainitic Structures of HP 9-4-45 Steel.

TABLE 47

TENSILE PROPERTIES OF TIG AND MIG WELDS MADE IN HP 9-4-45 1/2-INCH PLATE

Weld No.	Test Direction(a)	Filler Wire(b)	Welding Speed (ipm)	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elongation %(c)	R.A. (%)	Energy Input K-J/in./pass	% Joint Efficiency(d) Y.S.	% Joint Efficiency(d) U.T.S.	Comments
0272	L	17	10	201.3	241.3	13.0	32.4	24.8			No pre- or post-heat
	L	17	10	201.5	244.4	15.0	35.1	24.8			No pre- or post-heat
	T	17	10	192.5	207.5	2.5	12.6	24.8	99.8	92.7	(e) No pre- or post-heat
	T	17	10	193.5	207.5	2.5	13.4	24.8	100.0	92.7	(e) No pre- or post-heat
*0279	L	17	4	125.1	293.4	8.0	13.0	44.6			300°F post-heat 7 hours
	L	17	4	133.5	285.9	8.5	14.4	44.6			300°F post-heat 7 hours
	T	17	4	170.4	187.7	6.5	56.8	44.6	88.4	83.9	(f) 300°F post-heat 7 hours
	T	17	4	168.0	187.9	6.5	57.7	44.6	87.1	83.9	(f) 300°F post-heat 7 hours
0274	L	17	10	144.8	228.7	15.0	32.8	24.8			375°F post-heat 7 hours
	L	17	10	143.7	226.7	13.0	31.2	24.8			375°F post-heat 7 hours
	T	17	10	171.0	189.9	5.0	59.2	24.8	88.7	84.8	(e) 375°F post-heat 7 hours
0273	L	17	10	157.4	223.3	15.0	40.1	24.8			400°F post-heat 7 hours
	L	17	10	155.6	218.9	13.5	38.9	24.8			400°F post-heat 7 hours
	T	17	10	170.3	185.2	6.0	51.0	24.8	88.3	82.3	(f) 400°F post-heat 7 hours
	T	17	10	170.3	184.8	6.0	52.7	24.8	88.3	82.6	(f) 400°F post-heat 7 hours
0271	T	17	10	164.3	182.5	5.0	32.9	24.3	85.2	81.5	(e) 440°F post-heat 7 hours
	T	17	10	164.7	185.0	5.0	32.9	24.3	85.4	82.7	(e) 400°F post-heat 7 hours
0261	L	17	10	148.2	213.2	8.0	20.9	23.4			475°F post-heat 7 hours
	L	17	10	137.1	204.7	12.5	28.6	23.4			475°F post-heat 7 hours
0264	T	17	10	167.0	181.8	6.5	52.9	23.4	86.6	81.2	(f) 475°F post-heat 7 hours
	T	17	10	166.6	180.6	6.5	57.7	23.4	86.4	80.7	(f) 475°F post-heat 7 hours
0260	L	17	10	150.2	199.5	5.0	7.0	24.8			500°F post-heat 7 hours
0277	T	17	10	165.0	178.6	2.5	9.3	24.8	85.6	79.5	(g) 500°F post-heat 7 hours
	T	17	10	162.2	162.6	1.5	5.9	24.8	84.1	72.7	(g) 500°F post-heat 7 hours

TABLE 47 (CONTINUED)

Weld No.	Test Direction(a)	Filler Wire(b)	Welding Speed (ipm)	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elongation %(c)	R.A. (%)	Energy Input K-J/in./pass	% Joint Efficiency(d) Y.S.	U.T.S.		Comments
0275	L	17	10	162.4	212.1	16.0	53.4	24.8				525°F post-heat 7 hours
	L	17	10	157.2	207.1	13.5	35.1	24.8				Defect in specimen
	T	17	10	171.8	185.8	7.5	59.2	24.8	89.1	83.0	(f)	525°F post-heat 7 hours
	T	17	10	170.2	185.0	7.0	60.7	24.8	88.3	82.7	(f)	525°F post-heat 7 hours
0242	L	17	10	142.1	193.5	5.0	9.6	25.1				575°F post-heat 6 hours
	L	17	10	190.3	214.1	19.0	63.1	25.1				575°F post-heat 6 hours
	T	17	10	161.0	175.7	8.5	62.0	25.1	83.5	78.5	(h)	575°F post-heat 6 hours
	T	17	10	160.6	176.7	8.0	57.5	25.1	83.3	78.9	(h)	575°F post-heat 6 hours
0243	L	17	4	145.7	179.8	4.0	7.0	25.8				575°F post-heat 6 hours
	L	17	4	148.2	179.9	3.5	4.3	25.8				575°F post-heat 6 hours
	T	17	4	160.6	176.2	9.0	61.2	25.8	83.3	78.7	(h)	575°F post-heat 6 hours
	T	17	4	160.2	175.3	9.0	62.5	25.8	83.1	78.3	(h)	575°F post-heat 6 hours
0306	T	17	10	170.2	187.1	7.0	59.6	24.8	88.3	83.6	(f)	525°F post-heat 3 hours
	T	17	10	170.6	186.7	7.5	58.8	24.8	88.5	83.4	(f)	525°F post-heat 3 hours
0307	T	17	10	179.1	190.7	6.5	59.8	24.8	92.9	85.2	(f)	525°F post-heat 3 hours
	T	17	10	178.0	189.8	6.5	59.5	24.8	92.3	84.8	(f)	525°F post-heat 3 hours
x0300	L	17	17.4	134.4	192.3	8.5	13.1	24.8				525°F post-heat 3 hours
	L	17	17.4	140.0	200.9	10.0	24.1	24.8				525°F post-heat 3 hours
	T	17	17.4	166.2	182.3	6.5	59.6	24.8	86.2	81.5	(f)	525°F post-heat 3 hours
	T	17	17.4	166.2	183.1	6.5	57.3	24.8	86.2	81.8	(f)	525°F post-heat 3 hours

Notes: * Weld was made in argon.

x Weld was made by the MIG process.

(a) (L) specimens were taken parallel with the weld and consisted entirely of weld deposit.

(T) specimens were taken transverse to the weld and included weld, heat affected zones, and parent metal.

TABLE 47 (CONTINUED)

Notes: (Continued)

(b) Filler wire composition is presented in Table 2.

(c) (T) specimens had a gage length of 2 inches. (L) specimens had a gage length of 1 inch.

(d) Joint efficiency based on 192.8 and 223.8 ksi parent metal yield and ultimate strengths, respectively.

(e) Fracture occurred at the heat affected zone fusion line interface.

(f) Fracture occurred in the heat affected zone.

(g) Fracture occurred in the weld.

(h) Fracture occurred in the parent metal.

TABLE 48

TENSILE PROPERTIES OF WELD JOINT
EFFICIENCY TENSILE SPECIMENS

Specimen No.	Test Direction*	U.T.S. (ksi)	0.2% Y.S. (ksi)	Percent Elongation	R.A. (%)
1	T	216.7	203.4	18.7	59.2
2	T	216.9	200.0	21.2	61.1
3	T	216.8	204.6	19.6	60.2

*Test direction transverse to the weld and parallel to the plate rolling direction.

at 525°F during the welding operation caused lower ultimate tensile strength values. The hardness survey for weld 0275, Figure 123, indicates this same slight softening has occurred at least 1 inch from the weld centerline. In addition, the elongation and reduction of area of these specimens are considered desirable.

(5) Fracture Toughness

Only a few welds made in the HP 9-4-45 plate were examined for fracture toughness due to the generally low smooth tensile properties of the joints. Welds 0242 and 0243 were made under similar conditions excepting welding speed. As shown in Table 49, weld 0242 (welding speed = 10 ipm) had slightly higher K_{IC}* values. However, both welds were considered to have poor fracture toughness in comparison to the base metal (K_{IC} = 93.7 ksi $\sqrt{\text{inch}}$). Weld 0306, narrow V-joint and filler wire No. 17, exhibited somewhat higher K_{IC} values than the other weldments but still did not approach the parent metal toughness.

(6) Charpy Impact Properties

The V-notch impact properties of the HP 9-4-45 weld metal and heat-affected zone for TIG weld No. 0306 are presented in Table 50 and shown graphically in Figure 127 with the unaffected base metal properties. The weld metal impact strength was considerably lower than the plate, while the heat-affected zone impact strength was considerably greater than the plate. In general, the weld and heat-affected zone fracture ductility (lateral expansion) was greater than the parent metal.

The high impact energy absorption and high fracture ductility of the heat-affected zones are a reflection of the overtempering which also reduced strength and increased tensile ductility.

(7) Crack Susceptibility Test

A circular patch weld restraint specimen was made for the HP 9-4-45 material at 10 ipm using helium as the shielding gas. Filler wire No. 17 was evaluated for cracking tendency in this test. The weld was made using a 525°F pre-heat, and a weld interpass temperature of 525°F was maintained. The results of dye penetrant and radiographic inspection indicated that filler wire No. 17 was not susceptible to cracking when used for welding under the conditions described.

2. HP 9-4-45 Steel, 0.090-Inch Sheet

a. Base Metal Evaluation

The heat treatment of the HP 9-4-45 sheet was identical to that of the 1/2-inch plate of the same material (i.e., normalized at 1600°F for 1 hour, air cooled, austenitized at 1500°F in salt for 1 hour and austempered at 550°F for 7 hours. The inclusion content and the microstructure resulting from the above treatment are presented in Figures 128 and 129, respectively.

TABLE 49

CALCULATED FRACTURE TOUGHNESS, K_{IC}^*, OF TIG WELDS MADE IN 1/2 INCH HP 9-4-45 PLATE

(3-Point Loading)

Specimen Identity	Filler Wire(a)	Notch Position	Width, W (inch)	Thickness, B (inch)	Crack Depth, a (inch)	Major Span, L' (inches)	Curve Type(b)	Load (lbs.)	Relative Plastic Zone Size, ry/B(c)	σ_{nom}/σ_{ys}(d)	Calculated Fracture Toughness, K_{IC}^* (ksi $\sqrt{\text{inch}}$)
0242-1	16	HAZ	0.476	0.446	0.087	4.0	1	1435	0.004	0.77	46.6
-2	16	HAZ	0.475	0.446	0.085	4.0	1	1715	0.005	0.92	55.8
-3	16	Weld	0.478	0.446	0.058	4.0	1	2375	0.007	1.10	64.3
-4	16	Weld	0.475	0.446	0.075	4.0	1	1160	0.002	0.59	34.7
0243-1	16	HAZ	0.458	0.465	0.125	4.0	1	1200	0.004	0.85	51.0
-2	16	HAZ	0.458	0.466	0.062	4.0	1	1375	0.003	0.68	38.8
-3	16	Weld	0.458	0.466	0.104	4.0	1	1115	0.003	0.69	41.4
-4	16	Weld	0.458	0.464	0.097	4.0	1	1250	0.003	0.75	44.9
0306-1(e)	17	HAZ	0.484	0.492	0.086	7.0	1	2100	0.013	0.97	61.2
-2(e)	17	HAZ	0.484	0.492	0.075	7.0	1	2110	0.010	1.00	64.4
-3(e)	17	HAZ	0.484	0.492	0.081	7.0	1	2500	0.024	1.30	86.0
-4(e)	17	Weld	0.484	0.492	0.082	7.0	1	2150	0.015	1.07	58.5
-5(e)	17	Weld	0.484	0.492	0.099	7.0	1	1800	0.018	1.13	63.3

Notes:

(a) Filler wire compositions given in Table 2.

(b) Curve types are defined in Figure 16.

(c) Plastic zone size, r_y, equals the difference between the effective crack length a^* and the measured crack length a $(a^* = a + E\mathcal{G}/6\pi\sigma_{ys}^2)$.

(d) σ_{ys}/σ_{nom} = nominal stress at crack initiation divided by 0.2% yield strength.

(e) Four-Point Loaded.

TABLE 50

CHARPY V-NOTCH IMPACT PROPERTIES OF HP 9-4-45
WELD METAL AND HEAT AFFECTED ZONES
FOR TIG WELD NO. 0306

Identification	Notch Location	Test Temp. (°F)	Impact Energy (Ft. lb)	Lateral Expansion (Mils)
0306-1	Weld	Room	17.5	9.0
0306-2	"	0	14.0	7.5
0306-3	"	-100	9.0	3.0
0306-4	"	"	7.0	1.5
0306-5	"	-320	4.0	0.5
0306H-1	HAZ	Room	35.0	21.5
0306H-2	"	0	38.5	21.5
0306H-3	"	-100	25.0	10.5
0306H-4	"	"	27.5	12.0
0306H-5	"	-320	21.5	3.0

Note: Lateral expansion measured at base of fracture.

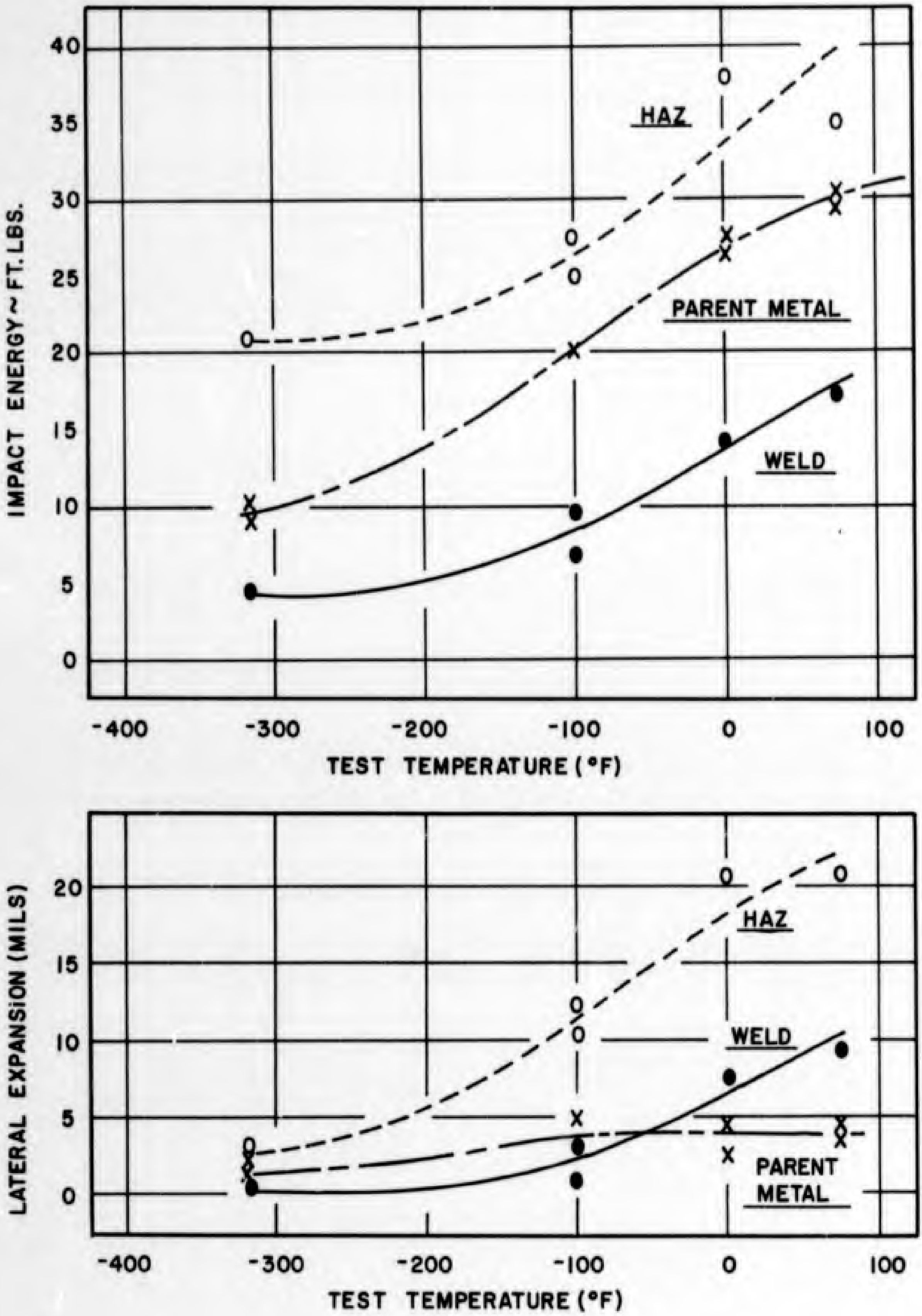
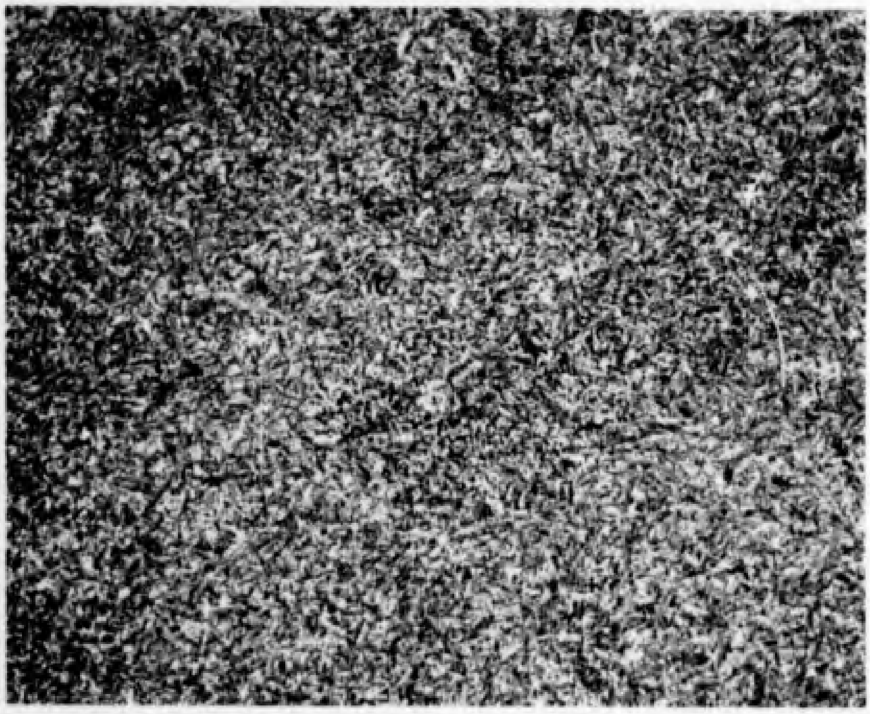


Figure 127. Charpy V-Notch Impact Properties of Bainitic HP 9-4-45 Weld Metal and Heat Affected Zones for TIG Weld No. 0306.

(a) Parallel to Rolling Direction 100X

(b) Perpendicular to Rolling Direction 100X

Figure 128. Unetched HP 9-4-45 0.090 Inch Sheet Showing Inclusion Levels



0.090 Inch Sheet 500X

Hardness: R_c 46

Figure 129. Microstructure (Bainite) of HP 9-4-45 Sheet Normalized 1600°F/1 Hour, Air Cooled, Austenitized 1500°F/1 Hour, Salt Quench to 550°F/7 Hours, Air Cooled.

The inclusion content was found to be quite high; however, no stringers were present and the inclusions were generally spheroidal in shape. Thus, no serious impairment of the base metal was expected due to the inclusions.

The smooth tensile properties of the base material are presented in Table 51. Although the heat treatment was identical to that of the 1/2-inch plate, the resultant strength was somewhat below that of plate but did meet the program requirements. This difference in strength was believed to be caused by a slight decarburized layer at the surface approximately 0.005-inch deep.

The fracture toughness of the sheet material was determined using fatigue and precracked center-notch tensile specimens. The material was found to have good toughness ($K_{IC}^* = 81.2$ ksi $\sqrt{\text{inch}}$), as shown in Table 52.

b. Evaluation of TIG Welds in 0.090-Inch Sheet

Gas tungsten-arc welds were made in 0.090-Inch HP 9-4-45 sheet at 4, 10, and 15 ipm using either helium or argon gas shielding and a 525°F pre- and post-heat treatment held for 2 hours. Fusion welding parameters for these welds are presented in Table 53.

(1) Weld Quality

Welds made at 4 and 10 ipm were generally sound and free from porosity. Weld No. P318 made at 4 ipm in helium contained one spot of porosity, and weld No. P316 made at 10 ipm in argon contained two small spots of porosity at the edges of the fusion zone. Welds P315 and P314 made at 15 ipm in argon and helium, respectively, contained appreciably more porosity.

(2) Weld Microstructure

The microstructure of TIG welds made in 0.090-inch HP 9-4-45 sheet at welding speeds of 4, 10, and 15 ipm are presented in Figures 130, 131, and 132, respectively. These structures appear to be primarily bainite with evidence of a second phase present. The cellular growth pattern is more evident in welds made using helium gas shielding than for welds made using argon shielding. In general, welds made using argon shielding were made with a slightly higher energy input than those made in helium. This slower cooling rate could produce a more homogeneous structure.

(3) Tensile Properties

The smooth tensile properties of all weldments were determined and are presented in Table 54. The general weakness of the heat-affected zones was again observed as it was in the 1/2-inch plate. Even though all failures occurred in the heat-affected zones, the weldments made at 4 ipm in helium or argon and at 10 ipm in helium (welds P318, P319, and P317, respectively) exhibited yield strengths comparable or higher than the parent metal. However, the lack of ductility (a maximum of 4 percent elongation) was completely undesirable.

TABLE 51

SMOOTH TENSILE PROPERTIES OF HP 9-4-45 STEEL 0.090 INCH SHEET

Specimen Identity	Test[a] Direction	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elong. (%)
1	T	180.6	203.1	9.5
2	T	181.8	204.9	9.0

(a) Test direction relative to rolling direction:
(T) Transverse direction

TABLE 52

CALCULATED PLANE STRAIN FRACTURE TOUGHNESS OF HP 9-4-45 0.090 INCH SHEET

(Center-Notched Tensile Specimen)

Specimen Identity	Width, W (inch)	Thickness, B (inch)	Crack Length, $2a_o$ (inch)	Curve Type(b)	Load (lbs.)	σ_{nom}/σ_{ys}	Calculated Plane Strain Fracture Toughness, K_{IC}* (ksi $\sqrt{\text{inch}}$)
1	1.779	0.087	0.746	1	9000	0.32	81.6
2	1.805	0.087	0.750	1	9100	0.32	80.7

Note: (a) Curve types are defined in Figure 16.

TABLE 53

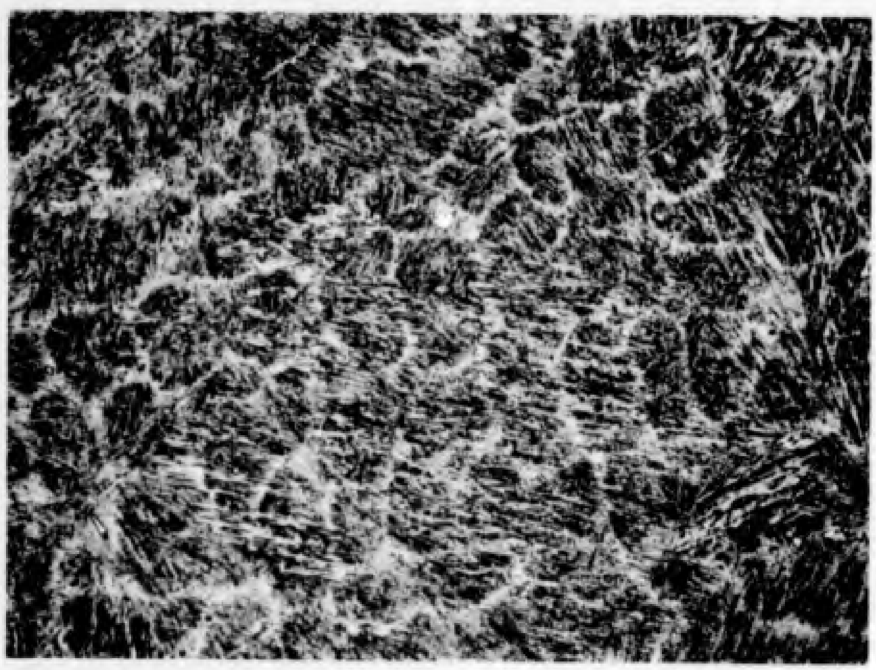
FUSION WELDING PARAMETERS FOR TIG WELDS MADE IN 0.090 INCH HP 9-4-45 SHEET

Weld No.	Filler Wire Diameter (inch)	Wire Composition[a]	Pre- and Post-Heat (°F)	No. Passes	W/S ipm	Wire Speed (ipm)	Amps	Volts	GAS (cfh) Torch	Backup	Comments[b]
P314	0.062	17	525	1	15	20.0	160	13	50 He	5 He	8 Spots Sidewall Por.
P315	0.062	17	525	1	15	20.0	205	11	35 A	3 A	13 Spots Sidewall Por.
P316	0.062	17	525	1	10	6.6	120	10	35 A	3 A	2 Sm. Sp. Sidewall Por.
P317	0.062	17	525	1	10	6.6	85	14	50 He	5 He	
P318	0.062	17	525	1	4	6.0	50	13	50 He	5 He	1 Spot Porosity
P319	0.062	17	525	1	4	6.0	90	8	35 A	3 A	

Notes: (a) Filler wire composition presented in Table 2.

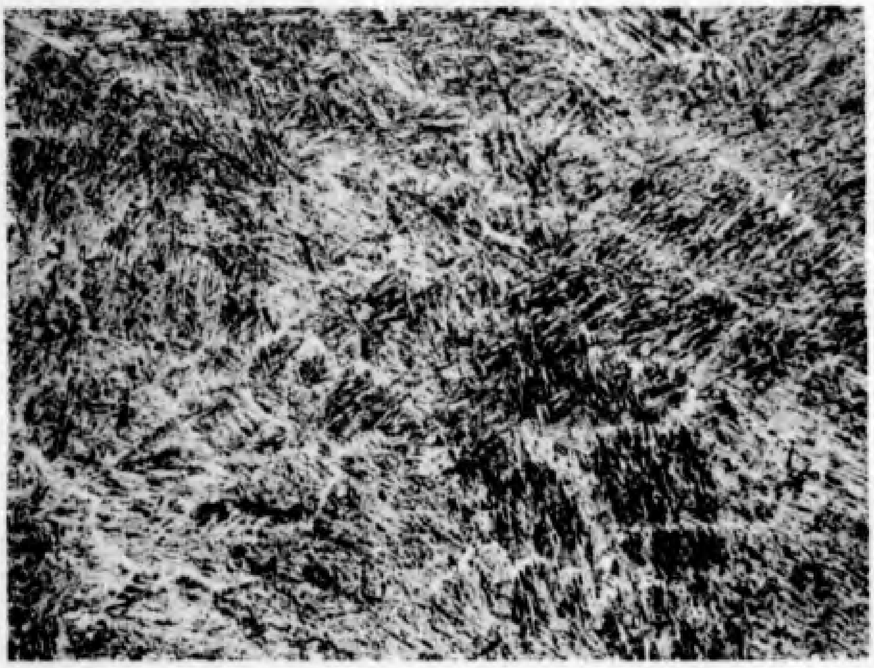
(b) Weld quality comments based upon radiographic inspection.

(a) Argon Shielded Weld P319 500X



(b) Helium Shielded Weld P318 500X

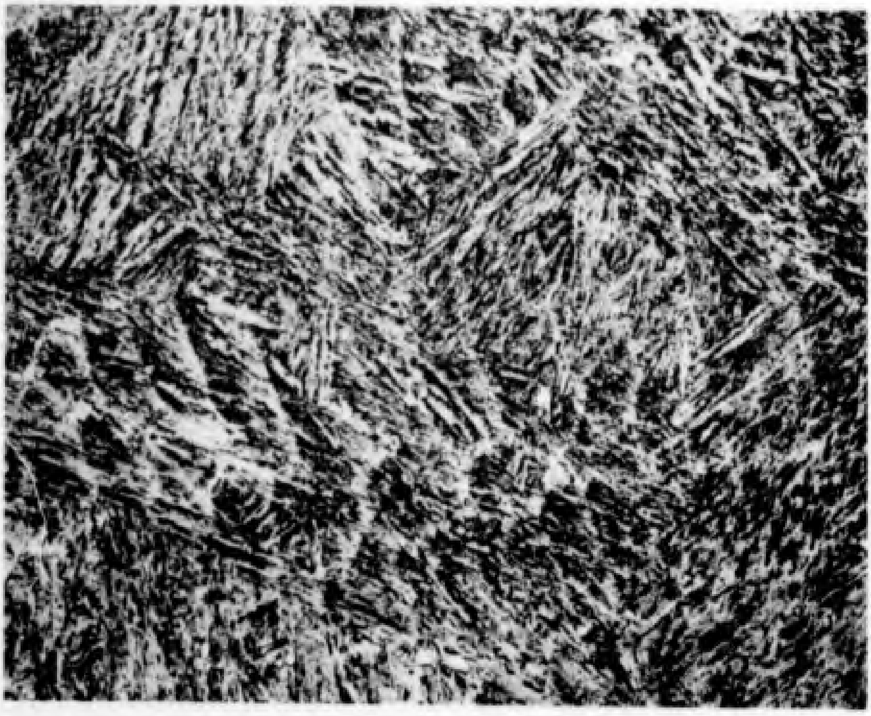
Figure 130. Microstructure of the Fusion Zone of Single Pass TIG Welds Made in HP 9-4-45 0.090 Inch Sheet at 4 ipm Using Filler Wire No. 17. Etch: 2% Nital.



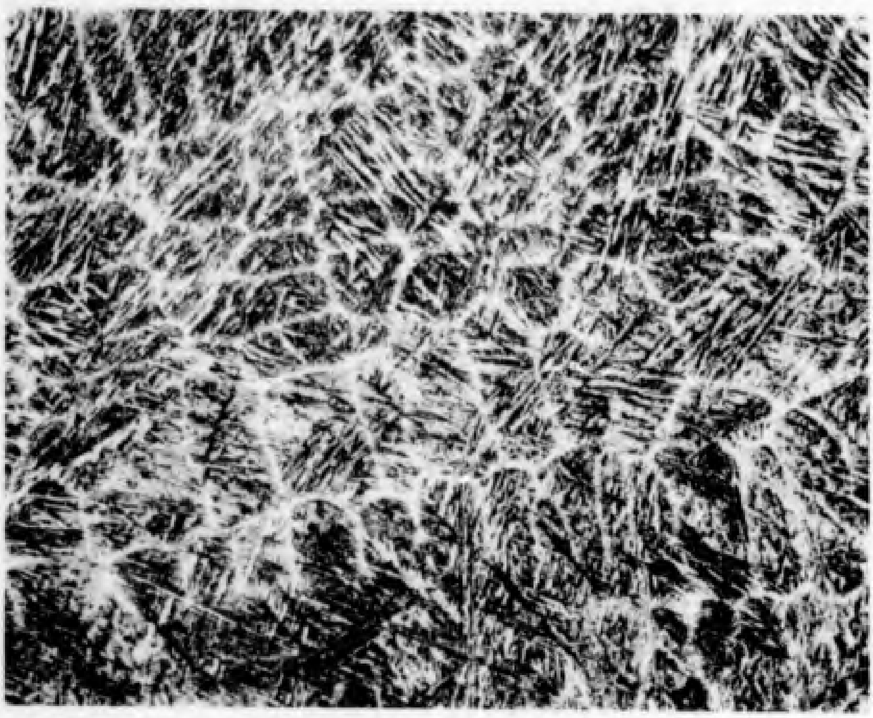
(a) Argon Shielded Weld P316 500X

(b) Helium Shielded Weld P317 500X

Figure 131. Microstructure of the Fusion Zone of Single Pass TIG Welds Made in HP 9-4-45 0.090 Inch Sheet at 10 ipm Using Filler Wire No. 17. Etch: 2% Nital.



(a) Argon Shielded Weld P315 500X



(b) Helium Shielded Weld P314 500X

Figure 132. Microstructure of the Fusion Zone of Single Pass TIG Welds Made in HP 9-4-45 0.090 Inch Sheet at 15 ipm Using Filler Wire No. 17.

TABLE 54

TRANSVERSE TENSILE PROPERTIES OF TIG WELDS MADE IN 0.090 INCH HP 9-4-45 STEEL SHEET

Weld No.(a)	Filler Wire(b)	Shielding Gas	Welding Speed (ipm)	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elong. (% 1")	% Joint Efficiency(c) Y.S.	U.T.S.	Comments
318	17	He	4	178.3	190.3	4.0	98.0	93.0	(d)
				189.6	198.6	4.0	100.0	97.0	(d)
319	17	A	4	184.0	198.7	2.5	100.0	97.0	(d)
				180.2	196.0	3.0	99.0	96.0	(d)
316	17	A	10	180.4	189.2	4.0	99.0	93.0	(d)
				173.0	189.9	4.0	95.0	93.0	(d)
317	17	He	10	190.3	204.4	4.0	100.0	100.0	(d)
				193.8	208.5	4.0	100.0	100.0	(d)
314	17	He	15	173.6	186.3	2.0	96.0	91.0	(d)
				178.4	194.0	3.0	99.0	95.0	(d)
315	17	A	15	165.3	180.2	3.0	91.0	88.0	(d)
				166.7	181.1	4.0	92.0	89.0	(d)

(a) All weldments pre- and post-heated at 525°F for 3 hours.

(b) Filler wire composition is presented in Table 2.

(c) Joint efficiencies based upon parent metal ultimate and 0.2% yield strengths of 204 ksi and 181.2 ksi, respectively.

(d) Failure occurred in heat affected zone.

(4) Fracture Toughness

Center-notched tensile specimens were examined to determine the plane strain fracture toughness of TIG welds made in HP 9-4-45 0.090-inch sheet. As indicated in Table 55, the weld deposit made at 15 ipm in helium (weld No. P314) possessed a K_{IC}* comparable to that of the parent metal. Good toughness values were also obtained in the weld deposits of P315 and P318 (15 ipm in A and 4 ipm in He, respectively). It was generally noted that the K_{IC}* of the heat-affected zones was less than that of the weld deposit and that argon shielding produced lower toughness than did helium at the same welding speed.

c. General Discussion

The smooth tensile properties of the HP 9-4-45 base material austempered at 550°F for 7 hours were satisfactory with regard to the criteria for the program. In addition, the plane strain fracture toughness was comparable to that of the HP 9-4-20 martensitic material; however, these values were less than those observed for the HP 9-4-25 1-inch plate heat treated to the martensitic condition. The Charpy impact properties were considered satisfactory, but the lateral expansion was considered poor. Although desirable smooth tensile properties were not obtained in TIG or MIG weldments, it was calculated that a 25 percent increase in the weld heat-affected zone area for a distance of 1-inch on either side of the weld centerline would cause fracture to occur in parent metal. However, the poor fracture toughness values observed for the weld and heat-affected zone, coupled with poor resistance to overtempering, make this material unattractive for this program.

3. D6AC Steel, 1/2-Inch Plate

a. Base Metal Evaluation

The heat treatment for the D6AC material was selected on the basis of laboratory heat treatments. The metallographic M_s temperature was determined by the Greninger and Troiano quench and temper technique[14]. The results of these studies are summarized in Figure 133(a) to (c). At 500°F, a significant amount of tempered martensite is present, and at 550°F this amount decreases; while at 600°F, only a small amount is present. On this basis of these results and work done by Emmerich and Nippes[15], the metallographic M_s temperature was defined as being between 600 and 625°F, and the transformation temperature was selected at 625°F. To determine the time necessary for complete transformation to lower bainite 1/2-inch cubes were austempered for times ranging from 10 minutes to 3 hours. The microstructures resulting from these heat treatments are presented in Figure 134(a) to (c). After 10 minutes transformation has progressed approximately 40 percent, and at 30 and 120 minutes is almost complete. Based upon these results, a transformation temperature of 625°F and a time of 4 hours was selected as the heat treatment. However, as will be discussed in a later section, a complete transformation was not realized, and smooth tensile properties were low with regard to those desired for the program. Additional work to determine the proper heat treatment for D6AC material consisted of heat treating tensile blanks by austempering at 1650°F for 1 hour and quenching directly into a salt bath at temperatures of 575, 650 and 725°F. Specimens were held at 575°F for 3 and 8 hours, at 650°F for 8 hours, and at 725°F for 4 hours. Based upon these results, a transformation of 575°F for 3 hours was selected for heat treating D6AC material.

TABLE 55

CALCULATED PLANE STRAIN FRACTURE TOUGHNESS OF TIG WELDS MADE IN HP 9-4-45 STEEL
0.090 INCH SHEET USING FILLER WIRE NO. 17

Center Notched Tensile Specimens

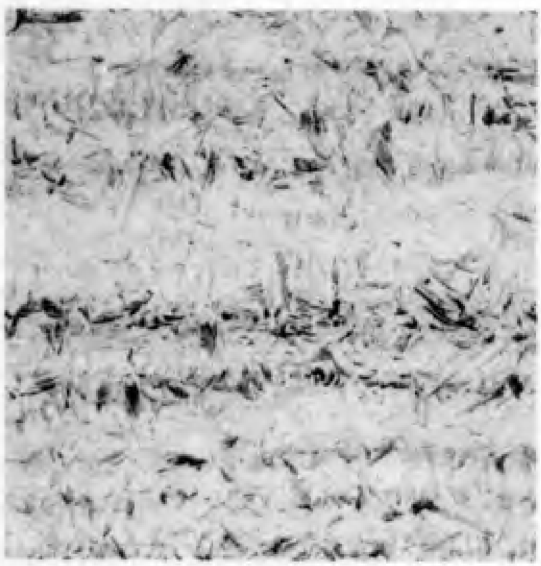
Specimen Identity	Welding Speed (ipm)	Shielding Gas	Notch Position	Width, W (in.)	Thickness, B (in.)	Length, $2a_o$ (in.)	Curve Type	Load (lbs)	$\frac{\sigma_n}{\sigma_{ys}}$	Calculated Plane Strain Fracture Toughness, K^{*}_{IC} (ksi $\sqrt{in.}$)
P318-3	4	He	Weld	2.003	0.054	0.791	1	7400	0.30	71.3
P318-4	4	He	Weld	1.965	0.068	0.846	1	8400	0.35	82.4
P318-5	4	He	HAZ	2.023	0.068	0.735	2	5900	0.30	69.1
P319-3	4	A	Weld	1.998	0.082	0.801	1	6800	0.23	55.6
P319-4	4	A	Weld	2.022	0.082	0.782	1	8200	0.27	65.9
P319-5	4	A	HAZ	2.091	0.082	0.721	1	8400	0.27	61.1
P317-3	10	He	Weld	1.969	0.058	0.744	1	5500	0.25	59.0
P317-4	10	He	Weld	2.026	0.065	0.737	1	6600	0.26	63.2
P317-5	10	He	HAZ	2.012	0.064	0.743	1	6900	0.28	69.1
P316-3	10	A	Weld	1.996	0.070	0.741	1	6200	0.23	55.8
P316-4	10	A	Weld	1.975	0.070	0.727	1	7600	0.19	40.8
P316-5	10	A	HAZ	1.988	0.070	0.738	1	6100	0.25	56.0
P314-3	15	He	Weld	1.993	0.074	0.675	1	9400	0.33	79.2
P314-4	15	He	Weld	2.013	0.074	0.678	1	10000	0.35	84.6
P314-5	15	He	HAZ	2.043	0.074	0.749	1	9500	0.30	73.3
P315-3	15	A	Weld	2.021	0.067	0.732	1	7800	0.32	75.4
P315-4	15	A	Weld	1.965	0.071	0.742	2	7620	0.30	71.0

(a) 500X

1650°F/1 Hour 500°F/50 Seconds
1000°F/10 Minutes Brine Quench

(b) 500X

1650°F 550°F/50 Seconds
1000°F/10 Minutes Brine Quence



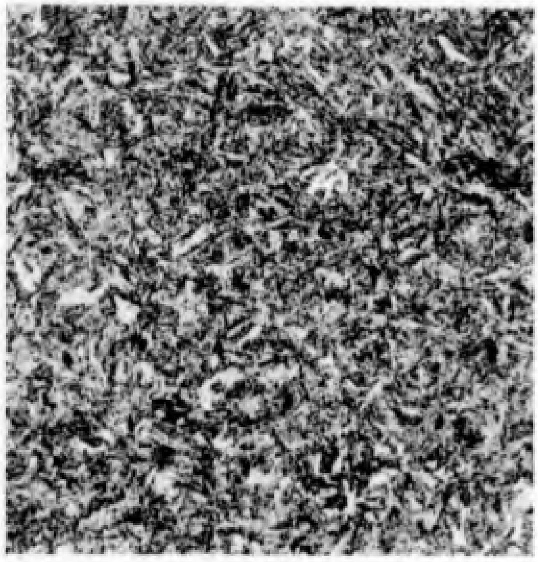
(c) 500X

1650°F/1 Hour 600°F/50 Seconds
1000°F/10 Minutes Brine Quench

Figure 133. Microstructure of D6AC 1/2 Inch Plate Austenitized at 1650°F in Air, Quenched to 500, 550 and 600°F in Salt Reheated to 1000°F in Salt Then Brine Quenched. Dark Constituent is Tempered Martensite, Light Areas Are Fresh Martensite. Etch: 2% Nital.

(a) 500X

Transformation Time: 10 Minutes
Structure: 40% Bainite 60%
Martensite (Light) Hardness: Rc 52



(b) 500X

Transformation Time: 30 Minutes
Structure: Nearly 100% Bainite
Hardness: R_c 48.8

(c) 500X

Transformation Time: 120 Minutes
Structure: Nearly 100% Bainite
Hardness: Rc 47

Figure 134. Microstructure of D6AC 1/2 Inch Plate Austenitized at 1650°F for 1 Hour Then Isothermally Transformed at 625°F for the Times Shown. Etch: 2% Nital.

Photomicrographs of unetched D6AC material were presented in Figure 87. The microstructure of a D6AC plate isothermally transformed at 625°F for 4 hours is presented in Figure 135. The microstructure indicates that the material has not completely transformed to bainite. X-ray diffraction studies of the metallographic specimen indicated that only 3.5 to 5.5 percent retained austenite was present. Therefore, it appears that the light areas are, to a large extent, fresh martensite. Figure 136 illustrates the microstructures obtained by austempering D6AC material at 575, 650 and 725°F. These photomicrographs indicate that transformation to 100 percent bainite was not achieved at these temperatures and times. However, the isothermal transformation diagram for D6AC material[16], Figure 137, indicates that there is a bay in the temperature region most attractive for producing the desired properties and that transformation to 100 percent bainite would take longer than one day. Although the transformation at 575°F for 8 hours appears to have progressed farther than the 650 and 725°F treatments, it can be questioned as to whether the microstructure is bainite or a mixture of tempered and fresh martensite. According to the transformation diagram, the 725°F treatment for 4 hours should have produced complete transformation. The shape of the light etching areas, as compared to those for fresh martensite in the 575 to 650°F treatment, have the appearance of ferrite rather than martensite needles. One explanation would be that ferrite stabilizers have gone into preferential regions and caused ferrite to be formed instead of ferrite and carbide. The hardness of this microstructure was quite low - R_C 42 to 43. The microstructure of D6AC material austempered at 575°F for 3 hours is presented in Figure 138. This microstructure indicates that transformation to bainite in 3 hours has progressed an equivalent amount as that indicated for 8 hours, Figure 136.

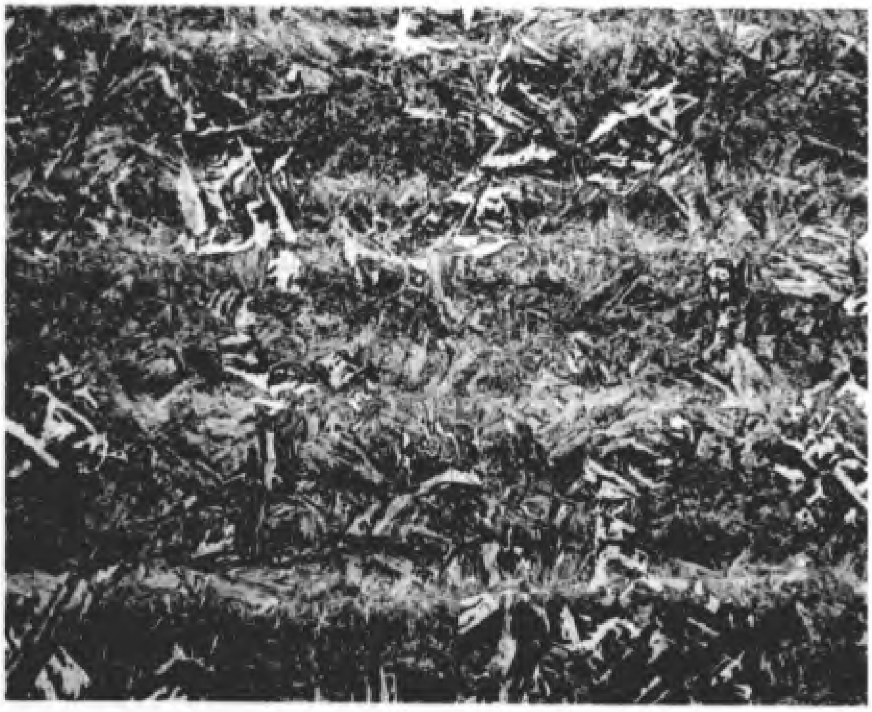
The smooth tensile properties for D6AC material austempered at 575, 625, and 725°F are presented in Table 56. The 725°F austemper resulted in low yield and ultimate strength. The 625°F austemper resulted in low yield strength; however, the ultimate strength was acceptable. The low yield strength with acceptable ultimate strength is believed to be the result of the duplex structure of bainite and fresh martensite, see Figure 135. Austempering at 575°F for 3 or 8 hours has produced desirable yield and ultimate strengths (202.7 and 195.4 yield and 259.2 and 249.2 ultimate strengths for the 8 and 3 hour heat treatments, respectively). In addition, the elongation and reduction of area are considered good. However, the 8 hour treatment resulted in more desirable ductility, indicating that time at temperature is beneficial. Due to the limited amount of work performed on bainitic D6AC material, no fracture toughness or Charpy V-notch impact data was obtained.

b. Evaluation of TIG Welds in 1/2-Inch Plate

To explore the feasibility of further interest in D6AC weldments in the bainitic condition, a limited amount of welding was performed on this material. Gas tungsten-arc welds were made in material austempered at 625°F for 4 hours and 575°F for 3 hours. These welds were made at 4 ipm in helium using wire No. 5 and at 4 ipm in argon using filler wire No. 6, respectively. Fusion welding parameters for these welds are presented in Table 57.

(1) Weld Quality

In general, the welds made in D6AC material were sound and free from porosity. However, a few very fine spots of porosity were observed in weld K278. In addition, no cracking was observed in any of the weldments.



Hardness: Rc 45.5-46 500X

Figure 135. Microstructure of D6AC 1/2 Inch Plate Isothermally Transformed at 625°F for 4 Hours. Etch: 2% Nital.

725°F 4 Hours 500X

650°F 8 Hours 500X

575°F 8 Hours 500X

Figure 136. Microstructure of D6AC Material Austempered at the Designated Temperatures.

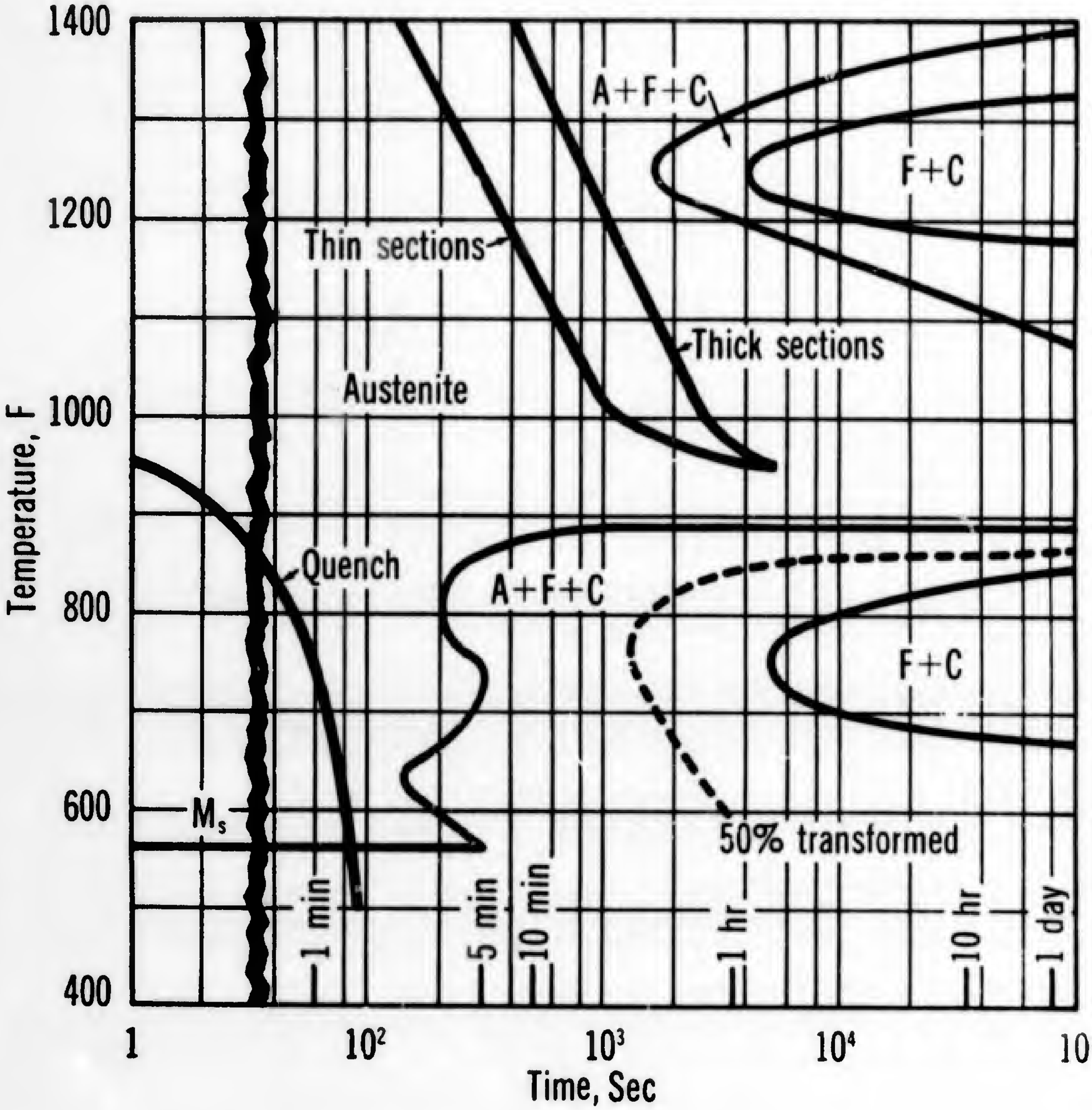


Figure 137. Isothermal Transformation Diagram for D6AC Steel. (Ref. 16).

Hardness R_c 49-51   500X

Figure 138. Microstructure of D6AC Material Austempered at 575°F for 3 Hours.

TABLE 56

SMOOTH TENSILE PROPERTIES OF D6AC STEEL 1/2 INCH PLATE

Heat No.	Test Direction(a)	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elongation (% - 1")	R.A. (%)	Austempering Temperature and Time
3920915	Transverse	203.1	257.6	12.0	43.7	575°F - 3 Hours
	Transverse	202.3	260.8	12.0	42.5	575°F - 3 Hours
3920915	Longitudinal	194.7	248.8	16.0	56.1	575°F - 8 Hours
	Longitudinal	196.1	249.6	16.0	54.5	575°F - 8 Hours
3920915	Longitudinal	168.0	223.9	16.0	58.7	625°F - 4 Hours
	Longitudinal	169.2	224.3	16.0	58.2	625°F - 4 Hours
3920915	Transverse	165.4	224.5	13.5	45.8	625°F - 4 Hours
	Transverse	166.4	224.5	15.0	50.4	625°F - 4 Hours
3920915	Longitudinal	143.5	194.7	16.0	48.4	725°F - 4 Hours
	Longitudinal	144.9	194.7	14.0	45.5	725°F - 4 Hours

Note: (a) Test direction relative to the rolling direction.

TABLE 57

FUSION WELDING PARAMETERS FOR TIG WELDS
MADE IN 1/2 INCH D6AC (BAINITE)

Weld No.	Filler Wire Diameter (inch)	Wire Compositions(a)	Pre- and Post-Heat (°F)	No. of Passes	W/S (ipm)	Wire Speed (ipm)	Amps	Volts	GAS (cfh) Torch	Backup
K240	0.062	5	575(b)	11	4	14	160	14.0	50 He	3 He
K241	0.062	5	625(b)	12	4	14	160	14.0	50 He	3 He
K278	0.062	6	(c)	8	4	28	220	13.5	35 A	5 A

Notes:

(a) Filler wire compositions are presented in Table 2.

(b) Weld K240 was post-heated at 575°F for 2 hours.
Weld K241 was post-heated at 625°F for 4 hours.

(c) Weld K278 was pre-heated at 480°F and the weld interpass temperature was maintained at 480°F. The weld was post-heated at 575°F for 2 hours.

(2) Weld Microstructure

The microstructure for welds K240 and K241 made in D6AC material at 4 ipm and post-heats of 575°F for 2 hours and 625°F for 4 hours are illustrated in Figures 139 and 140. These microstructures are typical of those for welds in this material. Evidence of coring is present in all areas. However, the microstructure of the fusion zone heat-affected zone illustrates the grain coarsening in the heat-affected zone in the weld made with a 625°F 4 hour post-heat. These welds fractured in the heat-affected zone with lower yield strengths than those transformed at 575°F for 2 hours.

(3) Weld Hardness Surveys

Hardness surveys for welds (K240 and K241) made in D6AC material with post-heats of 575°F for 2 hours and 625°F for 4 hours are presented in Figures 141 and 142, respectively. These surveys indicate that the 575°F post-heat temperature is slightly better than the 625°F temperature. The hardness of the weld made with the 575°F post-heat was more uniform in the center and upper part of the weld. In general, all passes show a higher hardness than those for the 625°F post weld temperature. These welds were made in base material transformed at 625°F for 4 hours. The hardness survey for the weld made in base material transformed at 575°F for 3 hours (weld No. K278) is presented in Figure 143. The hardness readings for the fusion zone are generally higher in all three areas than either of the other welds made in material transformed at 625°F. However, the 480°F pre-heat and weld bead interpass temperatures may have caused some martensite to form in these areas.

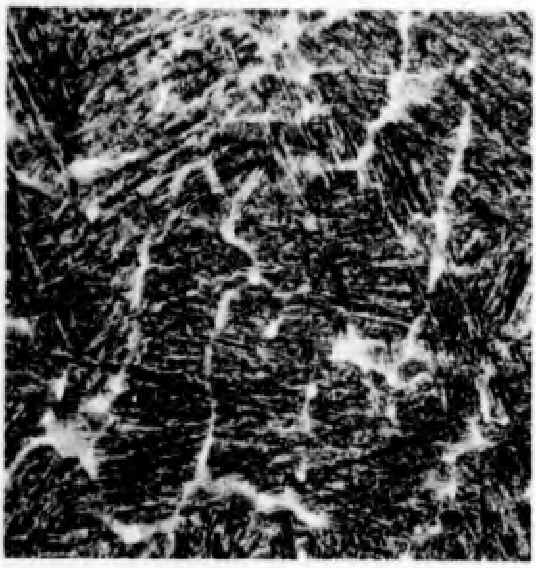
(4) Smooth Tensile Properties

The smooth tensile properties for TIG welds made in 1/2-inch D6AC bainitic plate are presented in Table 58. Although welds K240 and K241 were made at the same parameter, the pre- and post-heat treatments were different. As is illustrated by the results, the 575°F temperature appears to be better than the 625°F temperature. Weld K240, made with the 575°F transformation temperature and filler wire No. 5 and helium gas shielding, had properties in the all-weld metal longitudinal specimen quite close to those desired (178.1 to 191.9 ksi yield strength). In addition, the transverse properties for the weld made with the lower post-heat temperature are higher than those made with the 625°F temperature.

Both longitudinal and transverse specimens of weld K278, made in argon using filler wire No. 6, have desirable mechanical properties. However, this weld was made in material transformed at 575°F for 3 hours and would naturally be expected to have higher transverse properties as a result of the transverse specimens from all welds failing in the heat-affected zone area. In addition, the lower weld bead interpass temperature (480°F) for this weld is believed to be beneficial in increasing the yield and ultimate strengths. The transverse ductility and joint efficiency of each of the welds is considered to be undesirable.

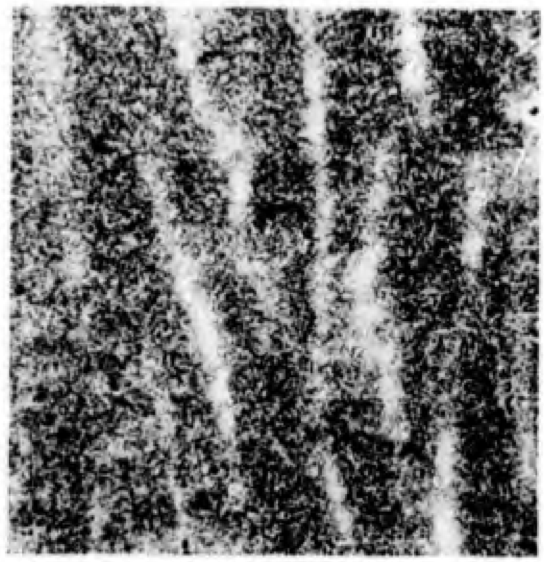
(5) Fracture Toughness

The fracture toughness of TIG welds made in D6AC 1/2-inch plate with pre- and post-heats of 575 and 625°F were determined by notch bend



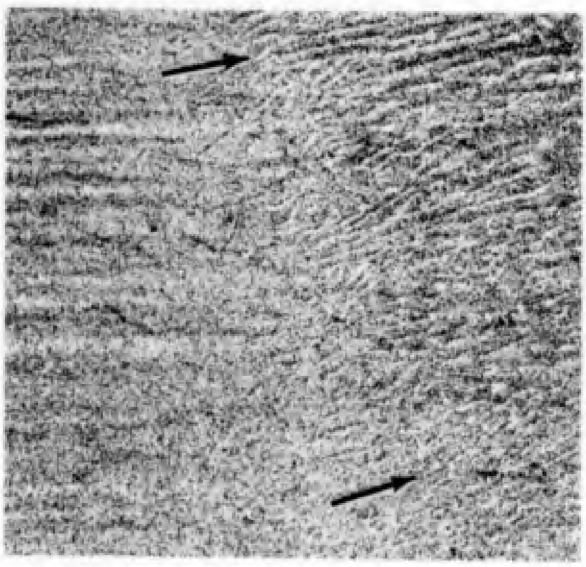
(a) 500X

Top of Fusion Zone



(b) 500X

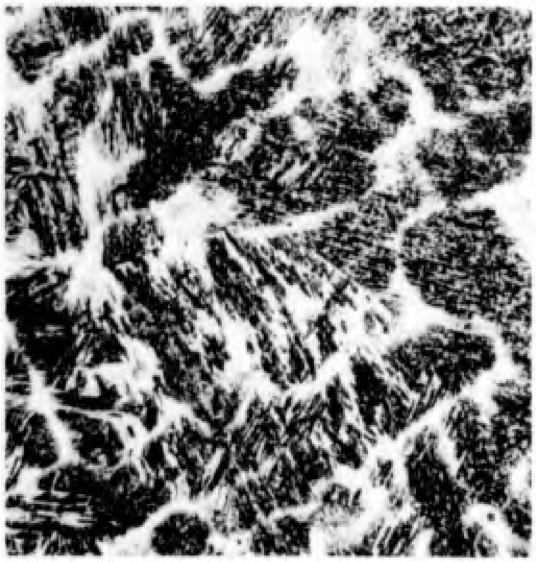
Center of Fusion Zone



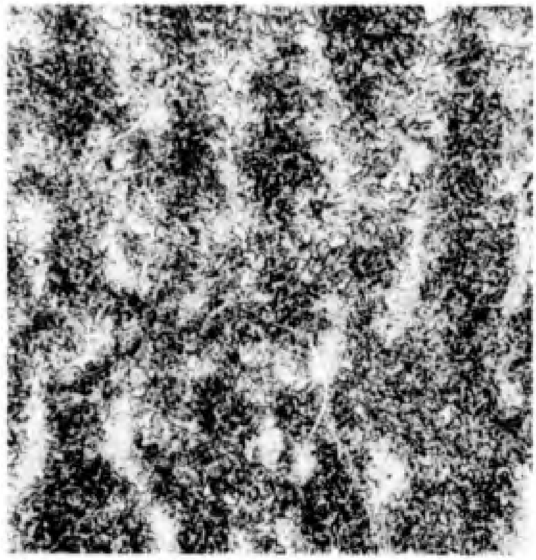
(c) 100X

Fusion Zone-Heat Affected Zone

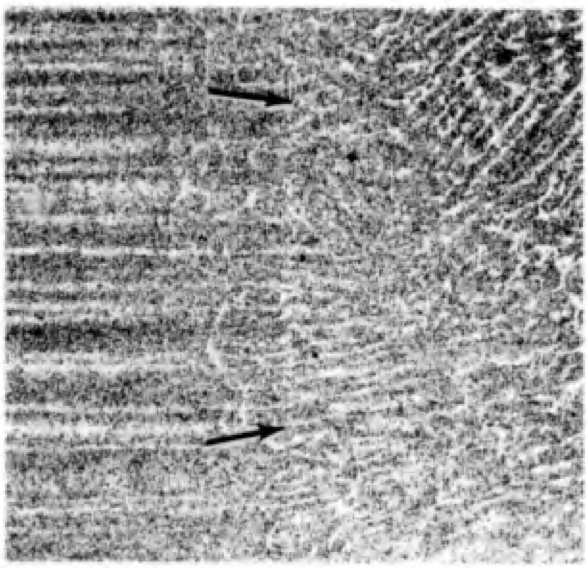
Figure 139. Microstructure of the Fusion Zone Heat-Affected Zone of TIG Weld No. K240 Made in D6AC Plate at 4 ipm. Post-Heated at 575°F for 2 Hours. Etch: 2% Nital.



(a) 500X
Top of Fusion Zone



(b) 500X
Center of Fusion Zone



(c) 100X
Fusion Zone-Heat Affected Zone

Figure 140. Microstructure of the Fusion Zone Heat-Affected Zone of TIG Weld No. K241 Made in D6AC Plate at 4 ipm. Post-Heated at 625°F for 4 Hours. Etch: 2% Nital.

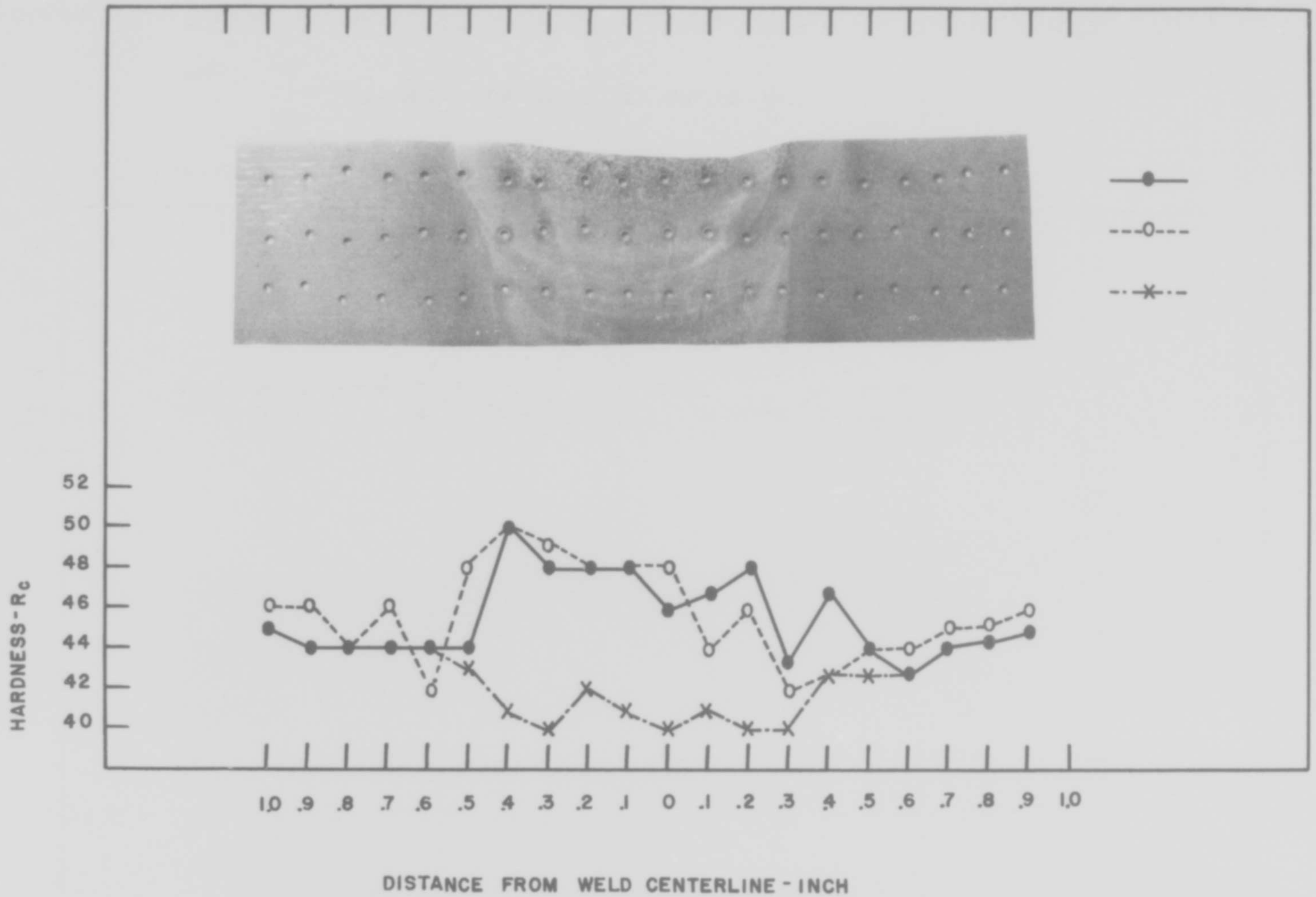


Figure 141. Hardness Survey of TIG Weld No. K240 Made in D6AC 1/2-Inch Plate Using a 575°F. Pre-Heat and Post-Heating at 575°F for 2 Hours. Base Material was Austempered at 625°F for 4 Hours.

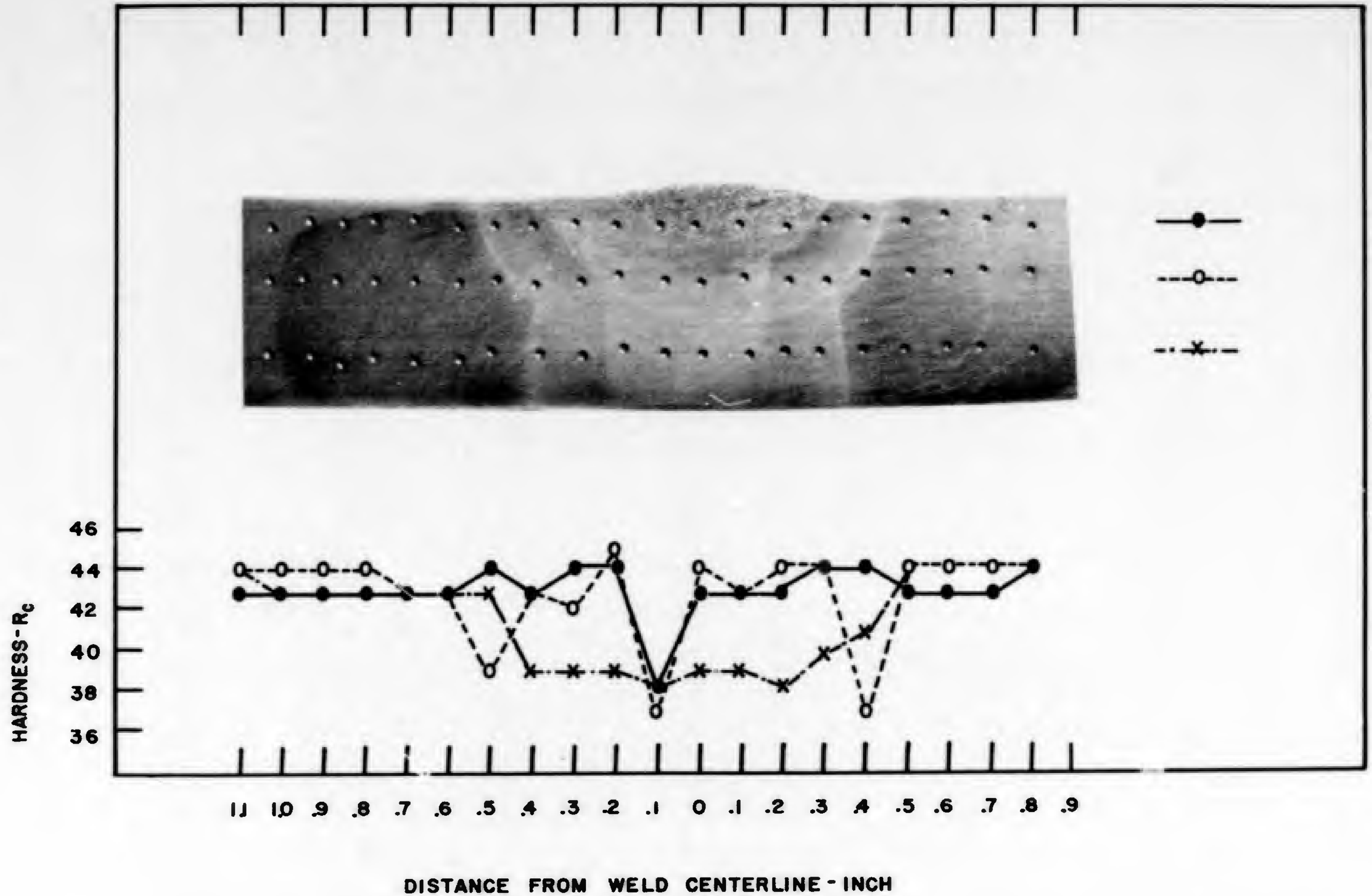


Figure 142. Hardness Survey of TIG Weld No. K241 Made in D6AC 1/2-Inch Plate Using a 625°F Pre-Heat and Post-Heating at 625°F for 4 Hours. Base Material was Transformed at 625°F for 4 Hours.

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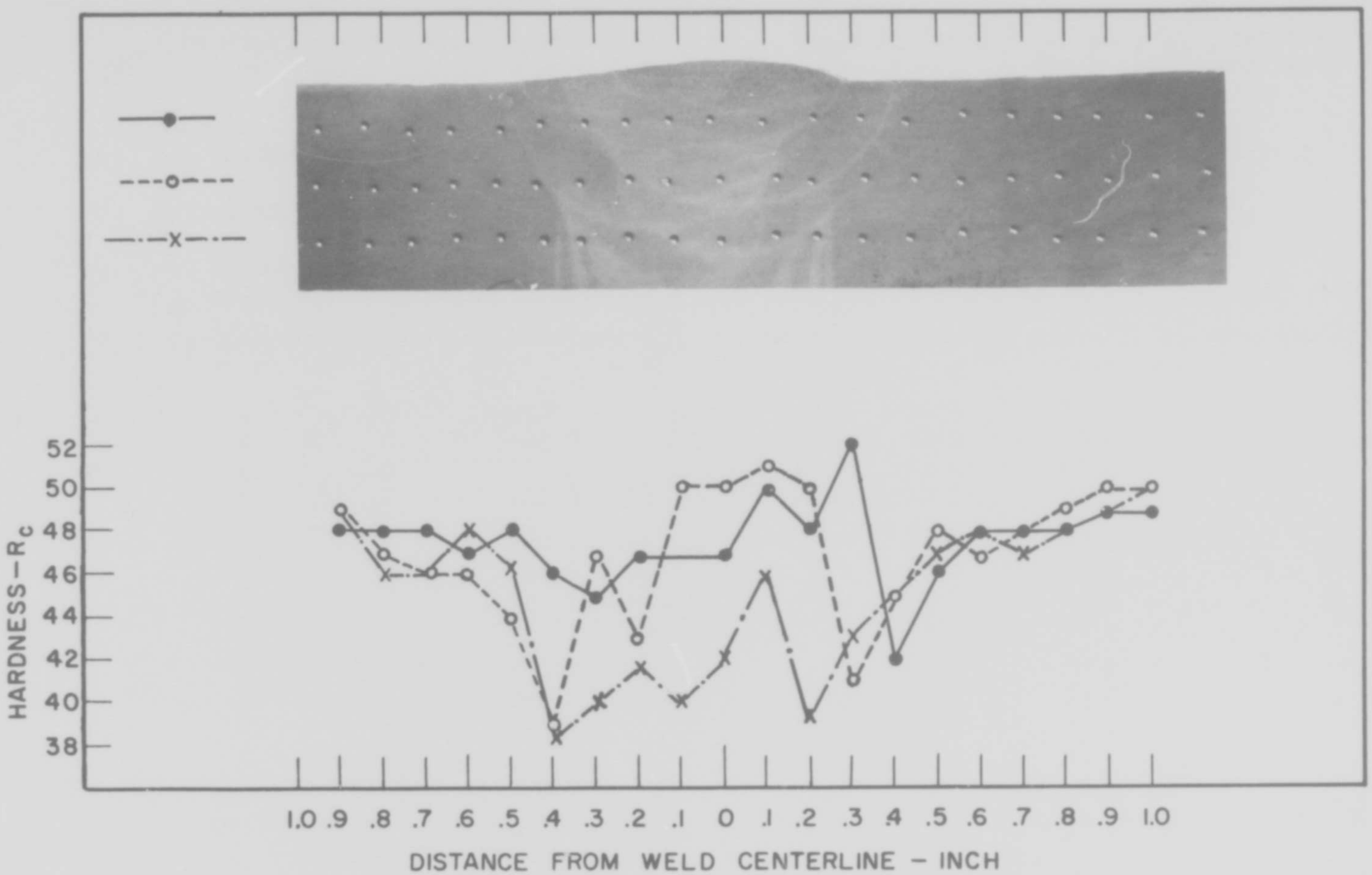

Figure 143. Hardness Survey of TIG Weld No. K278 Made in D6AC 1/2-Inch Plate Using a 480°F Pre-Heat and Interbead Temperature and a 575°F Post-Heat for 2 Hours. Base Material was Austempered at 575°F for 3 Hours.

TABLE 58

TENSILE PROPERTIES OF TIG WELDS

MADE IN D6AC 1/2 INCH PLATE

Weld No.	Test Direction(a)	Filler Wire(b)	Welding Speed (ipm)	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elong. %(c)	R.A. (%)	Energy Input K-J/in./pass	% Joint Efficiency(d) Y.S.	% Joint Efficiency(d) U.T.S.	Comments
K240	L	5	4	191.9	236.4	12.0	51.2	33.6			
	L	5	4	178.1	222.8	15.0	50.5	33.6			
	T	5	4	165.7	193.8	4.5	33.6	33.6	98.3	86.5	(e)
	T	5	4	167.7	193.6	5.0	27.8	33.6	99.5	86.4	(e)
K241	L	5	4	141.9	192.1	16.0	43.7	33.6			
	L	5	4	192.1	202.1	15.0	46.4	33.6			
	T	5	4	151.0	184.8	4.0	22.1	33.6	89.6	82.5	(e)
	T	5	4	150.6	185.0	4.0	20.7	33.6	89.3	82.6	(e)
K278	L	6	4	195.3	222.6	14.5	51.6	44.6			
	L	6	4	197.6	217.4	13.5	48.2	44.6			
	T	6	4	185.8	201.1	3.0	16.0	44.6	91.7	77.6	(e)
	T	6	4	183.2	196.7	3.0	20.9	44.6	90.4	75.9	(e)

Notes:

(a) (L) specimens were taken parallel with the weld and consisted entirely of weld deposit.

(T) specimens were taken transverse to the weld and included weld, heat affected zone, and parent metal.

(b) Filler wire composition is presented in Table 2.

(c) (T) specimens had a gage length of 2.0 inches. (L) specimens had a gage length of 1.0 inch.

(d) Joint efficiency for Welds K240 and K241 based upon 168.6 and 224.1 ksi parent metal yield and ultimate strengths, respectively. Joint efficiency for weld K278 based upon 202.7 and 259.2 ksi parent metal yield and ultimate strengths, respectively.

TABLE 58 (Continued)

Notes: (Con't.)

(e) Fracture occurred in the heat affected zone.

Weld K240 was made with a 575°F interpass temperature and post-heated at this temperature for 2 hours. Base material was austempered at 625°F for 4 hours.

Weld K241 was made with a 625°F interpass temperature and post-heated at this temperature for 4 hours. Base material was austempered at 625°F for 4 hours.

Weld K278 was made with a 480°F interpass temperature and post-heated at 575°F for 2 hours. Base material was austempered at 575°F for 3 hours.

testing under 3-point loading. As shown in Table 59, both weldments exhibited a K_{IC} value much lower than that of the parent metal ($K_{IC} = 85$ ksi $\sqrt{\text{inch}}$). The weld deposits had extremely low plane strain fracture toughness ($K_{IC} \approx 30$ ksi $\sqrt{\text{inch}}$) with the heat affected zones exhibiting somewhat higher values (35 to 55 ksi $\sqrt{\text{inch}}$).

c. General Discussion

The limited amount of work performed on bainitic D6AC indicates that desirable smooth tensile properties can be obtained in material transformed at 575°F for 3 or 8 hours. However, the 8 hour transformation time produced the properties most desirable for the criteria of the program (195.4 ksi and 249.2 yield and ultimate strengths respectively, with 16 percent elongation and 55.3 percent reduction of area). In addition, desirable weld deposit smooth tensile properties can be obtained when using filler wire No. 6, a welding speed of 4 ipm, argon shielding and energy input of 44.6 K-joules/inch/pass and a preheat and interbead temperature of 480°F with a post-heat of 575°F for 2 hours. However, the ductility and joint efficiency determined on transverse specimens which fracture in the heat affected zone were low. These results indicate that D6AC material is worthy of further investigation as a bainitic material.

C. Properties of the Heat Affected Zones

Prior to exposing the specimens to the various weld thermal cycles, they were heat treated according to the procedure used for heat treating plate of each steel before welding. The D6AC specimens were austenitized at 1650°F for 1 hour, salt quenched to 375°F and held there for 10 minutes, then air cooled. The specimens were then double tempered at 1050°F for 2 hours. The HP 9-4-45 specimens were normalized at 1600°F for 1 hour, air cooled, austenitized at 1500°F for 1 hour then isothermally transformed to bainite at 550°F in 7 hours. The thermally cycled specimens were evaluated for tensile properties and fracture toughness in accordance with the previously described procedure.

1. D6AC Martensitic Steel

The tensile properties as a function of heat affected zone peak temperature are given in Tables 60 and 61 and are plotted in Figures 144 and 145 for energy inputs of 25 and 50 K-joules/inch respectively. The yield (proportional limit) and ultimate tensile strengths are shown to drop appreciably at about 1350°F the increase markedly as peak temperature increased above 1350°F. The rapid increase between 1350 and about 1550°F is caused by the formation of untempered martensite. The slight reduction in strength between 1550°F and 2200°F is believed to be the result of grain coarsening.

The ductility as measured by percent reduction in area remains relatively constant between 35 and 45% until the peak temperature is raised into the austenitic region. The subsequent formation of fresh martensite drastically lowered the ductility which remained relatively stable above 1550°F. The occurrence of grain growth is believed primarily responsible for the slight increase in ductility observed at 2200°F.

It is important to note that for the 1350°F peak temperature the heat affected zone strength is above 90 percent of the unwelded plate strength

TABLE 59

CALCULATED FRACTURE TOUGHNESS, K_{IC}^*, OF TIG WELDS MADE IN D6AC (BAINITE) 1/2 INCH PLATE

(3-Point Loading)

Specimen Identity	Notch Position	Width, W (inch)	Thickness, B (inch)	Crack Depth, a (inch)	Major Span Length, L' (inches)	Curve Type[c]	Load (lbs.)	Relative Plastic Zone Size, r_y/B[d]	σ_{nom}/σ_{ys}[e]	Calculated Fracture Toughness, K_{IC}^* (ksi $\sqrt{\text{inch}}$)
K240[a]	Weld	0.457	0.463	0.076	4.0	3	690	0.001	0.37	21.4
	Weld	0.458	0.464	0.094	4.0	3	1675	0.006	0.97	59.8
	HAZ	0.456	0.464	0.101	4.0	3	1435	0.005	0.87	53.6
	HAZ	0.457	0.465	0.094	4.0	1	1300	0.003	0.76	45.9
K241[b]	Weld	0.455	0.500	0.055	4.0	2	720	0.001	0.32	17.8
	Weld	0.455	0.500	0.081	4.0	3	855	0.001	0.44	25.7
	HAZ	0.456	0.500	0.071	4.0	1	1250	0.002	0.60	35.2
	HAZ	0.456	0.500	0.078	4.0	1	1410	0.003	0.70	41.9

Notes:

(a) Pre-heated at 575°F; post-heated at 575°F for 2 hours.

(b) Pre-heated at 625°F; post-heated at 625°F for 2 hours.

(c) Curve types are defined in Figure 16.

(d) Plastic zone size, r_y, equals the difference between the effective crack length a^* and the measured crack length a $(a^* = a + E\mathscr{J}/6\pi\sigma_{ys}^2)$.

(e) σ_{nom}/σ_{ys} = nominal stress at crack initiation divided by 0.2% yield strength.

TABLE 60

TENSILE PROPERTIES OF SYNTHETIC WELD
THERMAL CYCLED D6AC MARTENSITIC STEEL

Energy Input 25 K-Joules/Inch

Specimen No.	Peak Temp. (°F)	Proportional Limit (ksi)	U.T.S. (ksi)	R.A. (%)	Ratio Spec. / Plate Strength*	
					Prop. Limit	U.T.S.
D- 1	1000	217.2	246.3	44.2	0.99	1.03
D- 2	"	218.1	244.0	46.0	0.99	1.02
D- 5	1200	227.8	247.8	43.0	1.04	1.04
D- 6	"	222.7	246.3	44.2	1.02	1.03
D- 9	1350	204.5	222.5	50.4	0.94	0.94
D-10	"	203.9	220.3	47.1	0.93	0.92
D-13	1450	258.2	307.3	**	1.18	1.28
D-17	1550	302.2	346.8	4.2	1.38	1.44
D-18	"	318.0	400.7	11.2	1.45	1.67
D-21	2200	301.2	389.6	15.7	1.37	1.62
D-22	"	316.1	391.9	11.2	1.44	1.63

*Based on 218.8 ksi Y.S. and 240.1 ksi U.T.S.

**Failed outside of peak temp. zone.

TABLE 61

TENSILE PROPERTIES OF SYNTHETIC WELD
THERMAL CYCLED D6AC MARTENSITIC STEEL

Energy Input 50 K-Joules/Inch

Specimen No.	Peak Temp. (°F)	Proportional Limit (ksi)	U.T.S. (ksi)	R.A. (%)	Ratio Spec. / Plate Strength*	
					Prop. Limit	U.T.S.
D-25	1000	219.4	248.3	22.2	1.01	1.04
D-26	"	223.1	248.4	45.3	1.02	1.04
D-29	1200	223.6	247.9	43.1	1.02	1.03
D-30	"	219.4	247.0	45.3	1.01	1.03
D-33	1350	209.9	227.8	46.4	0.96	0.95
D-34	"	206.9	225.9	46.1	0.94	0.94
D-37	1450	236.2	281.1	9.4**	1.08	1.17
D-38	"	220.8	263.3	10.6**	0.93	1.10
D-41	1550	290.7	374.3	4.8	1.36	1.56
D-42	"	302.2	281.2	20.6	1.38	1.59

*Based on 218.8 ksi Y.S. and 240.1 ksi U.T.S.

**Specimens failed outside of peak temp. zone.

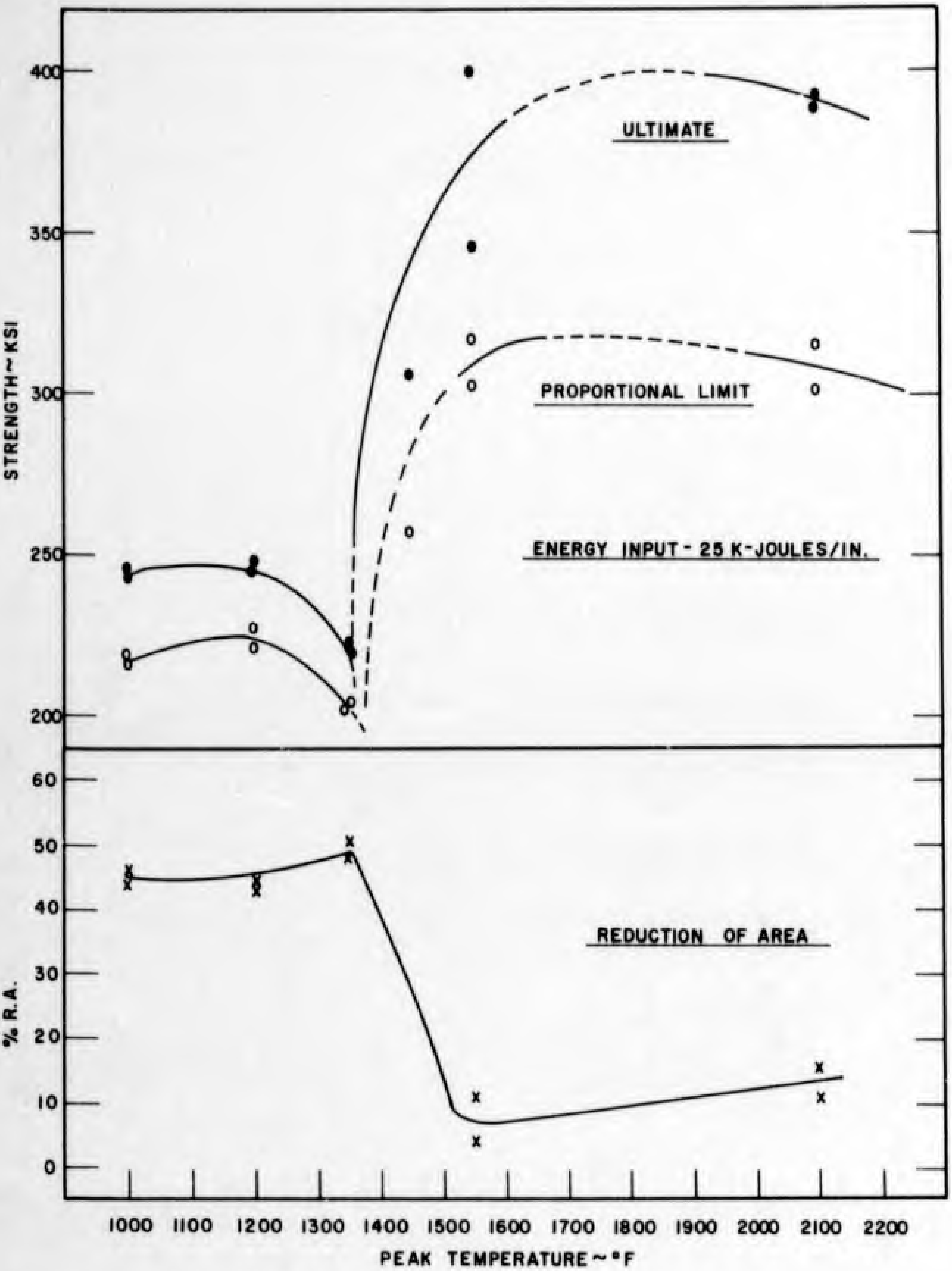

Figure 144. Influence of Peak Temperature of Synthetic Weld Thermal Cycle on the Tensile Properties of D6AC Martensitic Steel. 25 K Joules/in. Energy Input.

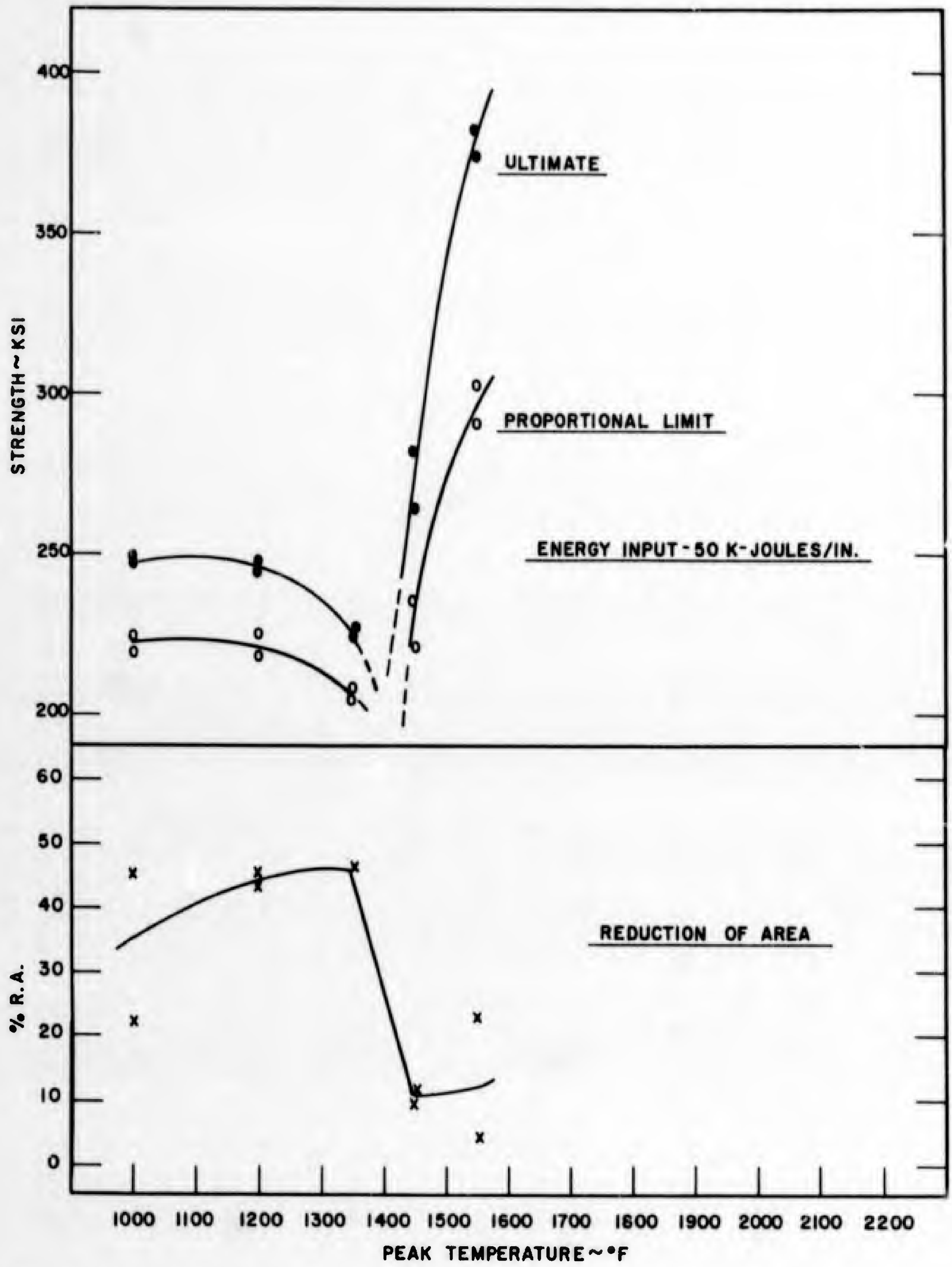

Figure 145. Influence of Peak Temperature of Synthetic Weld Thermal Cycle on the Tensile Properties of D6AC Martensitic Steel. 50 K Joules/in. Energy Input.

as shown in Table 60 and 61. This area in the heat affected zone is located about 0.4 inch away from the fusion line. Of some concern is the low ductility of these specimens located above 1350°F. These areas on either side of the weld are susceptable to brittle failure, however, the relatively ductile metal below 1350 and the ductile weld should be capable of deforming thereby reducing the stress field in the higher strength brittle region of the heat affected zone.

The results of fracture toughness tests are shown in Tables 62 and 63 for 25 and 50 K-joules/inch energy input respectively. As indicated in Table 62 the fracture toughness dropped slightly from 104.5 ksi $\sqrt{\text{inch}}$ peak to 100 ksi $\sqrt{\text{inch}}$ at 1350°F for the specimens cycled at 25 K-joules/inch of energy input. Those cycled at 50 K-joules/inch followed the same general trend but the K_{IC}^* values were considerably lower. All specimens cycled to peak temperatures above 1350°F were found to have virtually no measurable resistance to crack propagation. These specimens failed during fatigue precracking. This low fracture toughness was anticipated after determining the tensile ductility (% R.A.) which as shown in Figures 144 and 145 was very low.

2. HP 9-4-45 Bainitic Steel

Tensile properties as a function of heat affected zone peak temperature are given in Tables 64 and 65 and are plotted in Figures 146 and 147 for energy inputs of 25 and 50 K-joules/inch respectively. As shown in the figures, as the peak temperature is increased from 1000 to 1250°F, strength decreased significantly with a corresponding increase in ductility at temperatures above about 1250°F strength increased sharply and peaked at about 1450°F. Above 1450°F, the strength decreased slightly up to 1550°F, remained relatively constant up to about 2000°F then decreased.

Of particular significance is the strength level at 1200°F. As shown in the Figures and in Tables 64 and 65, the heat affected zone yield strength (proportional limit) was 85-87% (25 K-houles/inch) and 88-92% (50 K-joules/inch) of the unwelded plate. Based on ultimate strength, these percentages were even lower. Also, this overtempered region of the bainitic 9-4-45 plate exhibited yield strength levels less than the 180 ksi minimum desired for this program.

While the heat affected zone strength varied widely, the ductility appeared to remain relatively constant varying between 40 and 55% R.A. (25 K-joules/inch) and 35 to 54% R.A. (50 K-joules/inch). Thus there appears to be no area in the heat affected zone that can be considered to have excessively low ductility.

The fracture toughness results are presented in Tables 66 and 67 and are shown in Figure 148. The fracture toughness drops rapidly at temperatures up to 1350°F then regain somewhat at temperatures above 1350°F. The fracture toughness of specimens heated above 1000°F are all lower than that attained at 1000°F.

The D6AC martensitic material appears to be less susceptable to overtempering than the HP 9-4-45 bainitic material as can be seen by comparing the slopes of the peak temperature versus strength curves up to 1200°F in Figures 144 and 145 with Figures 146 and 147. This data further substantiates the comparison in tempering behavior at 1200°F that was presented previously in this report.

TABLE 62

CALCULATED FRACTURE TOUGHNESS, K_{IC}^{*}, OF D6AC MARTENSITIC PLATE SYNTHETIC HEAT AFFECTED ZONES (25 K-JOULES/INCH ENERGY INPUT)

(4-Point Loading)

Specimen Identity	Peak Temp. (°F)	Width, W (inch)	Thickness, B (inch)	Crack Depth, a (inch)	Major Span, L' (inch)	Load (lbs.)	Relative Plastic Zone Size r_y/B (b)	σ_{nom}/σ_{ys} (b)	Curve Type (a)	Calculated Fracture Toughness, K_{IC}^{*} (ksi $\sqrt{inch}$)
D-3	1000	0.421	0.421	0.103	3	5130	0.024	1.246	2	106.021
D-4	1000	0.421	0.421	0.087	3	5540	0.023	1.219	1	103.173
D-7	1200	0.421	0.421	0.123	3	4500	0.021	1.203	1	104.485
D-8	1200	0.421	0.421	0.099	3	5125	0.021	1.173	2	102.583
D-11	1350	0.421	0.421	0.100	3	5200	0.027	1.321	1	106.308
D-12	1350	0.421	0.421	0.108	3	4500	0.022	1.202	1	95.489
D-15	1450	Specimen Failed During Fatigue Precracking.								
D-16	1450	" " " " "								
D-19	1550	Specimen Failed During Fatigue Precracking.								
D-20	1550	" " " " "								
D-23	2200	Specimen Failed During Fatigue Precracking.								
D-24	2200	" " " " "								

Notes:

(a) Curve types are defined in Figure 16.

(b) Plastic zone size, r_y, equals the difference between the effective crack length a^{*} and the measured crack length a ($a^{*} = a + E\epsilon/6\pi\sigma_{ys}^2$).

(c) σ_{nom}/σ_{ys} = nominal stress at crack initiation divided by 0.2% yield strength.

TABLE 63

CALCULATED FRACTURE TOUGHNESS, K_{IC}^*, OF D6AC MARTENSITIC PLATE SYNTHETIC HEAT AFFECTED ZONES (50 K-JOULES/INCH ENERGY INPUT)

(4-Point loading)

Specimen Identity	Peak Temp. (°F)	Width, W (inch)	Thickness, B (inch)	Crack Depth, a (inch)	Major Span, L' (inches)	Curve Type(a)	Load (lbs.)	Relative Plastic Zone Size r_y/B(b)	σ_{nom}/σ_{ys}(c)	Calculated Fracture Toughness, K_{IC}^* (ksi $\sqrt{inch}$)
D-28	1000	0.421	0.421	0.117	3	1	4800	0.024	1.255	108.087
D-31	1200	0.421	0.421	0.083	3	1	4875	0.017	1.053	86.599
D-32	1200	0.421	0.421	0.092	3	1	4800	0.018	1.101	91.288
D-35	1350	0.422	0.421	0.085	3	1	4575	0.016	1.026	82.164
D-36	1350	0.422	0.421	0.100	3	1	5050	0.024	1.240	101.87
D-39	1450	Specimens Failed During Fatigue Precracking								
D-40	1450	" " " " "								
D-43	1550	Specimens Failed During Fatigue Precracking								
D-44	1550	" " " " "								

Notes:

(a) Curve types are defined in Figure 16.

(b) Plastic zone size, r_y, equals the difference between the effective crack length a^* and the measured crack length a ($a^* = a + E\mathcal{G}/6\pi\sigma_{ys}^2$).

(c) σ_{nom}/σ_{ys} = nominal stress at crack initiation divided by 0.2% yield strength.

TABLE 64

TENSILE PROPERTIES OF SYNTHETIC WELD
THERMAL CYCLED HP 9-4-45 BAINITIC STEEL

Energy Input 25 K-Joules/Inch

Specimen No.	Peak Temp. (°F)	Proportional Limit (ksi)	U.T.S. (ksi)	R.A. (%)	Ratio Spec. / Plate Strength* Prop. Limit	U.T.S.
H- 1	1000	186.5	198.6	47.4	0.97	0.89
H- 2	"	176.2	193.4	50.3	0.92	0.87
H- 5	1200	167.8	186.3	56.5	0.87	0.84
H- 6	"	164.2	184.5	55.2	0.85	0.83
H- 9	1350	228.2	252.6	45.1	1.18	1.13
H-10	"	239.0	259.3	48.6	1.24	1.16
H-17	1450	227.5	257.2	47.1	1.18	1.15
H-18	"	246.2	267.5	43.5	1.28	1.20
H-13	1550	227.8	252.0	41.4	1.18	1.13
H-14	"	228.2	256.2	45.6	1.19	1.15
H-21	1800	221.6	250.2	45.8	1.15	1.12
H-22	"	233.9	258.4	46.7	1.21	1.16
H-25	2200	223.5	249.9	48.7	1.16	1.11
H-26	"	230.6	251.8	49.1	1.20	1.12
H-29	2400	221.0	240.0	41.1	1.15	1.07
H-30	"	219.5	235.8	41.5	1.14	1.05

*Based on 192.7 ksi Y.S. and 223.8 U.T.S.

TABLE 65

TENSILE PROPERTIES OF SYNTHETIC WELD
THERMAL CYCLED HP 9-4-45 BAINITIC STEEL

Energy Input 50 K-Joules/Inch

Specimen No.	Peak Temp. (°F)	Proportional Limit (ksi)	U.T.S. (ksi)	R.A. (%)	Ratio Spec. / Plate Strength*	
					Prop. Limit	U.T.S.
H-33	1000	183.8	196.0	45.3	0.95	0.88
H-34	"	185.0	196.2	48.3	0.96	0.88
H-37	1200	176.3	190.4	48.0	0.92	0.85
H-38	"	169.6	189.5	52 8	0.88	0.85
H-41	1350	229.2	260.5	46.2	1.19	1.17
H-42	"	232.5	259.4	38.8	1.21	1.16
H-45	1450	224.5	247.9	43.5	1.17	1.11
H-46	"	221.2	253.0	41.7	1.15	1.13
H-49	1550	233.4	268.5	35.8	1.21	1.20
H-50	"	224.0	256.3	40.7	1.25	1.15
H-53	2200	220.8	254.3	43.0	1.14	1.14

*Based on 192.7 ksi Y.S. and 223.8 U.T.S.

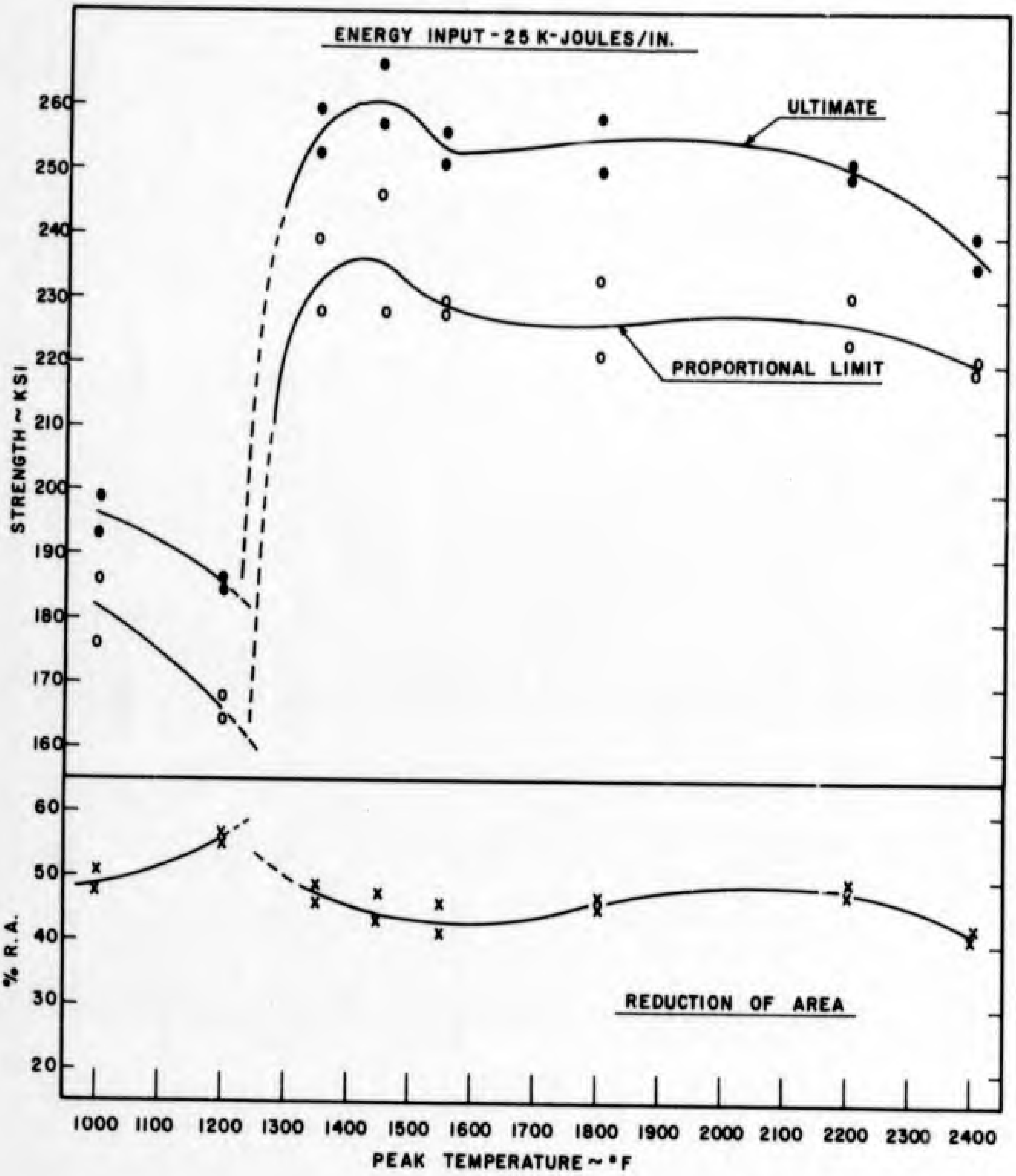

Figure 146. Influence of Peak Temperature of Synthetic Weld Thermal Cycle on the Tensile Properties of HP 9-4-45 Bainitic Steel - 25 K Joules/in Energy Input.

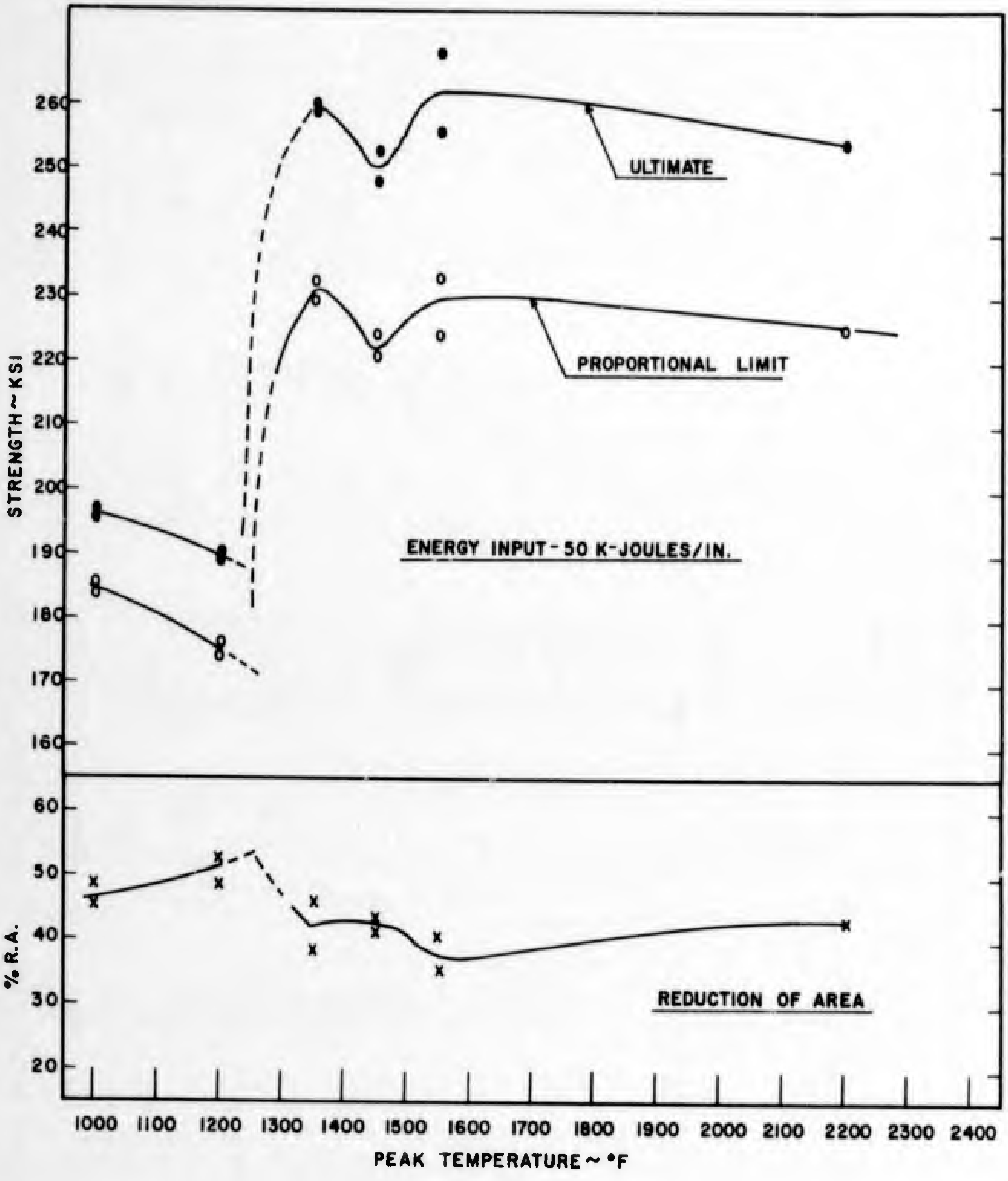

Figure 147. Influence of Peak Temperature of Synthetic Weld Thermal Cycle on the Tensile Properties of HP 9-4-45 Bainitic Steel. 50 K Joules/in. Energy Input.

TABLE 66

CALCULATED FRACTURE TOUGHNESS, K_{IC}^*, OF HP 9-4-45 BAINITIC PLATE SYNTHETIC HEAT AFFECTED ZONES (25 K-JOULES/INCH ENERGY INPUT)

(4-Point Loading)

Specimen Identity	Peak Temp. (°F)	Width, W (inch)	Thickness, B (inch)	Crack Depth, a (inch)	Major Span, L' (inch)	Curve Type(a)	Load (lbs.)	Relative Plastic Zone Size r_y/B(b)	σ_{nom}/σ_{ys}(c)	Calculated Fracture Toughness, K_{IC}^* (ksi $\sqrt{\text{inch}}$)
H-3	1000	0.419	0.420	0.081	3.0	2	6150	0.038	1.589	116.313
H-4	1000	0.420	0.419	0.084	3.0	2	5730	0.039	1.502	109.057
H-7	1200	0.418	0.419	0.099	3.0	2	4950	0.037	1.574	105.646
H-8	1200	0.413	0.419	0.102	3.0	2	4840	0.039	1.618	108.584
H-11	1350	0.421	0.419	0.099	3.0	3	4540	0.016	1.006	89.968
H-12	1350	0.419	0.420	0.088	3.0	2	5155	0.031	1.079	96.518
H-19	1450	0.419	0.420	0.099	3.0	2	4915	0.018	1.085	98.817
H-20	1450	0.420	0.420	0.103	3.0	1	4055	0.013	0.912	82.016
H-15	1550	0.419	0.419	0.100	3.0	2	5265	0.023	1.218	108.111
H-16	1550	0.420	0.420	0.111	3.0	2	4760	0.021	1.171	103.345
H-23	1800	0.419	0.420	0.104	3.0	2	4475	0.017	1.060	92.630
H-24	1800	0.419	0.420	0.103	3.0	2	4920	0.021	1.158	102.101
H-27	2200	0.420	0.419	0.090	3.0	2	5215	0.019	1.132	99.158
H-28	2200	0.419	0.419	0.107	3.0	1	4865	0.022	1.182	103.962
H-31	2400	0.421	0.419	0.105	3.0	1	4400	0.018	1.074	91.037
H-32	2400	0.420	0.419	0.110	3.0	2	4560	0.021	1.157	98.508

Notes: (a) Curve types are defined in Figure 16.

(b) Plastic zone size, r_y, equals the difference between the effective crack length a^* and the measured crack length a ($a^* = a + E\mathcal{G}/6\pi\sigma_{ys}^2$).

(c) σ_{nom}/σ_{ys} = nominal stress at crack initiation divided by 0.2% yield strength.

TABLE 67

CALCULATED FRACTURE TOUGHNESS, K_{IC}^*, OF HP 9-4-45 BAINITIC PLATE SYNTHETIC HEAT AFFECTED ZONES (50 K-JOULES/INCH ENERGY INPUT)

(4-Point Loading)

Specimen Identity	Peak Temp. (°F)	Width, W (inch)	Thickness, B (inch)	Depth, a (inch)	Major Span, L' (inch)	Curve Type(a)	Load (lbs.)	Relative Plastic Zone Size r_y/B(b)	σ_{nom}/σ_{ys}(c)	Calculated Fracture Toughness, K_{IC}^* (ksi $\sqrt{\text{inch}}$)
H-35	1000	0.420	0.419	0.102	3.0	1	4815	0.029	1.386	101.369
H-36	1000	0.420	0.419	0.110	3.0	1	5065	0.036	1.534	113.893
H-39	1200	0.419	0.419	0.117	3.0	1	3795	0.025	1.288	87.058
H-40	1200	0.419	0.420	0.119	3.0	1	4000	0.029	1.373	93.450
H-43	1350	0.420	0.419	0.117	3.0	3	3900	0.015	0.979	86.594
H-44	1350	0.420	0.420	0.110	3.0	2	3910	0.014	0.935	82.725
H-47	1450	0.420	0.420	0.099	3.0	2	4500	0.017	1.049	89.737
H-51	1550	0.419	0.420	0.113	3.0	3	4480	0.020	1.144	98.722
H-52	1550	0.419	0.420	0.122	3.0	2	4225	0.020	1.145	98.286
H-54	2200	0.420	0.420	0.103	3.0	1	4160	0.016	1.010	84.786

Notes:

(a) Curve types are defined in Figure 16.

(b) Plastic zone size, r_y, equals the difference between the effective crack length a^* and the measured crack length a ($a^* = a + E\mathcal{G}/6\pi\sigma_{ys}^2$).

(c) σ_{nom}/σ_{ys} = nominal stress at crack initiation divided by 0.2% yield strength.

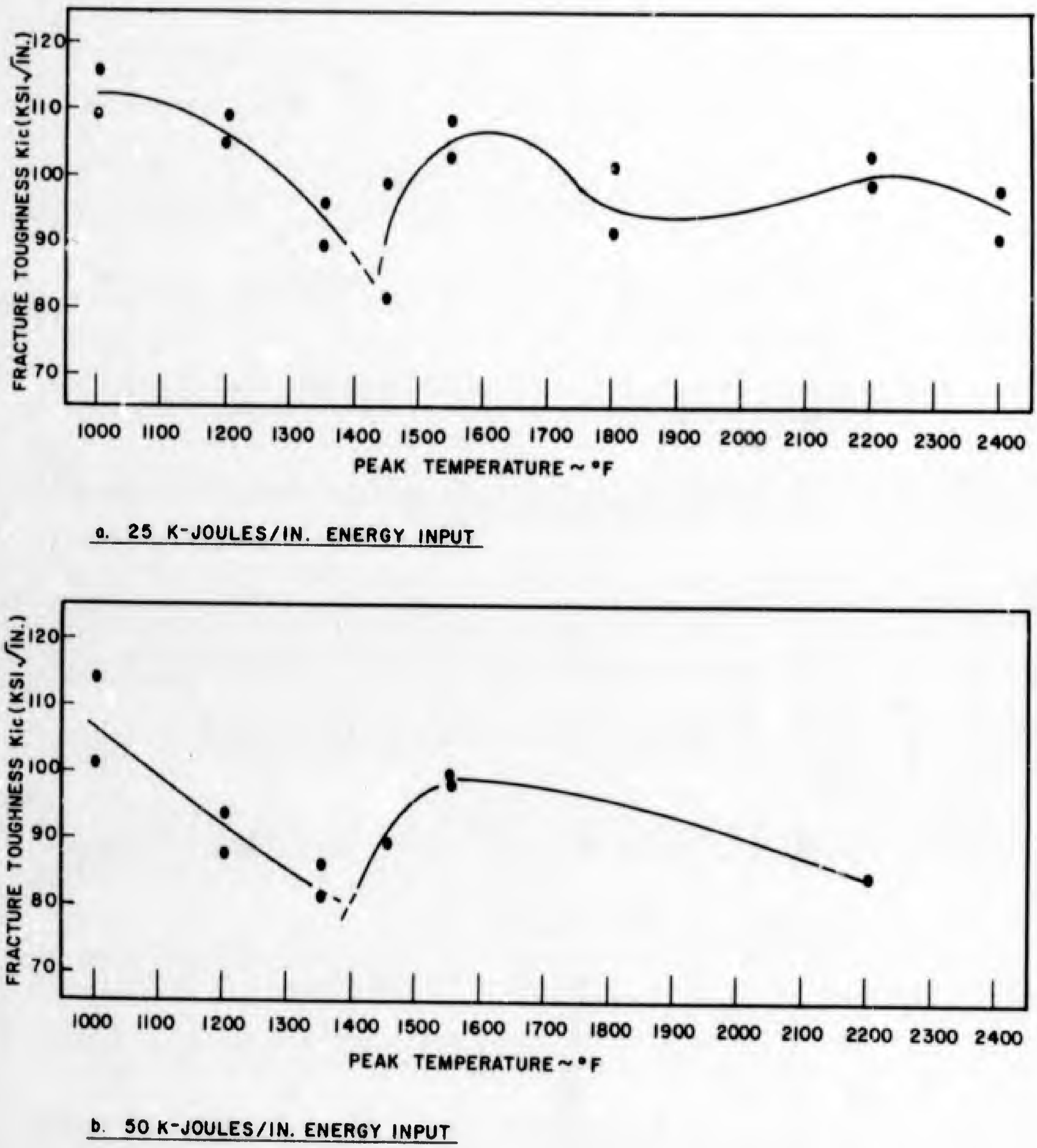

Figure 148. Influence of Peak Temperature of Synthetic Weld Thermal Cycle on the Fracture Toughness (K_{IC}) of HP 9-4-45 Bainitic Steel.

VI CONCLUSIONS

Weldments with yield strengths in excess of 180 ksi, adequate ductility, and plane strain fracture toughness comparable to parent metal with weld joint efficiencies greater than 95 percent can be produced in HP 9-4-20 1/2-inch plate without the use of pre-heat or post-heat. These properties can be obtained by either the automatic or manual gas tungsten-arc welding processes provided low energy inputs (24.8 K-joules/inch/pass) are used for the automatic process and the stringer bead technique is used for the manual process. Small additions of Al or Ti to HP 9-4-20 wire resulted in improved radiographic quality and strength. Improved fracture toughness was obtained only with aluminum additions. Welds made by the MIG process failed to meet the criteria of the program. This was attributed to microcracking in the weld.

Desirable tensile properties (in excess of 184.6 ksi yield strength and 199.4 ksi ultimate strength) with adequate ductility and fracture toughness comparable to parent metal can be obtained in 1-inch thick HP 9-4-25 material. In addition, automatic horizontal and manual vertical TIG welding can be successfully accomplished. However, TIG welds in double U-groove joint designs appear to be susceptible to centerline cracking.

The AMS 6435 parent metal quenched and tempered between 450 and 800°F resulted in yield strengths well within the desired 180 to 200 ksi range. However, relatively low ductility was obtained in transverse TIG weld specimens regardless of parent metal heat treatment or weld parameter. Adequate strength and ductility was obtained in each TIG weld deposit (all-weld metal specimens) consisting of low carbon D6AC, 1722 AS, and HP 9-4-20 wires. Based upon these results, work on this material was discontinued.

Desirable tensile properties were obtained in Vasco Jet X-2 1/2-inch plate; however, the fracture toughness properties in this material were low. In addition, the ductility and fracture toughness of TIG welds in this material were poor. Therefore, Vasco Jet X-2 was considered as not acceptable with respect to the program requirements and further work on it was discontinued.

The martensitic D6AC metal smooth tensile properties and fracture toughness were similar to that obtained in the HP 9-4-20 material. However, the Charpy V-notch impact properties for this material were low. This, coupled with the low ductility values obtained in transverse specimens from TIG weldments and the frequent failures of these specimens in the weld, indicates that this high carbon material possibly should not be investigated further as a martensitic material. However, D6AC material with a lower carbon level would possibly perform with better properties in the weldments.

The smooth tensile properties of the HP 9-4-45 base material austempered at 550°F for 7 hours were satisfactory with regard to the criteria for the program. In addition, the plane strain fracture toughness was comparable to that of the HP 9-4-20 martensitic; however, the values were less than those observed for the HP 9-4-25 1-inch plate heat treated to the martensitic condition. The Charpy impact properties were considered satisfactory, but the lateral expansion obtained was comparatively poor.

Although desirable smooth tensile properties were not obtained in TIG or MIG weldments, it was calculated that a 25 percent increase in the TIG weld heat-affected zone area for a distance of 1-inch on either side of the weld centerline would cause fracture to occur in parent metal. However, the poor fracture toughness values observed for the weld and heat-affected zone, coupled with poor resistance to overtempering, make this material unattractive for the requirements of this program.

Desirable smooth tensile properties can be obtained in D6AC material isothermally transformed at 575°F for 3 or 8 hours. However, the 8 hour transformation time produced the properties most desirable for the criteria of the program, (195.4 ksi and 249.2 yield and ultimate strengths, respectively, with 16 percent elongation and 55.3 percent reduction of area). In addition, desirable TIG weld deposit smooth tensile properties can be obtained when using filler wire No. 6, a welding speed of 4 ipm, argon shielding, and an energy input of 44.6 K-joules/inch/pass and a preheat and interbead temperature of 480°F with a post-heat of 575°F for 2 hours. However, the ductility and joint efficiency determined on transverse TIG weld specimens which fracture in the heat-affected zone were low. These results indicate that D6AC material is worthy of further investigation as a bainitic material.

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13. ABSTRACT

The object of this program was to develop welding procedures and filler materials for joining martensitic and bainitic steels in the 180 to 200 ksi yield strength range.

The martensitic steels studied were HP 9-4-20, HP 9-4-25, AMS 6435, Vasco Jet X-2, and D6AC. The HP 9-4-XX steels could be successfully joined using the gas tungsten arc (TIG) process without a subsequent post-heat. Manual TIG welding could also be similarly accomplished in the HP 9-4-20 material. Reduced porosity and improved mechanical properties were obtained in weldments in the HP 9-4-20 steel by making additions of Ti and Al to filler wires of base metal composition. The D6AC steel was capable of producing TIG weld joints of acceptable strength, but a definite lack of ductility was present and prosity in the weld deposits occurred often. The AMS 6435 and Vasco Jet X-2 steels could not be successfully joined without a post-heat during this program.

The bainitic steels examined consisted of HP 9-4-45 1/2-inch plate and 0.090-inch sheet and D6AC 1/2-inch plate. In no instance did welds in the HP 9-4-45 steel plate yield tensile properties comparable to that of the parent metal. However, it was calculated that a 25 percent material build-up at the joint could insure failure in the parent metal. Acceptable strength could be obtained in the sheet material, but low ductility was also invariably present. The D6AC steel could be TIG welded to produce acceptable properties in the weld deposit; however, the heat-affected zones were weak. Additional studies could possibly lead to successful welding techniques for this material.

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ABSTRACT (continued)

Heat-affected zone strength and toughness characteristics of D6AC and HP 9-4-45 were studied using a synthetic weld thermal cycle technique. Specimens were exposed to peak temperatures between 1000 and 2400°F. The lowest strengths were associated with peak temperatures of 1200 and 1350°F. In the D6AC steel exposed to peak temperatures between 1450 and 1850°F, very low fracture toughness was produced.