CONTROL OF RESIDUAL STRESSES USING NARROW GAP TECHNIQUE IN SMA WELDING OF STRUCTURAL STEEL

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ABSTRACT

Welding of structural steel plate having conventional V-groove and narrow grooves of different designs has been carried out by GTAW root pass followed by SMAW filler passes. The residual stresses of the weld and HAZ have been measured by centre drill hole technique using three-element strain gauge rosette. Effect of narrow gap welding of different groove design on residual stresses of weld joint has been studied. The effect of variation in heat input per pass in the SMAW filler passes of the narrow gap welds on residual stresses of the weld joint also has been studied. The residual stresses along with the microstructure and hardness of the conventional and narrow gap weld joints have been compared. It has been observed that the use of narrow gap welding with comparatively low heat input reduces the residual stresses of weld joint significantly compared to that observed in conventional V-groove weld. This is primarily attributed to reduction in amount of weld deposit lowering the contraction stresses in narrow gap weld.

INTRODUCTION

High quality of weld joints is of utmost importance to assure their safe performance, especially in long run applications. The absence of discontinuity defects and presence of microstructure having desired ductility in the weld and HAZ primarily define a superior quality weld joint. But in this regard considering the presence of residual stresses in weld joint also very much important due to its significant adverse influence on distortion, fatigue, corrosion and stress corrosion cracking properties [1-3] of the joint of different materials. The presence of high residual stresses is not desirable especially in the welds of thick section of structural steels. It becomes much more critical in case of welding of advanced materials like high strength steels, stainless steels etc. During welding of thick wall pipes the presence of residual stresses in weld joint possesses big threat to its corrosion resistance. In conventional practices depending upon technicality of the weld fabrication process the thick wall pipes are generally welded by submerged arc welding and also by using GTAW root pass followed by SMAW filler passes, as per ASME section IX. But, the weld joint may not provide desired safety to the high-risk installations, especially in their long run service, due to development of residual stresses in it of significant magnitude resulting primarily from the shrinkage of weld metal [4,5] along with the development of internal stresses due to phase transformation from austenite to martensite depending upon cooling rate of the matrix [6-8].

It is well known that the use of narrow gap welding technique improves weld quality especially with respect to its distortion and residual stresses [9-11] and also reduces the cost of weld fabrication primarily through the reduction in amount of weld metal deposition. The comparatively milder weld thermal cycle due to relatively less weld deposit in narrow gap weld, it results in a comparatively friendlier microstructure in weld joint than that observed in case of the conventional weld joint, giving rise to a further improvement in weld quality. So far the narrow gap welding is largely used for welding of thick steel plates (>40mm) by submerged arc welding process. However, the GTAW root pass followed by SMAW filler passes is also largely used in welding of thick (≥ 25mm) plates or pipes, especially in fabrications at sites. In view of the above an investigation has been carried out to study the effect of using narrow gap welding technique with different weld grooves on residual stresses of weld joint of structural steel plate prepared by GTAW root pass followed by SMAW filler passes.

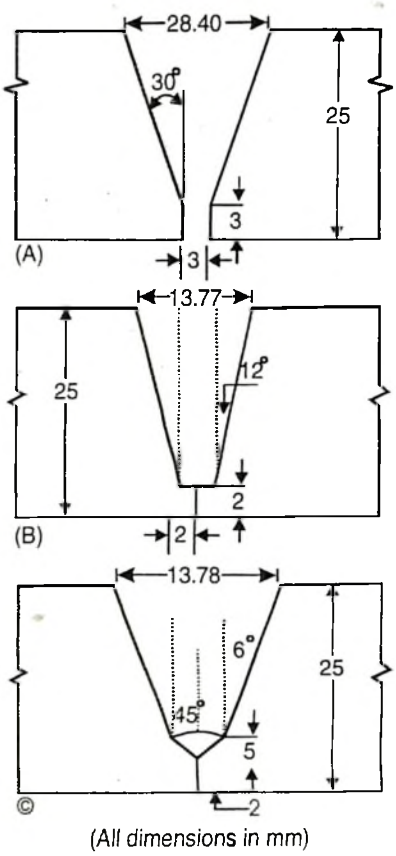

Fig. 1 : Schematic diagrams of different weld groove design

(a) Conventional V-groove,

(b) Narrow groove [NG1] and

(c) Narrow groove [NG2].

Table 1 : Chemical composition of the base material

Composition	C	Mn	Si	P	S
Wt. %	0.15	0.9	0.3	0.03	0.03

EXPERIMENTAL PROCEDURE

Welding

Welding of 25mm thick C-Mn structural steel plates, having chemical composition as shown in Table - I, has been carried out using the conventional and narrow gap groove designs. A conventional V-groove design (as per AWS specification) and two narrow groove designs were used as schematically shown in Fig. 1(a), (b) and (c) respectively. The welding was carried out on a copper backing plate of dimension 200x50x10 mm fitted in a thick mild steel supporting plate of size 350x300x40 mm. Prior to welding the base plate assembly was rigidly fixed on the supporting plate by proper weld tacking to avoid distortion during welding. The welding was performed by GTAW root pass and SMAW filling passes following the procedure and parameters as given in Table - II. The filler rods used in GTAW and the electrodes used in SMAW were having specifications as AWS ER 70 S-2 and AWS E 7018-1 respectively. During welding the preheating and interpass temperatures were maintained as 120^{0} C and 130 ± 10^{0} C respectively. The GTAW was carried out using water cooled torch with 7 mm diameter gas nozzle and 2.4 mm diameter 2% thoriated tungsten electrode under the shielding of commercial argon of 98.95% purity at a flow rate of 12 L/min. The GTAW and SMAW were car-

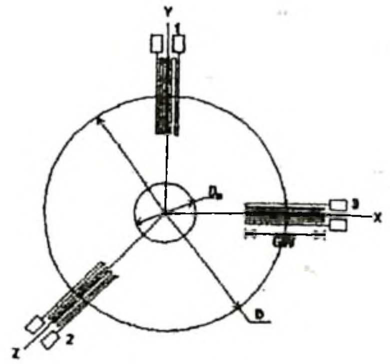

Fig. 2 : Schematic diagram of the three elements strain gauge rosette used in residual stress measurement by drill hole method; D is drill hole diameter, D_D is gauge circle diameter and GW is strain gauge length.

Table 2 : Welding procedure and parameters

Weld pass	R.F.			GTAW root run/SMAW filling passes													
WP	GTAW	GTAW		SMAW													
E/F (mm)	-	1.6	2.4	3.15	3.15	3.15	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.15	3.15
WC (A)	130	110	130	110	110	110	150	150	150	150	150	150	150	150	150	110	110
AV (V)	11	12	12	22	22	22	22	22	22	22	22	22	22	22	22	22	22
WG NG1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	X	X	X	✓	✓
WG NG2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	X	X	X	✓	✓
WG CG1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

R.F. : Root fusion
W.C. : Welding current
NG : Narrow groove
W.P. : Welding process
A.V. : Arc voltage
CG : Conventional V-groove
E/F : Electrode/filler rod diameter
W. G. : Weld groove
✓ : Yes X : No

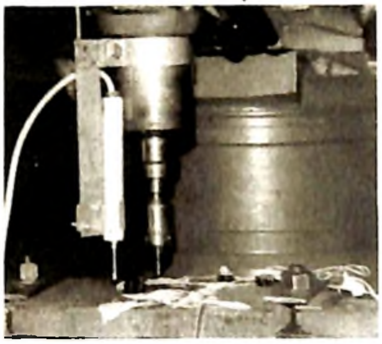

Fig. 3 : Experimental set-up of the drilling operation.

ried out at the electrode polarity of DCEN and DCEP respectively. The root fusion and root run (with both the 1.6 and 2.4m filler rod) by GTAW process was carried out at welding speed of about 0.8 and 1.25mm/s respectively. During conventional V-groove welding the deposition by SMAW process using both the 3.15 and 4.0 mm diameter electrodes was carried out at the welding speed of the order of 1.66mm/s. But the narrow gap welding of both the groove designs was carried out at different welding speeds to vary the heat input per pass. The heat input was varied at two levels classified as low and high. The low heat input was characterised by the use of 3.15 and 4.15 mm diameter electrodes at 1.071 and 1.461 kj/mm respectively whereas, the high heat input was characterised by the use of 3.15 and 4.15 mm diameter electrodes at 1.265 and 1.559 kj/mm respectively. During welding the current was measured through a shunt placed in the electric circuit and the arc voltage was measured by putting a voltmeter in the circuit. The narrow gap weld joints produced by using the groove designs depicted in Fig.1(b) and (c) are denoted as NG1 and NG 2 respectively.

Measurement of Residual Stresses

The residual stresses were measured by locating a three-element strain gauge rosette at the centerline of the weld and in HAZ 1 mm away from the fusion line. The strain gauges TML (FLA-2-1 l) of Tokyo Sokki Kenl Yojo Co. Ltd. used in this work were having gauge length of 2 mm, gauge resistance of 120 ± 0.3 Ω, gauge factor 2.13 and transverse sensitivity 0.4%. The surface area of the weld selected for the measurement of residual stresses was smoothened under a precisely controlled surface-grinding machine. The smooth surface was chemically etched with 5% alcoholic nitric acid to reveal the fusion line and also to remove any extra stresses introduced at the skin of the surface during the process of surface grinding. Prior to fixing the strain gauges the surface was further cleaned by acetone for removal of dirt or grease present on it. The gauges were oriented in radial direction and located at places equidistant from centre of the rosette. Two of the gauges were placed perpendicular to each other and the third one was placed along its bisector. The length and width of the strain gauge did not exceed the diameter of the drilled hole. The three-element strain gauge rosette arranged for the measurement of residual stress by centre drill hole method has been shown in Fig. 2.

Fig. 4 : Typical macrograph of transverse section of the conventional V-groove weld joint.

The experimental set up for the drilling operation has been shown in Fig. 3. Prior to introducing drilling in weld joint for measurement of residual stress the drilling speed was optimised by carrying

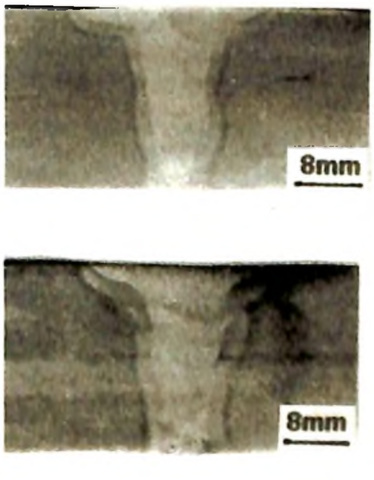

Fig. 5 : Typical macrographs of transverse section of the narrow gap weld joint NG1 prepared at (a) low and (b) comparatively high heat input.

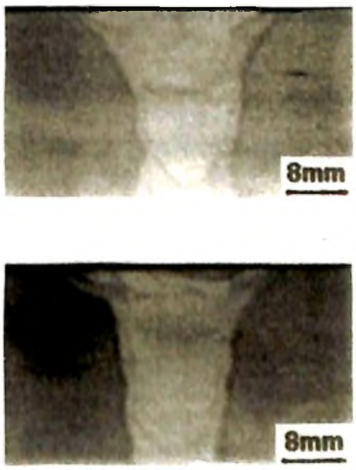

Fig. 6 : Typical macrographs of transverse section of the narrow gap weld joint NG2 prepared at (a) low and (b) comparatively high heat input.

out an identical process of the residual stress measurement at different drilling speed. The test was carried out on a stress free annealed plate of same material, where the reduction in residual stresses developed due to drilling was marked with the lowering of drilling speed from 580 rpm. Finally it was confirmed that the drilling operation in measurement of residual stresses of weld joint should be performed at the lowest speed of the drilling machine of about 240 rpm with practically negligible development of further residual stresses. The diameter of drilled hole (D) was kept as 3 mm in reference to the diameter of the rosette circle of 9 mm and the maximum depth of the hole was maintained as 1.2D = 3.6 mm according to the specification ASTM E-837 [12]. The depth of drilling was measured with the help of a linear variable differential transformer (LVDT) having least count of .001 mm connected to a digital displacement indicator. The depth of drilling was increased incrementally at the rate of 10% (0.36 mm) of the estimated final depth of drilling.

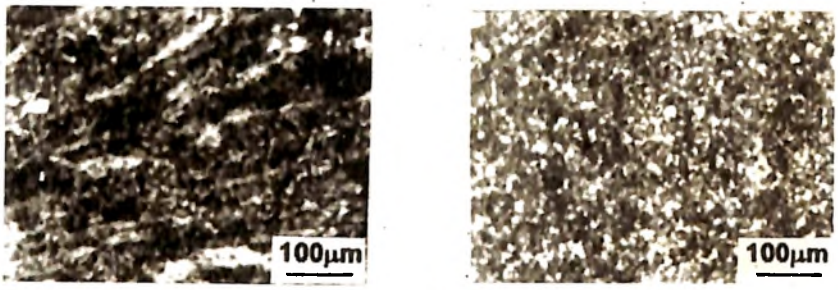

Fig. 7 : Typical microstructures of (a) weld and (b) HAZ of conventional V-groove weld Joint.

The amount of strain release by the incremental drilling was measured as ε_1, ε_2 and ε_3 by using a digital multi-channel recorder UPM-60 connected to the strain gauges placed at different directions (Fig. 2). Prior to starting of the incremental drilling operation zero setting of each strain gauges was always confirmed. Finally the release of strain at maximum depth of the hole drilling was recorded to estimate the corresponding residual stresses present at any location.

Microstructure and Hardness

The transverse sections of the weld joints were prepared by standard metallographic procedure and etched in 2% alcoholic nitric acid solution. The macroscopic appearances of the weld joints and the microstructures of their weld and HAZ at about 1 mm from the fusion line were studied under optical microscopes. Hardness of the weld and same location of HAZ chosen for the microstructural studies in each weld joint was measured by Vicker's diamond indentation method at a load of 5 kg.

RESULTS AND DISCUSSIONS

Weld Geometry

The cross sectional area of the conventional V-groove weld was estimated as 354.39 mm² whereas, the cross sectional areas of the narrow groove welds of groove designs NGI (Fig.1b) and NG2 (Fig. 1c) were estimated as 204.44 and 239.44 mm² respectively. As compared to the conventional V-groove the reduction of cross sectional area in the narrow grooves of NG1 and NG2 was of the order of 42.31 and 32.39% respectively. This has resulted in comparatively less weld metal deposition in NG2 and further lower volume of weld metal deposition in NG1 with respect to that resulted in conventional V-groove weld.

Table 3 : Measured straining at different locations of narrow groove and conventional V-groove weld joints

Classification of weld joint	Location	Strain measured at different direction (μm/m)		
		ε_1	ε_2	ε_3
NG 1	Weld centre	-436	-329	157
	HAZ	-68	-53	10
NG 2	Weld centre	-498	-336	121
	HAZ	-78	-62	13
NG 3	Weld centre	-586	--346	80
	HAZ	-90	-68	17
NG 4	Weld centre	-670	490	60
	HAZ	-104	-72	12
CG 5	Weld centre	-795	-507	30
	HAZ	-120	-74	7

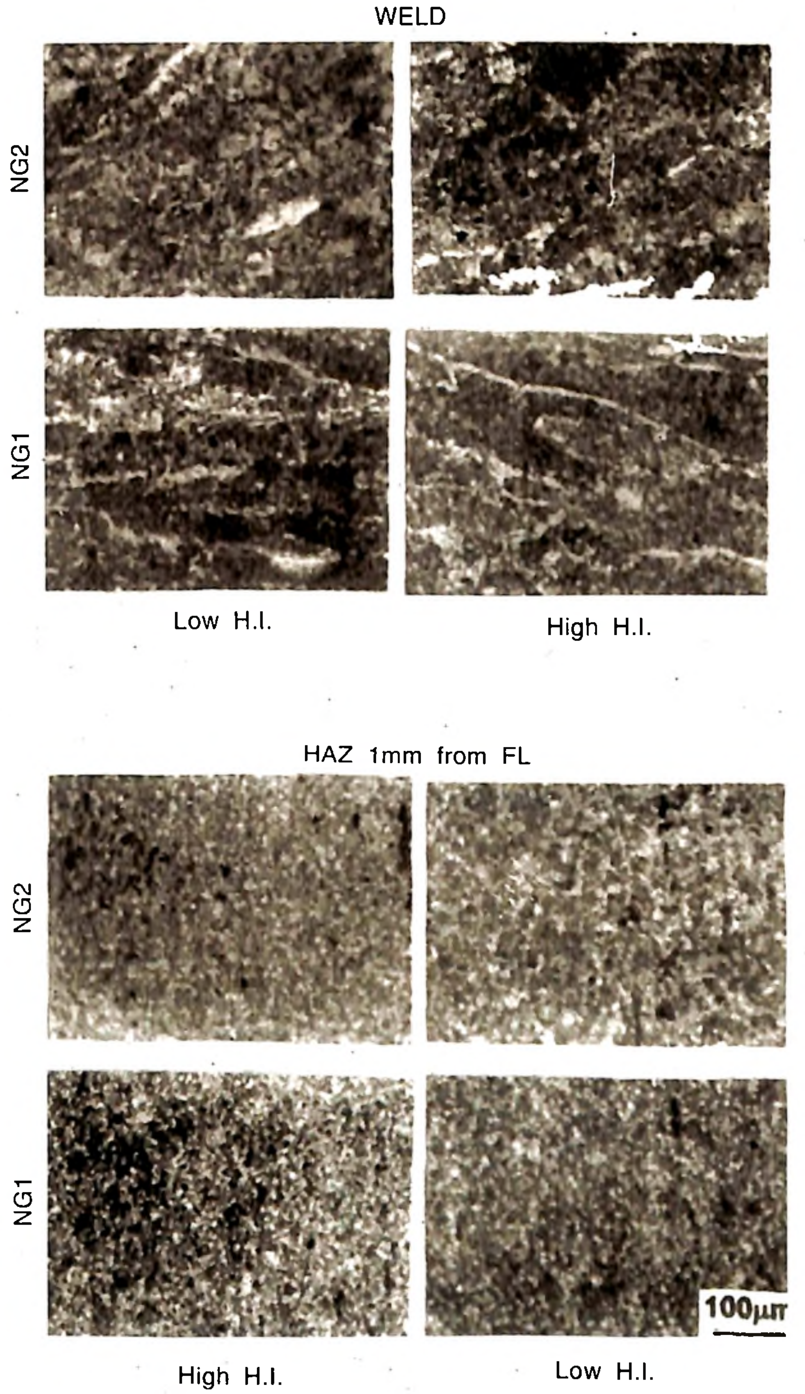

Fig. 8 : Typical microstructures of weld and HAZ observed in the narrow gap weld joints of NG1 and NG2 prepared at different heat inputs.

Microstructure and Hardness Studies

The macrograph of transverse section of the conventional V-groove weld joint has been shown in Fig 4. The typical macrographs of the narrow gap weld joints NG1 and NG2 prepared at the low and comparatively high heat inputs are depicted in Figs. 5 (a) and (b) and 6 (a) and (b) respectively. The macrographs reveal soundness of the weld with respect to the presence of any discontinuity defects like lack of fusion at groove wall. Thus, it qualifies the weld joints to undergo a valid measurement of residual stresses. The macrogrphs also show that the narrow gap weld joints are having comparatively narrower HAZ than that resulted in the conventional weld joint.

The typical microstructures of the weld and HAZ revealed in the conventionl V-groove weld are shown in Fig. 7 (a) and (b) respectively. In case of the narrow gap welds of NG1 and NG2 the typical microstructures of weld and HAZ observed in the weld joints prepared at the low and relatively high heat inputs are tabulated in Fig. 8. The micrographs presented in Figs. 7 and 8 reveal the comparative coarsening of dendrite in weld and grain size in HAZ with the increase of heat input.

The effect of groove design as well as the variation in heat input during narrow gap welding on hardness of the weld and HAZ has been shown in Figs. 9 and 10 respectively. The figures depict that the narrowing of weld groove results in remarkable enhancement in hardness of both the weld and HAZ, but the increase in heat input relatively lowers the hardness of those regions. The hardness of both the weld and HAZ of the weld joints

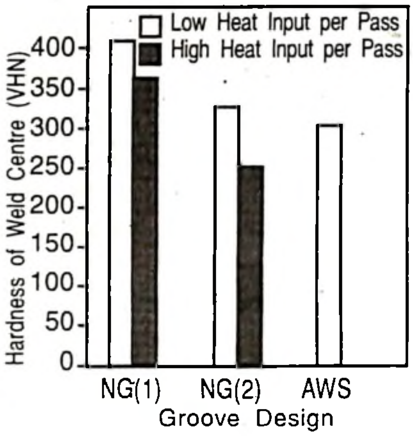

Fig. 9 : Effect of variation in heat input during welding at narrow gap of different designs on hardness of weld centre.

reveals the presence of bainitic microstructure in the matrix accompanied by certain amount of pearlite. Thus, it may be assumed that the microstructural phase transformation may have insignificant contribution to the residual stresses of the weld joint. However, generally the weld and HAZ of the narrow gap weld joints are found to have comparatively higher hardness than the hardness of the weld and HAZ of the conventional V-groove weld joints. This may be primarily attributed to comparatively higher cooling rate in the narrow gap welding than that prevailed in the conventional V-groove welding due to comparatively narrower HAZ and milder thermal effect from less weld deposit in the earlier one.

Residual Stresses of the Weld Joints

The values of straining measured at weld centre and HAZ of different weld joints are typically shown in Table - III. The effect of variation in volume of weld metal deposition, due to change in weld groove design from the conventional V-groove to the narrow weld groove of different design, on the longitudinal residual stresses at the weld centre and HAZ has been shown in Figs. 11 and 12 respectively. The figures show that the residual stresses reduce significantly with the lowering of the volume of weld metal deposition by application of narrower weld groove.

The effects of low and comparatively high heat input, in the narrow gap welds of NG1 and NG2, on longitudinal residual stresses at their weld center and HAZ have been shown in Figs. 13 and 14 respectively. In these figures the residual stresses of the weld and HAZ of the conventional V-groove weld are also respectively referred for a comparative analysis. The figures show that the increase in heat input relatively enhances the residual stresses of the weld and HAZ of the narrow groove welds, but, in all the cases they remain lower than those of the weld and HAZ of the conventional V-groove weld.

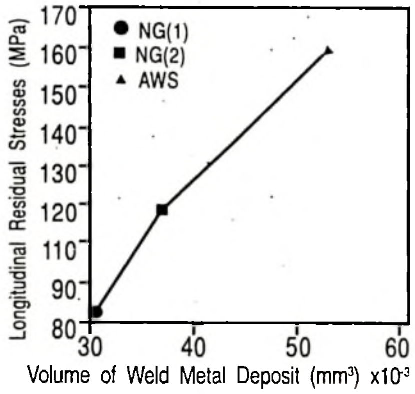

Fig. 11 : Effect of volume of weld metal deposition on the longitudinal residual stresses at the weld centre of the conventional and narrow gap welds.

The residual stresses at weld centre or HAZ adjacent to fusion line arises from either of the mechanical stresses developed by contraction, thermal stresses due to quenching and stresses resulting from phase transformation or all together. The residual stresses in weld joint are primarily contributed by the mechanical

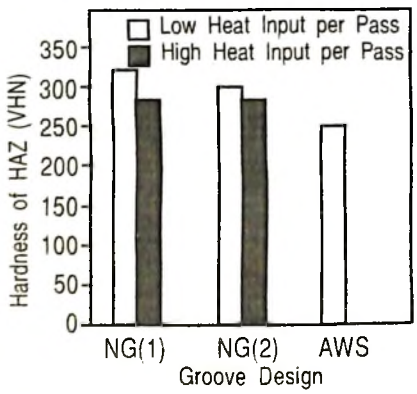

Fig. 10 : Effect of variation in heat input during welding at narrow gap of different design on hardness of HAZ.

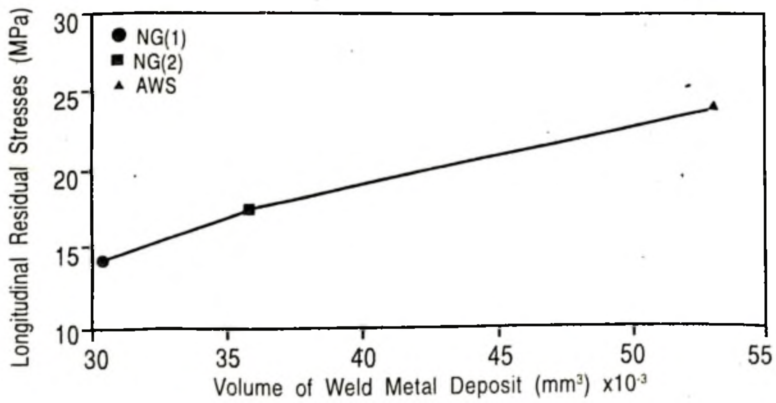

Fig. 12 : Effect of volume of weld metal deposition on the longitudinal residual stresses at the HAZ of the conventional and narrow welds.

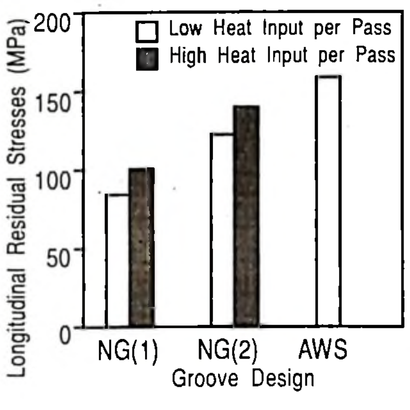

Fig. 13 : Longitudinal residual stresses at weld centre of the narrow gap welds of NGI and NG2.

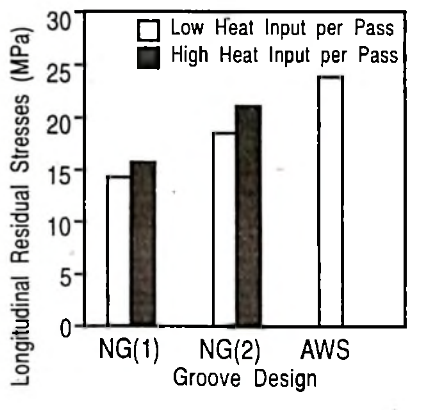

Fig. 14 : Longitudinal residual stresses at HAZ of the narrow gap welds of NGI and NG2.

stresses largely governed by the contraction of weld deposit, especially in case of simple C-Mn structural steel having insignificant chance of martensitic transformation uring SMAW. Thus, the severity of contraction stresses in a weld joint to a great extent depends upon amount of weld deposit, which is dictated by the design of weld groove. As a result the weld joint of narrower groove can have lower residual stresses in it. However, in this context it should also be remembered that the reduction in amount of weld metal by using narrow groove (gap) welding with respect to lowering of residual stresses is effective in case welding of thick plates carried out by multipass deposition processes. During multipass welding the subsequent weld passes modify the contraction stresses developed by the weld deposit of each pass and it lowers the residual stresses in weld joint. Thus, the use of higher heat input depositing larger amount of weld metal in each pass and reducing number of passes in weld groove develops more residual stresses in weld joint. These phenomena support and justify the observations of present investigation regarding significant lowering of residual stresses of weld joint by using comparatively narrower weld groove and lower heat input per pass during welding of 25mm thick C-Mn structural steel plates by multipass SMA weld deposition process.

CONCLUSIONS

The observations of this investigation can be primarily concluded as :

1. The use of narrow gap SMA welding significantly reduces the residual stresses of weld joint and it is largely dependent on the groove design accommodating the amount of weld metal.
2. Longitudinal residual stresses at the weld increases with the increase in amount of weld metal deposition.
3. Longitudinal residual stresses increase with the enhancement in heat input per pass.
4. During multipass SMA welding of structural steel the residual stresses primarily result from shrinkage of weld deposit.
5. The increase in heat input per pass reduces the hardness of HAZ at 1mm from the fusion line.
6. During multipass SMA welding of structural steel the increase in heat input per pass relatively coarsens the microstructures of weld and HAZ.

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