The effects of R_i/T ratio on residual stress of SAPH440 steel welding for auto parts

L X Chi1,2,3, S F Liang1, B L Yan1 and X Z Gao1

1College of Materials Science and Engineering, Chongqing University of Technology, Chongqing 400050, China
2Chongqing Municipal Engineering Research Center of Institutions of Higher Education for Special Welding Materials and Technology, Chongqing University of Technology, Chongqing 400050, China

E-mail: chiluxin200195@163.com

Abstract. In order to study the effect of R_i/T on welding residual stress in forging presses for Auto parts material, a welding experiment program was developed. The residual stress of thick pipe 10mm joint was measured by the blind hole drilling method. The simulation results within and near the weld joint, the transverse residual stresses are tensile on the inside surface which already close to yield strength with creasing the R_i/T ratio, and compressive on the outer surface; The prediction results from FEM are in a good agreement with the experimental measurement which are important to apply data for manufacturing plant.

1. Introduction

Due to a combination of high strength, toughness and good weld-ability, the new material SAPH440 steel has been used for auto parts [1]. The Lower arm and the Upper arm with longitudinal welding are the main equipment in auto parts, the superiority or inferiority of welding quality will directly affect the car normal operation.

Many studies show that the intense heat concentration will make the weld line and its vicinity to undergo severe thermal cycles, which cause non-uniform heating and cooling of the material, thus generated inhomogeneous plastic deformation and residual stress in welded joint [2]. Therefore, understanding the residual stress distribution and improving the welding quality can ensure auto parts normal operation safety. Residual stress investigations at present are mostly focused on circumferential butt welding, Lee [3] and Yaghi [4] employed a three-dimension finite element to simulate the residual stresses distribution in circumferential welds of pipe and parametric studies with inside radius to wall thickness ratio have been presented to investigate the effects of diameter on residual stress, but less focused on different R_i/T ratio. Owing to the residual stress state and distribution will change under own constrain conditions with the model size increasing, in this study, experimental measurement and finite element analysis are adopted to investigate the effects of R_i/T ratio on the temperature filed and the residual stress distribution of SAPH440 steel welding to provide data for manufacturing plant.

2. Experimental procedure

2.1. Material properties
The material properties especially at high temperature have been a critical issue in welding simulation, which is able to realize the nonlinear relation between physical parameters and temperatures in heating and cooling process. Thus, thermo-physical properties close to melting point were adopted according to the report [5, 6], the properties of the weld filler material H08Mn2Si (φ1.2 mm) were assumed to be the same as the base metal. Table 1 shows the chemical composition of SAPH440 steel, the Metal Active Gas Arc Welding conditions in experiment as in table 2, frequency was 143 HZ, and Gas flow was 15 L/min.

| Table 1. Chemical composition of SAPH440 steel. |
|----------------|
| C  | Si  | Mn  | P  | S  | Al  |
| 0.21 | 0.30 | 1.5 | 0.03 | 0.025 | 0.01 |

| Table 2. Welding condition in the experiment. |
|----------------|
| voltage | Current | Filter Speed | Protection gas |
| V      | (A)     | (mm/s)       |
| 40     | 80      | 8            | 80Ar+20CO₂    |

2.2. Experiment data measurement

After the completion of the welding, the thermal cycles were measured by K type thermocouples with spotting welded to the pipe. The strain gauges were used to measure the welding residual stress, the drilled holes diameter was 1.5 mm, and the holes were as deep as 2 mm. The locations and the strain gauges are shown in figure 1.

![Locations of the strain gauges. (a) Location of strain gauges and (b) Rosettes bounded on the outer surface of the pipe.](image)

After measuring released strains along the vertical welded joint, the longitudinal residual stress and the transverse residual stress were calculated according to the following equations:

\[
\sigma_{12} = \frac{E(e_1 + e_2)}{4A} + \frac{E}{4B} \sqrt{(e_2 - e_1)^2 + (2e_2 - e_1 - e_3)^2}
\]

\[
tg2\theta = \frac{2e_2 - e_1 - e_3}{e_3 - e_1}
\]

\[
\sigma_{13} = \frac{\sigma_1 + \sigma_2 + \sigma_3 - \sigma_1 \cos(2\theta)}{2}
\]

Where \(e_1, e_2, e_3\) are the released strains of strain gage rosette in three directions, respectively. \(\sigma_1, \sigma_2\) are the maximum principal stress and minimum principal stress. E is Young’s modulus of elasticity, A and B are the strain release coefficient, which can be get from the equipment manufacturer, \(E = 2.04 \times 10^{11}\) Pa, \(A = -0.07255, B = -0.1514\). \(\theta\) is the angle contained by \(\sigma_1\) and \(e_1\), along clockwise, if \(e_3 \geq e_1\), \(\theta = \theta\), and \(e_3 < e_1, \theta = \theta + 90^\circ\).
3. Finite element analysis
Welding residual stress was calculated by three-dimension thermal and mechanical finite element method. First, the temperature contours were computed according to the given welding parameters and the boundary conditions. Second, the temperature contours were taken as load in the structural analysis. Meanwhile, the improved substructure algorithm method was adopted to condense internal node for reducing calculation freedom, which was aimed to simplify loading and improve simulation efficiency for pipe.

3.1. Finite element model of pipe
Due to the intense heat concentration, a relatively fine mesh was designed at the weld zone, and element size increased progressively with distance from the weld center line, which reduced total number of nodes. In this study, based on ANSYS software, the simulation of the longitudinal welding has been performed on SAPH440 steel pipe with length of 1000 mm, thickness of 10 mm with different R/T ratio is listed in table 3, which have the same mesh density. The pipe was welded by four pass as shown in figure 2.

![Figure 2. Finite element model near welding center line.](image)

| Cylinder wall Thickness, T (mm) | Cylinder inside Radius, Ri (mm) | Inside radius to wall Thickness ratio, R/T |
|--------------------------------|--------------------------------|-----------------------------------------|
| 10                             | 100                            | 10                                      |
| 200                            | 20                             | 20                                      |
| 300                            | 30                             | 30                                      |
| 400                            | 40                             | 40                                      |
| 500                            | 50                             | 50                                      |

3.2. Thermal analysis
Element birth and death technique was used in FE model to simulate deposit filling, which activated element before analysis by multiplying their stiffness using a severe reduction factor, similarly, mass, damping, specific heat were set to zero for deactivated elements [5]. The heat flux from the moving welding arc was given by:

\[ Q = UI\eta/V \]

Where \( U \) is the welding voltage, \( I \) is the welding current, \( \eta \) is the arc efficiency, \( V \) is the activates element volume of heat source. The efficiency factor is assumed as 0.76 for the MAG process.

4. Results and discussion

4.1. Temperature contours
The distribution and the evolution of the temperature contours were almost the same, therefore, the fourth weld pass of 30 ratio are selected to be introduced as figure 3 with the time at 1 s, 50 s, 100 s and 500 s.

![Temperature contours](image)

**Figure 3.** Temperature contours of the fourth weld pass. (a) t=1 s; (b) t=50 s; (c) t=100 s; (d) t=500 s.

It can be seen that the transient temperature distribution with the moving arc at different time are almost identical, the maximum temperature in weld pool is assumed to experience 1800℃, the HAZ between 825~1125℃, away from the heat source the temperature is rapidly decreased, it can be concluded that the temperature field is steady along welding direction, as figures 3(a)-3(c). The maximum temperature at the start/stop is higher than other place, which influences the residual stress. The inter-pass temperature is controlled to be lower than 120℃ at the 400s as figure 3(d).

### 4.2. Thermal cycles

![Thermal cycle simulation](image)

**Figure 4.** Thermal cycle simulation with R/T ratio.

The thermal cycle simulation at welded joint is presented for the model with R/T ratio to 50 as figure 4.

It is known that the thermal cycles of the five models have a similar trend since the same welding parameters are given to the models along the welding direction.
4.3. Residual stress distribution

It is critical to establish four paths on the FE model to thorough analysis residual stress distribution as shown in figure 5. Path 1 is vertical weld center line on the outer surface of the pipe. Path 2 is vertical weld center line on the inside surface of the pipe. Path 3 is the weld centre line along the welding direction on the outer surface of the pipe. Path 4 is the weld centre line from the inside to the outer surface of the pipe along thickness. Residual stress distributions of the four paths with different R/T ratios are shown in figure 6.

![Figure 5. Path laying diagram.](image-url)
It can be observed that, the transverse residual stresses in the weld and its vicinity have slightly increased with increasing R/T to 50, and are all compressive stress on the outer surface, the longitudinal residual stress are mainly determined by the radial expansion and subsequent contraction, tensile stress at outer surface have the same trend when the R/T increase to 50 as shown in figures 6(a) and 6(b). From the weld joint to the metal on the inside surface, the transverse residual stress and the longitudinal residual stress have been maintained the maximum tensile stress, which already close to the material yield strength as figures 6(c) and 6(d). Spatial variations are present at start/stop positions due to the moving arc effect along the welding direction. Increasing the R/T to 50 lead to a significant decrease of transverse stress from thickness 3 to 6mm, but there is a more spectacular increase at the bottom with the maximum compressive stress, and the maximum tensile stress is about 423 MPa at the position of 2 mm from the outer surface as figures 6(e) and 6(f). From the weld joint to the metal on the outer surface, the transverse residual stresses are changed from compressive stress, tensile stress to compressive stress, and then reach the maximum value 300MPa at the fusion zone, longitudinal residual stresses are changed from tensile stress to compressive stress and achieve the maximum value 532 MPa at weld joint as figures 6(g) and 6(h).

5. Verification of FE modeling
To verify the simulation result, the same geometrical model, welding conditions were used in the experiment, the thermal curves and the residual stresses were measured on the outer surface, and the results as figure 7.
Figure 7. Comparison of experiment and analysis. (a) Comparison of thermal curves and (b) Comparison of residual stresses.

It is clear that the prediction results from FEM are in a good agreement with the experimental measurement. Although there is an error in the lower temperature which has no effect on the organization of the metal.

6. Conclusions
In this study, the simulation of residual stress on SAPH440 steel pipe were gained by three-dimensional uncoupled thermo-mechanical FE analysis, meanwhile, the influence of the R/T ratio on residual stress was clarified. The following conclusions can be drawn:

- It can be observed that within and near the welding joint, the transverse residual stresses are tensile on the inside surface, and compressive on the outer surface, and the longitudinal residual stresses from the outer surface to inner surface are all tensile with gradual increasing which already close to yield strength.
- The residual stresses in the weld and its vicinity are increased with increasing the R/T ratio.
- These observations are important to apply the residual stress results for manufacturing plant.

Acknowledgments
This work is financially supported by the Science and Technology Research Program of Chongqing Municipal Education Commission (Grant No. KJ1709197).

References
[1] Lee B S, Kim M C, Yoon J H et al 2009 Characterization of high strength and high toughness Ni-Mo-Cr low alloy steels for nuclear application Int. J. Pres. Ves. Pip. 2009 1-7
[2] Liu C, Zhang J X and Xue C B 2011 Numerical investigation on residual stress distribution and
evolution during multi-pass narrow gap welding of thick-walled stainless steel pipes Fusion Eng. Des. 86 288-95

[3] Lee C H and Chang K H 2008 Three-dimensional finite element simulation of residual stresses in circumferential welds of steel pipe including pipe diameter effects Mater. Sci. Eng., A 487 864-74

[4] Yaghi A, Hyde T H, Becker A A and Sun W 2006 Residual stress simulation in thin and thick-wall stainless steel pipe welds including pipe diameter effects Int. J. Pres. Ves. Pip. 83 210-8

[5] Sattari-Far L and Farahani M R 2009 Effect of the weld groove shape and pass number on residual stresses in but-welded pipes Int. J. Pres. Ves. Pip. 86 723-31

[6] Deng D, Murakawa H and Liang W 2007 Numerical simulation of welding distortion in large structures Comput. Method Appl. Mech. Eng. 196 4613-27