Weldability of controlled rolled micro alloyed thick HSLA steel plates for fabrication of penstock liners

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ABSTRACT

Weldability of a controlled rolled HSLA steel plates having thickness of 18, 25 and 34 mm has been studied by multipass SAW process with SMAW root pass. The mechanical and metallurgical properties of the all weld deposit and axial weld joint have been studied. In 34 mm thick plate the weld metal microstructure has been found comparatively finer with more reheat refinement than 18 mm and 25mm thick plates, with improved properties. The weld joints are generally found to fracture from the region away from fusion line showing the strength of the weld higher than the base material. However, the presence of certain amount of inclusions may have lowered the mechanical properties of weld deposits up to certain extent. Reheat refining has been found to improve the toughness of weld metal. The toughness of HAZ mostly found comparable to that of the base metal as such the weldability of controlled rolled HSLA steel has been qualified for welding fabrication of penstock liner.

INTRODUCTION

The micro alloyed high strength low alloy (HSLA) steels are high performance class of steels, intended for the use in civil constructions, machinery, transportation vehicles and containers and material handling equipment with reduced dead weight at high strength to weight ratio. These steels are typically containing small amount of alloying elements with relatively low carbon to achieve their high yield strength in the hot rolled conditions from at least 270 MPa to as high as 1035 MPa. They are generally not heat treated except for any annealing, normalizing or stress relieving done in connection with cold forming operations. However, controlled rolling often further strengthens the steels of this category, which have comparatively higher strength than the HSLA of similar chemical composition. These high strength steels are also having good formability commensurate with their strength level. The HSLA steels of different plate thickness are also largely used in fabrication penstock liners for diverting water at various points in modern hydroelectric power projects in place of the conventional structural steel. The primary reason for selecting such steels is that it has much higher strength than mild steel along with good weldability, formability and corrosion resistance. Thus, one can use plates of comparatively lower thickness reducing the amount of material and complexity in forming and weld fabrication that lowers the construction cost of the project.

The thick plates of controlled rolled micro alloyed HSLA steels can be readily welded by the multi-pass shielded metal arc (SMA) and submerged Arc (SA) welding processes. However, during welding the severity of weld thermal cycle may adversely affect the microstructure and mechanical properties of the controlled rolled micro alloyed HSLA steels at heat-affected zone (HAZ) of the weld joint. In this regard the selection of suitable welding consumables and appropriate welding procedure specification (WPS) is also very much important to provide desired properties of weld deposit matching with those of the high strength base material especially to control the residual stresses arising out of distortion in weld joints.

In view of the above an effort has been made in this work to study the weldability of 18, 25 and 34 mm thick plates of SAILMA 410 HI Type SA533 controlled rolled micro alloyed HSLA steel under submerged arc weld filling with shielded metal arc welding root pass. The mechanical properties of the weld and HAZ resulting in the plates of different thickness under a given welding procedure and parameter has been studied. The

Table - I Welding Parameters

Plate thickness (mm)	Welding Process and position of weld		Welding Current (A)	Arc Voltage (V)	Welding Speed (cm/min)	Heat input (kJ/cm)
18, 25 and 34	SMAW root pass	Root	130-180	22-26	75-100	2.3-2.8
	SAW filling pass	Inner groove	415-435	30-35	30	24-30
		Outer groove	450-500	30-35	30	27-35

mechanical properties are also correlated to the microstructures of the weld joints.

EXPERIMENTAL

Welding

The 18, 25 and 34 mm thick controlled rolled plates of SA 533 grade micro alloyed HSLA steel were welded by submerged arc welding (SAW) process with shielded arc welding (SMAW) root pass. The SMAW was carried out using the 4.0 mm diameter welding electrode of specification AWS A 5.1: E 7018 and the SAW was carried out using the 4.0 mm diameter filler wire and flux combination of specifications AWS A 5.17: EH 14 and A 5.17: F7 A2-EH 14 respectively.

The welding was carried out by multi-pass deposition from both sides at double-V groove butt joint having included angle of 60^0 with 3mm root face. Schematic diagrams of the grooves of different plate thickness, conforming the AWS specification [1], are shown in Fig.1. The welding parameters used during each side of the groove with comparatively smaller and larger weld size has been shown in Table-I.

Tensile Testing

The tensile properties of the base metal and weld joint, with respect to their ultimate tensile strength (UTS), yield strength (YS), fracture strength (FS), elongation and reduction in cross sectional area (RA), were studied by using specimens of different dimensions machined out from them. Tensile properties of the weld joint were studied by using specimens from axial weld and all weld materials. The specimens of axial weld and all weld were prepared by keeping the weld at center of the gauge length and by machining out specimens from the all weld deposit respectively. The dimensions of the axial weld and all weld specimens are schematically shown in Figs. 2(a) and (b) respectively. The specimens of the base metal and axial weld conforms the standard IS 1608: 1995 and the specimen of all weld deposit conforms the standard ASTM E8M. The tensile tests were performed under uniaxial loading at a crosshead speed of 1mm/min. The yield strength was estimated at 0.2% offset strain on stress-strain diagram of the tests.

Impact Toughness Testing

To study impact toughness of different region of the joint the Charpy V-notch (C_V) specimens were prepared as per ASTM E23 standard by placing the notch at desired locations. The schematic diagram of the C_V-specimens has been shown in Fig. 3. The impact toughness of the weld was studied by placing notch at perpendicular to and parallel to the direction of welding. The impact toughness of the heat-affected zone (HAZ) was studied by placing the notch at a distance of about 0.5 mm away from the fusion line. The tests were carried out at -30^0 C.

Table – II Chemical Composition of base metal and filler metal

Plate thickness (mm)	Material	Chemical Composition (Wt. %)									
		C	Si	Mn	Cr	Ni	Cu	Nb+Ti+V	Al	P	S
18	Base metal	0.178	0.37	1.57	0.003	-	0.037	0.25 max	0.08	0.012	0.002
	Weld metal	0.086	0.40	1.06	0.007	-	0.054	-	0.024	0.012	0.003
25	Base metal	0.152	0.32	1.6	0.011	0.035	0.042	0.25 max	0.038	0.012	0.002
	Weld metal	0.098	0.25	0.69	0.025	0.037	0.206	-	0.025	0.039	0.003
34	Base metal	0.113	0.30	1.50	0.006	0.031	0.033	0.25 max	0.087	0.016	0.003
	Weld metal	0.067	0.34	1.41	0.019	0.043	0.092	-	0.041	0.028	0.003

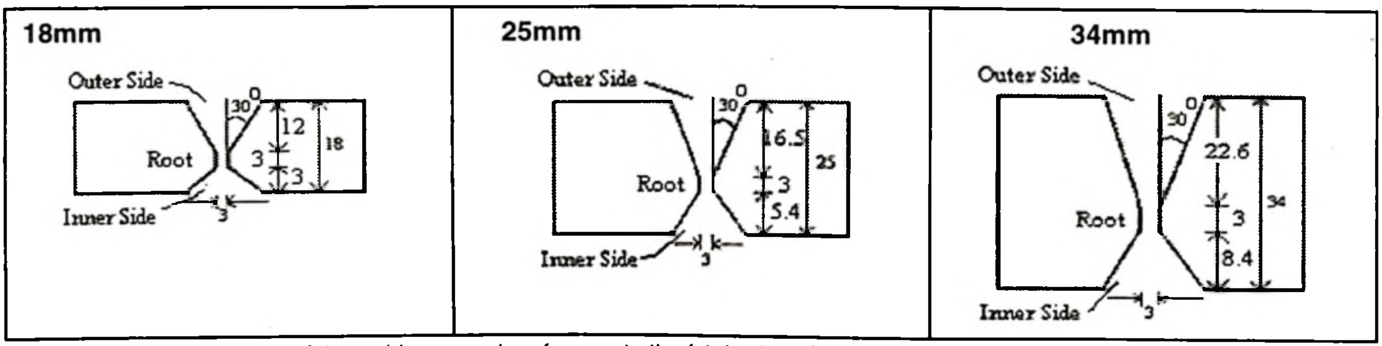

Fig. 1 : Schematic diagram of the weld grooves in reference to the fabrication of penstock liners of different plate thickness.

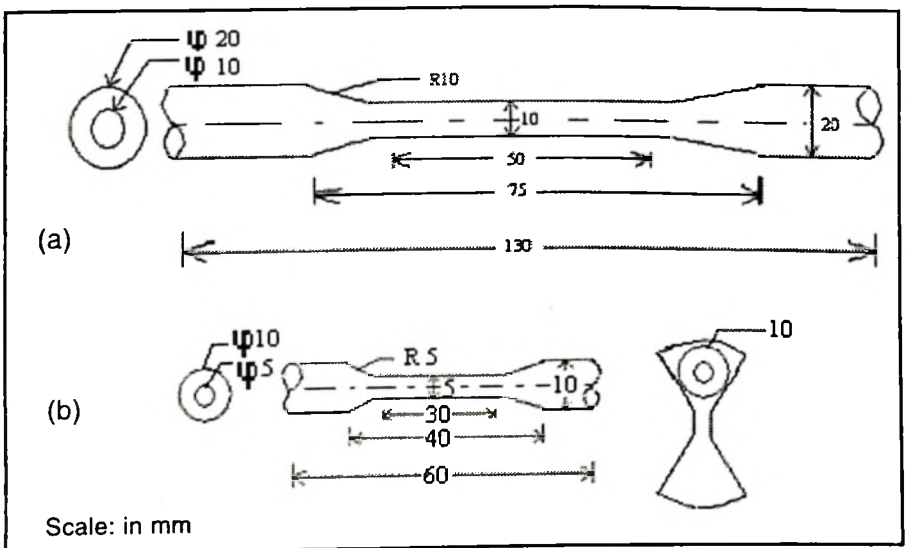

Fig. 2 : Schematic diagram of the tensile specimens (a) Axial weld and (b) All weld.

Metallography and Hardness Testing

The transverse section of the weld joints was prepared by standard metallographic procedure and etched with 2% alcoholic nitric acid solution to reveal the microstructure for studies under optical microscope. The studies were performed in the regions of weld and HAZ to reveal the distribution and details of the micro-structural constituents present in the matrix.

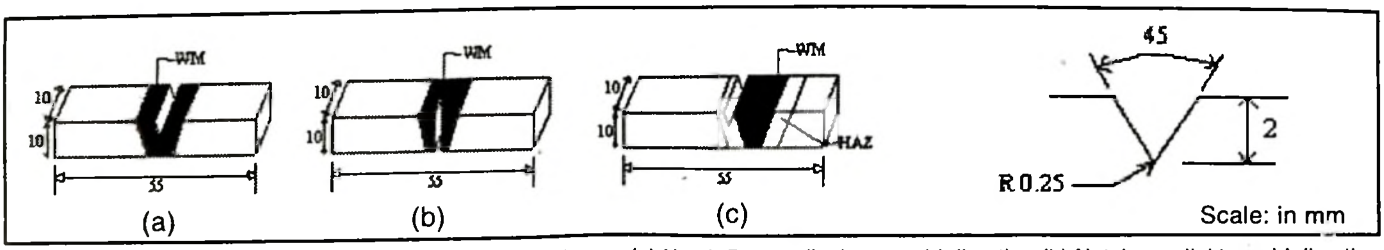

Fig. 3 : Schematic diagram of the Charpy impact specimens (a) Notch Perpendicular to weld direction (b) Notch parallel to weld direction and (c) Notch in HAZ

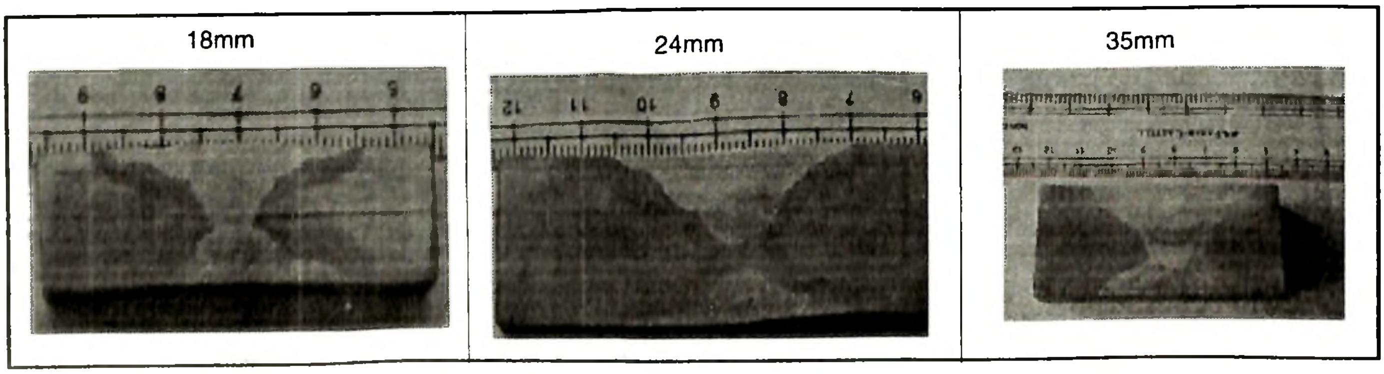

Fig. 5 : Macro photos of 18mm, 25mm and 34mm HSLA steel weldment.

Table – III Macrostructure analysis of multi pass SA weld deposit			
Plate Thickness mm	Weld location	Average area fraction of coaxial dendrite (%)	Average area fraction of reheat refinement (%)
18	SAW- Outer side	82.46	17.54
	SAW- Inner side	97.00	3.00
25	SAW- Outer side	94.18	5.81
	SAW- Inner side	52.52	47.48
34	SAW- Outer side	50.54	49.46
	SAW- Inner side	24.82	74.98

Table - IV Width of HAZ at different locations of weld joint in plates of different thickness			
Plate thickness	Width of HAZ at different locations of weld pass (mm)		
	SAW Outer side	SMAW Root	SAW Inner side
18	8.51 ± 0.23	2.86 ± 0.13	5.26 ± 0.29
25	5.51 ± 1.17	2.92 ± 0.24	8.41 ± 1.5
34	5.82 ± 1.71	2.44 ± 0.13	6.14 ± 1.70

Measurement of inclusion content

The inclusion content of the base metal and weld deposit was measured on the polished un-etched matrix with the help of image analyzer software. The software analysis was carried out on at least 21 randomly captured images of different locations of the matrix viewed under optical microscope at a magnification of x100. The analysis was made considering the black spots found on the polished surface.

Hardness measurements

Hardness test was carried out by Vickers's diamond indentation at a load of 15 kg on the metallographically prepared transverse section of the weld joints. A comparatively lower load has been selected to accommodate a minimum number of indentations in

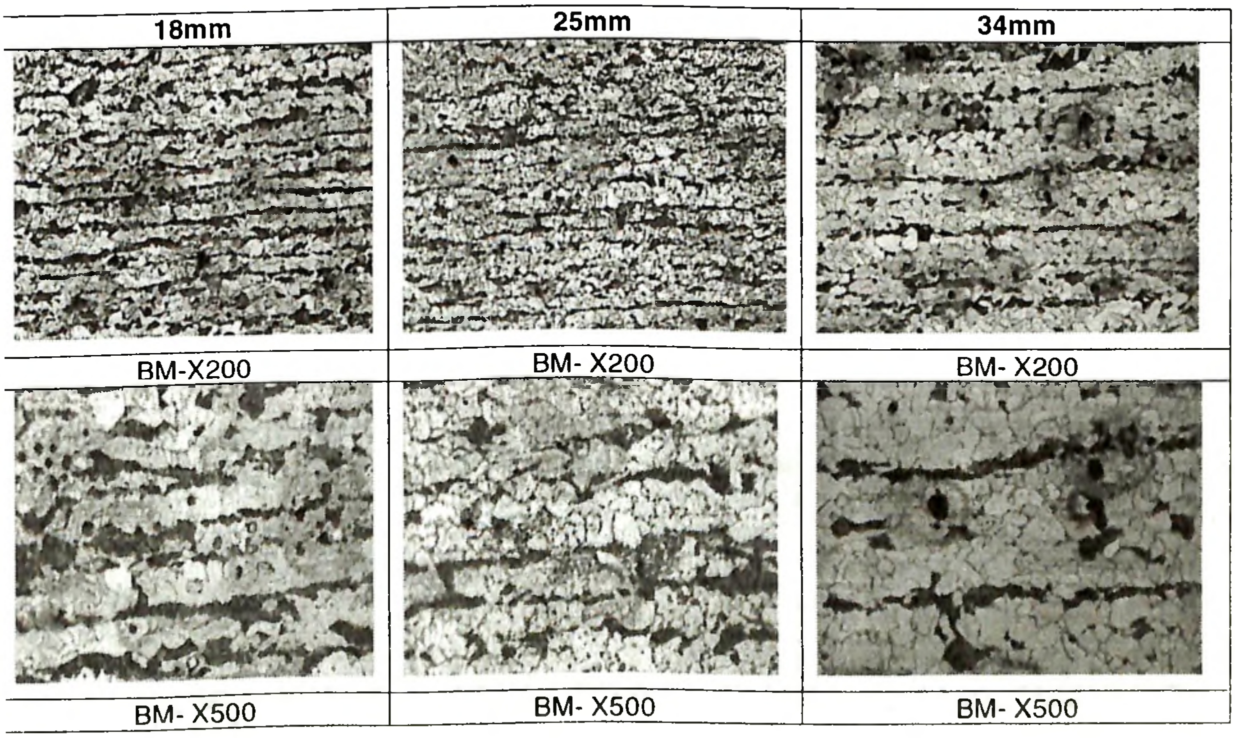

Fig. 4 : Microstructure of base metal with different thick plates

Table – V Hardness of the weld and HAZ at different locations of weld joint in plates of differentthickness						
Plate thickness (mm)	Hardness of different locations of the weld joint (VHN)					
	Weld metal			HAZ		
	SAW Outer side	SMAW Root pass	SAW Inner side	SAW Outer side	SMAW Root	SAW Inner side
18	215 ± 5	212 ± 5	184 ± 16	228 ± 10	233 ± 17	244 ± 14
25	174 ± 8	200 ± 8	171 ± 12	215 ± 8	216 ± 10	204 ± 6
34	172 ± 20	174 ± 9	172 ± 14	170 ± 24	197 ± 17	179 ± 23

Table – VI Tensile Properties of base metal and weld joints of different plate thickness						
Plate thickness (mm)	Sample	UTS (MPa)	YS (MPa)	Elongation (%)	RA (%)	Fracture Location
18	Base material	591 ± 10	438 ± 3	22 ± 2	68 ± 2	-
	All weld	546 ± 9	480 ± 10	20 ± 2	70 ± 2	-
	Axial weld	570 ± 10	468 ± 6	20 ± 3	60 ± 4	Weld
25	Base material	571 ± 9	435 ± 5	25 ± 2	74 ± 2	-
	All weld	540 ± 10	475 ± 6	24 ± 2	69 ± 3	-
	Axial weld	600 ± 10	448 ± 8	22 ± 2	70 ± 3	14.6 mm from FL
34	Base material	534 ± 5	421 ± 6	27 ± 3	76 ± 2	-
	All weld	583 ± 15	481 ± 20	26 ± 3	70 ± 2	-
	Axial weld	547 ± 12	438 ± 12	27 ± 2	73 ± 3	17.9 mm from FL

Table - VII Impact toughness of base metal and different locations of weld joints of different plate thickness				
Plate thickness (mm)	Impact toughness (J)			
	Base metal	Weld		HAZ
		Notch parallel to direction of welding	Notch perpendicular to direction of welding	
18	13	9	9	18
25	18	14	13	17
34	22	19	16	21

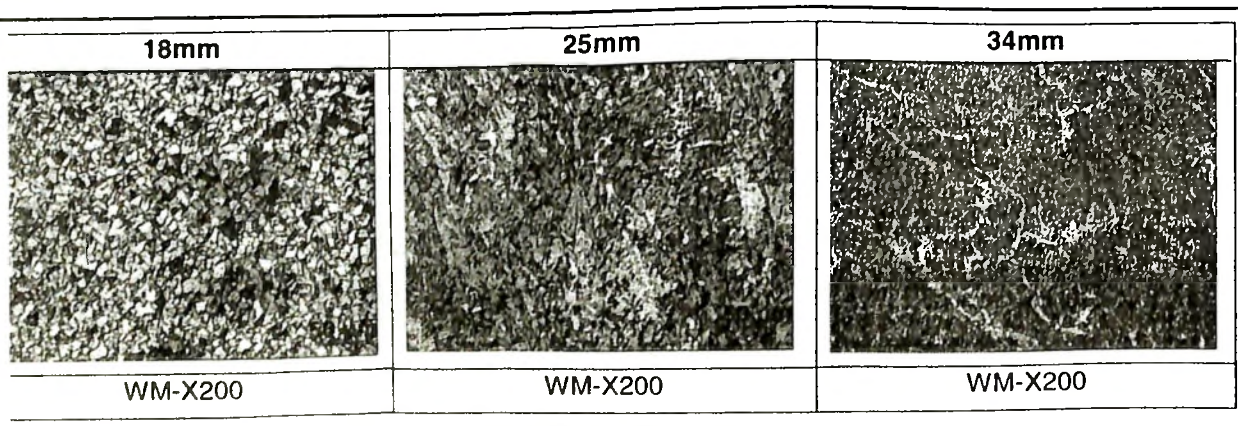

Fig. 6 : Microstructures of SMAW root weld in different plate thickness.

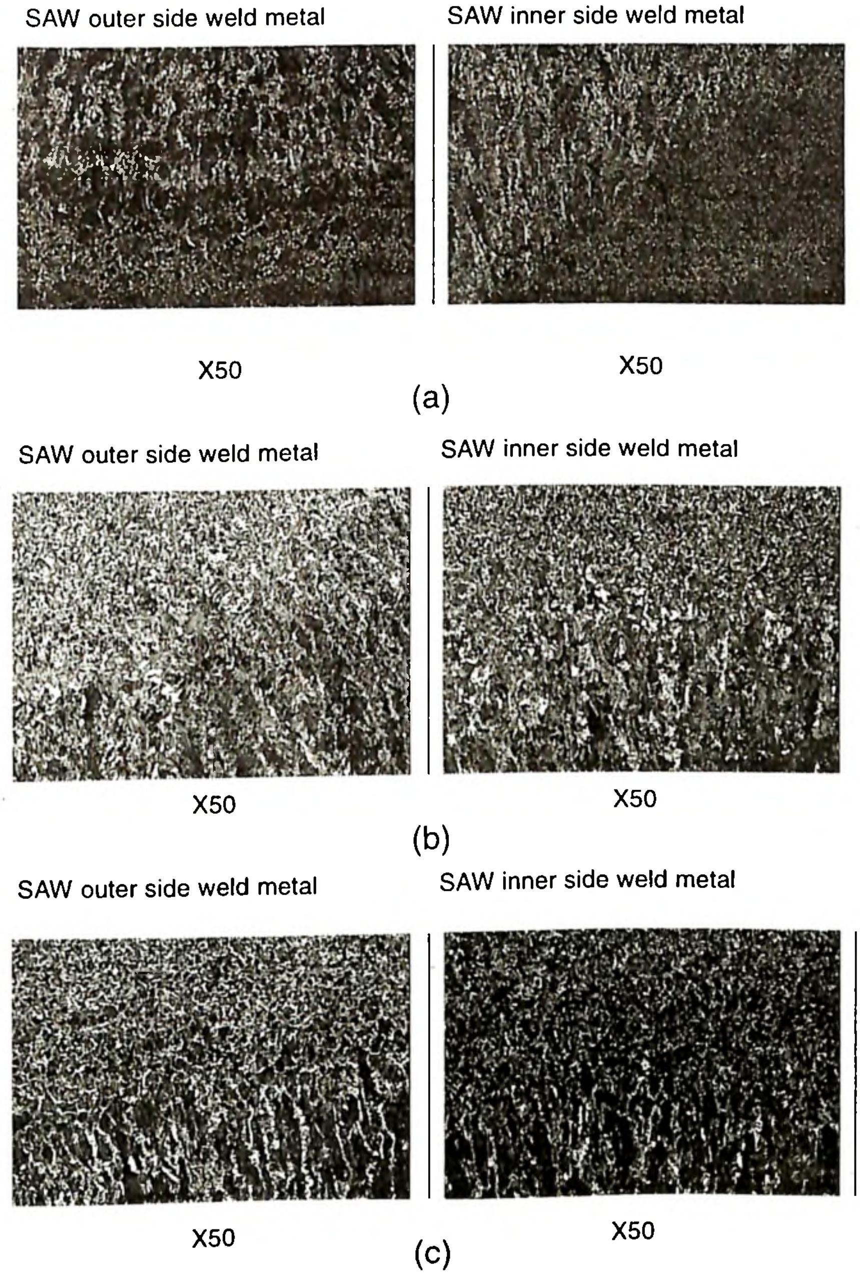

Fig. 7 : Typical microstructure of multi-pass SA weld deposits at the outer and inner sides of the weld joint containing coaxial dendrites and reheat refined regions in the matrix of different plate thickness, (a) 18 mm, (b) 25 mm and (c) 34 mm.

HAZ to characterize this region. The hardness measurement was performed in different locations of the weld joint with respect to the weld direction and the inner and outer surface of the penstock liner.

RESULTS AND DISCUSSIONS

Base Material

The chemical compositions of the base plates of different thickness of 18, 25 and 34 mm are shown in Table –II. The table shows that the plates are having micro alloying of Cr (0.003-0.011 wt.%) and Ni (0.031-0.035 wt.%) along with Cu of the order of 0.033-0.042 wt.%. It is also observed that the increase of plates of thickness from 18 to 34 mm comparatively lowers their carbon and silicon content from 0.178 to 0.113 and 0.358 to 0.295 wt.% respectively, where the Mn level remains almost constant lying in the range of 1.5-1.6 wt.%. The variation in chemical composition has been found to affect their microstructure and mechanical properties.

The controlled rolled microstructures of the base plates of different thickness of 18, 25 and 34 mm are shown in Fig. 4. The figure shows that the plates are having ferrite-pearlite (dark) microstructure of almost equiaxed grain with the presence of pearlite primarily along the lamination of matrix typical of rolled structure. The extent of lamination has been found comparatively lower in the thicker plate. In agreement to the carbon content the 34 mm thick plate shows comparatively lower amount of pearlite than that observed in the 18 mm thick plate.

Weld Joint

Configuration and soundness : The macro photographs of transverse section of the weldments are as shown in Fig. 5. The photographs typically show the uniformity of the weld joints and their soundness with respect to the presence of discontinuity defect in them. Prior to testing all the joints were tested by X-ray radiography, which in agreement to the macrographs further confirms the soundness of the joints, but shows the presence of certain amount of slag inclusions in weld deposit.

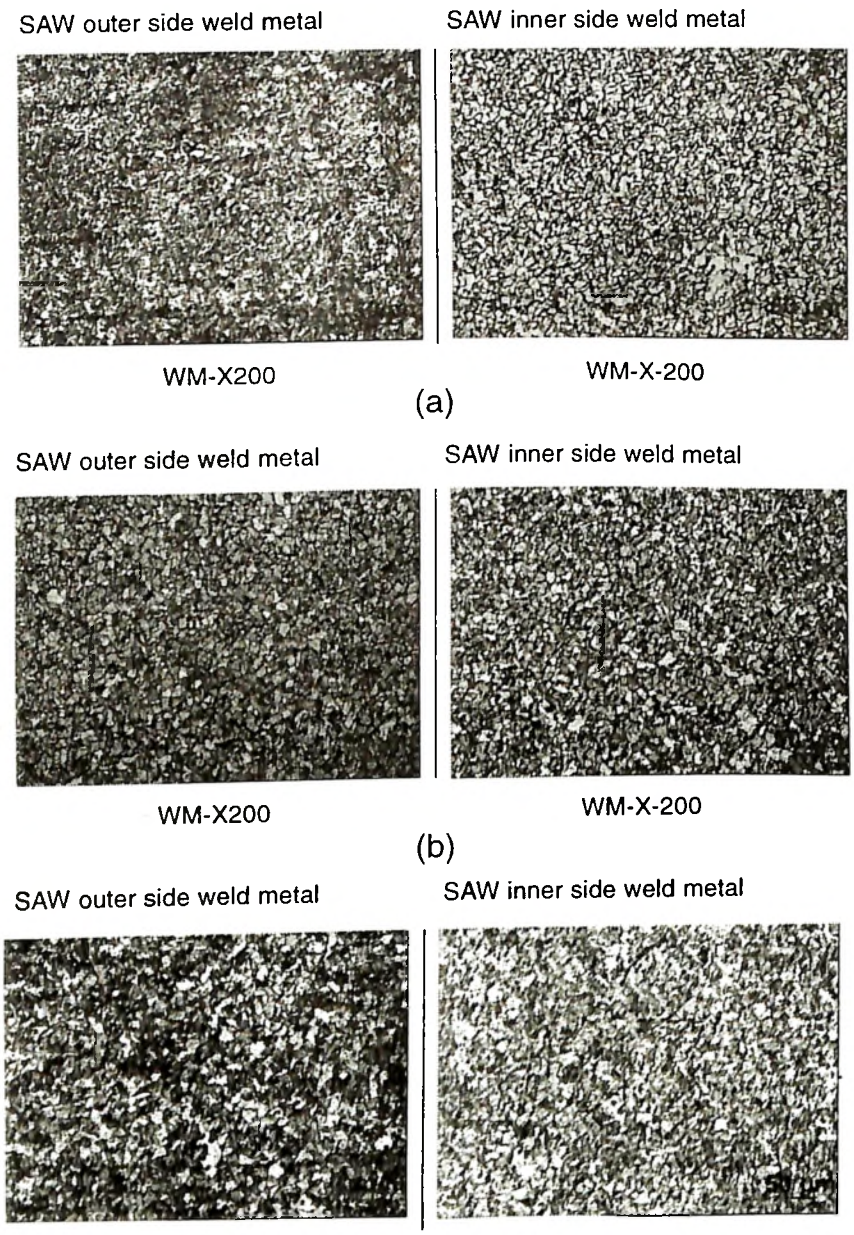

Fig. 8 : Typical microstructures of dendrite region of outer and inner side of the SA weld deposits in different plate thickness, (a) 18 mm, (b) 25 mm and (c) 34 mm.

Microstructure : The micro-structures of the SMAW root weld in different plate thickness are shown in Fig. 6. The microstructure has been found dendritic with a boundary layer of proeutectoid ferrite in the thick plate of 34 mm. But, the microstructure has been found to be increasingly reheat-refined by breaking of dendritic structure with the decrease in plate thickness leading to the formation of equiaxed ferrite-pearlite grain structure at the lowest plate thickness of 18 mm. However, the microstructure of multipass submerged arc weld deposit at the outer and inner sides of the weld joint has been found to consist of a mixture of coaxial dendrite and comparatively fine grain reheat-refined regions in the matrix of different plate thickness of 18, 25 and 34 mm as typically depicted in Figs. 7 (a), (b) and (c) respectively. The typical dendritic microstructure of the SA weld deposits in outer and inner sides of the weld groove in 18, 25 and 34 mm thick plates are shown in Figs.8 (a), (b) and (c) respectively. Similarly the typical reheat-refined microstructure of the SA weld deposits in outer and inner sides of the weld groove in 18, 25 and 34 mm thick plates are shown in Figs.9 (a), (b) and (c) respectively.

This may have primarily happened due to reheat refinement of matrix by multi pass deposition. In view of this the microstructure of weld joint predominantly referred by SA weld deposit has been characterized by measuring the extent of dendrite and reheat refined regions in it as given in Table - III. The table shows that except in case of the 18 mm thick plate the SA weld in outer side of the weld groove is having comparatively higher amount of coaxial dendrite than that observed in its inner counter part. This may be primarily attributed to the use of comparatively higher heat input of 27-35 kJ/cm at outer side of the groove resulting a deposition of relatively bigger size weld bead than that observed at the inner one having heat input of 24-30 kJ/cm. The appreciably less reheat refinement observed in the 18 mm thick plate might have primarily happened due to comparatively less effective multipass deposition in relatively smaller weld groove. In this case the cap pass with lower

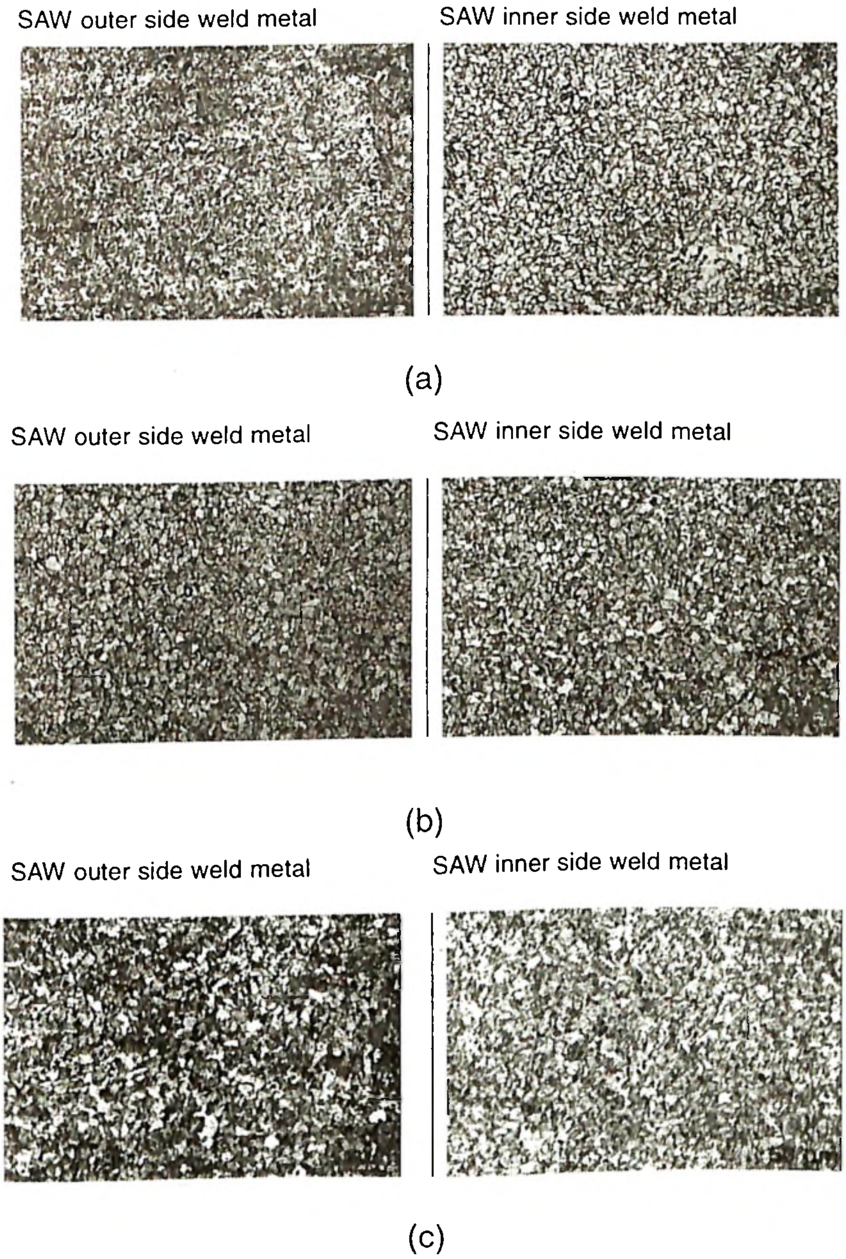

Fig.9 : Typical microstructures of reheat refined region of outer and inner side of the SA weld deposits in different plate thickness, (a) 18 mm, (b) 25 mm and (c) 34 mm.

penetration has to be laid down immediately after a filling pass of SA weld deposit.

In agreement to the above observations the microstructure of the multipass submerged arc weld deposits in the weld joints of the plates of all the three thickness of 18, 25 and 34 mm (Figs. 8 (a-c) and 9 (a-c)) shows that the cast structure of the outer weld deposit is comparatively coarser than the inner one. However, in case of weld joint of any plate thickness it is observed that the microstructures of SMAW root pass is comparatively finer than the submerged arc weld deposits. The microstructure of all the SA weld deposits has been found to have 1.34 ±1.18, 3.69 ±2.4 and 6.71 ±2.4 Vol.% inclusions in the weld joints of the 18, 25 and 34 mm thick plates respectively, which may impair their mechanical properties.

The microstructures of HAZ adjacent to the fusion line of the outer side SA weld deposit SMA root weld and inner side SA weld deposit in different plate thickness of 18, 25 and 34 mm are shown in Figs. 10 (a), (b) and (c) respectively. At any plate thickness the microstructure of HAZ in base metal adjacent to the SA weld deposit show that it mostly consists of bainite and acicular ferrite. It is also marked that the microstructures of HAZ of SA weld deposits are comparatively coarser than that of the SMAW root pass due to stronger isotherm resulted from higher heat input. This variation in weld thermal behavior has resulted a comparatively higher width of HAZ in base metal adjacent to the SA weld deposit than that observed in case of SMAW root pass as shown in Table – IV.

Hardness : The Hardness of weld deposit and HAZ at different locations of the weld joint has been given in Table-V. The table shows that for any weld deposit the hardness of HAZ is comparatively higher than that of weld. However, the hardness of weld deposit and HAZ of the SA weld in outer and inner side of the groove and the SMAW root pass has been found comparatively lower in the weld joints of 25 and 34 mm thick plates than that observed in the weld joints of 18 mm thick plate. This may have primarily happened due increase in annealing of both the weld deposit and HAZ by the more number of weld passes in multi

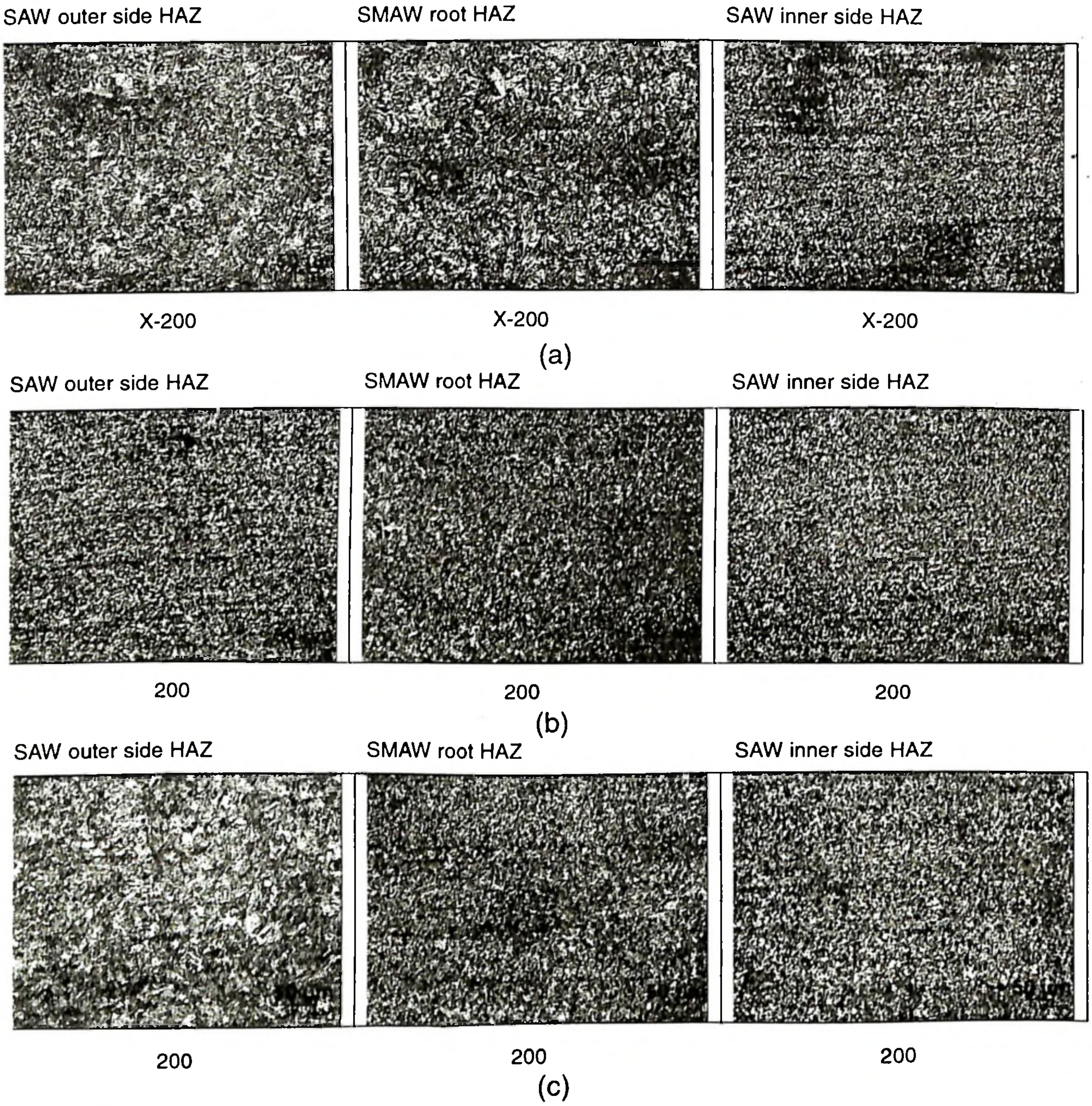

Fig. 10 : Microstructure of HAZ of adjacent to the outer SA deposit SMA root weld and inner SA deposit in different plate thickness (a) 18 mm, (b) 25 mm and (c) 34 mm.

pass deposit of thicker plate beyond 25 mm. This behavior of variation in hardness is also in agreement to the micro structures of weld deposit and HAZ, which is comparatively finer in case of the 18 mm thick plate than those of the 25 and 34 mm thick plates as discussed earlier.

Tensile properties : Tensile properties of axial weld and all weld samples of the weld joints of different plate thickness of 18, 25 and 34 mm has been studied in terms of their ultimate tensile strength (UTS), yield strength (YS), elongation (El) and reduction in cross sectional area (RA) as given in Table - VI. For a comparative study of the superiority of weld joint to the base metal the same tensile properties of the base plates are also presented in Table - VI. The table shows that the strength (UTS and YS) of the base plate reduces significantly with the increase of plate thickness from 18 to 34 mm.

But the increase of plate thickness has been marked to enhance appreciably their elongation and reduction in cross sectional area. This is in agreement to their chemical compositions primarily with respect to the carbon and silicon content (Table-II) and microstructure especially in reference to the pearlite content, which are found to be comparatively low in higher plate thickness as discussed earlier. The more coarsening of matrix morphology in comparatively thicker plate also supports the observed variation in tensile properties as stated above.

Tensile properties of all weld metal from the weld joints of different plate thickness show that the UTS varies widely in the range of about 540-583 MPa where the YS remains practically constant of the order of 475-481 MPa. .The significant variation in UTS may have primarily attributed to the presence of inclusions in the matrix as discussed above and that has drastically reduced the UTS in certain specimens by causing premature failure through early initiation of fracture from this region. However, the ductility of weld metal estimated by its elongation and reduction in cross sectional area has been found to lie within a rather close range of variation of 20-26 % and 69-70 % respectively. Except incase of the weld joint of 18 mm thick plate the axial weld specimens are always found to fracture from the base metal about 15-18 mm away from the fusion line, which can be considered as appreciably out of the HAZ. It infers that the properties of weld and HAZ are in general comparable to those of the base metal and the variation in properties follows similar behaviour to that of base metal as discussed earlier.

Impact Toughness : The impact toughness of the base metal of different plate thickness as well as the weld metal and HAZ of their weld joints measured by the Charpy impact energy absorbed by the notched specimens at -30^0 C are given in Table-VII. The toughness of the weld metal has been measured by placing the notch with different orientation to fracture parallel to weld direction and perpendicular to weld direction. In case of the weld joint of any plate thickness the toughness of weld has been found comparatively lower than the base material primarily due to its cast structure. However, the toughness of weld deposit has been found comparatively higher in larger plate thickness possibly due to significant amount of reheat refinement (Table-III) resulting from more number of weld passes. It is also found that the direction of cracking with respect to the direction of welding, marginally influences the weld toughness by a relative reduction in case of a notch perpendicular to the direction of welding. These variations in toughness of the weld with the orientation of cracking plane primarily result from its angle of interaction with the coaxial dendrite and inter dendrite segregation. But, it is observed that the C_v-impact toughness of HAZ in the weld joint of any plate thickness is in close approximation to that of the base material. This may have primarily happened due to coarsening of ferrite with acicular morphology.

In view of the comparable impact toughness of HAZ with that of the base metal and the general behaviour of failure under tensile loading of the axial weld joint showing fracture from base metal leaving behind the HAZ, infers that the weldability of the controlled rolled HSLA steel under the WPS used in this investigation is satisfactory to employ this material for fabrication of penstock liner.

CONCLUSIONS

In the present study on weldability of controlled rolled HSLA steel plates of different thickness of 18, 25 and 34 mm, where the welding has been carried out by SAW process with SMAW root pass the following conclusions can be made.

1) In 34 mm thick plate, weld etal microstructure is comparatively finer with more reheat refinement than 18 mm and 25mm thick plates, with improved properties.

2) The weld joints are generally found to fracture from the region far away from fusion line showing the strength of the weld higher than the base material. However, significant percent of inclusions lower the mechanical properties of weld deposits.

3) Reheat refining has significantly improved the toughness of weld metal.

4) The weldability of controlled rolled HSLA steel may suit the welding fabrication of penstock liner without any appreciable deterioration of properties of base material at HAZ.

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