FLORIDA ATLANTIC UNIVERSITY

BOCA RATON, FLORIDA 33431-0991

COLLEGE OF ENGINEERING
DEPARTMENT OF OCEAN ENGINEERING
CENTER FOR MARINE MATERIALS
(305) 393-3436

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Members, API Technical Advisory Committee and
Corrosion Fatigue and High Strength
Steels Joint Industry Project

Gentlemen:

Please find enclosed a copy of our report pertaining to material properties for our research project, "Fatigue of Selected High Strength Steels in Sea Water". It is our intention at this time to include this same material as an appendix to our final report for this project.

Best regards,

Bill

William H. Hartt
Professor and Director

WHH:mr
enc. 1
cc: D. Miller

Special Report
submitted to
The American Petroleum Institute

FATIGUE OF SELECTED HIGH STRENGTH STEELS IN SEA WATER - A COMPILATION OF MATERIAL PROPERTIES

by

W. H. Hartt and S. S. Rajpathak
Center for Marine Materials
Department of Ocean Engineering
Florida Atlantic University
Boca Raton, Florida 33431

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SUMMARY

The research project of which this report is a part, has as its objective the characterization of fatigue properties of high strength steels in sea water under conditions related to offshore structures. In conjunction with this activity a series of eight steels with yield stress in the range 372–985 MPa (54-143 ksi) have been obtained. These include two conventional, high toughness quenched and tempered steel (HY–80 and HY–130) for comparison purposes, a precipitation hardened steel (A 710), three microalloyed quenched and tempered steels and three processed either by control rolling or thermomechanically control processing (TMCP). Each of these was provided as 25.4 mm plate with butt welds in both the as–welded and ground and post weld heat treated conditions. This report presents material properties for these steels, as provided by the individual manufacturers. The data have been grouped according to properties to facilitate comparison between steels.

ACKNOWLEDGEMENTS

Authors express their sincere gratitude to Kawasaki Steel Corporation, NKK AMERICA, Inc. and Sumitomo Metal Industries, Ltd. for the gracious donation of steel alloys used in this research program, as well as for welding and mechanical property determination services. Financial support for this project was provided by the American Petroleum Institute and a consortium of organizations which include Chevron, Conoco, Exxon, Kawasaki, Marathon, Minerals Management Service, NKK, Pont-A-Mousson, Shell, Sohio and Sumitomo. Particularly critical to the success of this activity has been the guidance provided by the API Technical Advisory Committee on Corrosion Fatigue and a JIP advisory committee comprised of representatives from the member organizations. Acknowledgment is also due to Mr. Ernest Czyreca and the Naval Ship R and D Center for providing the HY-130 plate for comparative analysis.

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INTRODUCTION

The overall objective of this research project involves characterization of the fatigue properties of selected (representative) steels with yield stress in the range 372–985 MPa (54–143 ksi) and under conditions relevant to offshore structures. Particular emphasis was placed upon recently developed microalloyed and thermomechanically control processed steels but with the opportunity for comparison with more conventional steels in the same strength range. Welding was performed according to the best available technique, as recommended by the supplier, but with the procedure being qualified by a sub-committee of the Technical Advisory Committee.

This report constitutes a compilation of properties for the different steels employed in this program. Table I lists the steels, identifies the supplier and defines a designation system which is hereafter followed.

Properties were determined by the individual manufacturers, and no limit was placed on what data should be developed. Hence, the type and format of data is not always uniform. For ease of comparison, where it was necessary, data is normalized and presented in a separate table.

Steel	Manufacturer	Designation*
HY 80	Sumitomo	1(HY 80)
ASTM A710 Grade A Class 3	NKK	2(A 710)
NKHITEN 62E	NKK	3a(QT 80)
River ACE 80M	Kawasaki	3b(QT 108)
EH 36 (ABS)	Sumitomo	4(EH 36)
ASTM A537 Class 2, direct quenched	Kawasaki	5(A 537 d.q.)
ASTM A537, accelerated cool	Kawasaki	6(A 537 a.c.)
Pipe Line X 70	Sumitomo	7(X 70)
HY 130	Lukens Steel Co.	8(HY 130)

Table I : Test Materials and Manufacturers

* For the convenience of indexing test specimens, steels were referred to by numbers rather than by names. In this report however steels are identified by name.

Section I

Chemical Composition

STEEL ELEMENT	HY 80	A 710	QT 80	QT 108	EH 36	A 537 (d.q)	A 537 (a.c)	X 70	HY 130
C	0.13	0.04	0.08	0.11	0.13	0.12	0.07	0.09	0.10
Si	0.16	0.30	0.23	0.23	0.37	0.41	0.26	0.41	0.14
Mn	0.28	0.45	1.40	0.86	1.42	1.30	1.35	1.43	0.80
P	0.005	0.004	0.01	0.004	0.018	0.014	0.011	0.018	0.006
S	0.005	0.002	0.002	0.003	0.002	0.003	0.003	0.002	0.005
Cu	0.02	1.14	0.01	0.24	0.01	0.01	0.14	0.01	0.12
Ni	3.08	0.82	0.43	0.98	0.01	0.03	0.14	0.01	5.09
Cr	1.70	0.67	0.09	0.43	0.02	0.04	0.01	0.02	0.46
Mo	0.44	0.18	0.06	0.44	0.01	0.05	0.02	0.10	0.51
Nb	—·—	0.037	0.002	—·—	0.025	—·—	0.017	0.032	—·—
V	0.006	0.004	0.04	0.027	0.003	0.044	—·—	0.063	0.062
B	0.0001	0.0001	0.0001	0.0009	—·—	—·—	—·—	—·—	—·—
Ti	0.004	0.002	0.005	—·—	0.022	—·—	—·—	0.018	0.008
N	0.0089	0.0047	0.0026	—·—	0.0038	—·—	—·—	0.0026	0.010
Sol. Al	0.019	0.034	0.051	—·—	0.046	—·—	—·—	0.026	0.021
O	0.0031	—·—	—·—	—·—	—·—	—·—	—·—	—·—	0.0012
Carbon Equivalent	0.7108*	0.4165£	0.3807£	0.4853*	0.3890*	0.3781*	0.3163*	0.3700£	

* $C_{eq} = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14$

£ $C_{eq} = C + Mn/6 + Cu/15 + Ni/15 + Cr/5 + Mo/5 + V/5$

Table I.1 : Chemical Composition of Test Steels

Section II

Manufacturing Process

Steel Making	Electric Furnace
Steel Casting	Ingot Case
Slab Making	Universal Mill
Heating	Reheating Furnace
Rolling	Plate Mill
Heat Treatment	Quenching
	$900^{o}C$ x 30 min W.Q.
	Tempering
	$670^{o}C$ x 1 Hr A.C.

Table II.1 : Process Flow for Manufacture of HY 80 Plate.

PROCESS		FACILITIES	PROCEDURE
Steel Making	↓ Pig Iron ↓		
	Desulphurizing ↓	Mechanical stirring (KR Type)	Add CaC
	Deoxidation ↓	Basic oxygen furnace 250 tons/charge	
	Ladle Refining ↓	NK-AP P I	
	Degassing ↓	R II Process	
	Ingot making ↓	Ingot size thickness : 730-1100 mm width : 1870-2685 mm height : 2750-3200 mm Weight : 26-50 tons	Hot top : exothermic powder Pouring temperature : 1560 °C min.
Slabbing	Soaking ↓	Top one way type soaking pits	Soaking temperature : About 1300 °C
	Slabbing ↓	High lift slabbing mill	

Table II.2 : Process Flow for Manufacture of A 710 Plate.

PROCESS		FACILITIES	PROCEDURE
Plate rolling	Slab Cutting	Shear or flame cutting	Slab size thickness : 95-500 mm width : 1250-2304 mm length : 1650-5300 mm
	↓ Scarfing	Cold scarfers	
	↓ Surface and Dimension inspection		
	↓ Reheating	Continuous reheating furnace Batch reheating furnace	1). Slab thickness for continuous R. F. : 95-350 mm 2). Slab thickness for batch R. F. : 95-500 mm 3). Reheating temperature : 1150-1300°C
	↓ Rolling	Hydraulic scale breaker 150Kg/cm 216.5 inches 4-hi mill ray thickness gauge	Hydraulic A. G. C. Computer Control
	↓ Hot levelling	Hot leveler 4-hi type	
	↓ Cooling		
	↓ Surface examination		In process inspection

Table II.2 (continued...)

PROCESS	FACILITIES	PROCEDURE
↓ Rough Cutting	Mechanical Shear and/or Gas Cutter	
↓ Interim Marking		
↓ Shot Blasting	Shot blaster	De-scaling of plate surface before heat treatment
↓ Quenching	No. 1 heat treatment furnace with hearth roller (non-oxidize atmosphere)	Holding Temperature : 900 ° C ± 10 ° C
↓ Tempering	No. 2 heat treatment furnace	Holding Temperature : 660 ° C ± 5 ° C
↓ Surface Examination		In process inspection
↓ Cutting (Plate and Test coupons)	Flame planer	
↓ Dimension and visual inspection; ↓ Physical testing		

Table II.2 (continued...)

PROCESS		FACILITIES	PROCEDURE
Slabbing	Continuous Casting	No. 1 Slab Continuous Casting Machine (Vertical bending type with soft reduction) thickness : 250 mm width : 1595-2304 mm shape : square corner	Applicable plate thickness : max. 83 mm
	Slab Cutting	Shear or flame cutting	
	Scarfing	Cold scarfers	
	Surface and Dimension inspection		
Plate rolling	Reheating	Continuous reheating furnace Batch reheating furnace	1). Slab thickness for continuous R. F. : 95-350 mm 2). Slab thickness for batch R. F. : 95-500 mm 3). Reheating temperature : 1150 -1300 ° C
	Rolling	Hydraulic scale breaker 150Kg/cm 216.5 inches 4-hi mill ray thickness gauge	Hydraulic A. G. C. Computer Control
	Hot Levelling	Hot leveller 4-hi type	
	Cooling		

Table II.3 : Process Flow for Manufacture of QT 80 Plate.

PROCESS		FACILITIES	PROCEDURE
	Surface Examination ↓		In process inspection
	Rough Cutting ↓	Mechanical shear and/or Gas Cutter	
	Interim Marking ↓		
	Shot Blasting ↓	Shot blaster	De-scaling of plate surface before heat treatment
	Quenching ↓	No. 1 heat treatment furnace with hearth roller (non-oxidize atmosphere)	Holding Temperature : 900 ° C ± 10 ° C
	Tempering ↓	No. 2 heat treatment furnace	Holding Temperature : 620 ° C ± 5 ° C
	Surface Examination ↓		In process inspection
	Cutting (Plate and Test coupons) ↓ Dimension and visual inspection; ↓ Physical testing	Flame planer	

Table II.3 (continued...)

Desulfurizing

↓

Steel Making (Basic Oxygen Furnace)

↓

RH Type Vacuum Degassing

↓

Ingot Casting

↓

Slabbing

↓

Slab Conditioning

↓

Reheating

↓

Plate Rolling

↓

Quenching (Quenching Temperature: 930°C)

↓

Tempering (Tempering Temperature: 615°C)

↓

Ultrasonic Testing

↓

Cutting → Sampling → Mechanical Testing

↓

Surface and Dimension Inspection

↓

Marking and Stamping

↓

Delivery

Table II.4 : Process Flow for Manufacture of QT 108 Plate.

SteelMaking	Converter
Steel Casting	Continuous Case
Slab Making	________________
Heating	Reheating Furnace
Rolling	Plate Mill
Heat Treatment	Control Rolling

Table II.5 : Process Flow for Manufacture of EH-36 Plates

Desulfurizing

↓

Steel Making (Basic Oxygen Furnace)

↓

RH Type Vacuum Degassing

↓

Ingot Casting

↓

Slabbing

↓

Slab Conditioning

↓

Reheating

↓

Plate Rolling

↓

Direct Quenching

↓

Tempering (Temperimg Temperature : 680 $^{\circ}$C)

↓

Ultrasonic Testing

↓

Cutting → Sampling → Mechanical Testing

↓

Surface and Dimension Inspection

↓

Marking and Stamping

↓

Delivery

Table II.6 : Process Flow for Manufacture of A 537 d.q. Plate.

Desulfurizing

↓

Steel Making (Basic Oxygen Furnace)

↓

RH Type Vacuum Degassing

↓

Continuous Casting

↓

Slab Conditioning

↓

Reheating

↓

Plate Rolling

↓

Accelerated Cooling

↓

Ultrasonic Testing

↓

Cutting → Sampling → Mechanical Testing

↓

Surface and Dimension Inspection

↓

Marking and Stamping

↓

Delivery

Table II.7 : Process Flow for Manufacture of A 537 a.c. Plate.

Steel Making	250^T Converter
Steel Casting	Continuous Casting
Reheating	Reheating Furnace
Rolling	Controlled Rolling

Table II.8 : Process Flow for Manufacture of X 70 Plate.

Section III

Tensile Test Results

Steel	Yield Strength MPa (ksi)							Tensile Strength MPa (ksi)						
	Base Material					PWHT		Base Material					PWHT	
	L*	C	L	T	Z	L	T	L*	C	L	T	Z	L	T
HY80	636 (92.2)	654.6 (94.9)						736.5 (106.8)	742.9 (107.7)					
A710			563 (81.7)	563 (81.7)		546 (79.2)	553 (80.2)			622 (90.3)	621 (90.2)	623 (90.5)	617 (89.6)	615 (89.3)
QT 80			537 (77.9)	533 (77.4)		528 (76.6)	526 (76.4)			613 (88.9)	611 (88.6)	610 (88.4)	610 (88.3)	609 (88.3)
QT 108	745 (108)							824 (119)						
EH36	370.7 (53.8)	416.3 (60.4)						518.8 (75.2)	536 (77.7)					
A537 d.q.	500 (72.5)							598 (86.7)						
A537 a.c.	452 (65.9)					438 (63.9)		551 (80.3)					525 (76.4)	
X70			509 (73.8	534 (77.5)						612 (88.8)	613 (88.9)			
HY130	985 (143)							1006 (146)						

L*-Ladle, C-Check, L-Longitudinal, T-Transverse, Z-Through Thickness Direction

Table III.1 : Yield and Tensile Strengths - Comparative Analysis

THICK-NESS (mm)		YP Kgf/mm^2	YP 0.2%, Kgf/mm^2	TS Kgf/mm^2	EL %	RA %	YR YP/TSx100
25.4	L	-	64.5	74.5	GL=203.2mm 21.0	73.2	87
		-	65.2	75.7	21.4	74.0	87
	C	-	66.2	75.7	20.1	68.4	87
		-	67.3	75.8	20.4	68.7	89
	Spec.	-	56/70	-	GL=50.0mm >=20	>=50	-

L-Ladle, C-Check

Table III.2 Tensile Test Results for HY 80

Heat Treatment	Direction	YS MPa (ksi)	TS MPa (ksi)	EL %	RA %
As QT	L	563 (81.7)	622 (90.3)	31.8	82.7
	T	563 (81.7)	621 (90.2)	31.9	82.1
	Z	————	623 (90.5)	————	75.0
PWHT (600°C x 1hr)	L	546 (79.2)	617 (89.6)	31.1	82.1
	T	553 (80.2)	615 (89.3)	32.3	82.2

a) Tensile Specimen
12.5 mm diameter x 50.8 mm. gage length from the mid-thickness position for L and T direction
10 mm diameter for Z direction

b) L Longitudinal direction
T Transverse direction
Z Through Thickness direction

Table III.3 Tensile Test Results for A 710

Heat Treatment	Direction	YS MPa (ksi)	TS MPa (ksi)	EL %	RA %
As QT	L	537 (77.9)	613 (88.9)	27.9	81.6
	T	533 (77.4)	611 (88.6)	25.0	75.8
	Z	———	610 (88.4)	———	75.5
PWHT (600 °C x 1hr)	L	528 (76.6)	610 (88.4)	28.0	81.4
	T	553 (76.4)	609 (88.3)	24.6	74.7

a) Tensile Specimen
12.5 mm diameter x 50.8 mm gage length from the mid-thickness position for L and T direction
10 mm. diameter for Z direction

b) L Longitudinal direction
T Transverse direction
Z Through thickness direction

Table III.4 Tensile Test Results for QT 80

THICK-NESS	YIELD STRENGTH		TENSILE STRENGTH		ELONGATION
mm (inch)	MPa	ksi	MPa	ksi	%
25.4(1.0)	745	108	824	119	24

Table III.5 Tensile Test Results for QT 108

THICK-NESS (mm)		YP Kgf/mm²	YP 0.2%, Kgf/mm²	TS Kgf/mm²	EL %	RA %	YR YP/TSx100
25.4	L	40.0 39.6	37.3 38.3	52.9 52.9	35.2 34.6	74.6 75.4	70.5 72.4
	C	44.8 44.5	42.6 42.1	54.6 54.6	34.0 34.0	73.8 73.8	78.0 76.9
	Spec.	>= 36	——	50/63	GL=50.0mm >=22	——	——

L-Ladle, C-Check

Table III.6 Tensile Test Results for EH 36

THICK-NESS	YIELD STRENGTH		TENSILE STRENGTH		ELONGATION
mm (inch)	MPa	ksi	MPa	ksi	%
25.4(1.0)	500	73	598	87	28

Table III.7 Tensile Test Results for A 537 d.q.

Heat Treatment	YIELD STRENGTH		TENSILE STRENGTH		ELONGATION
	MPa	ksi	MPa	ksi	%
As received	452	65.9	551	80.3	30
PWHT	438	63.9	525	76.4	32

Table III.8 Tensile Test Results for A 537 a.c.

Heat Treatment	YIELD STRENGTH		TENSILE STRENGTH		ELONGATION
	MPa	ksi	MPa	ksi	%
L	509	73.8	612	88.8	45.8
T	534	77.5	613	88.9	44.6

Table III.9 Tensile Test Results for X 70

Section IV

Fracture Property Test Results

Steel	Condition	Direction	Charpy Energy, Joules					50% FATT
			0 C	−20 C	−40 C	−60 C	−85 C	C
HY 80		L*	288.3			278.5	277.5	
		C	207.9			210.8	188.3	
A 710	As QT	L			378	371		-112
		T			363	362		-127
	PWHT	L			368	366		-133
		T			366	364		-119
QT 80	As QT	L			333	319		-108
		T			302	278		-91
	PWHT	L			324	290		-89
		T			360	219		-76
QT 108	As Welded				215.8			
	PWHT			192.5	179.8			
EH 36		L	274.5		215.7			
		C	257.9		184.3			
A 537 d.q.	As Welded			126.5	121.9			
	PWHT			262.8	248.5			
A 537 a.c.								
X 70	L				267			
	T				176.3			
HY 130				79−84				

L*-Ladle, C-Check, L-Longitudinal, T-Transverse, Z-Through Thickness Direction

Table IV : Charpy Test Results − Comparative Analysis

	Thickness (mm)		vE_0 kgf·m		vE_{-40} kgf·m		vE_{-60} kgf·m		vE_{-85} kgf·m		vTs °C
				Ave.		Ave.		Ave.		Ave.	
	25.4	L	29.6 28.8 29.8	29.4	-	-	27.3 28.8 29.2	28.4	28.2 29.3 27.5	28.3	-160
		C	20.5 21.4 21.8	21.2	-	-	21.1 22.2 21.3	21.5	20.2 18.2 19.2	19.2	-130
		Spec.	-		-		-		≥0.7	≥6.9	-

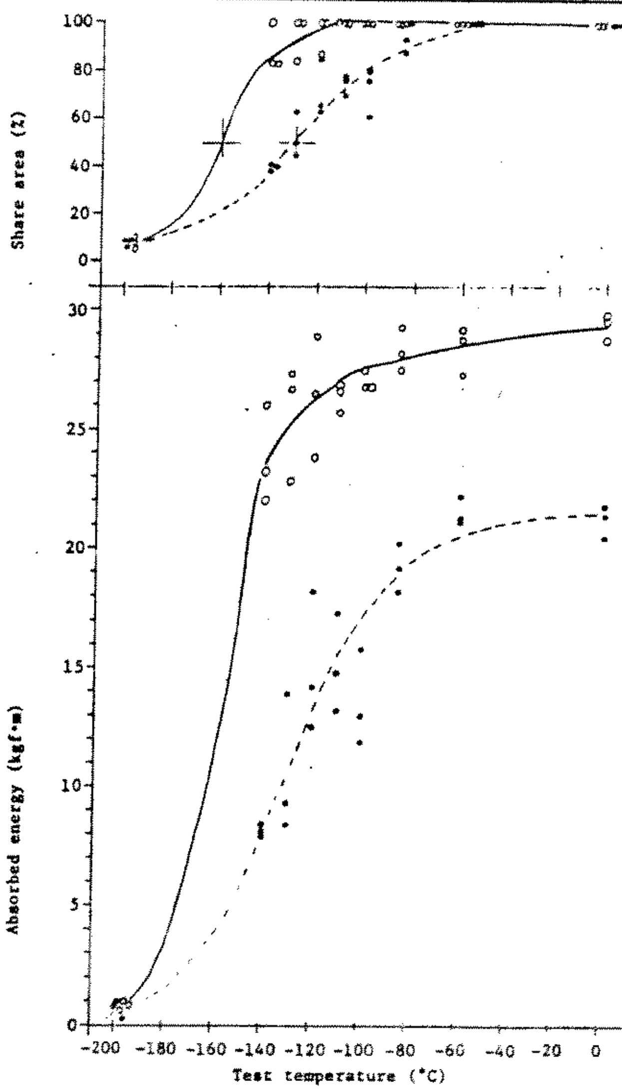


Table IV.1 : Charpy Impact Test Results for HY 80

	Thick-ness (mm)	Temper-ature °C	Result		
	25.4	-115	⦶	⦶	⦶
		-120	⦶	⦶	⦶
		-125	●	●	●
		NDT	-120		

Condition

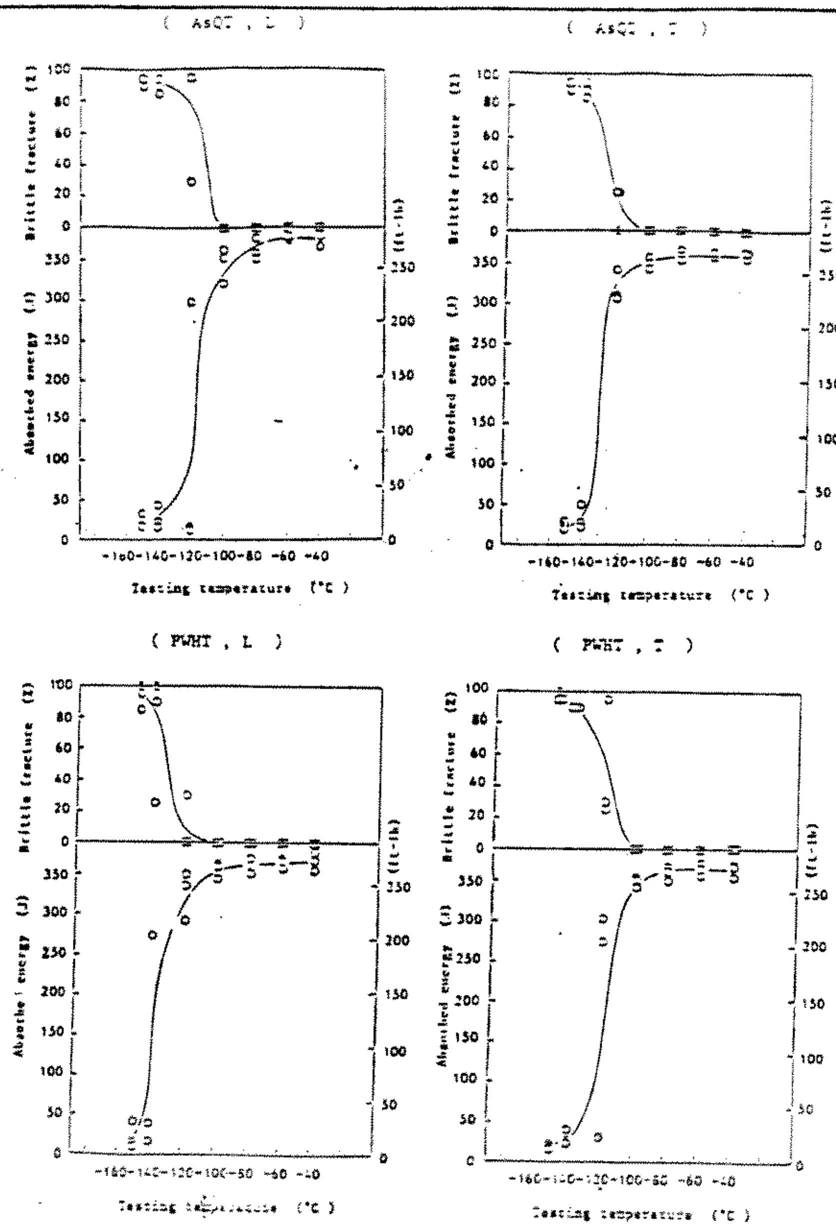
Test piece : P1

Direction : C

Energy : 83 kgf·m

Table IV.1a : NRL Drop Weight Test Results for HY 80

Heat Treatment	Direction	vE-40°C J (ft-lb)	vE-60°C J (ft-lb)	50% FATT °C (°F)
As QT	L	378(279)	371(274)	-112(-170)
	T	363(268)	362(267)	-127(-197)
PWHT (600°C x 1hr)	L	368(272)	366(270)	-133(-207)
	T	366(270)	364(268)	-119(-182)



Charpy Transition Curve

Table IV.2 : Charpy Impact Test Results for A 710
(2 mm V-notch Charpy impact Specimen, full size from quarter thickness position)

Test Condition ; Test Specimen : Type P-1 (ASTM E208)

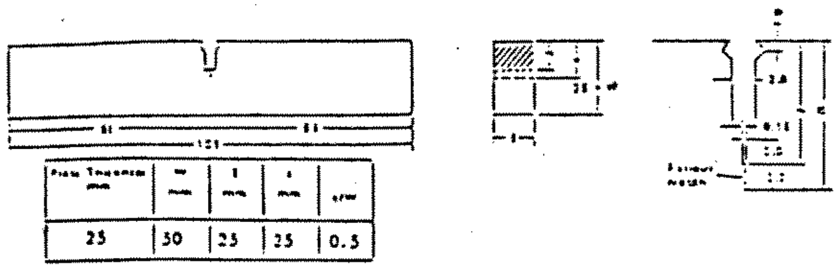
Drop Weight Energy : 813J

Electrode : NRL - S (KOBE Steel LTD)

NRL Drop Weight Test Results (As QT)

Direction	Testing Temperature °C(°F) -75(-103)	-80(-112)	-85(-121)	-90(-130)	NDTT °C(°F)
L	○ ○ ○	○ ○ ○	○ ● ●	● ● ●	-85(-121)
	○: No Break , ●: Break				

Table IV.2a : NRL Drop Weight Test Results for A 710



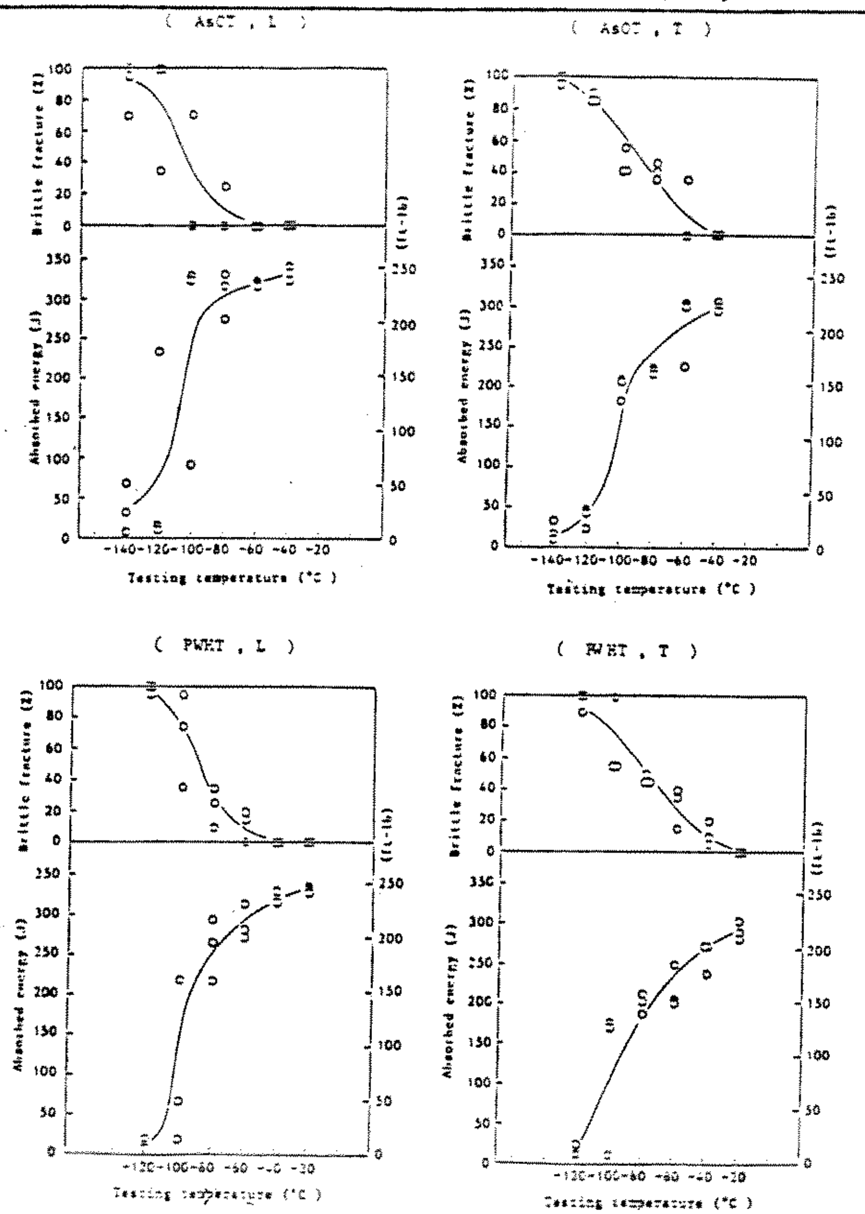
Dimension of Test Specimen and Notch Detail

CTOD Test Results (As QT)

Direction	B mm	W mm	a mm	Y	Testing Temp. °C(°F)	σy kg/mm^2	P kg	Vp mm	Critical CTOD Value mm(mil)
	25	50	25.8	11.18	-10 (14)	58.8	8440	>4.4	>1.34 (>52.8)
	25	50	26.3	11.56	-10 (14)	58.8	7770	>4.4	>1.29 (>50.8)
	25	50	26.0	11.33	-50 (- 58)	61.2	8150	>4.4	>1.32 (>52.0)
L	25	50	26.1	11.40	-90 (-130)	65.0	7410	>4.4	>1.29 (>50.8)
	25	50	25.5	10.96	-110(-166)	67.6	8250	0.93	0.35 (13.8)
	25	50	25.8	11.18	-130(-202)	71.2	9170	2.16	0.71 (28.0)
	25	50	26.6	11.79	-150(-238)	76.3	7180	0.05	0.079(3.1)
	25	50	26.1	11.40	-170(-274)	83.9	6850	0	0.050(2.0)

Table IV.2b : CTOD Test Results for A 710

Heat treatment	Direction	vE-40°C J (ft-lb)	vE-60°C J (ft-lb)	50% FATT °C (°F)
As QT	L	333(246)	319(235)	-108(-162)
	T	302(223)	278(205)	-91 (-132)
PWHT	L	324(239)	290(214)	-89 (-128)
(600°C x 1hr)	T	260(192)	219(162)	-76 (-105)



Charpy Transition Curve

Table IV.3 : Charpy Impact Test Results for QT 80
(2 mm V-notch Charpy Impact Specimen, full size from quarter thickness position)

Test Condition ; Test Specimen : Type P-1 (ASTM E208)

Drop Weight Energy : 813J

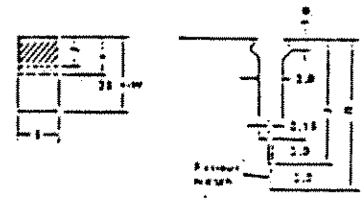
Electrode : NRL-5 (KOBE Steel LTD)

NRL Drop Weight Test Results (As QT)

Direction	Testing Temperature °C(°F)				NDTT °C(°F)
	-40(-40)	-45(-49)	-50(-58)	-55(-67)	
L	○ ○ ○	○ ○ ○	○ ● ●	● ● ●	-50(-58)

○ : No Break , ● : Break

Table IV.3a : NRL Drop Weight Test Results for QT 80



[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
25	50	25	25	0.5

Dimension of Test Specimen and Notch Detail

CTOD Test Results (As QT)

Direction	B mm	W mm	a mm	Y	Testing Temp. °C(°F)	σ_y kg/mm^2	P kg	Vp mm	Critical CTOD Value mm(mil)
L	25	50	25.0	10.61	-10(14)	56.2	8020	>4.4	>1.38 (>54.3)
	25	50	24.3	10.15	-10(14)	56.2	8520	>4.4	>1.44 (>56.7)
	25	50	26.0	11.33	-50(- 58)	58.6	7660	>4.4	>1.31 (>51.6)
	25	50	24.7	10.41	-70(- 94)	60.3	8540	3.78	1.22 (48.0)
	25	50	24.5	10.28	-90(-130)	62.4	7920	0.51	0.21 (8.3)
	25	50	26.8	11.96	-110(-166)	65.1	5610	0	0.048(1.9)
	25	50	26.3	11.56	-130(-202)	68.8	5210	0	0.037(1.5)
	25	50	25.8	11.18	-150(-238)	73.9	4530	0	0.024(0.9)

Table IV.3b : CTOD Test Results for QT 80

Heat treatment	Test temp.		Charpy impact strength					
			Weld metal		HAZ		Parent plate	
	°C	°F	Joule	ft-lbs	Joule	ft-lbs	Joule	ft-lbs
As welded	-20	-4	78.5 86.3 116.7 (93.8)	57.9 63.7 86.1 (69.2)	128.5 88.3 108.9 (108.6)	94.8 65.1 80.3 (80.1)	—	—
	-40	-40	77.5 78.5 70.6 (75.5)	57.2 57.9 52.1 (55.7)	79.4 85.3 68.6 (77.8)	58.6 62.9 50.6 (57.4)	198.1 224.6 224.6 (215.8)	146.1 165.7 165.7 (159.2)
PWHT	-20	-4	78.4 93.2 142.2 (104.6)	57.8 68.7 104.9 (77.1)	186.3 192.2 201.0 (193.2)	137.4 141.8 148.2 (142.5)	185.3 202.0 190.2 (192.5)	136.7 149.0 140.3 (142.0)
	-40	-40	65.7 69.6 57.9 (64.4)	48.5 51.3 42.7 (47.5)	165.7 160.0 165.7 (163.8)	122.2 118.0 122.2 (120.8)	194.2 214.8 130.4 (179.8)	143.2 158.4 96.2 (132.6)

Numbers in parentheses are the average of three specimens.

Table IV.4 : Charpy Impact Test Results for QT 108

Thick-ness (mm)		vEo kgf·m		vE₋₄₀ kgf·m		vE₋₆₀ kgf·m		vE₋₈₅ kgf·m		vTs °C
			Ave.		Ave.		Ave.		Ave.	
25.4	L	29.0 28.5 26.5	28.0	26.0 22.5 17.5	22.0	-	-	-		-82
	C	27.0 26.0 25.8	26.3	19.5 19.0 18.0	18.8	-	-	-	-	-70
	Spec.	-		L≥3.5 C≤2.4		-		-		-

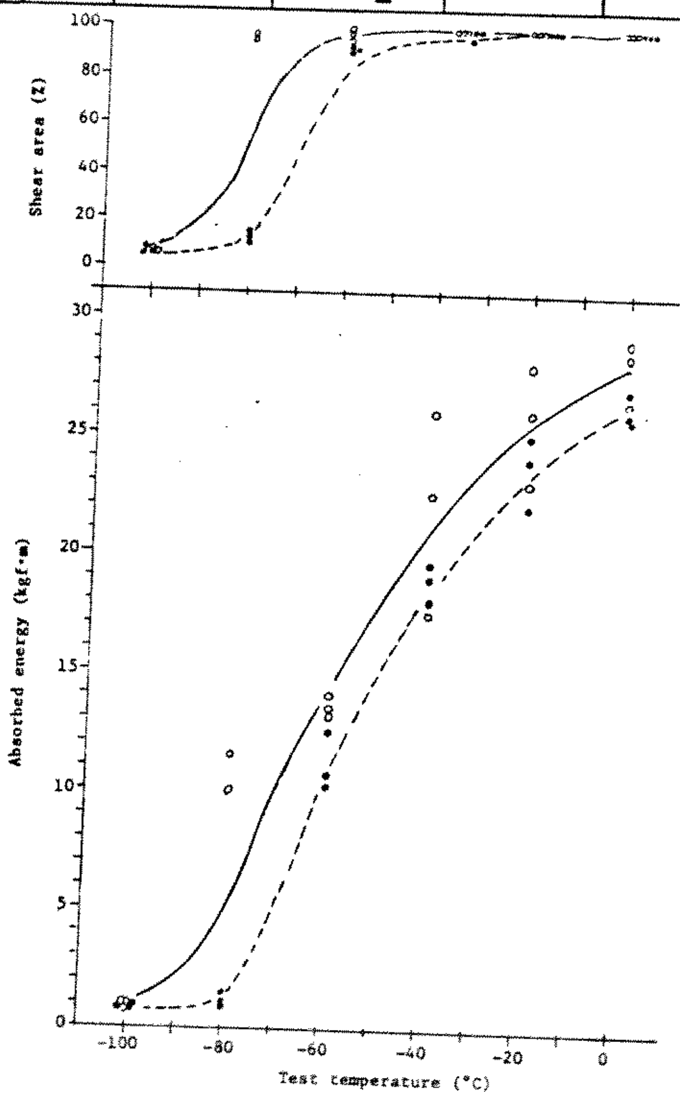


Table IV.5 : Charpy Impact Test Results for EH 36

	Thick- ness (mm)	Temper- ature °C	Result
	25.4	-40	8 ⦶ 4 0 ⦶ 0 0 ⦶ 0
		-45	◐ 20 15 ⦶ 16 5 ⦶ 12
		-50	● ● ●
		NDT	-45°C

Condition

Test piece : P1

Direction : C

Energy : 83 kgf·m

Table IV.5a: NRL Drop Weight Test Results for EH 36

Heat treatment	Test temp.		Charpy impact strength					
			Weld metal		HAZ		Parent plate	
	°C	°F	Joule	ft-lbs	Joule	ft-lbs	Joule	ft-lbs
As welded	-20	-4	175.5 175.5 150.0 (167.0)	129.4 129.4 110.6 (123.1)	120.6 104.9 111.8 (112.4)	88.9 77.4 82.5 (82.9)	159.8 146.1 73.5 (126.5)	117.9 107.8 54.2 (93.3)
	-40	-40	154.9 113.8 103.0 (123.9)	114.2 83.9 76.0 (91.4)	79.4 112.8 68.6 (86.9)	58.6 83.2 50.6 (64.1)	148.1 145.1 72.6 (121.9)	109.2 107.0 53.5 (89.9)
PWHT	-20	-4	181.4 195.1 193.2 (189.9)	133.8 143.9 142.5 (140.1)	117.7 95.1 96.1 (103.0)	86.8 70.1 70.9 (75.9)	240.3 304.0 244.2 (262.8)	177.2 224.2 180.1 (193.8)
	-40	-40	115.7 111.8 139.3 (122.3)	85.3 82.5 102.7 (90.2)	91.2 122.6 51.0 (88.3)	67.3 90.4 37.6 (65.1)	276.5 249.1 220.0 (248.5)	203.9 183.7 162.3 (183.3)

Numbers in parentheses are the average of three specimens.

Table IV.6 : Charpy Impact Test Results for A 537 d.q.

Heat treatment	Temp.(℃)	Weld metal		HAZ	
		Joule	ft · lbs	Joule	ft · lbs
As welded	−20	236.3	174.3	220.6	162.7
	−40	166.7	123.0	216.7	159.8
PWHT	−20	186.3	137.4	224.6	165.6
	−40	155.9	115.0	200.0	147.6

Table IV.7 : Charpy Impact Test Results for A 537 a.c.

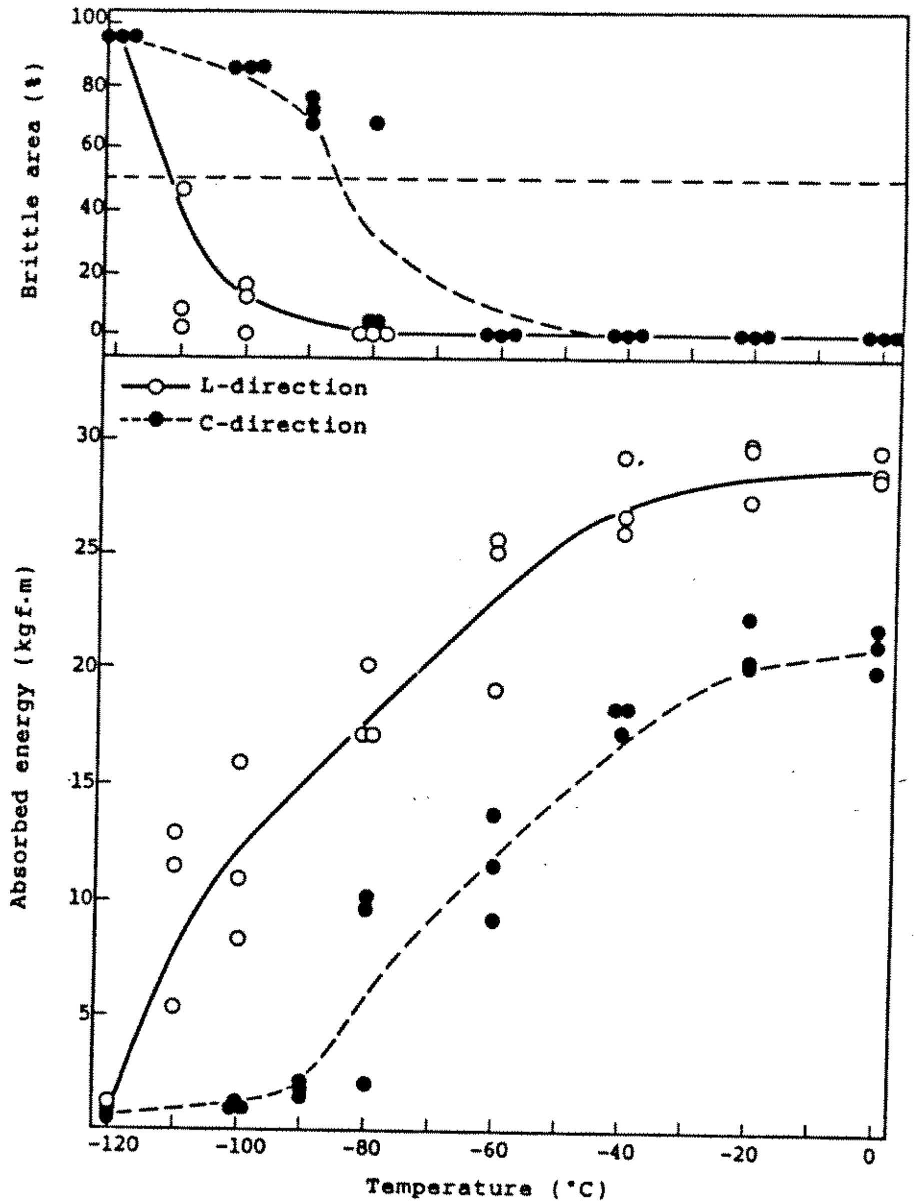


FIGURE IV.8 : Charpy Impact Test Results for X 70

Section V

Hardness Test Results

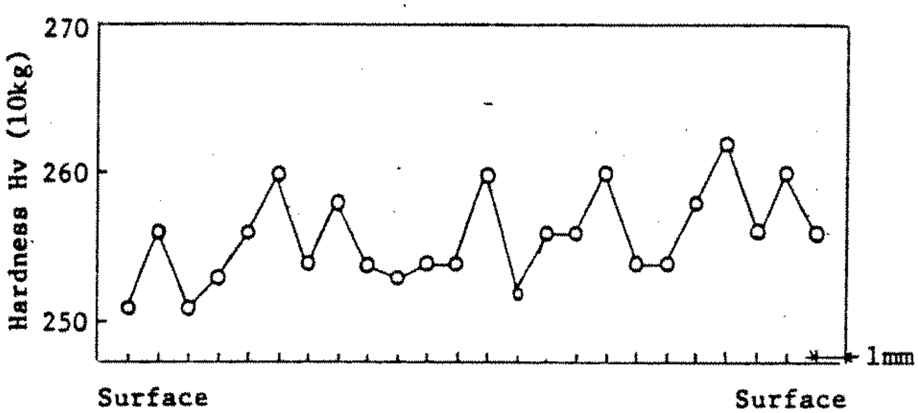


Figure V.1 : Hardness Test Results for **HY 80**

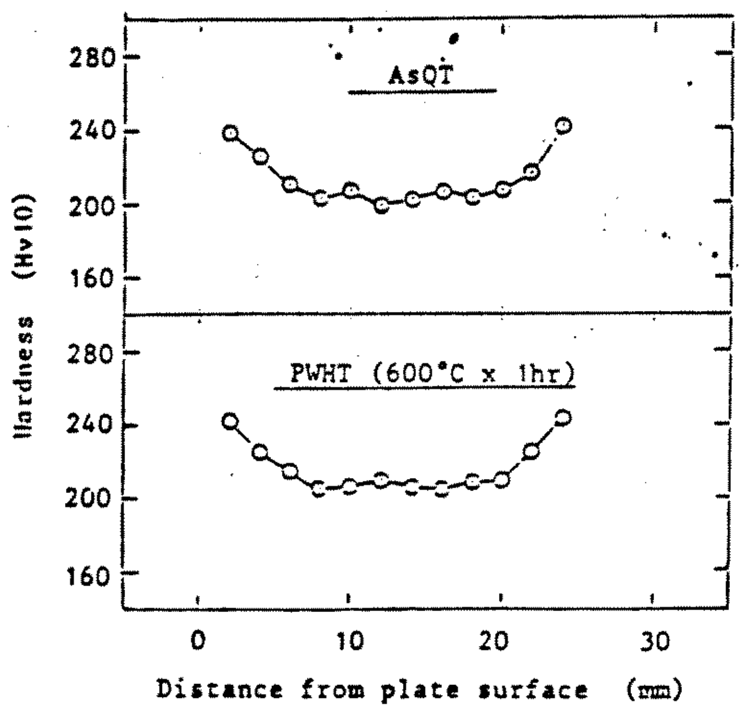


Figure V.2 : Hardness Test Results for **A 710**

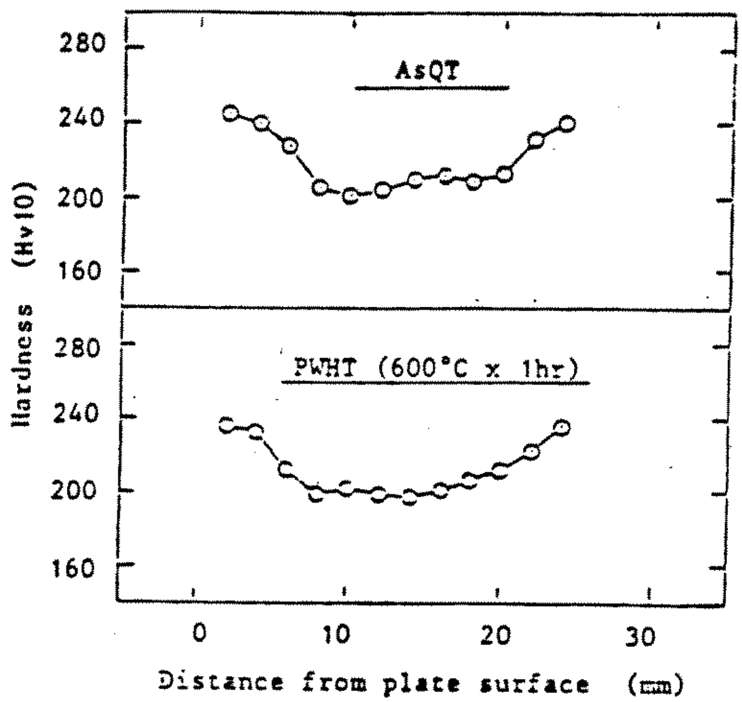


Figure V.3 : Hardness Test Results for **QT 80**

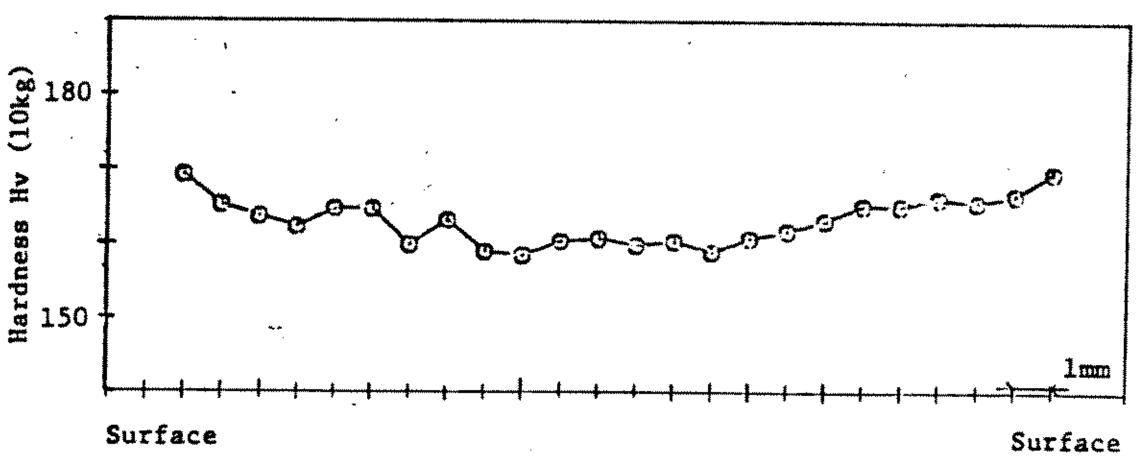


Figure V.4 : Hardness Test Results for **EH 36**

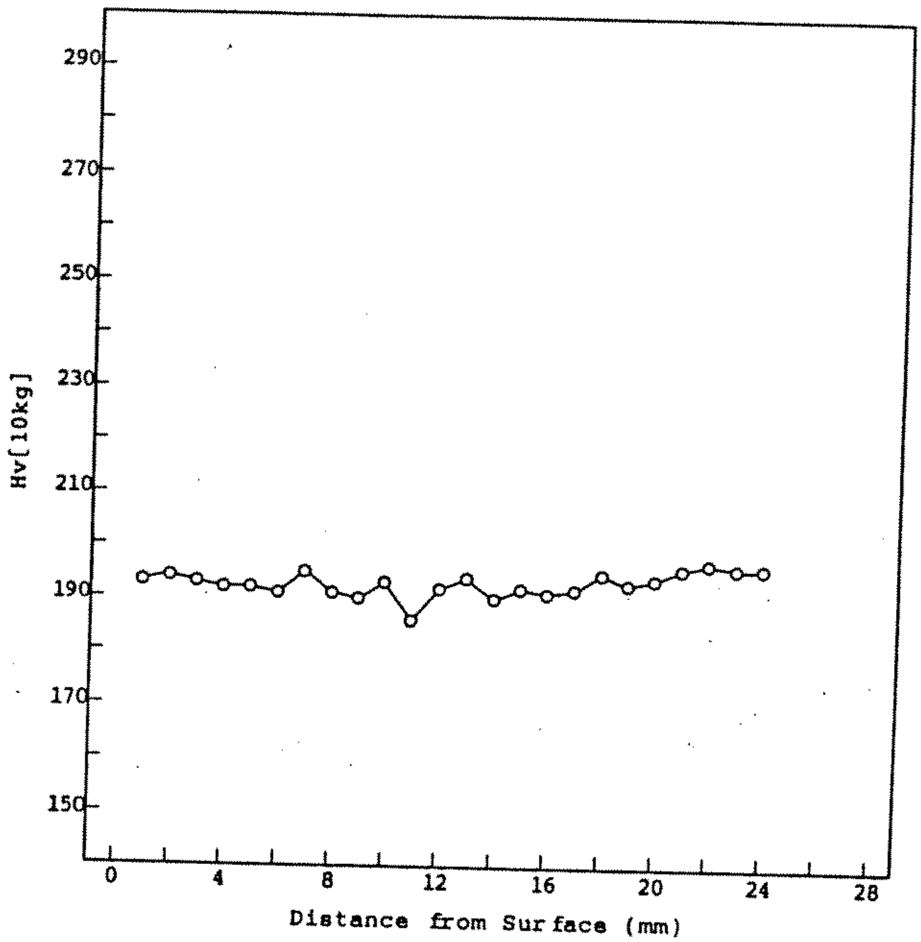


FIGURE V.5 : Hardness Test Results for X 70

Section VI

Microstructure

Section VII

Welding

A) Welding Procedure

B) Weld Properties

A) Welding Procedure

Welding Procedure Specification

1 Material HY 80

2 Welding Procedure

Welding Process S.A.W.

Manual or Machine Machine

Position of Welding Flat

Filler Metal W543(4mm¢)

Flux B2CM(Bond Flux)

Welding Current 650Amp

Welding Voltage 38Volt

Welding Speed 16.5Inch/min

Preheat and Interpass Temperature 150-200 C

Post Heat Temperature 600 Cx2Hr A.C.

Joint Detail

Edge Preparation Layer of Pass

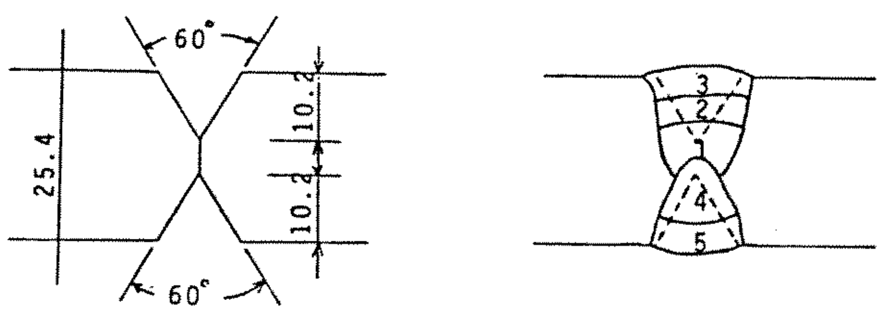


Figure VII A.1 : Welding Procedure for HY 80

1. Base plate

Plate No.2 ASTM A710 GradeA Class3 (σy : 70 - 80 Ksi)

Plate No.3 NKHITEN 62E (σy : 70 - 80 Ksi QT plate)

Note : The same welding procedure will be applied for both plates.

2. Welding procedure

(1) Welding process : Submerged arc (Multi-pass)

(2) Welding material

Wire : US- 40 (Kobe Steel Ltd.)
Wire diameter : 4 mm

Flux : PFH- 55S (Kobe Steel Ltd.)

AWS Classification : F8P6-EA3-A4

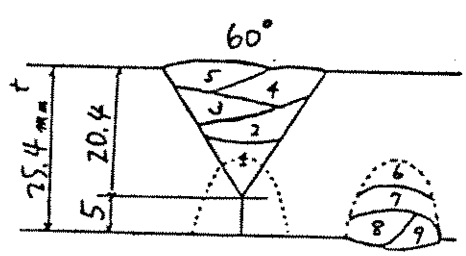
(3) Current and porality : AC

(4) Preheat temperature : Ambient t mperature

Interpass temperature : 200 °C

(5) Post weld heat treatment : 600 °C × 1 hr and As Welded

(6) Standard welding condition



Root pass (1 and 6)
500 A - 27 V - 30 cm/min
Other passes
550 A - 32 V - 30 cm/min

Back gouging : Arc air
(profile 5 R - 35° - 12 mm depch)

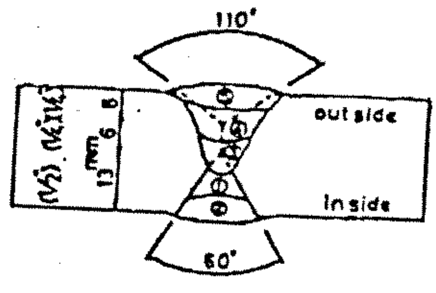
Figure VII.A.2 : Welding Procedure for A 710 & QT 80

Material specification ASTM A514F equivalent (QT 108)
Welding process SAW
Manual or machine Machine
Position of welding Flat
Filler metal specification AWS A5.23
Filler metal and flux classification F11A6-EG-G, KB-80C x KW-103B

Single or multiple pass Multiple
Single or multiple arc Single
Welding current AC
Root treatment Gouging
Preheat and interpass temperature 100-200 °C
Post heat treatment 580-600 °C x 1 hr/in

Welding Procedure

* in./min.

Pass no.	Electrode size	Welding current		Travel speed*	Joint detail
		Amperes	Volts		
1	4.0φ	550	28	10	
2 ~ 5			30		gouged after 2nd pass

This procedure may vary due to fabrication sequence, fit-up, pass size, etc., within the limitation of variables given in 4B, C, or of AWS D1.1, Structural Welding Code.

Procedure no. ________ Manufacturer or contractor ________

Revision no. ________ Authorized by Kozo Akahide

Date May 31 '84 Dr. Kozo Akahide, Senior Researcher

Figure VII.A.3 : Welding Procedure for QT 108

1 Material EH 36(Alloy type C.R.)

2 Welding procedure

Welding Process S.A.W.

Manual or Machine Machine

Position of Welding Elat

Filler Metal W36(4mm¢)

Flux BL55(Bond Flux)

Electrode and Flux combination A.W.S. A5.17 F7A8-EH14

Welding Current 1 Pass: 520Amp, 2-5 Pass: 600 Amp

Welding Voltage 1 Pass; 29Volt, 2-5 Pass: 32-34Volt

Welding Speed 13.0 Inch/min

Preheating Temperature 75°C

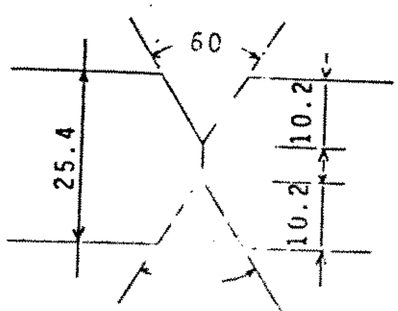
Interpass Temperature 75-125°C

Post Heat None(Sample No. EH36 B1-4)

600°Cx2 Hr A.C.(Sample No. EH36 A1-2, EH36 C1-2)

Joint Detail

Edge Preparation



Layer of Pass

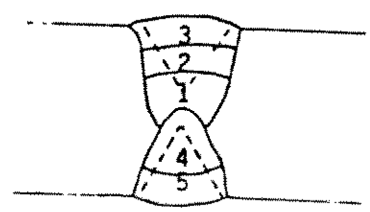
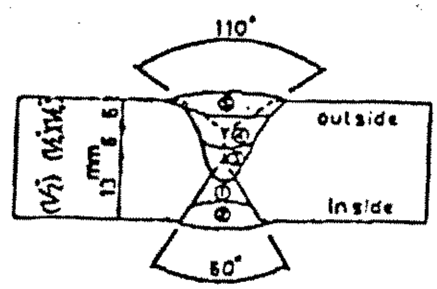


Figure VII.A.4 : Welding Procedure for EH 36

Material specification ASTM A537 cl. 2
Welding process SAW
Manual or machine Machine
Position of welding Flat
Filler metal specification AWS A5.23
Filler metal and flux classification F8A6-EG-G, KB-110 x KW-101B

Single or multiple pass Multiple
Single or multiple arc Single
Welding current AC
Root treatment Gouging
Preheat and interpass temperature 100-200 ℃
Post heat treatment 580-600 ℃ x 1 hr/in.

Welding Procedure * in./min.

Pass no.	Electrode size	Welding current Amperes	Volts	Travel speed*	Joint detail
1	4.0φ	550	28	10	 gouged after 2nd pass
2			30		
⁞					
5					

This procedure may vary due to fabrication sequence, fit-up, pass size, etc., within the limitation of variables given in 4B, C, or of AWS D1.1, Structural Welding Code.

Procedure no. ______ ______ Manufacturer or contractor ______

Revision no. ______ ______ Authorized by Kozo Akahide

Date May 31/84 Dr. Kozo Akahide. Senior Researcher

Figure VII.A.5 : Welding Procedure for A 537 d.q.

Material specification ASTM A537 class 2 (TMCP steel)

Welding process SAW

Manual or machine Machine

Position of Welding Flat

Filler metal specification AWS A5.23

Filler metal and flux specification F8A6-EG-G, KB-110×KW-101B

Single or multiple pass Multiple

Single or multiple arc Single

Welding current AC

Root treatment Gouging

Preheat and interpass temperature 100~200 ℃

Post heat treatment 580~600 ℃× 1 hr

Welding procedure

* in./min.

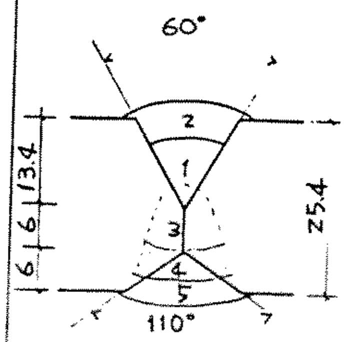
Pass no.	Electrode size (mm)	Welding current		Travel speed *	Joint detail
		Ampares	Volts		
1	4.0	550	28	10	
2	〃	〃	30	〃	
3	〃	〃	〃	〃	
4	〃	〃	〃	〃	
5	〃	〃	〃	〃	

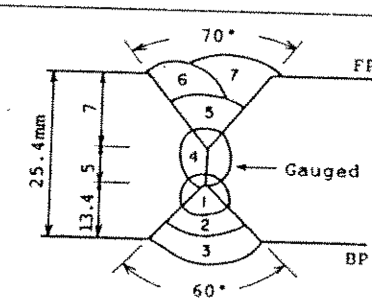
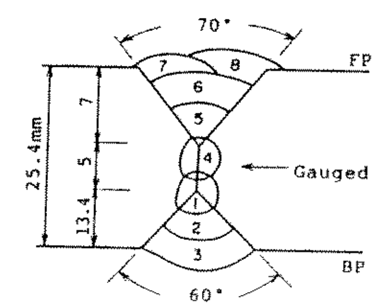
Figure VII.A.6 : Welding Procedure for A 537 a.c.

Welding Procedure

Process	:	SAW (Wire 4mmΦ)
Position	:	Flat
Filler metal and flux classification :		
		F8A6-EG-A4 (◆ W49 × ◆ BL55)
		F8P6-EG-A4
Welding current	:	AC
Root treatment	:	Gauging
Preheat temp.	:	Room temperature (10 ~ 16°C)
Interpass temp.	:	150°C max.
PWHT	:	580°C × 1Hr.

Welding Condition

Welding Condition

Specimen	Pass No.	Current (A)	Voltage (V)	Speed (cm/min.)	Joint Detail
A · B	1 2 , 3 4 5 ~ 7	520 640 600 640	34 34 35 34	31 31 31 31	
C	1 2 , 3 4 5 6 7 , 8	520 640 600 640 640 640	34 34 35 34 34 34	31 31 31 31 27 31	

Welding Procedure for X-70

B) Weld Properties

B1) HY 80 and EH 36

Tension test

Tension test

Steel	Thickness mm	PWHT	TS kgf/mm^2	Position of fracture
HY 80	25.4	o	79.4	M.M.
		o	80.0	M.M.
EH 36	25.4	–	58.7	W.M.
		o	54.7	W.M.

Charpy impact test

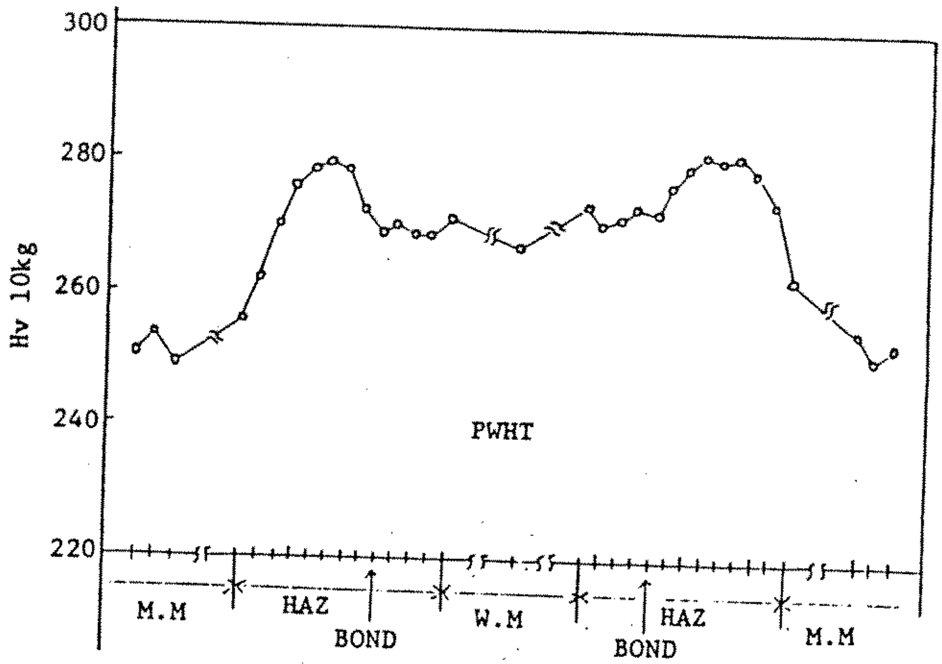
Charpy impact test

Steel	Thickness mm	PWHT		vE_{-20}		vE_{-46}		vE_{-85}	
				kgf·m	SA %	kgf·m	SA %	kgf·m	SA %
HY 80	25.4	o	W.M	6.6	60	3.6	28	2.0	8
				6.6	60	3.8	34	2.1	8
				6.6	62	4.4	35	2.3	13
			BOND	6.7	63	3.0	35	2.6	18
				8.8	68	4.0	48	2.7	18
				10.4	78	4.8	51	3.0	21
			HAZ 1mm	18.9	100	19.3	100	2.6	25
				18.9	100	19.5	100	2.7	25
				22.0	100	19.6	100	3.6	42

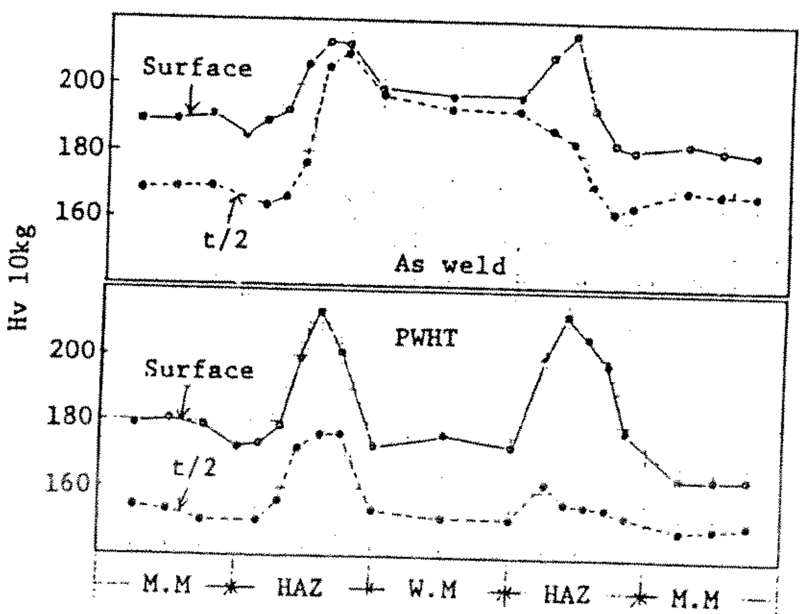
Charpy impact test

Steel	Thickness mm	PWHT		vE_{-20} kgf·m	vE_{-20} SA %	vE_{-40} kgf·m	vE_{-40} SA %
EH 36	25.4	-	W.M.	16.3	86	13.5	74
				16.2	85	14.1	76
						14.1	74
			BOND	10.8	70	13.3	66
				15.4	74	14.3	68
						13.2	64
			HAZ 1mm	12.4	72	6.5	46
				10.7	66	5.3	42
						4.9	38
		o	W.M.	16.8	72	13.5	54
				15.9	70	5.5	32
						1.7	20
			BOND	7.5	54	2.8	38
				5.9	50	3.1	36
						4.5	42
			HAZ 1mm	5.9	36	4.5	42
				7.1	48	4.0	38
						3.9	38

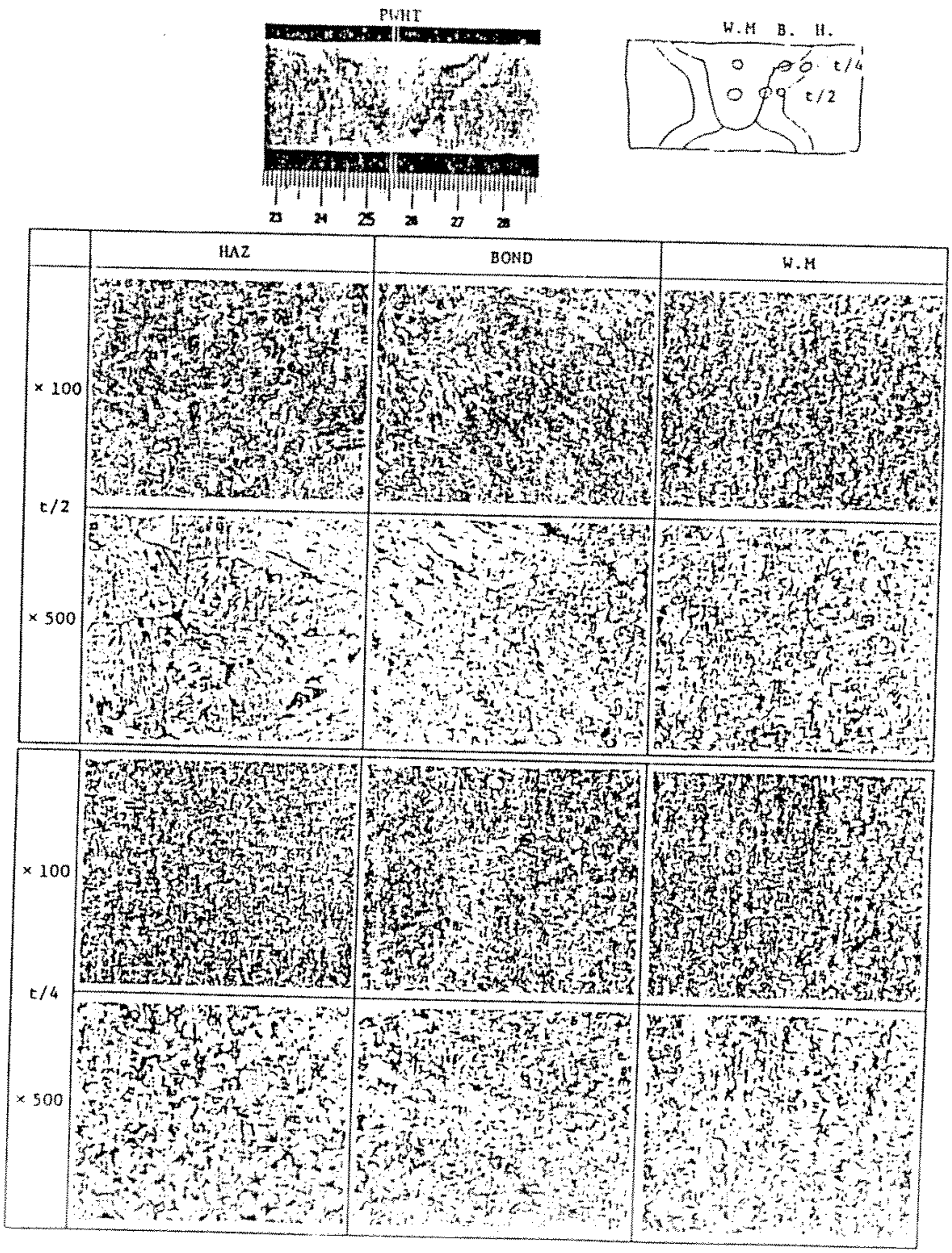
Hardness test



Hardness distribution - HY 80

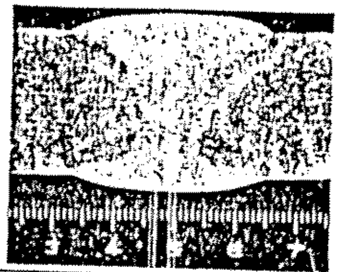


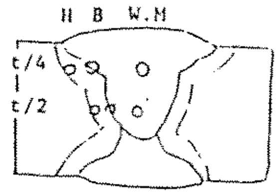
Hardness distribution - EH 36

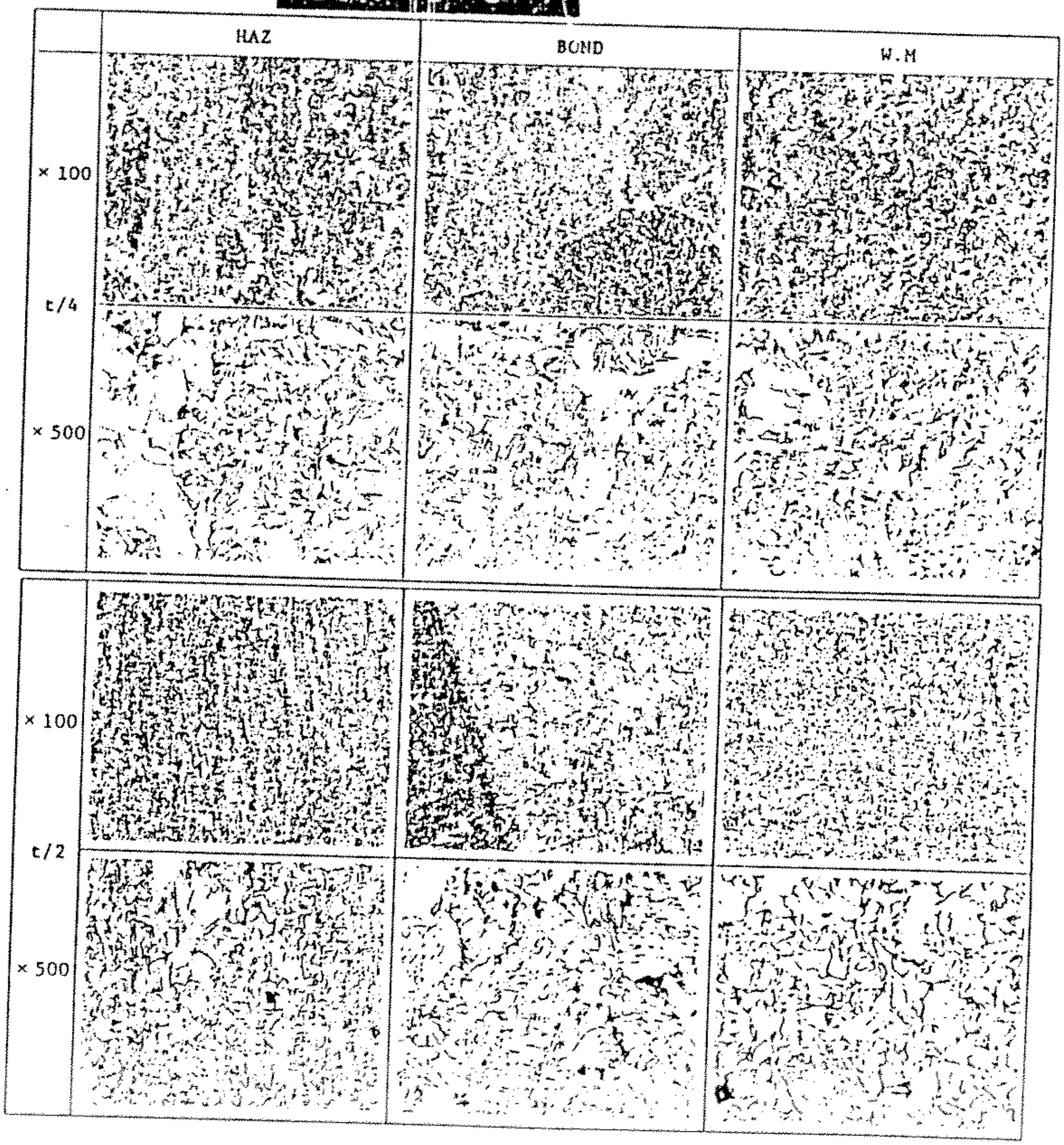


Microstructure of HY 80

As Weld







Microstructure of HY 80

B2) QT 80

1. Forward

A study on corrosion fatigue in saline water is being conducted between FAU and Steel makers cooperatively.

NIPPON KOKAN K.K. (NKK) studied two steel plates of NK-HITEN62E and A710-Gr. A-Cl.3.

This report is to describe the test results on the mechanical properties of the welded joint of NK-HITEN62E.

2. Tested Steel Plates

Table 1 Chemical composition of plate

(wt%)

		C	Si	Mn	P	S	Cu	Ni
QT 80	ladle	0.08	0.25	1.34	0.013	0.003	-	0.46
	check	0.08	0.23	1.40	0.010	0.002	0.01	0.43

Cr	Mo	Nb	V	Ti	B	sol Al	N
0.10	0.06	-	0.041	0.006	-	0.054	0.0031
0.09	0.06	0.002	0.040	0.005	0.0001	0.051	0.0026

3. Welding Condition

(1) Welding Method : SAW (Multi-pass)

(2) Welding Consumables

i) Wire : US-40 (KOBE STEEL Ltd.)

ii) Flux : PFH-55S (KOBE STEEL Ltd.)

AWS classification : F8P6-EA3-A4

Table 2 Typical chemical composition of wire-electrode

Brand	C	Si	Mn	P	S	Mo
US40	0.13	0.04	1.80	0.011	0.010	0.52

4mm in dia.

(3) Preheat : room temperature

Interpass temperature : 200 °C

(4) bead sequence and welding condition

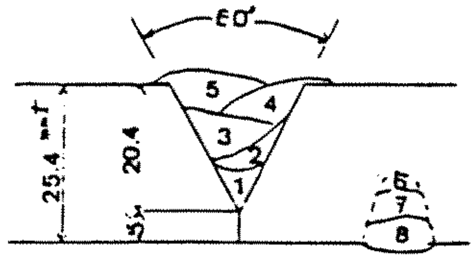


Fig.1 Bead sequence

Backing Passes (1 and 5)
500 ~550A - 27 ~32V -30cpm

Other passes
500 ~550A - 27 ~32V -30cpm

Back Gouging Profile
5R - 35° - 12mm depth

(5) PWHT

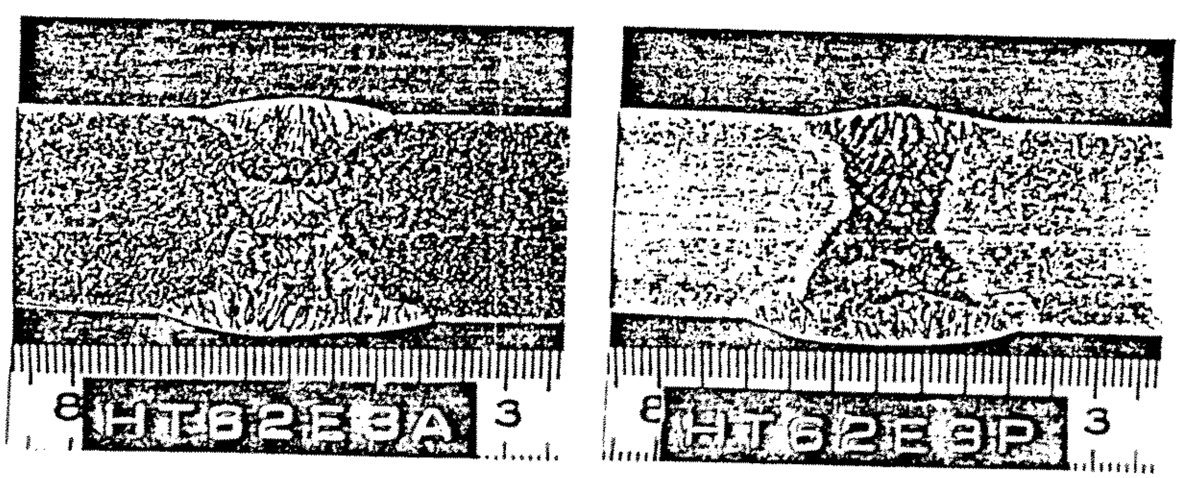
As welded

PWHT 600 °C x 1 hr

cooling rate 600 to 300 °C : 42 °C/hr.

4. Testing Results

4-1) Macrostructure



As Welded

PWHT

Microstructure of QT 80

4-2) Check analysis of weld metal

Check analysis of weld metal are shown in Table 3.

Table 3 Chemical composition of weld metal (wt%)

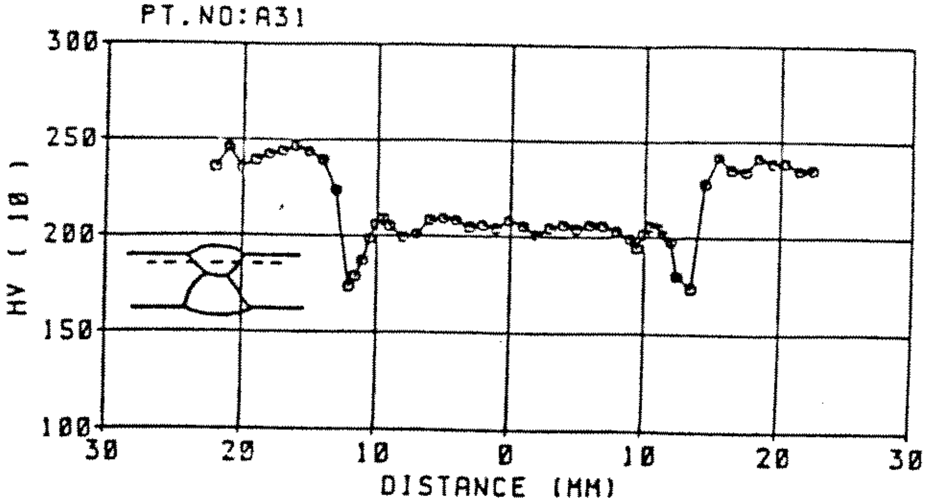
	C	Si	Mn	P	S	Cu	Ni	Cr
Weld Metal	0.07	0.16	1.33	0.010	0.007	0.08	0.16	0.06

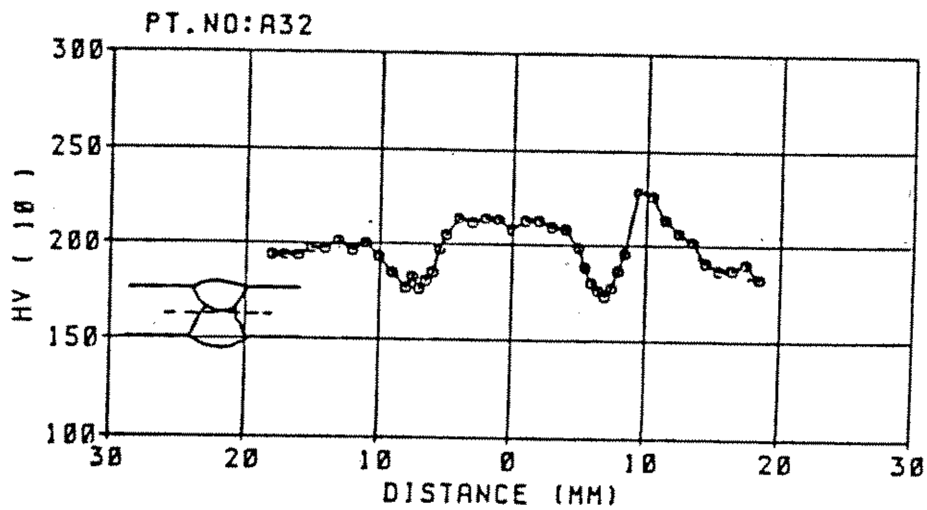
Mo	Nb	V	Ti	B	sol Al	N
0.34	Tr.	0.014	0.005	0.0005	0.006	0.0048

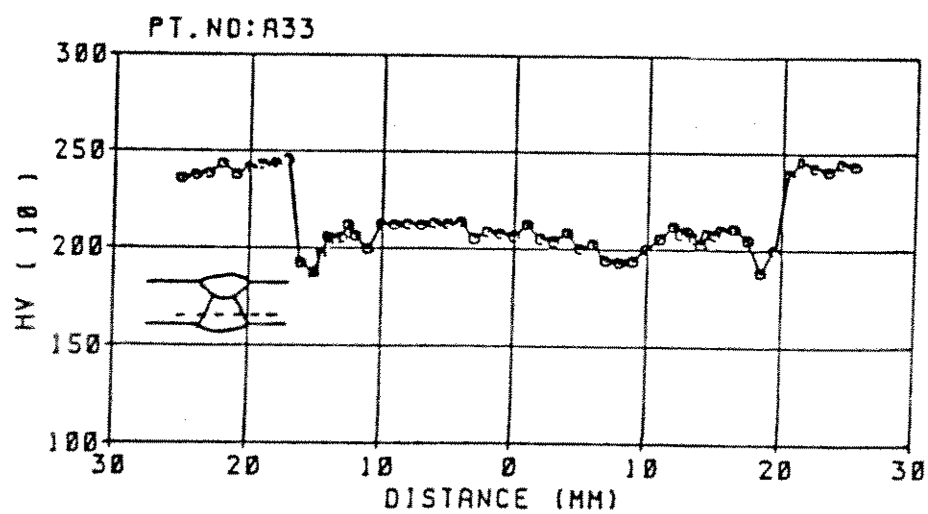
4-3) Hardness test results.

Vicker's hardness test was carried out on a weld area cross section with transverse of 2mm from top and bottom surfaces and mid-thickness of the plate using 10kg load.

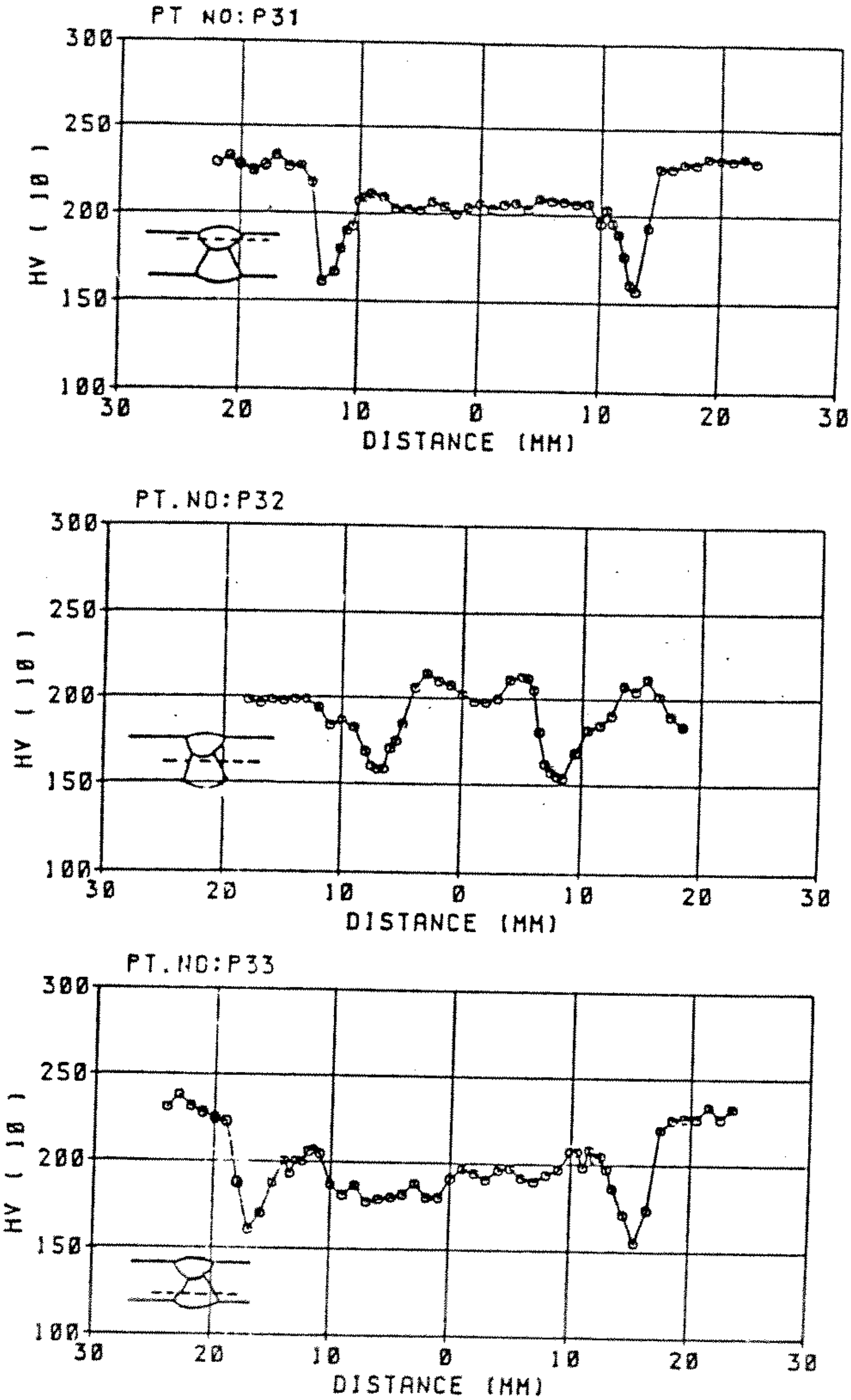
The results of hardness distribution are shown in Fig.2 in as welded condition and Fig.3 in PWHT.







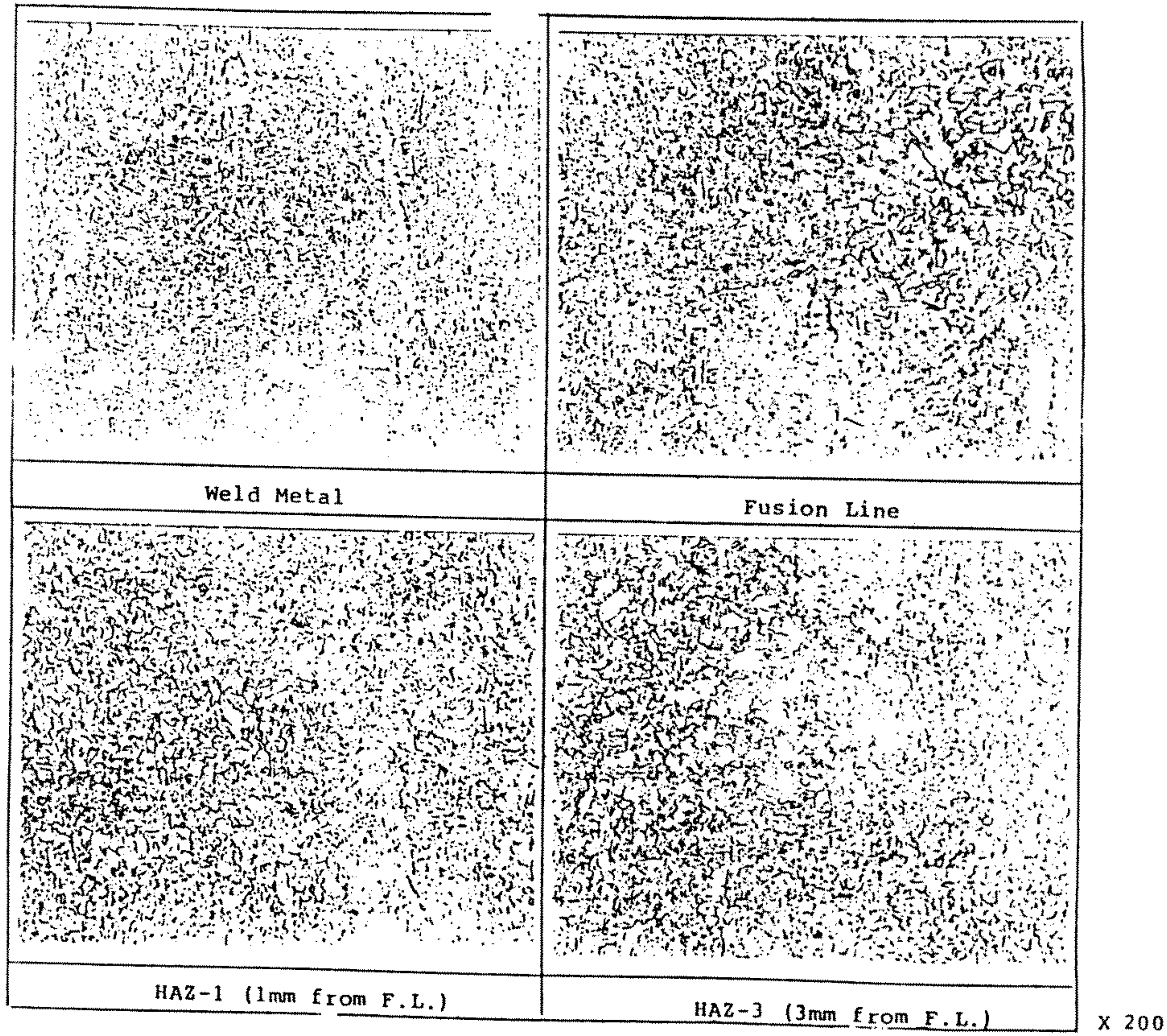
Hardness distribution of welded joint of QT 80
(As welded condition)



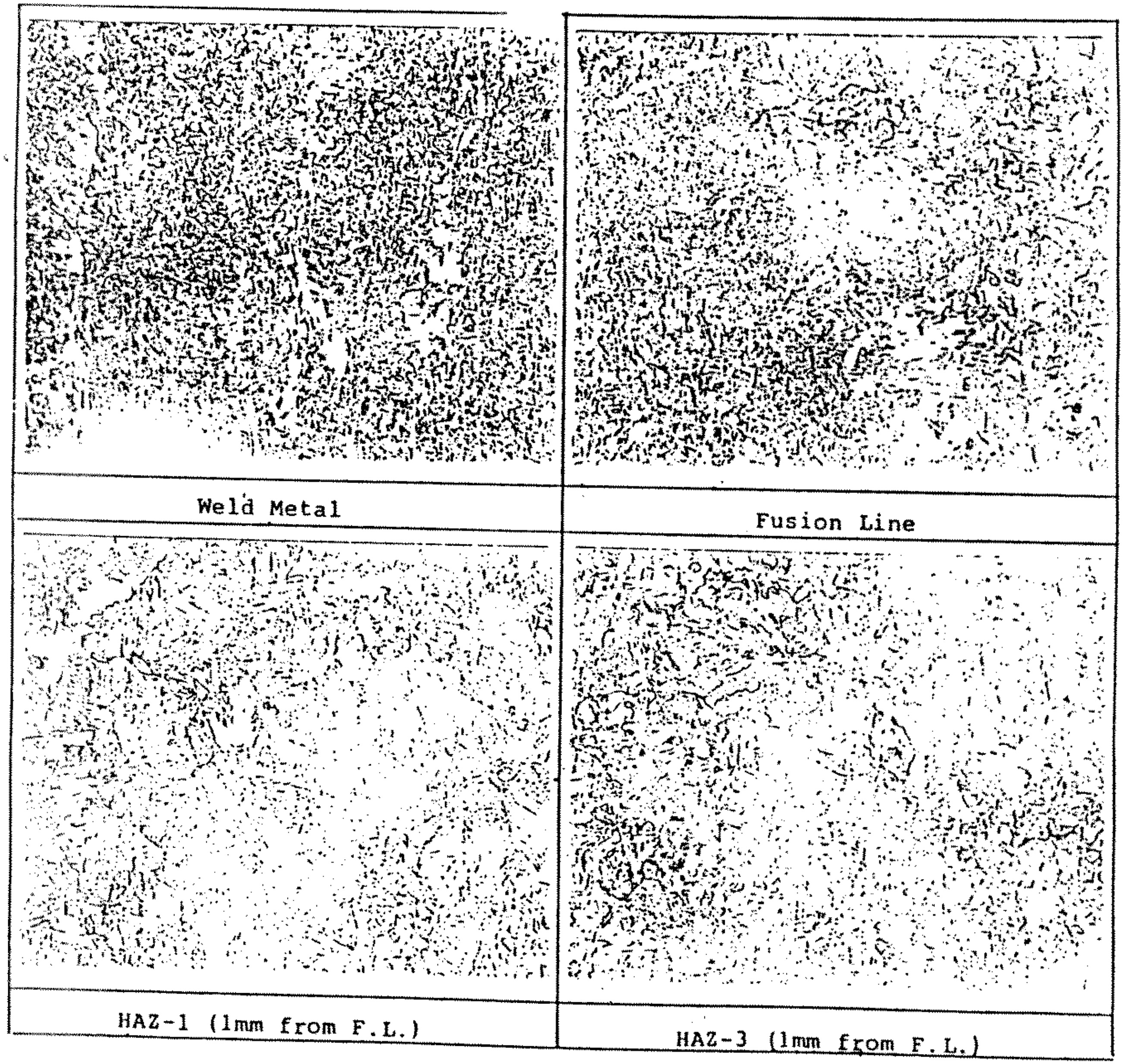
Hardness distribution of welded joint of QT 80
(After PWHT)

4-4) Microstructure of welded joint

Microstructures of weld metal, 1mm and 3mm distance from fusion line at a quater thickness in as welded condition and PWHT are shown in Photo 2 and 3. The magnification is 200 times.



Microstructure of weld portion of QT 80 in as welded condition



X 200

Microstructure of weld portion of QT 80 in PWHT condition

4-5) Result of Charpy test

Charpy test of weld portion was carried out in both as welded and PWHT condition.

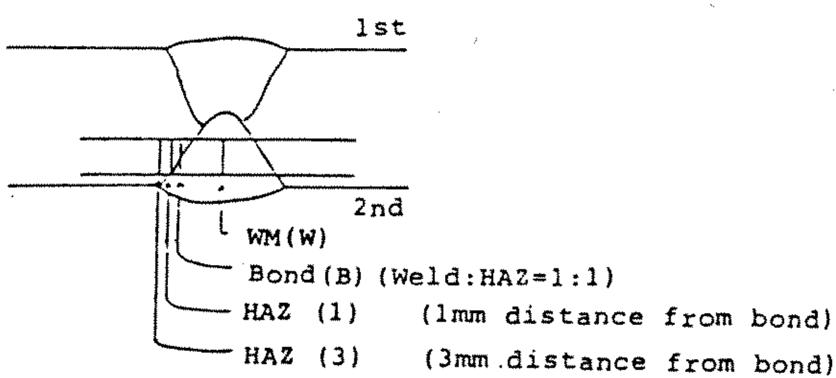
Test pieces were taken in a quater thickness of the plate.

Table 4 shows the results of Charpy test.

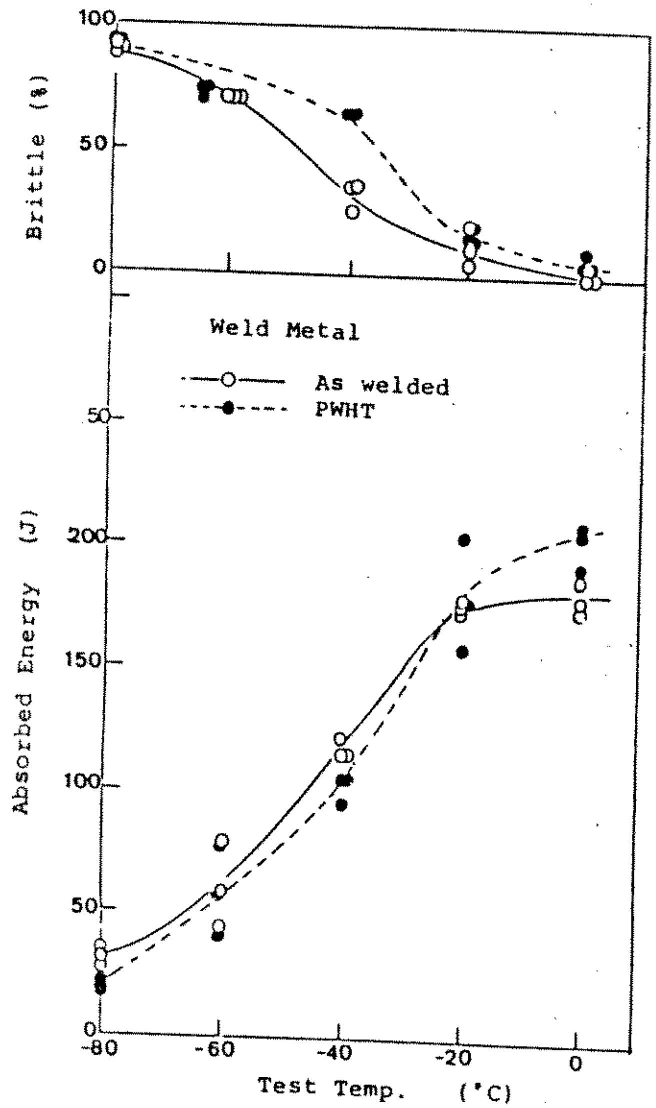
Fig.4 and 5 show the Charpy transition curves in the as welded and PWHT condition.

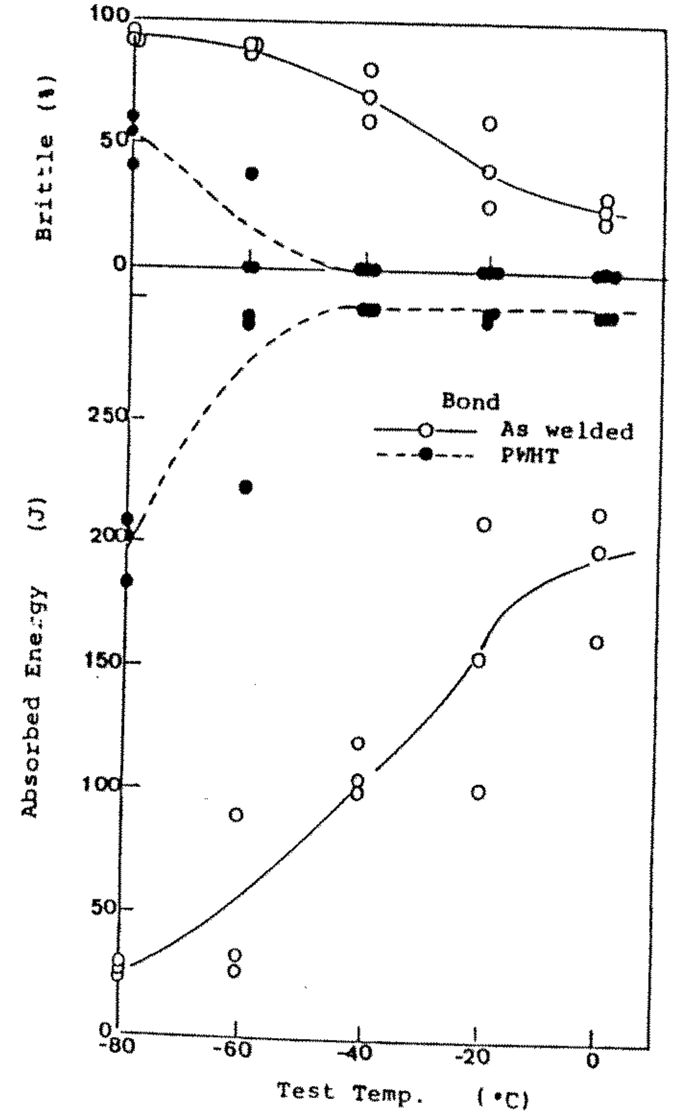
Charpy test result

	As weld			PWHT		
	vE−20℃ (J)	vE−40℃ (J)	vTrs (℃)	vE−20℃ (J)	vE−40℃ (J)	vTrs (℃)
Weld Metal	179 176 173	116 122 116	−49	160 179 206	110 111 94	−35
Ave.	176	118		182	105	
Bond	210 155 102	108 121 101	−25	294 291 294	294 294 294	−79
Ave.	156	110		293	294	
HAZ(1)	294 277 294	252 215 294	−44	294 294 294	294 294 294	−77
Ave.	288	254		294	294	
HAZ(3)	294 214 224	160 99 135	−24	294 294 294	294 294 294	< −80
Ave.	244	131		294	294	

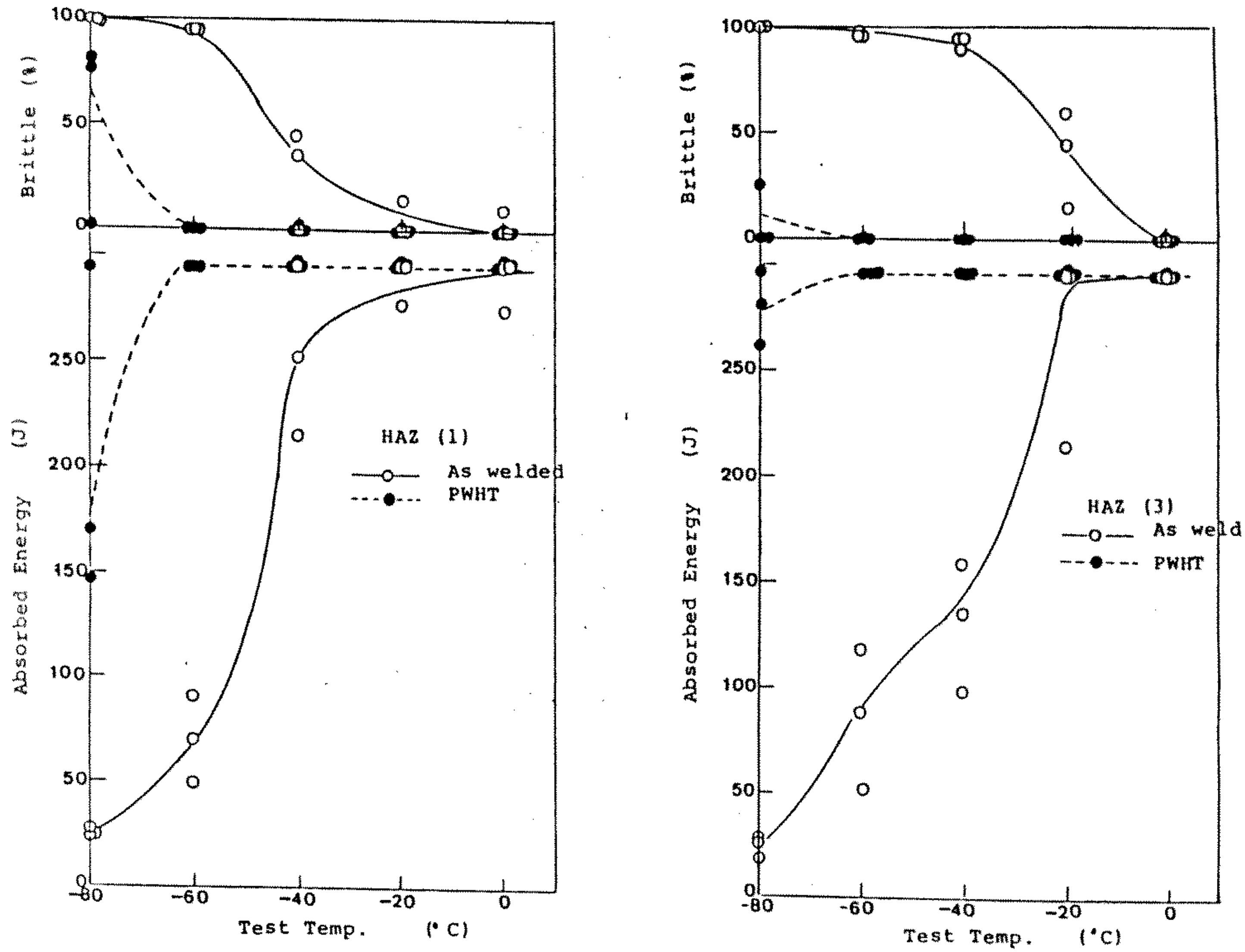


Notch Location of Charpy Specimen





Charpy transition curves of welded joints (1)



Charpy transition curves of welded joints (2)

4-6) Results of weld tensile test

Weld tensile test was carried out in accordance with the specimen shown in Fig.6. Weld reinforcement was grinded and followed by blashing.

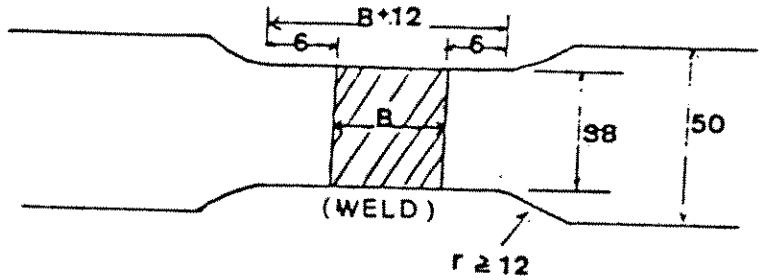


Fig.6 Shape and size of weld tensile specimen

The results of weld tensile test are shown in Table 5.

Table 5 Result of weld tensile test

	TS MPa. (Ksi)	Breaking Position
As welded	645 (93.8)	Weld Metal
PWHT	620 (88.3)	

4-7) Results of CTOD test in accordance with BS5762:1979

CTOD test specimens were taken from weld metal and HAZ. Fatigued side notch was adopted for the specimen.

The shape and size of test specimen are shown in Fig.7.

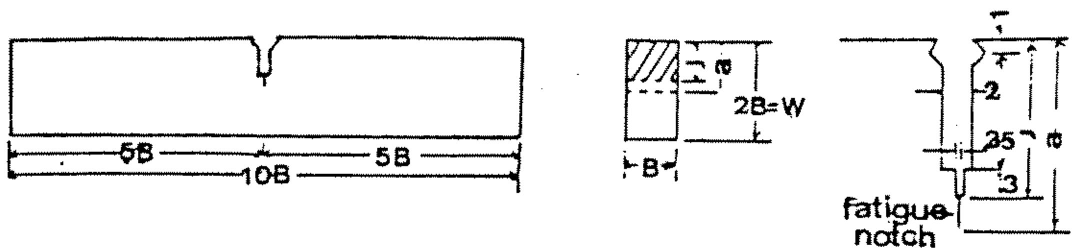
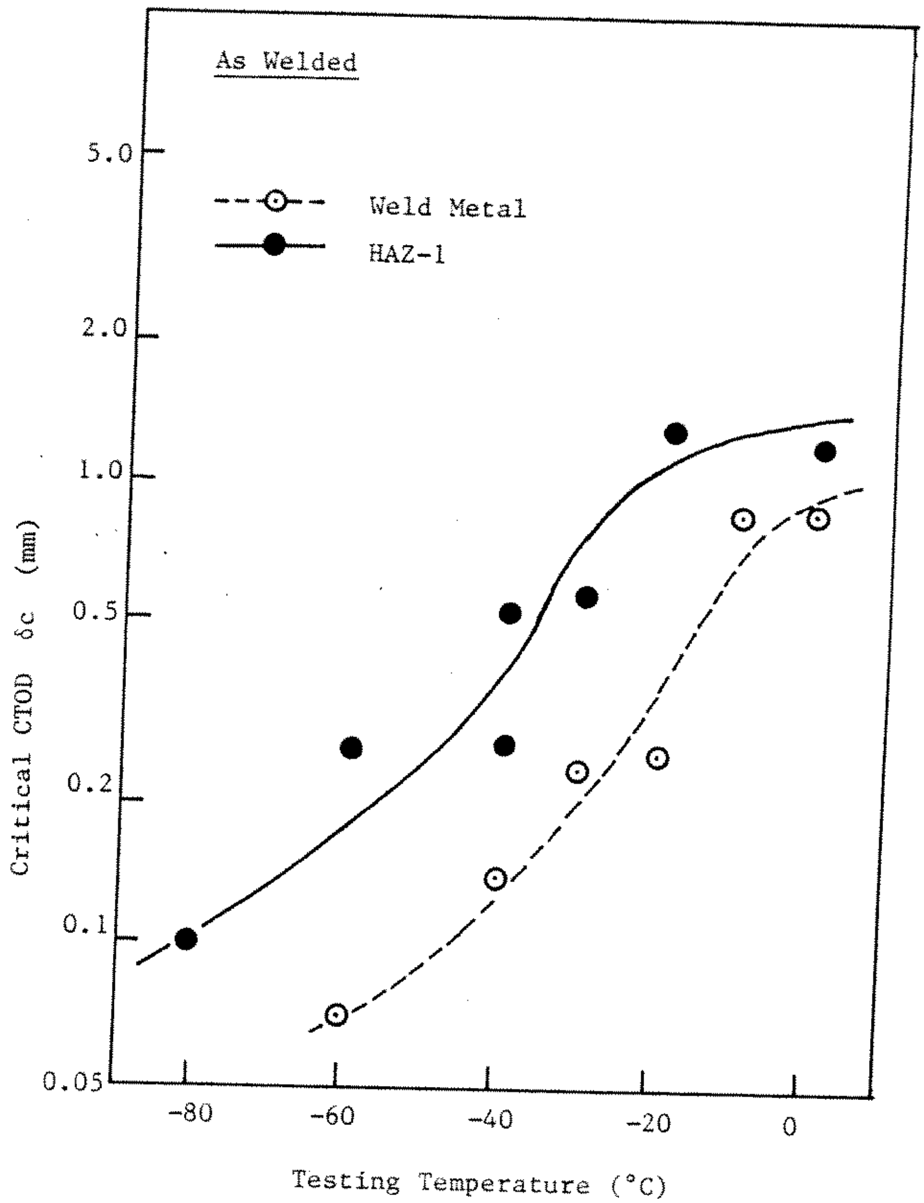
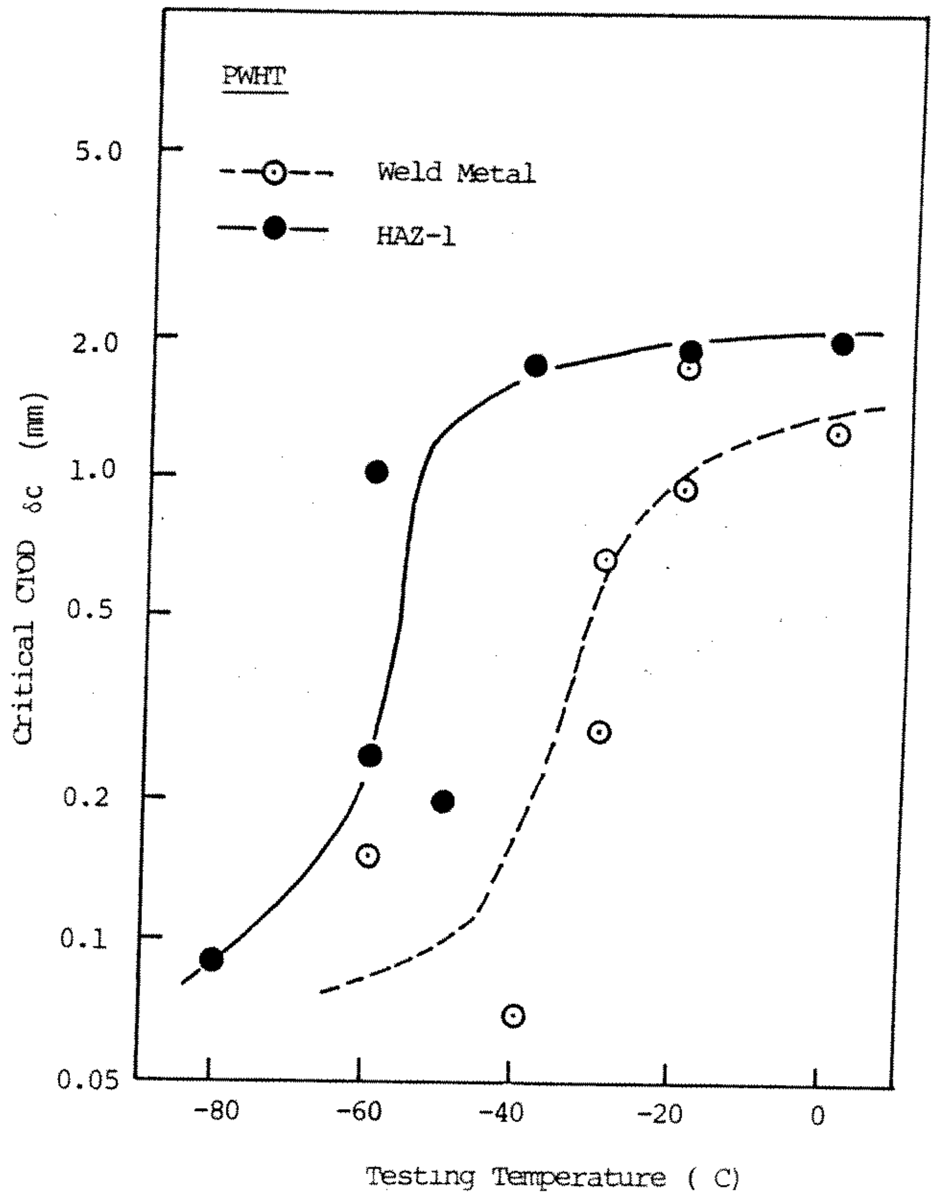


Fig.7 Dimension of test specimen and notch detail

The transition curves of CTOD test are shown in Fig.8 in as welded condition and Fig.9 in PWHT.



Transition curves of CTOD test of
Weld metal and HAZ-1 in as
welded condition



Transition curves of CTOD test of Weld metal
and HAZ-1 in PWHT

B3) QT 108 and A 537d.q.

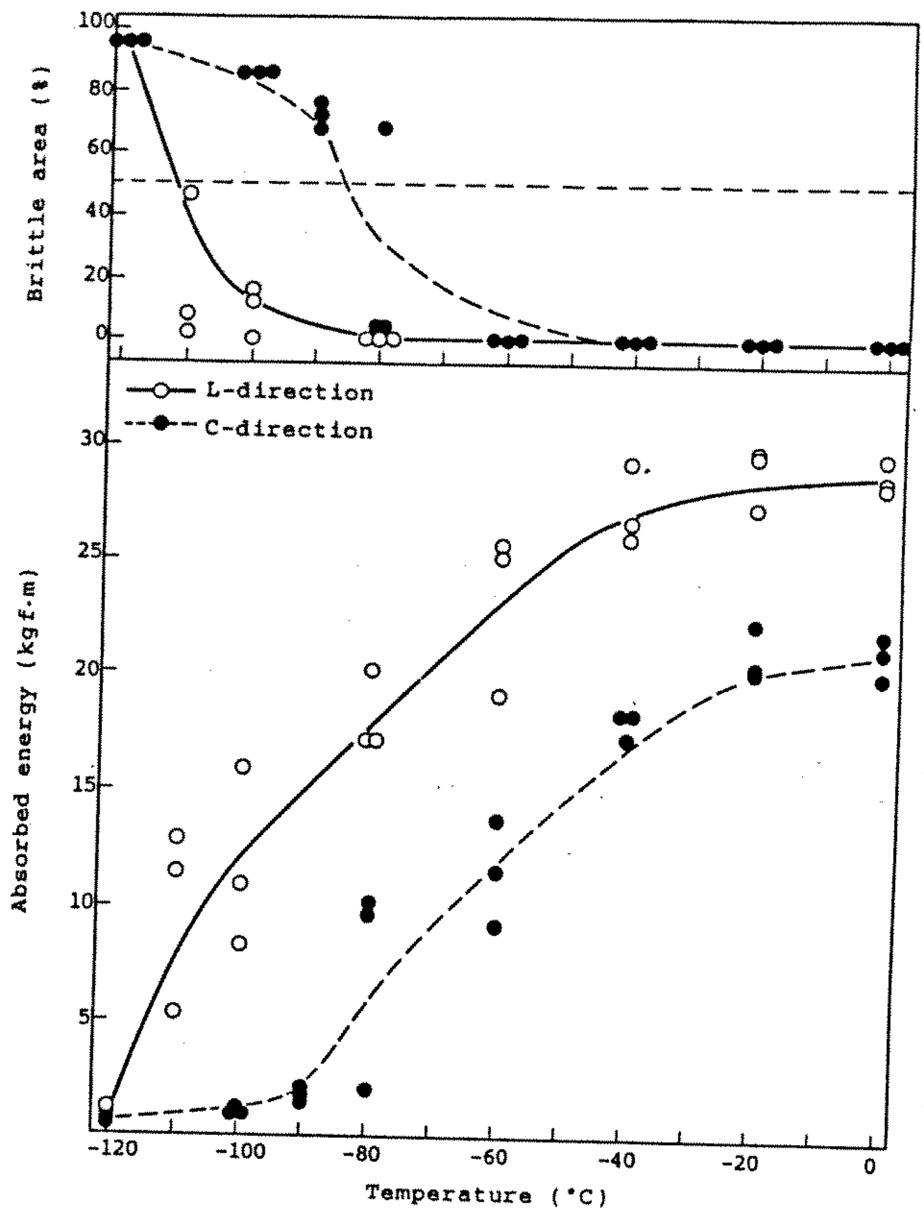
ASTM A370 half size (1/4" dia.) round specimens were used to investigate the tensile properties of the joints.

Tensile properties of the weld metal

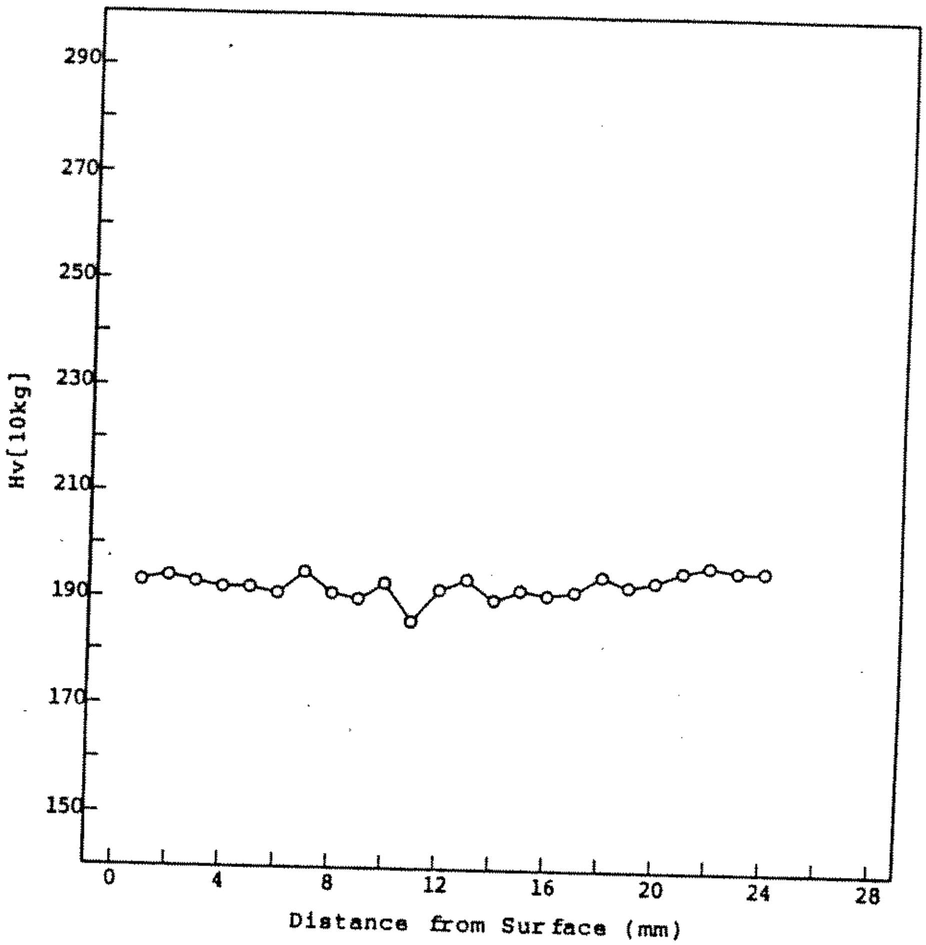
Steel	Heat treatment	Y.S.		T.S.		El.	R.A.
		MPa	ksi	MPa	ksi	%	%
QT 108	As welded	684	100	805	117	27	70
	PWHT	664	97	805	117	25	68
A 537d.q.	As welded	569	82	628	91	28	77
	PWHT	539	78	640	93	31	77

Impact strength was investigated by Charpy V-notch specimen. Location of these specimen were at 2 mm deep from the surface of finishing side weld.

B4) X 70



Charpy Impact Test Results



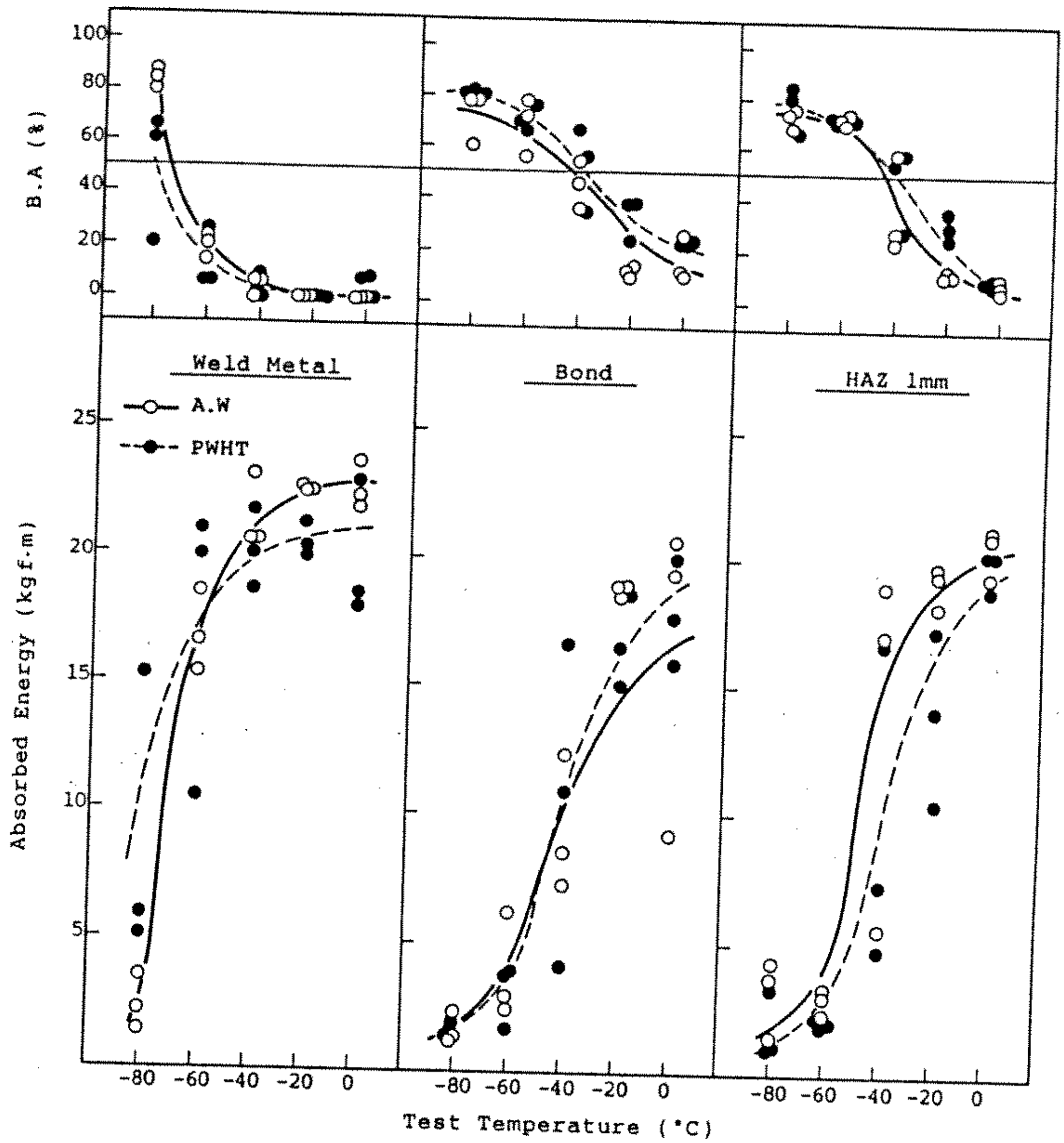
Hardness Test Results

Test Results of Welded Joint

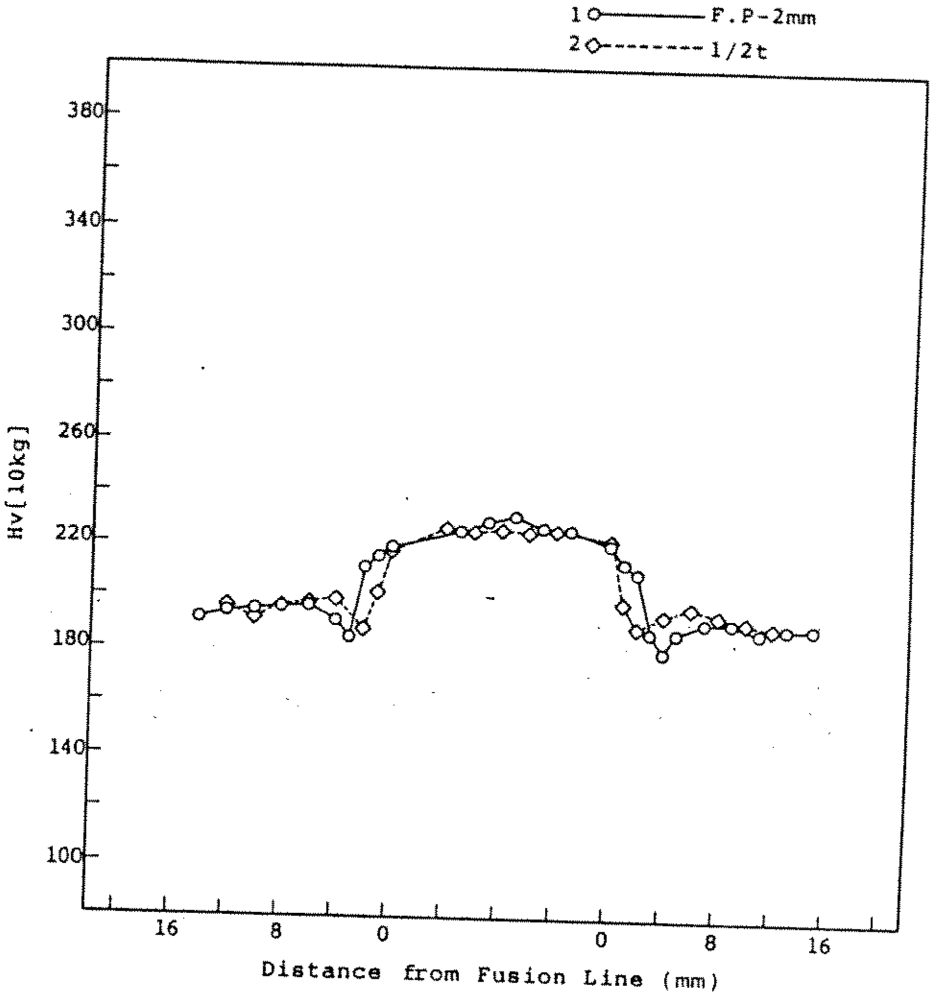
Tension and Charpy Test

Tension and Charpy Test

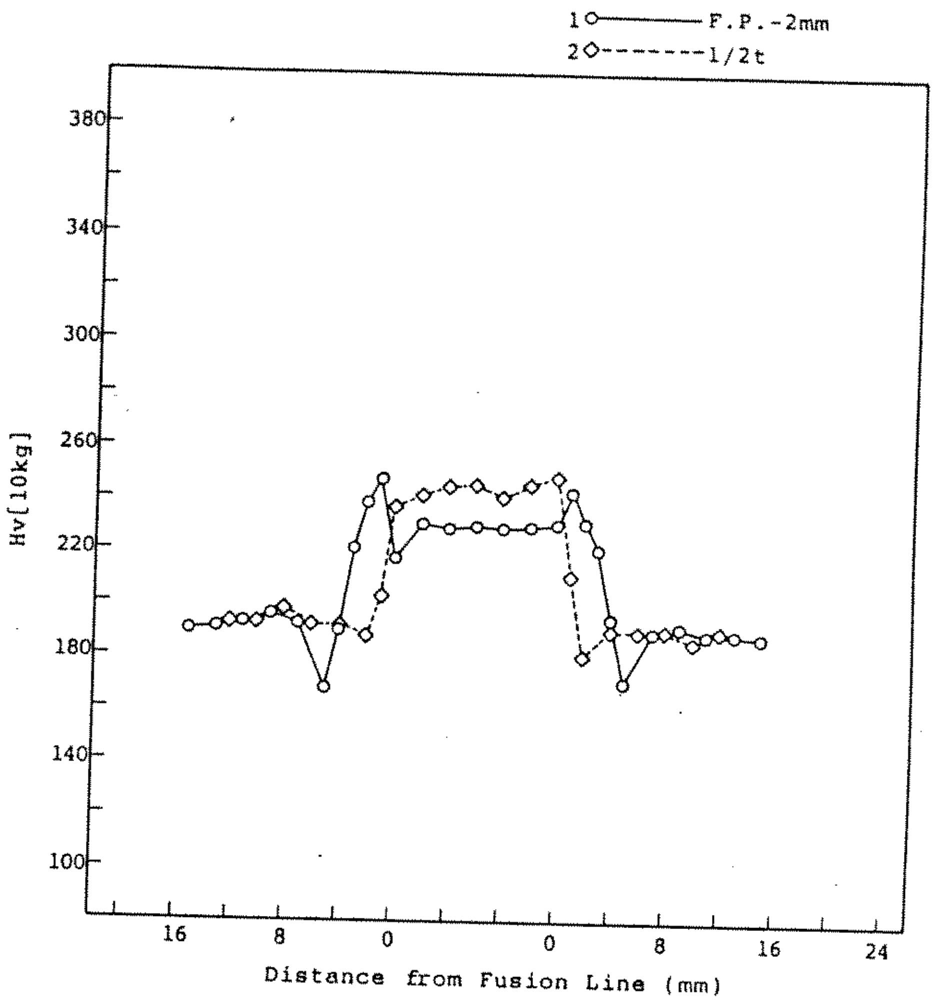
Condition	Tension Test		Charpy Test			
	TS (kg/mm^2) (ksi)	Fractured at	Notch Position (1/4t)	Absorbed Energy at -40°C (kg·m) (ft-lb)		vTrs (°C) (°F)
As Welded	67.4 (95.9)	Base Metal	Weld Metal	20.5 (149) 23.1 (167) 20.5 (149)	21.4 (155)	-74 (-101)
	68.1 (96.9)	Base Metal	Bond (WM50% HAZ50%)	7.2 (52) 8.5 (62) 12.3 (89)	9.3 (67)	-43 (-45)
			HAZ (Bond + 1mm)	5.6 (41) 17.1 (124) 19.0 (138)	13.9 (101)	-44 (-47)
PWHT	66.7 (94.9)	Base Metal	Weld Metal	21.7 (157) 20.0 (145) 18.5 (134)	20.1 (146)	-80 (-144)
	66.6 (94.7)	Base Metal	Bond (WM50% HAZ50%)	16.6 (120) 10.8 (78) 4.1 (30)	10.5 (76)	-38 (-68)
			HAZ (Bond + 1mm)	16.7 (121) 7.3 (53) 4.8 (35)	9.6 (70)	-40 (-40)



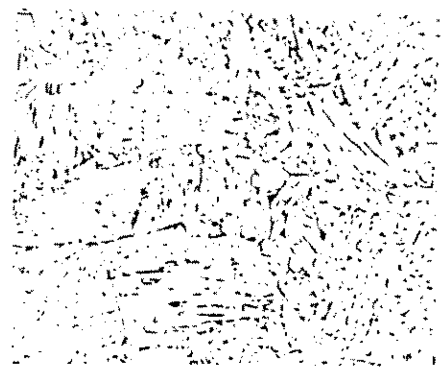
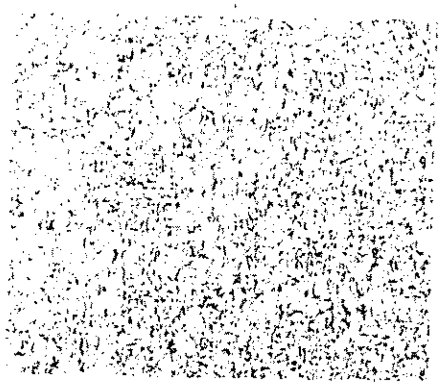
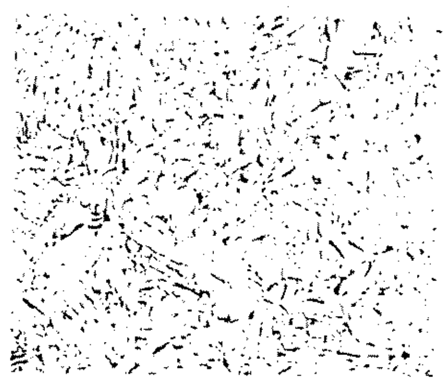
Charpy Impact Test Results of Welded Joint



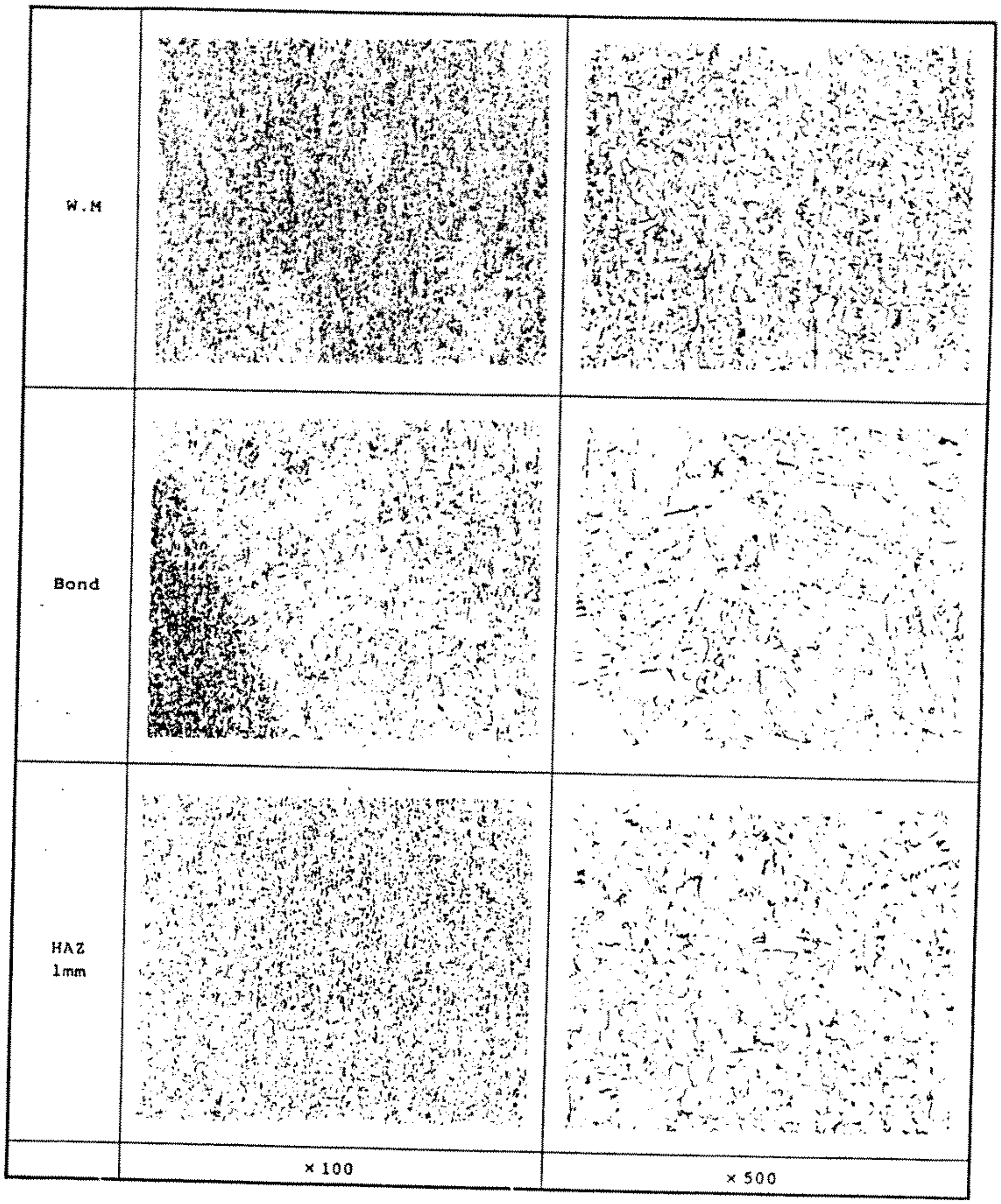
Hardness Test of Welded Joint (As Weld)



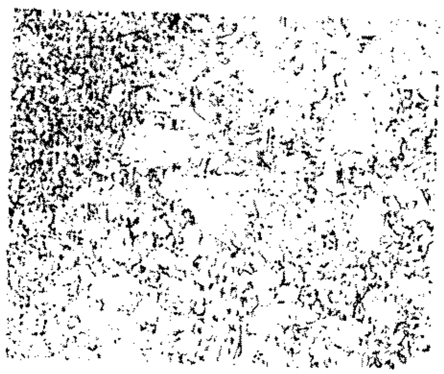
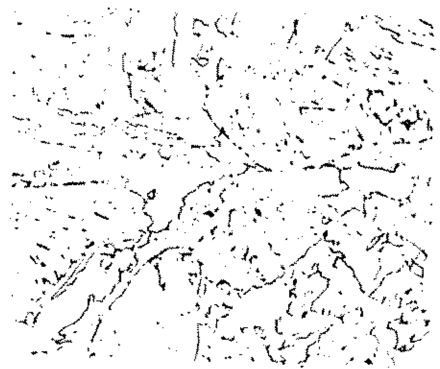
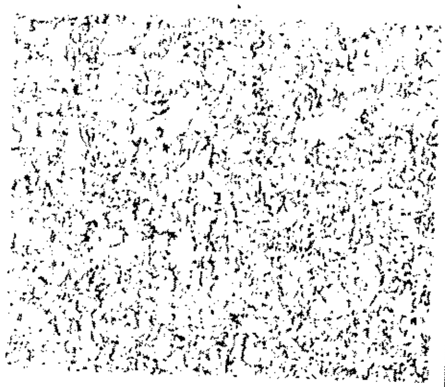
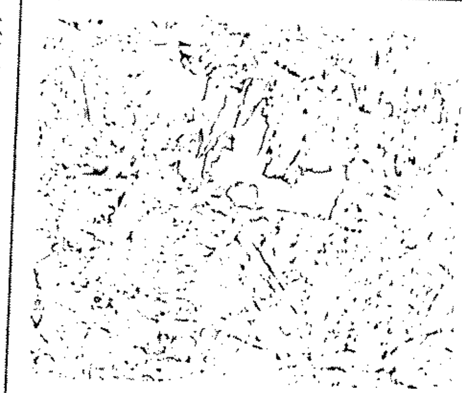
Hardness Test of Welded Joint (PWHT)

W.M		
Bond		
HAZ 1mm		
	× 100	× 500

Micro Structure of Welded Joint
(1/4t, As Welded)



Micro Structure of Welded Joint (1/2t, As Welded)

W.M		
Bond		
HAZ 1mm		
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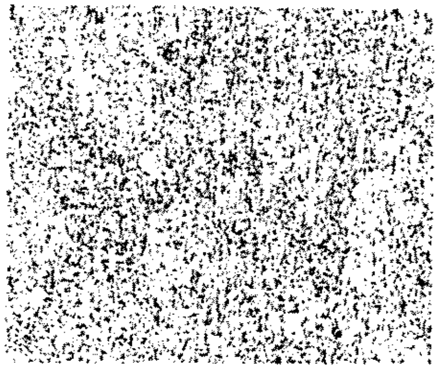
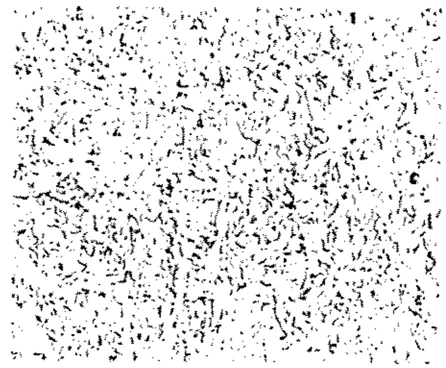
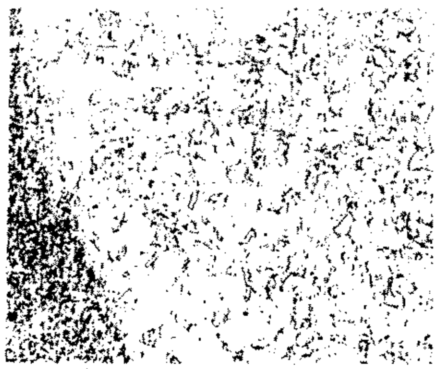
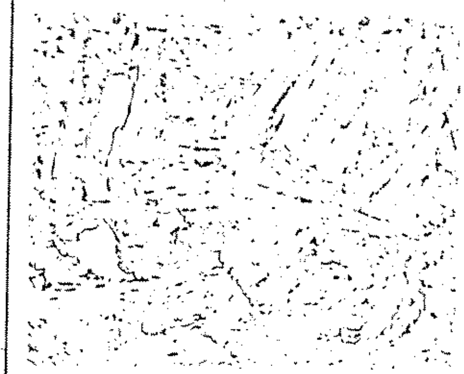
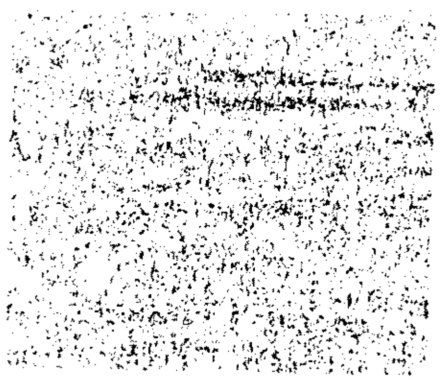
Micro Structure of Welded Joint (1/4t, PWHT)

W.M		
Bond		
HAZ 1mm		
	× 100	× 500

Micro structure of Welded Joint (1/2t, PWHT)