Distortion And Transverse Shrinkage Stress In Butt Welds Of Steel Plates Under Different Welding Procedure And Parameters Of GMAW And SMAW Processes

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ABSTRACT

The transverse shrinkage stress generated in welding of 10, 12 and 25 mm thick steel plates using different welding processes and procedures has been estimated and its varying effect has been verified with the help of experimental measurement of distortion produced during welding. The weld joints of 10 and, 12 mm thick plates have been prepared by using the GMAW and pulsed current GMAW (P-GMAW) processes with standard V-groove design whereas the 25 mm thick plate was welded by SMAW process employing V- groove and narrow groove design. At a given heat input and weld groove size the effect of welding processes and procedures on variation of shrinkage stresses in weld deposit causing distortion of weld joint has been substantiated by estimation of bending stress developed in the weld joint through measurement of bending of the plate. It is observed that the use of P-GMAW is advantageous over the GMAW with respect to reduction in stress development in weld joint. The use of narrow groove design has also been found beneficial for reduction of stresses generated in the weld joint in comparison to those observed in case of using V-groove design.

INTRODUCTION

Arc welding is an extensively used joining process where the coalescence of participating metals is achieved by fusion. During localized super heating of molten metal followed by rapid cooling under weld thermal cycle, certain thermal straining develops in the weld metal and its adjacent region to the base metal. The thermal straining of weld metal largely results from the shrinkage stresses developed during its solidification, which are primarily governed by the heat content and cooling rate of the weld pool comprising the amount of weld deposit and the fused base metal [1]. The shrinkage stresses developing in a weld joint can be estimated by thermal analysis of the system but can not be directly measured. However, the combined stresses resulting from the thermal strains reacting to develop internal forces causing weld-distortion, commonly observed as bending [2], often considered as a measure of the development of the shrinkage stresses in the weld joint.

During weld thermal cycle the strains are produced in different directions of the weld with respect to the direction of weld pass resulting into plastic upsetting. The strain produced along the direction of welding results from the longitudinal shrinkage whereas the strain produced in the component normal to the direction of welding is caused by the transverse shrinkage. Depending upon length of the weld the linear bending stress may be appreciable due to longitudinal shrinkage. However, the transverse bending always remain significant in reference to plastic upsetting in the zone adjacent to the weld. The shrinkage force and the size of the plastic zone determining the stress distribution in weld joint primarily depends upon welding process, procedure and parameters along with the thermo-mechanical characteristics of the material and secondarily on the nature of heat flow in the weld joint [3]. As a consequence of the in-homogeneous permanent deformation limited to the weld and its adjacent area, some residual stresses develop in the weld joint [4]. The presence of residual stress resulting in weld joint out of these phenomena may adversely affect the fatigue, stress corrosion cracking

Plate Thickness (mm)	Elements, Wt %						
	C	Si	Mn	Cu	P	S	Fe
10	0.18	0.26	0.95	0.037	0.009	0.002	Bal
12	0.17	0.37	1.06	0.042	0.012	0.002	Bal.
25	0.20	0.39	1.17	0.033	0.008	0.004	Bal.

Table I : Chemical composition of base material

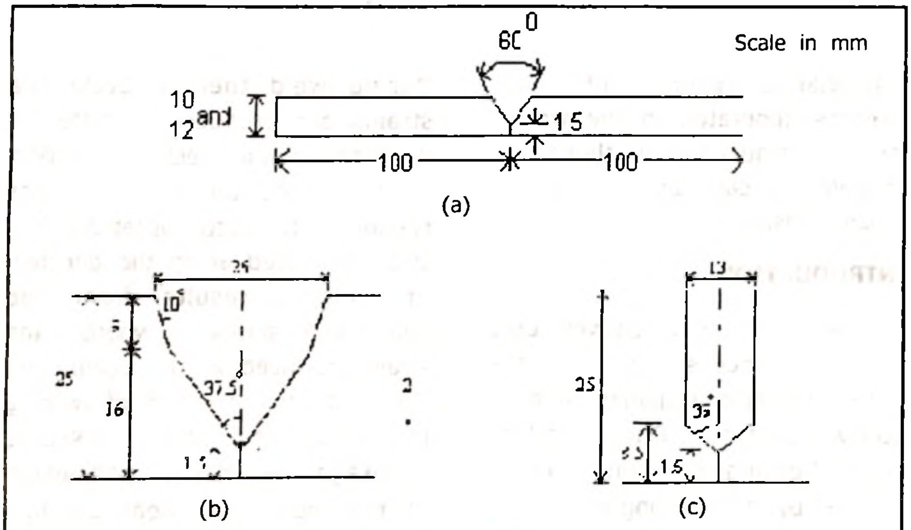


Fig. 1 (a) Single V-groove design for 10 and 12mm thick plates, (b)V-groove design for 25mm thick plate and (c) Narrow groove design for 25mm thick plate.

and fracture mechanics properties of weld joint depending upon characteristics of the material [5]. Thus, a critical look over the development of shrinkage during welding with respect to its process procedure and parameter has always been felt imperative to realize in welding engineering.

In view of the above an investigation on the effect of different welding processes and procedures on transverse shrinkage stress generated in welding of 10, 12 and 25 mm thick steel plates has been studied with the help of experimental measurement of distortion produced during welding. The weld joints of 10 and, 12 mm thick plates have been prepared by using continuous current gas metal arc welding (GMAW) and pulsed current gas metal arc welding (P-GMAW) processes with standard V-groove design whereas, the 25 mm thick plate was welded by shielded metal arc welding (SMAW) process employing V- groove and a narrow weld groove. After each pass of welding at certain heat input the deflection of the plate from its initial position was measured followed by estimation of transverse shrinkage, and transverse shrinkage stress using standard mathematical expressions [2, 3]. At a given heat input and weld groove size the effect of welding processes and procedures on variation of estimated shrinkage stresses in weld deposit causing bending of weld joint has been corroborated by estimation of bending stress developed in the weld joint through measurement of bending of the plate during welding. This may provide an opportunity to physically conform the effect of various welding processes and procedures on the scope of stress generation in weld joint.

EXPERIMENTAL

Weld Preparation

The mild steel plates of different thickness of 10, 12 and 25 mm having chemical composition as given in Table-I were used in this investigation. The 10 and 12 mm thick plates were butt welded using no root gap at single V- groove with included angle 60° confirming the AWS specification [6, 7] as schematically shown in Fig.1 (a). However, the 25 mm thick plate was welded by using a V-groove conforming the AWS specification [8] and also by using a suitably designed narrow groove with 13 mm groove opening as shown in Fig.1 (b) and (c) respectively.

Welding Fixture

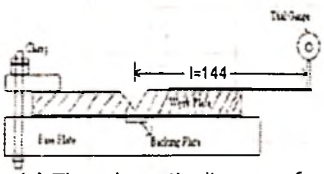
The welding was carried out by rigid clamping of one side of the weld joint where the other side of it was left free to respond to any distortion resulting from weld deposition. The schematic diagram of the fixture and the photograph of its experimental setup for GMAW and SMAW are shown in Fig 2 (a), (b) and (c) respectively.

Welding

The plates were welded by continuous current gas metal arc

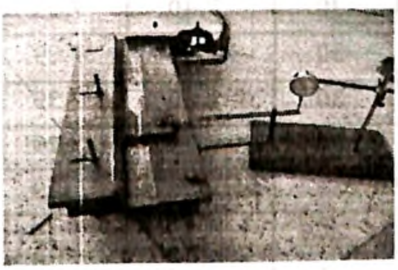
Welding Consumables	Elements	C	Mn	P	S	Si	Cu	Fe
GMAW filler wire	Wt.%	0.08	1.32	0.10	0.002	0.28	0.2	Bal.
SMAW electrode		0.06	1.02	-	-	0.44	-	-

Table II : Chemical composition of the GMAW filler wire and SMAW electrode



(a) The schematic diagram of welding fixture

(c) Photograph of experimental set up in SMAW process.



(b) Photograph of experimental set up in GMAW process

FIG-2

welding (GMAW), pulsed current gas metal arc welding (P-GMAW) and shielded metal arc welding (SMAW) processes. The GMAW and P-GMAW was carried out by using 1.2 mm diameter mild steel filler wire of specification AWS/SFA 5.18ER-70S-6 under argon (99.97%) gas shielding at a flow rate of 16-18 l/min, where the distance in between the nozzle and work piece was maintained at 14-16 mm. The SMAW was carried out using the 3.15 and 4 mm diameter basic coated electrodes of specification AWS/SFA 5.1E 7018-1. Prior to welding the electrodes were baked in an electric oven at temperature in the range of 150° - 200°C for one hour. Chemical composition of the consumables as GMAW filler wire and SMAW electrode are shown in Table-II. GMA welding of the plates was carried out using mechanized torch travel (ESAB-ARISTO-2000) at direct current electrode positive (DCEP). The SMA welding of the plates was also carried out at DCEP. The detail of the welding process, procedure and parameters used in welding of the plates of different thicknesses of 10, 12 and 25 mm have been shown in - III where, during the P-GMAW the pulse parameters such as the peak current (Ip), base current (Ib), pulse frequency (f) and pulse off time (Tb) have been kept as 434A, 104A, 148Hz and 4.36 ms respectively.

Measurement Procedure

During welding the deflection of free end of the weld joint per weld pass was measured using a dial gauge having least count of 0.01 mm placed at a given distance (straining length) of 144 mm from weld centerline (Fig. 2(a)), which was referred to the center of the weld groove. After each pass of welding at a certain heat input the deflection of the plate from its initial position was measured followed by estimation of transverse shrinkage, transverse shrinkage stress and bending stress using standard mathematical expressions as follows.

Estimation of Heat Input

The heat input (q_w) of welding was estimated in consideration of the heat generated by the welding arc as a function of welding current (I), arc voltage (V) and welding speed (S) as follows [3]..

$q_w = \eta_m\ VI/S$ -------------------- (i)

Where, ?m is the fusion efficiency estimated as a function of thermal efficiency of base metal (η), arc efficiency (η_a) and correction factor p as given below [3].

$\eta_m = p\ \eta\ \eta_a$ ---------------------- (ii)

The η_m of mild steel used as base material in this investigation was estimated considering p=1.0 and η= 0.368 [3] where the η_a for SMAW and GMAW is assumed as 65-75% and 75-85% respectively [3]. However, in case of the P-GMAW the heat input was estimated by using the mean current (I_m) instead of I of eq. (i). The I_m was estimated as [9]

$I_m = [I_pT_p + I_bT_b]/ (T_p+T_b)$------ (iii)

Where, T_p is the pulse duration.

Estimation of Transverse Shrinkage Stress

The transverse shrinkage stress (σ_{tr}) developed in the weld joints during their preparation using the mild steel plates of different thickness under varied thermal behaviour of different welding processes and procedures was estimated through evaluation of transverse shrinkage (Δ_{tr}) as follows [3].

$\sigma_{tr} = \Delta_{tr}\ E/l$ --------------------- (iv)

$\Delta_{tr} = (\mu_t\ 2\alpha\ q_w)/C_ph$ ----------- (v)

Plate Thickness (mm)	Weld Groove Design	Size of Filler Wire Electrode (mm)	Welding Process	Weld Pass No	Wire Feed Rate (m/min)	Welding/ Mean Current (A)	Arc Voltage (V)	Travel Speed (cm/min)	Heat Input (KJ/cm)
10	V-Groove	1.2	GMAW	1	8.5	234	25	25	4.13
				2	8.5	231	26	25	4.23
			P-GMAW*	1	8.5	227	25	25	4.00
				2	8.5	228	26	25	4.18
12	V-Groove	1.2	GMAW	1	8.5	233	25	25	4.11
				2	8.5	230	27	20	5.47
				3	8.5	230	29	20	5.88
			P-GMAW*	1	8.5	229	25	25	4.04
				2	8.5	220	26	20	5.05
				3	8.5	226	28	20	5.58
25	V-Groove	3.15	SMAW**	1	-	120	30	7.40	7.59
		3.15		2	-	120	30	7.31	7.68
		4		3	-	120	30	7.60	7.39
		4		4	-	120	30	7.70	7.29
		4		5	-	120	30	7.50	7.49
		4		6	-	120	30	7.40	7.59
		4		7	-	120	30	7.40	7.59
		4		8	-	120	30	7.60	7.39
		4		9	-	120	30	7.70	7.29
		4		10	-	120	30	7.92	7.09
		4		11	-	120	30	7.60	7.39
	Narrow Groove	3.15		1	-	120	30	7.60	7.39
		3.15		2	-	120	30	7.70	7.29
		4		3	-	120	30	7.50	7.49
		4		4	-	120	30	7.40	7.59
		4		5	-	120	30	7.40	7.59
		4		6	-	120	30	7.60	7.39
		4		7	-	120	30	7.70	7.29
		4		8	-	120	30	7.92	7.09

Where, E is the Young's modulus of base material, I is the straining length (Fig. 2 (a)), μ_t is the transverse stiffness factor, α is the coefficient of thermal expansion, C_p is the specific heat per unit volume and h is the plate thickness. The σ_{tr} of the mild steel weld joint was estimated [3] considering $E = 210 \times 10^3$ N/mm^2, $I = 144$ m, $\mu_t = 0.5$, $\alpha = 12 \times 10^{-6}$ K^{-1} and $C_p = 4.9 \times 10^{-3}$ J/mm^{3}K.

Estimation of Bending Stress

The bending stress (σ) developed due to distortion of weld joints of mild steel plates of different thickness during their preparation

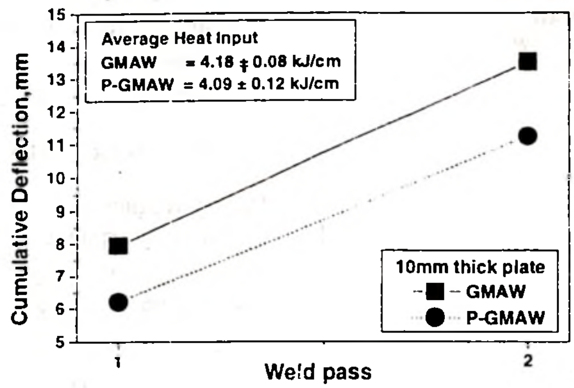


Fig.3 At a given heat input and weld pass the effect of welding process on cumulative deflection of 10mm thick plate.

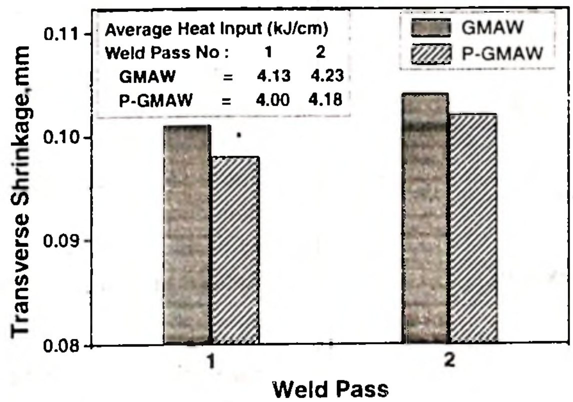


Fig.4 At a given heat input and weld pass the effect of welding process on transverse shrinkage in 10mm thick plate

under varied thermal behaviour of different welding processes and procedures was also estimated [10] as follows.

$\sigma = My/ I^m$ ------------------------ (vi)

Where, y is the distance of the measuring point (dial gauge tip) from the central axis of the weld joint. The bending moment (M) and moment of inertia (I^m) are estimated [10] as follows.

$M=Fl$ -------------------------------- (vii)

$I^m = bd^3/12$ --------------------- (viii)

Where, the b and d are the plate width and thickness respectively. The force (F) generated at the plate due to distortion was estimated through the measured deflection (δ) using the following expression [10].

$\delta = Fl^4/30E\ I^m$ ------------------ (ix)

ANALYTICAL EXAMPLE OF A GIVEN CASE

Typical estimation of heat input, transverse shrinkage, transverse shrinkage stress and bending stress in the GMA weld of 10 mm thick plate prepared at a given welding current (I), arc voltage (V) and travel speed (S) of 234 A, 25 V and 25 cm/min (0.416 cm/sec) respectively has been given below.

Heat Input (q_w) = η_m [VI/S] = 0.294 [25 x 234/0.416] = 4134.3 J/cm

Where, the $\eta_m = p\,\eta = 1 \times 0.368 \times 0.80 = 0.294$

Transverse Shrinkage (Δ_{tr}) = $[\mu_t\ 2\alpha\ q_w]/C_p h$ = $(0.5 \times 2 \times 12 \times 10^{-6} \times 413.4)/ (4.9 \times 10^{-3} \times 10) = 0.101$ mm

Transverse shrinkage stress (q_{tr}) = Δ_{tr} E/l = $(0.101 \times 210 \times 10^3)/144$ = 147.3 MPa

Bending Stress (σ) = My / I^m = 237600 x 5 / 8333 = 143 MPa

Where, $I^m = bd^3/12 = (100 \times 10^3) / 12 = 8333\ mm^4$

$\delta = Fl^4/30E\ I^m$

$F = 30E\ I^m\ \delta / l^4 = (30 \times 210 \times 10^3 \times 8333 \times 13.51) / 144^4 = 1650$ N

M = Fl = 1650 x 144 = 237600 N-mm and

y = d/2 =10/2 = 5 mm

RESULTS AND DISCUSSION

Effect of Welding Process on Transverse Shrinkage Stress

10 mm thick plate

During welding of 10 mm thick plate using GMAW and P-GMAW processes, with a close range of heat input (4.09-4.18 kJ/cm) at a given size of weld groove, the effect of number of weld passes on the measured cumulative deflection has been shown in Fig. 3. The figure shows that under the given condition of welding the increase in number of weld pass as usual enhances the cumulative deflection of the plate due to accumulation of more heat with the increase in amount of weld deposition. However, it is interestingly observed that at a given close range of heat input the use of P-GMAW appreciably reduces the cumulative deflection of the plate with respect to that observed in case of using GMAW at any weld pass. This may be primarily attributed to

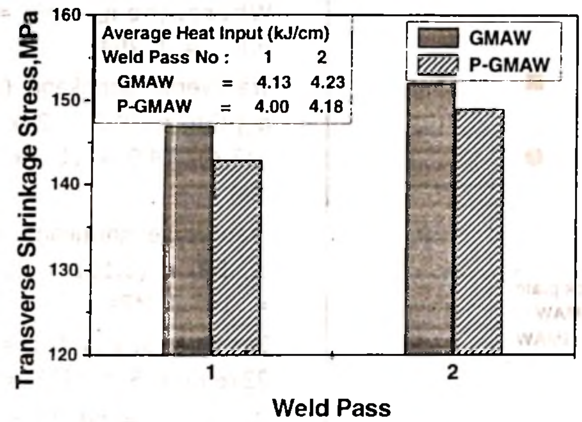


Fig.5 At a given heat input and weld pass the effect of welding process on transverse shrinkage stress in 10mm thick plate.

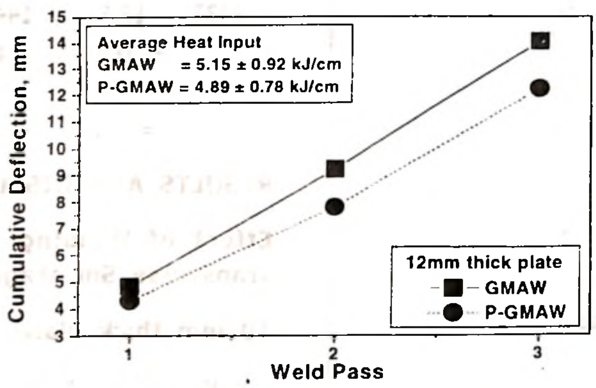


Fig.6 At a given heat input and weld pass the effect of welding process on cumulative deflection of 12mm thick plate.

comparatively lower thermal intensity of the P-GMAW weld due to reduction in heat built-up in weld deposit resulting from interruption in weld deposition under pulsed current. On the basis of these observations the change in estimated transverse shrinkage and transverse shrinkage stress with the variation in welding process of GMAW and P-GMAW studied at different weld passes has been shown in Figs. 4 and 5 respectively. The figures show that at a given weld pass and close range of heat input the transverse shrinkage and transverse shrinkage stress of the weld joint relatively reduces with the application of P-GMAW, showing again a clear advantage of this welding process in lowering them with respect to those observed in GMA weld. The shrinkage and shrinkage stress of weld joint of a given material are the function of weld thermal behaviour influenced by the weld pass and the process as discussed above. The observed variation in transverse shrinkage and shrinkage stress of the weld joint as an effect of weld pass and process is in agreement to their direct influence on measured cumulative deflection of the weld joint as stated earlier and it again clearly establishes the advantage of using P-GMAW over the GMAW in reference to reduction of stresses in weld joint.

12 mm thick plate

During welding of 12 mm thick plate using the GMAW and P-GMAW processes, with a close range of heat input (4.89 - 5.15 kJ/cm), the effect of number of weld passes on the measured cumulative deflection has been shown in Fig. 6. Here also it is observed that under the given condition of welding the increase in number of weld pass enhances the cumulative deflection of the plate due to accumulation of more heat with the increase in amount of weld deposition and the use of P-GMAW appreciably reduces the cumulative deflection of the plate with respect to that observed in case of using GMAW at any weld pass.

In order to study the effect of plate thickness on the characteristics of the deflection during welding the observations of the Figs. 3 and 6 have been compared. The study depicts that upto second weld pass the cumulative deflection of the 12 mm thick plate remains comparatively lower than that of the 10 mm thick plate followed by an increase in it with the third weld pass resulting in to a relatively higher deflection than that observed in the thinner plate. At a given close range of heat input the comparatively lower cumulative deflection of the thicker plate upto second weld pass is primarily attributed to necessity of larger force for unit deflection under the measurement procedure as described above.

In agreement to the earlier observations of welding of the 10

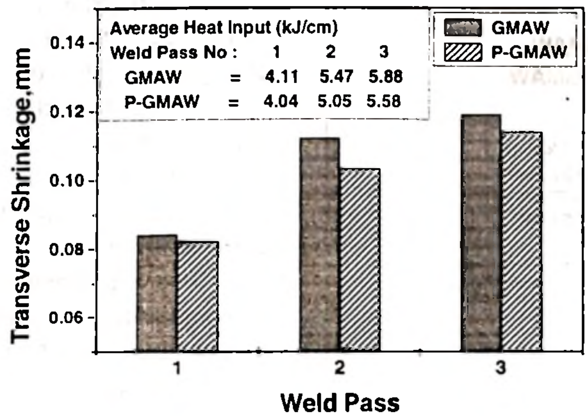


Fig.7 At a given heat input and weld pass the effect of welding process on transverse shrinkage in 12mm thick plate.

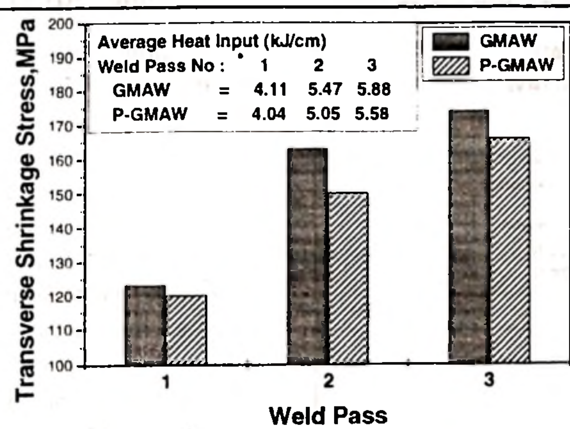


Fig.8 At a given heat input and weld pass the effect of welding process on transverse shrinkage stress in 12mm thick plate.

mm thick plate here also it is observed that the transverse shrinkage (Fig. 7) and transverse shrinkage stress (Fig. 8) of the weld joint enhances with the increase of weld pass. However, at a given weld pass and similar order of heat input the use of P-GMAW in place of GMAW appreciably lowers the transverse shrinkage and transverse shrinkage stress. The results observed in Figs. 7 and 8 can be understood in the light of the discussions given above in case of the welding of 10 mm thick plate. Here it is further interesting to note that the advantage of using P-GMAW over the GMAW in reduction of transverse shrinkage and shrinkage stress of the weld joint is comparatively more prominent in case thicker plate. This may be primarily attributed to the phenomena of heat built up of P-GMAW resulting into a comparatively milder thermal behaviour of weld joint.

Effect of Welding Process on Bending Stress

The cumulative deflection of the weld joints as discussed above is a measure of bending of the plate from its neutral axis. At a given order of heat input and weld groove size the effect of welding process on variation of shrinkage stresses in weld deposit causing distortion of weld joint can be corroborated by estimation of bending stress developed in the weld joint through measurement of degree of bending of the plate. This may extend a physical conformation of the effect of welding process on the stress generation in weld joint.

10 mm thick plate

At the practically similar heat input (4.09-4.18 kJ/cm) and same weld groove size the effect of GMAW and P-GMAW processes on bending stress developed in the weld joint estimated (Eq. iv) on the basis of measured bending of the 10 mm thick plate has been shown in Fig. 9. The figure shows that the bending stress developed in the weld joint prepared by the P-GMAW process is comparatively lower than that observed in the GMA weld joint. This may be primarily understood by the comparatively lower estimated shrinkage stress (Fig.5) of the P-GMA weld deposit, which has generated comparatively less force for bending of weld joint resulting from relatively smaller heat build-up as stated earlier than that noted in case of the GMA weld joint.

12 mm thick plate

The estimated shrinkage stresses causing distortion of the weld joint as verified by the estimated bending stress with the help of measured bending of weld joints of 12mm thick plate has been shown in Fig.10. The figure shows that in agreement to the earlier observations in 10 mm thick plate here also the use of P-GMAW has been found to develop

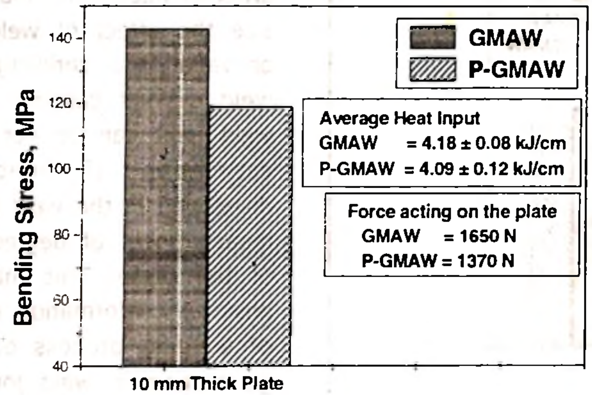


Fig.9 Estimated Bending Stress of the weld joint in different welding processes of 10 mm thick plate.

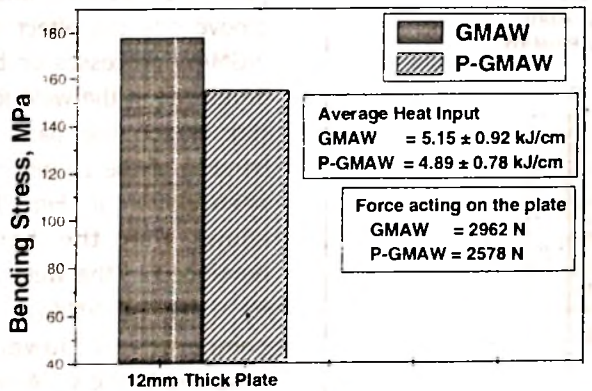


Fig.10 Estimated Bending Stress of the weld joint in different welding processes of 12 mm thick plate.

comparatively lower bending stress in weld joint than that observed in case of using GMAW to weld 12 mm thick plate at a close range of heat input (4.89 - 5.15 kJ/cm) and same size of weld groove. The effective role of P-GMAW in lowering the bending stress of weld joint with respect to that observed in case of employing GMAW follows the same argument as stated above. However, the comparatively higher bending stress developed in the weld joint of comparatively thicker (12 mm) plate (Fig. 10) than that observed (Fig. 9) in the weld joint of the thinner one (10 mm) may have primarily attributed to relatively bigger weld size of the former one which produces comparatively higher shrinkage stress than that produced in the thinner plate as resulted in the Figs 8 and 5 respectively.

Effect of Welding Procedure on Cumulative Deflection

At a practically same (7.39-7.43 kJ/cm) heat input per weld pass the effect of different welding procedure under a given welding process has been studied by using the V-groove and narrow groove welding in multi-pass SMA welding of 25 mm thick plate. During welding the influence of weld pass on cumulative deflection of the weld joints has been shown in Fig. 11. The figure shows that at a given number of weld pass the cumulative deflection of narrow groove weld joint is relatively less than that observed in case of the V-groove weld joint and the difference increases with the increase of weld pass. This is primarily happened due to comparatively lower amount of weld metal deposition in filling of narrow groove weld joint than that required in V- groove weld joint.

Effect of Welding Procedure on Bending Stress

At the practically same heat input the effect of different weld groove design (V-groove and narrow groove) on variation of bending stress in the weld joints has been shown in Fig. 12. The figure shows that in agreement to the above observations the use of narrow groove develops comparatively lower bending stress in weld joint than that observed in case of using V-groove weld joint. The effective role of narrow groove in lowering of bending stress in weld joint with respect to that observed in case of V-groove weld joint follows the same argument as stated above with respect to the amount of weld metal deposition.

CONCLUSIONS

The experimental evaluation on distortion and transverse shrinkage stress generated in welding of 10, 12 and 25 mm thick steel plates using different welding processes and procedures can be concluded as follows.

1. The use of P-GMAW process results comparatively less cumulative deflection with the number of weld pass and

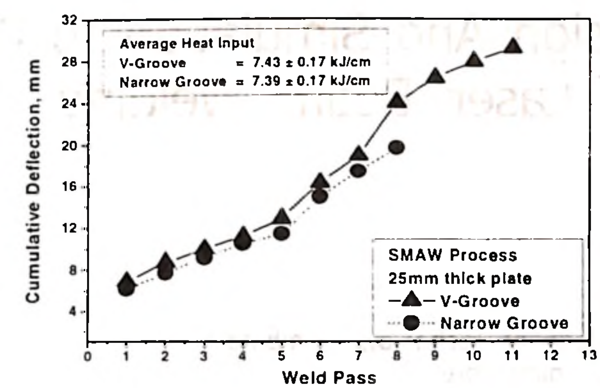


Fig.11 Estimated Bending Stress of the weld joint in different welding processes of 12 mm thick plate.

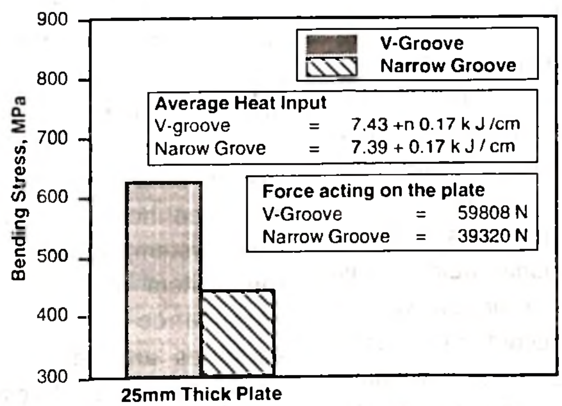


Fig.12 Estimated Bending Stress of the weld joint in different welding procedures of 25 mm thick plates.

transverse shrinkage and transverse shrinkage stress in weld than that observed in case of using GMAW process in welding of 10 mm and 12 mm thick plates, at a given close range of heat input per weld pass.

2. During welding at a heat input of practically similar order per weld pass by any process, the 12mm thick plate shows comparatively higher deflection, transverse shrinkage and transverse shrinkage stress than that found in case of relatively thinner 10mm thick plate.

3. The significant effect of SMA welding on cumulative deflection with the increase of filling passes of 25 mm thick weld joint has been found relatively less in case of using narrow groove instead of V-groove at a practically same heat input per weld pass.

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