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Special Report

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

compiled by

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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 372–745 MPa (54–108 ksi) have been obtained. These include a conventional, high toughness quenched and tempered steel (HY–80) for comparison purposes, a precipitation hardened steel (A 710), three microalloyed quenched and tempered steels and three thermomechanically control processed (TMCP) steels. 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

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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 372-745 MPa (54-108 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 to a more conventional steel 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	DESIGNATION
HY-80 (Sumitomo)	1
ASTM A710 Grade A Class 3 (NKK)	2
NKHITEN 62E (NKK)	3a
River ACE 80M (Kawasaki)	3b
EH 36 (ABS) (Sumitomo)	4
ASTM A537 Class 2 direct quenched (Kawasaki)	5
ASTM A537, accelerated cool (Kawasaki)	6
Pipe Line X 70 (Sumitomo)	7

Table I : Material and Specimen Designation Convention

Section I

Chemical Composition

STEEL NO.	1	2	3a	3b	4	5	6	7
ELEMENT								
C	0.13	0.04	0.08	0.11	0.13	0.12	0.07	
Si	0.16	0.30	0.23	0.23	0.37	0.41	0.26	
Mn	0.28	0.45	1.40	0.86	1.42	1.30	1.35	
P	0.005	0.004	0.01	0.004	0.018	0.014	0.011	
S	0.005	0.002	0.002	0.003	0.002	0.003	0.003	
Cu	0.02	1.14	0.01	0.24	0.01	0.01	0.14	
Ni	3.08	0.82	0.43	0.98	0.01	0.03	0.14	
Cr	1.70	0.67	0.09	0.43	0.02	0.04	0.01	
Mo	0.44	0.18	0.06	0.44	0.01	0.05	0.02	
Nb	—.—	0.037	0.002	—.—	0.025	—.—	0.017	
V	0.006	0.004	0.04	0.027	0.003	0.044	—.—	
B	0.0001	0.0001	0.0001	0.0009	—.—	—.—	—.—	
Ti	0.004	0.002	0.005	—.—	0.022	—.—	—.—	
N	0.0089	0.0047	0.0026	—.—	0.0038	—.—	—.—	
Sol. Al	0.019	0.034	0.051	—.—	0.046	—.—	—.—	
O	0.0031	—.—	—.—	—.—	—.—	—.—	—.—	
Carbon Equivalent	0.7108*	0.4165£	0.3807£	0.4853*	0.3890*	0.3781*	0.3163*	

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

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

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^{0}C x 30 min W.Q.
	Tempering
	670^{0}C x 1 Hr A.C.

Table II.1 : Process Flow for Manufacture of Steel 1 Plates

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 : 1560ºC min.
Slabbing	Soaking	Top one way type soaking pits	Soaking temperature : About 1300ºC
	Slabbing	High lift slabbing mill	

Table II.2 : Process flow for Manufacture of Steel 2 Plates.

PROCESS		FACILITIES	PROCEDURE
Plate rolling	Slab Cutting	Shear or flame cutting	Slab size thickness : 95-300 mm width : 1250-2304 mm length : 1650-5300 mm
	Soarfing	Cold soarfers	
	Surfaoe and Dimension inspeotion		
	Reheating	Continuous reheating furnaoe Batch reheating furnaoe	1). Slab thiokness for continuous R. F. : 95-350 mm 2). Slab thiokness for batch R. F. : 95-500 mm 3). Reheating temperature : 1150-1300ºC
	Rolling	Hydraulio soale breaker 150Kg/om 216.5 inohes 4-hi mill - ray thiokness gauge	Hydraulio A. G. C. Computer Control
	Hot levelling	Hot leveler 4-hi type	
	Cooling		
	Surfaoe examination		In process inspeotion

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 : 900ºC ± 10ºC
Tempering	No. 2 heat teratment furnace	Holding Temperature : 660ºC ± 5ºC
Surface Examination		In process inspection
Cutting (Plate and Test coupons)	Flame planer	
Dimesion and visual inspection / Physical testing		

Table II.2 (continued...)

PROCESS		FACILITIES	PROCEDURE
	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
Slabbing	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 ºC
	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 Steel 3a Plates.

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 : 900ºC ± 10ºC
↓		
Tempering	No. 2 heat teratment furnace	Holding Temperature : 620ºC ± 5ºC
↓		
Surface Examination		In process inspection
↓		
Cutting	Flame planer	
(Plate and Test coupons)		
↓ ↓		
Dimesion and visual inspection / Physical testing		

Table II.3 (continued...)

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

Table II.4 : Process Flow for Manufacture of Steel 4 Plates

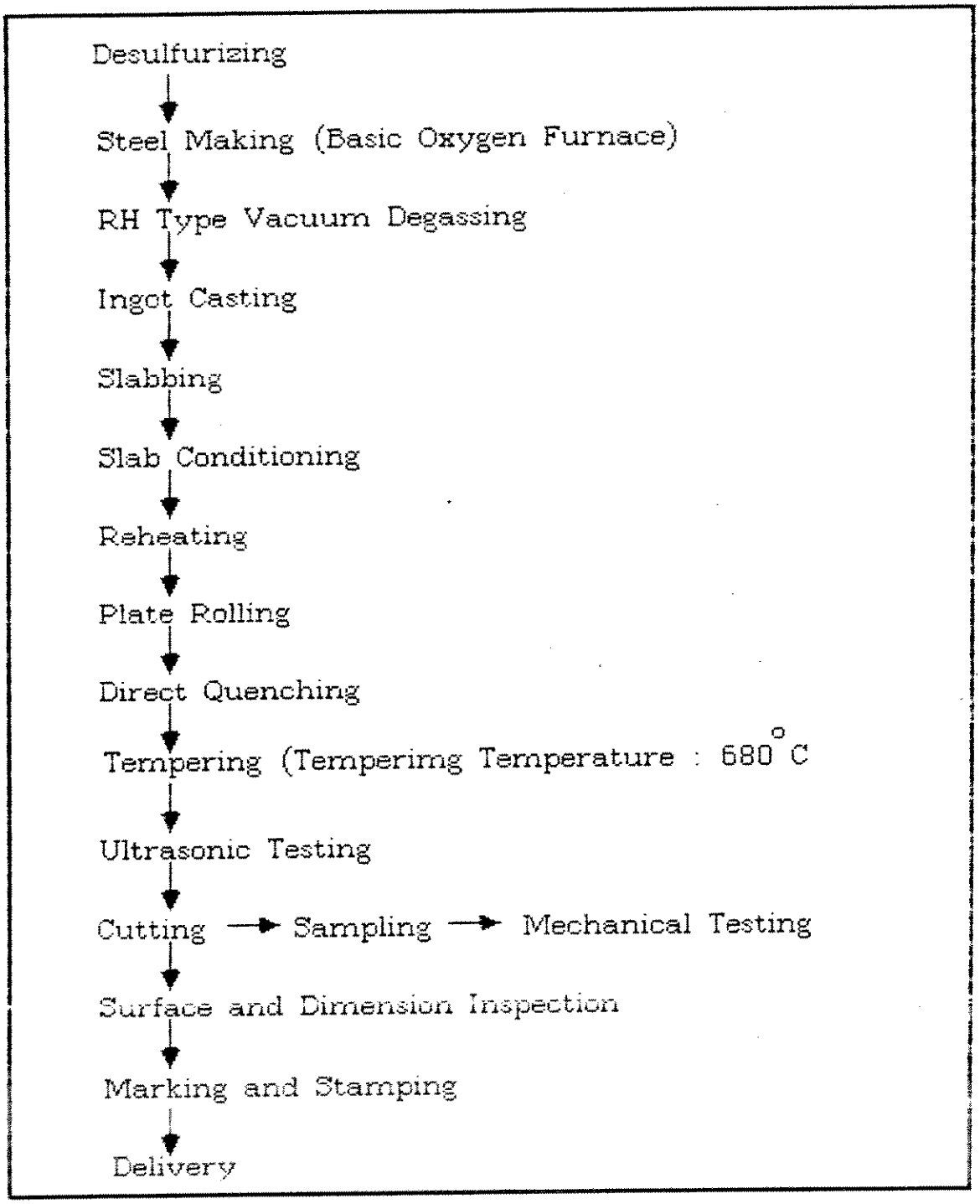


Table II.5 : Process flow for Manufacture of Steel 5 Plates

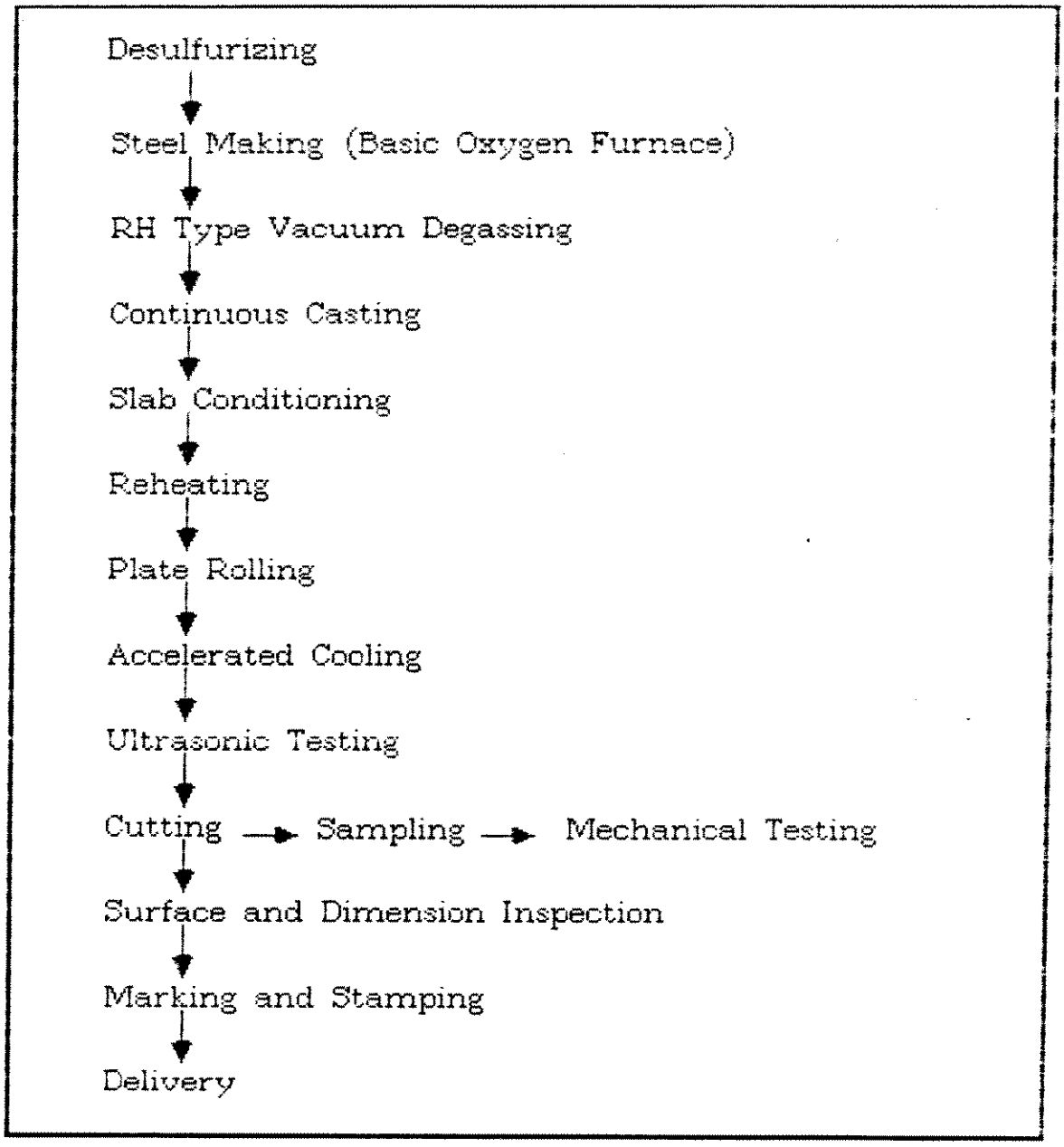


Table II.6 : Process flow for Manufacture of Steel 6 Plates

Section III

Tensile Test Results

Steel	Yield Strength MPa (ksi)								Tensile Strength MPa (ksi)							
	As QT						PWHT**		As QT						PWHT**	
	L*	C	Spec.	L	T	Z	L	T	L*	C	Spec.	L	T	Z	L	T
1	636 (92.2)	654.6 (94.9)	549.2 (79.7) 686.5 (99.6)						736.5 (106.8)	742.9 (107.7)						
2				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)
3a				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)
3b	745 (108)								824 (119)							
4	370.7 (53.8)	416.3 (60.4)							518.8 (75.2)	536 (77.7)	490.4 (71.1) 617.8 (89.6)					
5	500 (72.5)								598 (86.7)							
6	452 (65.9)						438 (63.9)		551 (80.3)						525 (76.4)	
7																

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	-	GL=203.2mm 64.5 65.2	74.5 75.7	21.0 21.4	73.2 74.0	87 87
	C	- -	66.2 67.3	75.7 75.8	20.1 20.4	68.4 68.7	87 89
	Spec.	-	56/70	-	GL=50.0mm >=20	>=50	-

L-Ladle, C-Check

Table III.2 Tensile Test Results for Steel 1

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 ($600^{\circ}C$ 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
0.5 in. diameter x 2 in. gage length from the mid-thickness position for L and T direction
0.4 in. diameter for Z direction

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

Table III.3 Tensile Test Results for Steel 2

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
0.5 in. diameter x 2 in. gage length from the mid-thickness position for L and T direction
0.4 in. diameter for Z direction

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

Table III.4 Tensile Test Results for Steel 3a

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 Steel 3b

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	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 Steel 4

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 Steel 5

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 Steel 6

Section IV

Charpy Impact and CTOD Test Results

Steel	Condition	Direction	Charpy Energy, Joules					50% FATT
			0 °C	−20 °C	−40 °C	−60 °C	−85 °C	°C
1		L*	288.3			278.5	277.5	
		C	207.9			210.8	188.3	
2	As QT	L			378	371		−112
		T			363	362		−127
	PWHT	L			368	366		−133
		T			366	364		−119
3a	As QT	L			333	319		−108
		T			302	278		−91
	PWHT	L			324	290		−89
		T			360	219		−76
3b	As Welded				215.8			
	PWHT			192.5	179.8			
4		L	274.5		215.7			
		C	257.9		184.3			
5	As Welded			126.5	121.9			
	PWHT			262.8	248.5			
6								
7								

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

Table IV.1 : Charpy Test Results – Comparative Analysis

Steel	Thick-ness (mm)		vEo kgf·m		vE$_{-40}$ kgf·m		vE$_{-60}$ kgf·m		vE$_{-85}$ kgf·m		vTs °C
				Ave.		Ave.		Ave.		Ave.	
1	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	-

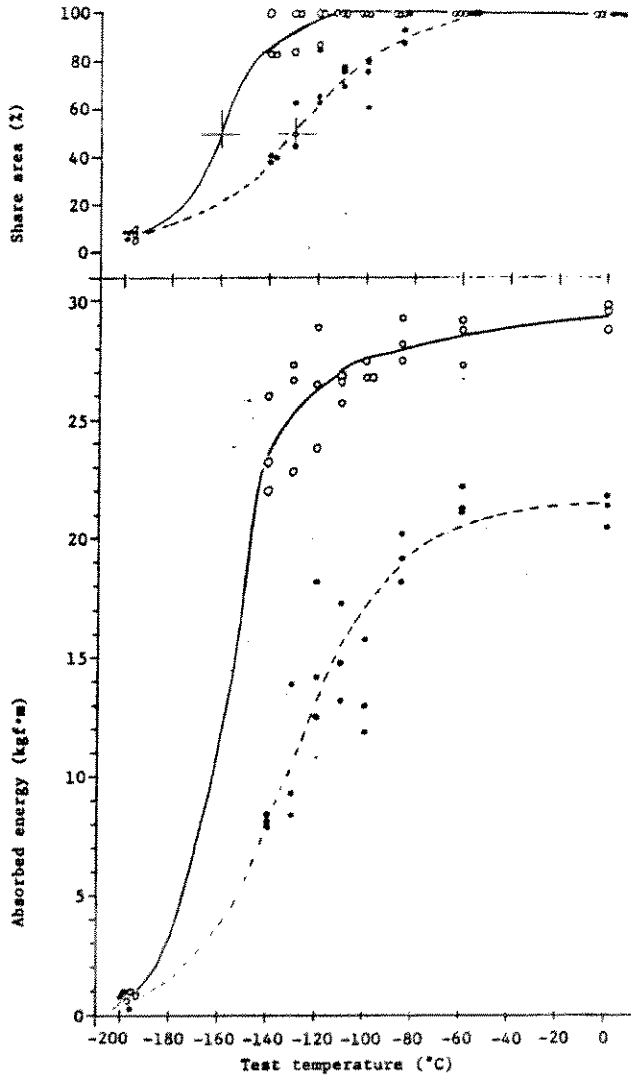


Figure IV.1 : Charpy Impact Test Reults for Steel 1

Steel	Thick-ness (mm)	Temper-ature °C	Result
1	25.4	-115	◐ ◐ ◐
		-120	◐ ◐ ◐
		-125	● ● ●
		NDT	-120

Condition

Test piece : P1

Direction : C

Energy : 83 kgf·m

Figure IV.1a : CTOD Test Results for Steel 1
(NRL Drop Weight Test)

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	L	368(272)	366(270)	-133(-207)
(600°C x 1hr)	T	366(270)	364(268)	-119(-182)

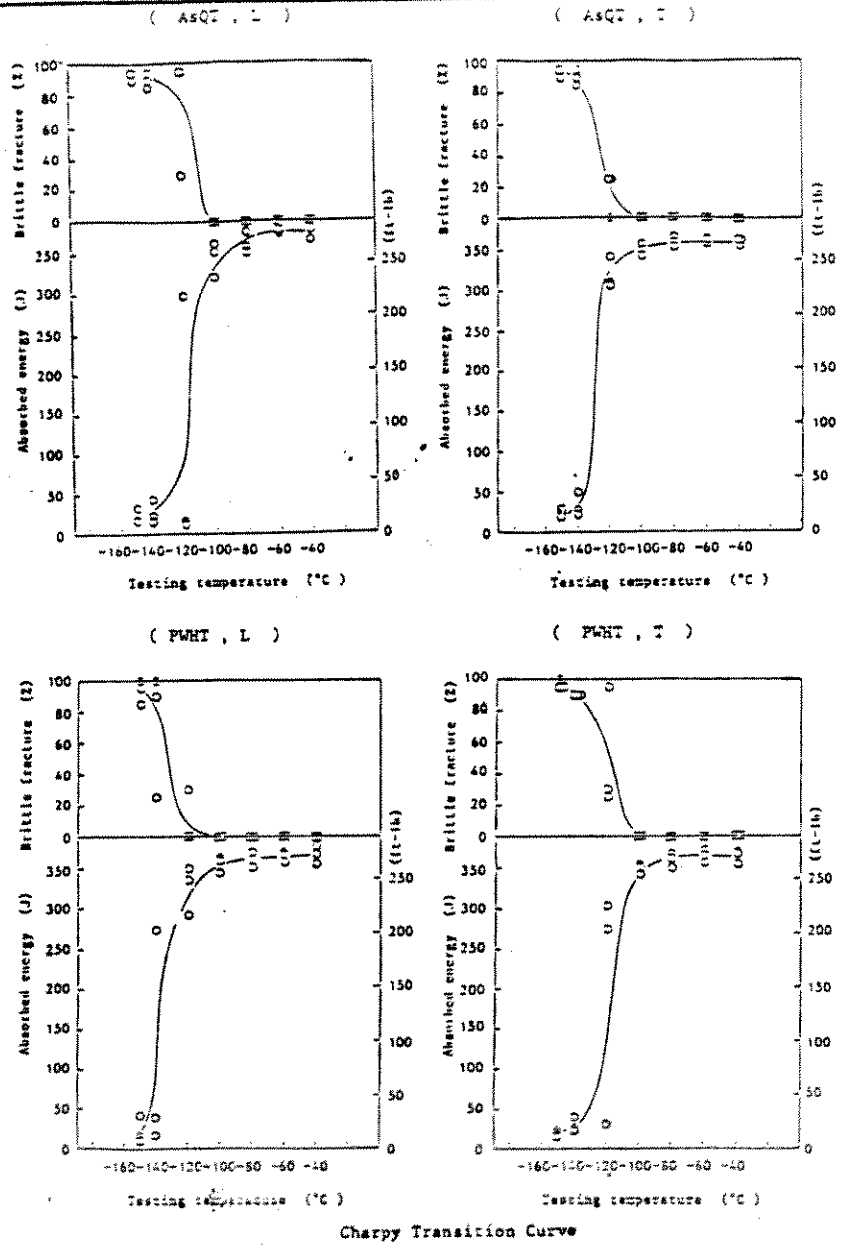


Figure IV.2 : Charpy Impact Test Reults for Steel 2

(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

CTOD Test

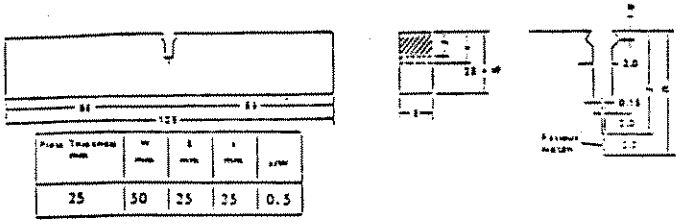


Plate Thickness mm	W mm	B mm	a mm	a/W
25	50	25	25	0.5

Dimension of Test Specimen and Notch Detail

CTOD Test Results (As QT)

Direction	B mm	W mm	a mm	Y	Testing Temp.°C(°F)	σy kg/mm^2	P kg	Vp mm	Critical CTOD Value mm(mil)
L	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)
	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)

Figure IV.2a : CTOD Test Results for Steel 2

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)

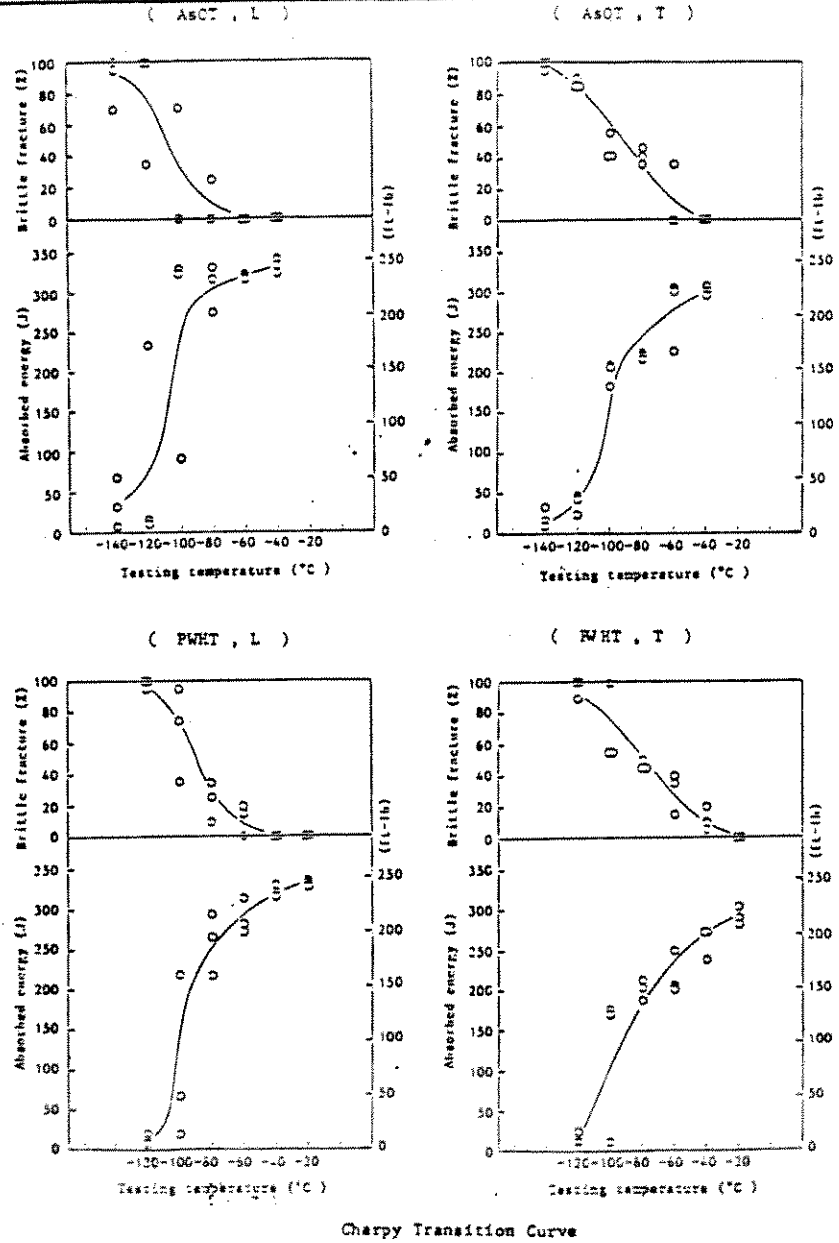


Figure IV.3 : Charpy Impact Test Reults for Steel 3a
(2 mm V-notch Charpy Impact Specimen, Full size from quarter thickness position)

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

○ : No Break , ● : Break

CTOD Test

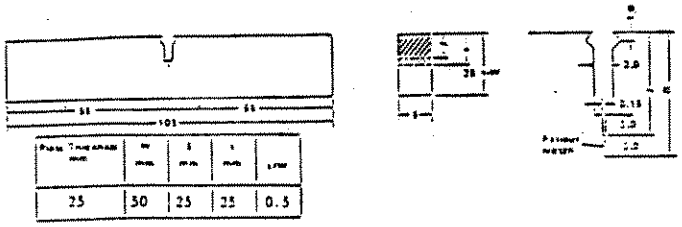


Plate Thickness mm	W mm	a mm	t mm	B mm
25	50	25	25	0.5

Dimension of Test Specimen and Notch Detail

CTOD Test Results (As QT)

Direction	B mm	W mm	a mm	Y	Testing Temp.°C(°F)	σy kg/mm²	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)

Figure IV.3a : CTOD Test Results for Steel 3a

Steel	Heat treatment	Test temp.		Charpy impact strength					
				Weld metal		HAZ		Parent plate	
		°C	°F	Joule	ft-lbs	Joule	ft-lbs	Joule	ft-lbs
3b	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.

Figure IV.4 : Charpy Impact Test Reults for Steel 3b

Steel	Thick-ness (mm)		vEo kgf·m		vE₋₄₀ kgf·m		vE₋₆₀ kgf·m		vE₋₈₀ kgf·m		vTs °C
				Ave.		Ave.		Ave.		Ave.	
4	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		-		-		-

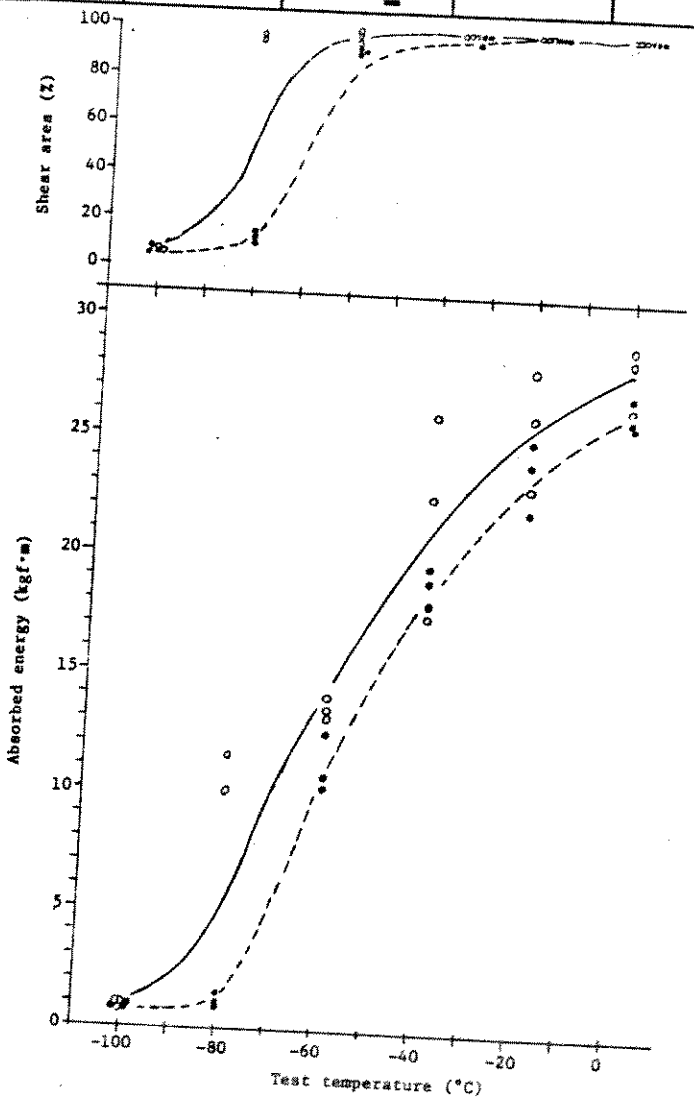


Figure IV.5 : Charpy Impact Test Reults for Steel 4

Steel	Thick-ness (mm)	Temper-ature °C	Result
4	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

Figure IV.5a : CTOD Test Results for Steel 4
(NRL Drop Weight Test)

Steel	Heat treatment	Test temp.		Charpy impact strength					
				Weld metal		HAZ		Parent plate	
		°C	°F	Joule	ft-lbs	Joule	ft-lbs	Joule	ft-lbs
5	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.

Figure IV.6 : Charpy Impact Test Reults for Steel 5

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

Figure IV.7 : Charpy Impact Test Results for Steel 6

Section V

Hardness Test Results

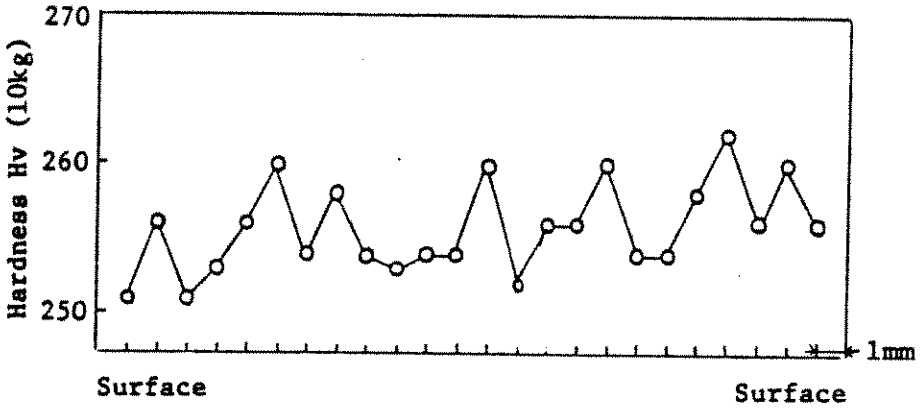


Figure V.1 : Hardness Test Results for Steel 1

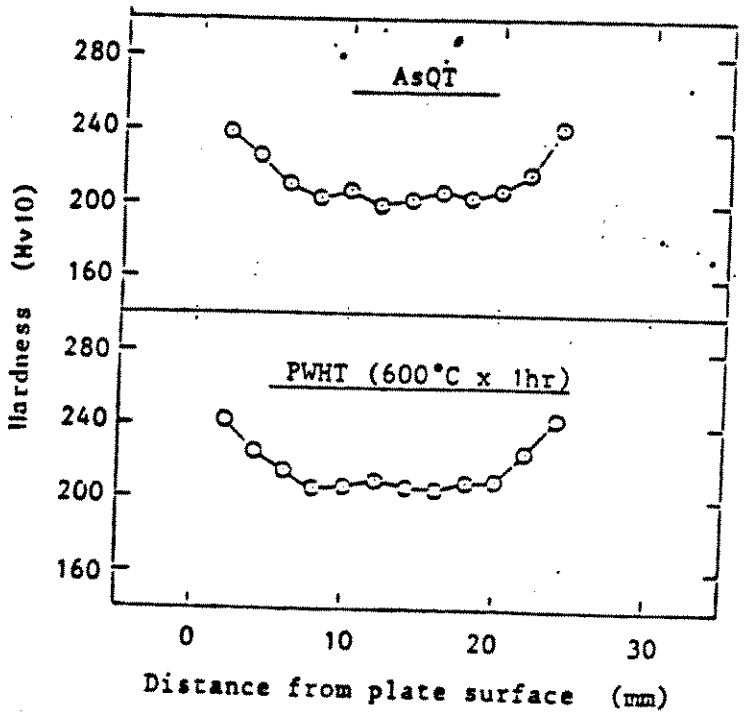


Figure V.2 : Hardness Test Results for Steel 2

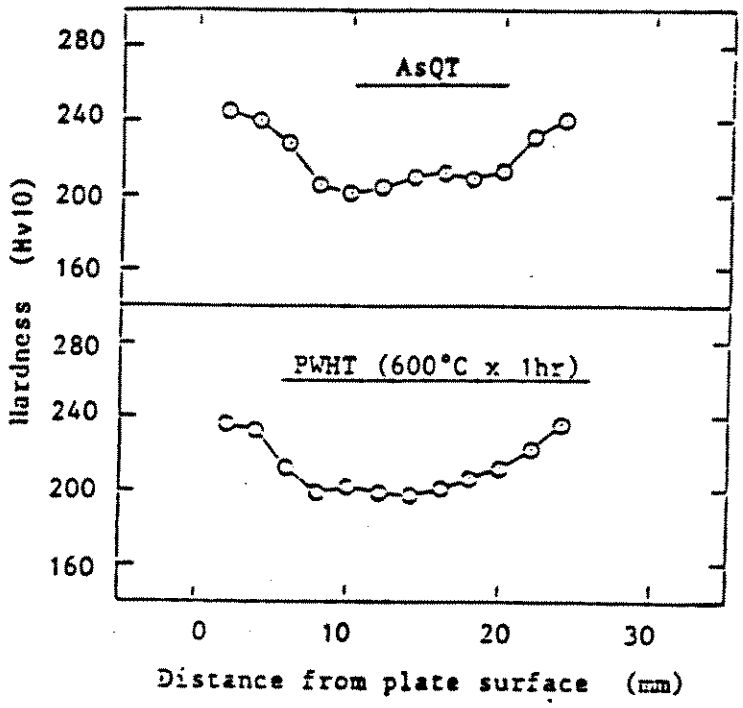


Figure V.3 : Hardness Test Results for Steel 3a

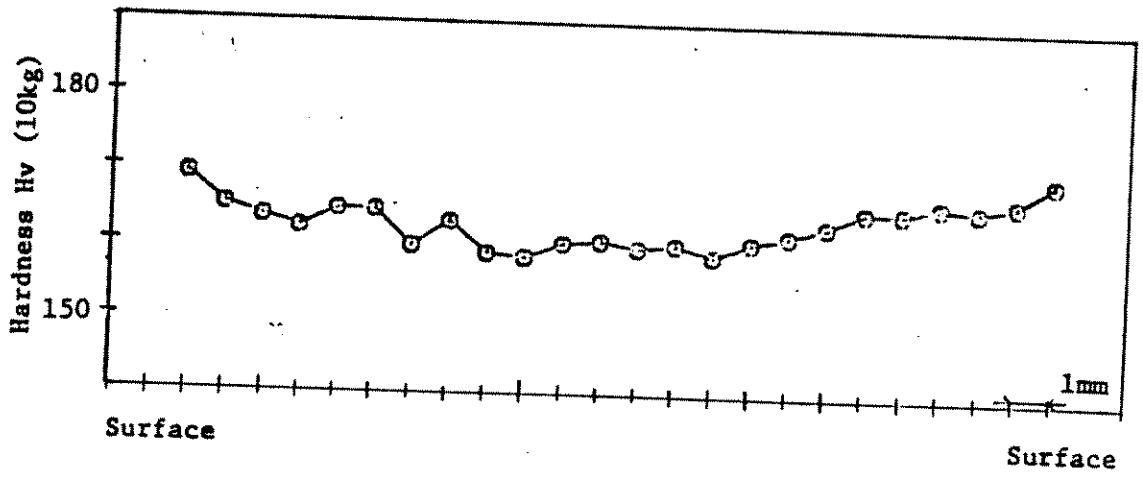


Figure V.4 : Hardness Test Results for Steel 4

Section VI

Microstructure

Figure VI.1 : Microstructure of Steel 1 (400 X)

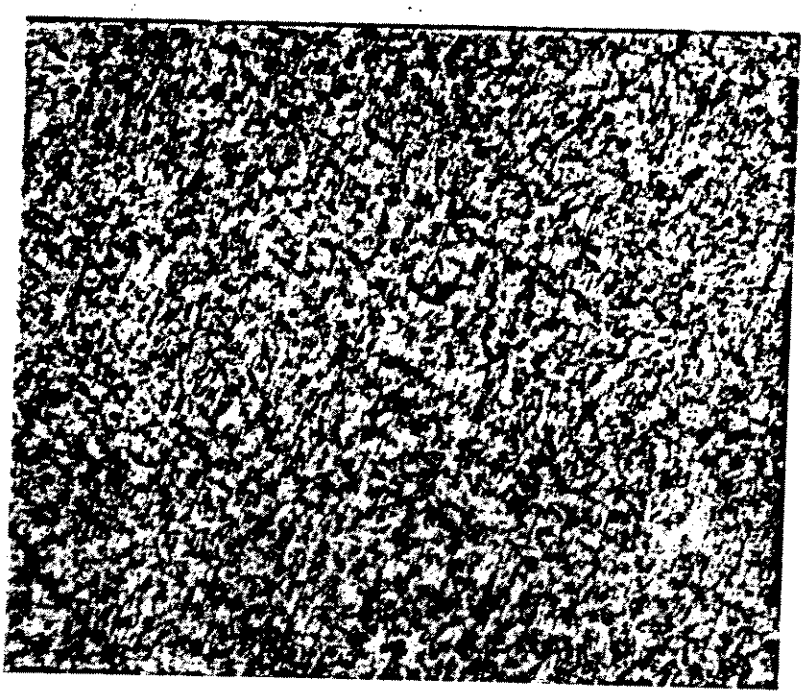


Figure VI.2 : Microstructure of Steel 2 (400 X)

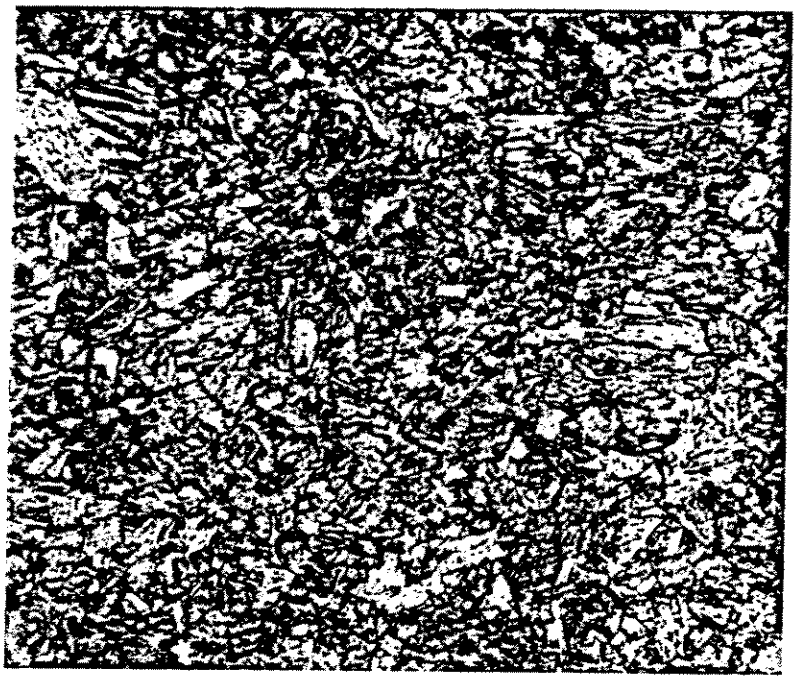


Figure VI.3 : Microstructure of Steel 3a(400 X)

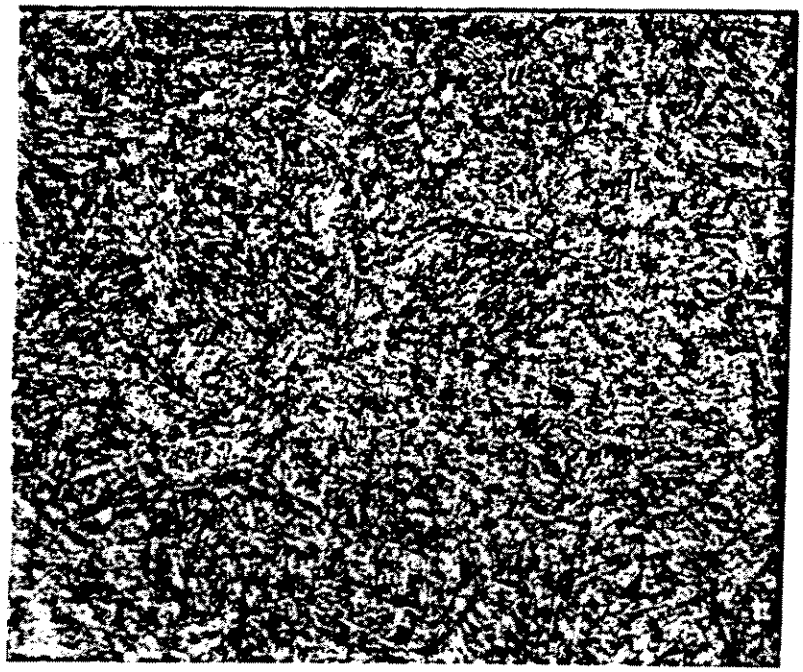


Figure VI.4 : Microstructure of Steel 3b(400 X)

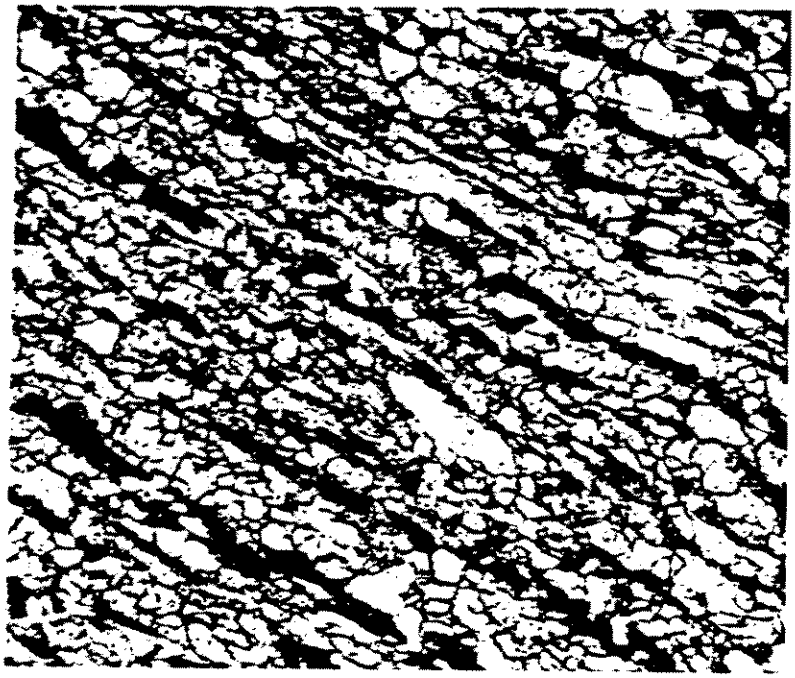


Figure VI.5: Microsructure of steel 4 (400 X)

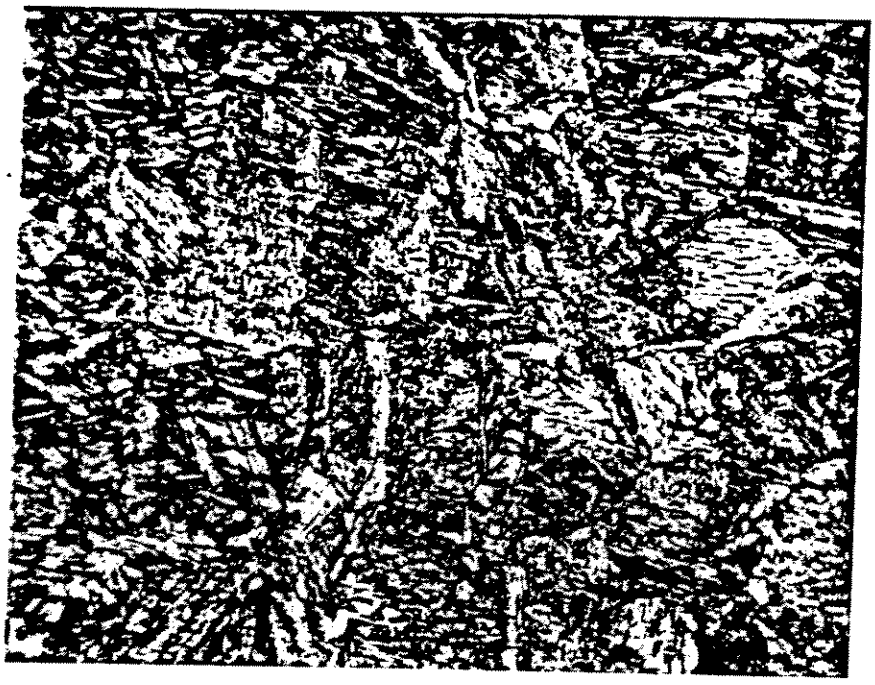


Figure VI.6 : Microstructure of Steel 5 (400 X)

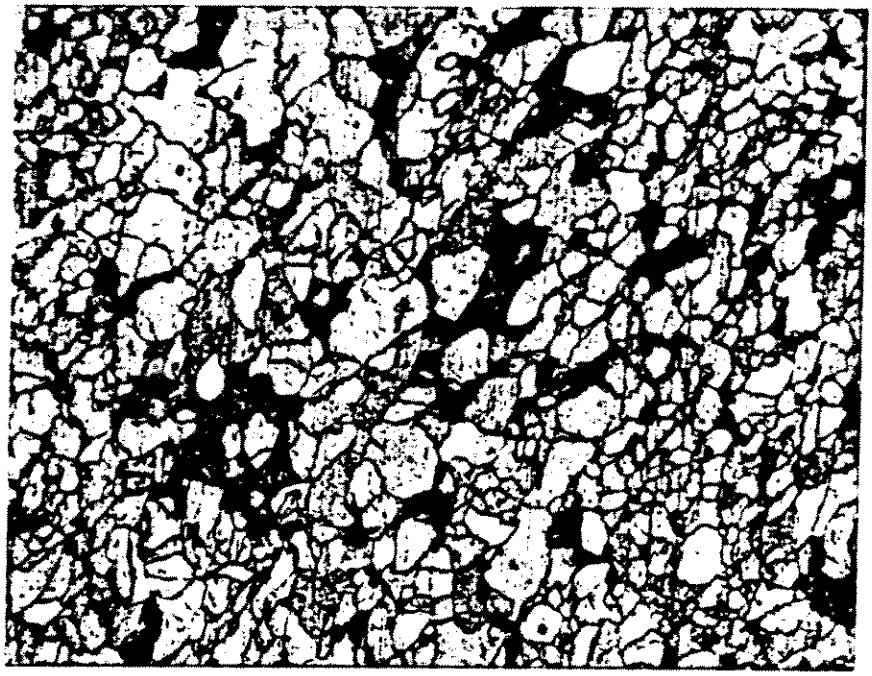


Figure VI.7: Microsructure of steel 6 (400 X)

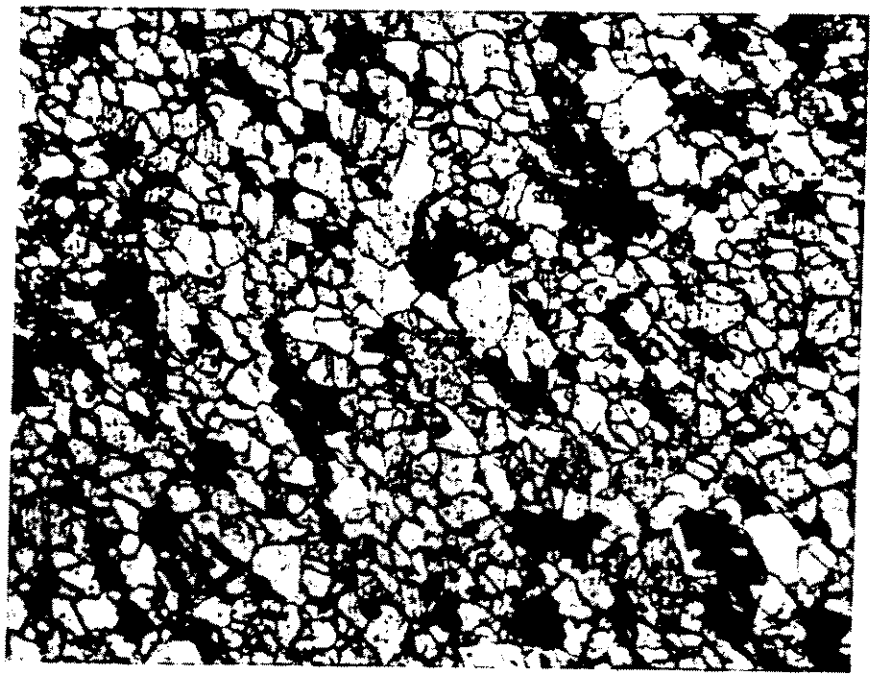


Figure VI.8 : Microstructure of Steel 7 (400 X)

Section VII

Welding

A) Welding Procedure

B) Weld Properties

A) Welding Procedure

Welding Procedure Specification

1 Material 1

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

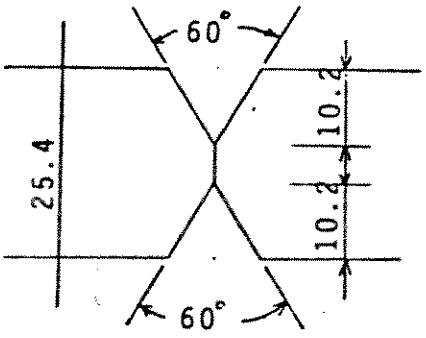
Welding Speed 16.5Inch/min

Preheat and Interpass Temperature 150-200 C

Post Heat Temperature 600 Cx2Hr A.C.

Joint Detail

Edge Preparation



Layer of Pass

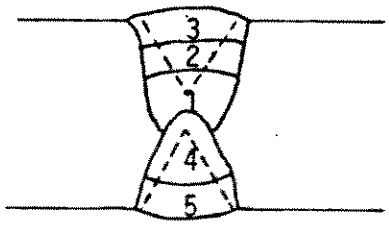


Figure VII.A.1 : Welding Procedure for Steel 1

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

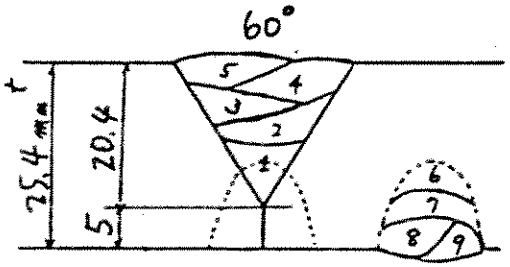
(3) Current and porality : AC

(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 depth)

Figure VII.A.2 : Welding Procedure for Steel 2 & 3a

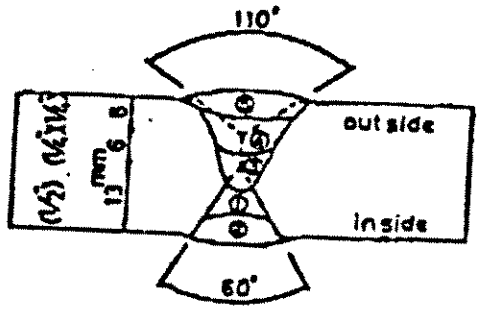
Material specification ASTM A514F equivalent (3b)
Welding process SAW
Manual or machine Machine
Position of welding Flat
Filler metal specification AWS A5.23
Filler metal and flux classification F11A6-EG-G, KB-80C x KW-103B

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 Amperes	Welding current Volts	Travel speed	Joint detail
1	4.0ϕ	550	28	10	
2			30		
≀					
5					



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 Steel 3b

1 Material EH-36(Alloy type C.R.) **(4)**

2 Welding procedure

Welding Process S.A.W.

Manual or Machine Machine

Position of Welding Flat

Filler Metal W36(4mmϕ)

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

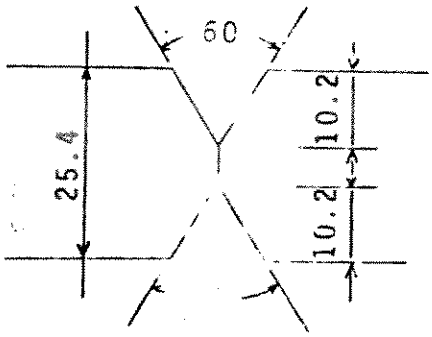
Interpass Temperature 75-125°C

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

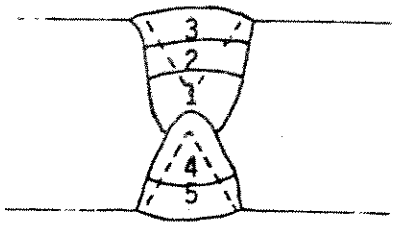
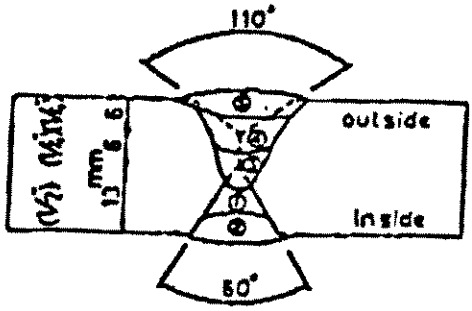


Figure VII.A.4 : Welding Procedure for Steel 4

Material specification ASTM A537 cl. 2 (5)
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	Welding current Volts	Travel speed*	Joint detail
1	4.0φ	550	28	10	
2			30		
1					
5					

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 1984 Dr. Kozo Akahide, Senior Researcher

Figure VII.A.5 : Welding Procedure for Steel 5

Material specification ASTM A537 class 2 (TMCP steel) (6)

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	〃	〃	〃	〃	

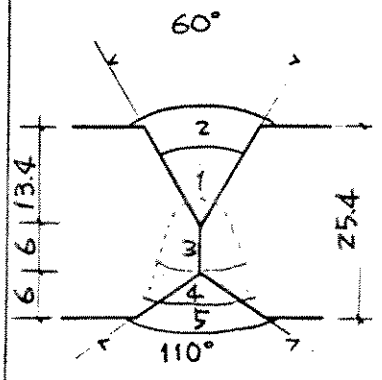


Figure VII.A.6 : Welding Procedure for Steel 6

B) Weld Properties

B1) Steel 1 and 4
B2) Steel 3a
B3) Steel 3b and 5

B1) Steel 1 and 4

results for the welded joint

Tension test

Tension test

Steel	Thickness mm	PWHT	TS kgf/mm^2	Position of fracture
1	25.4	o	79.4	M.M.
		o	80.0	M.M.
4	25.4	-	58.7	W.M.
		o	54.7	W.M.

Charpy impact test

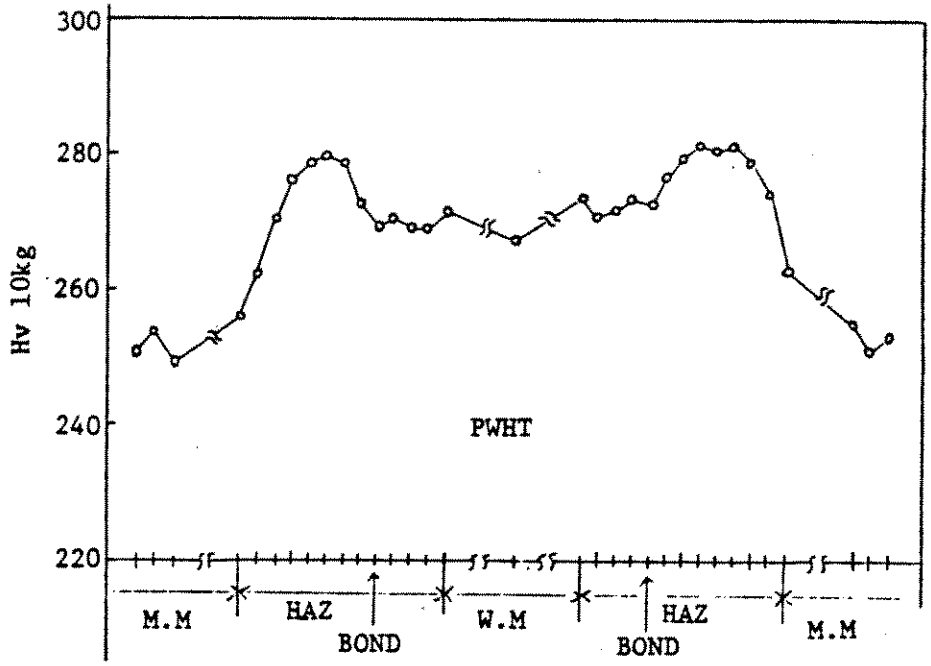
Charpy impact test

Steel	Thickness mm	PWHT		vE_{-20}		vE_{-46}		vE_{-85}	
				kgf•m	SA %	kgf•m	SA %	kgf•m	SA %
1	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

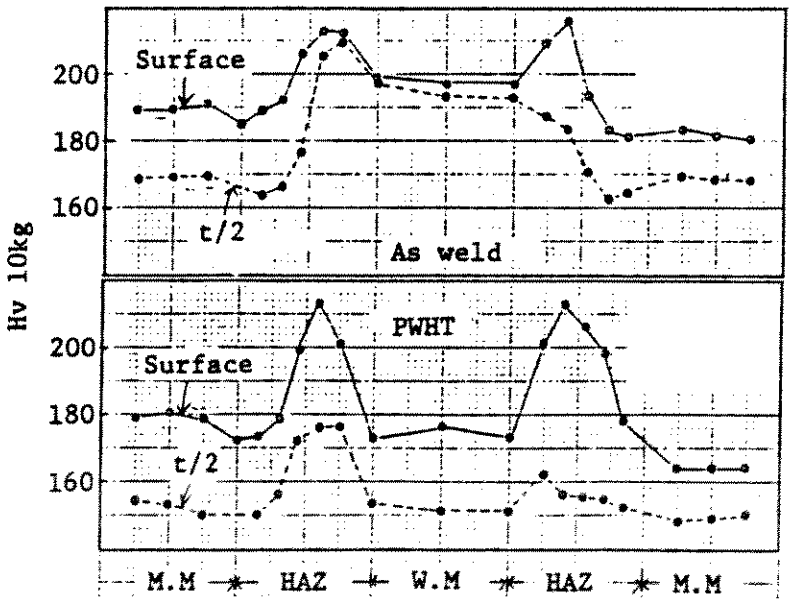
Charpy impact test

Steel	Thickness mm	PWHT		vE_{-20}		vE_{-40}	
				kgf·m	SA %	kgf·m	SA %
4	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

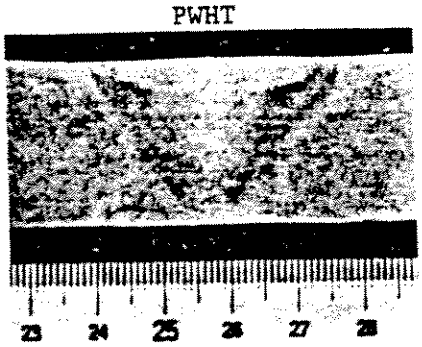
Hardness test

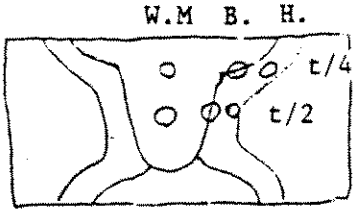


Hardness distribution - steel 1



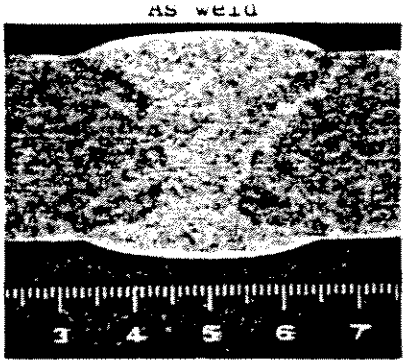
Hardness distribution - steel 4

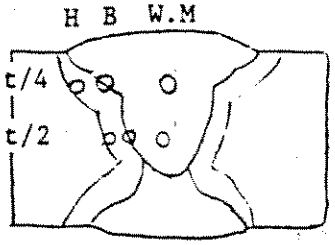




	HAZ	BOND	W.M
× 100 t/2			
× 500 t/2			
× 100 t/4			
× 500 t/4			

Photo. 3. Micro structure - steel 1





	HAZ	BOND	W.M
× 100 t/4			
× 500 t/4			
× 100 t/2			
× 500 t/2			

Photo. 4. Micro structure - steel 1

B2) Steel 3a

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
3a	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

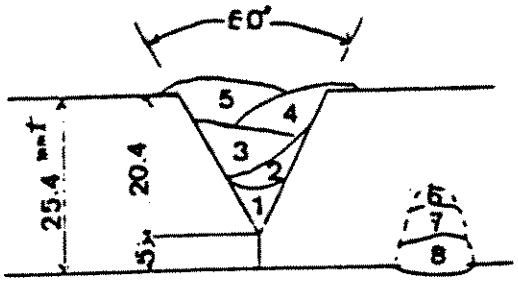
Brand	C	Si	Mn	P	S	Mo
US40	0.13	0.04	1.80	0.011	0.010	0.52

4mm in dia.

(3) Preheat : room temperature

Interpass temperature : 200 °C

(4) bead sequence and welding condition



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

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

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

Fig.1 Bead sequence

(5) PWHT

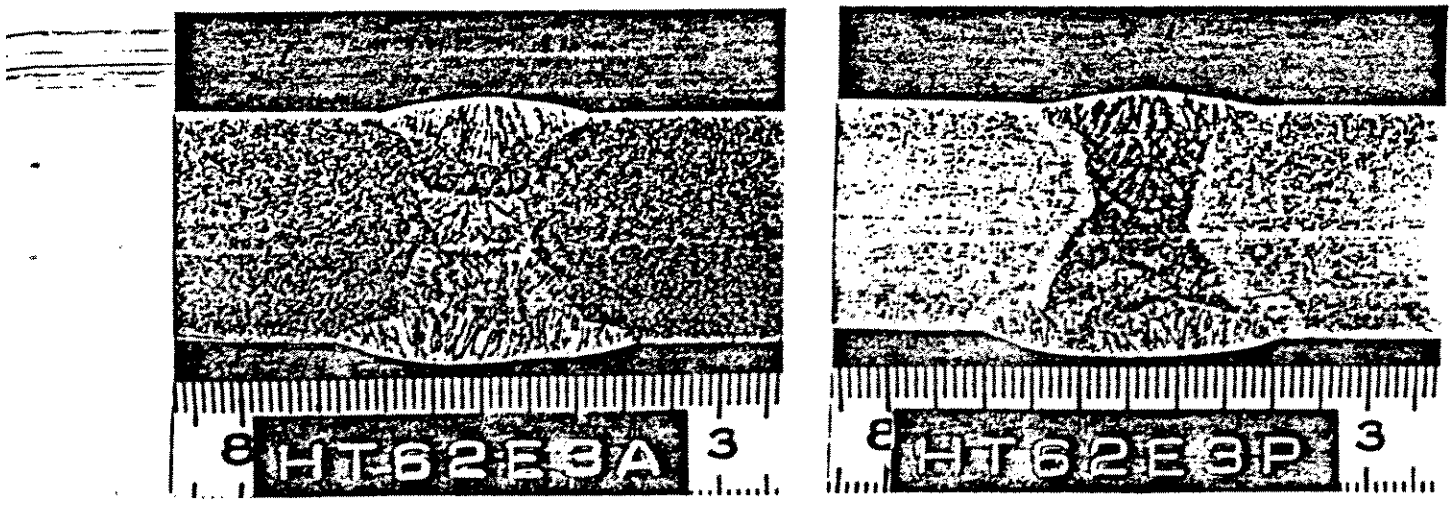
As welded

PWHT 600 °C x 1 hr

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

4. Testing Results

4-1) Macrostructure



As Welded PWHT

Photo 1 Macrostructure - steel 3a

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%)

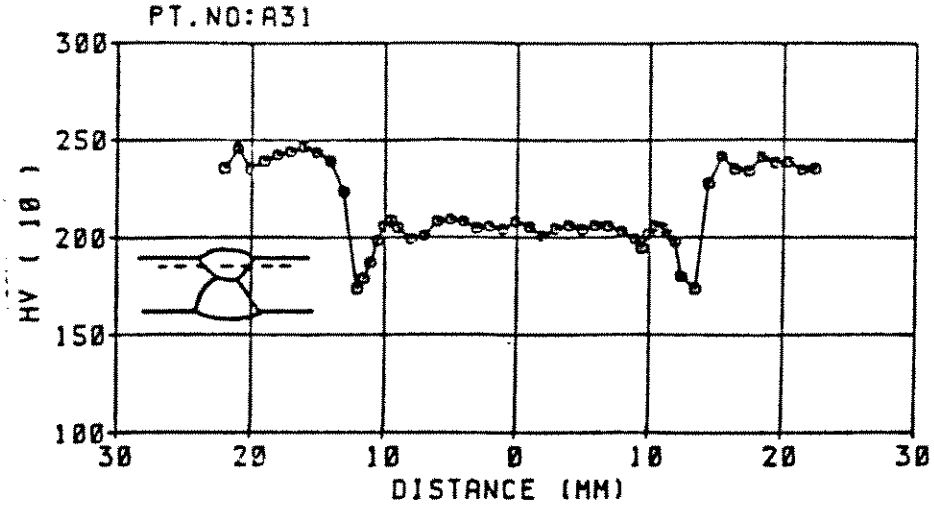
	C	Si	Mn	P	S	Cu	Ni	Cr
Weld Metal	0.07	0.16	1.33	0.010	0.007	0.08	0.16	0.06

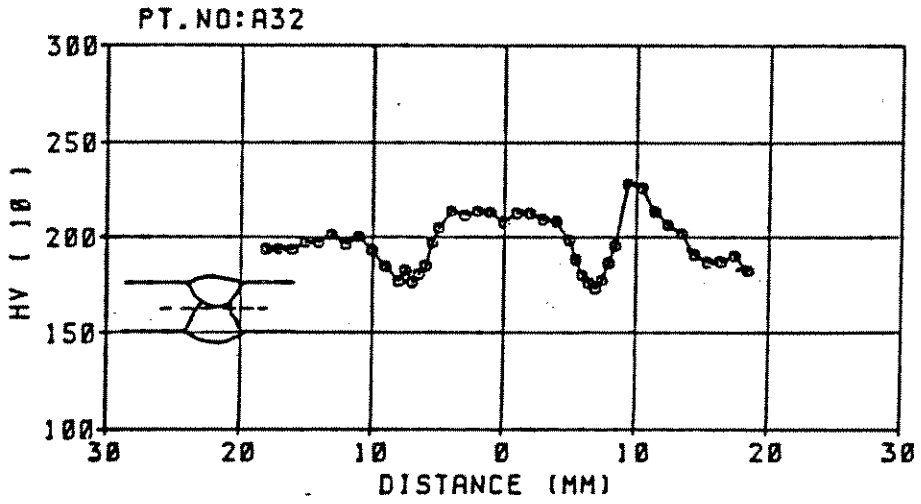
Mo	Nb	V	Ti	B	sol Al	N
0.34	Tr.	0.014	0.005	0.0005	0.006	0.0048

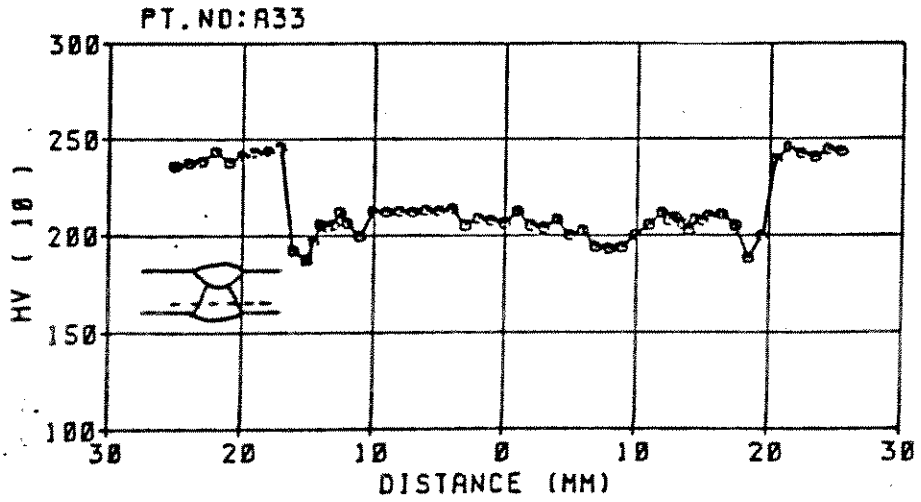
4-3) Hardness test results.

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.

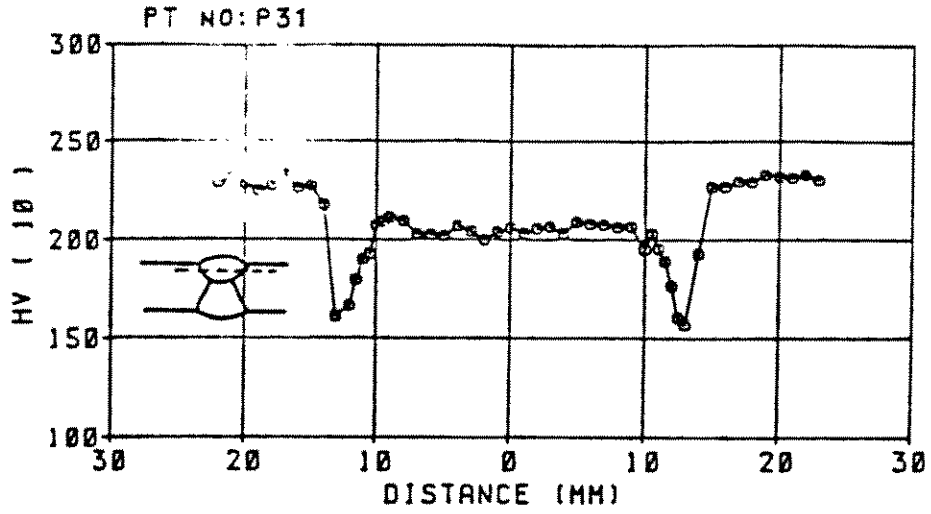
The results of hardness distribution are shown in Fig.2 in as welded condition and Fig.3 in PWHT.

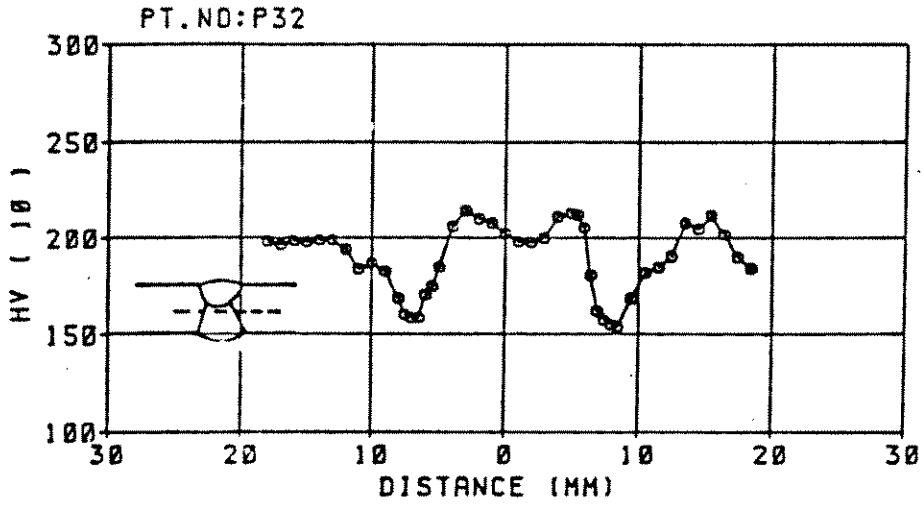


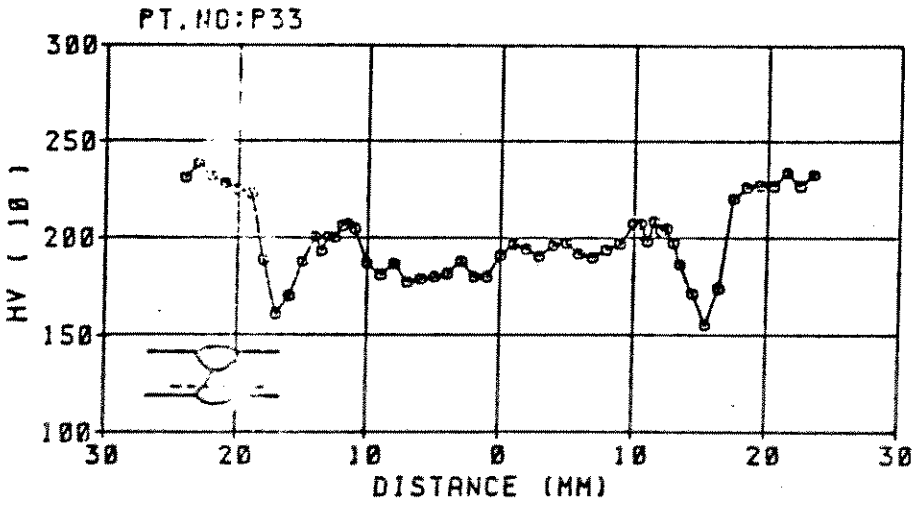




Hardness distribution of welded joint of Steel 3Q
(As welded condition)



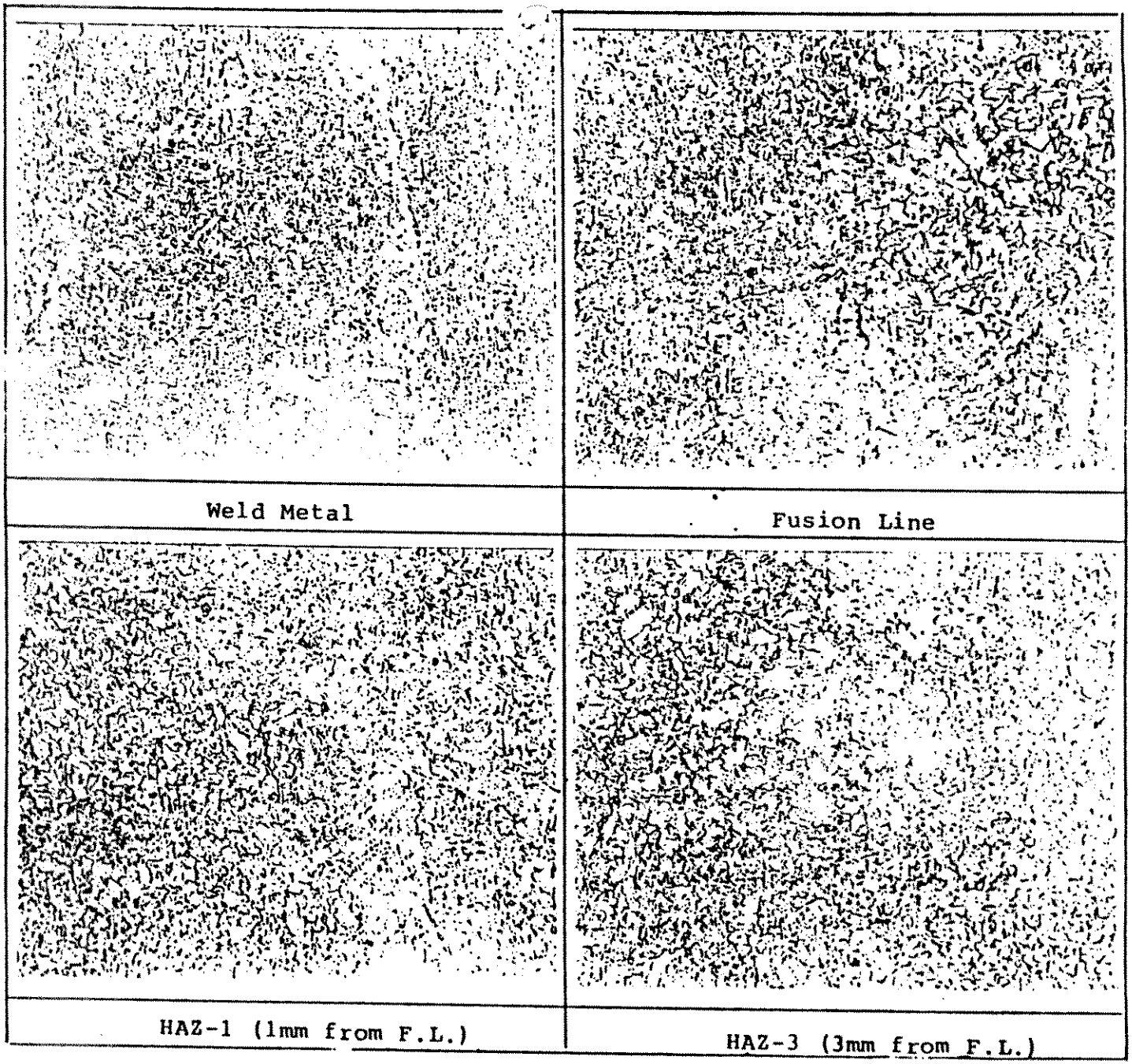




Hardness distribution of welded joint of steel 3a
(After PWHT)

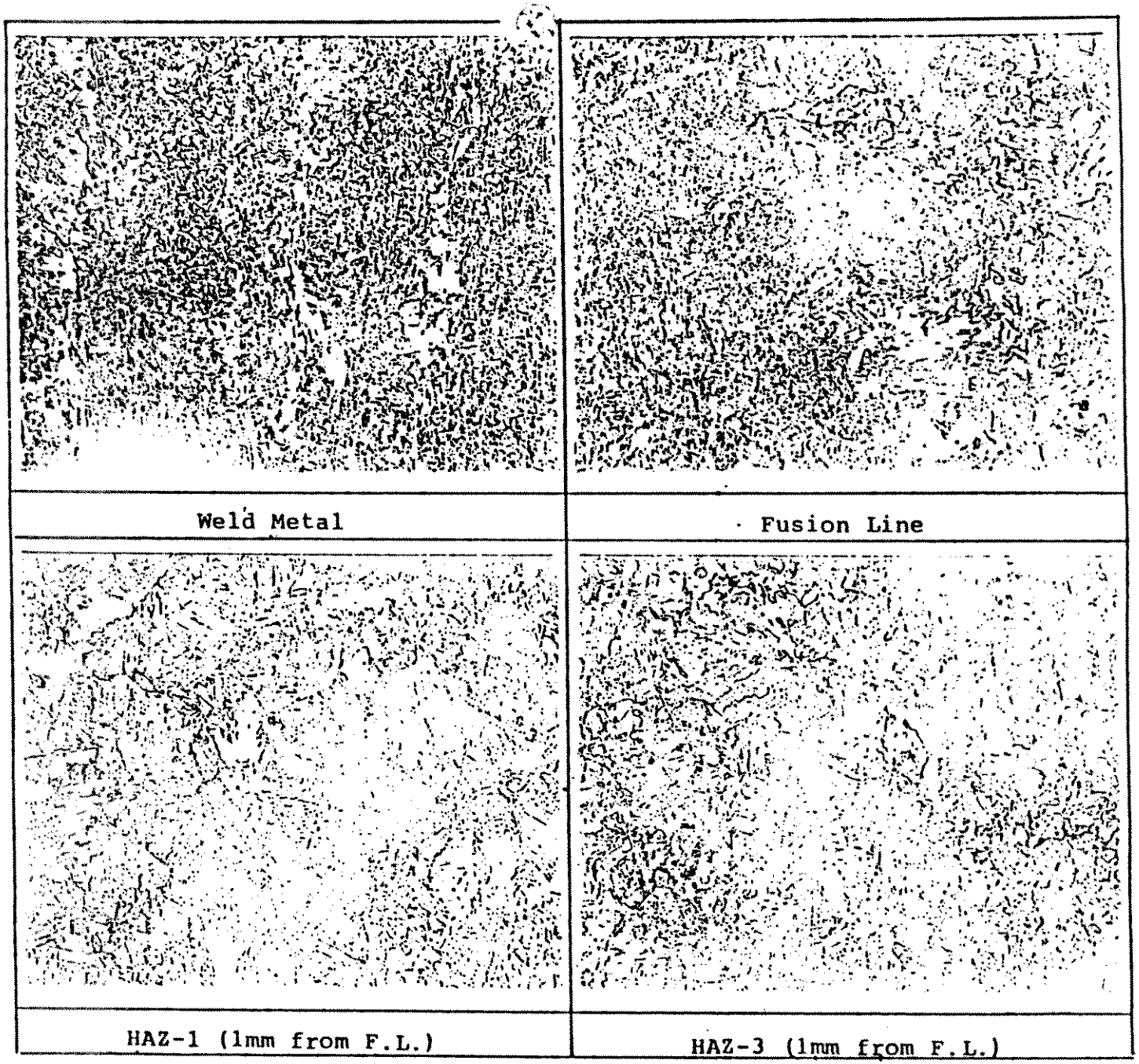
4-4) Microstructure of welded joint

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.



X 200

Photo.2 Microstructure of weld portion of steel 3a in as welded condition



X 200

Photo.3 Microstructure of weld portion of in PWHT condition

4-5) Result of Charpy test

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

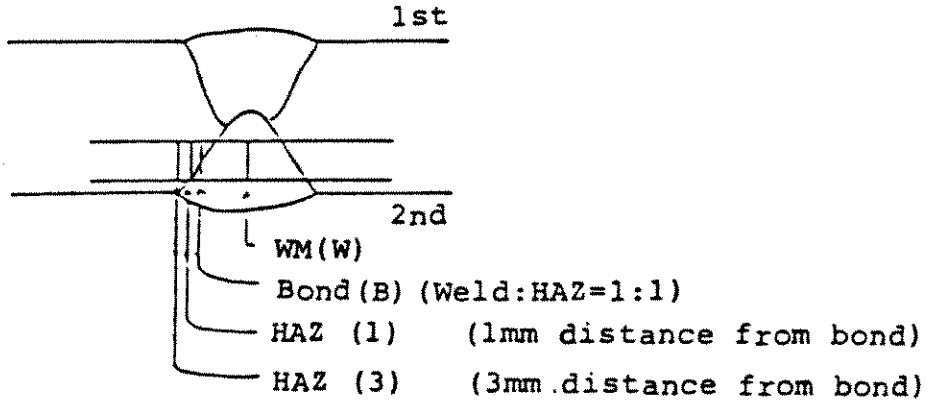
Test pieces were taken in a quater thickness of the plate.

Table 4 shows the results of Charpy test.

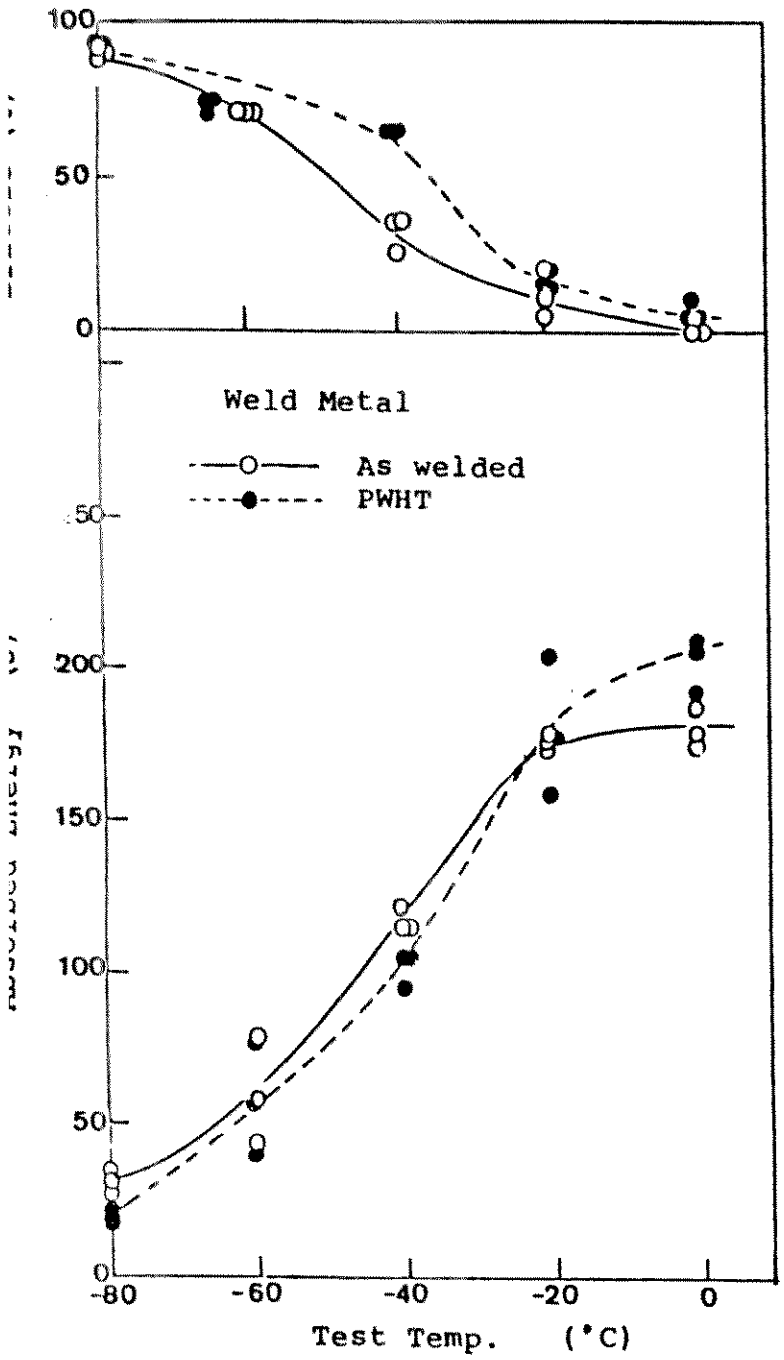
Fig.4 and 5 show the Charpy transition curves in the as welded and PWHT condition.

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



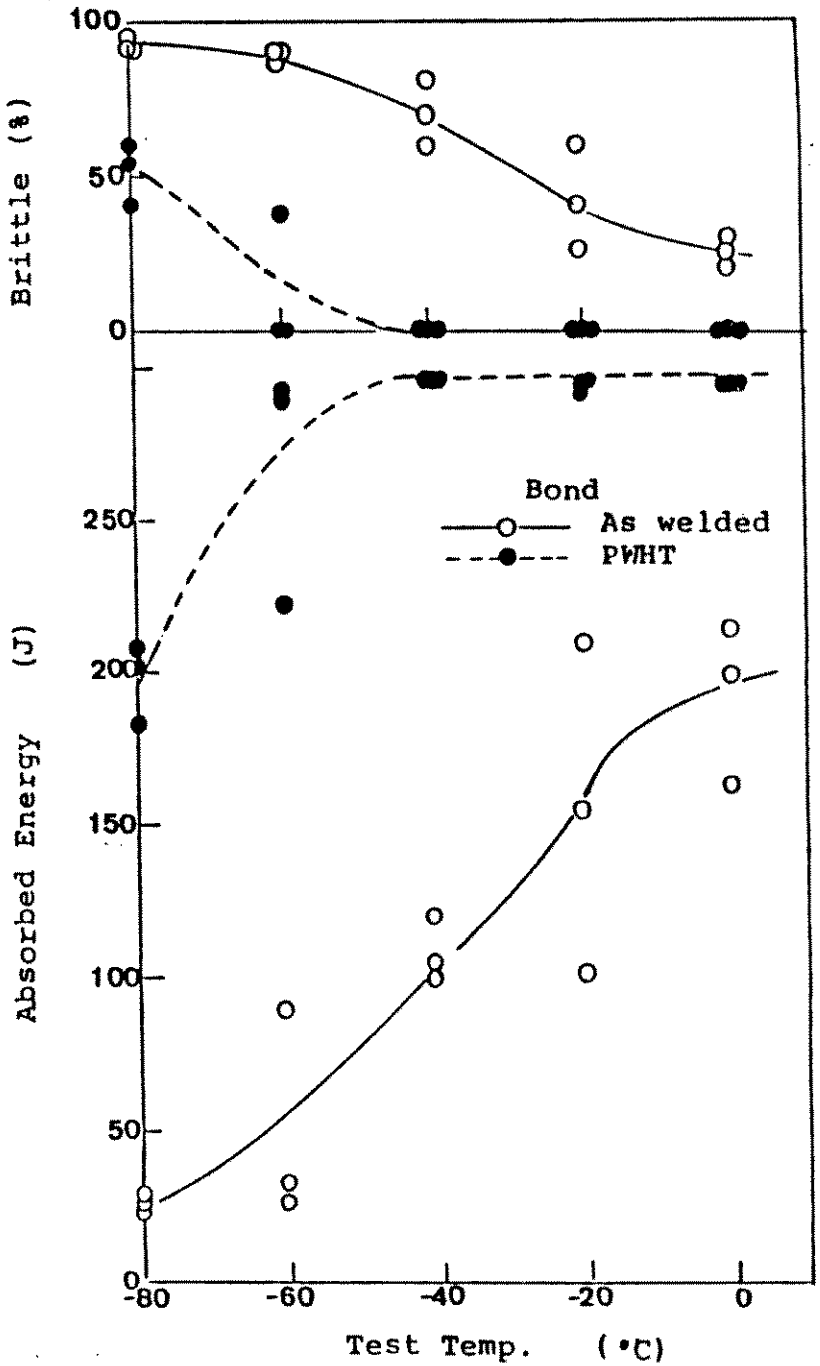


Fig.4 Charpy transition curves of welded joint (1)

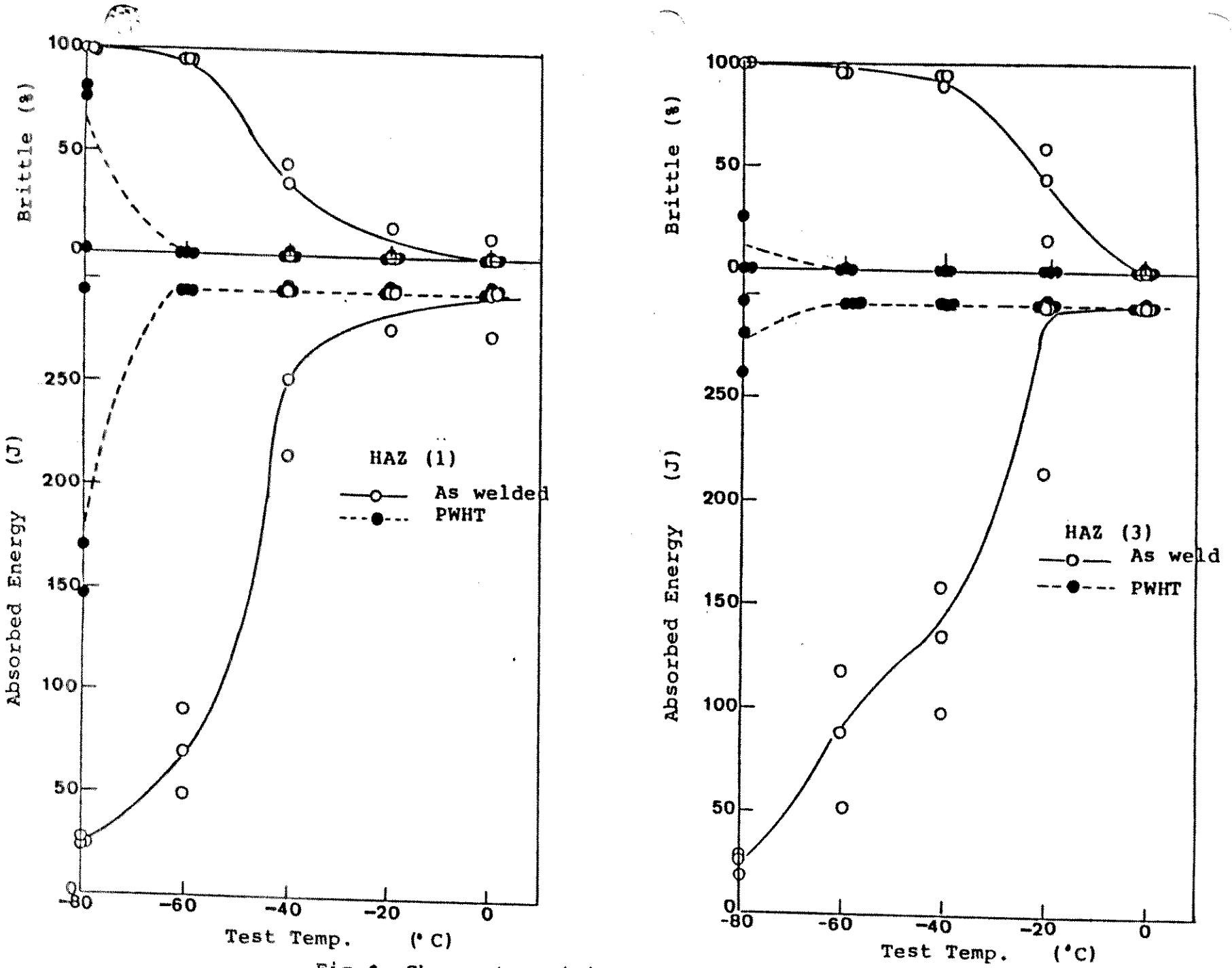


Fig.5 Charpy transition curves of welded joint (2)

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.

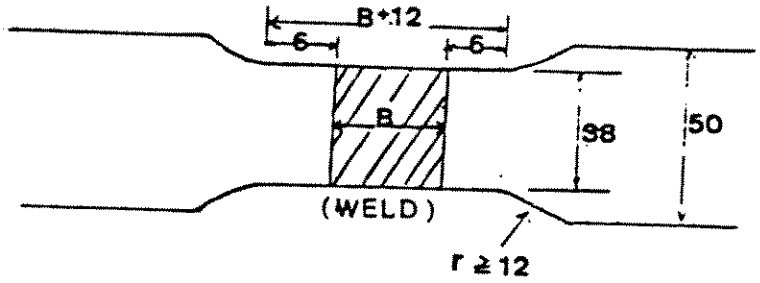


Fig.6 Shape and size of weld tensile specimen

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.

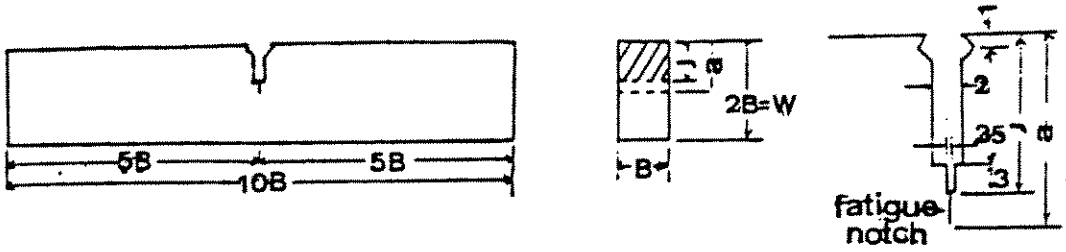


Fig.7 Dimension of test specimen and notch detail

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

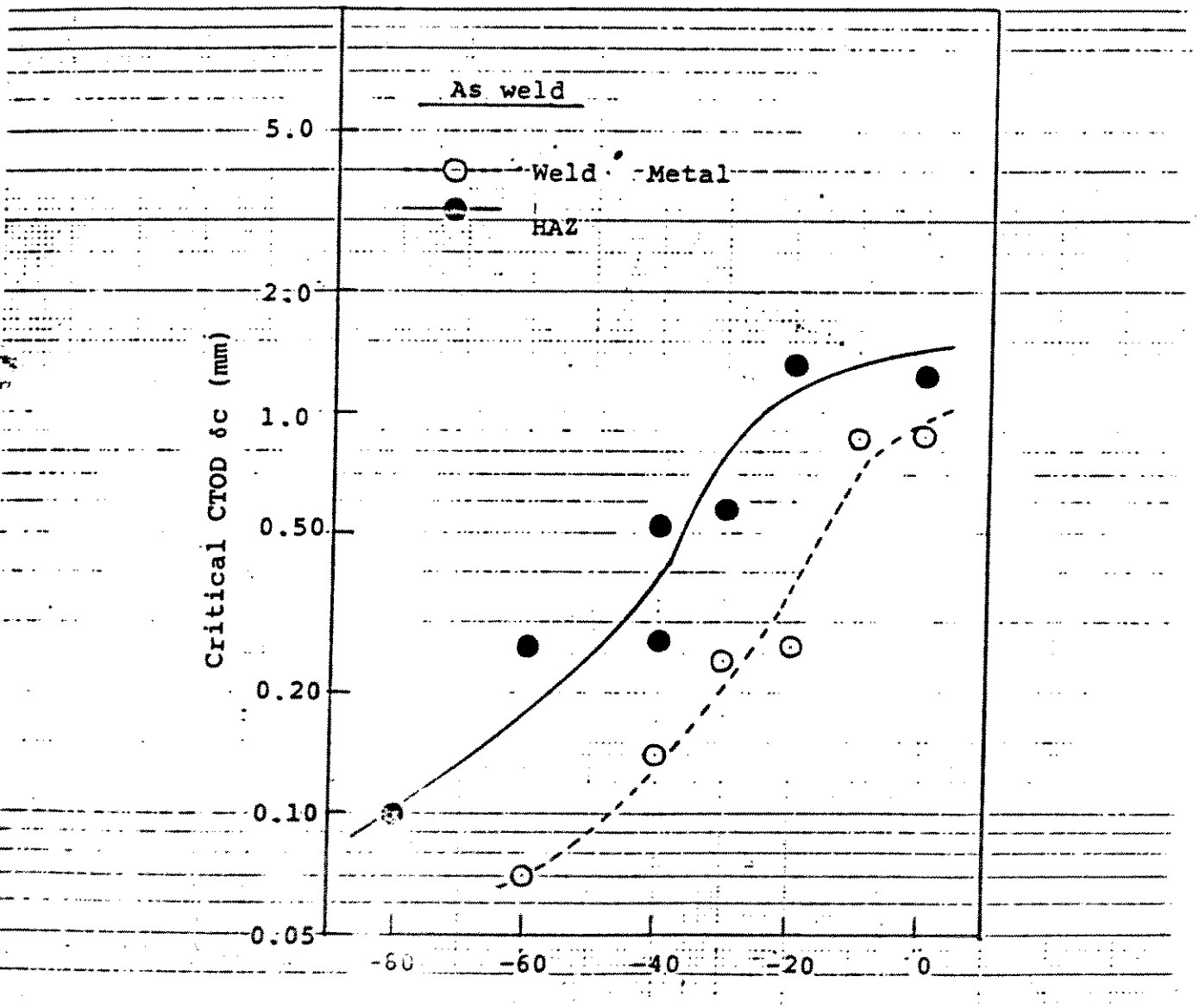


Fig.8 Transition curves of CTOD test of weld metal and HAZ-1 in as welded condition

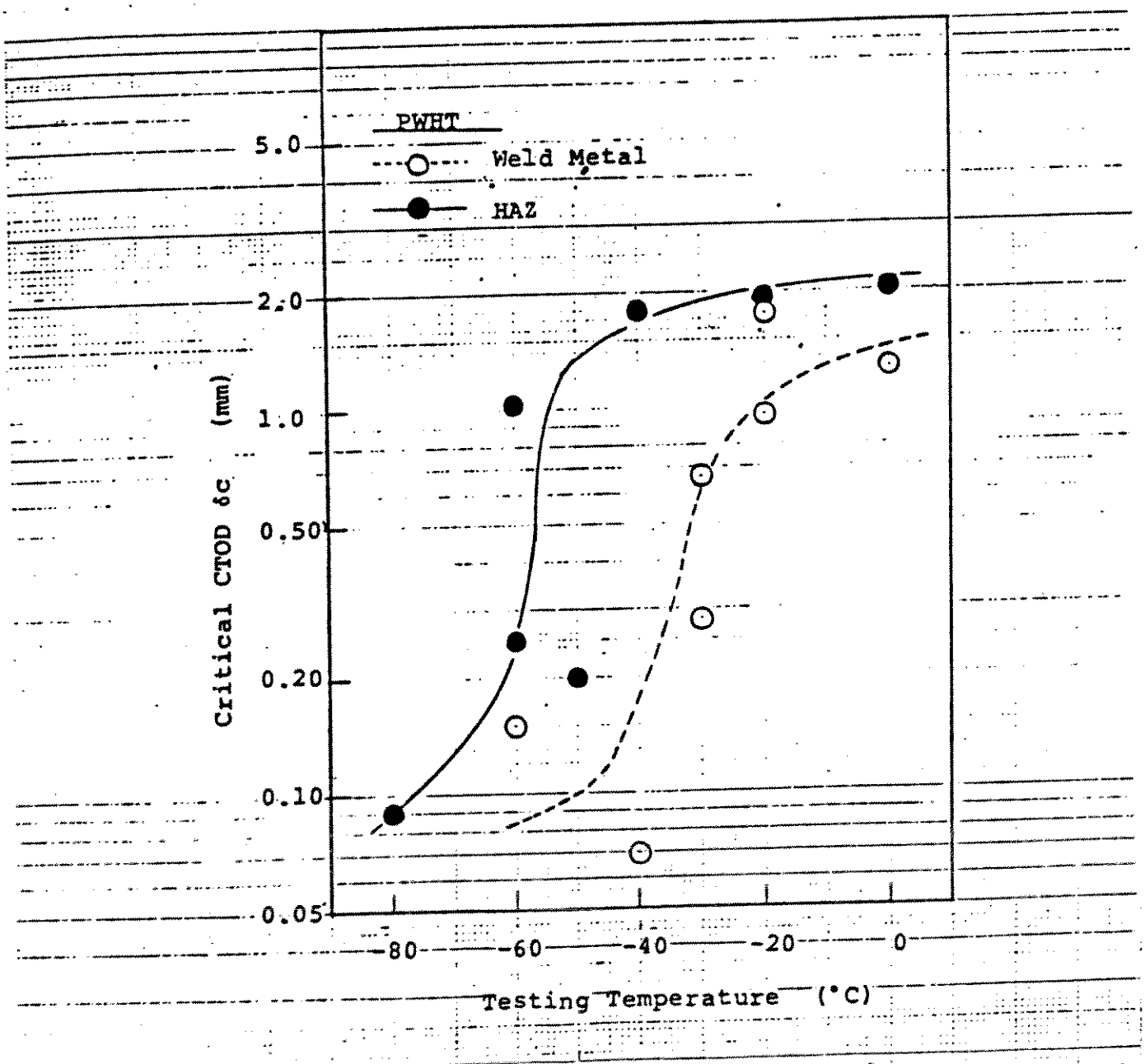


Fig.9 Transition curves of CTOD test of Weld metal and HAZ-1 in PWHT.

B3) Steel 3b and 5

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	%	%
3b	As welded	684	100	805	117	27	70
	PWHT	664	97	805	117	25	68
5	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.