Finite Element Simulation of Residual Stresses in Butt Welding of Two AISI 304 Stainless Steel Plates

Gurinder Singh Brar

Department of Mechanical Engineering, Guru Nanak Dev Engineering College, Gill Road, Ludhiana. 141006, Punjab, India

E-mail: brar.gurinder@gmail.com

Abstract - Welding is one of the most reliable and efficient permanent metal joining processes in the industry. When two plates are joined by welding, a very complex thermal cycle is applied to the weldment. Thermal energy applied results in irreversible elastic-plastic deformation and consequently gives rise to the residual stresses in and around fusion zone and heat affected zone (HAZ). It is well established fact that structural integrity of components is substantially affected by the residual stresses when subjected to thermal and structural loads. Presence of residual stresses may be beneficial or harmful for the structural components depending on the nature and magnitude of residual stresses. Using finite element based commercially available software, coupled thermal-mechanical three dimensional finite element model was developed by making an approximate geometry of the butt welded joint. Finite element analysis was performed to understand the complete nature of residual stresses in manual metal arc welded joint of AISI 304 stainless steel plate. Variation of residual stress in the plates in the heat affected zone was also being studied. The results obtained by finite element method agree well with those from X-ray diffraction method as published in literature for the prediction of residual stresses.

Keywords-finite element analysis; residual stresses; butt weld; AISI 304 stainless steel; manual metal arc welding.

I. INTRODUCTION

AISI 304 stainless steel has excellent properties like better corrosion resistance, high ductility, excellent drawing, forming and spinning properties, so it is used in application like chemical equipment, flatware utensils, coal hopper, kitchen sinks, marine equipment etc. But due to introduction of residual stresses during welding it is very essential to understand the behavior and nature of the joint. Residual stresses are defined as the stresses that exist inside the structure without the application of external loads and are suppose to be self balancing within the bulk. Presence of residual stresses may be beneficial or harmful for the structural component depending on the nature and magnitude. The beneficial effect of compressive stresses have been widely used in industry as these are believed to increase fatigue strength of the component and reduce stress corrosion cracking and brittle fracture [1]. In several practical application these are deliberately introduced through some post manufacturing treatment such as shot penning or water jet penning etc.

In large steel fabrication industries such as shipbuilding, marine structures, aero-space industry, high speed train guide ways and pressure vessels and piping in chemical and petrochemical industry the problem of residual stresses and overall distortion has been and continue to be a major issue. During welding a very complex thermal cycle is applied to the weldment which in turn causes irreversible elastic- plastic deformation and consequently gives rise to the residual stresses in and around fusion zone and heat affected zone (HAZ). In spite of the vast application of welding joints in the industry, still weldments have been considered as a weak point in the mechanical engineering design. This is due to the shortcomings of welding technology and mismatch of the mechanical properties at the joints, and, last but not least, due to the residual stresses. For the vast application of welding joints in the industry, analysis of the residual stresses in these joints is an important task in mechanical engineering design of the weldments. The effect of residual stresses in fatigue and creep lifetime adds to this importance. These stresses not only cause unwanted deformation, but also reduce the fatigue and creep lifetime of the weldments. While it is known that welding can cause highly localized tensile residual stresses that often approach the yield stress of the metal, yet it is not completely understood how various parameters of the welding process influence their distributions. Because of the inherent complexities of the welding process, many factors, both process related and geometry dependent, affect the final residual stresses.

II. Literature Review

There are many experimental approaches available (e.g. X-ray diffraction) to measure residual stresses, however, most of them are expensive and destructive. Therefore, a general trend is to use numerical methods. Since the heat generated during a welding process is dissipated through convection, conduction and radiation, a severe temperature gradient would exist around the welding point. This gradient, together with the rapid quenching and the phase transformation of the melted filler will cause the residual stresses along the joint. Nevertheless, progress has been made in modeling initially one-pass and then multi-pass girth- or butt-welds. The existing temperature gradient has a major role in producing residual stresses [2]. Rybicki et al. presented a finite element study for girth welding of pipes. A two dimensional axisymmetric finite element model for simulation of two pass weld on stainless steel pipes was developed and temperature distribution was determined by finite element solution of thermal stress analysis [3]. Free and Goff, developed a finite element model to calculate the residual stresses in complex multi-pass weldments [4]. Dissimilar butt-welded plates were studied by authors, Lee and Chang [5].

In all these models, some simplifying assumptions were made to deal with the inherent complexities of the welding process. These results show that 2D modeling of the residual stresses is unable to capture the effect of the electrode movement; therefore it is needed to use a 3D model to determine the variation of the residual stress in three directions (welding direction, plate width and plate thickness). Murugan et al. modeled a multi-pass weld and showed that the patterns of the residual stresses change in each welding pass. This has been confirmed by using the experimental measurements for welded plates with different thickness [6]. Using finite element based software ANSYS, coupled thermal-mechanical three dimensional (3D) finite element models was developed and employed to evaluate the transient temperature and the residual stress fields during welding [7].

Sattari-Far and Farahani used a finite element technique to analyze the thermo-mechanical behavior and residual stresses in butt-welded pipes. The residual stresses were also measured in some welds by using the Hole-Drilling method. The results of the finite element analysis were compared with experimentally measured data to evaluate the accuracy of the finite element modeling. The developed FE modeling was used to study the effects of weld groove shape and weld pass number on welding residual stresses in butt-welded pipes. The hoop and axial residual stresses in pipe joints of 6 and 10 mm thickness of different groove shapes and pass number were studied. It was shown that these two parameters may have significant effects on magnitude and distribution of residual stresses in welded pipes [8].

III. Simulation Of Welding Process

In the present study, the butt-weld joint of two AISI 304 stainless steel plates is modeled using a commercially available finite element software. Two semi-infinite plates of the joint are 6 mm thick and 50 mm wide (along the welding direction). The weld-groove angle is 60°. Various dimensions of the front view of the butt weld joint are shown in Fig. 1. Fig. 2 shows the meshed isometric view of the two plates that are to be butt welded. Mesh consists of solid tetrahedral 10-node element with three translational degrees of freedom per node. Mesh control is applied to the weldment area. Plates are fixed at the ends and heat convection was allowed at the top surface of two plates.

AISI 304 stainless steel material can be welded by different methods like electric arc welding, resistance and induction welding or by means of radiation process. From all these types the analysis of stainless steel in this paper is performed by manual metal arc welding, or MMAW.

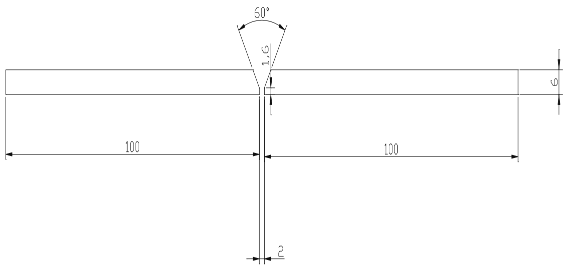

Figure 1. Detail of geometry

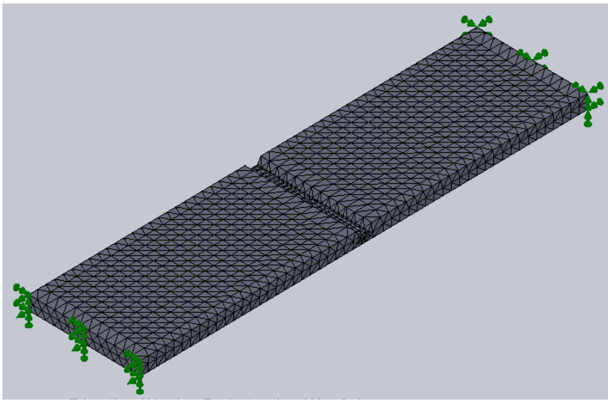
Figure 2. Meshed geometry of the parts

To simplify the welding simulation, it is computationally efficient to perform thermal and mechanical analyses separately.

Firstly the computation of the temperature history during welding and subsequent cooling is completed and this temperature field is applied to the mechanical model as a body force to perform the residual stress analysis. The heat input during welding is modeled in a commercially available software by the equivalent heat input which includes body heat flux.

The amount of heat input, Q has been calculated by using empirical relation shown in Eq. 1. Arc efficiency is denoted by η, arc voltage by U, arc current by I and travel speed by V. Typical welding parameters taken in this study are travel speed 2mm/sec, arc voltage 22volts, arc current 65amp and arc efficiency 75%.

$$Q = \frac{\eta U I}{V} \qquad (1)$$

To simulate the moving heat source it is necessary to model the heat source during each time increment. In this analysis the moving heat source is simplified by assuming that the welding arc stayed at an element with constant specific volume heat flux, and then moved to the next element at the end of the load step as the welding is finished. To accomplish this, arc welding process of butt joint is simulated into two steps. Step 1 depicts the time increment of welding from 0sec to 25sec, while step 2 consists of time increment of 25sec to 50sec. Fig. 3(a) shows temperature field developed during butt welding in step one. Peak temperature attained during welding of AISI 304 stainless steel in first pass is 728.3°K. Simulated temperature fields for time increment 25-50sec is shown in Fig. 3(b).

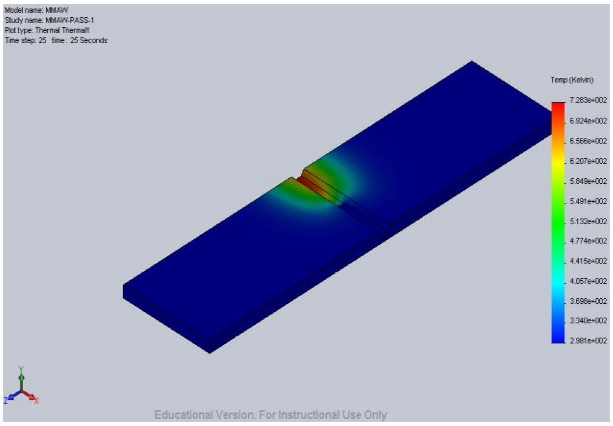

Figure 3(a). Temperature field in butt weld by MMAW (Step I)

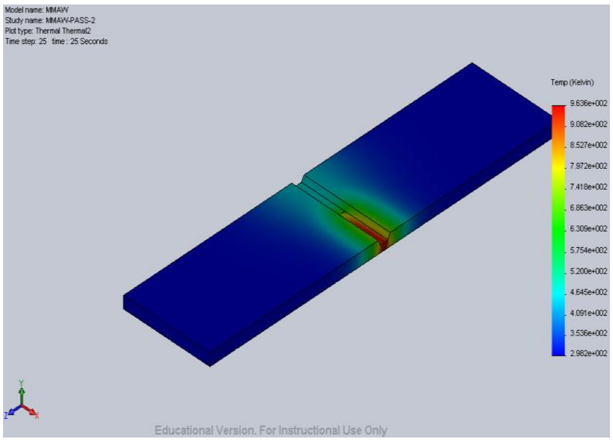

Figure 3(b). Temperature field in butt weld by MMAW (Step II)

Peak temperature attained during this step comes out to be 963.6°K. By using this value of heat input first of all by thermal analysis the temperature at different points are noted and after that the values of residual stresses are calculated by means of stress analysis. This simulated temperature field is then used in analysis step for calculating the residual stresses.

IV. RESULTS

A three dimensional finite element model is developed and the movement of the electrode is simulated using the birth and death of element technique. The technique implies that birth of an element takes place when heat is applied to the element. Element is active until the temperature is dissipated to the surrounding through conduction, convection and radiation. Death of element occurs when heat dissipation ends and temperature of element reaches the ambient temperature. For simulating birth and death technique, a coupled thermo-mechanical solution method is used.

CFig. 4 shows the residual stress in axial direction for manual metal arc welding when plate thickness is 6mm. Fig. 5 gives the values of residual stresses distribution against the distance from weld centre. It is clear from the plot that heat affected zone extends up to 38 mm on both sides of the weldment. It is seen that the residual stress in the transverse direction for butt welding of 6 mm thick plates comes out to be maximum (288.97 MPa) in the centre of weldment. The result of finite element analysis agrees well with the values of X-ray diffraction measurement method as seen in Fig. 6. The lower value of welding current resulted in lower heat inputs and lower residual stresses. Effect of plate thickness on residual stresses induced is studied and plotted in Fig. 7.

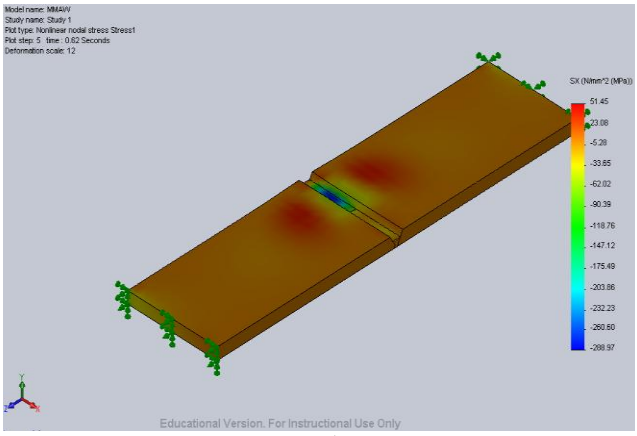

Figure 4. Residual stress plot of butt welding by MMAW

(288.97 MPa)

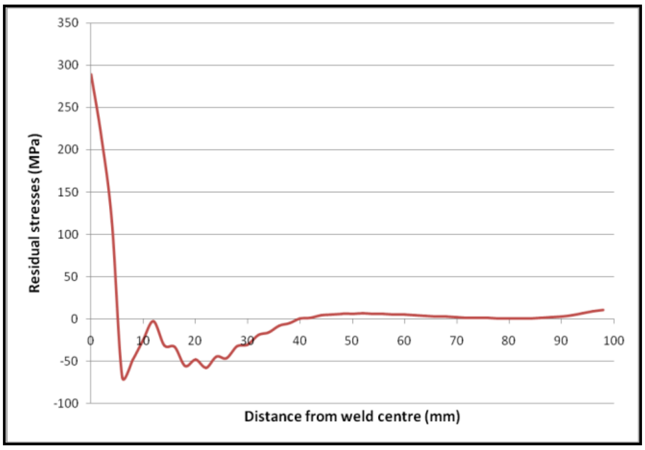

Figure 5. Transverse residual stresses v/s distance from weld centre

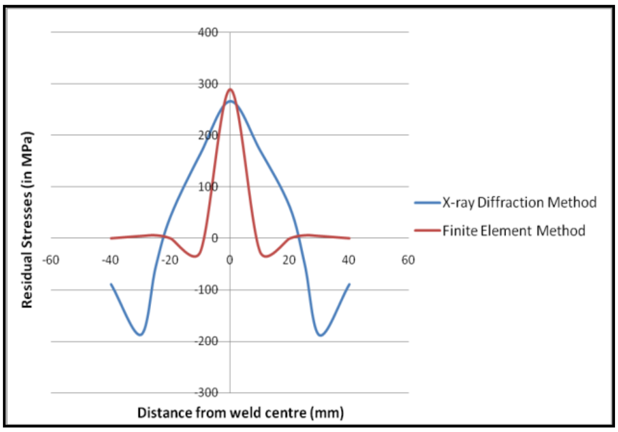

Figure 6. Residual stress value

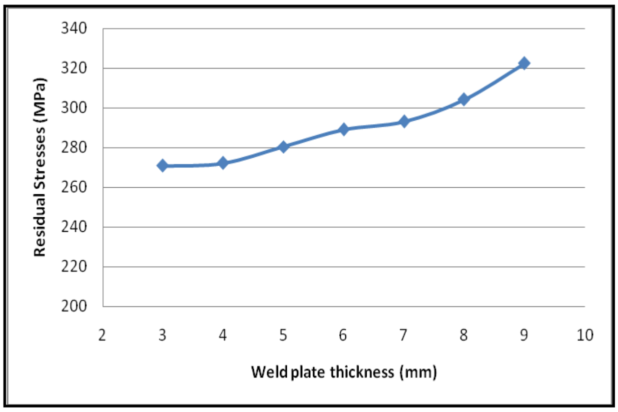

Figure 7. Residual stress v/s thickness of weld plates

Residual stress increases with increase in plate thickness. Arc voltage and welding current have direct effect on the residual stress in the welding process as increase in the voltage and current increases heat input thus increasing residual stresses. Also, increase in welding speed reduces residual stresses but reduces quality of weld as well.

V. CONCLUSIONS

The finite element method is an efficient technique in analyzing residual stresses in welding processes. A 3-D finite element welding simulation was carried out assuming welding is carried out by manual metal arc welding. The welding simulation was considered as a sequential coupled thermo-mechanical analysis and the element birth and death technique was employed for the simulation of filler metal deposition. The finite element analysis results of the residual stress distributions of two butt welded plates in the transverse direction are presented. It can be concluded that residual stresses are high in and around the weld zone and it is this zone which needs further investigation. Also it can be concluded that the decreasing of heat input decreases the distribution of residual stresses in the material.

VI. REFERENCES

[1] P. V. Ramana, G. M. Reddy, T. Mohandas, A. V. S. S. K. S. Gupta, "Microstructure and Residual Stress Distribution of Similar and Dissimilar Electron Beam Welds – Maraging Steel to Medium Alloy Medium Carbon Steel," Materials & Design, vol. 31, 2, 2010, pp. 749-760, doi: 10.1016/j.matdes.2009.08.007

[2] H. D. Hibbitt and P. V. Marcal, "A Numerical Thermo-Mechanical Model for the Welding and Subsequent Loading of a Fabricated Structure," Computers & Structures, vol. 3, 5, 1973, pp. 1145-1174, doi: 10.1016/0045-7949(73)90043-6

[3] E. F. Rybicki, D. W. Schmueser, R. W. Stonesifer, J. J. Groom and H .W. Mishler, "A Finite-Element Model for Residual Stresses and Deflections in Girth-Butt Welded Pipes," Journal of Pressure Vessel Technology, vol. 100, 3, 1978, pp. 256-262, doi: 10.1115/1.3454464

[4] J. A. Free and R. F. D. P. Goff, "Predicting Residual Stresses in Multi-Pass Weldments with the Finite Element Method," Computers & Structures, vol. 32, 2, 1989, pp. 365-378, doi: 10.1016/0045-7949(89)90048-5

[5] C. H. Lee and K. Chang, "Three-dimensional Finite Element Simulation of Residual Stresses in Circumferential Welds of Steel Pipe Including Pipe Diameter Effects," Material Science and Engineering: A, vol. 487, 1-2, 2008, pp. 210-218, doi: 10.1016/j.msea.2007.10.011

[6] S. Murugan, S. K. Rai, P. V. Kumar, T. Jayakumar, B. Raj and M. S. C. Bose, "Temperature Distribution and Residual Stresses Due to Multipass Welding in Type 304 Stainless Steel and Low Carbon Steel Weld Pads," International Journal of Pressure Vessels and Piping, vol. 78, 4, 2001, pp. 307-317, doi: 10.1016/S0308-0161(01)00047-3

[7] F. Vakili-Tahami and A. H. D. Sorkhabi, "Finite Element Analysis of Thickness Effect on the Residual Stress in Butt-Welded 2.25Cr1Mo Steel Plate," Journal of Applied Sciences, vol. 9, 7, 2009, pp. 1331-1337.

I. Sattari-Far and M. R. Farahani, "Effect of the Weld Groove Shape and Pass Number on Residual Stresses in Butt-Welded Pipes," International Journal of Pressure Vessels and Piping, vol. 86, 11, 2009, pp. 723-731, doi: 10.1016/j.ijpvp.2009.07.007.

❑❑❑