Thermo Mechanical Analysis of Multipass Butt-Welded Joints by Finite Element Method

T. Raja, P. Anand, M. Sundarraj, M. Karthick, and A. Kannappan

Abstract Welding is an unswerving and competent metal joining process broadly used in industries. Residual stresses and distortion are most important challenges to the safety of system and constructions of butt-welded joints. The difficulties of the archaic measurement of residual stress are time intense and destructive. A three-dimensional fleeting thermomechanical analysis of butt-welded joint has been performed using FEM method in two steps to forecast the residual stresses and distortion. The first step is fleeting thermal analysis that yields dynamic temperature distribution throughout weld and the plates. The next step is the mechanical analysis which yields the residual stress, strain and displacement. It comprises of moving heat source, metal plasticity and elasticity has done during the material deposition, temperature dependent on material properties, element true and death technique was used for filler metal deposition in ANSYS software.

Keywords Dynamic temperature distribution · Residual stresses · Distortion · Butt-welded joints · ANSYS software

1 Introduction

Arc welding method is used to join the plates in butt joints, [1]. The results of tensile stress with the depositions of weld beads and the relation between maximum temperature and the residual stress in the welded metal pass were discussed. X-ray diffraction technique was used to measure stresses in the welded plate, [2]. The nodal displacements were measured in both welding simulations. The elastic-plastic analysis was used to measure structural displacement of the material [3]. In another work, three-dimensional model is used to predict the residual stress and distortion induced in laser beam welding of circumferential-welded pressure vessel simulated in aluminium butt-welded joint, [4]. To measure the residual stress in pressure vessel

T. Raja (✉) · P. Anand · M. Sundarraj · M. Karthick · A. Kannappan
Department of Mechanical Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai 600062, India
e-mail: rajasd28@gmail.com

L.-J. Yang et al. (eds.), *Proceedings of ICDMC 2019*,
Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-3631-1_15

joint used keyhole drilling method, numerical results are agreed with experimental results and analysed the residual stresses on a welded tee joint plate using contour method, [5]. Plain carbon steel plates and gas metal arc welding process are used. It is observed cutting a welded joint, deformations occurred at the cut surfaces as a result, relaxation of residual stresses are measured, [6]. The TIG welding distortions in austenitic stainless steel welded plate are compared with numerical results. In this analysis, coordinate measuring machine was used to measure the distortion in thin welded plates, [7]. A residual stress and distortion are generated when welding a flat bar-stiffened steel plate. In this analysis, Gaussian surface heat flux was used as a moving heat source. Combined convection and radiation boundary conditions are used for heat losses during and after welding, [8]. From the above motivation, to determine the residual stress, structural and thermal analysis of butt welded joints for 304 duplex stainless steel material plate by applying element.

2 Experimental Method

In this work, the arc welding was used for joining the two plates. The temperature is more in the area near the welding torch; this area expands more than regions further away. During the heat input, stresses in the area near to welded joint are compressively in plastic stage because the thermal growth in this area is controlled by adjacent metal with less temperature and more yield stress. The process of welding has been finished, and welded plate starts to cool; then, its deformation was in reverse direction. As a result of compressive plastic strains was formed in the area near welded region, the deformation of welded plate during and after the joining process is shown in Fig. 1.

Both the residual stresses and deformations are associated with each other. These residual stresses exist in a body if there are no external loads or body forces. Plastic deformation is one of the sources which occur in many manufacturing processes.

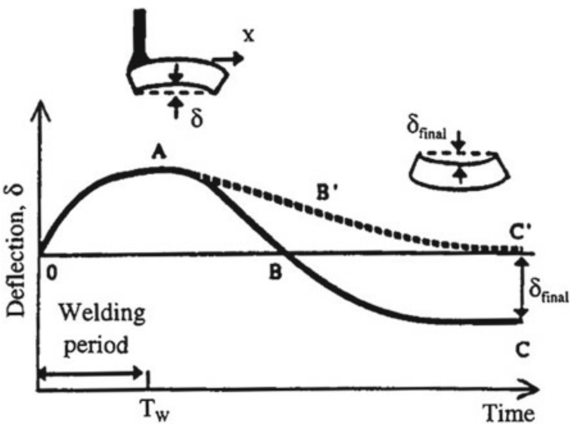

Fig. 1 Deformation during and after weld

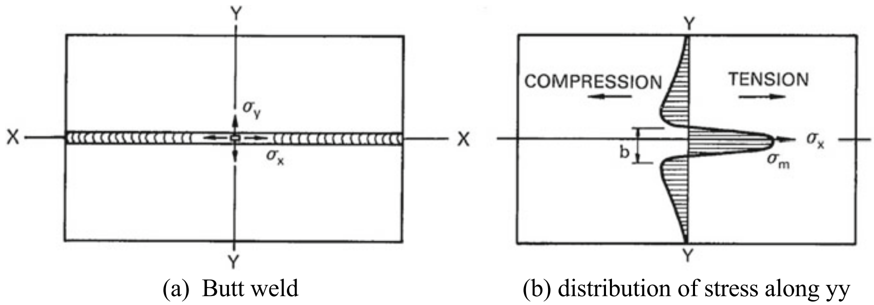

Fig. 2 **a**, **b** Residual stress distribution in butt-welded joint

Non-uniform plastic deformation occurs, if an initially stress-free body is subjected to loading, [9]. The body will elastically unload when these loads are removed. After all loads were removed, the stresses remaining are the residual stresses, which are smaller or equal to than the yield stress existing after the weld has completely cooled. Distortion and residual stresses are two faces of same problem, namely thermally induced plasticity. To control the residual stress and distortion is crucial in manufacture of welded structure. A typical distribution of longitudinal residual stress in butt-welded joint is shown in Fig. 2a, b; these stresses are parallel to the welding direction.

In this experimental study, duplex stainless steels (DSS) are used as welding joint. The matching filler metal is used where a welding was performed, whereas welds made with the filler metal enriched with nickel were used in as-welded condition. The weld metal microstructure from a composition exactly matching that of the parent steel will contain high ferrite content. The increase in nickel is made to improve the as-welded phase balance and increase austenite content. Furthermore, traditional trial and error approach is costly and time consuming. Numerical simulations based on finite element (FE) models provide a very suitable tool for investigating the thermal and mechanical consequences of welding process. FE simulation techniques for welding processes have been a major topic in welding research for several years, [10–12].The availability of 64-bit high-performance computing machines and enhanced finite element computational techniques has made it possible to simulate temperature fields developed from welding process. The computer simulation of welding processes enables the welding engineers to predict transient and residual stress fields and deformation behaviour of welded structures. These can be further used for the evaluation of structural misalignments and premature failures due to in service loads and weld-induced residual stresses.

3 Result and Analysis

3.1 3D Modelling of Welding Joint

In these modelling techniques, solid modelling as well as finite element modelling is created. In solid modelling, the graphical entities are used such as key points, lines, areas and blocks (Fig. 3).

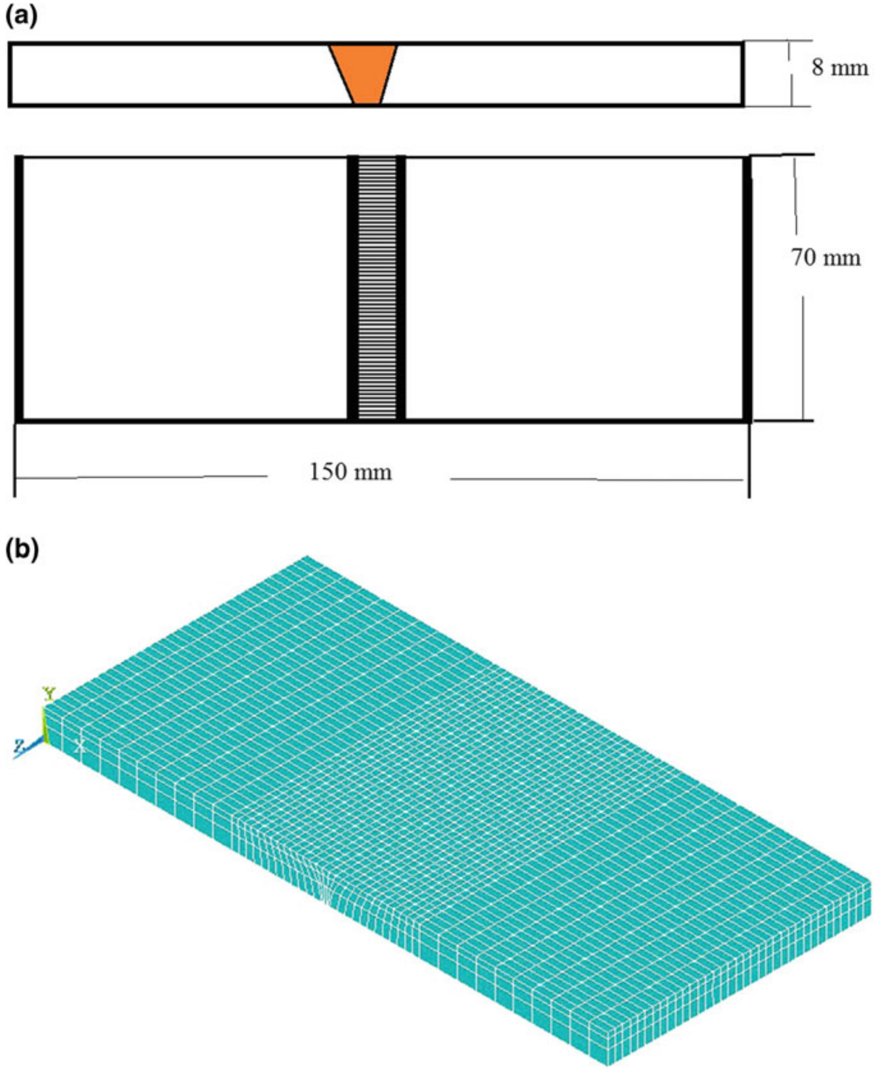

Fig. 3 **a** CAD model of weld plate, **b** finite element model of weld plate

3.2 Heat Source Modelling

A heat input during welding process with particular path on top of the work piece material fusion process was done. Residual stresses, distortion and reduced strength of structures directly from the thermal series are caused by localized strong heat input (Table 1).

General heat conduction for constant thermal conductivity:

$$\frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{x}^2} + \frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{y}^2} + \frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{z}^2} + \frac{\boldsymbol{q_g}}{\boldsymbol{k}} = \frac{\boldsymbol{\delta c}}{\boldsymbol{k}} \frac{\partial \boldsymbol{T}}{\partial \boldsymbol{\tau}}$$

$$\frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{x}^2} + \frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{y}^2} + \frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{z}^2} + \frac{\boldsymbol{q_g}}{\boldsymbol{k}} = 0$$

$$\frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{x}^2} + \frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{y}^2} + \frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{z}^2} = 0$$

The finite differential equation for x-, y- and z-axis is

$$\frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{x}^2} = \frac{\boldsymbol{T}(\boldsymbol{i}+1, \boldsymbol{j}, \boldsymbol{k}) - 2\boldsymbol{T}(\boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}) + \boldsymbol{T}(\boldsymbol{i}-1, \boldsymbol{j}, \boldsymbol{k})}{\boldsymbol{\Delta x}^2}$$

$$\frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{y}^2} = \frac{\boldsymbol{T}(\boldsymbol{i}, \boldsymbol{j}+1, \boldsymbol{k}) - 2\boldsymbol{T}(\boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}) + \boldsymbol{T}(\boldsymbol{i}, \boldsymbol{j}-1, \boldsymbol{k})}{\boldsymbol{\Delta y}^2}$$

$$\frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{z}^2} = \frac{\boldsymbol{T}(\boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}+1) - 2\boldsymbol{T}(\boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}) + \boldsymbol{T}(\boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}-1)}{\boldsymbol{\Delta z}^2}$$

Figure 4 shows the three-dimensional view of heat sources. From the figures, the heat flux is maximum at centre of the arc. The heat flux value gradually decreased away from the centre arc (Figs. 5 and 6).

Table 1 Experimental results for heat source model

x-coordinate from centre of arc (1×10^{-3} m)	z-coordinate from centre of arc (1×10^{-3} m)	Heat flux (W/m^2)
0	0	198,625,369
1	1	101,977,664
2	2	13,801,176
3	3	492,343
−1	−1	101,977,664
−2	−2	13,801,176
−3	−3	492,343

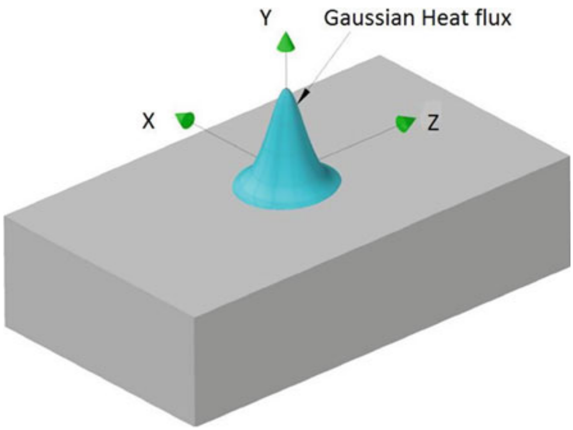

Fig. 4 Distribution of heat source

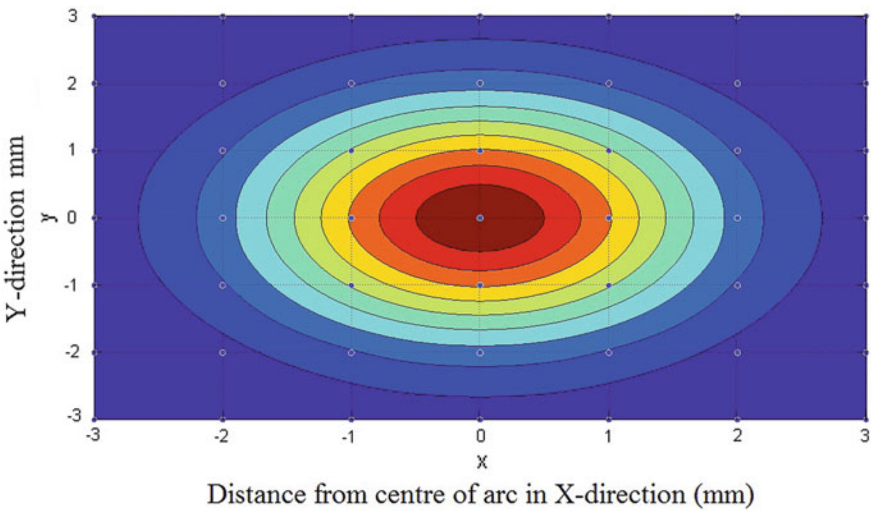

Fig. 5 Two-dimensional view of heat source model

3.3 Factor Birth and Death Process

The element death effect, by the ANSYS software, deactivates the element by multiplying their stiffness by a reduction factor. That the severe factor was set to 1.0E-6 by default, [13, 14]. Similarly, the other elements like specific heat, damping and mass deactivated by the elements are set to zero. The mass and energy of killed elements are not added over the model, and the strain value also is to zero; then, the

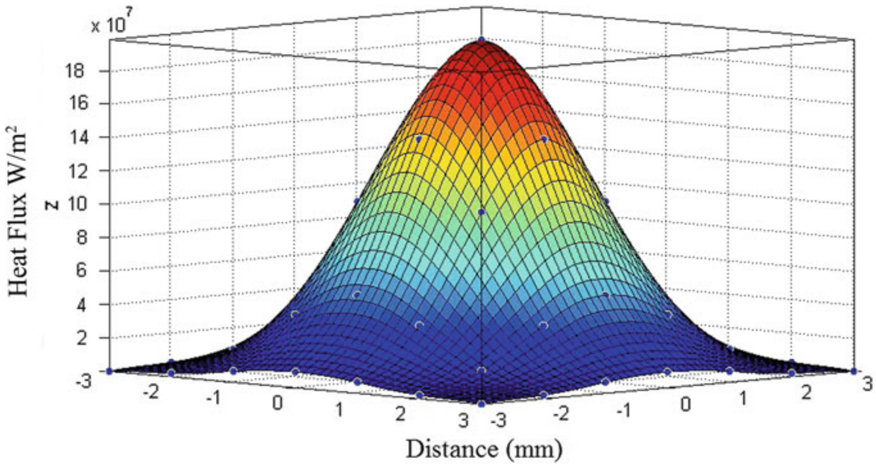

Fig. 6 Three-dimensional view of heat source

process of element deactivated was quick reaction. The element birth process was not actually added to the model; the elements are reactivated like, temperature, mass, stiffness. So that the element birth technique which was the factor of the model is simply reactivated, and the death technique which was the factor is deactivated from the model.

Figure 7 shows the FEM of weld plate with weld pool elements. Figure 8 shows that the weld pool elements are deactivated for filler metal deposition and temperature of plate is 300 K. The temperature distribution analysis during the welding and cooling at different time periods is shown in Figs. 7 and 8.

Welded plate returns to room temperature after cooled for more than one hour. The temperature is suddenly dropped after the welding, but more time is taken to drop temperature from 350 to 300 K.

3.4 Solving the Structural Analysis

The nodal temperatures were obtained from thermal analysis which is applied for the structural analysis to predict the residual stress and distortion in welded joint. In thermal analysis, nodal temperature distribution alone predicted, [15, 16]. In this analysis, full Newton–Rapson method is used to update the stiffness matrix. It is also used in thermal analysis.

The total strain was calculated by assembling the elastic strain, plastic strain and thermal strain. For the elastic-plastic analysis or thermomechanical analysis for calculating the elastic and plastic strains, rate-independent bilinear isentropic

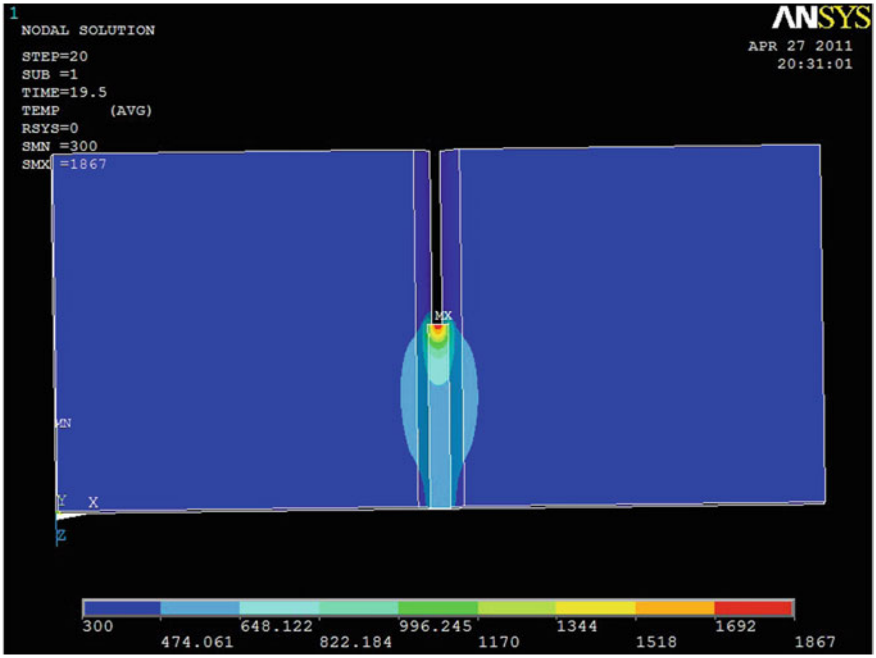

Fig. 7 Temperature distribution of first pass $t = 19.5$ s

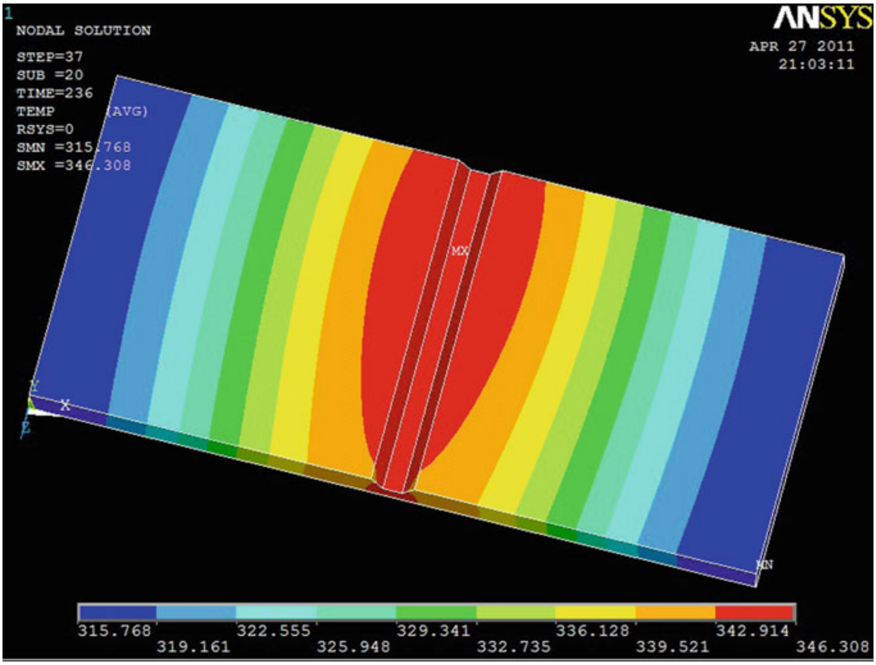

Fig. 8 Temperature distribution during cooling $t = 236$ s

hardening rule was considered. The thermal strain was calculated by its thermal expansion described in equation.

During the heating phase, the metal is heated from room temperature to higher temperature. So, the metal expands during the heating phase due to its coefficient of thermal expansion; distorted weld plate during heating phase is shown in Fig. 8. During the cooling phase, hotter regions in the weld plate produce shrinkage. Due to this shrinkage, the metal is distorted in the opposite direction of heating phase, shown in Fig. 9. This is called as welding distortion. The vertical displacement of welded plate is shown in Fig. 10. In this vertical displacement, both edge plates move upwards because the centre of weld plate is the hotter region during welding. During cooling, the metal in heat-affected zone (HAZ) shrinks, so the edges of plate move upward.

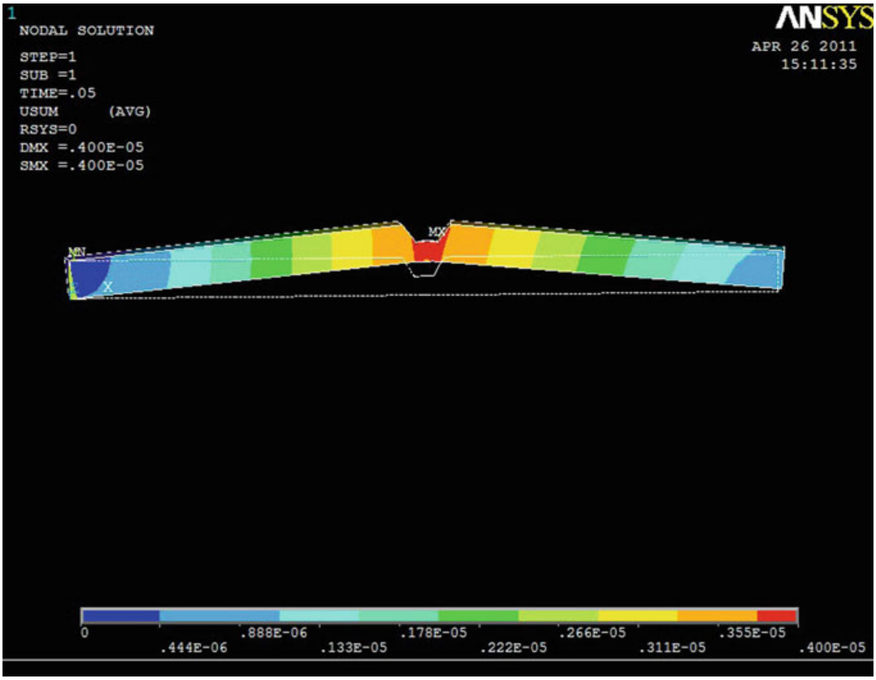

Fig. 9 Distortion during heating

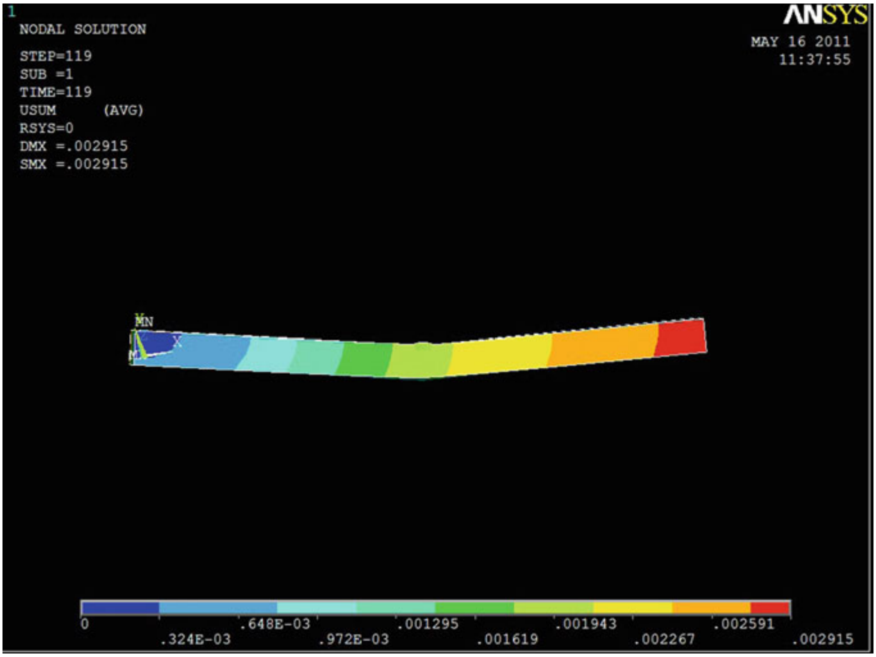

Fig. 10 Distortion after cooling

4 Conclusion

- A three-dimensional transient thermomechanical simulation of welded butt joint has been performed using finite element method. It also includes a moving heat source, material deposit, temperature dependant material properties, metal plasticity and elasticity. Element birth and death technique was used for filler metal deposition.
- During the heating phase, the metal is distorted in opposite direction of final distortion. The vertical displacement of welded plate is shown in Fig. 11. In this vertical displacement, the edges of the plate bend upwards look like *V* shape. The maximum vertical displacements 2.915 mm are shown in Fig. 10.
- The peak value often residual stress by the simulation is 402 MPa and the compressive residual stress 122 MPa. Yield stress of duplex stainless steel at room temperature is 470 MPa. The peak value often residual stress obtained by the simulation is almost equal to the yield stress of the material at normal ambient temperature. From the observation, the compressive residual stress region was a smooth curve than the tensile stress region. Coarser elements were used in weld zone to reduce the CFD weld time.

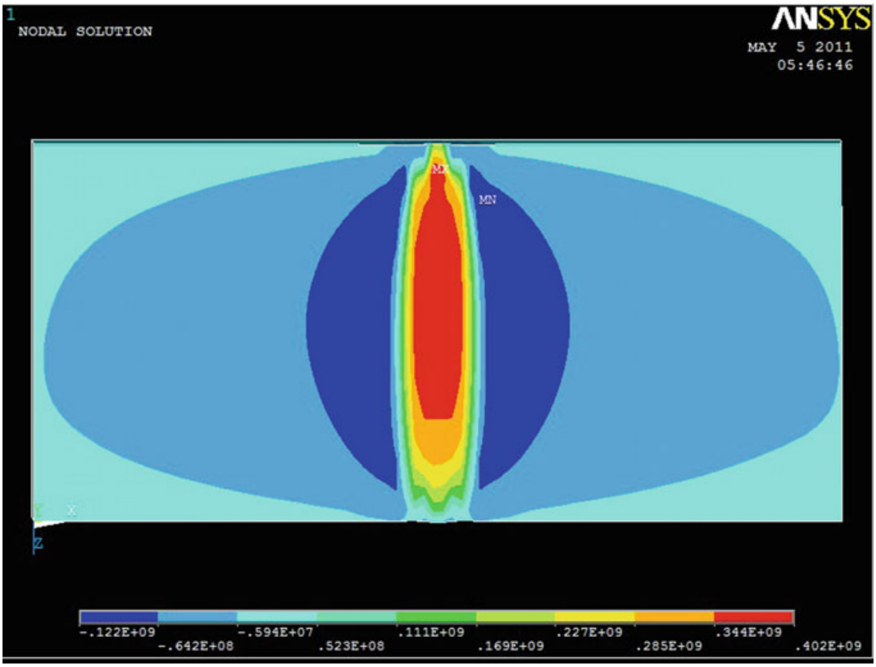

Fig. 11 Residual stress distribution in a welded plate

References

1. Withers PJ (2007) Residual stress and its role in failure. Rep Prog Phys 70(12):2211–2264
2. James MN (2011) Residual stress influences on structural reliability. Eng Fail Anal 18(8):1909–1920
3. Caron C, Heinze C, Schwenk M, Rethmeier SS, Babu J (2010) Lippold, Effect of continuous cooling transformation variations on numerical calculation of welding-induced residual stresses. Weld J 89:151–160
4. Neubert S, Pittner A, Rethmeier M (2017) Influence of non-uniform martensitic transformation on residual stresses and distortion of GMA-welding. J Constr Steel Res 128:193–200
5. Guo Y, Wu D, Ma G, Guo D (2014) Numerical simulation and experimental investigation of residual stresses and distortions in pulsed laser welding of hastelloy C-276 thin sheets. Rare Met Mater Eng 43(11):2663–2668
6. Yaghi AH, Hyde TH, Becker AA, Williams JA, Sun W (2005) Residual stress simulation in welded sections of P91 pipes. J Mat Process Technol 167:480–487
7. Lee CH, Chang KH (2012) Temperature fields and residual stress distributions in dissimilar steel butt welds between carbon and stainless steels. Appl Therm Eng 45–46:33–41
8. Moraitis GA, Labeas GN (2008) Residual stress and distortions calculation of laser beam welding for aluminium lap joints. J Mater Process Technol 198:260–269
9. Moraitis GA, Labeas GN (2009) Prediction of residual stresses and distortions due to laser beam welding of butt joints in pressure vessels. Int J Press Vessel Pip 86:133–142
10. Fallahi A, Jafarpur K, Nami MR (2011) Analysis of welding conditions based on induced thermal irreversibility's in welded structures: Cases of welding sequences and preheating treatment. Sci Iran 18(3):398–406

11. Mrvar P, Medved J, Kastelic S (2011) Welding sequence definition using numerical calculation. Weld J 90(8):148s–151s
12. Gannon L, Liu Y, Pegg N, Smith M (2010) Effect of welding sequence on residual stress and distortion in flat-bar stiffened plates. Mar Struct 23(3):385–404
13. Brown S, Song H (1992) Finite element simulation of welding of large structures. J EngInd 114(44):441–451
14. Deng D (2009) FEM prediction of welding residual stress and distortion in carbon steel considering phase transformation effects. Mater Des 30(2):359–366
15. Yaghi AH, Hyde TH, Becker AA, Sun W (2011) Finite element simulation of welded P91 steel pipe undergoing post-weld heat treatment. Sci Technol Weld Join 16(3):232–238
16. Venkatkumar D, Ravindran D, Selvakumar G (2018) Finite element analysis of heat input effect on temperature, residual stresses and distortion in butt welded plates. Mater Today Proc 5(2):8328–8337