Superiority of Narrow Gap SMA Welding of 304 in Stainless Steel Pipe

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ABSTRACT

Shielded metal arc (SMA) welding of 25mm thick wall 325mm O.D, 304LN austenitic stainless steel pipe has been carried out with GTAW root pass by using conventional V-groove and narrow groove welding techniques at appropriately designed WPS to produce sound weld of significantly narrow weld groove. The characteristics of the narrow groove weld joints with respect to their weld size, microstructure, residual stresses, mechanical properties and corrosion susceptibility have been studied and compared to those of the conventional V-groove weld joints. It is observed that the use of narrow groove instead of conventional V-groove in welding of thick wall stainless steel pipe is beneficial especially with respect to reduction in grain coarsening at HAZ adjacent to the fusion line and lowering of residual stresses of weld joint by keeping the mechanical properties and susceptibility to IGC comparable to those of the V-groove weld joint. However the inclusion content of the narrow groove SMA weld has been found comparatively higher than that of the conventional V-groove weld.

Keywords

Austenitic stainless steel, shielded metal arc welding, narrow gap welding, V-groove welding, residual stresses, microstructure, inclusion content, mechanical properties, corrosion.

INTRODUCTION

The joining of thick wall piping systems used in chemical, fertilizer as well as thermal and nuclear power industries are often carried out by shielded metal arc welding (SMAW) process with gas tungsten arc welding (GTAW) root pass using AWS specified conventional weld groove. But the intense heat of large amount of weld metal deposition in the conventional V-groove (included angle of 60-70°) weld introduces significant amount of transverse and axial shrinkage in the weld joints resulting in significant amount of residual stresses in it. In order to have larger life of a thick wall piping system the use of 304LN stainless steel pipe has been found as a comparatively better prospective material considering its good inter granular corrosion resistance along with better mechanical and fracture mechanics properties[1-6] at ambient and elevated temperatures. The arc welding of thick austenitic stainless steel pipes carried out by the similar welding processes and procedure using the conventional weld groove as stated above has been found to impair the corrosion properties of the weld joint due to severity of weld thermal cycle adversely affecting the residual stresses and microstructures of the weld and heat affected zone. Moreover the intense weld thermal cycle of the conventional V-groove weld joint often produces metallurgical defects such as micro-crack, non-metallic inclusions and undesirable micro structural transformations in reheat region of two adjacent welding passes and HAZ of base metal causing heterogeneity in mechanical and metallurgical properties of the material[7-9]. It is well known that instead of conventional V-groove welding the use of narrow gap welding can reduce the severity of weld thermal cycle and shrinkage stresses in weld joint primarily by reducing the amount of metal deposition in weld groove and thus gives rise to a favorable residual stress profile[8-10]) and microstructure in it. But, the application of narrow gap SMA welding to improve the properties of weld joint is quite critical due to its susceptibility to introduce weld defects primarily as inclusion and lack of fusion because of difficulties in manipulation of electrode for weld deposition requiring appropriate welding procedure specification (WPS). However, the application of narrow gap SMA welding may become further interesting by proper control of the welding process and procedure primarily to reduce the residual stresses and grain coarsening of HAZ to improve corrosion properties of the weld joint. But, in a sound joint of thick wall pipe weld with respect to the presence of lack of fusion the nature of distribution and the magnitude of residual stresses develop at the top and especially at the root of the narrow gap weld joint is not well understood so far due to relatively complex nature of stress generation in the circular section.

In view of the above an effort has been made to carry out comparative studies on the characteristics of conventional V-groove and different size of narrow groove SMA welds of 304LN SS pipe prepared by using appropriately designed WPS resulting in a practically sound weld with respect to lack of fusion. The weld quality has been analysed primarily with respect to the distribution of longitudinal and transverse residual stresses at the top and the root across the weld joints and the microstructure of the weld and HAZ. The weld joints are also characterised by studying their mechanical and corrosion properties.

EXPERIMENTATION

Welding of pipes

The welding of 25mm thick wall and 325mm OD AISI 304LN stainless steel pipe was carried out by using the conventional V-groove confirming the ASME Section IX of Boiler and Pressure Vessel Code and newly designed narrow grooves of various sizes as shown in Fig. 1. Multipass welding was performed in 1GR position by holding the pipes in a rotating table with the help of three jaw clamping system. The weld joints were prepared by GTAW autogenous root pass followed by some GTAW filler passes and SMAW filling passes. The GTAW root pass was carried out by using 308L SS consumable insert having cross section as shown schematically in Table 1. The welding consumables as well as the welding parameters and procedures used in conventional V-groove welding and narrow gap welding of the stainless steel pipes are also given in Table 1. The GTAW was carried out using water cooled torch with 7 mm diameter gas nozzle and 3.2 mm diameter 2% thoriated tungsten electrode under the shielding of commercial argon of 99.98% purity at a flow rate of 12 L/min. All the welding parameters were recorded with the help of WMS 4000 software installed in a computer connected to the circuit of the welding power source. The transverse axial shrinkage after each pass was also measured for conventional V-groove and narrow groove multi-pass weld deposition. Heat input per pass of the SMA welding was estimated as follows.

$$Heatinput(kJ/cm) = \frac{Weldingcurrent(A) \times Arcvoltage(V)}{Weldingspeed(cm/s)} \quad \text{(i)}$$

The characteristics of weld joint were correlated to the average heat input of SMAW per pass estimated as mean value of heat input employed in its multiple filler passes. During welding the dye penetration test of weld deposit was carried out intermittently after each weld pass and finally the weld joints were tested by 100% X-ray radiography.

Measurement of Residual Stresses

The residual stresses at the top and the root of the weld joints of the pipes were measured by placing three-element strain gauge rosette system in the desired location and using blind centre hole drilling technique on it. The measurement of residual stresses has been carried out at different locations in weld and HAZ adjacent to the fusion line (FL). The surface area of the region selected for the measurement of residual stresses was mechanically smoothened and cleaned by acetone prior to fixing the strain gauge. The measurement of residual stresses and their estimation was carried out in accordance to the procedure ASTM E-837. After the hole drilling operation the joint surface was metallographically polished and etched to reveal the location of drill with respect to weld fusion line.

Chemical Analysis

The chemical analysis of different samples was carried out under spark emission optical spectroscopy at a spot size of 3 mm diameter on solid specimens. The analysis was performed on weld metal at polished transverse section of the weld joint, base metal and mechanically flattened welding electrode to accommodate the test spot size. However the nitrogen content of the base metal and weld deposit which may have nitrogen due to dilution was analyzed under CHN infrared analyzer using a 10 mm long pin sample of 5mm diameter.

Micro Structural Studies

The transverse sections of the pipe and weld joints were prepared by standard metallographic procedure and etched in a solution containing 10% nitric acid, 10% acetic acid, 15% hydrochloric acid and 5% glycerol. Metallographic studies were carried out under optical microscope on base metal, multi-pass weld deposit and HAZ especially in the region adjacent to the fusion line. The grain size of HAZ within 0.1mm from the fusion line (FL) on either side of weld joint was measured at 6-10 randomly selected spots in the parts primarily affected by the SMA and GTA filler weld deposits by using the image analyzer software as per ASTM E112. However grain size of HAZ adjacent to GTA autogenous pass could be measured at 2-3 spots primarily due to lower thickness of this layer.

Measurement of Inclusion and Porosity Content

The inclusion and porosity content of the base metal and weld deposit was also measured with the help of the image analyser software used in optical microscopic studies on the metallographically polished unetched transverse section of weld joint. The software analysis was carried out on at least 21 randomly captured images of different locations of the matrix viewed at a magnification of X100. The analysis was made considering the area fraction of practically round shape black spots observed on the matrix of weld deposit as porosity or a void containing inclusions in it. The volume fraction of the spots present in the matrix was estimated by assuming it as a linear function of their measured area fraction.

Measurement of weld size

The size of the weld as revealed on the metallographically polished and etched transverse section of all the weld joints was graphically measured under optical microscope. The accuracy of measurement of the weld area was limited to the use of graphic grid of $1mm^2$.

Testing of Mechanical Properties

Tensile Test

The tensile testing was carried out by using round tensile specimens confirming the ASTM E8M specification and the properties are reported as an average of at least three specimens testing. The tests were carried out at a strain rate of 0.003/s. The specimens were machined out from the base metal, axial weld joint having weld at its centre and circumferential all weld metal. The tensile specimens of the base metal and axial weld joint were having 50mm gauge length whereas the all weld tensile specimens were having 25mm gauge length. The diameters of the specimens were 5 and 10 mm within the gauge lengths of 25 and 50 mm respectively. The yield strength was estimated at 0.2% offset strain.

Charpy Impact Test

The charpy V-notch (Cv) impact toughness test of the base material and weld centre was carried out at ambient temperature using the specimens of square cross section (10X10mm) confirming the ASTM E23 specification. At the weld centre the notch was located in the circumferential direction of the weld so that the cracking plane lies along the direction of welding. The Charpy impact test was also carried out with notch location in radial direction at the weld centre such that the cracking plane lies across the direction of welding.

Hardness Test

The hardness of the base metal and weld joint across the weld and HAZ was studied with reference to the weld centre and fusion line of each weld joint by Vickers hardness testing at a load of 5 kg. The relatively low load was used to get a small indentation which may be more effective to study the characteristics of different locations of HAZ more precisely.

Inter Granular corrosion (IGC) Test

The IGC test of the conventional and narrow groove weld joints was carried in accordance with the ASTM E262 Practice A. The rapid oxalic acid etch test was carried out on the metallographic polished transverse section of weld joint by dipping it in the electrolytic solution of 100 g reagent grade oxalic acid (H2C2O4. 2H2O) in 900 ml distilled water and connecting it to the positive pole of a DC power supply maintaining a current density of the order of 1 0.1 A/cm2 at a voltage of 15V. The etched specimens were thoroughly examined under the optical microscope at magnifications of 500X to study the susceptibility of intergranular attack in different locations of HAZ by evaluation of the etched structures developed under the test exposure. The evaluation was primarily made on the basis of identification of the presence of step structure, dual structure and ditch structure in the HAZ, as per the norms prescribed in the said ASTM standard.

RESULTS AND DISCUSSION

Welding of Pipes

The X-ray radiography of the conventional and narrow gap welds shows that the welds are sound enough from the viewpoint of the discontinuity defects as per ASME section III. It confirms that the welding procedure specifications used for preparation of both the conventional and narrow gap welds are appropriate. The macro photographs of the weld joints as revealed in transverse section of the conventional V-groove and various narrow groove weld joints are as shown in Fig. 1. The figure depicts that the welds are practically free from any defects like lack of welding or root wall fusion. The macro photographs of the weld joints given in Fig. 1 also typically reveals that the conventional groove weld joint is having weld width of the order of 20-21 mm at the top whereas the narrow groove weld joints with U-groove keeping 16mm groove width and U-groove with 13mm groove width are having 13-14 mm and 11-12 mm parallel weld width respectively. This may have primarily happened because the average heat input employed per pass in SMA weld deposit and its corresponding overall transverse axial shrinkage of the weld was considerably reduced with narrowing down the weld groove in comparison to that of conventional V-groove weld joints as shown in Table 2.

Hence it can be inferred that the narrow groove weld joints may be beneficial in reducing the induction of strain especially at the root of the pipe weld in comparison to that of the conventional V-groove pipe weld, which can consequently minimise the residual stresses in it.

Weld Size

The area of weld revealed in transverse section of the conventional V-groove and narrow groove weld joints has been shown in Table 3. The table shows that the area of weld is considerably reduced by about 31 % using the narrow groove with 11mm weld width with respect to that obtained in the weld joint of conventional V-groove design. As the reduction in weld area can be considered apparently to a large extent proportional to the reduction in amount of weld deposit it may favourably influence the lowering of shrinkage stresses resulting in to reduction of residual stresses of narrow groove weld joint.

Residual Stresses

The longitudinal and transverse residual stresses present at different locations on top of the weld in reference to the centre and fusion lines of the conventional V-groove and various narrow U-groove weld joints are shown in Fig. 2 (a) and (b) respectively. Similarly the longitudinal and transverse residual stresses in different locations at root of the weld with respect to the centre and fusion lines of the said V-groove and various narrow U-groove weld joints are shown in Fig. 3 (a) and (b) respectively. The figures show that a substantial reduction in longitudinal residual stresses both at the top and root of the weld takes place with narrowing down the weld groove in comparison to those observed in case of the conventional V-groove weld joint. The transverse residual stress has also been found to follow a similar trend but having a magnitude comparatively lower than the longitudinal residual stress of the weld joint as it is commonly observed[11-14]. The considerable difference in development of residual stresses in the conventional and narrow gap welds may have primarily attributed to the severity of thermo mechanical characteristics arising out of differential expansion and contraction stresses resulting from multipass deposition, which becomes comparatively milder in case of narrow gap weld holding appreciably lower amount of weld deposit[8,14,15]. However, the Figs. 2 and 3 further shows that there is a considerable variation in distribution of residual stresses across the weld and its nature significantly changes with narrowing down the weld groove. It appears that the top of the conventional V-groove weld is having a dual peak of residual stresses with a depression of stress at the weld centre, which could not be so well identified at the root of the weld due to its narrowness causing difficulties in multiple spot analyses within it. The presence of dual peak of residual stresses distributed in either side of weld centre line in weld joint of austenitic stainless steel has also been reported by earlier workers arising out of interactions of shrinkage and quenching stresses[13-15]. But it is interesting to note that the dual peak of residual stress behavior of the weld gradually vanishes with narrowing down of the weld groove showing either maximum or large order of stresses at weld centre. However, it is noted that although of considerably low magnitude but the presence of residual stresses is extended up to a comparatively larger distance from the fusion line in HAZ of the narrow gap weld than that observed in V-groove weld joint. The significance of this nature of distribution of residual stresses in HAZ of narrow gap weld may be carefully considered with due respect to its characterization in reference to the influence of residual stresses on kinetics of sensitization at locations away from the fusion line.

Chemical Analysis

The chemical analysis of the base metal, filler metal and weld deposit of different groove joints are given in Table 4. The table shows that the weld metal of narrow groove weld joint is having comparatively higher amount of carbon in comparison to that of the conventional V-groove weld joint primarily caused by lower dilution of base metal due to using relatively shallow included angle of attack with the groove wall and lower amount of metal deposition as compared to that used in case of the V-groove weld joint.

Metallurgical Tests

Inclusion/Porosity Content of Base and Weld Metals

Inclusion content observed in the base metal and the weld deposits of different weld joints has been shown in Table 5. The table depicts that the narrow groove weld joints are having comparatively higher inclusion content in comparison to that of conventional V-groove weld joints. Increase in inclusion content of the narrow groove welds with respect to the V-groove weld may have primarily happened due to relative difficulties faced in inter-pass cleaning of narrow gap weld, resulting in certain amount of slag entrapment in weld deposit. The typical appearance of the presence of inclusion in the matrix of narrow groove weld deposit has been shown in Fig. 4.

Micro Structural Studies

The typical microstructure of the base metal has been shown in Fig. 5. The microstructures of the SMA weld deposit in the conventional V-groove and narrow groove weld joints having 14mm and 11mm weld width are shown in Fig. 6 (a), (b) and (c) respectively. The typical microstructures of HAZ adjacent to the fusion line in the V-groove and narrow groove weld joints having 14mm and 11mm groove width are shown in Fig. 7 (a), (b) and (c) respectively.

The studies on microstructures (Fig.6) of the conventional and narrow groove weld joints apparently show similar characteristics of multipass weld deposit primarily consist of dendritic and reheat refined regions. However, the area fraction of these two regions depicts that the narrow groove welds are having significantly higher percentage of dendrite region (Table 6) in comparison to the V-groove weld. It is also marked that the narrow groove weld contains comparatively finer reheat refined region than that observed in the V-groove weld (Fig. 6). Such a variation in microstructure between the conventional and narrow groove welds may be attributed to the change in severity of weld thermal cycle of multipass deposition, which becomes comparatively milder in case of narrow groove weld due to lower amount of weld deposit.

The microstructure of HAZ adjacent to the fusion line (Fig. 7) of both the conventional and narrow groove welds show certain extent of grain coarsening. The grain size of the conventional and narrow groove weld joints has been compared in Table 7. The narrow groove weld joints has been found to have comparatively less grain coarsening than that observed in case of the conventional weld joint. This may have primarily happened due to comparatively low angle of attack to the groove wall used in case of narrow gap welding providing relatively larger area of heat distribution reducing the thermal intensity per unit area of HAZ adjacent to the fusion line. Such a characteristic of HAZ may improve the resistance to stress corrosion cracking susceptibility of weld joint while using narrow gap weld in place of the comparatively wider conventional V-groove weld.

Mechanical Properties

Tensile Test

The tensile properties of the base metal in circumferential and longitudinal directions of the pipe are as shown in Table 8. Similarly the tensile properties of the conventional and narrow groove weld joints in axial (having weld joint at centre of the gauge length) and circumferential (all weld) directions are shown in Table 9 and Table 10 respectively. The dimensionless material constant (?) and strain hardening exponent (n) was estimated during tensile testing of the specimens of the base metal and weld joint using Romberg Osgood expression as follows

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n \qquad \text{(ii)}$$

Where, ? is the stress at any instant, ? is the strain at ?, ?0 is the flow stress estimated as (?u + ?y)/2, ?0 is estimated as ?0/E, wherein E is the modulus of elasticity.

In all the cases of axial weld testing the specimens are found to fracture from the weld and thus, it primarily reveals the tensile properties of weld deposit. The Tables 8 to 10 show that with a considerable sacrifice in elongation with respect to base metal the yield strength to ultimate tensile strength ratio of weld has been significantly increased lying in the range of 0.61-0.78, which is considerably higher than that of base metal found of the order of 0.5. In this regard it is also interesting to note that the all weld metal of the narrow gap joint shows considerably higher YS/UTS ratio (0.72-0.78) as compared to that of the conventional V-groove weld (Table 10). However, the base material has shown considerably higher UTS in comparison to the weld joints. This may have primarily happened due to comparatively lower UTS and elongation (Table 10) of the weld deposit from the E308L-15 SMA electrode in agreement to its test certificate provided by the supplier showing the UTS and elongation of 586 MPa and 38.1% respectively

The narrow groove weld joint with 11mm weld width is having comparatively higher strength and elongation than that observed in the weld joints having conventional groove and narrow groove with 14mm weld width in both the axial and circumferential directions. It has been further observed that conventional and narrow groove weld joints have shown comparatively better tensile properties in circumferential direction than those observed in axial direction. It infers that the tensile properties of the weld metal may have been significantly influenced by the ratio of the dendrite region/reheat refined region which is significantly higher in narrow groove with 11mm weld width in comparison to other weld joints along with the orientation of morphology of the weld deposit in reference to the axis of loading.

Charpy Impact Test

Charpy impact energy absorbed in various weld joints with notch orientation in longitudinal and circumferential direction has been given in Table 11. The table depicts that conventional and narrow groove weld joints have comparable Cv-impact toughness and lateral expansion. This indicates that the change in welding process and procedure has not affected the impact properties primarily due to the use of same electrode material (E308L-15) for preparation of the conventional and narrow groove weld joints, where the observed variation in microstructure of the multipass weld deposit also has no significant influence on it. However in comparison to the base metal, both the V-groove and narrow groove welds have shown comparatively inferior impact properties may be primarily due to their cast structure.

Hardness Test

The hardness of the base material has been found of the order of 220-260 VHN. The hardness across the weld joint in the conventional groove, narrow groove with 14mm and 11mm weld width are shown in Fig. 8 (a), (b) and (c) respectively. The figure shows that there is comparatively more scattering of hardness in the narrow groove weld deposit than that observed in conventional one. A similar nature of scattering in hardness is also marked in HAZ of both the welds. The variation in distribution of hardness in weld deposit is primarily attributed to the inherited nature of multipass weld containing at least three different kind of zones having dendritic, coarse grain reheat refined and fine grain reheat refined microstructures. The hardness of HAZ in conventional groove weld joint has been found of similar order to that of the base metal. The effect of grain coarsening on lowering of hardness may have been partly compensated by certain extent of sensitisation at HAZ under repeated weld thermal cycle of multipass deposition. In narrow groove and in certain regions of conventional groove weld joints the hardness of HAZ has been marked to be comparatively higher than the base metal, which may have also attributed to sensitisation under the repetitive weld thermal cycle of multipass weld deposit.

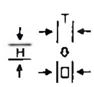
Inter Granular Corrosion (IGC) Test

The typical effect of oxalic acid etch test on microstructure of HAZ adjacent to fusion line in the conventional groove weld joint and narrow groove weld joints of 14mm and 11mm weld width have been typically shown in Fig. 9 (a), (b)

Welding parameters used in preparation of the conventional and narrow groove weld joints.

CONSTANT PARAMETERS

Welding Consumable Class

(a) GTAW SS Filler rod	SFA 5.9 ER 308L
(b) SMAW SS Electrode	SFA 5.4 E 308L-15
Welding Current Polarity	
(a) GTAW	DCEN
(b) SMAW	DCEP
Electrode baking temperature.	175^{0}C
Preheat temperature.	Nil
Interpass temperature.	120-1500C
308L SS Insert 	D= 3.2mm, H= 3.1mm and T= 0.82mm

Process	Passes	Dia. of consumable	Conventional V-groove weld joint				Narrow groove weld with 11 mm weld width			
			Weld Layer (s)	Welding Current (A)	Arc Voltage (V)	Travel Speed (mm/min)	Weld Layer (s)	Welding Current (A)	Arc Voltage (V)	Travel Speed (mm/min)
GTAW	Root fusion	-	I	130	12	80-85	I	125	12	80-85
GTAW	Root run	2.0	II	140	14	40-45	II	130	12	65-75
GTAW	Root run	2.5	III	150	15	45-50	-	-	-	-
SMAW	Filler	3.15	IV	110	26	80-85	III	110	26	190-200
SMAW	Filler	3.15	-	-	-	-	IV a, b	110	26	180-190
SMAW	Filler	4.0	Va,b	140	28	90-95	V a, b	140	28	200-210
SMAW	Filler	4.0	Contd.	140	28	90-95	Contd.	140	28	200-210
SMAW	Cap	4.0	VIIII a, b, c	140	28	95-100	X a, b	140	28	205-215

a,b,c denotes the parallel passes in a layer

Table 1 : Welding parameters used in preparation of the conventional and narrow groove weld joints.

and (c) respectively. The microstructure of HAZ adjacent to fusion line shows that minor ditches exist only at some grain boundaries resulting in dual structure as per ASTM 262 practice A. It indicates that the narrow groove weld joints along with the conventional V-groove weld joints have passed the oxalic acid etch test and can be acceptable with respect to their resistance to IGC attack. 4.

CONCLUSION

The observations of the present investigation conclude that as compared to the SMA weld joint with conventional V-groove the use of narrow groove shows the following characteristics.

1. An appropriate welding procedure specification (WPS) can produce a sound narrow gap weld joint having weld width of 11-12 mm in place of a 20-21 mm weld width conventional V-groove weld joint.
2. The narrow groove weld joint with the weld width of about 11-12 mm reduces the area of weld by about 31%.
3. Narrow grove weld joints have appreciably lower overall transverse axial shrinkage
4. The narrow gap welding can reduce the residual stress of weld up to about 30%. 5. Narrow groove weld joints show more reheat refinement in weld deposit and less grain coarsening of HAZ adjacent to fusion line. 6. Narrow groove weld show similar yield strength, hardness across the weld joint and CV -impact toughness, but significantly high ratio of YS/UTS.
7. Narrow gap SMA weld may have comparatively higher inclusion content than that of the conventional V-groove weld.
8. As per ASTM 262 practice A the HAZ of narrow gap weld joints shows acceptable resistance to IGC under the oxalic acid etch test.

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Type of weld joint	Average heat input in SMAW filler pass (KJ/cm)	Overall transverse axial shrinkage (mm)
Conventional V-groove	23.05	5.73
Narrow groove with 14 mm weld width	15.12	4.58
Narrow groove with 11 mm weld width.	11.36	2.98

Table 2 : Heat input per pass and overall transverse shrinkage of conventional and narrow groove weld joints

Type of weld joint	Area of weld joint, (mm^2)	Inclusion and porosity (Vol. %)
Conventional V-groove	319	--
Narrow groove with 14 mm weld width	254	20.38
Narrow groove with 11 mm weld width.	220	30.94

Table 3 : Amount of weld deposition as a function of area of weld joint in conventional and narrow groove weld joints.

Metal Weld Joint	Chemical analysis (Wt.%)									
	C	Cr	Ni	Mn	N	Mo	Si	Cu	S	P
Base metal (304LN)	0.023	19.02	9.14	1.82	0.16	0.19	0.57	0.30	0.002	0.021
GTAW filler wire (308L)	0.020	18.73	11.68	2.01	-	0.20	0.40	0.08	0.010	0.019
SMA electrode (308L)	0.049	19.87	11.90	1.77	-	0.10	0.22	0.12	0.006	0.016
Conventional V-groove	0.027	18.12	11.06	2.27	0.10	0.038	0.37	0.14	0.013	0.020
Narrow groove with 14 mm weld width	0.028	18.45	11.10	2.34	0.10	0.057	0.50	0.12	0.008	0.015
Narrow groove with 11 mm weld width	0.043	18.35	11.12	2.42	0.10	0.084	0.58	0.15	0.012	0.019

Table 4 : Chemical composition of the base metal, filler metals and SMA weld deposit

Metal/ Weld Joint	Inclusions rating	Inclusion and porosity content, (Vol. %)
Base metal	D thin, D thick	1.42
Conventional V-groove	D thin, D thick	2.34
Narrow groove with 14mm weld width	B thin, B thick,	2.32
Narrow groove with 11mm weld width	B thin, B thick, D thin, D thick	3.19

Table 5 : Slag inclusion of base metal and different weld joints

Type of weld Joint	Region	Dendrite region, D ± σ (%)	Reheat refined region R ± σ (%)
Conventional V-groove	SMAW	59.2 ± [12.9]	40.8 ± [12.9]
	GTAW	93.3 ± [1.7]	6.7 ± [1.7]
Narrow U-groove with 14 mm weld width	SMAW	56.1 ± [12.4]	43.9 ± [12.4]
	GTAW	94.0 ± [1.7]	6.0 ± [1.8]
Narrow U-groove with 11 mm weld width	SMAW	69.6 ± [24.0]	30.4 ± [24.0]
	GTAW	97.2 ± [1.87]	2.8 ± [1.87]

Table 6 : Dendrite measurement at various locations in conventional V-groove and narrow groove weld joints.

Type of weld Joint	Location	Average Grain Dia., d ± σ (μm)	ASTM No
Conventional V-groove	SMAW	28 5	7.5
	GTAW Filler	28 5	7.5
	GTAW Autogenous	23	7.5
Narrow groove with 14mm weld width	SMAW	20 3	8.5
	GTAW Filler	18 2	8.5
	GTAW Autogenous	16	9.0
Narrow groove with 11mm weld width	SMAW	18 2	9.0
	GTAW Filler	16.8 5	8.5
	GTAW Autogenous	17	9.0

σ is standard deviation

Table 7 : Grain size measured at various locations in HAZ adjacent to fusion line in conventional and narrow groove weld joints.

Gauge Length (mm)	Orientation	Tensile properties of base material						
		UTS (Mpa)	YS (Mpa)	YS/UTS	Elongation %	Reduction in area %	n	α
25	Circumferential	682	360	0.53	71.3	85.0	4.11	45.39
50	Longitudinal	656	338	0.51	70.6	84.6	4.34	40.91

Table 8 : Tensile properties in base material of different gauge length.

Type of Weld Joint	Orientation	Tensile properties of axial weld joint of 50 mm gauge length							Failure Location
		UTS (Mpa)	YS (Mpa)	YS/UTS	Elongation %	Reduction in area %	n	α	
Conventional V-groove	Longitudinal	555	353	0.64	16.0	58.8	5.75	16.03	Weld
Narrow groove with 14mm weld width	Longitudinal	556	350	0.63	22.8	54.0	6.25	20.54	Weld
Narrow groove with 11mm weld width	Longitudinal	582	353	0.61	23.4	32.9	5.92	21.26	Weld

Table 9 : Tensile properties of Conventional V-groove and Narrow groove axial weld joints.

Type of Weld Joint	Orientation	Tensile properties of axial weld joint of 50 mm gauge length						
		UTS (Mpa)	YS (Mpa)	YS/UTS	Elongation %	Reduction in area %	n	α
Conventional V-groove	Circumferential	569	365	0.64	37.9	60.57	7.07	34.28
Narrow groove with14mm weld width	Circumferential	577	448	0.78	32.2	41.4	7.53	23.10
Narrow groove with 11mm weld width	Circumferential	599	430	0.72	39.0	36.71	6.45	50.48

Table 10 : Tensile properties of Conventional V-groove and Narrow groove all weld joints.

Type of weld joint	Notch location			
	Radial		Circumferential	
	Energy absorbed (J)	Lateral expansion (mm)	Energy absorbed (J)	Lateral expansion (mm)
Base metal	120	2.67	133	2.83
Conventional V-groove	86	1.00	97	1.86
Narrow groove with 14mm weld width	81	0.84	84	1.25
Narrow groove with 11mm weld width	85	1.0	91	1.55

Table 11 : Energy absorbed in Charpy impact toughness test in base material and weld joints.

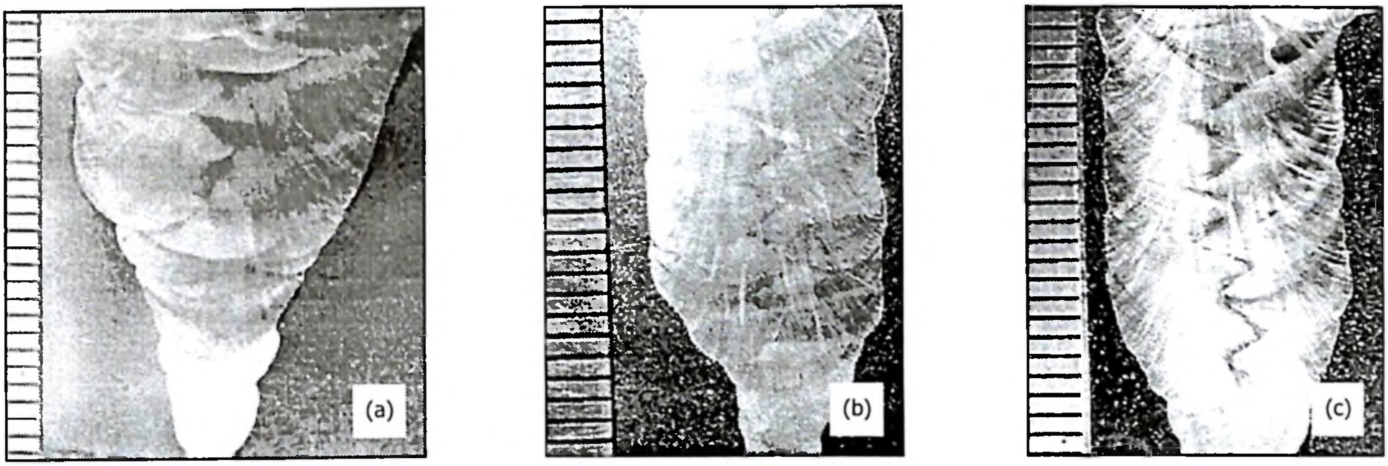


Figure 1 : Typical Microphotograph showing (a) Conventional V-groove of 20-21mm weld width (b) Narrow U-groove with 13-14mm weld width and (c) Narrow U-groove with 11-12mm weld width.

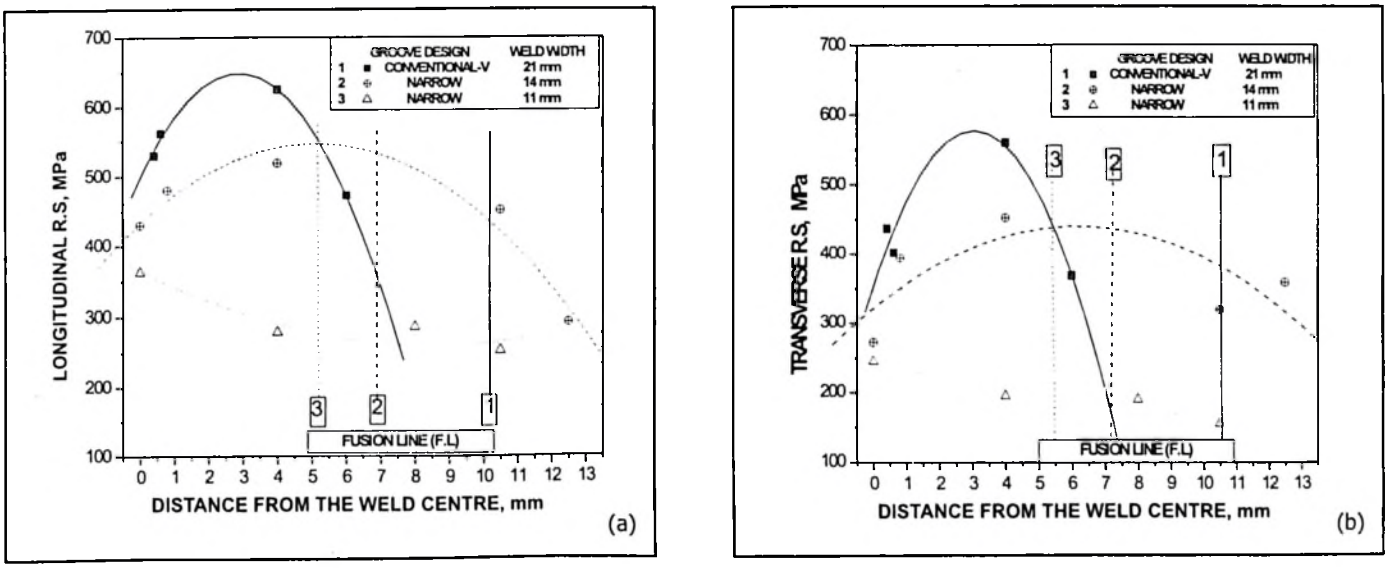


Figure 2 : Distribution of (a) Longitudinal residual stresses and (b) Transverse residual stresses at the top of the weld joint.

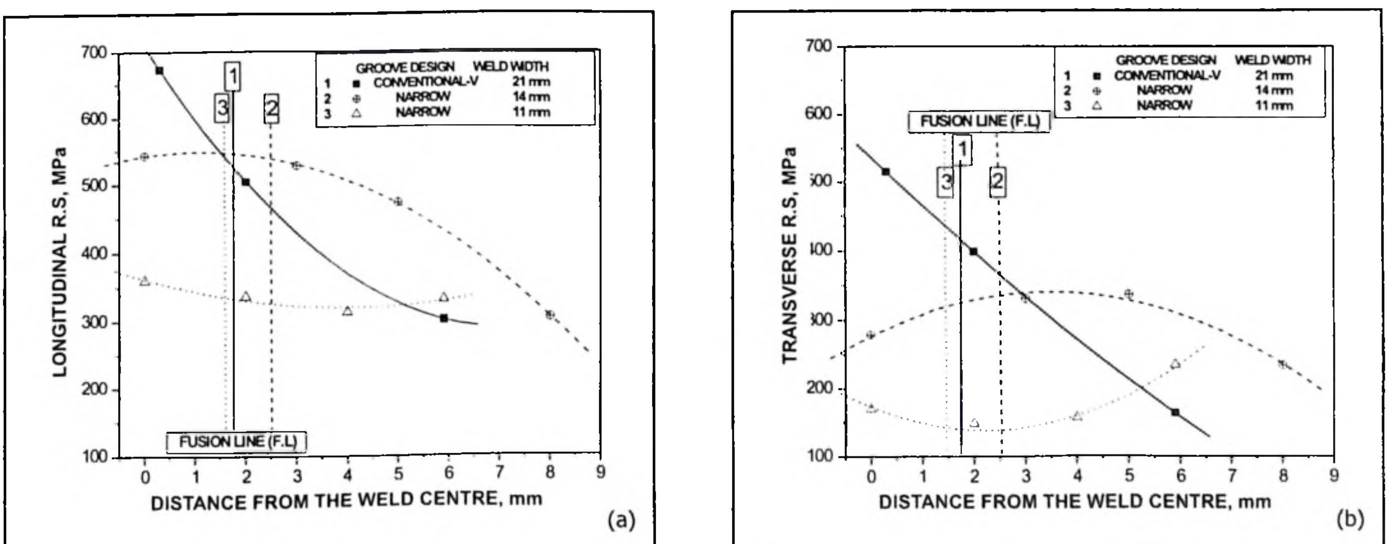


Figure 3 : Distribution of (a) Longitudinal residual stresses and (b) Transverse residual stresses at the root of the weld joint.

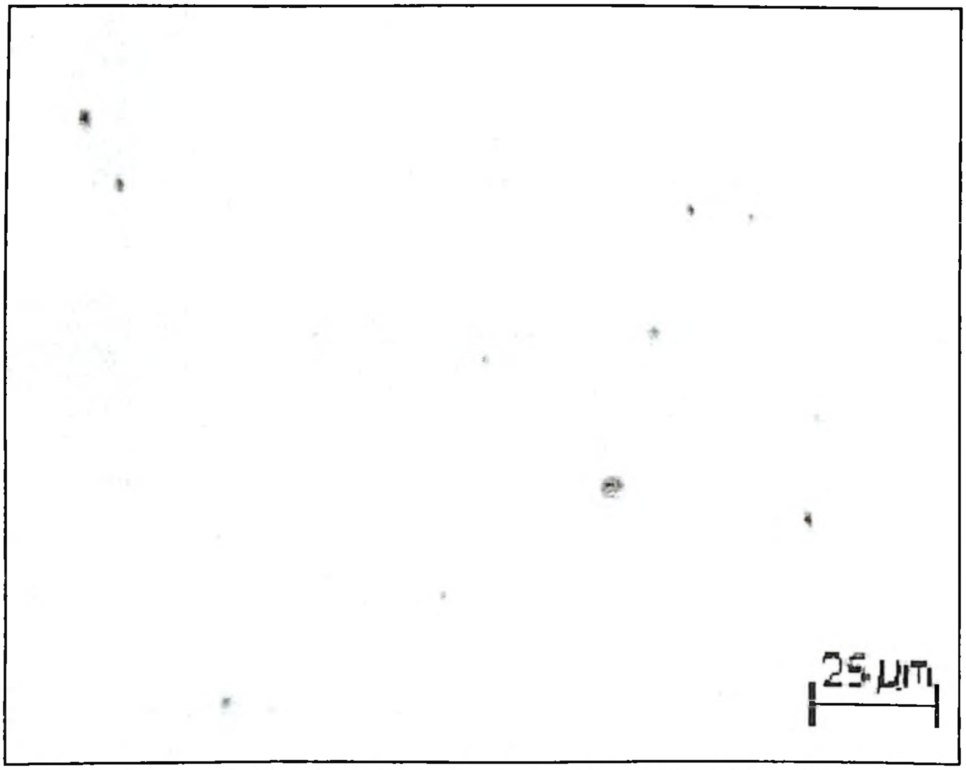


Figure 4 : Typical microphotograph of inclusions observed in SMA weld deposit of narrow groove with 11mm weld width.

Figure 5 : Typical microstructure of 304LN stainless steel pipes.

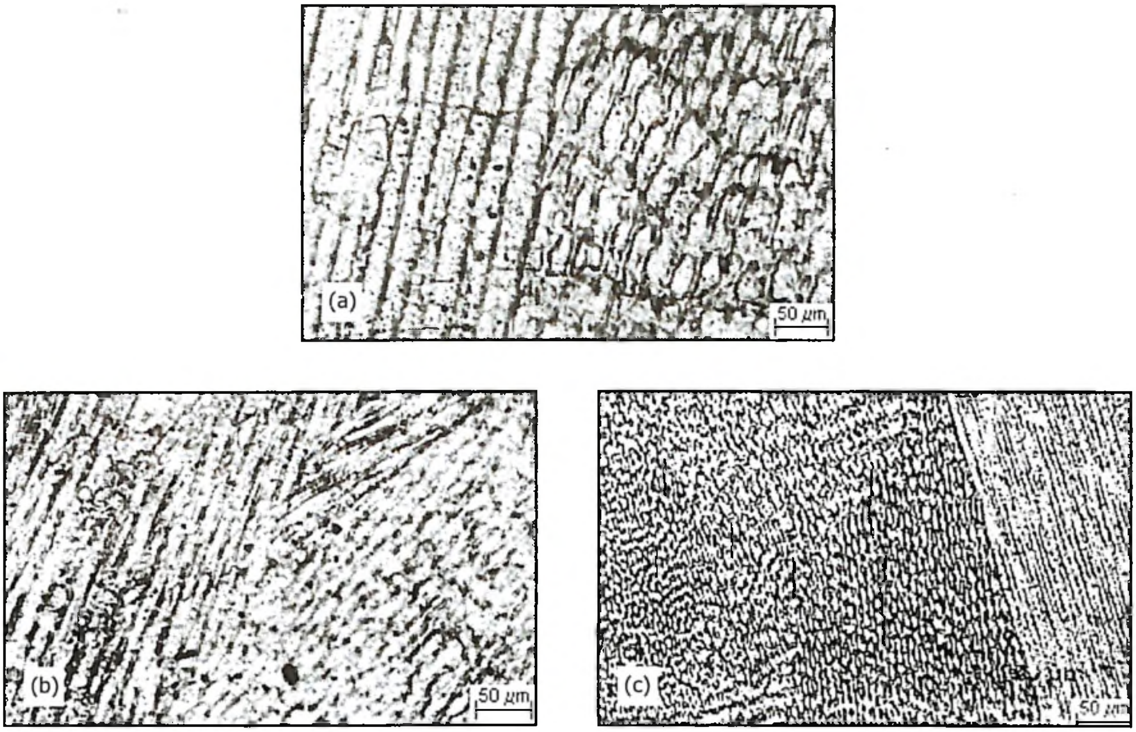


Figure 6 : Typical microstructure of reheat refined region observed in SMA weld deposit prepared by using (a) conventional groove (b)Narrow groove with 14mm weld width and (c) Narrow groove with 11mm weld width.

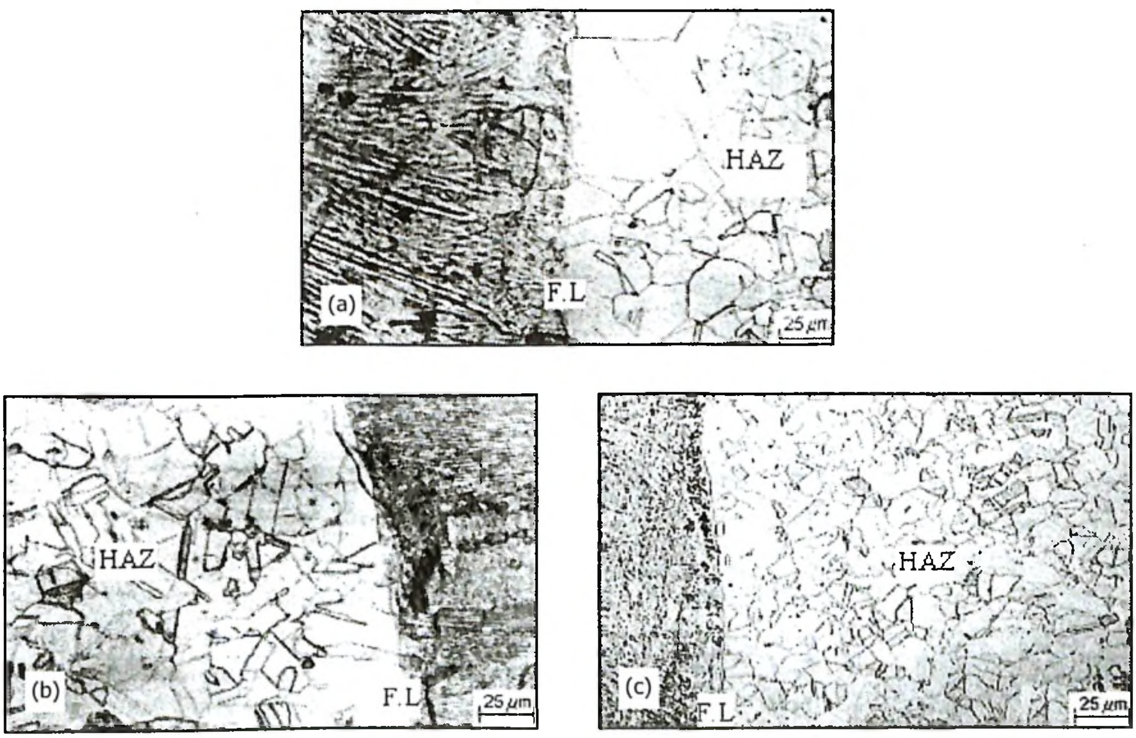


Figure 7 : Typical microstructure of HAZ adjacent to fusion line observed in SMA weld deposit prepared by using (a) Conventional groove (b) Narrow groove with 14mm weld width and (c) Narrow groove with 11mm weld width.

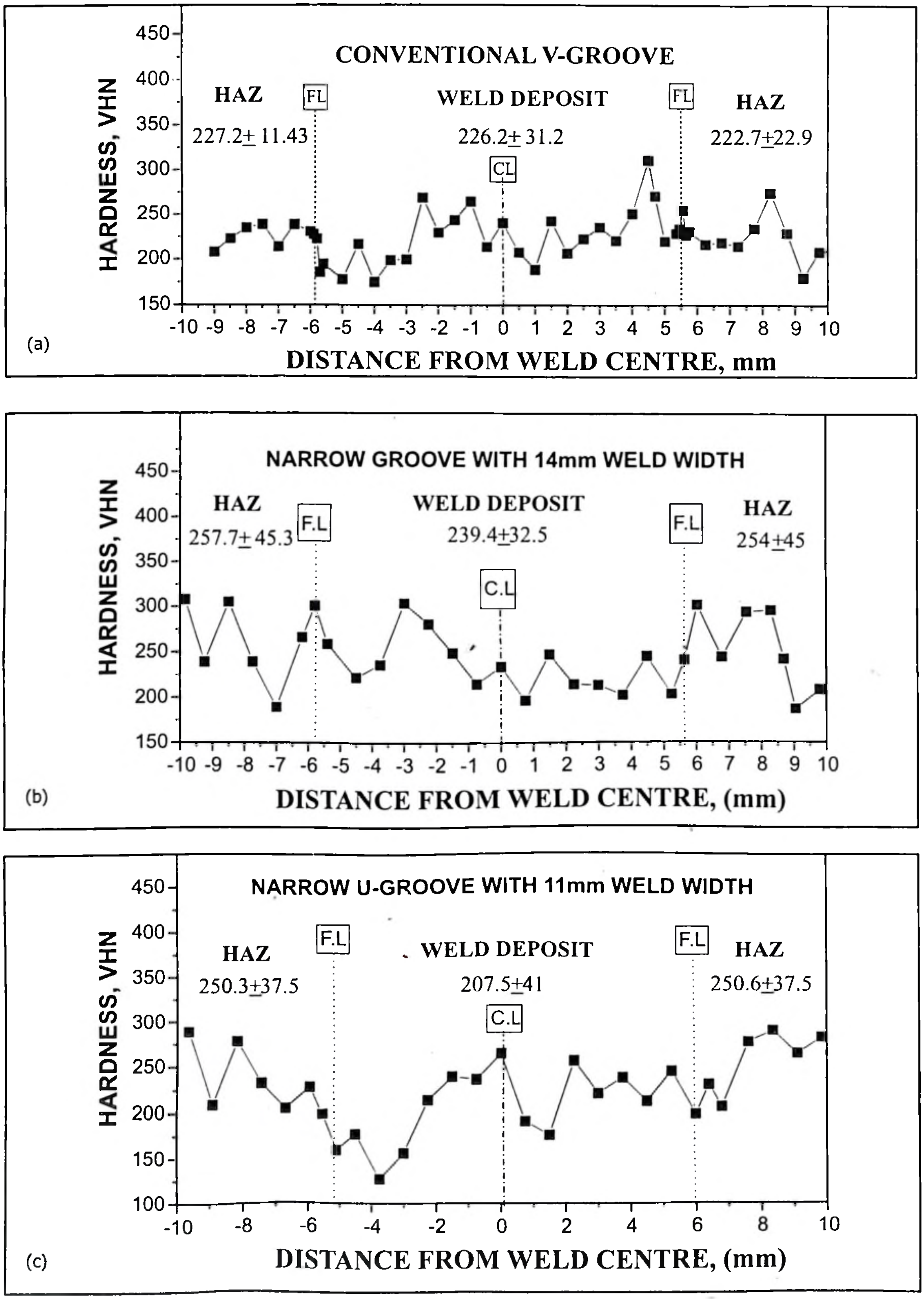
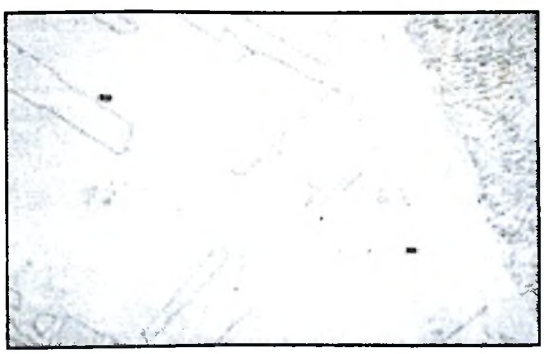


Figure 8 : Variation in hardness across the weld joint prepared by using (a) Conventional V-groove (b) Narrow groove with 14mm weld width and (c) Narrow groove with 11mm weld width.

(a)

(b)



(c)

Figure 9 : Typical microstructure of HAZ adjacent to fusion line observed after oxalic acid etch test in weld deposit prepared by using (a) Conventional V-groove (b) Narrow U-groove with 14mm weld width and (c) Narrow U-groove with 11mm weld width