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Numerical Simulation to Study the Influence of Welding Sequence on Distortion and Residual Stresses of Butt-Welded Plates

El-shrief E.[1], *Saber M.*[2], *Nassef A.*[3] *and Shaker M.*[4]

Abstract

In many accurate industries such as gas turbine and aerospace, welding technique is used to weld thin parts during the assembling process. Due to uneven heating and cooling during the welding process, welded parts are prone to sever distortions and/or non-desirable residual stresses. The distortion causes problem in shape in assembly and when residual stresses combined with applied stresses, unexpected failure occurs. In this paper, three dimensional sequentially thermo-mechanical analysis is used to simulate welding process in Nical base super alloy plates (INCONEL718) for predicting the temperature field, distortion and residual stresses. The study was carried out on butt welded joint with 2 mm thickness, using the commercial Finite Element (FE) package (ABAQUS). The obtained results are compared with the numerical and experimental results obtained by other researchers. Good accordance is found between them. In order to control the distortion, it was proposed to carry out the welding process on several steps with different sequences. The cases of the welding sequences are: one step in one direction, two steps in opposite directions and four steps in two directions the study successfully predicted temperature and residual stress in the welded plates. Moreover, it was found that the more the steps of the welding process the less the distortion takes place in the plates.

Keywords: Welding simulation- Heat transfer- Finite element- Welding distortion –Residual stresses.

1. Introduction

Welding is one of the most popular methods of joining processes that is used to fasten material either metals or non metals with or without using filler metal. Moreover, welding is extensively used in many active applications specially ship and bridges building, trains, constructions, automotive industries, pressure vessels, etc.

In spite of having all these advantages, welding process has many also disadvantages like distortion in welded structure and residual stresses generated from high transient heat input in welding. This distortion causes change in welded joint shape and residual stresses, Therefore this point has been the focus of many researchers[1, 2].

Many of researchers focused their search on how to measure the residual stresses, distortions and concluded that the measurements techniques of residual stresses divided to destructive technique such as hole drilling method[3, 4] and non-destructive techniques including neutron diffraction, magneto-elastic , X-Ray [5- 7] and analytical method. However, all of these methods are very complicated and costly. Therefore, finite element (FE) method is being used in predicting the distortion and the peak position of residual stresses by using finite element software such as ANSYS and ABAQUS. Choobi.,et al.[8], introduced comparison between different cases for clamped joint and predict distortion and residual stresses for each case and found that, clamping during welding and after cooling to ambient temperature reduces distortion and increase residual stresses. Chand.,et al.[9],carried out thermo mechanical analysis to evaluate distortion and residual stresses in butt welded joint. Several cases are proposed which clamped the joint from a different position in each case to study temperature field, size and shape of the heat affected zone (HAZ), fusion zone (FZ) and residual stresses in each case and compared results with experimental work. Yin, et al.[10], used ANSYS finite element software to simulate thermo elastic-plastic model with different welding parameters taking on considerations melting and solidification processes to study temperature field and residual stresses distribution in a single V-butt welded joint and concluded that welding parameters have significantly effects on residual stresses distribution. In this paper, studying the effect

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[1] *Department of Production Engineering and Mechanical Design, Faculty of Engineering, Port Said University, Port Said, Egypt, E-mail:* eng_merna_elshrief@yahoo.com

[2] *Assistant Professor, Department of Production Engineering and Mechanical Design, Faculty of Engineering, Port Said University, Port Said, Egypt (on leave)*
*Assistant Professor, Department of Mechanical Engineering, College of Engineering, King Faisal University, Kingdom of Saudi Arabia, E-mail:*msaber@kfu.edu.sa

[3] *Professor, Department of Production Engineering and Mechanical Design, Faculty of Engineering, Port Said University, Port Said, Egypt, E-mail:*nassef12@hotmail.com

[4] *Professor, Department of Production Engineering and Mechanical Design, Faculty of Engineering, Port Said University, Port Said, Egypt, E-mail:*
profmshaker@hotmail.com

of different sequences of welding on residual stresses and deformation is presented. Thermo mechanical FE analyses were carried out on nickel base super alloy INCONEL718 which is used extensively in accurate industries such gas turbine. This material has convenient weldbillity because its good strength, excellent resistance to oxidation at high temperature [11]

2. Design of welded joint

A closed square butt joint without filler metal is chosen with sheet dimensions (200*100*2) mm to investigate the intended simulation as shown in Fig. 1 The auto genus tungsten inert gas welding (TIG) is also chosen for welding

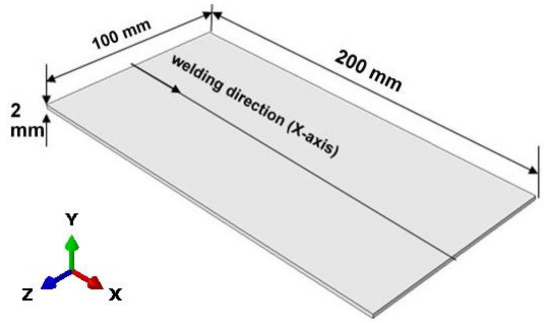


Fig. 1: Design of welded joint.

3. Sequentially Thermo-mechanical Analysis

Sequentially thermal-stress analysis is used to simulate welding process and to predict distortions and residual stresses. It consists of two analyses: thermal analysis and mechanical analysis. Firstly, the transient (i.e. time dependent) thermal analysis is carried out to determine the temperature history for each node in FE mesh. Secondary, the mechanical analysis is carried out using the temperatures, that are read as predefined field from thermal analysis, to predict the stresses and displacements due to changing thermal effects [12].

3.1 Transient Thermal Analysis

To focus on the temperature field of the welding analysis, severe physical and chemical reactions occur during welding process have been neglected during this simulation, Such as the phase transformation and convection phenomena. For the case of a thin plate, it is sufficient to assume that the heat transfer of energy to the work piece occurs within a circular source of absolute power (Q_p) and radius (a) [11]Within this source, the power density q is taken to be constant and, hence, has a magnitude of

$$\mathbf{q} = \frac{\eta\, Q_p}{\pi\, a^2} \qquad \mathbf{(1)}$$

where, q is the applied power density (heat flux),(Qp)is a absolute power obtained from TIG process presents in the open literature[15] , (a) is the radius of circular heat source and (η) is the thermal efficiency of welding process.

Heat flux focused around the weld centreline and then transfers throughout the rest of the plate by conduction as follow:

$$\mathbf{q_{con}} = \mathbf{h}\,(\mathbf{T} - \mathbf{T}_\infty) \qquad \mathbf{(2)}$$

Where(qcon)is the convective flux to the environment, (h) is the convective cooling coefficient, (T) is the local temperature and (T_∞)is ambient temperature that has been assumed to be 20°.Values of the above parameters were obtained from literature [11] and are given as:-

$\eta = 0.57$, Q_p= 1000 watt, a= 4mm, v = 1.6 $mm.s^{-1}$, h=35 $m^{-2}\,K^{-1}$.

3.1.1 Heat Source Model

Heat input to the welding joint and how it can be simulated has an important effect on the heat distribution on the plate. Temperature distribution, which is time depend, is leading to formation the thermal strain which is a remarkable constituent in the final total strain. Therefore, it was important to search the literature of heat sources models. It has been found that many researchers have carried out intensive research in this area beginning with Rosenthal where, developed an analytical solution of heat flow during welding process [13] Subsequently, the Gaussian Distributed heat source model was proposed by Friedman in 1975. Then, Goldak, et al. modified the heat source model to double ellipsoidal model heat source [14]. The motion of the heat source model can be represented in ABAQUS (the used FE package) by using the DFLUX user subroutine. The subroutine is written in FORTRAN. In this research, a Gaussian distributed heat source expresses approximately the heat flux as follows:-

$$\mathbf{q} = \frac{\eta Q_p}{\pi a^2}\, e^{-3z^2/a^2}\, e^{-3[x+v(\tau-t)]^2/a^2} \qquad (3)$$

Where,(x) axis of welding direction, ($\boldsymbol{\tau}$) is a lag factor(to define source position at t = 0), (v) is the welding speed (mm/s) ,(a) is the radius of circular heat source

3.1.2 Finite Element Mesh

When using any numerical analysis, it is important to minimise computation time as much as possible without compromising the accuracy of the simulation. Therefore, in this paper, a half model of the welded sheet is simulated with symmetric boundary condition Mesh design are based on set of guidelines employed by [11] shows two sections for the mesh where on the weld centreline the element size should be no larger than (1 * 1 * 0.5) mm in order to simulate adequately the heat source, while in the far-field elements, a size of(4 * 4 * 1) mm is adequate as shown in Fig.2. Regular hexahedra is the most suitable element type which give more accurate results in large deformation problem [11]

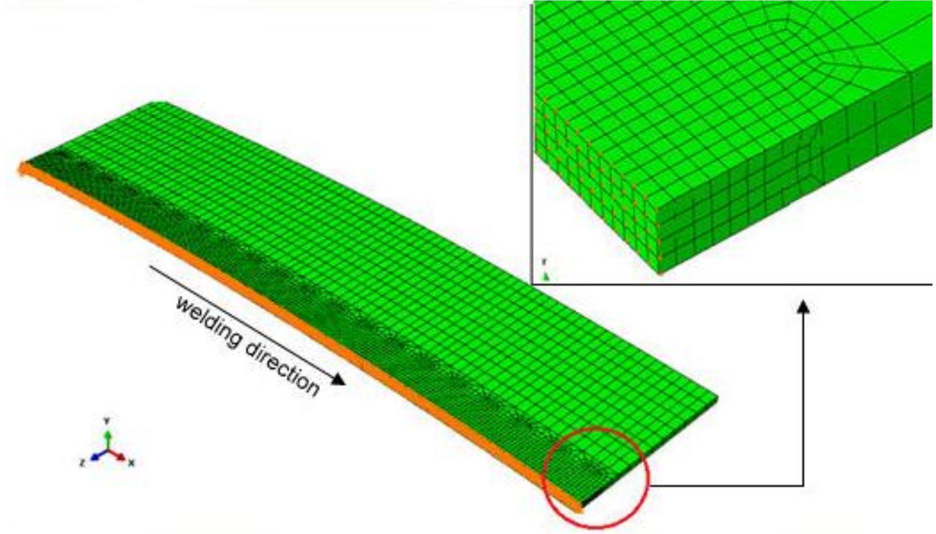


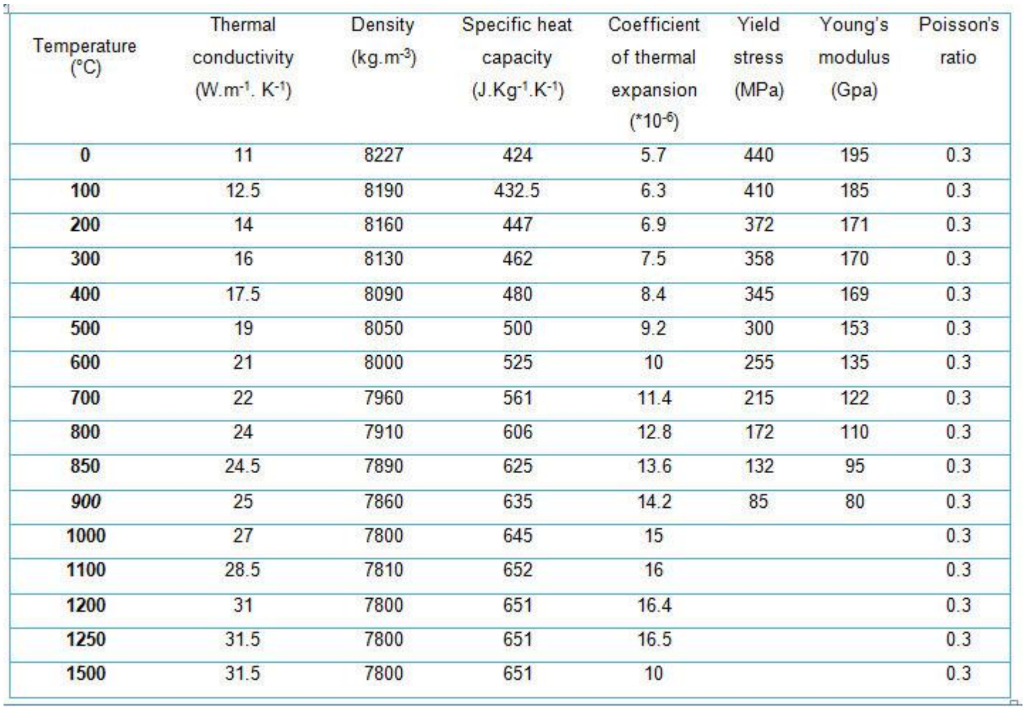
Fig.2: Mesh design of welded joint with symmetric boundry condition.

3.2 Material Properties

The material properties which are assigned to the model are temperature depended. This is because of the nature of the welding process where heats is generated and affect the material properties in the vicinity of the weld. The temperature-dependent material properties employed in the simulation are presented below

Thermal analysis: (Thermal conductivity, Density and Specific heat capacity).

Mechanical analysis: (coefficient of thermal expansion, Yield stress, Young's modulus and Poisson's ratio)



Temperature (°C)	Thermal conductivity (W.m^{-1}. K^{-1})	Density (kg.m^{-3})	Specific heat capacity (J.Kg^{-1}.K^{-1})	Coefficient of thermal expansion (*10^{-6})	Yield stress (MPa)	Young's modulus (Gpa)	Poisson's ratio
0	11	8227	424	5.7	440	195	0.3
100	12.5	8190	432.5	6.3	410	185	0.3
200	14	8160	447	6.9	372	171	0.3
300	16	8130	462	7.5	358	170	0.3
400	17.5	8090	480	8.4	345	169	0.3
500	19	8050	500	9.2	300	153	0.3
600	21	8000	525	10	255	135	0.3
700	22	7960	561	11.4	215	122	0.3
800	24	7910	606	12.8	172	110	0.3
850	24.5	7890	625	13.6	132	95	0.3
900	25	7860	635	14.2	85	80	0.3
1000	27	7800	645	15			0.3
1100	28.5	7810	652	16			0.3
1200	31	7800	651	16.4			0.3
1250	31.5	7800	651	16.5			0.3
1500	31.5	7800	651	10			0.3

Table 1: **Temperature-dependent material properties of INCONEL718 [11]**

3.3 Mechanical Analysis

In sequential thermal mechanical analyses, a thermal analysis is followed by a mechanical analysis where the only applied load is the thermal load. Both of the analyses are carried out on the same model with different element types. In mechanical analysis, the total strain is a summation of three strains, (thermal strain, elastic strain, and plastic strain). The thermal analysis uses time step of 0.16 seconds. After heating is completed, a step with automatic time incrementation was carried and the maximum allowable temperature increment is taken as 160℃ to allow weld to call back to ambient temperature [11].The element type were used for thermal analysis are regular linear diffusive heat transfer element (DC3D8 in ABAQUS for 3D). For mechanical analyses, the used element type is fully integrated linear elements with additional incompatible bending modes designated in ABAQUS as (C3D8I for 3D) with automatic time incrementation by ABAQUS. Thermal strains are generated by using the temperatures history imported from the thermal analysis (.ODB) file in ABAQUS software as an input file for the mechanical analysis. The total strains is equal the summations for the elastic strain, plastic strain, and thermal strain. In the mechanical analysis, boundary conditions must be applied to the model and based on fixation the two corner ends at point (A,B) on weld centre line to prevent the rigid body motion, as shown in Fig. 3

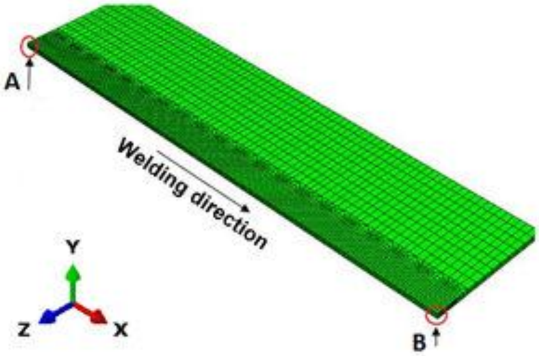


Fig. 3: Mechanical boundary condition.

4. Distortion control

Distortion occurred after welding of butt joint can be divided into two modes: cambering distortion which results from bending around transverse axis centreline and butter flying (or angular) distortion which results from bending around the weld centre line see Fig.4

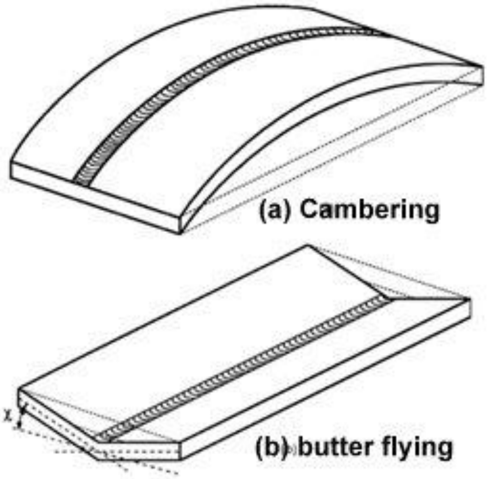


Fig.4: distortion modes in welded plates (a)cambering, (b)butter flying distortion[15].

4.1 Studying of welding sequence

In order to control the distortion, it was proposed to carry out the welding process on several steps with different sequences in order to control distortion of welded plates, different methods can be used. One of these methods is to clamp the welded plates firmly. However, this methods leads to an increase in the residual stresses. Alternatively, it is possible to minimize distortion using a welding technique called “welding sequence” in which several steps with different sequences are employed. The aim of this study is to control distortion and residual stresses by carrying out welding process on several sequences as shown in Fig. 5.The numerical results of distortion and longitudinal residual stresses due to welding sequence were obtained.

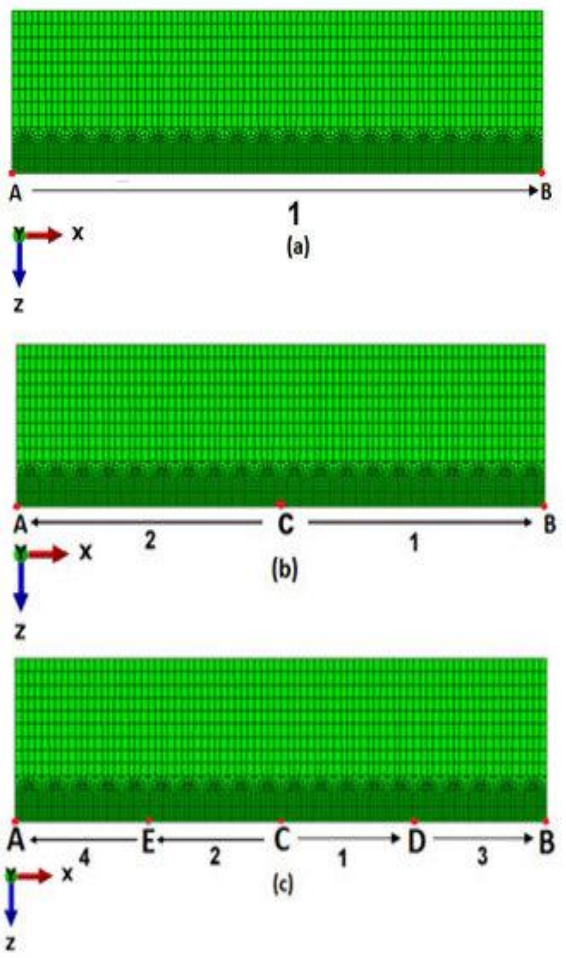


Fig. 5: Sequence of welding process (a) one step, (b) two-steps welding: step 1 from C to B; step 2 form C to A, and (c) four-steps welding: step 1 from C to D; step 2 from C to E; step 3 from D to B and Step 4 from E to A.

5. RESULTS and Discussions

5.1 Temperature field distribution

Fig.6: illustrates the temperature distribution through the welding process where the maximum temperature is achieved after approximately 10s.

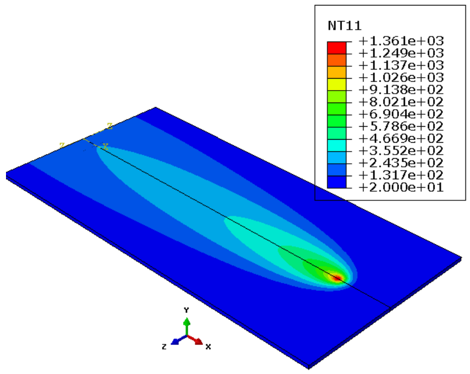


Fig.6: Temperature distribution through the welding process

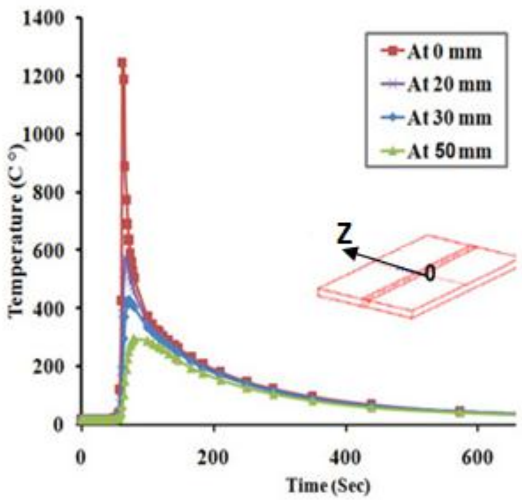


Fig. 7: Temperature behavior of points in transverse direction of welding line.

Fig. 7: shows the temperature history of points in transverse direction where 0 mm is at the centerline to the end of the sheet.It can be seen that the peak temperature far from weld zone was 300c° is less than the peak temperature in the weld zone was approximately 1360 c° which is affected directly by the heat source model.

5.2 Distortion and residual stress analysis

Fig. 8: Illustrate the effect of the welding sequence shown in Fig. 5 on deformation in welded plates. It can be seen that deformation have the same pattern but with different values. Fig (7-a) shows that the maximum distortion was obtained from applied welding on one-step, which equal 5.6mm. Fig(7-b), (7-c) illustrate the values of distortion decreased when applied welding sequence on two-steps, four

steps by 83% and 76% from one step to become distortion 4.7mm,4.3mm respectively.

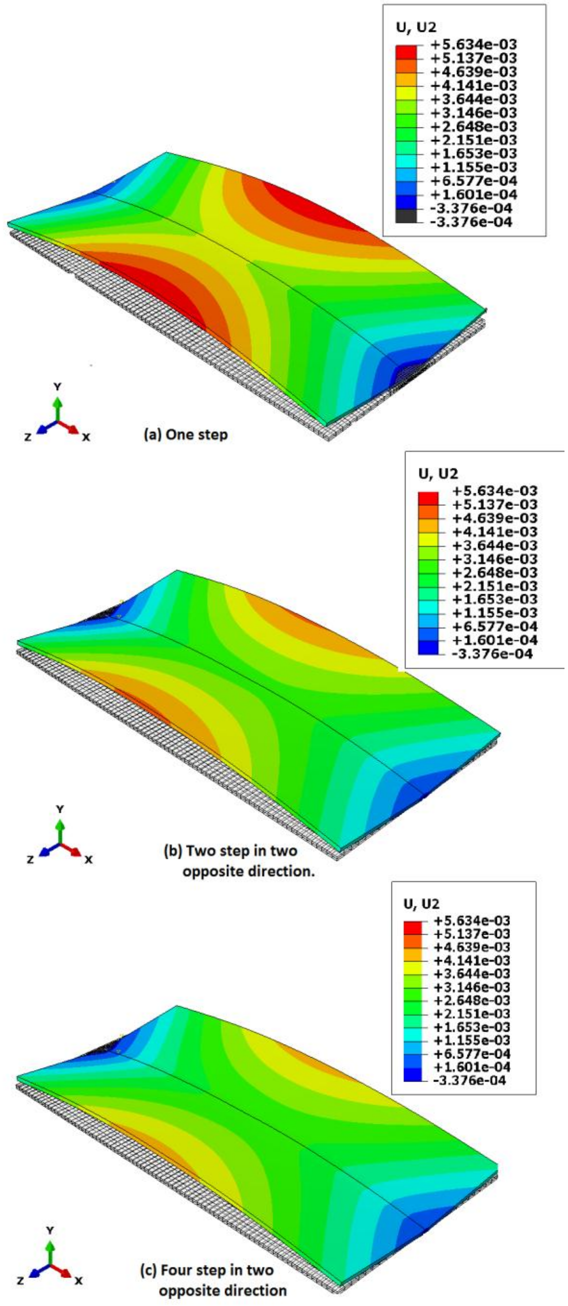


Fig. 8: Distortion due to different sequences of welding processes (m)

The results of cambering distortion for all welding sequences of plates that discussed before in Fig. 8 were collected and compared in Fig. 9 which shows the maximum distortion took place when the welding was carried out in one step. The distortion is decreased as the number of steps, increased, on which the welding takes place, i.e. two steps and four steps

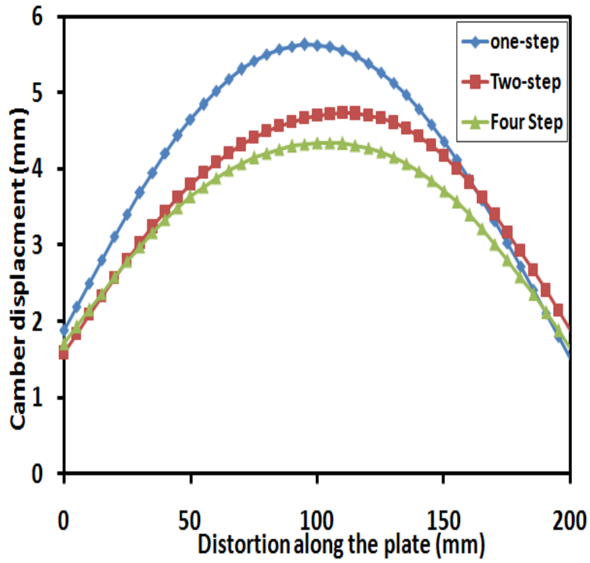
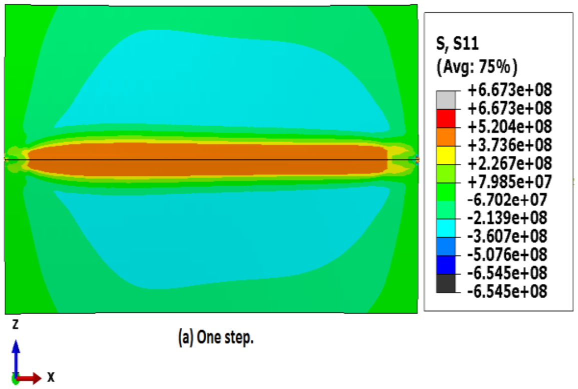


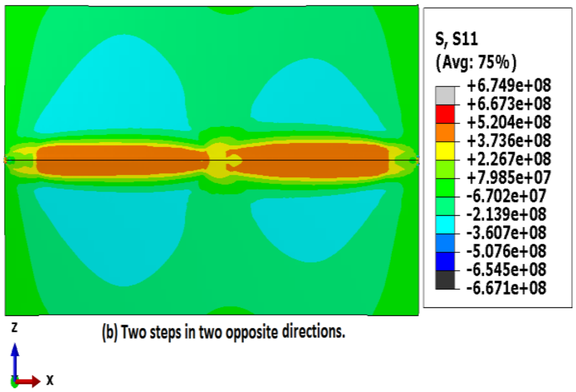
Fig. 9: Comparison between camber distortions due to welding sequences.

Fig. 10 shows the residual stress along the weld center line for different cases of the welding process. Similar to welding distortions, the maximum residual stress distribution was found to be along the sheet in the heat affected zone (HAZ). Fig (9-a) shows the residual stress distribution for one-step welding sequence. Fig (9-b) and Fig (9-c) show the residual stress distribution for two-steps and four-steps welding sequence. It can be clearly seen that when the number of welding steps increase, the zones affected by residual stresses decreased.

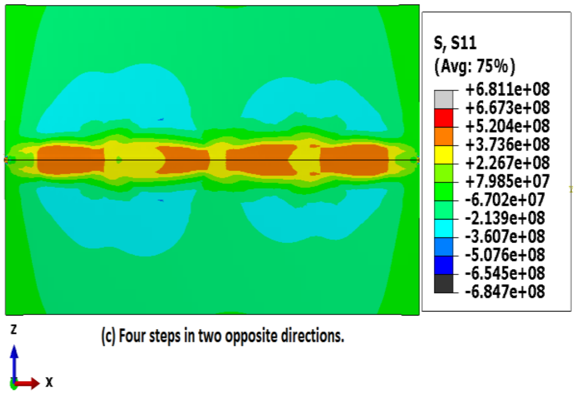
From the obtained results, thermal analysis is the main factor for reduction in distortion and residual stresses. In one-step welding sequence, the heat concentrated along the welding line because the heat sources move continuously from point A to B as shown in Fig. 5-a).the effect of heat concentration is reduced when carrying out the welding process on two-steps from (C to B) then from (C to A) as shown in Fig. 5-b).Similarly, the effect of heat concentration is reduced more due to carrying the welding on four-steps as shown in Fig. 5-c).



(a) One step.



(b) Two steps in two opposite directions.



(c) Four steps in two opposite directions.

Fig. 10: Residual stress distribution (MPa) due to different sequences

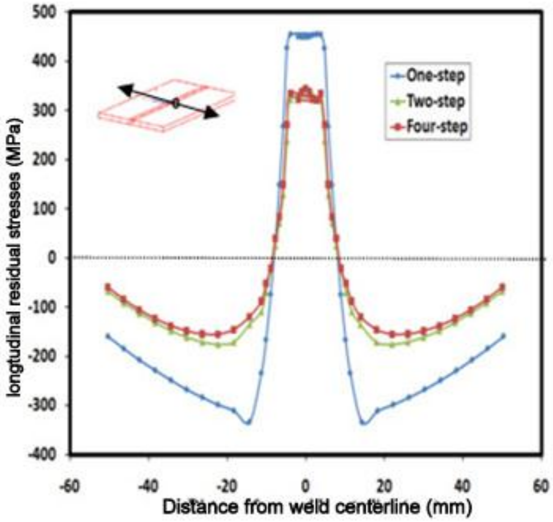


Fig. 11: Comparison between residual stresses due to welding sequences analysis in a mid length transverse to welding direction.

Fig. 11: shows the comparison between distributions of longitudinal residual stresses in a mid-length transverse to the welding direction for all welding sequences of plates. It can be seen that the values of residual stress in two- and four- steps welding sequences are quite similar. However, the large difference in zones affected by residual stress can be seen between the values of multiple steps welding on one side and the single step welding on the other side. These results illustrate that splitting the welding process on many steps successfully reduces the residual stresses. More studies are needed for more control of the distortion and the residual stresses by sequencing the welding process. One suggestion is to carry out the welding process on sequential steps on the front and back surface of the plates.

6. CONCLUSIONS

Based on the obtained simulation results, the following conclusions can be drawn:

- By using the numerical analysis, it can be estimated the distribution of temperature for each point on the plates, whether in the longitudinal or transverse direction.
- Sequence welding analysis is an effective tool for controlling the residual stresses and distortion without increase in cost where more methods for controlling on residual stresses increase cost
- The distortion values decrease clearly in four welding steps compared with one-step and two steps.

- The maximum values of tensile residual stresses are found to occur in the HAZ
- Residual stresses could be predicted easily by using finite element simulation and their values decrease clearly in four welding steps compared with one-step and two steps.

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