EFFECTS OF WELDING SEQUENCE AND EXTERNAL RESTRAINT ON BENDING DEFORMITY IN THIN-PLATE ARC-WELDED JOINTS

A thesis

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Department of Mechanical Engineering

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Abstract

Bending deformity as a troublesome metallurgy issue is surely create in thin-plate arc-welded parts (mainly inferior 4 mm in thickness). This study aims to clarify the impact of welding sequence and external restraint on out-of-plane deformity in thin plates to learn a productive and practical design for the stop of welding-induced bending deformity. The exploratory method was taking advantage of for search present. The experimental results reveal that the outside limitation cannot avoid bending deformity in the thin-secure weldments, while it can considerably mitigate the amount of transverse (about 1.9 mm in this place) but not long turning. The welding sequence method can halt warping deformity, but it cannot remove the transverse bending persuaded by the non-uniform temperature field in the thin-plate thickness direction. In the present work, the transverse turning in the well-proportioned connecting is the lowest (about 1.9 mm), while that in the back-step welding is the largest (about 7.6 mm). In addition, symmetrical welding and continuous welding introduce the lowest (about 0.2 mm) and maximal (about 3.5 mm) longitudinal bending, individually. Two together outside restraint and welding sequence keep affect the bending deformity trend. For the thin-plate arc-welded components, symmetrical welding combined with external restraint is a very direct strategy for avoiding bending deformity. So the best result is symmetrical welding combined with external restraint (about 0.4 mm longitudinal bending and 0.2 mm transverse bending).

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Chapter 1

Introduction

1.1 Literature review

Arc welding has still been widely used in conveyance, shipbuilding and offset steel structures to join materials by way of its ability to move and low cost [1], [2]. Nevertheless, bending deformity is normally prone to be generated in thin-plate (usually less than 4 mm in thickness) arc-welded components [4], [5], [6]. Once the bending deformity is generated after welding, its magnitude usually tends to be very large, which evidently reduces the dimensional accuracy and consequently affects the fabrication process [5]. The straightening of bending deformity is not only costly but also very hard or even impossible [7]. For lightweight design to reduce the structural mass and save energy, high-strength steels (HSSs) with ultimate tensile strength higher up to 550 MPa have been increasingly applied in engineering sectors [8], [26]. The lightweight component means thin-walled thickness in general [8]. Because of this, it has been in urgent need to develop effective and practical methods for preventing and avoiding the formation of bending deformity in thin-plate weldments.

Earlier, numerous alleviation and control plans of welding deformity have happened developed, that can be categorized into four types [6], [22]: (i) Component design method; (ii) Heat input control method; (iii) Restraint method; (iv) Active mitigation method. The component design method including the determination of structural geometry and the selection of weld joint type and groove, etc. is a very effective approach to control and reduce welding deformity [9], [10]. Nevertheless, this method is mainly used in the design stage for the thick plates. The active mitigation method using force cooling technique, static/transient thermal tensioning, additional heat sources, etc. is highly useful to prevent and mitigate welding deformity in thin plates [9]. Whereas, this approach usually requires additional specialized devices and introduces lots of extra process parameters making the optimization process more complicated. Therefore, the heat input control method and restraint method are more desirable in engineering practice for the prevention and mitigation of welding deflection in thin plates.

It has been found that heat input has a great effect on all types of welding deformation [7]. Furthermore, heat input plays a crucial role in the magnitude of longitudinal shrinkage force (tendon force), which determines whether bending deformity occurs or not [11], [23], [29]. Currently, the heat input control method mainly includes the replacement of conventional arc welding by low heat input welding methods such as beam welding and cold metal transfer (CMT) welding, the substitution of continuous welding by intermittent welding, and the optimization of welding direction and sequence. [12] experimentally and numerically compared the welding deformity produced by CO2 gas arc welding and laser beam welding (LBW) in thin plates. The large bending deformity is found to be generated by using the traditional arc welding (large heat input method), while LBW produces nearly ignorable welding deformation. [13] contrasted the welding deformity caused by three different laser-

based welding processes and submerged arc welding (SAW) in 4 mm plates. They found that the maximum deformity in SAW is highly decreased by shifting to LBW. [14] experimentally studied the impact of welding processes on welding deformity in 4 mm plates. Their work systematically clarified the relationship between heat input and welding deformity. [15] numerically illustrated the predicted welding deformity in thin-plate large-scale ship panels by using continuous and intermittent welding procedures. They indicated that bending deformity generated in continuous welding can be avoided when intermittent welding is employed. [16] illuminated the effect of welding sequences on out-of-plane deformity in fillet joints. They showed that the obtained welding deformation by a long pass at one side is larger than that by two short passes. Nevertheless, low heat input welding methods like beam welding are generally very expensive and not portable in practice yet. Furthermore, there is nearly no systematic investigation on the impact of different welding sequence types on bending deformity.

The restraint method engaging fixture/clamping is the most realistic approach to minimize bending deformation [6], [7]. A series of research has found that the external restraint has a conspicuous effect on the reduction of angular deformity/ transverse bending, which contributes the principal out-of-plane deformation in thick plates [6], [7], [9]. Furthermore, the restraint force, location, and releasing time have significant effect on the mitigation amplitude of angular deformity [17], [21], [25]. For years' plentiful work has been implemented to investigate the impact of external constraints on welding-induced bending deformity. [27] experimentally and numerically investigated the clamping time on the amount of bending deformity in DP600 thin-plate overlap joints. It was found that the magnitude of bending deformity decreases with the increase of release time until the weldment cools down to room temperature (T_{RT}). Afterward, it becomes stable and is nearly constant. [18] studied the impact of jig constraint on bending deformity in thin-walled bead-on joints. It came to know that the mechanical restraint can not only mitigate the amount of bending deformity but also vary the bending deformity type when the welding heat input is very low. [2] compared the generated welding deformity in thin-walled pipes with and without external restraint. They realized that the constraint distance to the weld center has great effect on the reduction effectiveness of welding deformation. Nevertheless, the thin-plate weldments may snap back into bending again once the fixturing is removed. The recovery mechanism of bending deformity is still unclear.

Depended on the same research, the effect of the heat input control procedure and restraint procedure on welding deformation has happened clarified separately. However, these two methods have usually been separately considered to control welding deformity. There are few literatures to systematically clarify the combined effect of the application of both heat input control method and restraint method on the amplitude of bending deformity in thin-plate welded structures. Welding deposition sequence such as skip welding is one of the effective methods to reduce the arc welding heat input while almost without change in weld dimensions. Nevertheless, there is less work to quantitatively and qualitatively investigate the impact of welding deposition sequences on the out-of-plane deformity in thin plates and the behind effect mechanism. Furthermore, it is still unclear the impact of mechanical external restraint on bending deformity in thin plates under various welding sequences.

In the current work, the high-strength structural steel ASTM A36 thin plate with the thickness of 4 mm was selected for investigation. The welding experiments were carried out by employing four different welding sequences, which are continuous welding, skip welding, back-step welding, and symmetrical welding here. Furthermore, there are two different restraint conditions during welding for each welding sequence. One is with external restraint (under restrained condition) and the other is without external restraint (under free condition). After welding, the out-of-plane deformations were measured for comparison and analysis. Based on the present work, an effective and practical strategy for the prevention of welding-induced bending deformity in the thin-walled components was developed.

1.2 Objective

a) To clarify the impact of welding sequence.
b) To the experiment about external restraint on out-of-plane deformity.
c) To know about different types of welding sequences.
d) To clarify the best welding sequence in arc welded joint.

Chapter 2

Experimental cases

2.1 Experimental procedure

Table 1 indicates the measured as-received ultimate tensile strength steel ASTM A36 chemical composition. Fig. 1 shows the dimensions of the prepared samples for welding. The gas tungsten arc welding (GTAW) method was manipulated here as seen in Fig. 2. Table 2 displays the determined welding parameters. In the current work, the initial and welding-induced deformation were measured by measurement tape on flatness surface and Table 3 exhibits the measured initial deformation before welding, which is very small and ignorable. Note that the heat treatment (at 600◦C for 0.5 h with oven cooling) was applied before welding to remove the initial residual stress.

Table 1

Measured chemical composition of base metal ASTM A36 steel, wt.%

Elements	Carbon (C)	Manganese (Mn)	Phosphorus (P)	Sulfur (S)	Silicon (Si)	Copper (Cu)	Iron (Fe)
Value (Max)	0.25-0.29	1.03	0.04	0.05	0.28	0.20	Balance

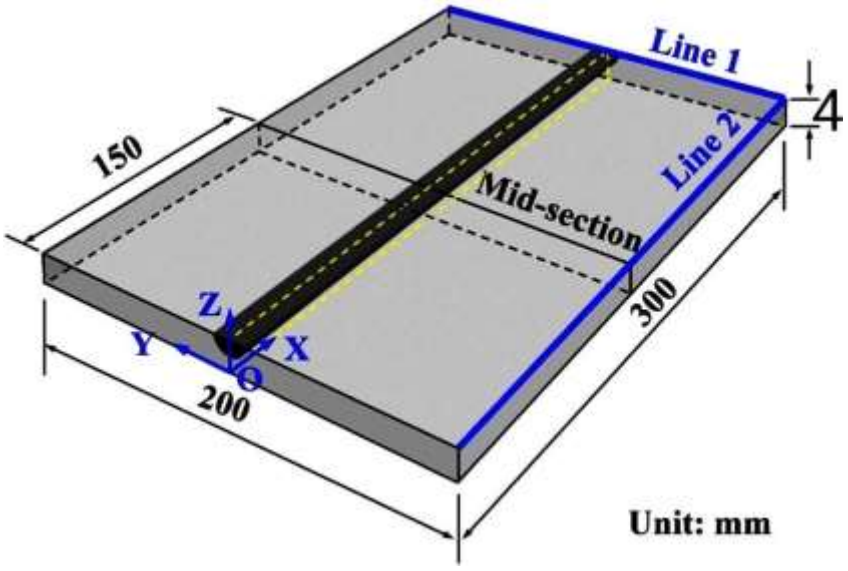


Fig. 1. Designed geometry of the weld specimen (300 x 200 x 4) mm.

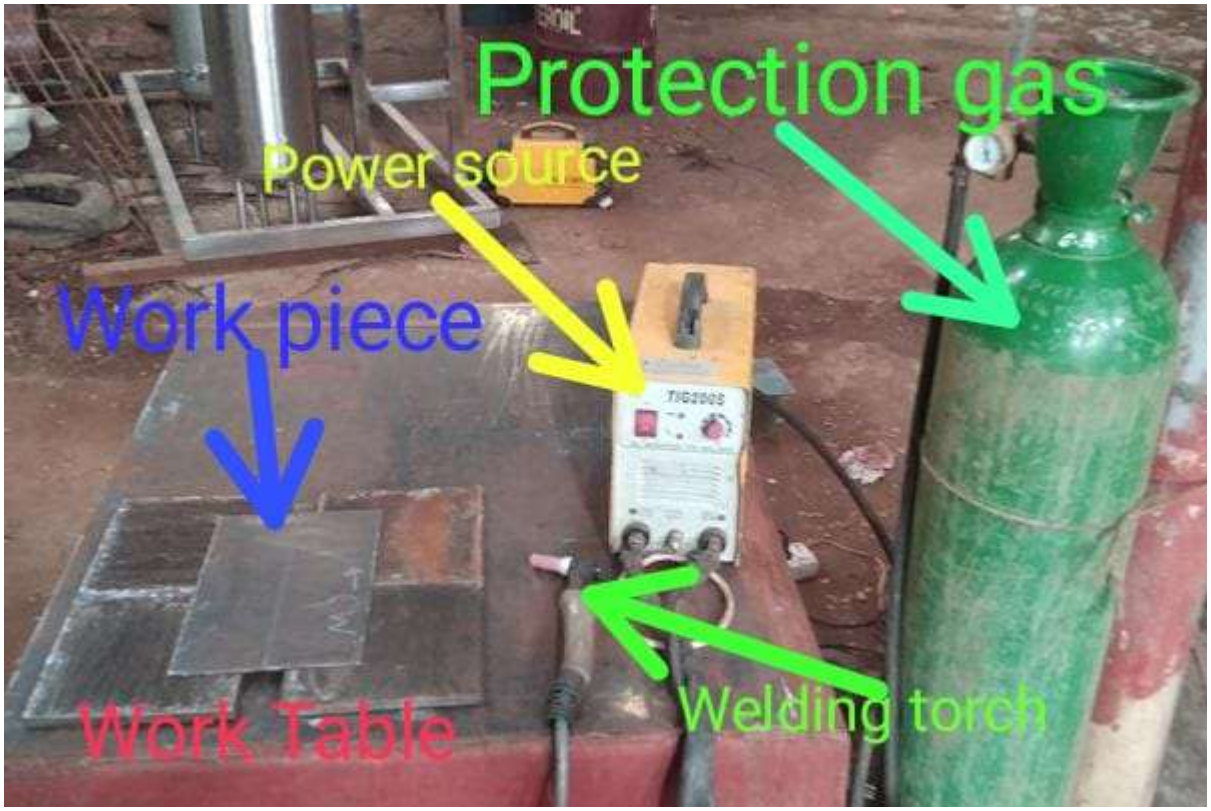


Fig. 2. Welding device and setup under free condition.

Table 2

Welding parameter

Parameter	Current (I-A)	Voltage (U-V)	Shielding Gas	Speed (v-cm/min)	Gross heat input (q-J/mm)
Value	100	12	100% Ar.	11	655

Table 3

Initial deformation distribution.

Sequence	**Continuous Welding (CW)**		**Skip Welding (SW)**		**Back-step Welding (BW)**		**Symmetrical Welding (SYW)**	
Axis	**Free**	**Restrained**	**Free**	**Restrained**	**Free**	**Restrained**	**Free**	**Restrained**
X	00	0.05	0.05	0.05	00	0.01	00	00
Y	0.05	0.01	0.01	0.05	0.05	00	00	00

2.2 Experimental Cases

Table 4 demonstrates the planned welding experimental cases in this study. In Table 4, "free" means the welding is performed without external restraint as seen in Fig. 2. The "restrained" means the external restraint is employed during welding as seen in Fig. 4. It is noteworthy that the external constraint is released after the welded component cools down to T_{RT}. Furthermore, the restraint type here is the "face restraint" mode. In groups A, B, C, and D, continuous welding, skip welding, backstep welding, and symmetrical welding as seen in Fig. 4 were utilized, respectively. It should be mentioned that the length of the short welding pass is the same. Furthermore, the welding parameters of both short and long pass are the same (see Table 2). Meanwhile, the next short pass is performed only when the component welded by the former short pass cools down to T_{RT}. In other words, the interpass temperature is T_{RT} in groups B, C, and D.

Table 4

Welding experimental cases

Cases		Welding sequence	Restraint condition
Group A	Case A-1	Continuous Welding(CW)	Free
	Case A-2		Restrained
Group B	Case B-1	Skip Welding (SW)	Free
	Case B-2		Restrained
Group C	Case C-1	Back-step Welding (BW)	Free
	Case C-2		Restrained
Group D	Case D-1	Symmetrical Welding (SYW)	Free
	Case D-2		Restrained

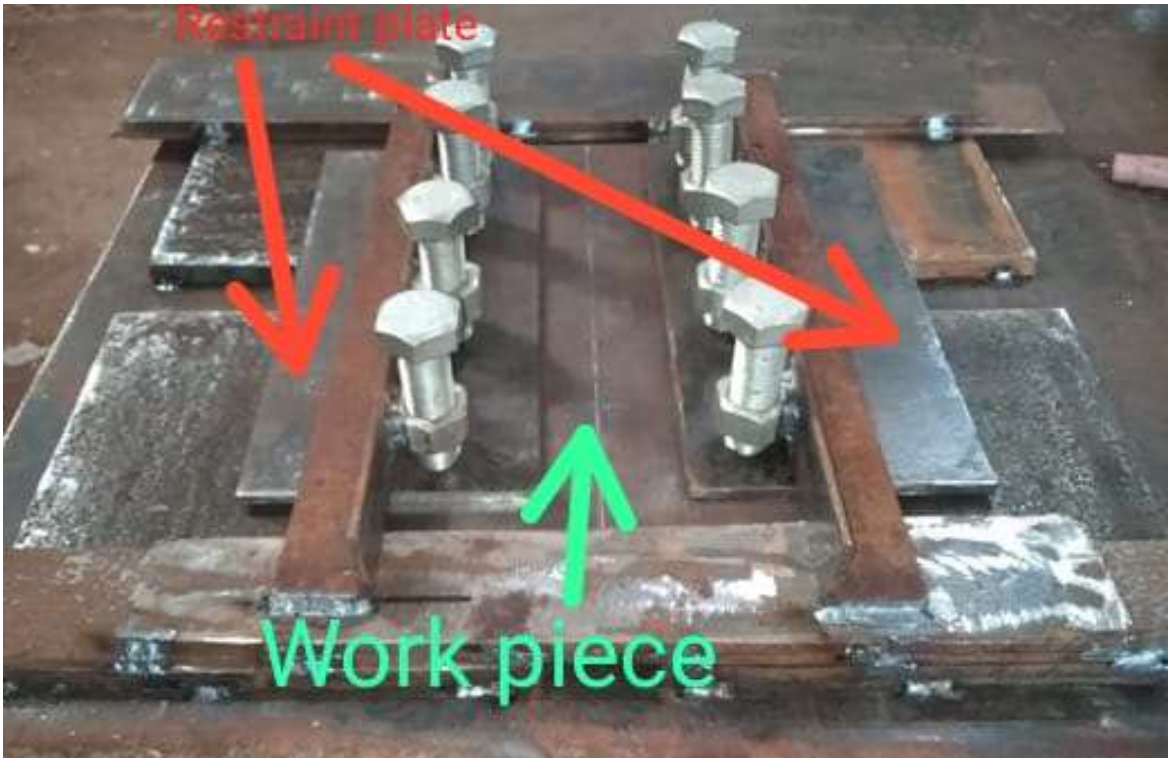


Fig. 3. External restraint arrangement during welding.

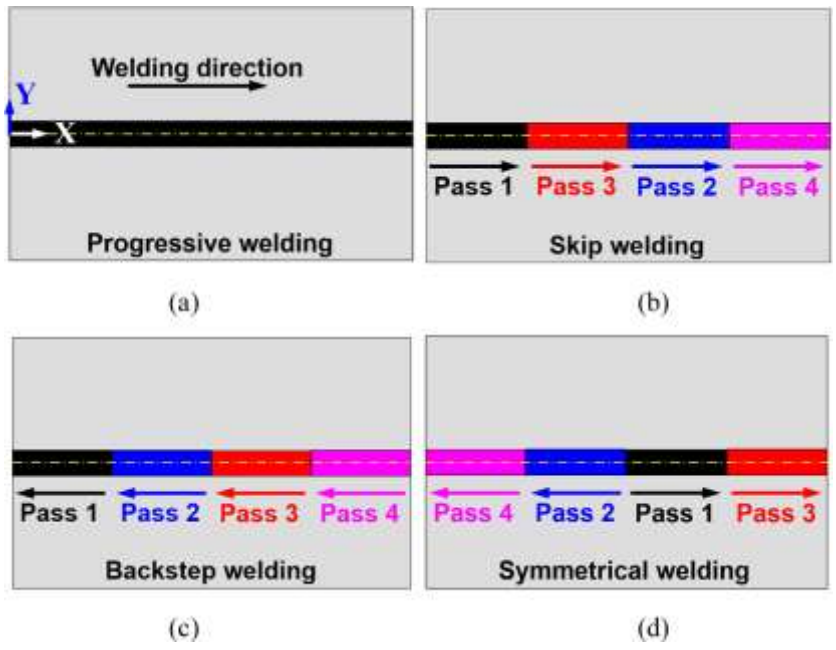


Fig. 4. Welding sequences: (a) progressive/continuous welding, (b) skip welding, (c) backstep welding, and (d) symmetrical welding.

Chapter 3

Experimental results

3.1 Continuous welding

From Fig. 7, it can be seen that the bending deformity generated in cases A-1 and A-2 is the concave-convex mode. It is well known that the bending deformity mode is mainly related to the distribution of longitudinal shrinkage force (tendon force) [18]. Because of the generated larger downward transverse bending (angular deformity) as seen in Fig. 7, the tendon force above the neutral plane is smaller than that underneath [28]. That is why the concave-convex mode is shown here. Fig. 7 exhibits the measured magnitude and distribution of welding deflection along line 1 and line 2 (see Fig. 1). From Figs. 7a, one can see that the magnitude of angular deformity along line 1 in Case A-1 (about 2.3 mm) is much lower than that in Case A-2 (about 3.6 mm). Nevertheless, the amount of longitudinal bending along line 2 in cases A-1 (about 3.5 mm) and A-2 (about 5.8 mm) respectively.



(a) (b)

Fig. 5. After welding deflection of Case A-1: (a) Top view and (b) Side view.



(a) (b)

Fig. 6. After welding deflection of Case A-2: (a) Top view and (b) Side view.

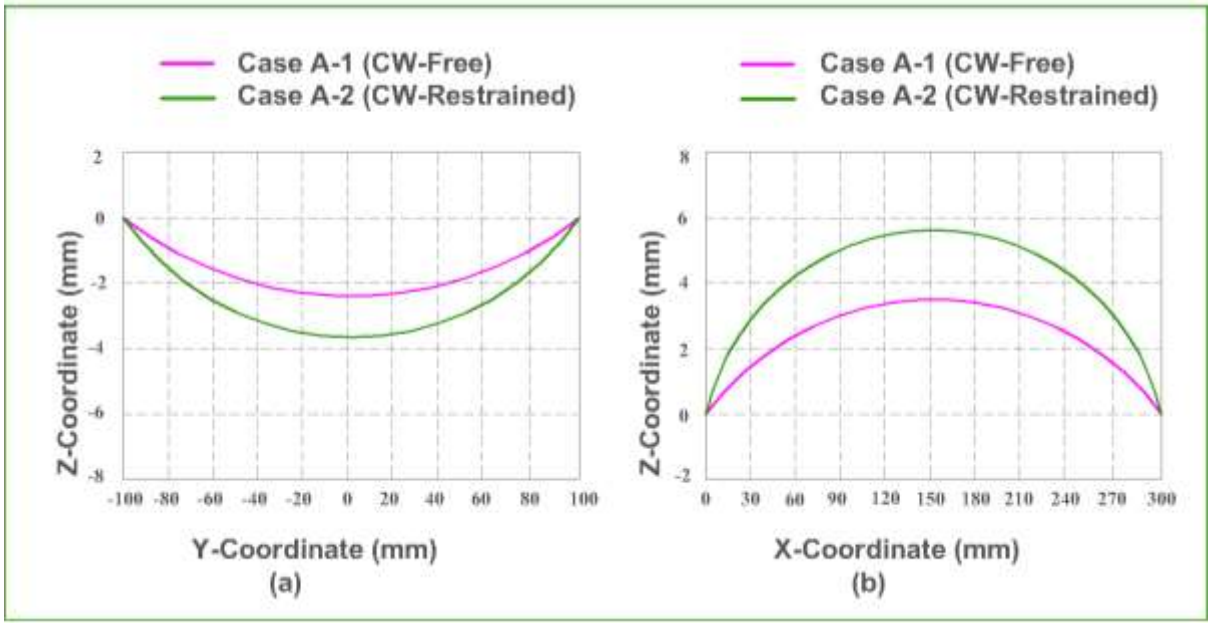
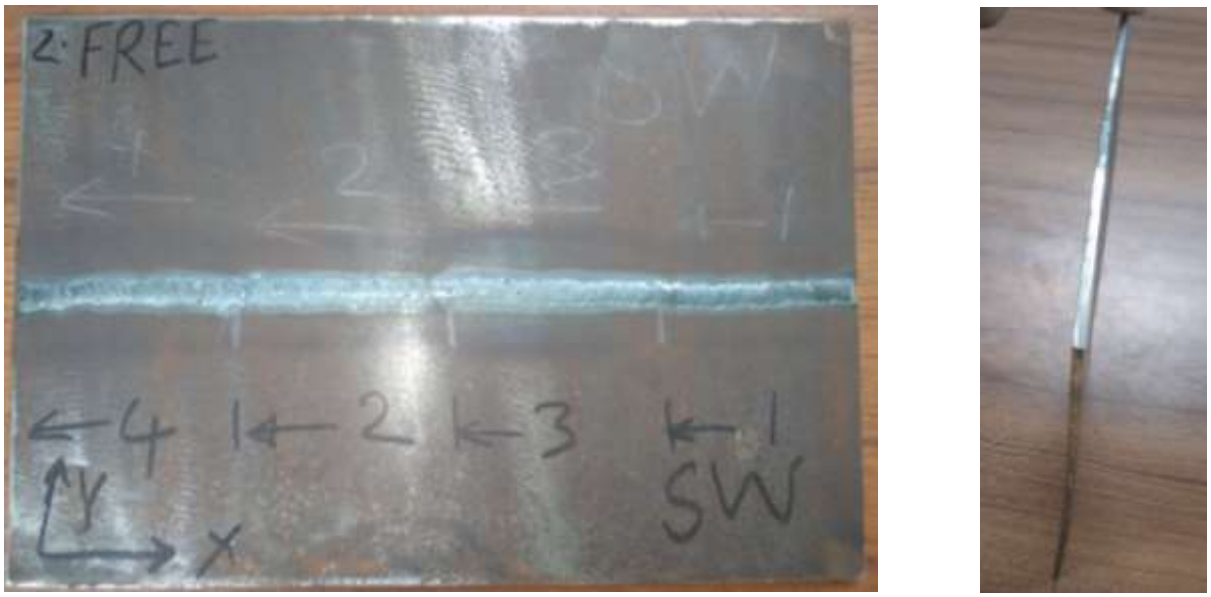


Fig. 7. Measured distribution of welding deflection in Group A: (a) along line 1 and (b) along line 2.

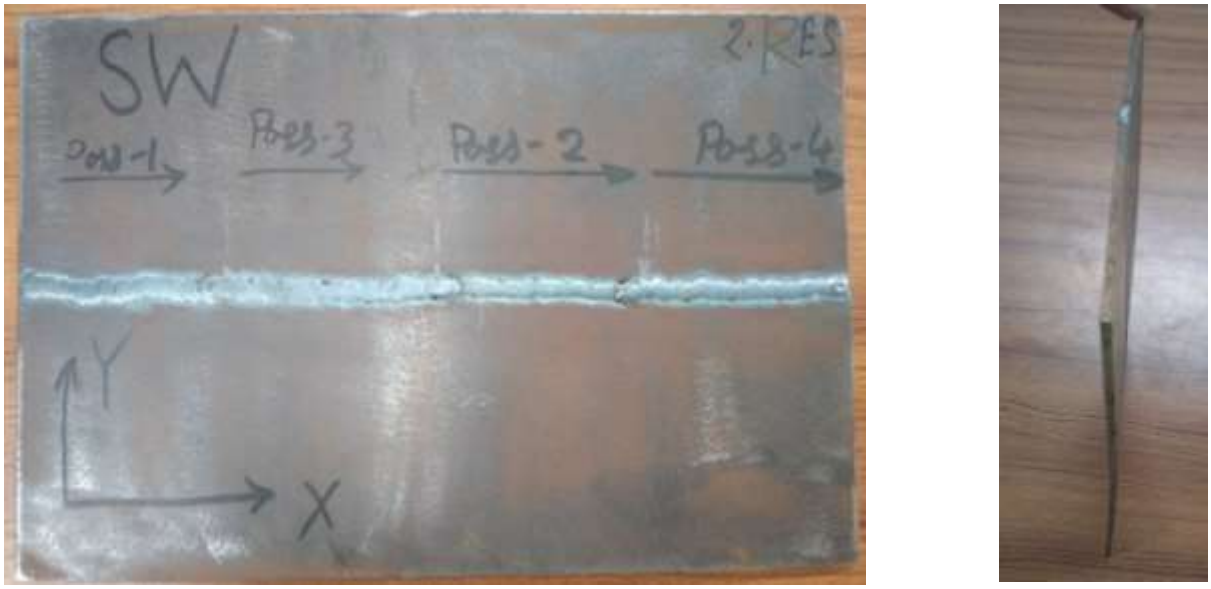
3.2 Skip welding

From Fig. 10, it can be seen that the bending deformity generated in cases A-1 and A-2 is the concave-convex mode. This is because the shrinkage of Pass 3 during cooling in Case B-1 causes the upward warping deformation of Pass 1 area as seen in Fig. 8. Due to this phenomenon, the tendon force below the neutral plane is smaller than that above. Since the upward warping deformation effect is removed when the external restraint is applied in Case B-2, the concave-convex mode is displayed. Fig. 10 shows the measured magnitude and distribution of welding deflection along line 1 and line 2 (see Fig. 1). In Figs. 10a, the magnitude of transverse bending along line 1 in Case B-2 (about 3.6 mm) is much lower than that in Case B-1 (about 3.7 mm). Furthermore, the amount of longitudinal bending along line 2 in cases B-1 and B-2 is about 7 mm and 6.5 mm, respectively.



(a) (b)

Fig. 8. After welding deflection of Case B-1: (a) Top view and (b) Side view.



(a) (b)

Fig. 9. After welding deflection of Case B-2: (a) Top view and (b) Side view.

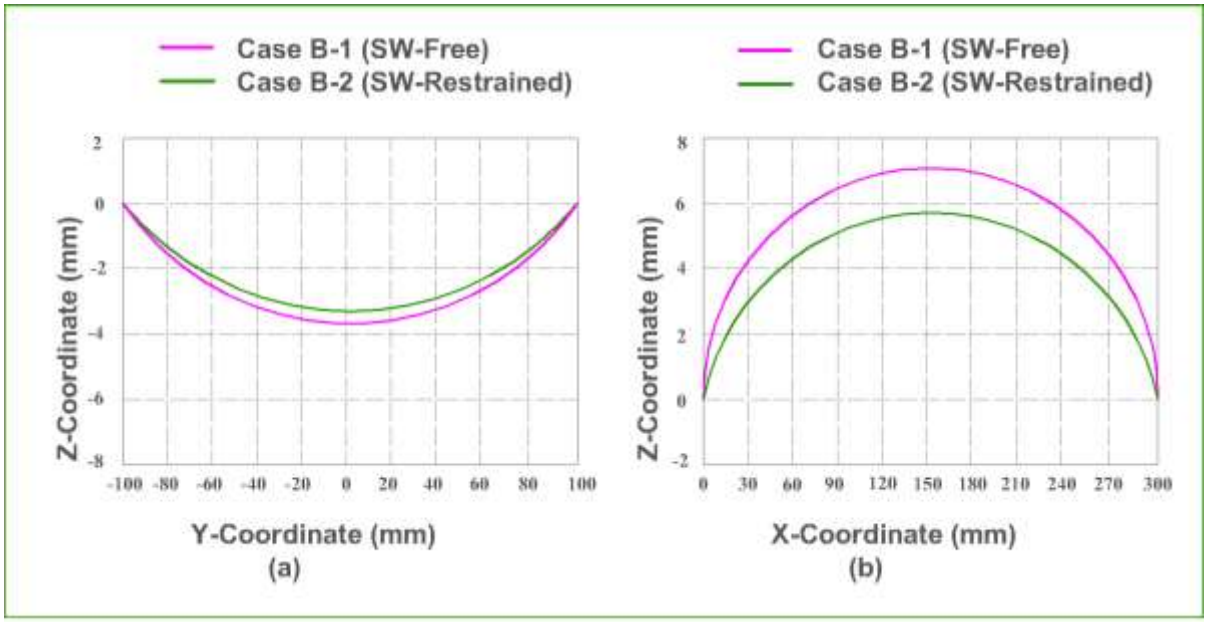
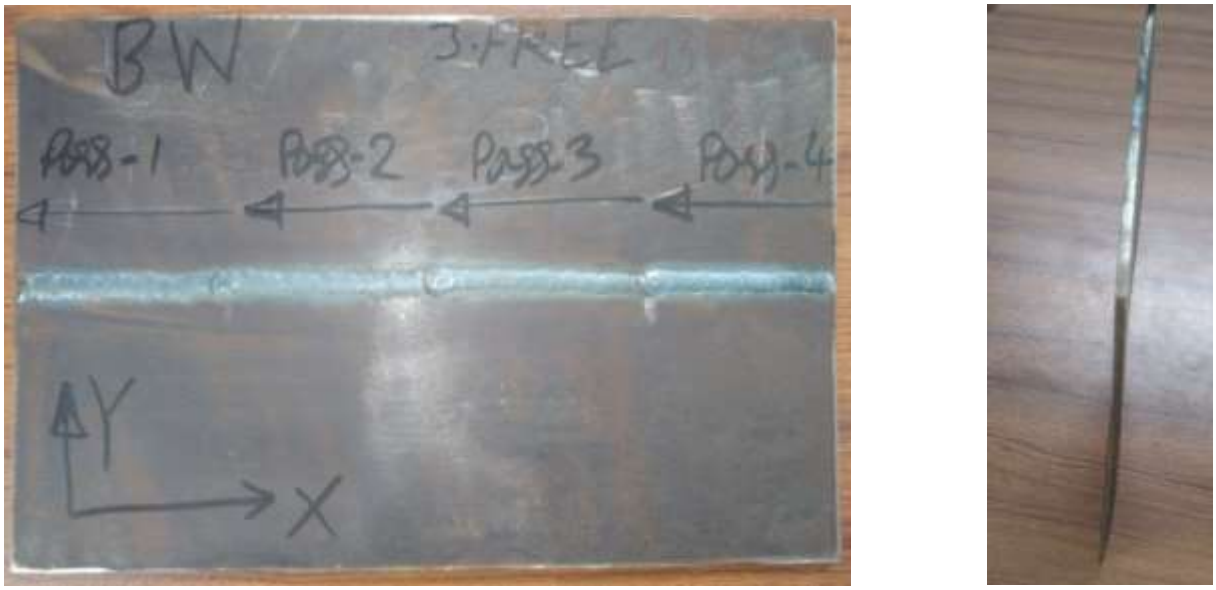


Fig. 10. Measured distribution of welding deflection in Group B: (a) along line 1 and (b) along line 2.

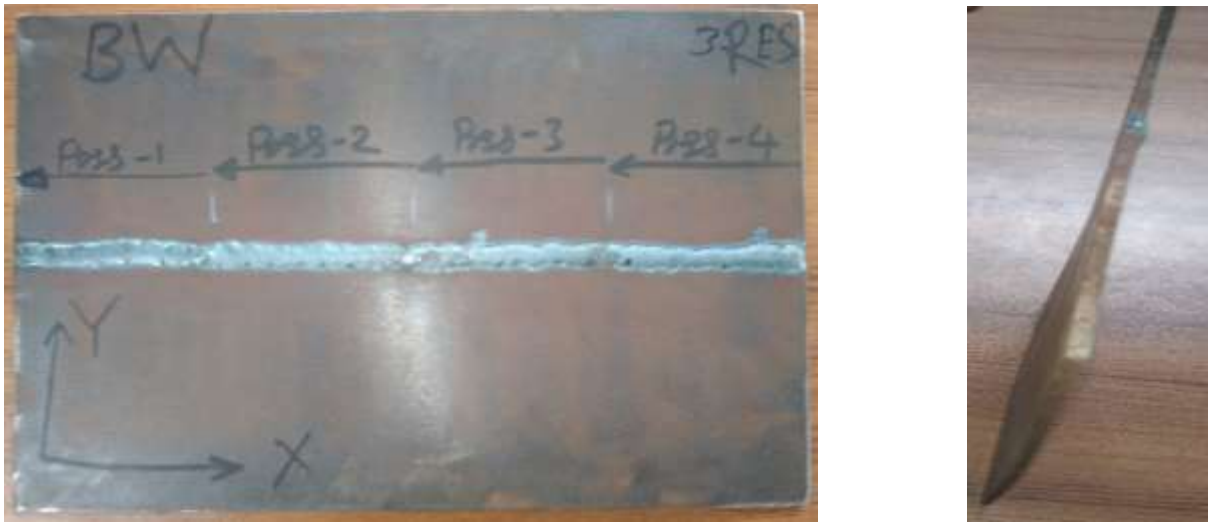
3.3 Back-step welding

Fig. 13 shows the measured welding deformation distribution in Group C. In Fig. 13, the deformation mode in cases C-1 and C-2 is the same, which is concave-convex type. Fig. 13 compares the measured welding deflection along line 1 and line 2. In Fig. 13a, angular deformity in Case C-2 (about 4 mm) is smaller than that in Case C-1 (around 5.7 mm). Nevertheless, the amount of longitudinal bending in cases C-1 and C-2 is about 7.6 mm and 6.5 mm, respectively.



(a) (b)

Fig. 11. After welding deflection of Case C-1: (a) Top view and (b) Side view.



(a) (b)

Fig. 12. After welding deflection of Case C-2: (a) Top view and (b) Side view.

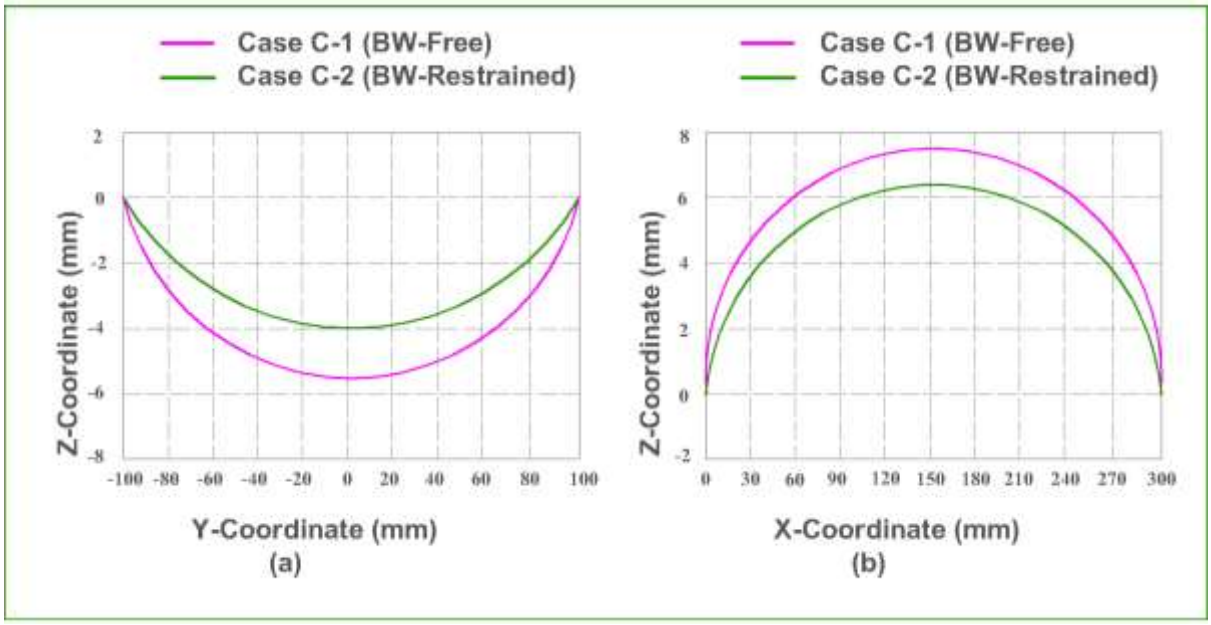


Fig. 13. Measured distribution of welding deflection in Group C: (a) along line 1 and (b) along line 2.

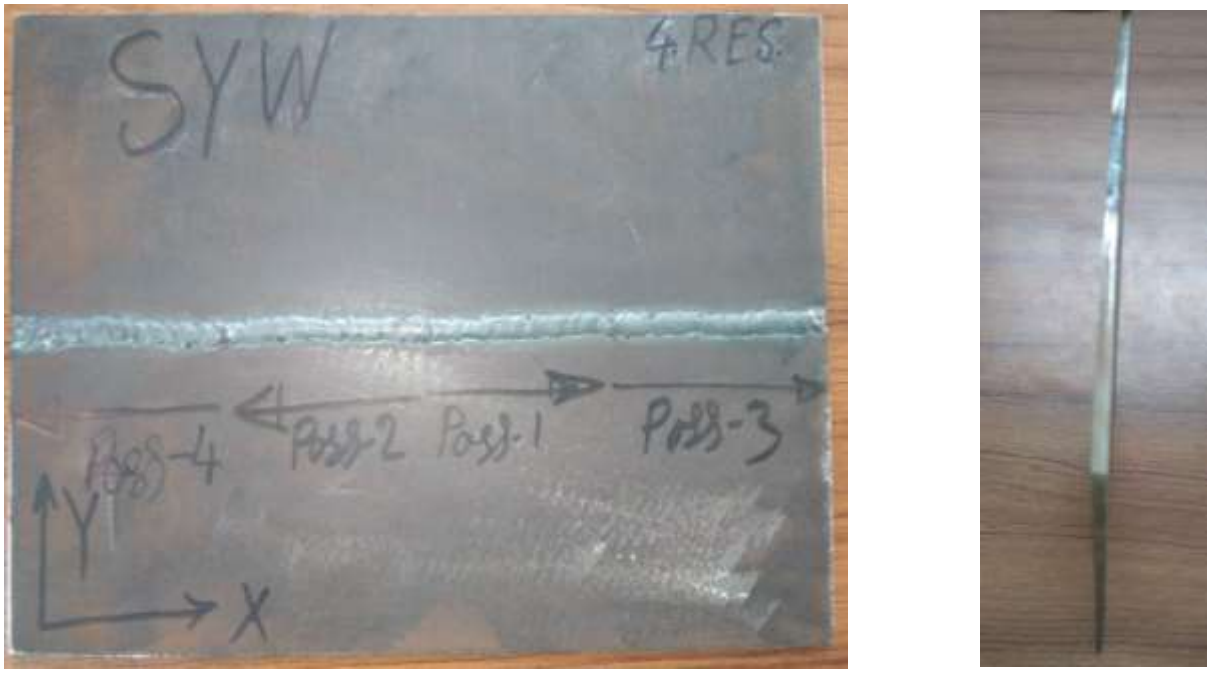
3.4 Symmetrical welding

In Fig. 16, Case D-1 shows the concave-convex bending deformity mode. Nevertheless, it should be mentioned that the bending deformity characteristic is not obvious here as the longitudinal bending is not apparent but the angular deformity is manifest. In Fig. 16, Case D-2 nearly has no welding deformation. Fig. 16 contrasts the measured welding deflection along line 1 and line 2 in Group D. From Fig. 16a, it can be found that the angular deformity in Case D-1 is about 1.9 mm, while that in Case D-2 is close to 0.4 mm. In Fig. 16b, the amplitude of longitudinal bending in Case D-1 (about 2 mm) is higher than that in Case D-2 (about 0.2 mm).



(a) (b)

Fig. 14. After welding deflection of Case D-1: (a) Top view and (b) Side view.



(a) (b)

Fig. 15. After welding deflection of Case D-2: (a) Top view and (b) Side view.

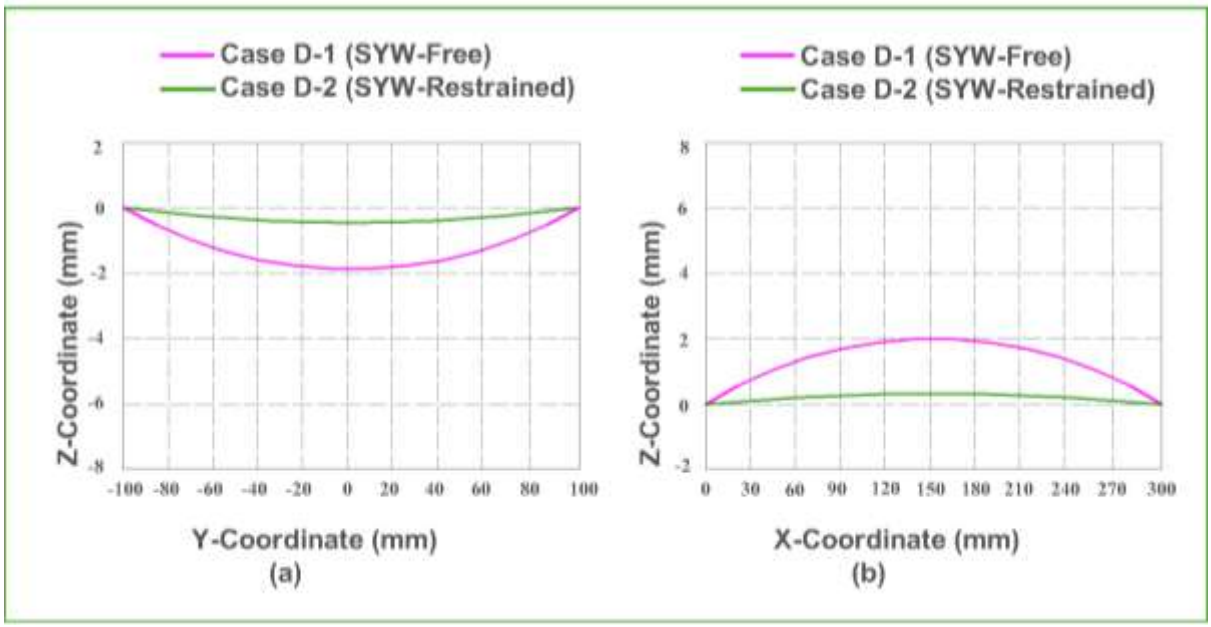
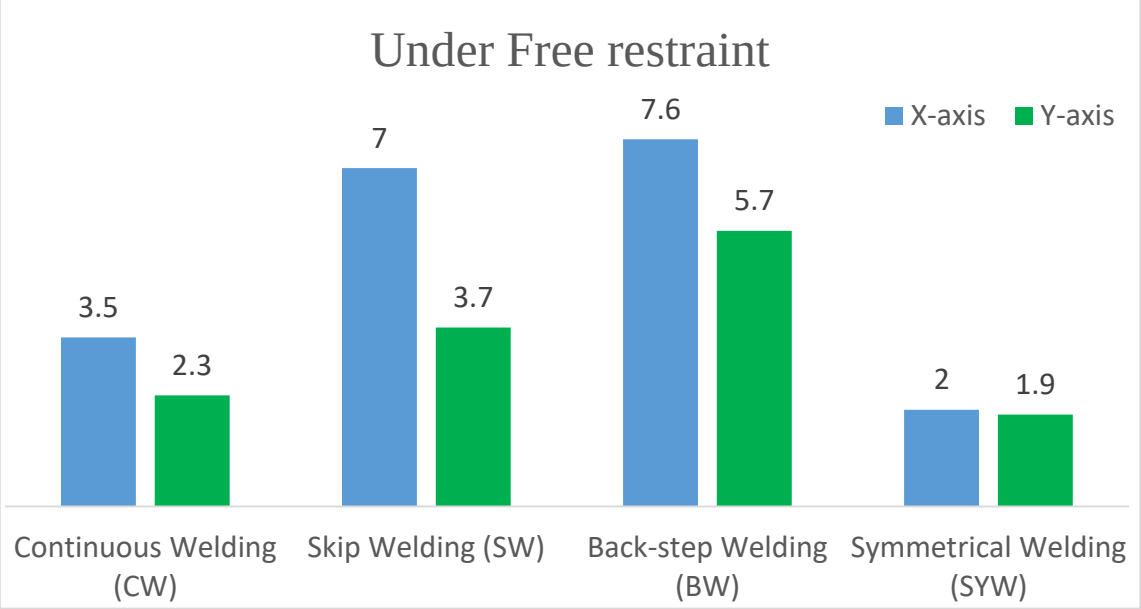


Fig. 16. Measured distribution of welding deflection in Group D: (a) along line 1 and (b) along line 2.

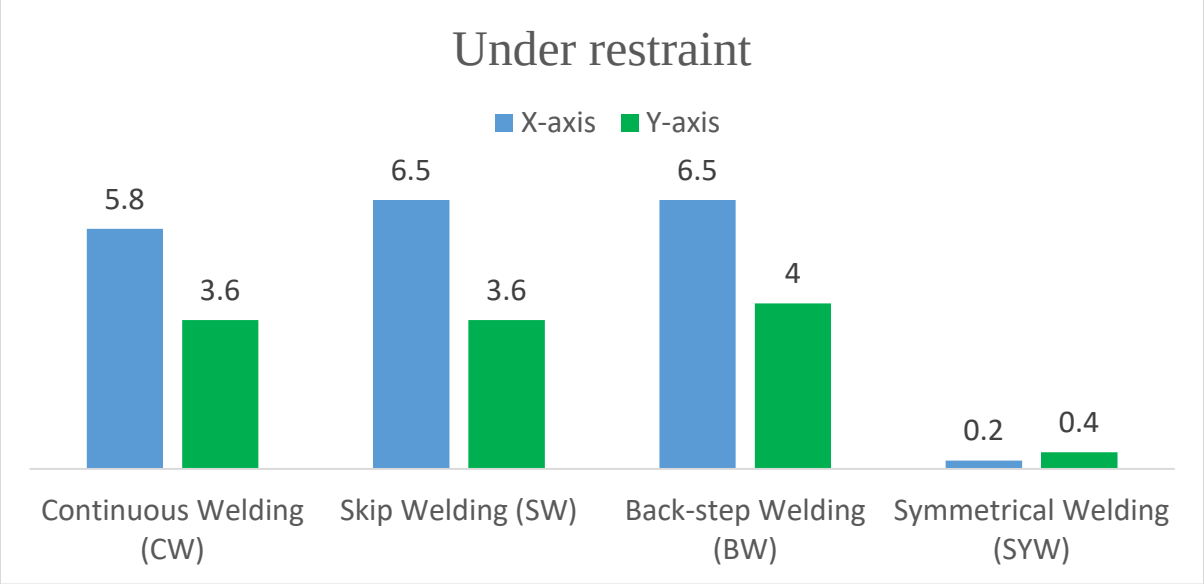
Table 5

Final (After Welding) deformation (mm).

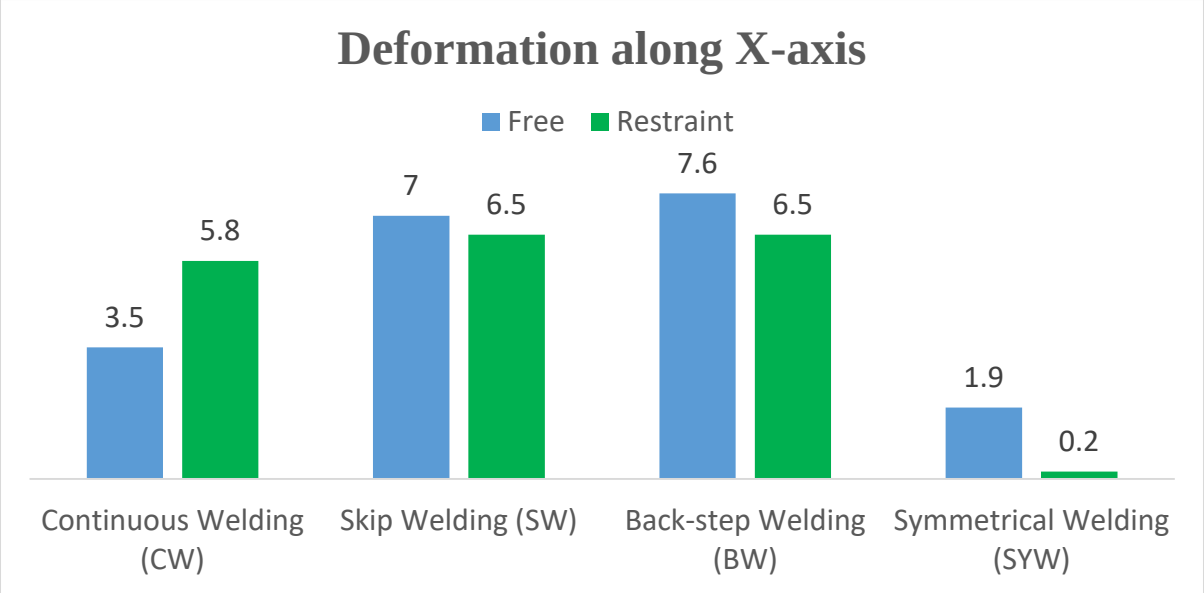
Sequence	Continuous Welding (CW)		Skip Welding (SW)		Back-step Welding (BW)		Symmetrical Welding (SYW)	
Axis	Free	Restrained	Free	Restrained	Free	Restrained	Free	Restrained
X	3.5	5.8	7	6.5	7.6	6.5	2	0.2
Y	2.3	3.6	3.7	3.6	5.7	4	1.9	0.4


Under Free restraint
X-axis
Y-axis
3.5
2.3
7
3.7
7.6
5.7
2
1.9
Continuous Welding (CW)
Skip Welding (SW)
Back-step Welding (BW)
Symmetrical Welding (SYW)

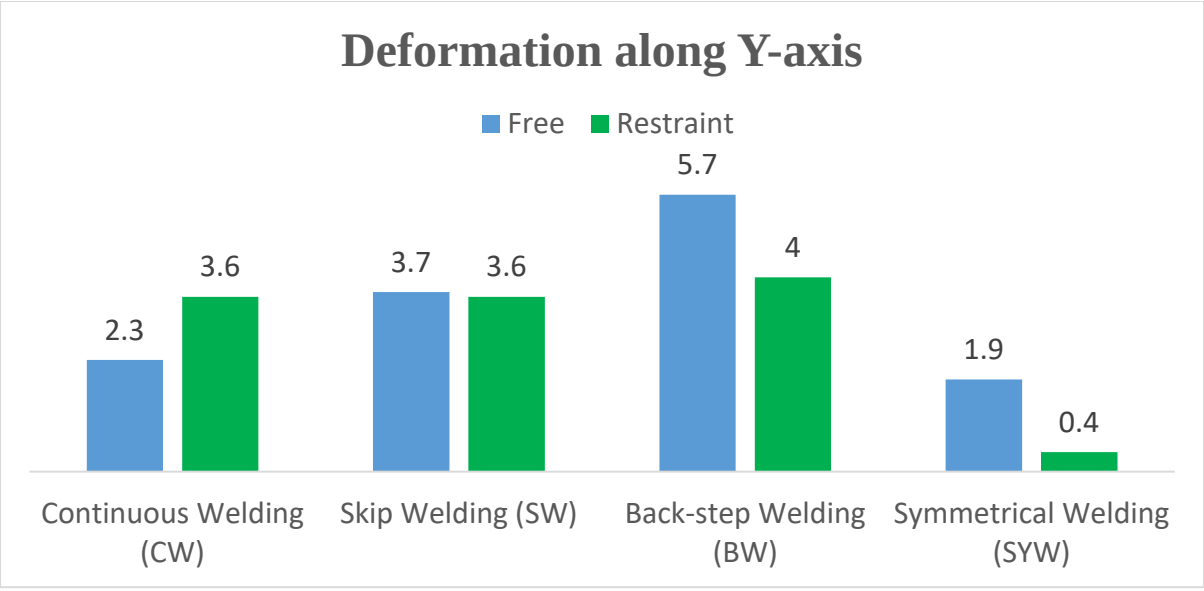
(a)


Under restraint
X-axis
Y-axis
5.8
3.6
6.5
3.6
6.5
4
0.2
0.4
Continuous Welding (CW)
Skip Welding (SW)
Back-step Welding (BW)
Symmetrical Welding (SYW)

(b)



(c)



(d)

Fig. 17. Deformation chart of welding sequences and Restraint (a) Under free restraint, (b) Under restraint condition, (c) Deformation along X-axis, and (d) Deformation along X-axis.

Chapter 4

Discussion

4.1 External Restraint

Angular deformity after welding in the case under the free condition is about 2.3 mm, 3.7 mm, 5.7 mm, and 1.9 mm, respectively. That under restrained condition is around 3.6 mm, 3.6 mm, 4 mm, and 0.4 mm, respectively. Obviously, the external restraint can considerably mitigate transverse bending. This is because the non-uniform welding temperature field distribution in the plate thickness direction generates angular deformity [24]. The high-temperature area at the top side is larger than that at the bottom side. In that case, the transverse thermal shrinkage at the top side is larger than that at the bottom during cooling under the free condition, which causes angular deformity. When the external restraint is applied during welding, the transverse restraint degree is highly enhanced. Then the transverse thermal shrinkage is strongly restrained during cooling. As a consequence, the tensile plastic strain is produced. That is why the angular deformity is significantly decreased by external restraint.

In Fig 16b, the external restraint has almost no impact on the magnitude of longitudinal bending. It is well known that longitudinal bending in thin-plate welded joints is generated due to the compressive loading and the low stiffness as seen in Fig. 18 [19]. If the welding is carried out under the free condition, the compressive loading is the longitudinal shrinkage force (tendon force) during cooling. Nevertheless, the longitudinal thermal expansion and contraction during welding in thin plates are both highly restrained when the external restraint is utilized. Furthermore, the generated compressive plastic strain during heating is higher than the produced tensile plastic strain during cooling [20]. Consequently, the longitudinal shrinkage still occurs when the external restraint is released at T_{RT} because of the generated longitudinal compressive plastic strain. In that case, the compressive loading is tendon force due to the thermal effect directly for the free condition, while that is the compressive plastic strain due to the thermal effect conversion for the restrained condition. Therefore, the longitudinal bending is not affected by external restraint here. Nevertheless, from Fig. 16b, one can see that bending. This is because the magnitude of longitudinal bending is related to the amount of compressive loading and its distribution [18], [19]. Since the angular deformity is very small as seen in Fig. 16a, which results in even compressive loading distribution below and above the neutral plane. Consequently, the amount of longitudinal bending in Fig. 16b decreases.

A question naturally arises why the very strong external restraint (see Fig. 4) here can not totally eliminate the transverse bending as in Figs. 7a, 10a, and 13a, although the transverse thermal shrinkage is highly constrained generating the tensile plastic strain (permanent deformation) here as explained before. This is because the remained transverse bending here is not from the non-uniform temperature field in the plate thickness direction anymore but from the bending effect. It is well known that the longitudinal shrinkage force (compressive loading)

causes the longitudinal bending in the thin-plate welded joints with low stiffness as mentioned before (see Fig. 18). To resist the bending tendency of the longitudinal strip, the transverse strip deflects out the plate in the plate thickness direction [3] generating the transverse bending synchronously. Combined with the produced longitudinal and transverse bending, the bending deformity is finally shown in the thin-plate welded components. It is known that the out-of-plane deflection generally consists of three types as seen in Fig. 19 [7]: (1) Type 1-transverse bending; (2) Type 2-longitudinal bending; (3) Type 3-bending deformity. Based on the above analysis, it can be deduced that the bending deformity in cases A-1 and C-1 under free condition is the "broad" one, which is the combination of Type 1 and Type 3 deflection. Nevertheless, that in cases A-2 and C-2 under restrained condition is the "narrow" bending deformity, which is equal to Type 3 deflection only. That means the Type 2 deflection can be removed by fittings here and the "broad" bending deformity in cases A-1 and C-1 changes back to the "narrow" one in cases A-2 and C-2.

When the external restraint is applied in welding thin-walled plates, the Type 1 deformity (if exists) can be reduced or even removed depending on the restraint degree/ location (Ma et al., 2015). Note that maybe there exists no Type 1 deflection if the temperature field is almost uniform in the thin-plate thickness direction. Nevertheless, the external restraint mainly affects the longitudinal compressive loading mode but not the amount almost as discussed before. Therefore, the thin-plate weldments generally snap back to bending again (called "bending recovering") when the mechanical fixturing is removed. Furthermore, the external restraint almost has no impact on the magnitude of Type 3 deflection.

This is because the generated upward warping by the former pass can be removed by the subsequent welding pass, no matter external constraint exists or not here.

4.2 Welding sequence

In Figs. 7b, 10b, 13b, and 16b, the magnitude of longitudinal bending in continuous welding, skip welding, back-step welding, and symmetrical welding under the free condition is about 3.5 mm, 7 mm, 7.6 mm, and 2 mm, respectively. Hence, the welding sequence can significantly affect the amount of longitudinal bending. Here, the longitudinal bending in symmetrical welding is the lowest, while that in back-step welding is the largest. Therefore, the longitudinal shrinkage force in back-step welding is the largest. For symmetrical welding (see Fig. 15a), the longitudinal shrinkage in pass 1 and pass 2 (or pass 3 and pass 4) is hindered interactively. In that case, the longitudinal compressive loading in the symmetrical welding is the lowest causing the minimum longitudinal bending. From Figs. 7a, 10a, 13a, and 16a, one can see that the angular deformity can be influenced by the welding sequence as well. The amount of transverse bending under the free condition using the symmetrical welding is the lowest (about 1.9 mm) and that using the back-step welding is the largest (about 5.7 mm). This is because the bending effect in symmetrical welding is the lowest as analyzed above. In the back-step welding (see Fig. 15a), the subsequent short pass next to the former short pass further shrinks in the transverse direction based on the former generated transverse shrinkage. However, it should be stressed that the welding sequence cannot eliminate the angular deformity mainly from Type 1 understood from Fig. 18

4.3 Avoidance of Bending Deformity

Restraint nearly cannot prevent the welding-induced bending deformity, while that can significantly mitigate or even eliminate the magnitude of transverse bending induced by the inhomogeneous temperature field in the thin-plate thickness direction. The welding sequence method can prevent bending deformity, but it cannot eliminate the transverse bending caused by the heterogeneous temperature field in the thickness direction.

It can be known that the bending deformity is either the “broad” one (Type 1 and Type 3) or the “narrow” one (only Type 3). If the welding temperature field is very even in the plate thickness direction, the Type 1 deflection is ignorable. In that case, the welding sequence method (symmetrical welding here) would be enough to remove bending deformity and the external restraint is not needed. That can be also very beneficial to reduce the risk of the formation of weld cracking as the application of fittings generally results in wide-high transient/ residual stresses. When there exist obvious non-uniform welding temperature fields, symmetrical welding combined with external restraint would be a very effective strategy to prevent and avoid out-of-plane deformation in thin-walled weldments (see Fig. 16b).

It should be mentioned that it is necessary to further clarify the impact of the heat input, short pass length, pass number, and ratio of weld to plate length on bending deformity for symmetrical welding. Furthermore, symmetrical welding introduces many stops and starts as seen in Fig. 8, which might increase the notch effect and then influence the fatigue strength. In the near future, it is interesting to further comparatively study the fatigue strength in thin-plate welded components using continuous and systematical welding.

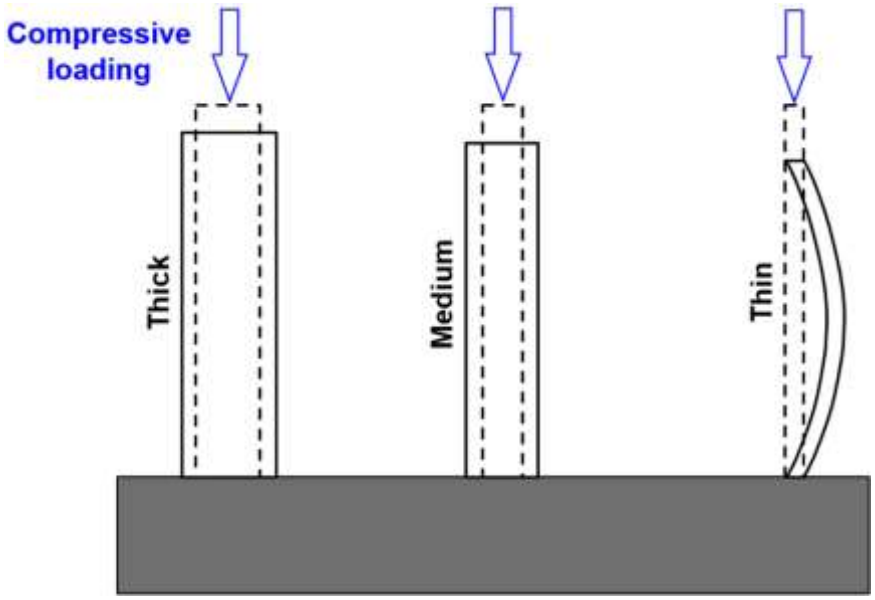


Fig. 18. Schematically representation of bending deformity mechanism [5].

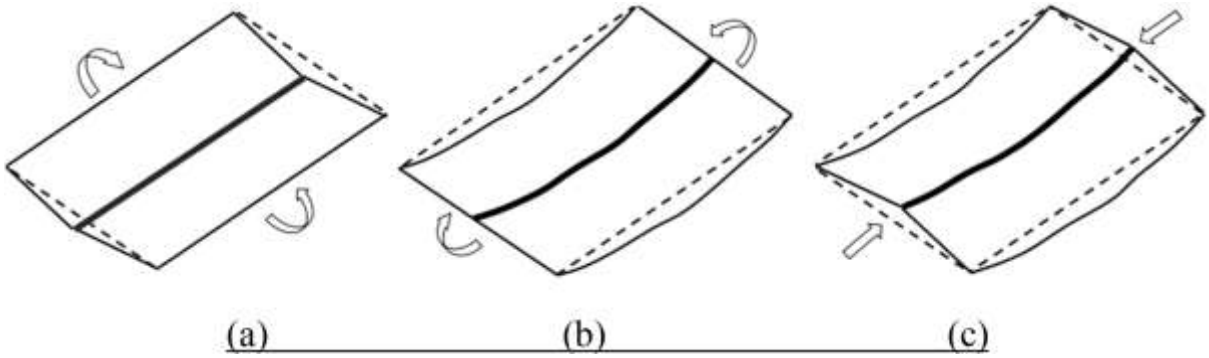


Fig. 19. Out-of-plane deformity types [7]: (a) type 1- transverse bending, (a) type 2- longitudinal bending, and (c) type 3- Bending deformity.

Chapter 5

Conclusions

(1) External restraint cannot prevent bending deformity in the thin-walled weldments, while it can significantly mitigate the amount of transverse (about 2-3 mm here) but not longitudinal bending.
(2) In the thin-plate welded components under the free condition, the appropriate welding sequence could prevent bending deformity.
(3) The welding sequence could not eliminate the transverse bending induced by the non-uniform temperature field in the thin-plate thickness direction.
(4) Symmetrical welding introduces both the lowest transverse (about 1.9 mm here) and longitudinal (about 2 mm) bending, while back-step welding generates the largest transverse bending (about 5.7 mm) and continuous welding produces the largest longitudinal bending (about 7.6 mm).
(5) Both external restraint and welding sequence could affect the bending deformity mode.
(6) For the thin-plate arc-welded components, symmetrical welding combined with external restraint is a very effective and practical strategy for the prevention of bending deformity.

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