MARAD RESEARCH PROJECT

HIGHER STRENGTH STEELS SPECIALLY PROCESSED FOR HIGH HEAT INPUT WELDING

FEBRUARY 1985

American Bureau of Shipping
65 Broadway
New York, N.Y. 10006

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FOREWORD

This report presents the results of a research and development project initiated by the Ship Production Committee of the Society of Naval Architects and Marine Engineers and financed through a cost sharing contract between the U.S. Maritime Administration, Newport News Shipbuilding and Drydock Corporation and the American Bureau of Shipping. The principal objective was to identify steels used for hull construction that are resistant to heat affected zone degradation when welded with high heat input welding processes.

Special acknowledgement is made to the members of Welding Panel SP-7 of the SNAME Ship Production Committee who served as technical advisors in the preparation of inquiries and evaluation of subcontract proposals; to Mr. B.C. Howser, Newport News Shipbuilding, SP-7 Panel Chairman and to Mr. M.I. Tanner, Newport News Shipbuilding, SP-7 Program Manager.

The program was carried out by the American Bureau of Shipping under the direction of Mr. I.L. Stern; Mr. M. Wheatcroft was the Project Manager; Dr. D.Y. Ku served as the Project Engineer and Mr. R.F. Waite supervised the laboratory testing.

In addition, the services of Avondale Shipyard; New Orleans, Louisiana in preparing the test weldments, the U.S. Naval Ordnance Station; Manufacturing Technology Department, Louisville, Kentucky in conducting the explosion bulge tests and the Nippon Steel Corporation and Kawasaki Steel Corporation who supplied the base metals are acknowledged.

EXECUTIVE SUMMARY

ABS Grade EH36 steel plates, specially formulated and produced with advanced metallurgical techniques are shown to have a significantly greater resistance to weld heat affected zone (HAZ) degradation than conventional EH36 steel. Welds made in these steels with the electroslag welding process at high heat input rates retained adequate toughness in the heat affected zone at -4°F (-20°C); similar welds in conventional EH36 steel plate exhibit excessive HAZ toughness loss. The above was confirmed on the basis of small scale Charpy V-notch and large scale explosion bulge testing. In view of their superior resistance to HAZ degradation, the steels should also be useful for applications where HAZ degradation is of particular concern, such as for ABS, Coast Guard and International Maritime Organization (IMO) weld requirements for Liquefied Gas Carriers.

1.0 Background

A previous project, “Toughness Evaluation of Electrogas and Electroslag Weldments,” was completed by ABS under a welding research project sponsored by MARAD and ABS(Ref. 7). In this project the properties of welds in ABS ordinary and higher strength hull structural steels made with the electrogas (EG) and electroslag(ES) high heat input welding processes were compared with those from the shielded metal arc (SMAW) and submerged arc (SAW) welding processes with a view toward extending the applicability of the high heat input processes in shipbuilding. Comparisons were made with respect to toughness, as evaluated by Charpy V-notch (CVN), explosion bulge, drop weight and dynamic tear tests. Several general conclusions regarding the applicability of the welding processes to the ordinary and higher strength hull steels were drawn; one conclusion was that the principal impediment to extending the application of ES and EG welding to ABS Grade EH36 is low toughness properties in the HAZ.

A fundamental solution to the problem is to utilize steels metallurgically designed to retain adequate toughness in the HAZ. Such steels could also be advantageous for all welding processes in low temperature applications where HAZ toughness requirements are imposed.

2.0 Objective

The principal objective was to determine the suitability of specially treated and processed ABS Grade EH36 steels for welding with high heat input welding processes.

3.0 Achievement

The project has demonstrated the suitability of versions of ABS Grade EH36 steel plate which are specially suited for marine applications where resistance to HAZ degradation is of concern. Use of these steels should provide for welding of EH36 steel with the high deposition rate welding processes such as electroslag. These new steels should also be advantageous in applications such as low temperature service for carriage of liquefied gases, wherein minimum HAZ Charpy V-notch values are specified.

4.0 Approach

High toughness steels which are designed to retain significant toughness levels in the HAZ of welds have been recently developed. The approach in this project was to select candidate steels and weld these steels with ES welding processes which utilize exceptionally high heat input rates. Weldments in these steels were then evaluated by examining the results of small scale CVN impact tests of the HAZ, and of large scale explosion bulge tests to substantiate the CVN toughness indications. Results were compared with ES, SAW and MMA weldments obtained from a previous investigation of conventional normalized ABS EH36 steel (Reference 7).

5.0 Base Material Selection

Based on a literature search (l-4) and the availability of steel, the candidate steels selected were:

a. Ti-treated steel.

b. Ti-B-treated steel.

C. Ti-REM-B-V-treated steel (Note: REM = Rare Earth Metal).

The features common to these steels which distinguished them from the reference conventional EH36 steel were: extremely low sulfur levels, low carbon equivalents, fine ferrite grain size and intentionally added titanium. In addition, all had been produced with advanced metallurgical techniques (Thermomechanical Control processing and Thermomechanical Control Rolling).

Chemical composition and mechanical properties of base materials are shown in Tables 1 & 2. A discussion on the metallurgical characteristics of these steels is in the Appendix.

6.0 Weldment Preparation

The ES welds were made with a heat input rate of 480 KJ/in. at a shipyard. This heat input, which is toward the low end of the range typically used in ES welding, was used because available filler metals will not meet ABS required CVN values for EH36 when deposited with heat inputs of the order of 1000 KJ/in. Table 3 indicates the welding conditions and plate thicknesses.

Consumable nozzle electroslag (CES) weldments submitted by one of the manufacturers of the candidate steels were also evaluated. The steels, Ti-treated and Ti-B-treated were CES welded with the welding conditions shown in Table 4; heat inputs were 1252 KJ/in and 1146 KJ/in respectively.

Table 5 indicates the chemical composition of the electrodes used in ES and CES welding.

7.0 Testing Procedure

7.1 Mechanical Testing and Examination of Base Materials

The following testing was conducted for each base plate:

a) Longitudinal Tensile Tests (0.50 inch diameter specimen with 2 inch gauge length).

b) Longitudinal Charpy V-notch Tests.

c) Metallographic Examination.

7.2 Mechanical Testing and Examination of Weldments

7.2.1 Nondestructive Testing

Welds were evaluated by radiography and/or ultrasonic testing as indicated in 8.2.1.

7.2.2 Small Scale Mechanical Testing of Welds

The following mechanical testing was carried out:

a) Two transverse weld tensile tests (0.50 inch diameter specimen with 2 inch gauge length).

b) Charpy V-notch impact tests: Notches were located at the centerline of the weld, at the fusion line, and in the HAZ at 1, 3, 5, 7 and 9 mm from the fusion line.

c) Vickers Traverse of the Weld and HAZ.

7.2.3 Explosion Bulge Tests

Explosion bulge tests were conducted generally following standard procedures (5,6). The weight of the pentolite explosive charge (12 lb.) and the stand off distance (19 in.) to produce an approximate 3% thickness reduction after the initial shot were the same as were previously used for ABS Grade EH36 weldments (Reference 7). Data regarding charge and stand off distance used and thickness reduction obtained for an unwelded EH36 plate are shown in Table 6. A typical set up is shown in Figures 1 and 2.

Each weldment was cooled to 0°F (-18°C), tested (detonation of explosive charge) and subsequently measured and examined for evidence of separation. If separation was observed, the test was terminated. The above testing cycle was repeated until the weldment separation or after three shots.

7.2.4 Metallographic Examination of Weld and HAZ

Polished sections of the weld (including the HAZ) were etched with 2 percent Nital and examined at 100X magnification (see Appendix for discussion and photomicrographs).

8.0 Results and Discussion

8.1 Evaluation of Base Materials

The chemical composition and tensile properties of each base material are shown in Tables 1 and 2. The results of the CVN tests are shown in Table 7 for these candidate steels. Transition curves plotted for absorbed energy and lateral expansion to indicate transition characteristics are shown in Figures 17 and 18.

All results of the tensile and CVN tests met the specification requirements for ABS higher strength steel Grade EH36. The average CVN values of Ti-3 treated, Ti-B-REM-V treated and Ti-treated plates were substantially above the ABS requirement for EH36: at -40C 25 ft-lbs minimum for longitudinal specimens (See Table 2).

The microstructure of all the plates consisted of fine ferrite and pearlite as shown in Figure 3.

8.2 Evaluation of Weldinents

8.2.1 Nondestructive Tests

Radiographic inspection was performed by the shipyard for the ES welds used for large scale explosion bulge testing. Ultrasonic inspection was conducted by ABS for all ES welds used for small scale testing and all the CES welds made by the steel manufacturer. All welds met the applicable ABS Class A radiographic or ultrasonic inspection criteria.

8.2.2 Transverse Weld Tensile Tests

The test results are shown in Table 8. All the transverse weld tensile tests met ABS minimum tensile strength requirements for Grade EH36. All fractures occurred in base metal and HAZ locations. However, the tensile strengths of the weld joints for Ti-treated and Ti-B-treated plates are somewhat lower than their base metal strengths. This decrease is attributable to softening(9) of the HAZ with high heat input welding. The decrease could be taken into account by specifying base plate with 75 ksi minimum tensile strength in lieu of 71 ksi minimum for conventional EH36. The loss of strength occurred in Ti-treated and Ti-B-treated steels with thermomechanical control processing (TMCP) and accelerated cooling by water. The loss in strength was not observed in the weld in the Ti-B-REM-V-treated plate produced by thermomechanical control rolling (TMCR) without accelerated cooling. Reference 9 also indicates that a decrease in strength of low carbon equivalent steels may be expected after high temperature reheating treatments such as hot working and stress relief.

8.2.3 Hardness Tests

Vickers hardness surveys taken across the welds and converted to Rockwell B scale are indicated in Table 9 and Figure 19. As would be expected from their lower carbon equivalents the candidate steels showed less HAZ hardening as compared to the conventional ABS EH36 steel. The minimum HAZ harnesses of Ti-treated and Ti-B-treated weld joints were slightly lower than base metal harnesses. Ti-B-REM-V-treated plate weld joint did not show lower hardness at the HAZ as compared to the base metal. These results were consistent with the observed reductions of tensile strength noted in 8.2.2.

8.2.4 Charpy V-notch Impact Tests

Results of tests are shown in Table 10. Weldments of all three specially treated steels exhibited HAZ CVN impact energy values considerably above those previously obtained for the conventional EH36 ES weldments (Ref. 7 & 8). All results exceeded the ABS requirements for the EH36 weldments, with the Ti-B-treated steel exhibiting the highest CVN impact values. The EH36 reference weldment exhibited CVN impact values below the requirement of 30 ft-lbs at -20^{0}C.

8.2.5 Explosion Bulge Tests

The results of the explosion bulge tests are shown in Table 11 and photographs of the weldments after the final shot are shown in Figures 10 through 16. The results are summarized as follows:

Ti-treated Steel:

1. ES weldment (480 KJ/in, Figure 10) - The weldment fractured on the second shot at a thickness reduction of approximately 7 percent. The fracture initiated at the weld toe and arrested in base metal forming a “U” shaped path across the weld metal.
2. CES weldment (1252 K3/in, Figure 11) - This weldment withstood three shots without cracking. A fourth shot did not separate the specimen. The thickness reduction was approximately 15%.

Ti-B-treated Steel:

1. CES weldment (1146 KJ/in, Figure 12) - The weldment fractured on the first shot at a thickness reduction of approximately 3 percent. The fracture initiated in and propagated along the HAZ (for about) inch) before branching and arresting in the base metal. The fracture “path” crossed the weld at two locations.
2. ES Weldment (480 K3/in, Figure 13) - The weldment sustained two shots without fracture and separated along the weld toe on the third shot with approximately 12%A reduction in thickness.

Ti-B-REM-V-treated Steel:

1. ES weldment (480 KJ/in, Figure 14) - The weldment sustained one shot without cracking. On the second shot a multi-pathed, star-type fracture initiated in the base metal about 2 inches from the weld toe. Generally, all fractures arrested in base metal. The fracture paths crossed the weld metal at three locations. After two shots the weldment showed a reduction in thickness of approximately 7 percent.

2. ES weldment (480 KJ/in, Figure 15)-This weldment was exposed to three shots and exhibited approximately 1596 thickness reduction with no visible cracks.

3. ES weldment (480 KJ/in, Figure 16) - On the first shot a fracture initiated at and propagated along the weld toe (for about 1 inch) before propagating into and arresting in the base metal forming a “U’’-shaped fracture path. The reduction in thickness was approximately 3 percent.

The thickness reduction of the explosion bulge tested candidate steel weldments was considerably in excess of the previously tested electroslag weldments of conventional normalized EH36 steel (Ref. 7) and showed general correlation with thickness reduction results of previously tested manual metal arc and submerged arc weldments of conventional normalized EH36 steel (Ref. ‘7), which are shown in Table 12. In this regard, the general correlation of the candidate steel weldment results with those obtained for shipbuilding materials and welding processes that have shown satisfactory service experience, strongly indicates that the candidate steels welded by the electroslag processes described herein should also provide satisfactory service.

The candidate steel electroslag weldments exhibited good HAZ toughness; fracture at HAZ locations generally propagated away from the HAZ and arrested in the base metal. These results were greatly superior to the conventional normalized EH36 electroslag weldments where complete separation along the weld (at the HAZ) occurred on the first shot for three of four test specimens.

9.0 Conclusions

On the basis of this study and the results obtained, the following conclusions are drawn:

1. The three steels studied showed significant resistance to toughness degradation in the HAZ when exposed to high heat input welding processes.
2. The HAZ toughness of three candidate steels welded with a heat input 480 KJ/in. met ABS Grade EH36 weldment requirements.
3. The HAZ toughness of Ti-treated and Ti-B-treated steel welds with consumable nozzle electroslag (CES) heat input 1252 KJ/in. and 1146 KJ/in. respectively, met ABS Grade EH36 weldment requirements.
4. The resistance of the three specially treated steels to HAZ degradation make them attractive for use in applications where HAZ requirements are mandated (as for liquefied gas carriers).
5. Ti-treated and Ti-B-treated plates (thermomechanical treated and accelerated cooled) exhibited a small loss of strength in the HAZ of high heat input welds. The effect was not observed in the Ti-B-REM-V-treated steel which was thermomechanical treated with no accelerated cooling. Special studies would be required to determine if the above observations were characteristic of the treatments noted.

10.0 Recommendations

It is recommended that specially processed and treated steels of the type investigated be considered for applications, such as liquefied gas carriers where HAZ toughness is a requirement, and for electroslag welding of ABS higher strength steels..

APPENDIX

Commentary on the Effects of Chemical Composition and Manufacturing Processes on HAZ Toughness of Microalloyed Steels.

The HAZ toughness of normalized, vanadium or niobium treated steels, such as Grade EH36 is impaired when welded with high heat input processes. At a temperature of 1050°C dispersed niobium or vanadium carbides, nitrides or carbo-nitrides dissolve(10,11). This decrease in the amount of the precipitates, which function as grain growth inhibitors and strengtheners, is a factor in the resultant degradation of HAZ properties. The reduced Charpy V-notch HAZ toughness developed by high heat input welding is considered partly related to grain growth and partly related to the resultant microstructure. In order to obtain adequate HAZ toughness, good weldability and adequate base material characteristics, consideration is generally given to the following:

A) Chemical Composition

1) Carbon Equivalent - It is generally recognized that the most effective way to imrove weldability is to lower the carbon equivalent and thereby reduce the likelihood of untempered martensite formation, with its attendant high hardness and low notch toughness. Table 5 of the test indicates that all three candidate steels investigated had significantly lower carbon equivalents than that of conventional, normalized EH36 whose Ceq was 0.46. The carbon equivalents of Ti-treated, Ti-B-treated and Ti-B-REM-V-treated plates were 0.30%, 0.31% and 0.35% respectively. This low carbon equivalent is a contributing factor in the superior HAZ

toughness for the subject steels as compared with the conventional, normalized EH36 steel.

2) Grain Refinement in HAZ - For Ti-treated steel, austenite grains can be refined through “pinning” ability of finely dispersed titanium nitrides (TiN). Fine TiN precipitates, smaller than 0.05µn in size, remain undissolved at 1400^0C(12) and are effective in retarding austenite grain coarsening. The stoichiometric ratio of Ti to N should be equal to or no more than 3.5:1. In addition, calcium or magnesium may also be used together with Ti (or Zr) to form fine precipitates (13) for inhibiting grain growth. Very fine Ca or Mg inclusions serve as nucleation sites for TiN precipitate. In the case of Ti-B-REM-V treated steels, the rare earth metal forms globular inclusions(3)of cerium sulphides (Ce_2S_5) and oxysulphldes (Ce_20_2S) which are resistant to deformation during hot rolling and maintain their globular form, unlike manganese and” iron sulphides which elongate. The favorable effect of globular inclusions and increased cleanliness of the grain boundaries generally improves toughness in the HAZ. With optimized Ce additions, rapid grain growth is retarded up to 1200^0C(14). Boron also refines ferrite grains by creating ferrite nucleation sites of BN.

3) Lowering Impurity Content - Reducing sulfur, phosphorus, nitrogen and oxygen in a steel improves toughness in both the base metal and HAZ. The sulphide or phosphide formed in steel with a lower melting point can dissolve and precipitate in the grain boundaries in the overheated HAZ. All three candidate steels had approximately the same amount of phosphorus as EH36 materials shown in Table 5. However, the sulfur content for all three candidate steels is considerably less than EH36.

B) Manufacturing Process

To enhance weldability, all candidate steel had been formulated with a lower carbon equivalent than conventional, normalized EH36 steel. A drawback associated with lowering of the carbon equivalent is a commensurate reduction of base metal strength. This drawback can be alleviated by plate rolling practices that afford strict control of rolling temperature, rolling reduction ratios and accelerated cooling of the finished plate.

The Ti-treated plates and the Ti-B-treated plates had been manufactured by Thermomechanical Control Processing (TMCP); the Ti-B-REM-V-treated plates had been manufactured by Thermomechanical Control Rolling (TMCR) process.

In both TMCP and TMCR the first stage rolling is conducted in the recrystallized austenite region between 1150°C and 950°C, to produce fine austenite grains. The second stage rolling is performed in the non-recrystallized austenite region between 950°C and 750°C. The rolling reduction in this region induces deformation bands; consequently, during austenite-ferrite transformation, ferrite is generated not only from the initiation site of the austenite grain boundaries but also from deformation bands produced by rolling in the non-recrystallization zone, resulting in a finer grain structure. The above two steps are similar to conventional controlled rolling (CR); TMCP and TMCR differ from CR in that after second stage rolling, the following additional processing is applied.

TMCP:	Accelerated cooling by water, carried out after CR; this enhances mechanical properties.
TMCR:	A third stage rolling in the austenite-ferrite two phase region after CR; this enhances mechanical properties.

C) HAZ Microstructure

Conventional ordinary and higher strength steels welded with electroslag exhibit coarsened grains in the HAZ. These coarse grains are delineated by proeutectoid ferrite which nucleates at, and grows from the austenite grain boundaries. Also a large amount of Widmanstatten secondary ferrite plates develop from grain boundaries (see Reference 7 of text). In general, the mixed structure of coarse mesh-like proeutectoid ferrite and Widmanstatten side plates result in low toughness.

Macrosections representative of each candidate steel weldment are shown in Figure 4. Photomicrographs of the weld metal and HAZ representative and illustrated in Figure 5 through 9 for candidate steels. The photomicrographs reveal uniform microstructures consisting of relative fine acicular ferrite and pearlite instead of coarse intermediate stage structures for conventional ordinary and higher strength steels in the HAZ. Because of the effect of the low carbon content(15)or pinning effect of TiN, generation of ferrite in the austenite grain boundary and intragranular ferrite side plate was suppressed, resulting in a significant improvement in HAZ toughness. The results of Charpy and bulge tests confirm this.

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TABLE 1. CHEMICAL COMPOSITION OF BASE MATERIAL

Plate Type	Chemical Composition %															
	C	Mn	Si	P	S	Al	Ti	Cu	Ni	Cr	Mo	V	Cb	B	REM	Ceq*
ABS EH 36 (Ref.7)	0.18	1.44	0.27	0.009	0.02	0.043		0.03		0.17	0.005		0.036			0.46
Ti-treated	0.12	1.05	0.20	0.011	0.003	0.035	0.009									0.30
Ti-B-treated	0.08	1.38	0.27	0.007	0.001	0.054	0.007							0.0011		0.31
Ti-B-REM-V treated	0.08	1.54	0.46	0.01	0.001	0.026	0.008					0.042		0.0013	0.007	0.35
ABS Req't. EH36	0.18 max.	0.90-1.60	0.10-0.50	0.04 max.	0.04 max.			0.35 max.	0.40 max.	0.25 max.	0.08 max.	0.01 max.	0.05 max.			

Note * Ceq = C + Mn/6 + (Cu + Ni)/15 + (Cr + Mo + V)/5

TABLE 2 TENSILE PROPERTIES OF BASE MATERIALS(1,2)

Plate	EH36 (Ref .7) Killed Fine grain Normalized	Ti-treated Killed Fine grain TMCP	Ti-B-treated Killed Fine grain TMCP	Ti-B-REM-V treated Killed Fine grain TMCR
Tensile Strength(ksi)	73.7	73.2	75.5	71.2
Yield Point (ksi)	51.3	51.8	60.6	52.7
Elongation in 2 in.	30.0	35.5	32.5	36.0

Note (1) Average of 2 tests.

(2) ABS Requirement for EH36

Tensile Strength (ksi)	71-90
Yield (ksi, min.)	51
Elongation in 2 inches (% min.)	22
CVN Impact Test	
Temperature (°C)	-40
Energy - (ft-lbs,Avg.Min)	
Longitudinal Specimen	25
or	
Transverse Specimen	17

TABLE 3 WELDING PARAMETERS FOR ELECTROSLAG WELDING (ES) BY SHIPYARD

Steel	ABS Grade EH36	Ti-treated	Ti-B-treated	Ti-B-REM-V treated
Filler Wire	Linde MI88	Linde MI88	Linde MI88	Linde M188
Flux	Linde 124	Linde 124	Linde 124	Linde 124
Wire Size (in.)	3/32	3/32	3/32	3/32
Current (A)	390	500	500	500
Voltage (V)	37	40	40	40
Travel Speed (in./min.)	2	2-1/2	2-1/2	2-1/2
Approx. Heat Input (Kilo Joule/in.)	432	480	480	480
Plate Thickness (in.)	1-1/4	1-3/8	1-1/4	1-1/4

Joint Design

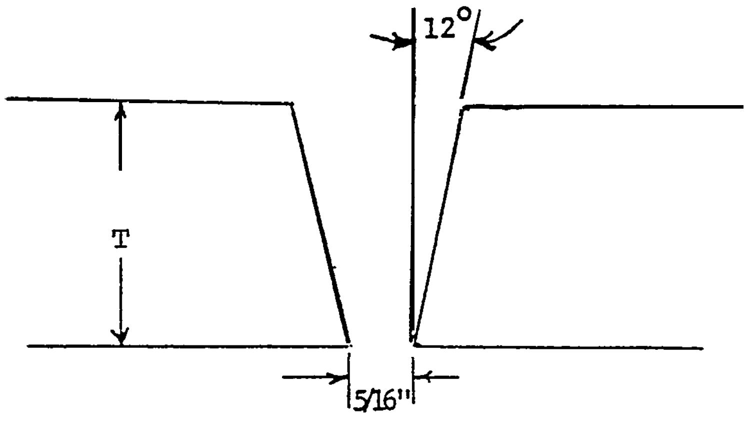


TABLE 4 WELDING PARAMETERS FOR CONSUMABLE NOZZLE ELECTROSLAG WELDING (CES) BY STEEL MANUFACTURER

Steel	Ti-treated	Ti-B-treated
Filler Wire	A	A
Consumable Nozzle	B	C
Flux	D	D
Wire Size (mm)	2.4	2.4
Nozzle Size (mm)	12	12
Current (A)	450	400
Voltage (V)	42	40
Travel Speed (in./min.)	0.906	0.839
Approx. Heat Input (Kilo-Joule/in.)	1252	1146
Plate Thickness (in.)	1-3/8	1-1/4

Joint Design

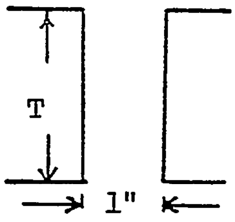


TABLE 5 CHEMICAL COMPOSITION OF FILLER WIRE

Electrode	Welding Process	C	Mn	Si	P	S	Cr	Ni	MO	Cu
Linde MI88	ES	0.04	1.65	0.35			0.25	1.5	0.4	-
A	CES	0.07 I 0.13	1.35 1 2.00	0.08 max.	0.02 max.	0.023 max.	0.15 max.		0.40 0.60	0.15 max.

TABLE 6 EXPLOSION BULGE TEST - CHARGE AND STAND OFF DISTANCES VS DEFORMATION

Grade	Thickness (in.)	Test Temp. (F)	Stand Off Distance (in.)	Charge (lb.)	Shot No.	% Reduction		Depth of Bulge (in.)		Remarks
						A	B	A	B	
EH36 (Unwelded plate)	1-1/4	-20 (-29C)	19	12	1	2.8	3.2	1.2	1.2	No cracks
					2	6.2	5.9	2.1	2.1	No cracks
					3	9.7	8.6	2.7	2.8	No cracks

TABLE 7 INDIVIDUAL CHARPY V-NOTCH TEST RESULTS ON BASE PLATES

Plate	Test Temperature (c°)	Energy Absorbed (ft-lbs)	Shear Fracture Appearance (%)	Lateral Expansion (MILS)
EH36	-29	103, 98, 101 98, 107	100, 100, 100 100, 100	69, 72, 70 69, 70
	-40	67, 70, 69 49, 66	50, 60, 65 50, 60	53, 54, 52 40, 52
	-62	37, 36, 33 30, 19	5, 10, 25 15, 5	21, 28, 43 23, 16
	-73	15, 25, 14	2, 5, 2	10, 18, 9
Ti-Treated	-20	125, 127, 184	100, 55, 100	81, 82, 82
	-40	86, 85, 68	10, 10, 10	66, 65, 57
	-60	6, 43, 46	0, 5, 0	4, 41, 37
	-80	29, 11, 10	5, 5, 0	24, 7, 6
	-100	2, 3, 6	0, 0, 0	4, 0, 0
Ti-B-Treated	-20	262:,262:,262:	100:,100:,100:	
	-40	262*,262 ,262*	100*,100, 100*	91*,90*,99;
	-60	262 ’169 ,262	100 , 60, 100	88 ,94 ,92
	-80	19, 81, 39	0, 60, 10	17, 76, 38
	-100	9, 9, 27	5, 0, 5	9, 9, 28
	-120	4, 4, 4	0, 0, 0	4, 1, 1
Ti-E-REM V-Treated	-20	262*,262:,262*	100: 100; 100*	106*,81**103*
	-40	126, 262 , 98*	50, 100* 50	95, 103 ,67*
	-60	100, 55, 262	30, 10, 100	82, 47, 85
	-80	8, 100, 7	5, 40, 5	7, 73, 07
	-100	4, 5, 4	0, 0, 0	0, 2, 1

NOTE : *Partial break. Maximum test machine capacity 264 ft-lbs.
Data for information only: not valid according to ASTM E23.

TABLE 8 ELECTROSLAG WELD TRANSVERSE TENSILE PROPERTIES

WELDMENT BASE METAL	HEAT INPUT (KJ/IN.)	TENSILE STRENGTH (KSI)	FRACTURE LOCATION
ABS EH36 (Ref.7)	432	82.4, 81.5	Base Metal
Ti-treated	480	69.5, 71.0	HAZ
	1252	68.0, 69.5	HAZ
Ti-B-treated	480	68.0* 67.7:	HAZ
	1146	71.4, 70.0	HAZ
Ti-B-REM-V-treated	4S0	73.6, 74.3	Base Metal
ABS Req’t EH36		68-90	Base Metal

Note: # For base metal tensile strengths, see Table 2

* Steel manufacturer’s test data

\+ Considered (68 ksi)

TABLE 9 VICKERS HARDNESS TRAVERSE ACROSS WELDS
HARDNESS CONVERTED TO ROCKWELL “B” NUMBERS

Plate	EH36	Ti-treated	Ti-treated	Ti-B-treated	Ti-B-treated	Ti-B-REM-V treated
Heat Input K. J/in.	432	1252	480	480	1146	480
Specimen No.	E7	M36	N1	M52	M56	M64
Base Metal	82	82	80	79	60	81
11 mm from F.L.	84	79	76	81	76	86
9 mm from F.L.	86	80	76	81	76	83
7 mm from F.L.	87	78	76	80	77	81
5 mm from F.L.	90	80	76	81	78	84
3 mm from F.L.	95	80	77	82	79	84
1 mm from F.L.	96	85	82	86	83	88
Fusion Line	98	87	86	91	83	87
Weld Metal	99	89	90	90	94	94
Fusion Line	96	83	87	89	87	90
1 mm from F.L.	96	74	83	80	84	93
3 mm from F.L.	94	78	77	78	80	87
5 mm from F.L.	90	77	76	77	76	86
7 mm from F.L.	86	76	76	76	77	85
9 mm from F.L.	86	77	75	73	79	85
11 mm from F.L.	84	76	77	75	81	84
Base Metal	82	79	79	80	77	78

TABLE 10 INDIVIDUAL CHARPY V-NOTCH TEST RESULTS FOR ELECTROSLAG WELDS

:e	Heat Input KJ/in.	Test Temp °C	Absorbed Energy (ft-lbs)							
			Weld	F.L.	HAZ 1 mm	HAZ 3 mm	HAZ 5 mm	HAZ 7 mm	HAZ 9 mm	Base Metal
;	315	-20	33, 31, 31	23, 29, 22	12, 10, 10	89, 93, 99	74, 78, 77	93, 95, 85		88, 90, 91
.7&8)	432	-40	25, 25, 30	30, 49, 57	7, 8, 10	19, 22, 17	98, 101, 101	98, 74, 97	112, 98, 105	67, 70, 69
			30, 35, 20	5, 8, 8	6, 7, 9	8, 22, 6	68, 67, 101	99, 100, 86	100, 79, 108	49, 66
eated	480	-20	23, 22, 35	47, 24, 147	112, 128,24	116, 134,140	122, 234+, 240+	262*, 262*, 262*	262*, 262*, 262*	101, 124, 135
		-40	14, 14, 14	72, 17, 89	96, 90,84	92, 114, 96	255*, 262*, 258+	262*, 258*, 262*	262*, 262*, 262*	
	1252	-20	33, 31, 15	143, 64, 93	42, 82, 113	98, 114, 219+	253*, 262*, 252*	262*, 262*, 262*	262*, 222, 262*	175, 127, 184
			22, 28, 66	86, 76, 25	227, 28, 132					
		-40	9, 11, 13	13, 12, 15	24, 110, 112	24, 101, 199+	217+, 258,* 215+	262*, 262*, 262*	262*, 262*, 262*	86, 85, 68
treated	480	-20	86, 49, 77	262*, 262*,262*	56,260*, 262*	262*,262*,262*	262*, 262*, 262*			262*, 262*,262*
		-40	38, 34, 24	46, 28, 89	261*,262*	262*,262*,262*	262*,262*, 262*			262*,262*,262*
	1146	-20	84, 69, 71	262*,120,260*	261*,262*,262*	262*,261*,262*	262*,262*, 262*			262*,262*,262*
		-40	114,262*, 60	76, 30, 52	262*,262*,262*					
				120						
REM-V ted	480	-20	33, 38, 34	132, 35, 131	62, 48, 20	259*, 99, 155	262*,150,262*			262*,262*,262*
			49, 64, 52	17, 50, 43	262*,104, 35					
		-40	25, 24, 33	17, 78, 16	126,100, 80	51, 21, 65	105, 15, 82			126,262*,127

Note * Maximum test machine capacity 264 ft-lbs., partial break. Data for information only; not valid according to ASTM E23.

\+ Energy value above 80% of the test machine scale range is considered approximate according to ASTM E23.

TABLE 11 EXPLOSION BULGE TEST RESULTS FOR ES WELDS

Plate	Specimen No.	Heat Input (Kj/ln.)	Shot No.	Thickness Reduction% A	Thickness Reduction% B	Depth of Bulge(in.) A	Depth of Bulge(in.) B	Longest Crack (in.)	'Remarks
EH 36	E-7	432	1	3.2	3.6	1,3	--1.3		No visible cracks
			2	6.4	7.2	2,3	2.3		No visible cracks
			3	-	10.2	-		5.5	Large piece broke out of center area. Separation along weld A side right of center from hole to 1.8 in. of left edge along the weld part of this dietance. 5 cracks radiating from center area into base material with longest 5.5 in.
EH36	E-7A	432	1	3.3	3.6	1.4	1.3	10.0	Plate separated along weld from right of center of left edge. Crack across the weld into base material 8 in. long. 3 other cracks from center area into base material 3.2 to 3.5 in. long.
EN36	E-8	432	1	2.9	2.7	1.5	1.5	Plate Separated	Plate separated along weld with 2 small cracks into base material from weld.
EH36	E-8A	432	1	1.4	1.1	2.0	1.7	Plate Separated	Plate separated along weld.
Ti-Treated	M36-1	480	1	3.2	2.7	1.3	1.3		No visible crack
			2	7.4	6.5	2.6	2.5	17,38	Mainly U shaped tear from 4″ right of center across weld into base material A side 9-5/8″ B side 7-3/4″. Crack from 4″ right of center from 3/4″ from toe of weld. 2″ long on A aide and 1-1/2″ into base material B side.
Ti-Treated	M36	1252	1	3.2	3.7	1.2	1.2		No visible crack
			2	9.7	9.5	2.2	2.1		No visible crack
			3	11.1	11.2	2.7	2.7		No visible crack
			4	17.2	15.0	3.3	3.2		No visible crack
Ti-B-Treated	M56	1146	1	3.7	1.7	2.1	1.8	9.75	Crack A side toe of weld from 1″ left of center′ to 3-3/4″ left of center. Tear radiating from one end - 1" left center Into base material A side 2-1/4″ and B 2-1/4″, and from another end - 3-3/4″ left of center into base material Aside 2-5/8″ and B side 1-1/2″.
Ti-B-Treated	M52	480	1	5.0	3.9	1.6	1.5		No visible crack
			2		9.3	2.6	2.4		No visible crack
			3	12.3	11.3	3.3	3.5	18.0	Plate separated along weld on A side from right edge of plate to 2″ from left edge.

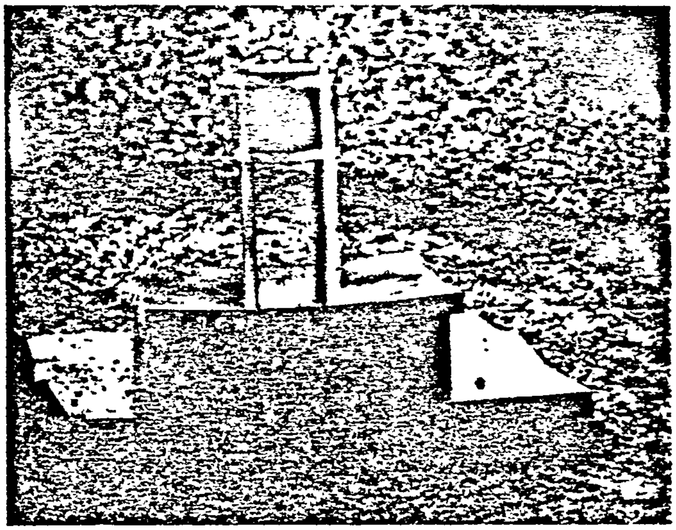
TABLE 11 EXPLOSION BULGE TEST SESULTS FOR ES WELDS (CONT’D)

Plate	Specimen No.	Neat Input (KJ/in.)	Shot No.	Thickness Reduction%		Depth of Bulge(in.)		Longest Crack (in.)	Remarks
				A	B	A	B		
Ti-B-REM-V Treated	K-1	480	1	5.9	6.3	1.6	1.6		No visible crack
			2	7.5	7.2	-	-	6.0	Plate failed in center with numerous tears radiating from toe of weld A side. Crack A aide from 4″ left of center into base material 1-1/4″ propagating to 1/2″ from edge of left side.
Ti-B-REM-V Treated	K-2	480	1	3.2	3.8	1.6	1.6		No visible crack
			2	7.5	7.0	2.6	2.5		No visible crack
			3	15.3	14.8	3.4	3.2		No visible crack
Ti-B-REM-V Treated	K-3	480	1	4.7	2.7	1.9	No reading Broken	11.25	U shaped tear B side from center into base material left 6-3/4″ center to right 4-1/2″. Crack B side l-1/2" from weld, 1-1/2″ from center to right 7-1/2″.

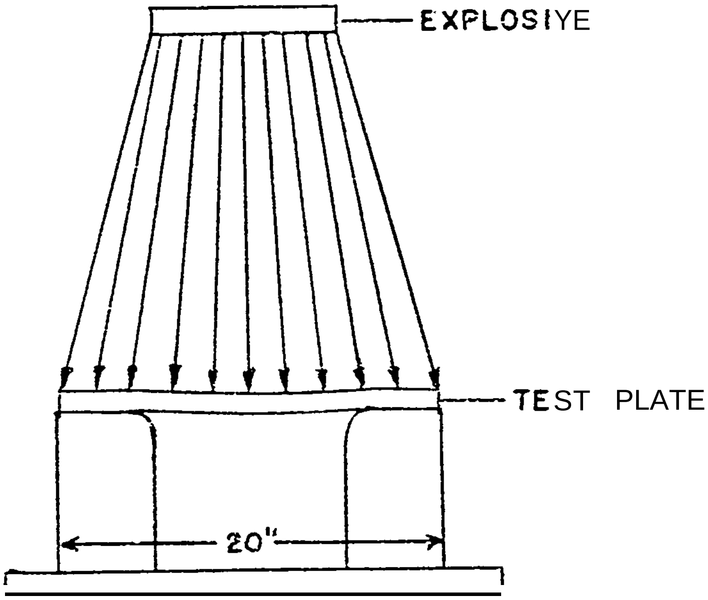
Note: All tests conducted at temperature of OF (-18C).

TABLE 12

Specimen No.	Welding Method	Heat Input (KJ/in.)	Shot No.	% Thickness Reduction A	% Thickness Reduction B	Depth Bulge(in.) A	Depth Bulge(in.) B	Longest Crack (in.)	Remarks
E-1	MMA	66	1	3.5	3.9	1.4	1.4		No visible cracks
			2	6.6	7.4	2.3	2.4		No visible cracks
			3	-	-	-	-		Entire center area blew out.
E-2	MMA	66	1	2.9	3.0	1.3	1.3		No visible crack
			2	7.2	6.7	2.4	2.3		No visible crack
			3	10.3	10.4	3.0	3.0		No visible crack
E-5	SAW	79	1	3.1	3.0	1.3	1.3		No visible crack
			2	6.8	6.7	2.3	2.2		No visible crack
			3	10.1	10.2	2.3	2.2		No visible crack
E-6	SAW	79	1	2.8	3.1	1.1	1.1		No visible crack
			2	6.3	6.8	2.2	2.2		No visible crack
			3	10.1	10.2	3.0	3.0		No visible crack

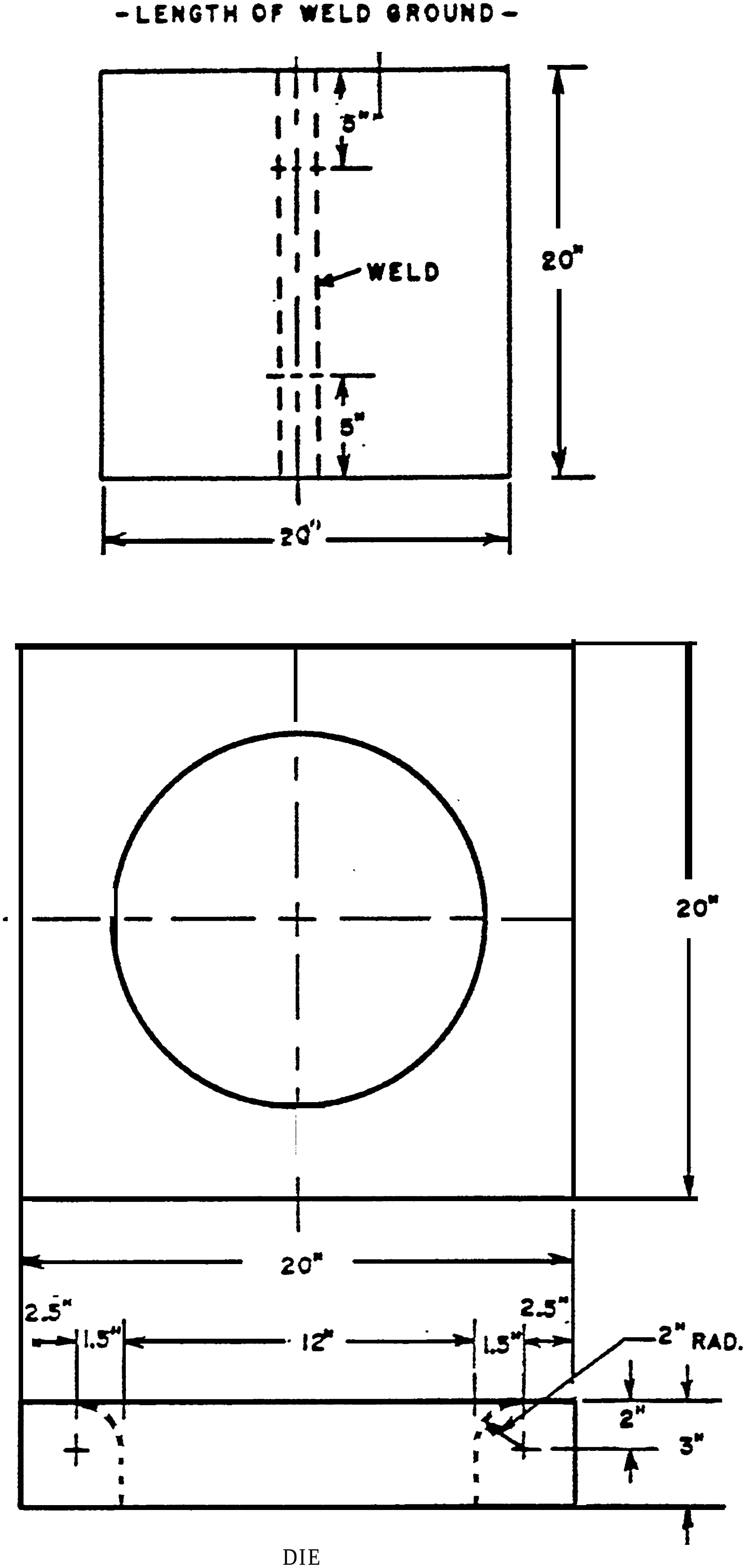


PHOTOGRAPH OF EXPLOSIVE CHARGE, SPECIMEN AND DIE



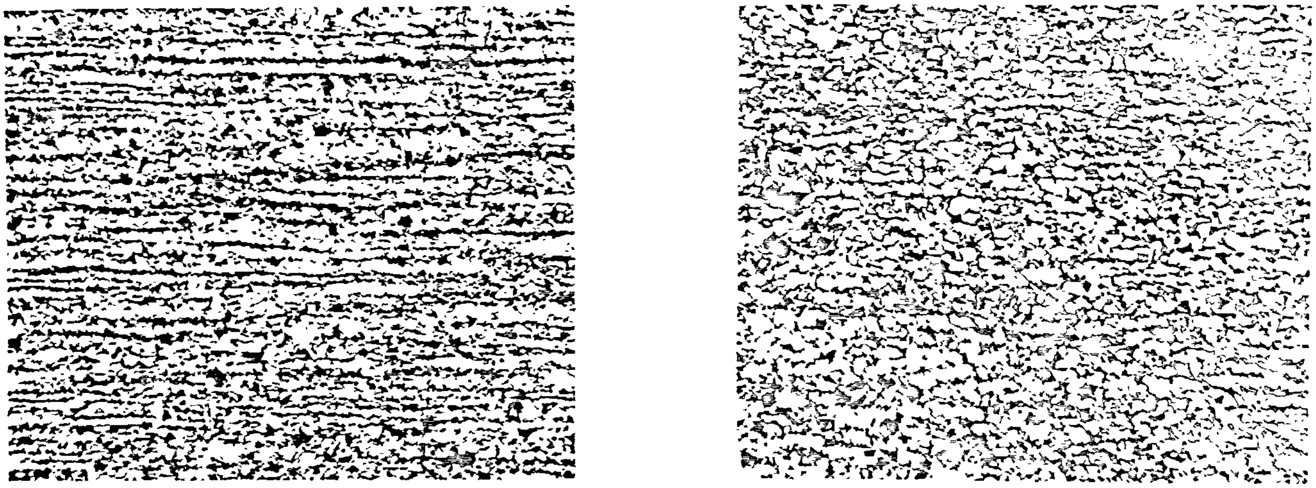
SCHEMATIC DRAWING OF EXPLOSION BULGE TEST

FIGURE 1- TYPICAL EXPLOSION BULGE SET-UP



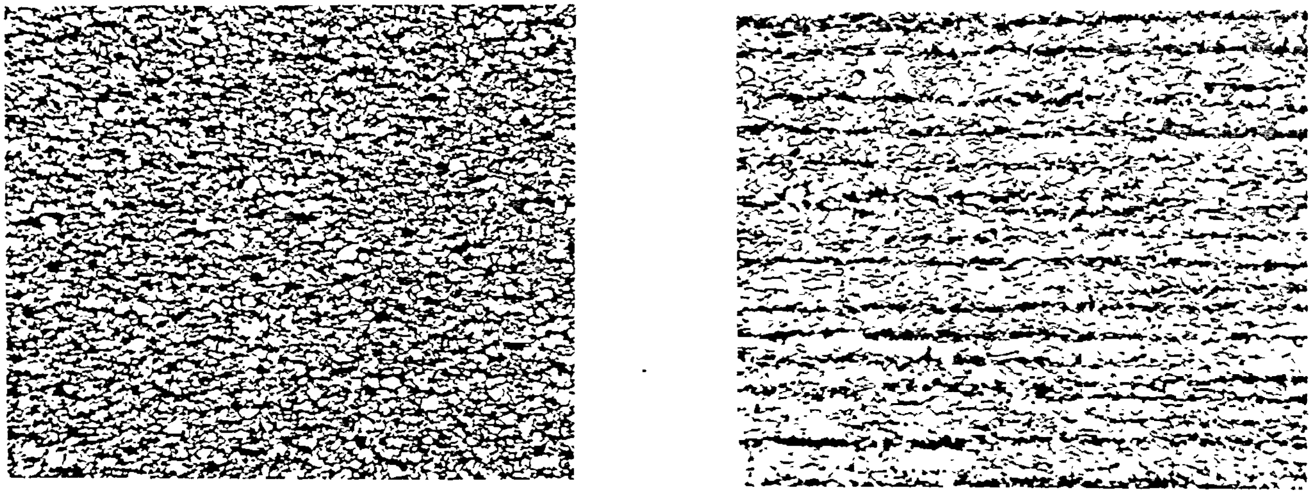
DIE

FIGURE 2 EXPLOSION BULGE SPECIMEN AND DIE



EH36

TI-TREATED

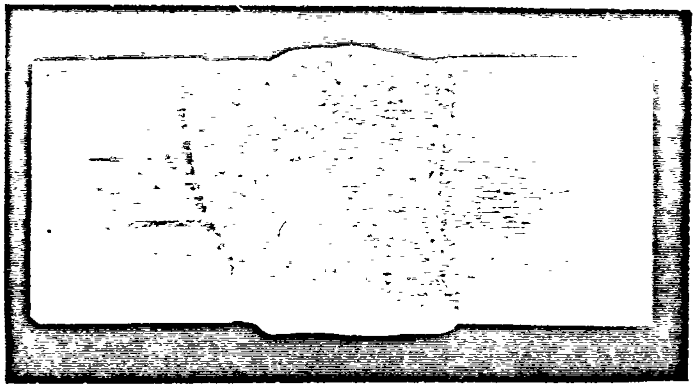


TI-B-TREATED

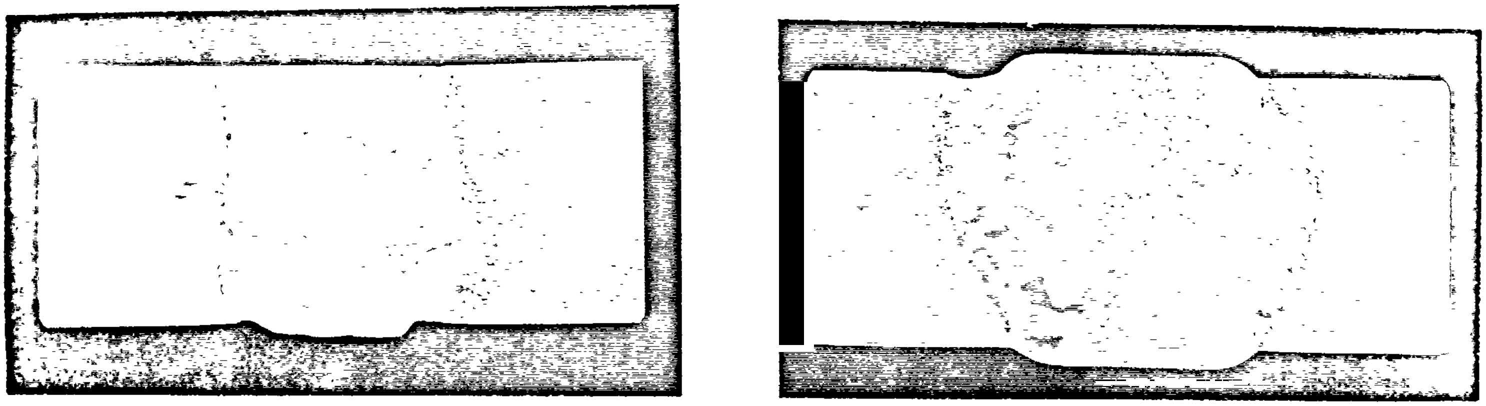
TI-B-REM-V-TREATED

(2% NITAL ETCH, 100X)

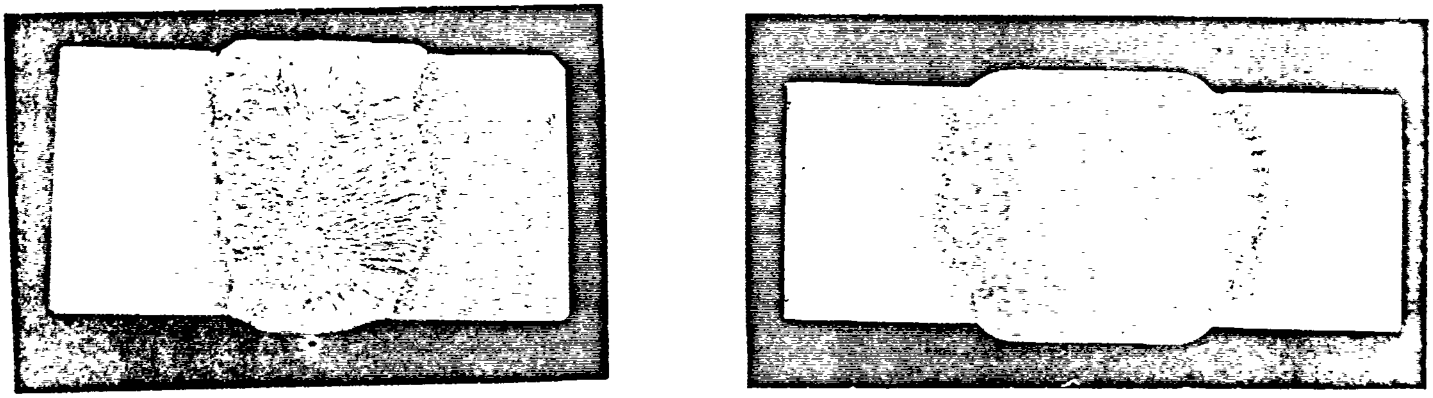
FIGURE 3 BASE METAL MICROSTRUCTURE



480 KJ/IN., TI-B-REM-V-TREATED



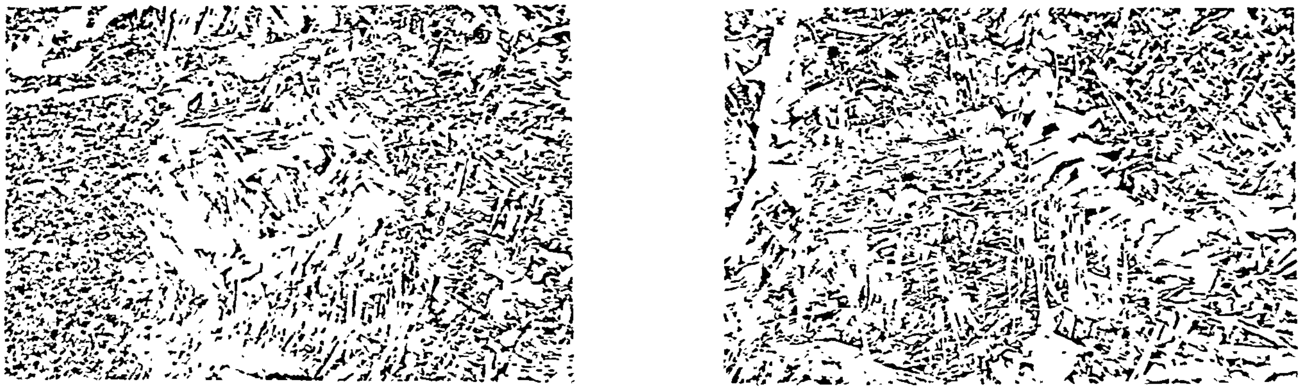
480 K. J/IN. TI-TREATED 1252 KJ/IN.



480 KJ/IN. TI-B-TREATED 1146 KJ/IN.

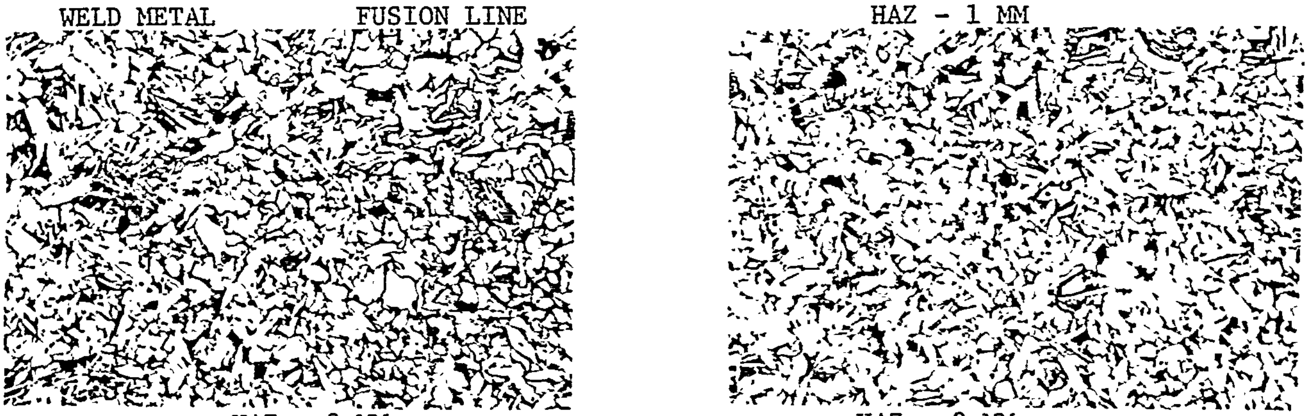
(10% NITAL ETCH, ACTUAL SIZE)

FIGURE 4 MACROSECTION OF WELDS



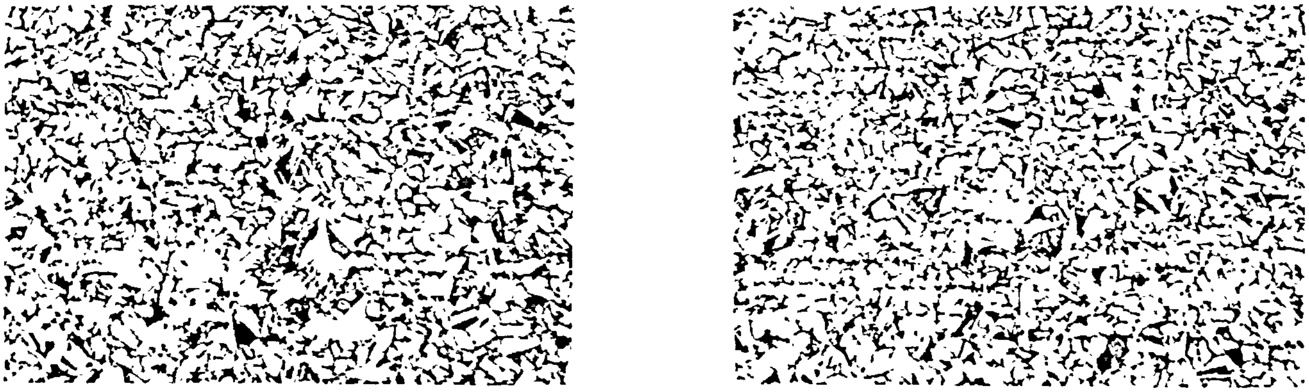
WELD METAL FUSION LINE

HAZ - 1 MM



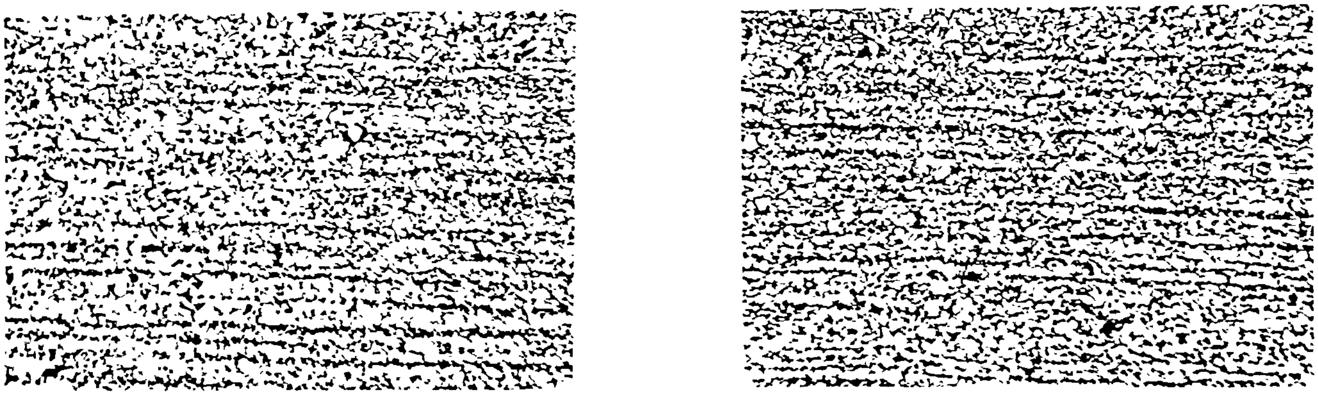
HAZ - 2 MM

HAZ - 3 MM



HAZ-4MM

HAZ-5MM

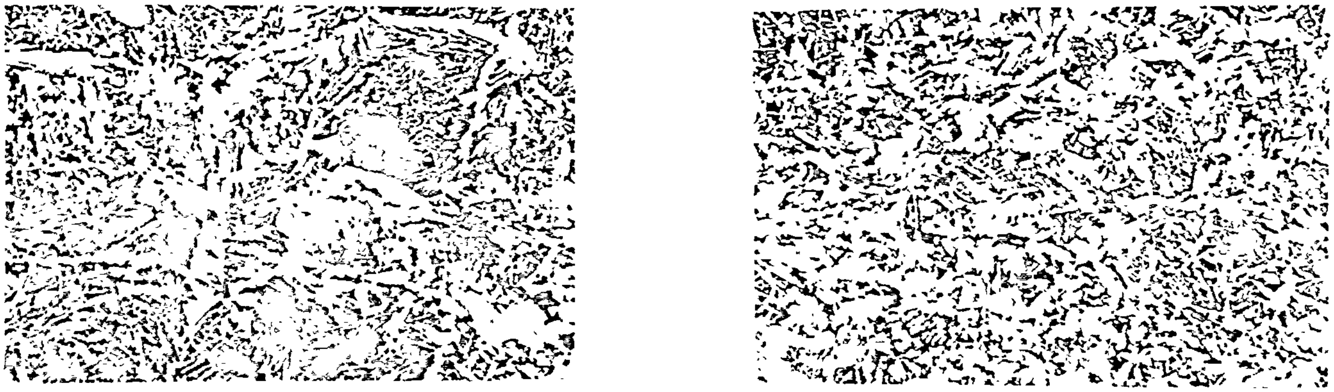


HAZ-7MM

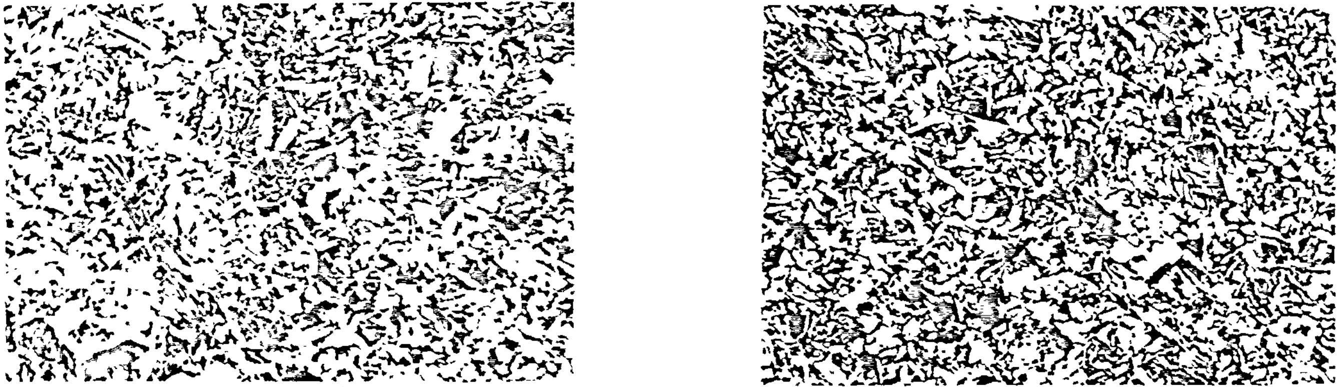
HAZ - 9 MM

(480 KJ/IN., 2% NITAL, 100X)

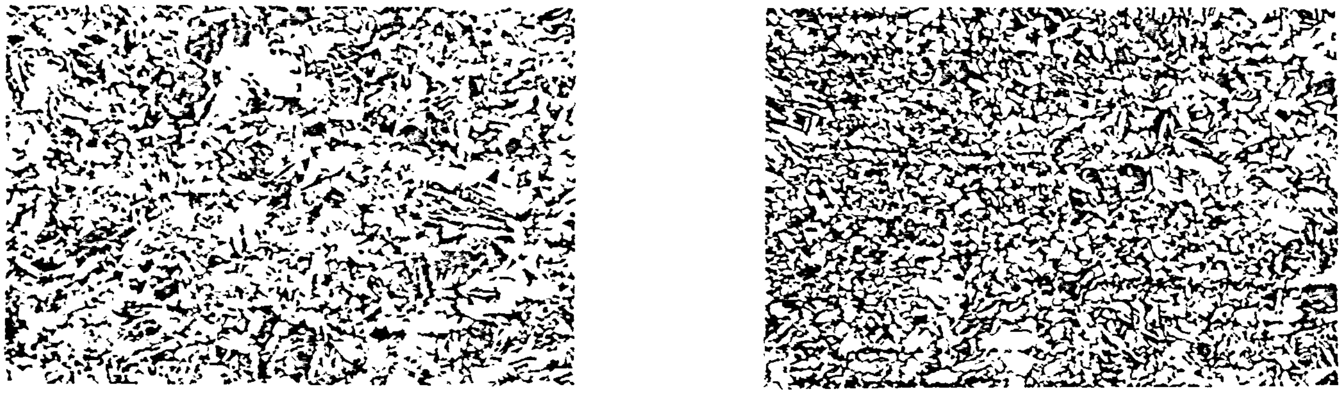
FIGURE 5 PHOTOMICROGRAPHS OF ES WELDMENT IN TI-TREATED STEEL


WELD METAL FUSION LINE

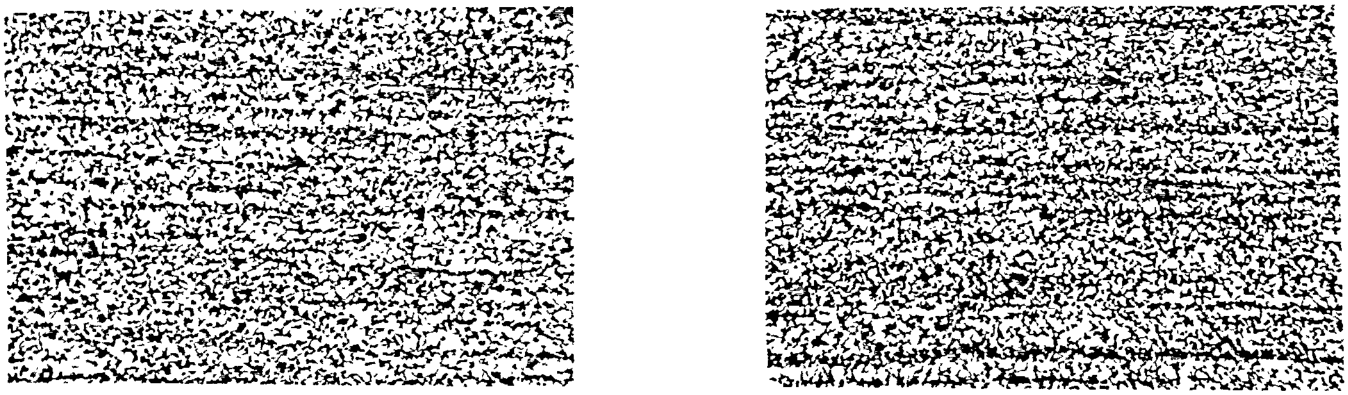
HAZ-1MM


HAZ-2MM

HAZ - 3 MM


HAZ -4MM

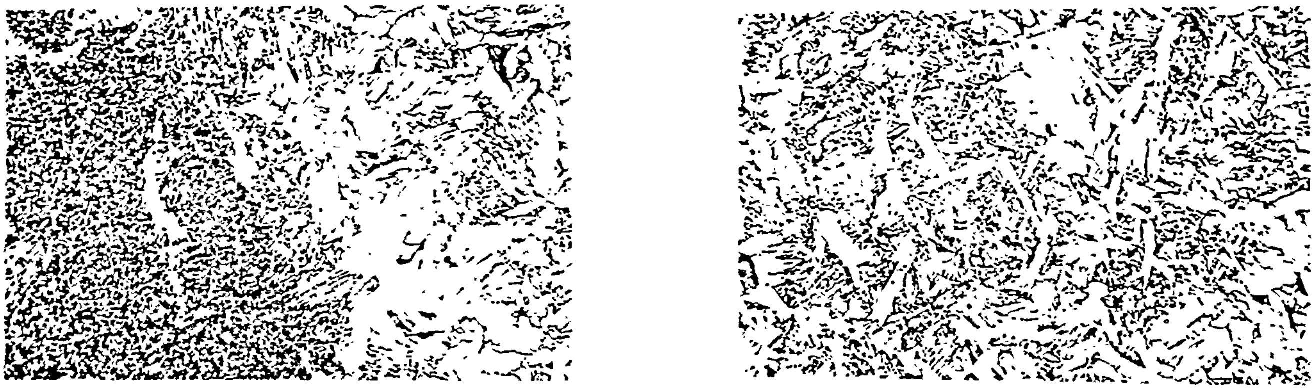
HAZ-5MM


HAZ-7MM

HAZ - 9 MM

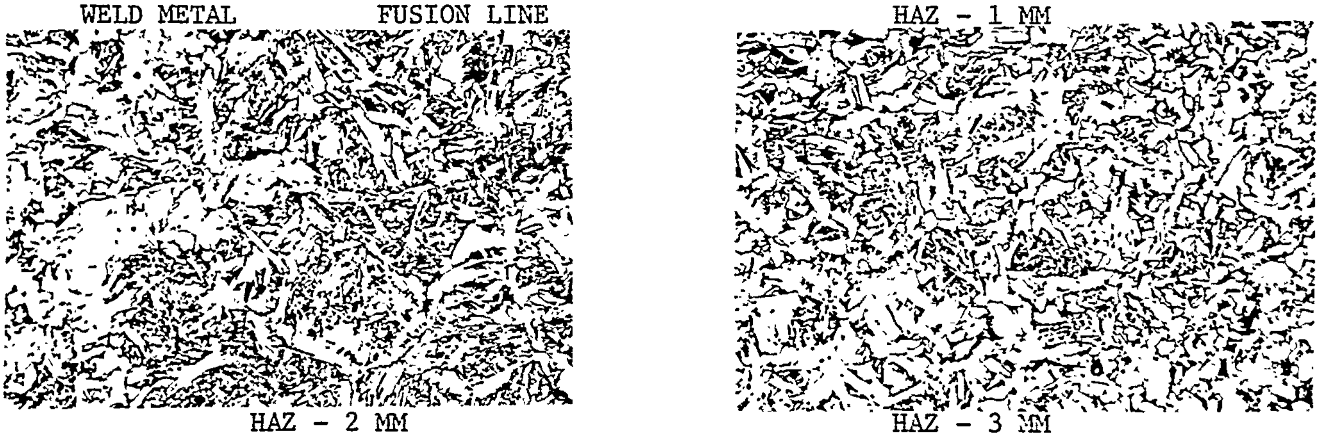
(1252 KJ/IN., 2% NITAL , 100X)

FIGURE 6 PHOTOMICROGRAPHS OF CES WELDMENT IN TI-TRJZATED STEEL



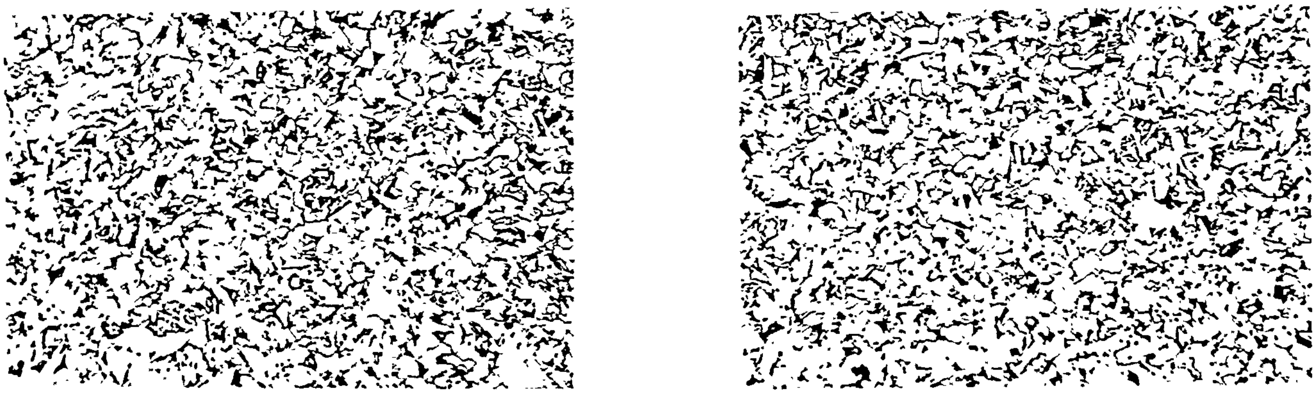
WELD METAL FUSION LINE

HAZ - 1 MM



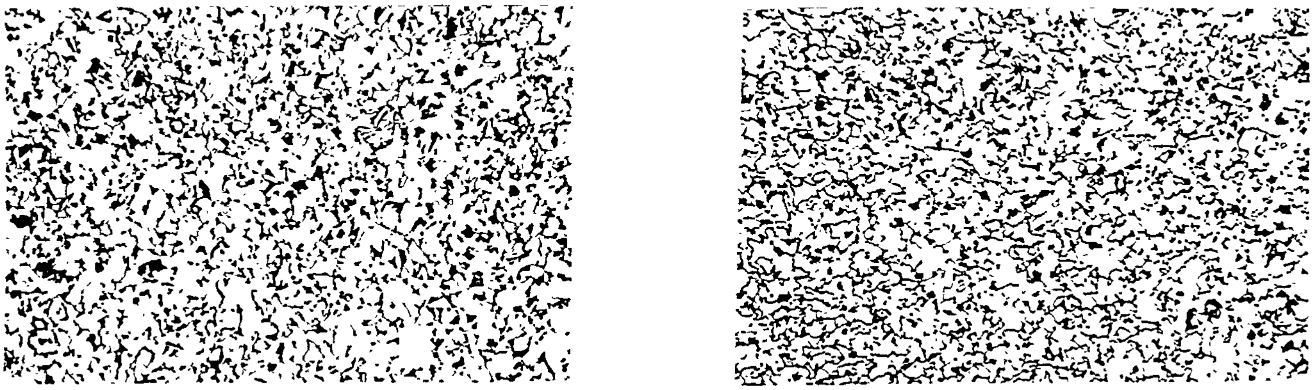
HAZ - 2 MM

HAZ - 3 MM



HAZ-4MM

HAZ-5MM



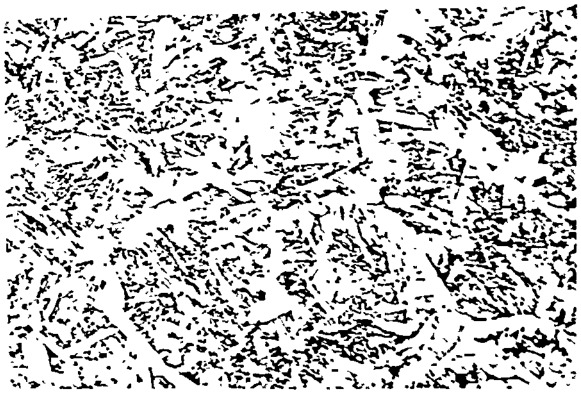
HAZ - 7 MM

HAZ-9MM

(480 KJ/IN., 2% NITAL, 100X)

FIGURE 7 PHOTOMICROGRAPHS OF ES WELDMENT IN TI-B-TREATED STEEL

WELD METAL FUSION LINE



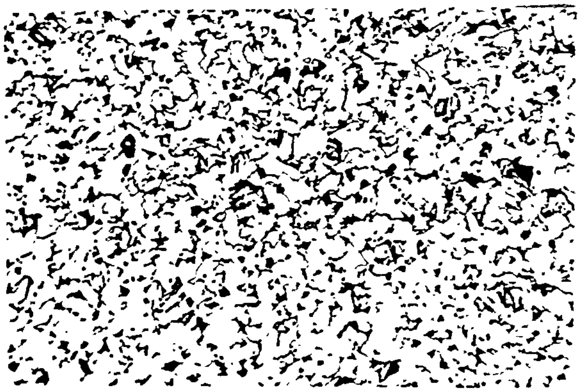
HAZ- 1 MM

HNZ-2MM

HAZ-3MM

HAZ-4MM

HAZ -5MM



HAZ-7MM

HAZ - 9 MM

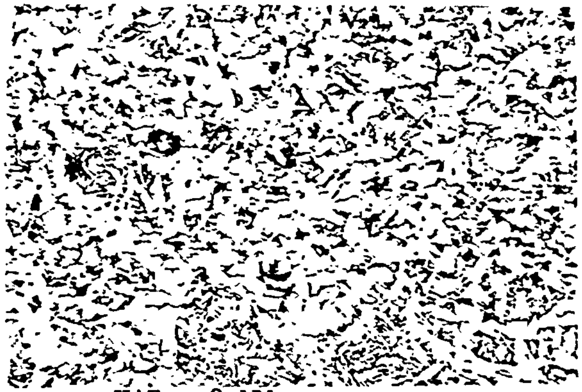
(1146 KJ/IN., 2% NITAL ETCH, 100X)

FIGURE 8 PHOTOMICROGRAPHS OF CES WELDMENT IN TI-B-TREATED STEEL

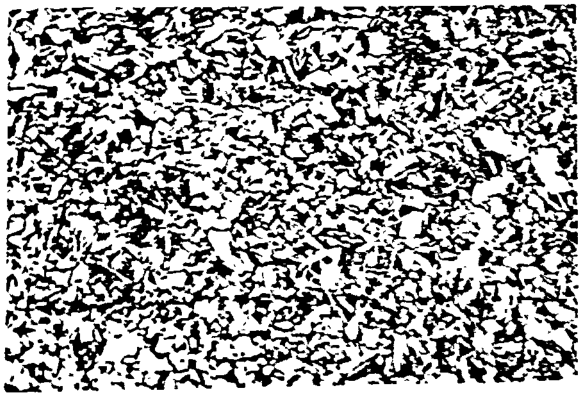
WELD METAL FUSION LINE

HAZ - 1 MM

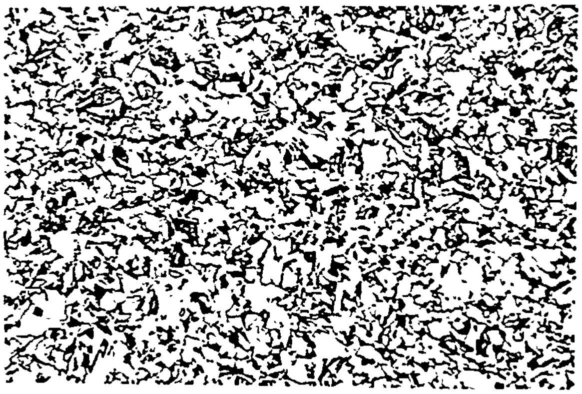
HAZ - 2 MM



HAZ - 3 MM

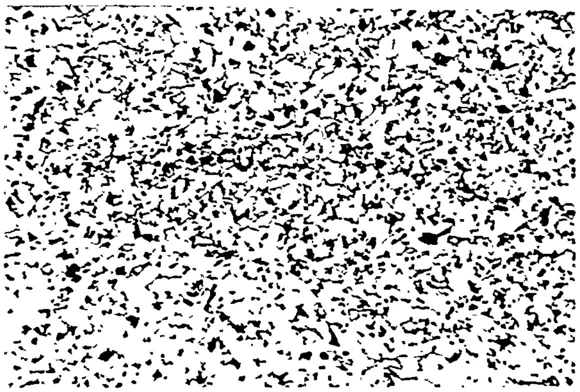


HAZ-4MM



HAZ-5MM

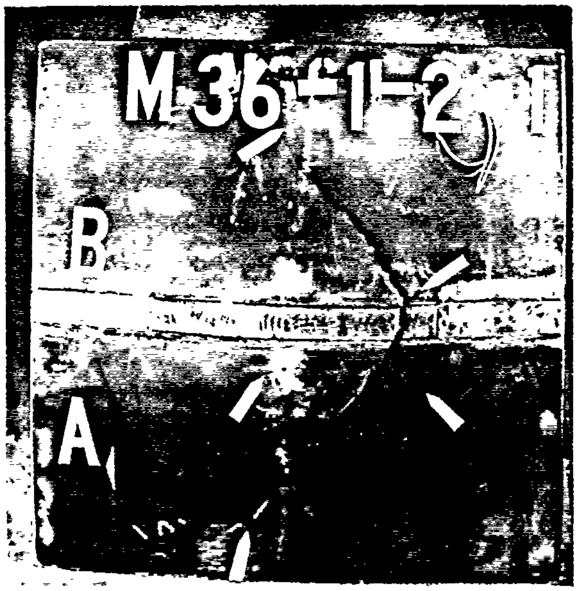
HAZ -7MM



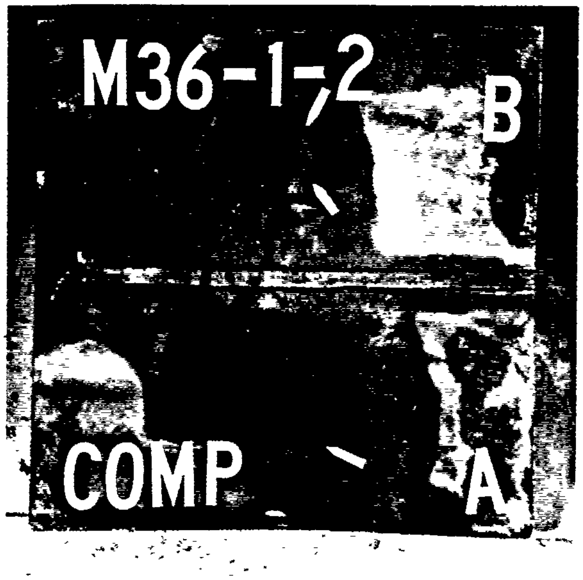
HAZ-9MM

(480 KJ/IN., 2% NITAL ETCH, 100X)

FIGURE 9 PHOTOMICROGFUPHS OF ES WELDMENT IN TI-B-REM-V-TREATED STEEL



TENSION SIDE



COMPRESSION SIDE

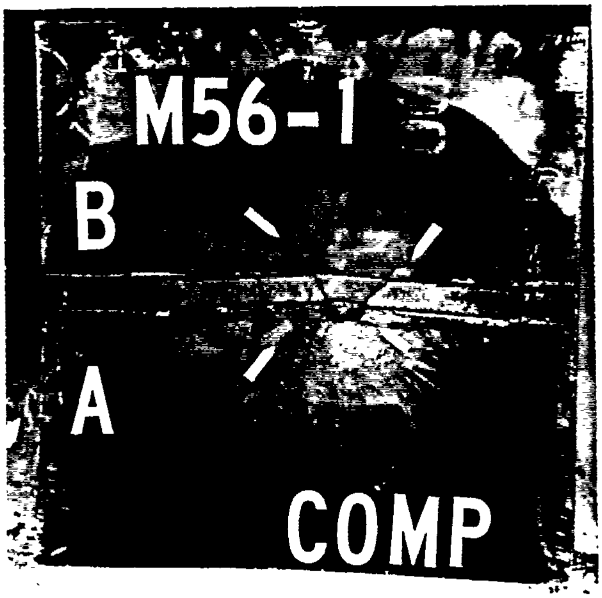
(NO. M36-1 AFTER 2 SHOTS, TEST TEMP. o°F)

FIGURE 10 ES TI-TREATED STEEL EXPLOSION BLTGE SPECIMEN

(NO. M36 AFTER 4 SHOTS, TEST TEMP. 0°F)

FIGURE 11 CES TI-TREATED STEEL EXPLOSION BULGE SPECIMEN

TENSION SIDE



COMPRESSION SIDE

(NO. M56 AFTER 1 SHOT, TEST TEMP. 0°F)

FIGURE 12 CES TI-B-TREATED STEEL EXPLOSION BULGE SPECIMEN

TENSION SIDE

COMPRESSION SIDE

(NO. M52 AFTER 3 SHOTS, TEST TEMP. 0°F)

FIGURE 13 ES TI-TREATED EXPLOSION BULGE SPECIMEN

TENSION SIDE

COMPRESSION SIDE

(NO . K1. AFTER 2 SHOTS, TEST TEMP. 0°F)

FIGURE 14 ES TI-B-REM-V-TRJQ4TED STEEL EXPLOSION BULGE SPECIMEN

(NO. K2 AFTER 3 SHOTS, TEST TEMP. 0°F)

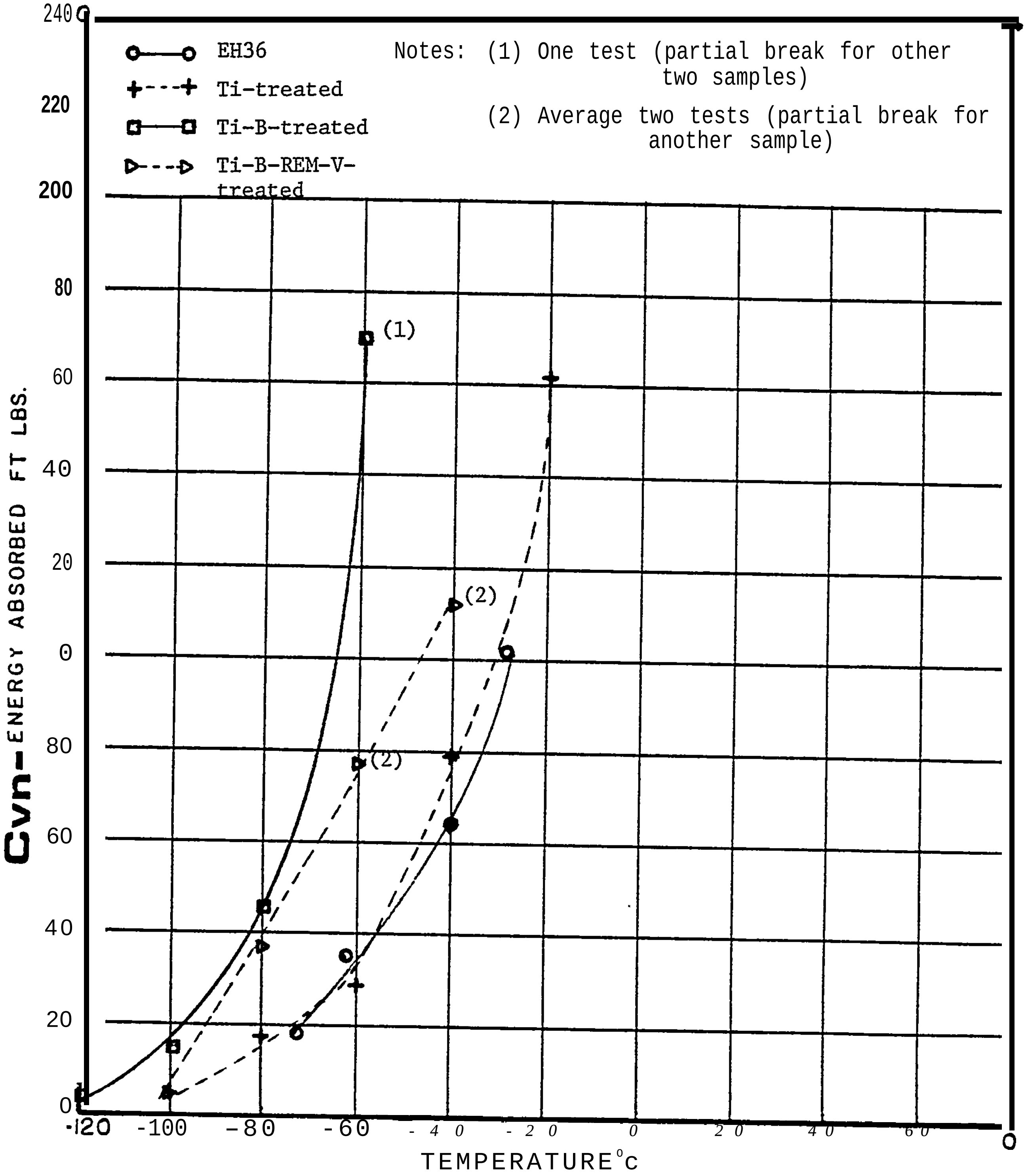
FIGURE 15 ES TI-B-REM-V-T~ATED STEEL EXPLOSION BULGE SPECIMEN

TENSION SIDE

COMPRESSION SIDE

(NO . K3 AFTER 1 SHOT, TEST TEMP. 0°F)

FIGURE 16 ES TI-B-REM-V-TREATED STEEL EXPLOSION BULGE SPECIMEN



Notes: (1) One test (partial break for other two samples)

(2) Average two tests (partial break for another sample)

FIGURE 17 CVN IMPACT ENERGY OF BASE METALS

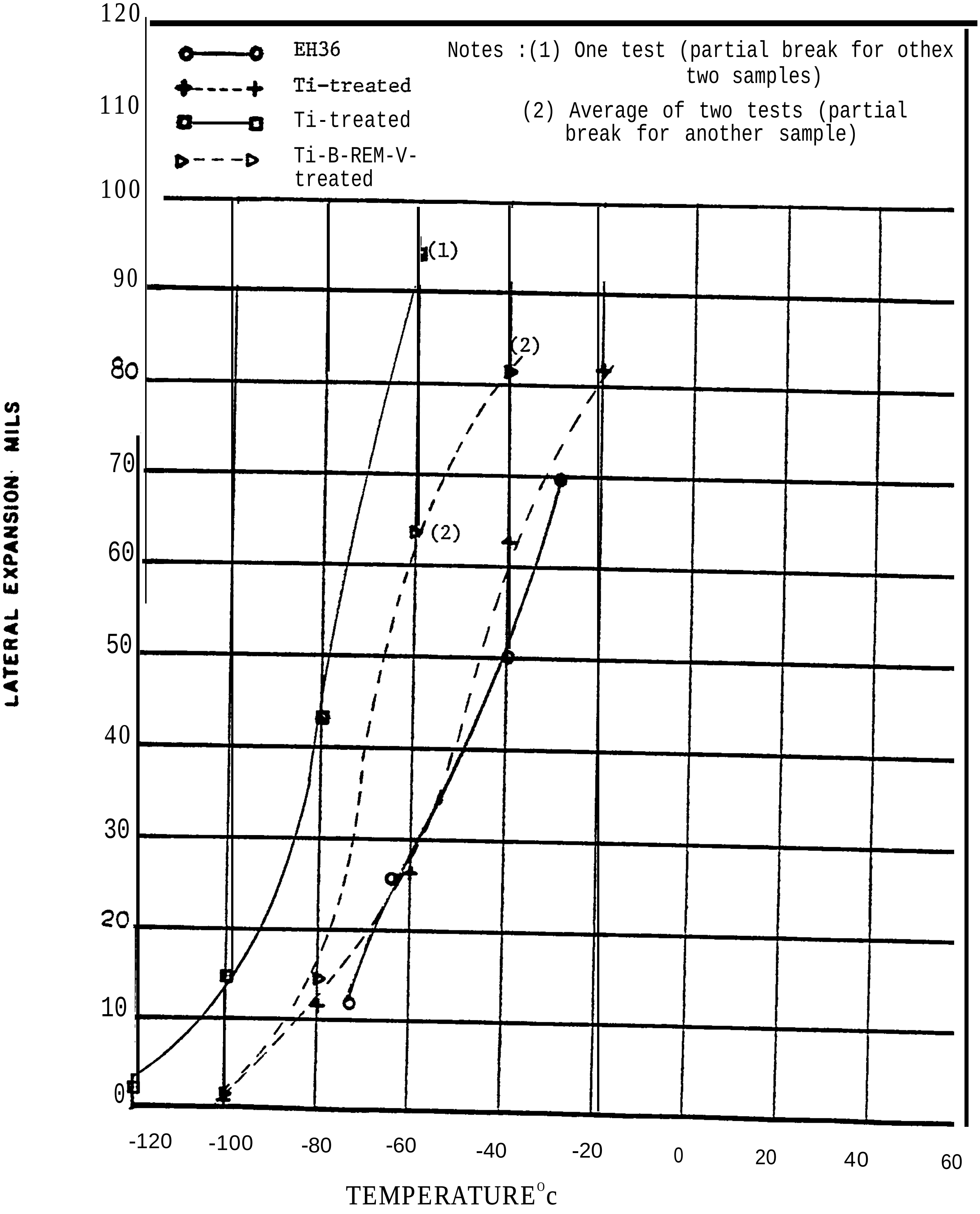


FIGURE 18 LATERAL EXPANSION OF BASE METALS

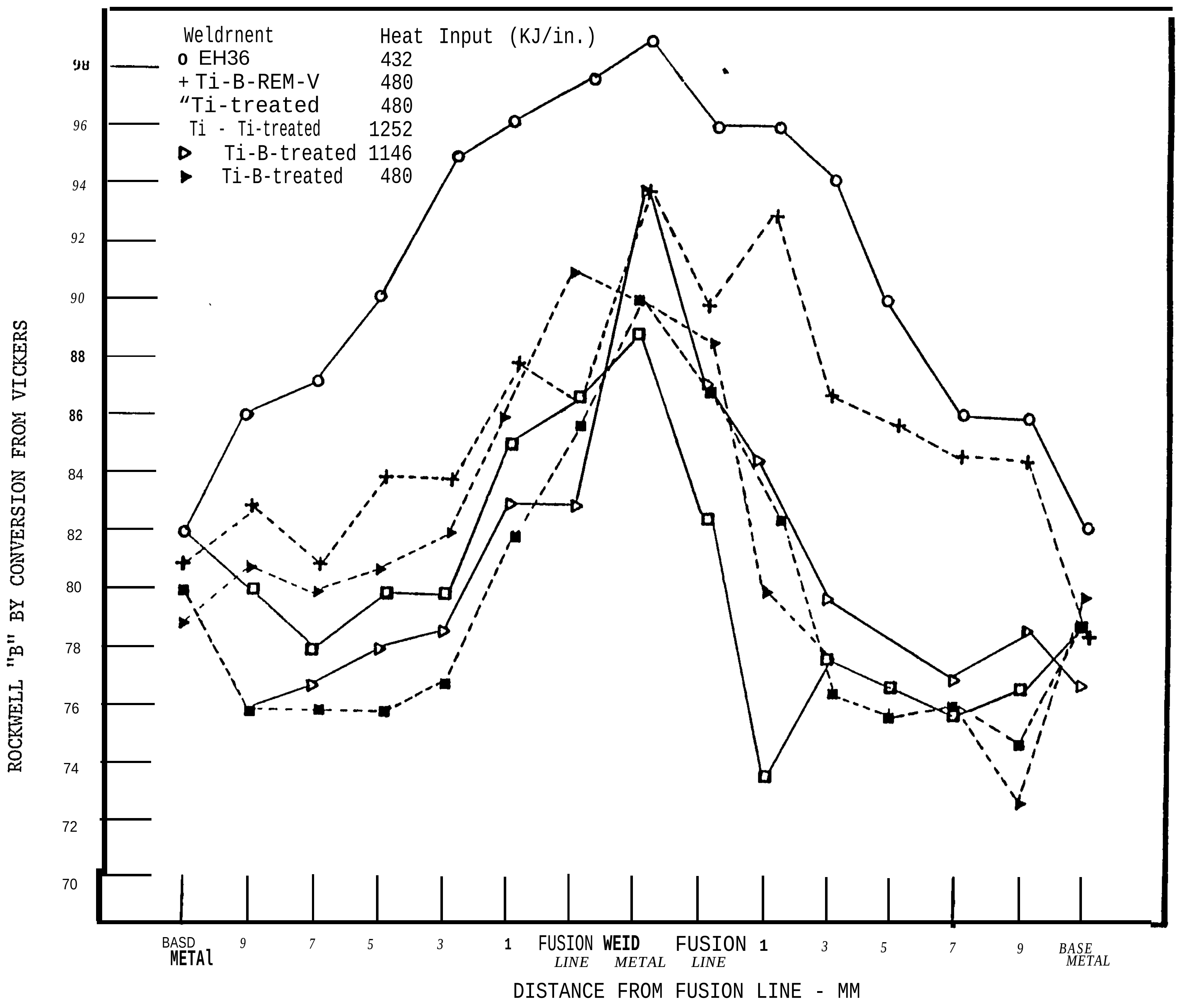


FIGURE 19 HARDNESS TRAVERSE ACROSS WELDS