Finite element simulation of residual stresses in welded steel butt joints and their experimental verification and mitigation

V Eswara Kumar 1, Dr. D V N J Jagannadha Rao 2 and Dr. Y Seetharama Rao 3

1,2,3DEPARTMENT OF MECHANICAL ENGINEERING, GAYATRI VIDYA PARISHAD COLLEGE OF ENGINEERING (AUTONOMOUS), JNTUK UNIVERSITY

Abstract. The localized, intense, and moving heat source existing in welded fabrication results in residual stresses and distortion. Residual stresses remain inside the material even after the external forces or thermal gradients are removed after welding. Residual stresses decrease fatigue life of the welded joint leading to premature failures and associated distortion cause problems in fitment during assembly. Estimation of residual stresses before actual fabrication is essential for elimination or mitigation after fabrication. In this work, finite element thermo-mechanical analyses are carried out to estimate the levels of residual stresses of thin welded similar butt joints of 1018 steel and SS 304 steel. The numerically obtained results of the joints are compared with experimental results of identical joint geometry, welding conditions, and material properties existing in the literature. The comparison of numerically obtained thermal histories with those from experiments yielded good agreements. Longitudinal residual stresses are found to be dominant and comparison of these longitudinal stresses with experimental data also found to be in good agreements. Further, the levels of residual stresses are computed with three different preheat temperatures (600°C, 700°C and 800°C) to study the effect of preheating temperature in the mitigation of residual stresses. It has been found that the peak value of longitudinal stress decreased considerably with preheat temperature. Increasing preheat temperature has a marginal reduction in the peak value of longitudinal stress.

Keywords: TIG welding, FEM, residual stress, mitigation, preheat.

1. INTRODUCTION

Residual stresses in welding appear due to improper fit between various parts, various phases, or various regions within the part that originating out of non-uniform thermal strain, and strains originating from the solidification and solid-state phase transformations [1]. Residual stresses can be classified into two categories one is macro stresses and the other is micro stresses [2]. Micro stresses occur within a grain of the component but macro stresses occur along with the component. Macro stresses are three types tensile, compressive, and shear stresses. Compressive stresses are good for welded components and cause stress relaxation, whereas tensile stresses also called longitudinal stresses harm the welded joint. Residual stresses decrease fatigue life of the joint leading to premature failure and associated distortion causes problems in fitment during assembly. The prediction of residual stresses and distortion before actual fabrication of the joint is necessary for the safe design of the joint. Experimental methods like strain gauging, X-ray diffraction, and neutron diffraction can be used for the measurement of residual stresses. However, these are prohibitively expensive and provide limited information. In this context, a numerical method like the finite element method (FEM) offers a cost-effective alternative. So, residual stresses and distortion can be computed within the whole domain are the problem which can be validated by limited experimentation.
Residual stresses in welding are a well-researched topic in literature. Many authors carried out experimental measurements using hole drilling, strain gauging, X-ray diffraction, and neutron diffraction. Two dimensional, axisymmetric, and three-dimensional finite element analyses are also carried out to assess the levels of residual stresses in welding problems. Mitigation methods are proposed to reduce the levels of residual stresses. A detailed review on welding residual stress distributions can be found in the publication of Syahida et al. [3]. A brief summary of the research work carried out recently in the welding of plates is given as follows.

Vijay et al. studied the variation of temperature in TIG welded SS 304 plate butt joint of 3 mm thickness using ANSYS workbench and found that comparison of temperature distributions predicted by numerical analyses are in good agreements with thermocouple measurements [4]. Siddique and Khwaja developed mathematical relationships using Taguchi design to predict temperature distribution and effect of process parameters like welding speed and input power of TIG welding of 304 stainless steel [5]. Kartal et al. studied the comparisons of the residual stress profiles generated by two different welding techniques (multi-pass and single pass welding) in 80 mm thick ferritic steel welds [6]. Bajpei et al. developed a finite element model using ANSYS software for the minimization of the residual stresses and distortions in thin butt-welded aluminium alloy 5052-H32 plates during gas metal arc welding process by using three different heat sink models employing thick backing plate and cooling fluids [7]. Almeida et al. proposed a finite element model for the simulations of a TIG butt-welding process applied to thin plates made of an AISI 316L austenitic stainless steel [8]. Subsequent measurement of residual stresses using hole drilling method yielded good agreements with numerical predictions. Hashemzadeh et al. used regression methods to develop relationships to estimate the distortion and residual stresses in thin butt-welded plates using analytical and finite element methods [9]. Vekatkumar et al. studied the effect of welding heat input on temperature and residual stresses induced by single pass V-butt joint gas tungsten arc welding using a 3D Finite Element (FE) numerical model of 304 stainless steel [10]. Tianci et al. proposed a novel heat source model combining Gaussian surface and uniform volume heat source for the simulation of temperature distribution and residual stresses of a S355 steel T welding. The comparison between measured results by the hole drilling and X-ray diffraction (XRD) and simulation indicates that the combined heat source is sufficient to allow for an overall prediction of the entire welding process of T joints [11]. Luca et al. used the Finite Element (FE) method to numerically analyse the thermo-mechanical behaviour and residual stresses in dissimilar welded T-joints [12]. Balaram et al. carried out experimental and numerical investigation to analyze the residual stress distribution in the dissimilar TIG weldments of AISI 304 and Monel 400 and found that the residual stresses developed in weldments are within the yield limits [13]. A coupled thermo-metallurgical-mechanical numerical model is used for the simulation of residual stresses on bead on plate TIG welding of S355J2 steel by Zhang et al. This model is validated by measurement of residual stresses by X-ray diffraction and relaxation methods with good success by the authors [14]. Suman and Biswas investigated residual stresses in a square butt submerge arc welded Creep Strength Enhanced Ferritic (CSEF) steel plate experimentally and numerically. The mitigation of residual stresses using preheating is also discussed in this paper [15]. However, there is enough scope for research in this topic as it is associated with nonlinearities like phase change, temperature dependence on material properties, path dependence of stress-strain response, plasticity, moving distributed heat source, and filler metal deposition.

In this work, 3-dimensional thermo-mechanical simulation using ANSYS FE program is used to predict the residual stress distribution developed in the butt joints welded by the TIG welding technique. The similar joints are of AISI 1018 steel and SS 304 steel. The thermal histories at various locations of these joints are measured by thermocouples and residual stresses are measured by neutron diffraction as reported in the literature [16]. This experimental data is compared with present data obtained by finite element simulation of joints of identical geometries and welding conditions as reported in the previous literature cited above. The comparison of numerical thermal histories with those
obtained experimentally yielded good agreements. Longitudinal residual stresses are found to be dominant. Comparison of numerically obtained longitudinal residual stresses with those obtained experimentally also yielded good agreements. Further the levels of residual stresses are computed with three different preheat temperatures (600°C, 700°C, and 800°C) to study the effect of preheating temperature in the mitigation of residual stresses. It has been found that the peak value of longitudinal stress decreased considerably with preheat temperature. Increasing preheat temperature has a marginal reduction in the peak value of longitudinal stress.

2. FINITE ELEMENT SIMULATION OF TIG WELDING

FE simulation of welding is a challenging numerical problem involving localized, intense moving heat source, phase changes from solid to liquid and vice versa, the temperature dependence of material properties, and plasticity. Sequential thermo-mechanical analyses are to be carried out to evaluate residual stress distributions.

![Figure 1. Geometry of the joint along with locations of thermocouples](image)

The geometry of the butt joint and welding parameters used in this study are given in figure 1 and table 1 respectively. Dimensions of the two plates that are butt welded are 300 mm x 150 mm x 3 mm. The locations of placement of thermocouples are shown by letters A, B, and C in figure 1 and these are at 30 mm, 40 mm, and 50 mm transverse from the weld centreline top and middle of the joint.

| Voltage (V) | Current (A) | Bead height (mm) | Bead width (mm) | Efficiency | Speed (mm/s) |
|-------------|-------------|------------------|-----------------|------------|--------------|
| 150         | 18          | 3                | 6               | 0.4        | 4            |

A numerical 3-D model has been created in ANSYS using mechanical APDL 19.2 for the TIG welding simulation process. The moving heat source in the welding processes has been modelled in
many ways such as point heat source, volumetric heat source, Gaussian distribution model, and double ellipsoidal model in the literature. In the present work double ellipsoidal heat flux density distribution has been used because of its capability to model 3-D situations. The double ellipsoidal heat flux density distribution (figure 2) is modelled by the following equations [17]

$$ Q = \eta VI $$ (1)

$$ q_f(x,y,z,t) = \frac{6\sqrt{3} f_f Q}{\pi^{3/2} abc_1} \exp \left( -3 \frac{x^2}{a^2} \right) \exp \left( -3 \frac{y^2}{b^2} \right) \exp \left( -3 \frac{(z-vt)^2}{c_1^2} \right) $$ (2a)

$$ q_r(x,y,z,t) = \frac{6\sqrt{3} f_r Q}{\pi^{3/2} abc_2} \exp \left( -3 \frac{x^2}{a^2} \right) \exp \left( -3 \frac{y^2}{b^2} \right) \exp \left( -3 \frac{(z-vt)^2}{c_2^2} \right) $$ (2b)

In the equation (1) Q is the total heat input, V is voltage, I is current and $\eta$ is arc efficiency. The factors $f_f$ and $f_r$ in the above equations denote the fractional ratios of total heat input ($Q$) in both forward and backward welding directions. Here, $v$ is the speed of welding, $a, b, c_1$ and $c_2$ are the parameters of heat source. In many cases these parameters are usually found to be correlated with the geometry of the bead. The benefit of applying these equations is to directly calculate the given flux density from the position of an individual node. In the current analysis, slightly changed parameters of double ellipsoidal model are used in which $c_1 = c_2 = a$, $f_f = 1/3$, and $f_r = 2/3$. It was recommended that the values of $a$ and $b$ to be $(1.3) \times$ (half of bead width) and $(0.8) \times$ (depth of penetration) respectively [18].

The geometry of the butt joint currently under consideration is symmetric along the weld centreline. The geometry is meshed with an 8-noded thermal element, SOLID70 available in the ANSYS element library to compute thermal solutions; corresponding 8-noded structural element, SOLID185 also available in the ANSYS element library is used to compute structural solutions. The geometrical and meshed models of the symmetric half of the butt joint are shown in figure 3 and figure 4 respectively.

Figure 2. Double ellipsoidal heat flux density distribution.
In the sequential thermo-mechanical analyses first, the energy equation is solved with appropriate boundary conditions to get a thermal solution. This thermal solution is given as input to the succeeding structural analysis to get the stress solution. The welding and subsequent cooling process is divided into 200-time steps in which 150 steps are of the same time step during actual arc burning period and the remaining 50-time steps are for the cooling period of the joint. The time steps in the cooling period are in the geometric progression with a common ratio 1.1. The generation of thermal solutions and succeeding structural solutions are carried out sequentially for all 200-time steps. The butt joints analysed in this work are of two materials namely 1018 steel and SS 304 steel. The thermo-mechanical properties of these two materials are given in table 2 and table 3 respectively. The other properties density, latent heat, and melting temperatures of 1018 steel and SS 304 steel are given in table 4 and table 5 respectively are taken from the web.

### Table 2. Thermo-mechanical properties of AISI 1018 steel [17]

| Temperature (℃) | Thermal conductivity (W/m K) | Specific heat (J/kg K) | Enthalpy (10^9 J/cum) | Poisson’s ratio | Yield stress (MPa) | Stress At strain =1 (MPa) | Young’s Modulus (GPa) | Coefficient of Thermal Expansion (10^-6/°C) |
|----------------|-------------------------------|------------------------|-----------------------|----------------|-------------------|------------------------|----------------------|------------------------------------------|
| 0              | 51.90                         | 450                    | 1.00                  | 0.2786         | 290               | 314                    | 200                  | 10.0                              |
| 100            | 51.10                         | 499.20                 | 2.00                  | 0.3095         | 260               | 349                    | 200                  | 11.0                              |
| 300            | 46.10                         | 565.50                 | 2.65                  | 0.3310         | 200               | 440                    | 200                  | 12.0                              |
| 450            | 41.05                         | 630.50                 | 3.80                  | 0.3380         | 150               | 460                    | 150                  | 13.0                              |
| 550            | 37.50                         | 705.50                 | 4.10                  | 0.3575         | 120               | 410                    | 110                  | 14.0                              |
| 600            | 35.60                         | 773.30                 | 4.55                  | 0.3738         | 110               | 330                    | 88                   | 14.0                              |
| 720            | 30.64                         | 1080.4                 | 5.00                  | 0.4238         | 9.8               | -                      | 20                   | 14.0                              |
| 800            | 26.00                         | 931.00                 | 5.23                  | 0.4738         | 9.8               | -                      | 20                   | 15.0                              |
| 1450           | 29.45                         | 437.93                 | 9.00                  | 0.4990         | 9.8               | -                      | 2.0                  | 15.0                              |
| 1510           | 29.70                         | 400.00                 | 11.00                 | 0.4990         | 9.8               | -                      | 0.2                  | 15.0                              |
| 1580           | 29.70                         | 735.25                 | 13.25                 | 0.4990         | 0.009             | -                      | 0.00002              | 15.0                              |
5000  42.20  400.00  28.40  0.4990  0.009  -  0.00002  15.5

Table 3. Thermo-mechanical properties of SS 304 [17]

| Temperature (°C) | Thermal conductivity (W/m K) | Specific heat (J/kg K) | Enthalpy (10^9 J/cum) | Young’s modulus (GPa) | Thermal Expansion (10^-6/°C) | Poisson’s ratio | Yield stress (MPa) | Tangent modulus (MPa) |
|-----------------|------------------------------|------------------------|-----------------------|-----------------------|----------------------------|----------------|-------------------|---------------------|
| 20              | 15.0                         | 442                    | 1.036                 | 200                   | 19e-6                     | 0.278          | 230               | 2800                |
| 200             | 17.5                         | 515                    | 1.73                  | 185                   | 19e-6                     | 0.288          | 184               | 2590                |
| 400             | 20                           | 563                    | 2.59                  | 170                   | 19e-6                     | 0.298          | 132               | 2380                |
| 600             | 22.5                         | 581                    | 3.51                  | 153                   | 19e-6                     | 0.313          | 105               | 2142                |
| 800             | 25.5                         | 609                    | 4.46                  | 135                   | 19e-6                     | 0.327          | 77                | 1890                |
| 1000            | 28.3                         | 631                    | 5.45                  | 96                    | 19e-6                     | 0.342          | 50                | 9.6                 |
| 1200            | 31.1                         | 654                    | 6.48                  | 50                    | 19e-6                     | 0.350          | 10                | 5.0                 |
| 1340            | 31.1                         | 669                    | 7.22                  | 10                    | 19e-6                     | 0.351          | 10                | 1.0                 |
| 1390            | 66.2                         | 675                    | 9.57                  | 10                    | 19e-6                     | 0.353          | 10                | 1.0                 |
| 2000            | 66.2                         | 675                    | 12.86                 | 10                    | 19e-6                     | 0.357          | 10                | 1.0                 |

Table 4. Other properties of 1018 steel

| Property                        | Value            |
|---------------------------------|------------------|
| Density                         | 7800 Kg/m³      |
| Melting temperature             | 1539 °C         |
| Latent heat of solidification   | 260 kJ/kg       |

Table 5. Other properties of SS 304

| Property                        | Value            |
|---------------------------------|------------------|
| Density                         | 8000 Kg/m³      |
| Liquidus temperature            | 1390 °C         |
| Solidus temperature             | 1340 °C         |
| Latent heat of solidification   | 260 kJ/kg       |

A macro in ANSYS APDL is written to apply the moving double ellipsoidal heat flux density distribution with welding speed along the weld centreline. The applied heat flux density distribution
when the torch is at the middle of the joint is shown in figure 5. Symmetry boundary conditions are applied at the symmetric plane of the joint for both thermal and structural analyses. Natural convection is applied on all boundary surfaces of the problem domain except symmetric surface as cooling load, the heat transfer coefficient is taken as 15 W/m²K and the ambient temperature is taken as 30°C (figure 6). All nodes on a line at the bottom of symmetric surface are arrested in all three degrees of freedom to prevent rigid body motion in the structural solution. Kinematic hardening is assumed to represent plastic behavior.

![Figure 5. Heat flux density distribution of double ellipsoidal when the welding torch at the center of the joint](image)

![Figure 6. Convective boundary conditions (h = 15 W/m² K)](image)

3. RESULTS AND DISCUSSION
Sequential thermo-mechanical analyses have been carried out to compute temperature distribution and levels of residual stresses of a welding problem of an experimental work reported in the literature. The butt joints are of two materials namely 1018 steel and SS 304 steel. Temperature distributions and residual stresses are computed for these joints separately.

The accuracy of a finite element solution is assessed by performing a convergence study. It is well-established fact that the solution tends to converge to the exact solution as the number of elements are increased so that element size becomes smaller and smaller. Three meshes (table 6) of increasing mesh density are tested for convergence of peak temperature at a particular location of the 1018 steel butt joint. Thermal histories at the distances of 30mm, transverse to the weld centreline top surface and middle section of the joint extracted from the solutions of three meshes and plotted in figure 7. Finally, it is found that all the thermal histories are concurrent. Hence, it can be concluded that convergence has been achieved.

| Mesh no | No of nodes | No of elements |
|---------|-------------|----------------|
| Mesh 1  | 7852        | 5400           |
| Mesh 2  | 13741       | 10800          |
| Mesh 3  | 19630       | 16200          |

Table 6. Meshes for convergence study
**Figure 7.** Convergence study: Thermal histories of three meshes at 30 mm distance from the weld centreline

Temperature distributions of 1018 steel butt joint after 25 s, 50 s, 75 s, 656 s from the start of welding are displayed in figure 8, figure 9, figure 10 and figure 11. The position of the torch and formation of weld pool (red color region) can be clearly seen from these figures. Thermal histories of 1018 steel at distances 30mm, 40mm, and 50mm, transverse to the weld centreline top and middle section of the joint are plotted in figure 12. From this figure, it is evident that the peak value of the temperature decreases with an increase in the distance from the weld centreline.

**Figure 8.** Temperature distribution after 25 s from the start of welding of 1018 steel

**Figure 9.** Temperature distribution after 50 s from the start of welding of 1018 steel
Figure 10. Temperature distribution after 75 s from the start of welding of 1018 steel

Figure 11. Temperature distribution after 656 s from the start of welding of 1018 steel

Figure 12. Thermal histories at various locations from the weld centerline top and middle of the joint (mild steel)
3.1. Comparison of experimental thermal histories with numerical thermal histories

The comparison of present numerically obtained thermal histories with those experimentally obtained in the literature of 1018 steel butt joint at 30 mm, 40 mm, and 50 mm from weld centreline at the top and middle of the joint are shown in figure 13, figure 14, and figure 15 respectively. From these figures, it can be concluded that the agreements between corresponding thermal histories obtained numerically and experimentally are good. A similar observation can be made from figure 16 which represents the comparison of numerically obtained thermal history with that obtained experimentally in the case of SS 304 steel butt joint also.

Figure 13. Comparison of numerical and test warm thermal histories of 1018 steel butt joint at a 30 mm from the weld centerline

Figure 14. Comparison of numerical and test warm thermal histories of 1018 steel butt joint at a 40 mm from the weld centerline

Figure 15. Comparison of numerical and test warm thermal histories of 1018 steel butt joint at a point 50 mm from the weld centerline top and middle of the joint

Figure 16. Comparison of numerical and test warm thermal histories of 304 stainless steel butt joint at a point 30 mm from the weld centerline top and middle of the joint
The peak temperature obtained in thermal histories of AISI 1018 steel is greater than the thermal histories obtained in SS 304 steel. The peak temperatures obtained at 30 mm, 40 mm, and 50 mm locations away from weld centerline are 174°C, 165°C and 136°C. Numerically obtained thermal histories are in good agreement with experimentally obtained thermal histories.

3.2. Comparisons of residual stress distributions
Numerically obtained transverse, normal, longitudinal and von-Mises residual stress distributions of 1018 steel are shown in figure 17, figure 18, figure 19, and figure 20 respectively. The transverse, normal, longitudinal and Von-Mises residual stress distributions on a line transverse to weld centreline middle and top of the joint are shown in figure 21. From this figure, it can be observed that normal stresses are nearly zero as they represent stresses normal to open surface. Longitudinal stresses are dominant from the rest of the stresses.

Figure 17. Transverse residual stress distribution of 1018 steel
Figure 18. Normal residual stress distribution of 1018 steel
Figure 19. Longitudinal residual stress distribution of 1018 steel
Figure 20. Von-mises residual stress distribution of 1018 steel
The comparison of longitudinal residual stresses obtained numerically with those obtained experimentally using neutron diffraction which are existing in the literature on a line transverse to weld centreline middle and top of the 1018 steel butt joint in figure 22. From the figure, the comparison between numerical and experimental results has been good. However, the numerical simulation could not able to capture the stresses near the weld centreline. This may be attributed to the omission of weld metal deposition in the FE simulation. A similar observation (figure 23) can be made from the comparison of numerically obtained and experimentally obtained longitudinal residual stress distributions on the same line mentioned above given in the case of SS 304 steel butt joint. The peak value of numerically obtained longitudinal residual stress of 1018 steel under present welding conditions is 289 MPa whereas the same for SS 304 steel is 237 MPa. This can be attributed to the lower value of virgin yield stress of SS 304 steel when compared with that of 1018 steel.

Figure 21. Component residual stress distributions on a line transverse to weld centreline top and middle of the joint of 1018 steel

Figure 22. Comparison numerical and experimental longitudinal residual stress distributions on a line transverse to weld centreline top and middle of 1018 steel

Figure 23. Comparison numerical and experimental longitudinal residual stress distributions on a line transverse to weld centreline top and middle of SS 304 steel
3.3. Effect of preheat temperatures on longitudinal stress distribution

Preheating the plates to be joined before actual welding is a method to reduce residual stresses. Analyses are carried out with three preheat temperatures 600 °C, 700 °C and 800 °C of SS 304 steel joint under identical welding parameters of the case with no preheating. The comparisons of longitudinal residual stress distributions with these preheat temperatures and that obtained with no preheating are illustrated in figure 24. It may be observed from this figure that the peak value of residual stress decreased considerably with preheating and there is a marginal decrease in peak value of residual stress with an increase in preheat temperature also as reported in table 7. This is because of the fact that preheating the joint before welding reduces temperature gradients consequently reduces residual stresses.

![Figure 24. Effect of preheat temperature on longitudinal residual stresses](image)

Table 7. Peak values of longitudinal residual stress with preheating temperatures of SS 304 steel

| Preheat temperature (°C) | Peak value of longitudinal residual stress (MPa) |
|-------------------------|-----------------------------------------------|
| 30 (without preheat)    | 237                                           |
| 600                     | 216                                           |
| 700                     | 213                                           |
| 800                     | 205                                           |

4. CONCLUSIONS

Sequential thermo-mechanical analyses are carried out to compute temperature distribution and residual stress distribution of a welding problem whose experimental results are existing in the literature using the finite element method. Following observations are made from this work:

- Comparison of experimental thermal histories with numerical thermal histories yielded a good agreement.
• Longitudinal residual stresses are dominant in comparison with other component stresses.
• The peak value of numerically obtained longitudinal residual stress of 1018 steel (289 MPa) is more than that of SS 304 steel (237 MPa) under identical welding conditions. This may be due to the fact that virgin yield stress of 1018 steel (290 MPa) is more than that of SS 304 steel (230 MPa).
• Comparison of experimentally obtained longitudinal residual stresses are in good agreement with corresponding numerical results. However, FE simulation could not able to capture stresses near the weld centreline. This may be due to the omission of weld bead within the FE simulation.
• The peak value of longitudinal residual stress is decreased with preheating.
• There is a marginal decrease in longitudinal residual stress with an increase in preheat temperature.

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