Investigation of Residual Stresses on Post Weld Heat Treated A106-GRB Steel Pipe by Hole-Drilling and FEM

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***Abstract*— In this paper, the effects of post weld heat treatment (PWHT) by ceramic pad heater to relieve residual stresses of an A106GRB carbon steel pipe is presented. At first, the pipe was welded in 3 passes by GTAW and SMAW process. The thermal cycle was measured during welding with k-type thermocouple. Hole drilling method has been used for measuring residual stresses before post weld heat treatment and after it to investigate on relieving residual stresses. Also, a 3D finite element analysis was used for predicting residual stresses before PWHT and after it for comparison with experimental data. The results show that the post weld heat treatment by ceramic pad heater can relief residual stresses up to 60% at HAZ and welding area.**

***Index Terms*— post weld heat treatment (PWHT), ceramic pad heater, residual stresses, hole drilling, finite element**

I. Introduction

Residual stresses may be produced in materials by any manufacturing processes that cause thermal gradients or plastic deformation. The importance of them is that this stresses could have same effect as external forces. They can sum up with external forces and cause yield in materials [1]. In oil and gas industries, butt welding in pipes is a common joint method in which GTAW welding process is used for root pass because of good penetration and SMAW welding process for filling and cap. This two welding methods are different in many items such as amperage, voltage, polarity and the way of moving torch that complicate predicting of residual stress values and distribution. PWHT process, used in pressure vessels and piping for relieving residual stresses, is suggested in various codes and standards including ASME SEC VIII [2] , API RP 579 [3] , EN 13445 [4]. All of these codes are based on 3 stages: heating rate, holding time and temperature and cooling rate. Investigations on PWHT on carbon steel at furnace represent holding time and temperature has more effect than other parameters in relieving residual stresses [5]. Smith and Garwood [6] reported the effect of PWHT on relieving residual stresses of BS1501 steel. They found maximum residual stress decrease after PWHT is about 100-140 MPA. Skouras et al. [7] investigated on residual stress in p92 stainless steel. They found that maximum residual stress after welding is about 350-400 MPA that reduces to 200 MPA after PWHT. Investigation showed an estimate of residual stress reduction about 30% of yield stress that is adopted by various assessments of API RP 579 and BS7910 [8]. Dong et al. [9] and Zhang et al. [10] employed a series of FE PWHT process for estimating residual stress reduction in furnace. They conclude for furnace based PWHT, the procedures in codes are significantly conservative and can be reduced for achieving an expected residual stress which can result in economic benefits. Ceramic pad heater is an instrument that is widely used for PWHT process to relieve pipe residual stresses. It is consist of many ceramics with some elements between them. This can be used near weld areas and those places affected by severe thermal cycle. The advantages of this method are economical benefits as well as less consuming energy, although this method has some disadvantages that are investigated in this study. There is a gap between each two pieces of ceramic pads causing non uniform temperature distribution through surface and thickness of specimen.

II. Experimental Procedures

A. Welding Setup

The A106 GRB Carbon steel pipe was circumferentially but welded in 3 passes as usually using in oil and gas industries. Root and second passes are welded by GTAW process using ER70S electrodes. Filling pass is SMAW process by using E7018-H electrode. Selecting GTAW process for root pass is based on proper penetration of weld metal and selecting SMAW for filling is based on high strength of weld metal. The pipe with outer diameter 114.3 *mm* and thickness 8.56 *mm* was used. The single-v groove joint was prepared as

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shown in Fig. 1. The pipes fixed with four tack welds with sequence of 90°, 270°, 180° and 315° to maintain a uniform 3 *mm* gap between them. The pipes welded in 3 passes without preheating based on ASME SEC VIII [2]. Welding conditions are shown in table 1.

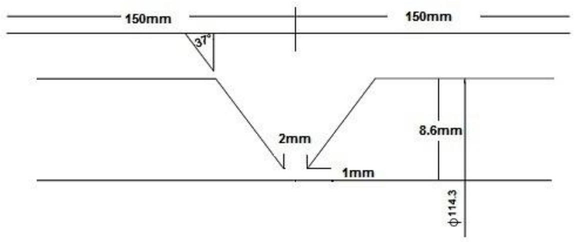


Figure 1. A schematic of single-v groove joint design.

TABLE I. THE WELDING CONDITION USED IN WELDING EXPERIMENT

Pass No.	Amperage	Voltage (V)	Net Heat Input	Polarity
1	138	23-25	2800	DC-
2	138	25	2800	DC-
3	104	40	3500	DC+

B. Thermal Measurement

In order to measure thermal cycle temperature and verify F.E model, temperature measurements were conducted in 3 places with different distances from centreline by three k type thermocouples with diameter 1.5 mm placed at holes drilled to 5 mm depth. The locations of thermocouples are 3 mm, 13 mm and 18 mm from groove edge as shown in Fig. 2. To record measured data, a Lutron data logger with 0.1 °C precision was used. Fig. (2) shows the picture and schematic of the thermocouples.

C. PWHT Procedure

The PWHT process was applied using a ceramic pad heater as shown in Fig. 3. One k type thermocouple placed between pipe and ceramic pad heater to measure thermal cycle temperature. Fig. 4 shows measured thermal cycle temperature.

D. Measuring Residual Stress

To evaluate effect of PWHT by ceramic pad heater on relieving residual stress, hole drilling method was used before PWHT and after the process. The rosette strain gauges were used in center, 10mm and 20 mm of weld line at 90 degree to the welding start point. A hand grinder is utilized to remove spatters while water has been used continuously to control temperature. Fig. 5 shows the strain gauges and hole drilling process that is used for measuring residual stress.

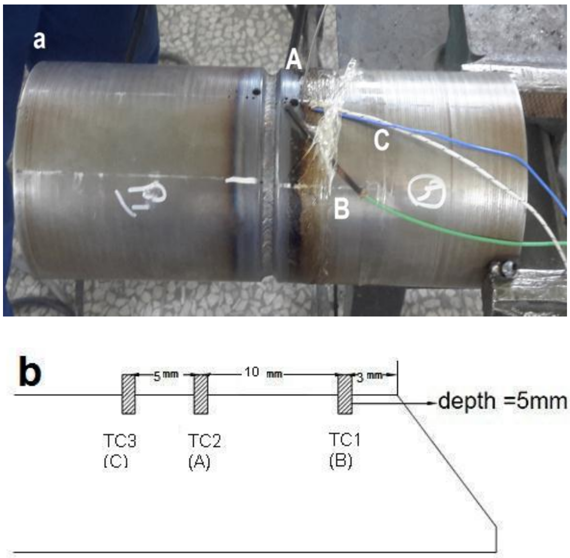


Figure 2. (a) The picture and (b) schematic of thermocouples location.

Figure 3. (a) Ceramic pad heater on outer surface of pipe and (b) insulation by ceramic wool.

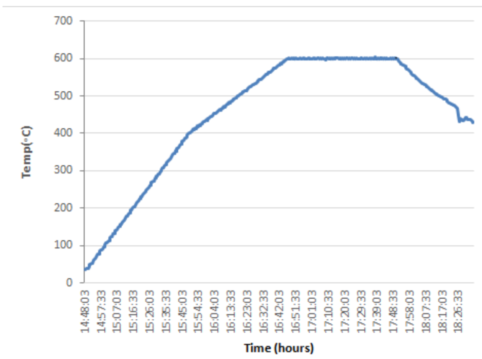


Figure 4. PWHT thermal cycle temperature measured by thermocouple.

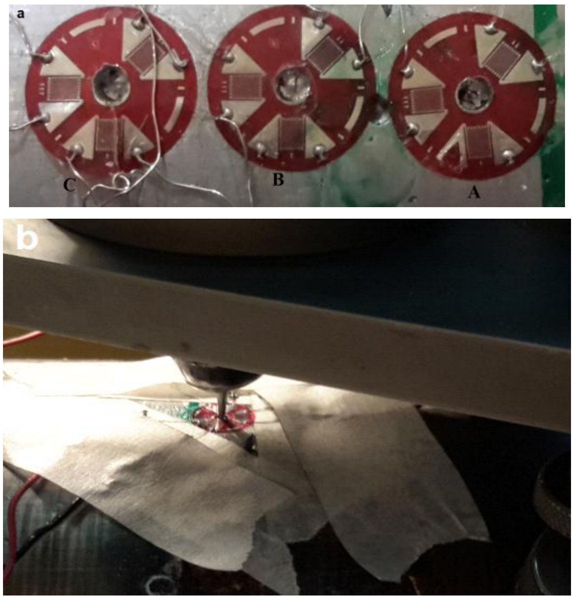


Figure 5. (a) Strain gauges attached on external surface of pipe and (b) hole drilling process.

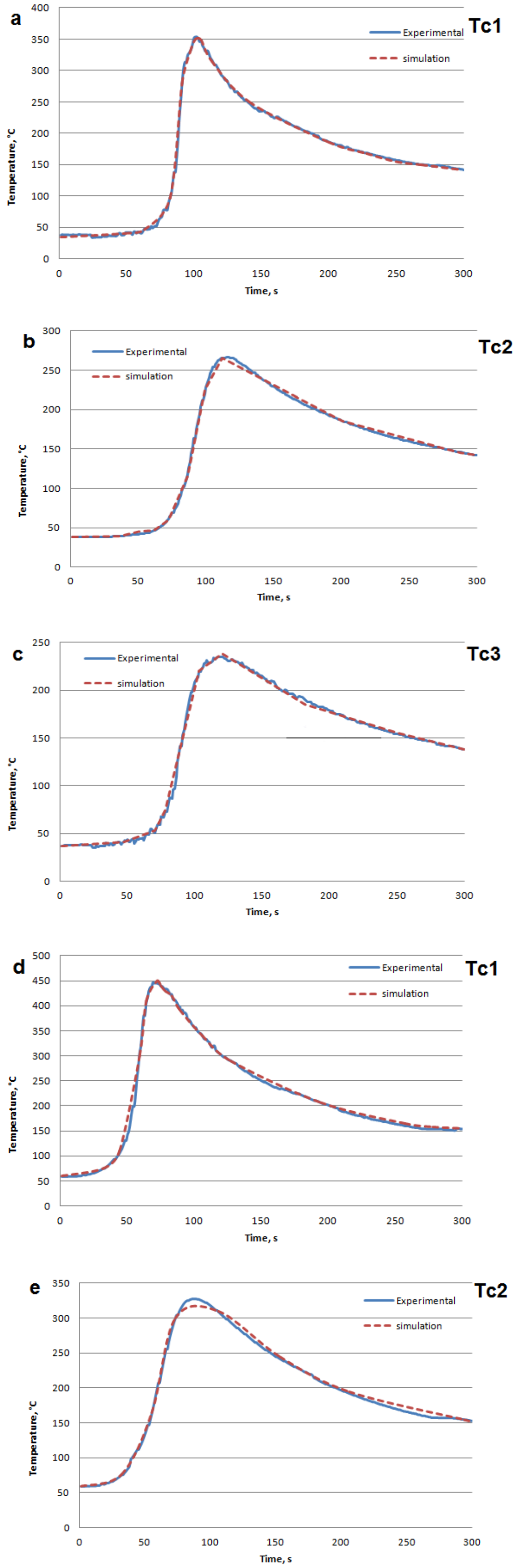
III. Result and Discussion

A. Finite Element Simulation

The distributions of residual stress and temperature field have been investigated by means of finite element method. For finite element analyzing, a three dimensional coupled thermo-mechanical model is developed. The based metal and weld metal are defined as same materials. Because of symmetry, just one half of specimen was modeled. During the analysis, the model change option was used to simulate adding weld metal and sequences of passes. In present study, the Goldak's double ellipsoid distribution was used to model heat source [11]. As thermal boundary condition, heat losses due to radiation was considered for higher temperature near and inside weld zone and convection considered for lower temperature away from weld area [12]. Same as circumstances seen in experiments, for mechanical boundary condition in finite element simulation before PWHT, left side of pipe set fixed and after PWHT, all mechanical boundary conditions were removed for relieving residual stresses.

B. Thermal Results

Temperature measurements in three locations of thermocouples were performed and compared with simulation results for verification as shown in Fig. 6. As it can be seen, all plots have experienced their maximum values while the torch passes the thermocouple line. From this figure, we can observe good agreement between experimental and simulation results in first and second passes. In third pass, there is low agreement between experimental and simulation results because of electrode wave moving style and arc instability in SMAW process.



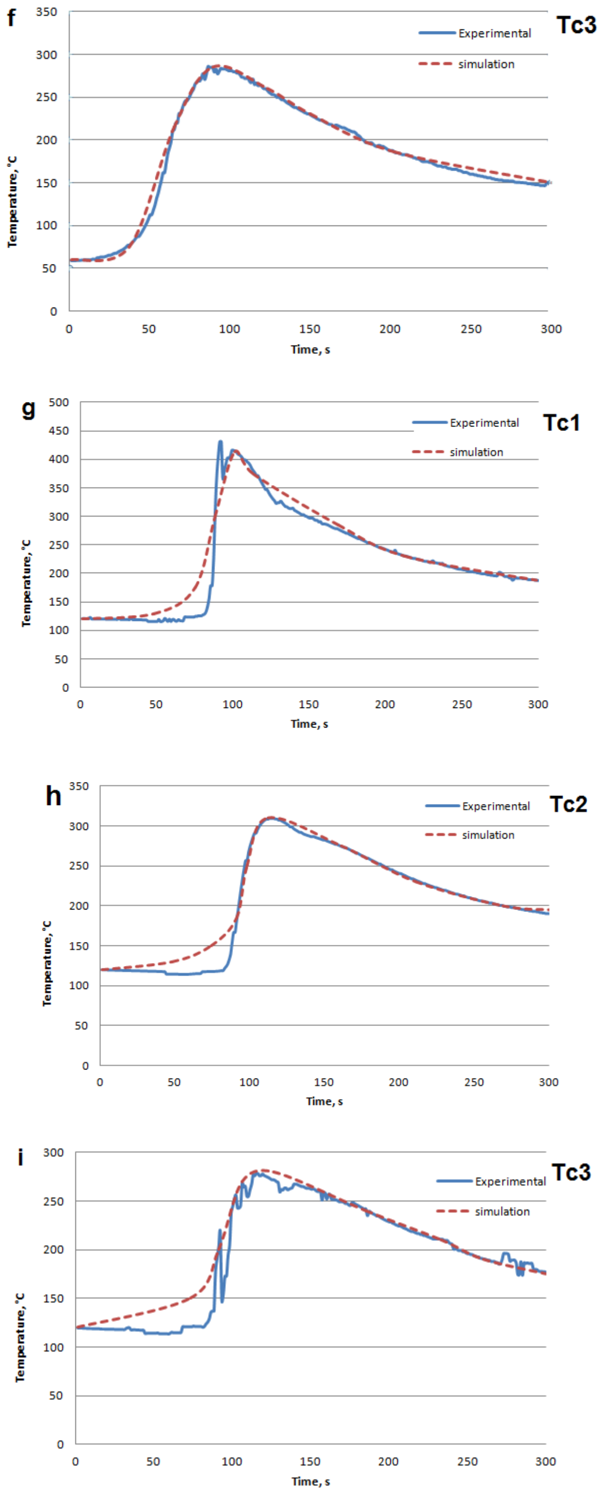


Figure 6. Comparison between experimental data and simulation results for : (a) TC1 in pass1 , (b) TC2 in pass1, (c) TC3 in pass1, (d) TC1 in pass2, (e) TC2 in pass2, (f) TC3 in pass2, (g) TC1 in pass3, (h) TC2 in pass3, (i) TC3 in pass3.

A few cases of the simulation results for temperature field in all 3 passes are shown in Fig. 7. Since heat source function is locally concentrated, temperature near HAZ area and weld metal rapidly change with increasing distance from center line. Maximum temperature is occurred in second pass at 3 *mm* distance from groove edge in accordance to Fig. 7(b).

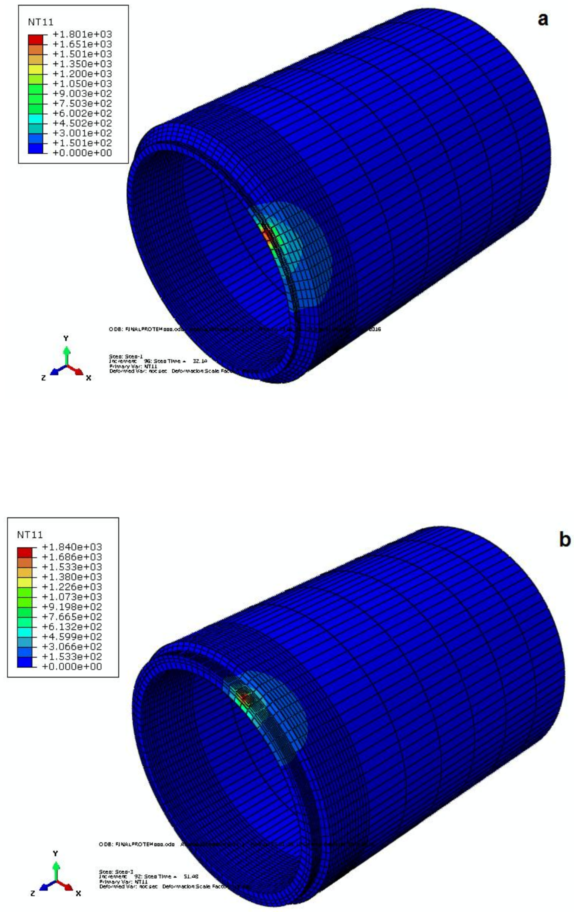


Figure 7. The simulated temperature fields of the circumferentially butt-welded pipe in 3 passes: (a) pass 1, (b) pass 2.

C. *Mechanical Results*

Figs. 8 and 9 show axial and hoop residual stresses that have been determined by employing hole drilling method and finite element simulation. This figures show residual stresses before PWHT and after it by ceramic pad heater. From this figures it can be seen that the hoop stress is in very good agreement with experimental data, but in axial stress where distance from weld line is larger than 15 *mm*, there is low agreement between simulation and experimental results. This issue may be caused by initial residual stress that produced in manufacturing process before welding. As cited before, weld area and HAZ experienced much temperature values during welding, therefore plastic strains were generated and initial residual stress have no effect on final residual stress except in parts which are far from the weld zone, where the initial residual stress is not affected by welding and therefore is added to the welding residual stresses. The results in these figures show that maximum residual stress is at HAZ area that decreases substantially after applying PWHT by ceramic pad heater. Comparison of diagrams depicted in Figs. 8 and 9 shows that the axial residual stress eliminated approximately but residual hoop stress decreased about 60% and changed toward the tensile stress that may cause initiation of micro cracks in welding area and HAZ region.

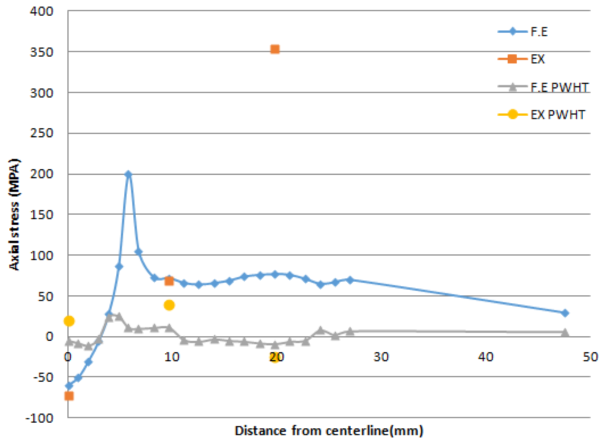


Figure 8. Axial stress distribution on outside surface.

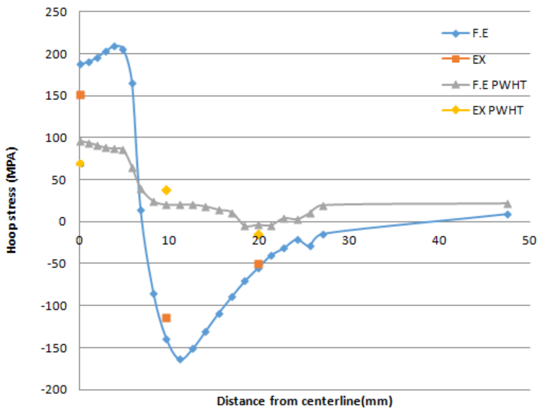


Figure 9. Hoop stress distribution on outside surface.

IV. Conclusions

It can be concluded from this study that based on simulation and experimental results, it is clear that temperature distribution in weld line and HAZ area is very high except at distances more than 15mm from weld line. The maximum temperature is occurred in second welding pass at 3 mm distance from groove edge. Therefore the maximum residual stress is at HAZ area. The hoop stress is in very good agreement with experimental data, but in axial stress where distance from weld line is larger than 15 *mm*, there is low agreement between simulation and experimental results due to initial residual stress that produced in manufacturing process before welding. Axial residual stress approximately eliminated and residual hoop stress is reduced substantially up to 60% by means of ceramic pad heater near weld area and HAZ region but changed toward the tensile stress that may cause initiation of micro cracks.

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