Indian Journal of Engineering & Materials Sciences
Vol. 24, June 2017, pp. 201-206

Investigations on effect of direction of welding on distortion in combined butt and filled joint using finite element analysis

S Kumanan* & S J Vaghela

Department of Production Engineering, National Institute of Technology, Tiruchirappalli 620 015, India

Received 5 October 2015; accepted 9 February 2017

Weld distortion is one of the important quality measures. Because of non-linearity of variables and interaction among them, it is difficult to predict its behavior. In this study, a three dimensional thermo mechanical finite element analysis is carried out to understand effect of weld direction; and start and end points on angular distortion of combined butt and fillet weld joint using gas metal arc welding. Seven different weld sequences are considered to study the effects. The geometry is modeled using visual mesh and simulated using visual weld. Moving heat source is considered as double ellipsoidal volumetric heat source available in code. Results obtained from numerical analysis depict the effect of different sequences on angular distortion.

Keywords: Finite element analysis, Angular distortion, Weld sequence, Weld direction, Gas metal arc welding

Welding process is a multi-physic phenomenon and several physical cum chemical changes occur during the process. Due to rapid heating and cooling while welding, there is metal expansion and contraction in vicinity of weld area. The cooling process is a metal shrinkage process happen in three stages such as volume contraction in liquid stage, volume change during solidification and solid metal contraction[1]. The expansion of weld metal creates compressive force on material away from weld region and tension during contraction. The volumetric shrinkage in weld area and uneven forces generated on solidification result in distortion. The types of distortion are longitudinal shrinkage, transverse shrinkage, angular distortion, buckling and twisting. The longitudinal shrinkage occurs parallel to weld line, the transverse shrinkage occurs perpendicular to weld line and non-uniform metal contraction through thickness creates angular distortion. Controlling and predicting weld distortion is still a challenging task in manufacturing industries. Minimization of weld induced distortion is a decision to trade off among time, cost and other weld quality measures. The effect of welding distortion is studied under the following categories design related parameters, process related parameters, material related, pre-welding parameters and post-welding parameters as shown in Fig. 1. The effects of heat input, welding procedure, welding sequence, thickness of skin plate and stiffener spacing on distortion were analyzed by Deng and Murukawa[2]. Tsai *et al.*[3] detailed a comprehensive review on weld distortion, where the parameters were grouped as design related parameters such as plate thickness, stiffness spacing, number of attachments, mechanical constraints, assembly sequence; and process related parameters such as heat input, welding speed and welding sequence. The techniques to control distortion were also discussed in the review. Murugan and Gunaraj[4] analyzed effect of inter pass time, number of weld passes and wire feed rate on distortion and established that the inter pass time and wire feed rate were having inverse relationship with angular distortion. Number of passes has a direct effect on distortion. Deng *et al.*[5] studied about the distortion in fillet weld and concluded that thinner flanges are more prone to distortion than thicker ones and also observed that the effect of striking the arc and point of starting the welding influences the distortion. Murakawa *et al.*[6] studied effect of root gap and tack weld position on distortion for butt weld and fillet weld. Manurung *et al.*[7] numerically and experimentally analyzed distortion of combined butt and fillet weld using Sysweld software. Keivani*et al.*[8] in their work, considered nine different weld sequences to study the distortion and residual stresses and the effect of reversing weld direction and heat flux deposition over time along neutral axis were

*Corresponding author (email: kumanan@nitt.edu)

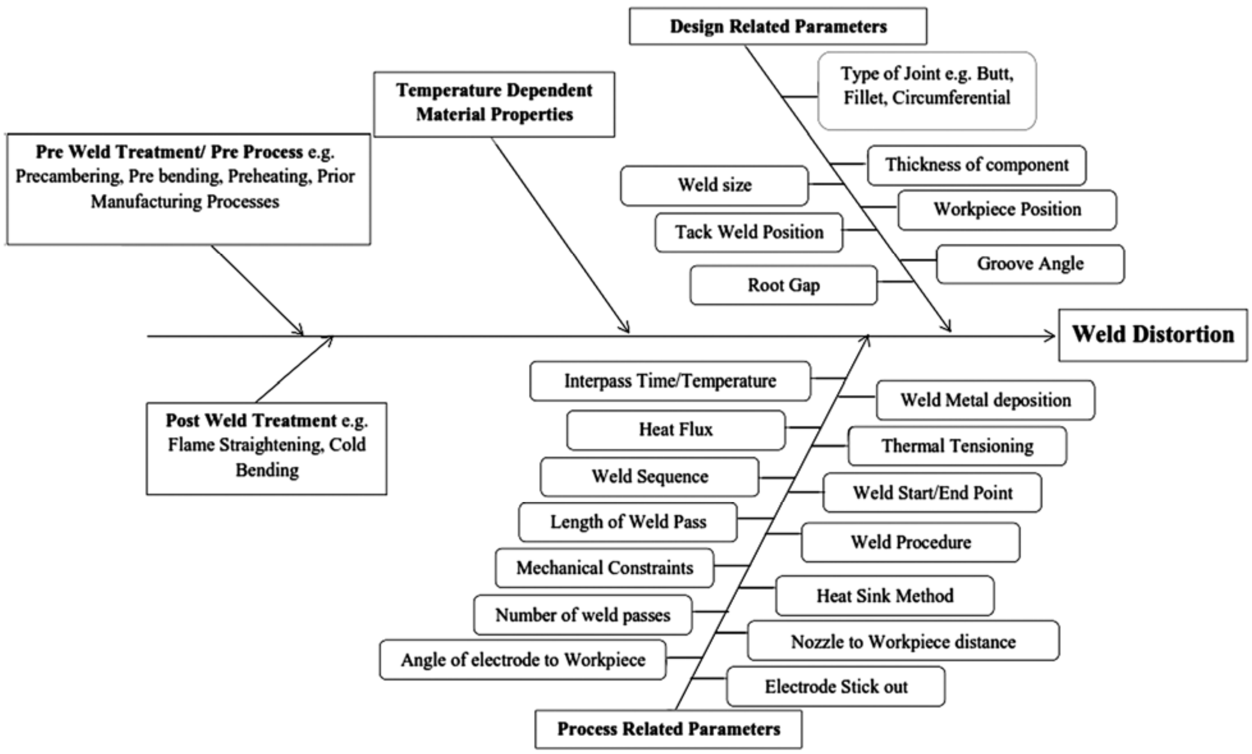

Fig. 1 — Factors affecting weld distortion

studied. It is observed that the distortion was minimum when welding was started from middle and carried towards end. Iranmanesh *et al.*[9] developed an algorithm to minimize distortion based on thermal simulation. It was observed that among other factors the change in weld sequence affects distortion. Selvan *et al.*[10] explained out of plane distortion mechanism for circumferential butt joint of boiler header-nipple and observed that the distortion in circumferential joint is different than that of the flat geometries. Welding direction; and start and stop point was found to have effect on out of plane distortion. Wen *et al.*[11] **s**tudied and analyzed before and after effects of submerged arc welding process using finite element modeling**.** Several attempts have been made to analyze distortion in butt weld and fillet weld. Limited attempts have been made to analyze distortion in combined butt and fillet joint[7,12-14].

Several techniques such as controlled preheating, heat sinking, thermal stretching, mechanical straightening, pre-bending, pre-cambering, post weld heat treatment have been attempted to control weld distortion in welded structures. Most of the mitigation techniques are costly and requires special attention and skills. As the complexity of geometry increases, the complexity of controlling and predicting of distortion also increases. Among the mitigation techniques, change in weld sequence could be a least expensive option. The effect of different weld sequences in the combined butt and fillet joint to reduce distortion needs attention. In this research, a finite element model is proposed and analyzed to study the effect of welding sequence on angular distortion for combined butt and fillet joint by gas metal arc welding. The focus is on development of an offline procedure to model and simulate the welding process and investigate the effect of the sequence and direction on angular weld distortion.

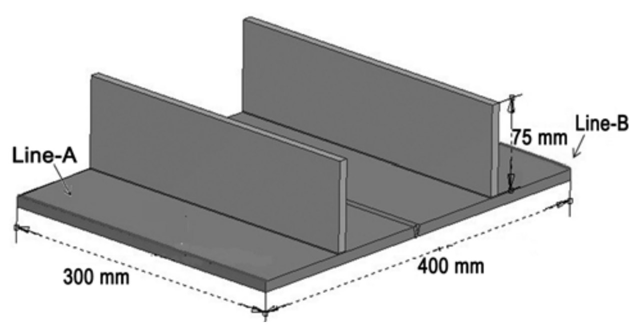

Fig. 2 — Geometry and displacement measurement line A and B in the combined butt and fillet joint weld model

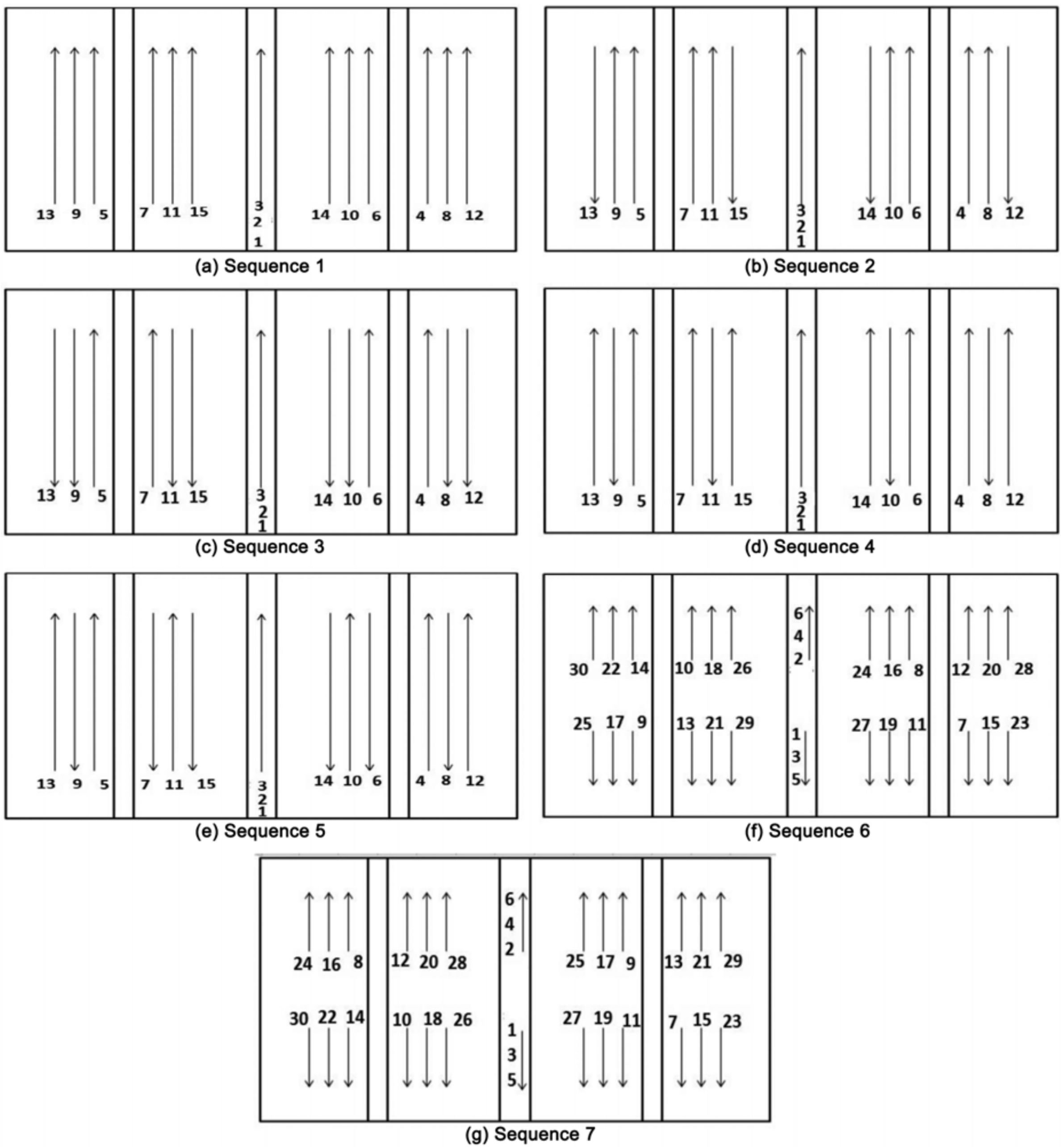

Fig. 3 — Investigated weld sequences for distortion analysis on combined butt and fillet weld joint

Proposed Finite Element Analysis

Finite element simulation and analysis were carried out in a decoupled approach using exclusive welding simulation software SYSWELD. Thermo-metallurgical, mechanical behavior and hardening laws are predefined in material library. The selected material type is S355J2G3[15] an equivalent to mild steel in term of carbon content, which contains 0.2% C, 0.55% Si, 1.6% Mn, 0.035% S and 0.035% P. The geometry was created using visual mesh. As shown in Fig. 2, dimension of flange and web are 200 × 300 × 9 mm and 75 × 300 × 9 mm, respectively. Length, width and thickness were considered to be in Y, X and Z directions, respectively. The weld sequences for combined butt and fillet joint are shown in Fig. 3. For sequence 1 to sequence 5 the model consists of total fifteen weld passes, three weld passes at butt joint and three passes at either side of each of the two webs. In sequence 6 and sequence 7, there total 30 numbers of weld passes: six passes at butt joint and 6 passes at either side of two webs. The base sequence will be as considered by Manurung *et al.*[7] In the second sequence as shown in Fig. 3(b) last four fillet weld passes were reversed so the temperature distribution may differ from the base sequence. For sequence 3, last eight passes have been reversed as shown in Fig. 3(c). As shown in Fig. 3(d) the sequence 4 can be considered as identical to sequence 2 as the number of passes in opposite direction are same as that of sequence 2. In this sequence instead of last four passes, the passes 8, 9, 10 and 11 were reversed. Sequence 5 was taken by reversing the direction of weld passes of sequence 4, which are lying between two webs, i.e., weld passes 6, 10, 14 and 7, 11, 15 as shown in Fig. 3(e). In sequence 6 and 7, the weld passes were divided into two sub-passes. Weld was started from mid plate and carried out towards the end point. In sequence 1 to sequence 5, the heat flux deposition is symmetrical to one axis, whereas in sequence 6 and 7 the heat flux deposition is symmetrical to two axes. The only difference between sequence 6 and 7 is that the distance between consecutive weld pass in sequence 7 is higher than that in sequence 6. Modelled seven sequences with suitable material properties and boundary conditions are then solved invidually. Fine mesh was created near weld and heat affected zone areas and coarser mesh away from weld vicinity to reduce computation time and to maintain accuracy. The mesh pattern is shown in Fig. 4. Same mesh pattern was used for all welding conditions. The heat source was modeled using Goldak double ellipsoidal heat source model suggested by goldak *et al.*[16], whose value can be calculated by Eqs (1) and (2).

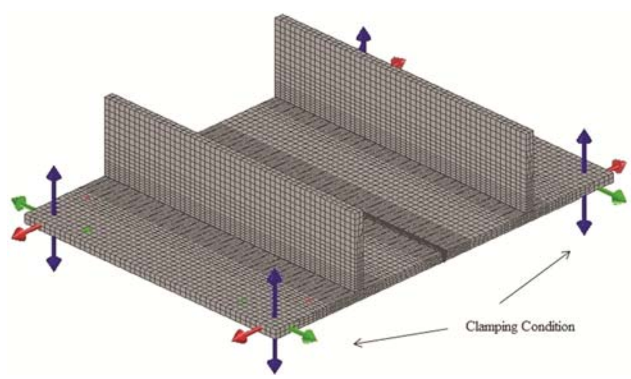

Fig.4 — Meshpattern and clamping condition in proposed Finite Element Analysis

$$q_f = \frac{6\sqrt{3} f_f Q}{a b c_f \pi \sqrt{\pi}} e^{-3\left(\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c_f^2}\right)} \quad \ldots (1)$$

Table 1 — Angular distortion

Position of point relative to Y direction	Left side of flange		Right side of flange	
	dz (mm)	θ (degree)	*dz* (mm)	θ (degree)
Front	2.13	0.65	1.41	0.43
Middle	2.82	0.87	5.31	1.64
End	2.13	0.65	1.53	0.47
$\bar{X}$	2.36	0.73	2.75	0.85

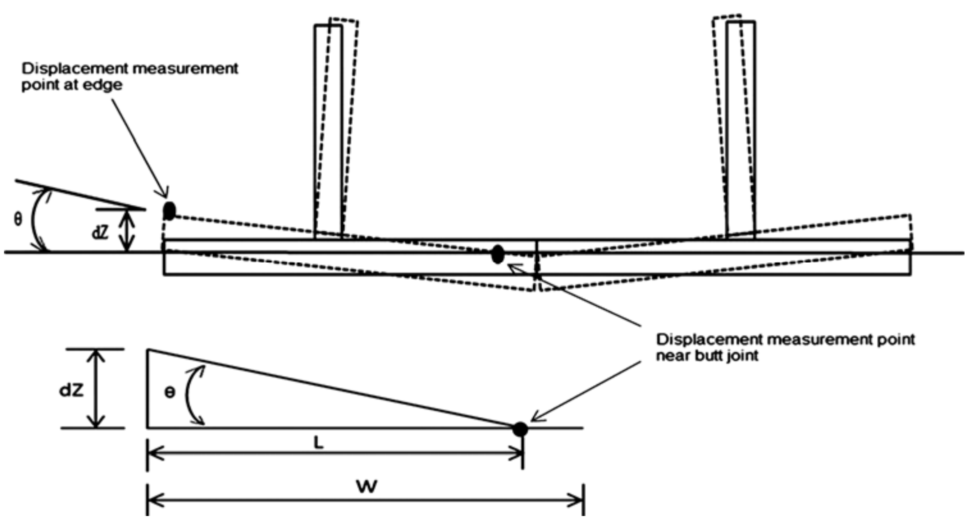

Fig. 5 — Displacement measurement to access the angular distortion in combine butt and fillet joint

Table 2 — Comparison of angular distortion of the proposed model with experimental values reported in literature

Sequence	Position	Experiment (degree) (Manurung *et al.*[7])	3 D analysis (degree) (Proposed FEA model)
Sequence 01	Left side of flange	0.88	0.73
	Right side of flange	0.92	0.85

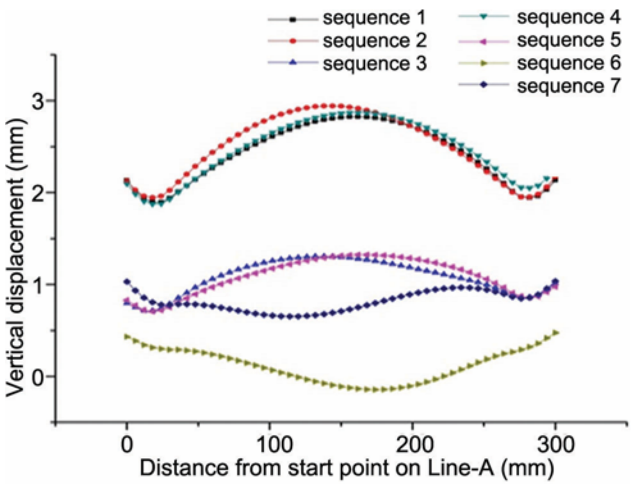

Fig. 6 — Vertical displacement along edge line A to access the angular distortion in combine butt and fillet joint

$$q_r = \frac{6\sqrt{3} f_r Q}{abc_r\pi\sqrt{\pi}} e^{-3(\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c_r{}^2})} \quad \ldots (2)$$

Where q_f and q_r are power density in front and rear quadrant of heat source. *a* and *b* are the width and depth of heat source respectively. Q is net heat input, which is given by product of arc power (*V*×*I*) and arc efficiency (η). $c_f$and c_r are fractional factor for heat deposition in front and rear quadrant respectively. Thermal boundary condition; Heat transfer from specimen to atmosphere was modeled by Eq. (3).

$$Q = h_{conv}(T_s - T_\infty) + \varepsilon\sigma(T_s - T_\infty) \quad \ldots (3)$$

Where, h_{conv} is heat convection transfer coefficient, ε is thermal emmisivity, σ is Stefan Boltzmann's constant, T_s is body temperature and T_∞ is surrounding temperature. Heat transfer in specimen is given by Fourier's law of heat transfer by Eq (4).

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right) + Q \quad \ldots (4)$$

Table 3 — Experimental validation on angular distortion of flange and web on combined butt and fillet joint using GMAW

Position		Average angular distortion (degree) Experiment	Simulation
Flange	Left side	0.79	0.71
	Right side	0.77	0.68
Web	Left side	-1.17	-1.22
	Right side	-0.53	-0.48

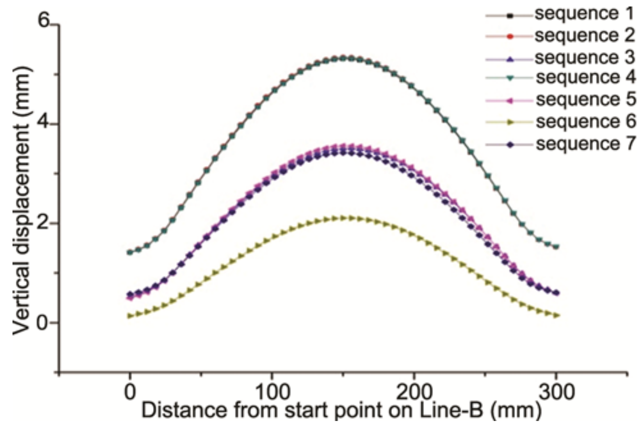

Fig. 7 — Vertical displacement along line-Bto access theangular distortion in combine butt and fillet joint

Where, ρ is density C_p is specific heat, k is thermal conductivity and Q is internal heat source. The specimen is clamped at four points in all direction as shown in Fig. 4**.** The clamping condition is common in all welding conditions.

Results and Discussion

Displacement was measured along Line-A and Line-B in Z direction, as shown in Fig. 2**.** Three points at front, middle and at the end are chosen on each line. Angular distortion was calculated as explained by Manurung *et al.*[7] using formula $\theta=\sin^{-1}(dz/L)$, as shown in Table 1, where *dz* is displacement in Z direction of point and *L* is the distance as shown in Fig. 5**.** These three angular distortion values are averaged on the left side and right side; and used to validate the proposed FEA model as shown in Table 2. The angular distortion along Line-A and Line-B is given in Fig. 6 and Fig. 7, respectively. As it can be seen from Fig. 2**,** Line-A is on left side and Line-B is on right side to the flanges. From Fig. 6 it can be seen that, the maximum deflection on Line-A was found 2.94 mm for sequence 2. Minimum deflection was found -0.14 mm for sequence 6. For sequence 1 to 5 there is a common trend in distortion, at start and end point it is low, and at the middle point is high. Distortion for sequence 1, 2 and 4 was found almost similar, where in sequence 3 and sequence 5 it's almost half of sequence 1 (2 or 4). The trend in sequence 6 and sequence 7 is different from other sequences. In middle the distortion value is less compared to start and end point. In overall, distortion for sequence-6 is least on left side. For Line-B, from Fig. 7, maximum deflection was found 5.34 mm for sequence 2, and minimum was 0.13 mm for sequence 6. The trend of deflection was same as that of left side for sequence 1 to sequence 5. Distortion of sequence 1, 2 and 4 is similar, distortion of sequences 3, 5 and 7 are also similar but less than that of sequence 1, 2 and 4. Distortion for sequence 6 is found to be least on the right side. On both sides sequence 1, sequence 2 and sequence 4 have higher distortion than sequence 3 and sequence 5. This can be concluded as the heat flux in opposite direction for sequence 1, sequence 2 and sequence 4 is same. For sequence 3 and sequence 5, heat flux deposited in reverse direction is more than that of sequence 1(sequence 2 or sequence 4). From Figs 6 and 7, it can be inferred that values on right side are more than that of left side. The joint is asymmetrical. The difference of maximum values on right side and left side was found to be maximum as 2.48 mm and as minimum 1.63 mm. Hence for least asymmetry, sequence-6 was found best among selected sequences. Different distortion patterns resulted from different sequences suggest that, there is influence of welding direction on distortion. For the given set of sequences, from sequences 1 to sequence 5, the heat flux application was symmetrical about Y axes, while for sequence 6 and sequence 7 it is symmetrical along X axes also. Distortion trend for sequence 6 and sequence 7 is similar but the magnitude of sequence 7 is higher than sequence 6. The large distance between start of consecutive weld reduces distortion. For both sides left and right, sequence 6 has resulted less distortion. Hence it can also be said, symmetrical heat flux deposition about neutral axes over time results in reduction in distortion.

Validation of proposed model

Two test samples were fabricated as combined butt and fillet joint using gas metal arc welding with established parameters. The base sequence and the best sequence reported by the proposed FEA model were adopted. The distortion was measured in the flange and on the web using coordinate measuring machine and reported in Table 3. It is inferred from the table that the simulation model agrees well with experimental observations for both flange and web side distortions.

Conclusions

A finite element method is proposed and used for the analysis of weld distortion. A combined butt and fillet weld joint is fabricated using gas metal arc welding to understand the intricacies of the process and the data were forwarded for further processing in finite element modelling. In combined butt and fillet joint for a given clamping conditions the welding direction and heat flux deposition along neutral axis affects the angular weld distortion of flange and web. In combined butt and fillet joint the distance between consecutive weld passes was found to have an effect on weld distortion. The distortion was found less when the distance between consecutive weld pass is more. The proposed method could be extended to complex structures fabricated with different welding processes with multiple joints.

References

1 Gourd L M, *Principles of Welding Technology* (Edward Arnold, London), 1995.
2 Deng D & Murakawa H, *Comput Mater Sci*, 43 (2008) 591-607.
3 Tsai C L, Park S C & Cheng W T, *Weld J*, (1999) 156s-165s.
4 Murugan VV & Gunaraj V, *Suppl Weld J*, (2005) 165s - 171s.
5 Deng D, Liang W & Murakawa H, *J Mater Process Technol*, 183 (2007) 219-225.
6 Murakawa H, Sano M & Wang J, *Trans JWRI*, 41 (2012) 65-70.
7 Manurung Y H P, Lidam R M, Rahim M R, Zakaria M Y, Redza M R, Sulaiman M S, Tham G & Abas S K, *Int J Press Vessel Pipe*, 111-112 (2013) 89-98.
8 Keivani R, Jahazi M, Pham T, Khodabandeh A R & Afshar M R, *Int J Adv Manuf Technol,* 73 (2014) 409-419.
9 Iranmanesh M, Azad N & Zabihpoor M, *Ships and Offshore Struct*, 9 (2014) 489-497.
10 Selvan R V, Sathiya P & Ravichandran G, *J Manuf Process*, 19 (2015) 67-72.
11 Wen S W, Hilton P & Farrugia D C J, *J Mater Process Technol*, 119 (2001) 203-209.
12 Lidam R N, Manurung Y H P, Haruman E, Redza M R, Rahim M R, Sulaiman M S, Zakaria M Y, Tham G, Abas S K, Chau C Y, *Int J Adv Manuf Technol*, 69 (2013) 2373-2386.
13 Manurung Y H P, Sulaiman M S, Abas S K, Tham G & Haruman E, *Int J Adv Manuf Technol*, 77 (2015) 775-782.
14 Gannon L, Liu Y, Pegg N & Smith M, *Mar Struct*, 23 (2010) 385-404.
15 *SYSWELD Reference Manual,* 2012.
16 Goldak J, Chakravarti A & Bibby M, *Metall Mater Trans B*, 15 (1984) 299-305.