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Finite Element Analysis of Residual Stress in Welded Joints of T91 Steel

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Abstract. The pressure equipment is the key equipment in the petrochemical industry, natural gas chemical industry and coal chemical industry. Without safe and reliable pressure equipment, advanced process industry cannot be realized. It is important of the quality assurance of pressure vessel in order to prevent the failure of pressure vessel, especially some rupture accidents. One of the key reasons for quality assurance of pressure vessel is the treatment of residual stress in welded joint. In this paper, the working stress and welding residual stress of the thick plate of pressure equipment material and the welding joint of pressure equipment have been measured and analyzed successively by means of actual stress measurement and finite element simulation analysis. The influencing factors of welding stress are introduced, and the control of residual stress is analyzed and some suggestions are put forward in this paper.

1. Introduction

At present, the main strategic position in the national economy is energy, and boilers are widely used in all walks of life as the most commonly used energy storage containers. The T91 steel is commonly used in supercritical boiler heating surface tubes. SA213T91 is a kind of material between 12Cr1MoV and stainless steel. Its structure is improved 9Cr1Mo high strength martensitic heat resistant steel with high fracture strength and heat corrosion resistance. SA213T91 is an ideal tube for boiler heating surface tubes in the temperature range of 600-650℃. It has good oxidation resistance, higher thermal conductivity than austenitic steel, similar linear expansion coefficient to pearlitic steel, and lower price than austenitic steel [1]. The allowable stress of the steel is higher than that of austenitic stainless steel when the service temperature is lower than 620 ℃, especially the dissimilar steel welded joints with austenitic stainless steel. The thermal strength performance of the welded joints can reach the same level as that of the steel itself. It is well known that all high-temperature equipment and pipeline manufacturing is usually completed by welding process, and the use of welding components at high temperature becomes one of the key structural components. In order to ensure the structural integrity and safe and reliable service performance of high temperature components, it is necessary to ensure the reliability of welded joints of high temperature components. In a large number of equipment and pipeline failure accidents, the early failure of welds is often reported. As a weak link of high temperature device system, welded joints of high temperature components have been paid more and more attention by engineering circles. Because of the high concentration of instantaneous heat input in the welding process, there will be huge welding residual stress and deformation in the welding process and after welding.

Through analysis, we can easily conclude that the main reason affecting the safe operation of these components is the residual stress. People have been paying more attention to accurately predicting welding residual stress.

Since the 1980s, the finite element technology has been widely developed. Tekriwal and other scientists have used the finite element method to simulate the arc welding process and predict the welding temperature field [2]. Brust and other scientists used the THERMOELASTIC-PLASTIC finite element model to calculate the welding residual stress of 304 stainless steel pipes for boilers. Professor Tekriwa used three-dimensional finite element transient heat transfer model to simulate the thermal flow in tungsten argon arc welding (TIG) process. Considering the welding speed and current input strength, the width of heat affected zone and weld fusion zone was predicted and compared with the experimental data. Dong has carried out numerical simulation and analysis of two-dimensional and three-dimensional butt welding of circular pipes, and satisfactory results have been obtained [3].

2. Residual Stress Measurement of Welded Joints

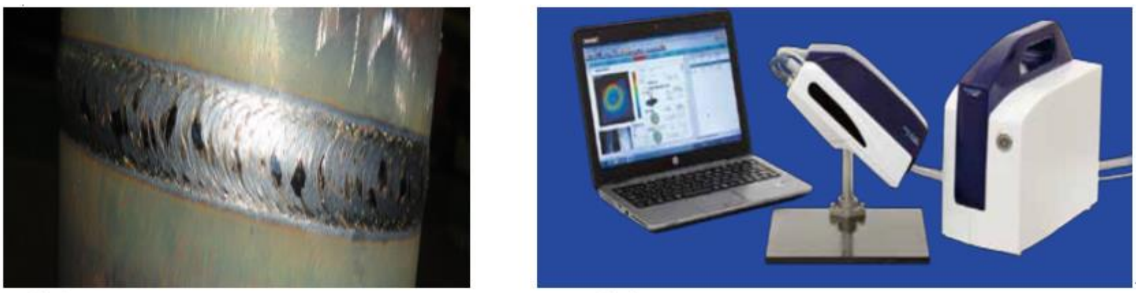
2.1. Generation Principle of Welding Stress.

2.1.1 Welding temperature field. The welding process of the boiler is a very uneven local heating process, which will cause uneven shrinkage and expansion of the metal. Therefore, in principle, the stress and deformation caused by welding are the same as that caused by uneven temperature field. However, the stress and deformation of welding are relatively complex, which complexity is shown in the following three aspects： There is a wide range of temperature changes during welding. In the central part of the weld, the highest temperature can reach the boiling point of the material, but the temperature drops sharply when leaving the heat source, so the temperature gradient of the difference is very large; Because the temperature of heating is very high and the range of variation is large, the mechanical properties and thermophysical properties of the metal material vary with the temperature; Because the temperature range of welding varies greatly, so the situation is great. Local phase transition occurs when the phase transition temperature exceeds the phase transition temperature.

2.1.2 Formation of Welding Stress and Welding Deformation. Phase transition will cause many changes in mechanical parameters and physics. For the metals constituting the boiler, after welding, deformation and residual stress will occur in the components, which reason is that the welding area will produce a lot of uneven deformation because of the huge temperature difference, which in turn will be restrained by the effect of deformation around the development of cold metal cannot be free. In the heating stage, because it is not free expansion, it must also emphasize the instantaneous thermal stress on both sides and the tensile stress far away from the weld in the welding and adjacent areas. Because the material has lost its elasticity when the weld and adjacent area T > 800℃, it is limited to the plastic deformation of the expansion and compression of the generated part. In the cooling stage, because it is not free of cooling shrinkage, there will be residual stress [4]. The welding seam and adjacent areas are limited by the shrinkage of residual tensile stress, and the stress is far away from both sides of the weld.

2.2. Preparation of Welded Joints.

The specimens are SA213-T91 straight pipe welding specimens with a diameter of 51mm 8mm. The inert gas shielded welding (TIG) method is used to test the residual stress of pipeline welding and the testing equipment, as shown in Fig1.Heat treatment is required after the completion of welding work. The standard of post-weld heat treatment is as follows. The heating rate is less than 220/h from 420 ℃, the holding temperature is 730-760 ℃, the holding time is 2 h, the cooling rate after holding is less than 275/h ℃, and the cooling temperature is less than 420/h, then it is cooled in static air. The Welding Test Plates and Welding Stress Testing equipment are shown as the figure 1.

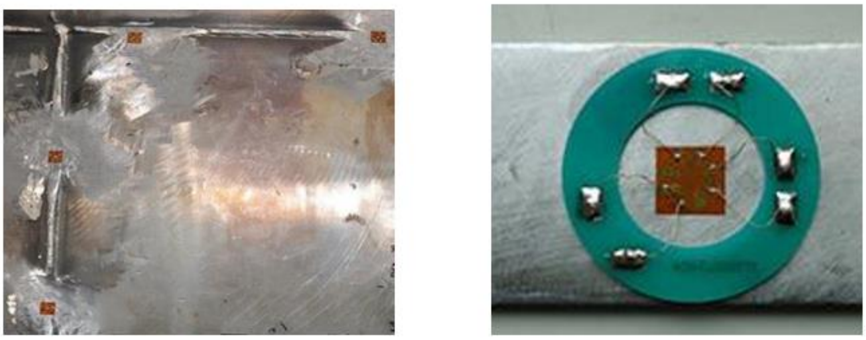


（a）Welded test plate （b）Welding Stress Testing Equipment

Figure 1. Welding Test Plate and Welding Stress Testing Equipment

2.3. Welding Residual Stress Testing.

In order to ensure the accuracy of the test, it is necessary to treat the surface of the test site of the pipeline before X-ray spot strikes the surface of the sample without scattering. The weld surface of this sample has a high smoothness and smoothness, so in order to avoid the pressure stress on the sample surface during grinding with grinding wheel or abrasive paper, this step is cancelled and the sample is electropolished directly until there is enough light and no scratches at the test point. First, we use X-ray diffractometer to measure the axial residual stress on the outer wall of T91 pipeline. Then we cut the pipeline by wire cutting. Then we cut the pipeline along the middle line to measure the axial residual stress on the inner wall. The distribution of welding residual stress test points in the inner and outer walls is shown in Figure 2.



(a)Inside (b) External

Figure 2. Residual Welding Stress of Pipeline Samples

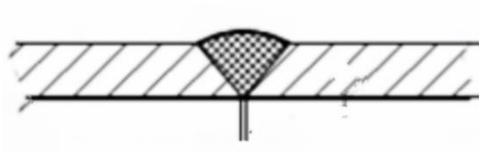
2.4. Comparison of Residual Stress Test Results with Finite Element Results.

In order to verify the validity and reliability of the finite element method for simulating welding residual stress, the test results of axial welding residual stress of inner and outer walls after testing are collated and compared with the results of finite element simulation. By comparing the welding residual stress after heat treatment with that of finite element method, it can be seen that the measured residual stress at the measuring point is close to the corresponding results of finite element simulation, and the distribution trend is also consistent, which can prove that it is feasible to use finite element method to analysis welding residual stress. From the experimental and finite element values, it can be seen that the residual stress at the weld is relatively high, the inner wall is tensile stress, while the outer wall is compressive stress, and the stress value decreases gradually with the increase of the weld distance.

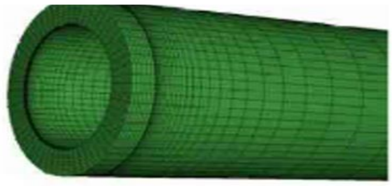
3. Finite Element Analysis of Residual Stress in Welded Joints

3.1. Establishment of Finite Element Model .

The whole finite element analysis process of welded joints is based on the solving process of mesh elements and nodes. In the finite element analysis of welded structure, because of the large heat input at the weld seam and the instantaneous heat conduction, the thermal gradient and stress-strain gradient are the key parts of finite element analysis. The non-linearity of structure and solution equation is very high, which is the key area of finite element analysis [5]. Therefore, the mesh density of the weld and its heat-affected zone increases relatively, while in most base metal areas far from this area, the mesh element size can be gradually enlarged to improve the calculation efficiency. Dimensions and mesh models of T91 steel welded joints are shown in Figure 3.



(a)Welded Joint Model



(b) Finite Element Mesh Model

Figure 3. Establishment of Finite Element Model

3.2. Load and boundary conditions.

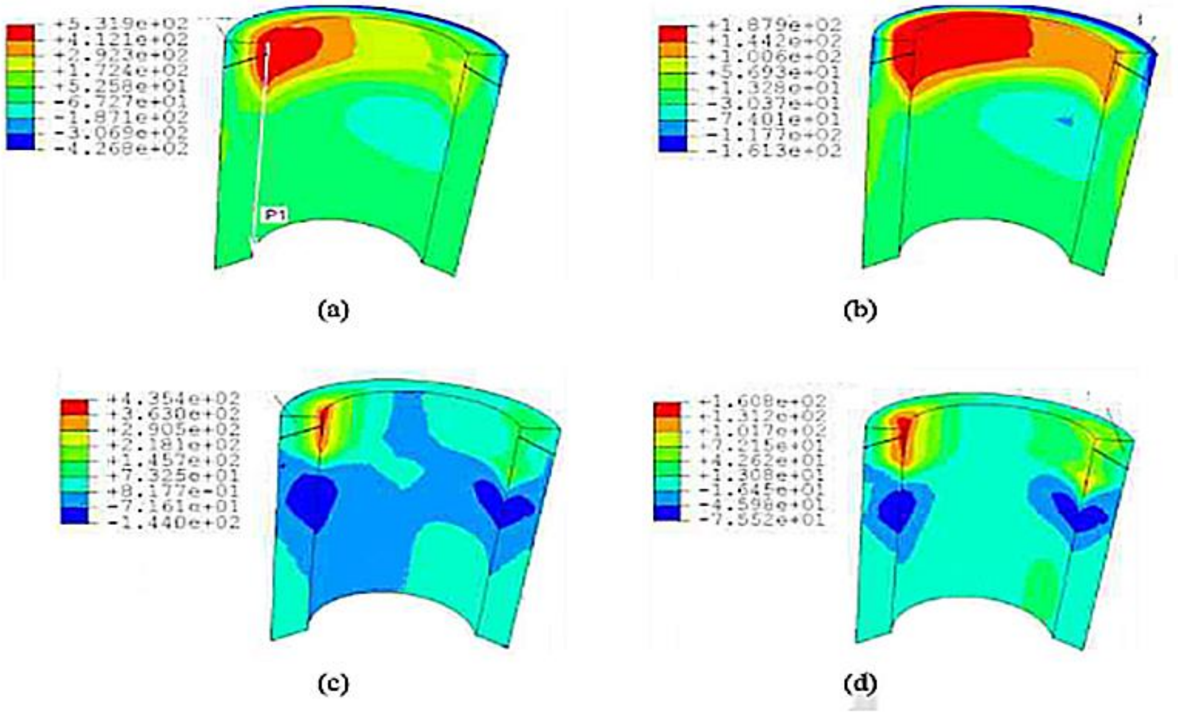
The load and boundary conditions of the finite element model should simulate the actual welding process as much as possible. For the heat source model of endogenous heat system, the heat source model of thermal welding is used to load the amplitude curve (* AMPLITUDE) into the welding method to simulate the movement of welding heat source by increasing the time. Welding heat source can be effectively converted into heat input per unit time per unit volume of the weld by assuming that internal heating is applied to the weld element. Heat input refers to the heat input from welding energy to the weld of unit length during fusion welding. In the welding process, in order to prevent the whole structure from rigid movement of the welded parts, it is necessary to keep the welded structure away from the weld seam with fixed constraints.

$$q = \eta \mathrm{UI}/\mathrm{v}$$

In the formula:
Q - heat input (J/mm);
U - arc voltage (V);
I - welding current (A);
V - Welding speed (mm/s);
η-thermal efficiency (arc welding = 0.7-0.8; submerged arc welding = 0.8-0.95; TIG welding= 0.5).

3.3. Analysis of Welding Stress Simulation Results.

3.3.1. Welding Stress Analysis. Figure 4 shows the residual stresses of the welded joints of straight pipes in the axial and annular welding of the inner wall after as-welded and heat-treated. It can be seen from the diagram that the maximum axial stress and the maximum circumferential stress of the inner wall after welding are 531.9 MPa and 435.4 MPa. As shown in Figure (a), (c), the axial stresses of the heat affected zone and the inner wall weld are tensile stresses. After heat treatment, the maximum axial stress and circumferential stress of the welded joint decreased to 187.9 MPa and 160.8 MPa respectively. After welding heat treatment, the residual stresses were redistributed, and the axial stresses in the inner weld and heat affected zone were more uniform than those in the welded state, and showed tensile stresses. After welding heat treatment, the maximum circumferential stress of the inner wall is still tensile stress.



（a）Axial welding stress of welded inner wall；(b) Axis of inner wall after heat treatment；
(c) circumferential welding stress of welded inner wall；(d) Circumferential welding stress of inner wall after heat treatment

Figure 4. Distribution of residual stress in axial and circumferential welding of inner wall after as-welded and heat-treated

3.3.2. Postweld heat treatment. The axial and circumferential stresses in the weld seam and heat affected zone of the welded outer wall are compressive stresses, while the axial and circumferential stresses in the weld seam and heat affected zone are compressive stresses. The maximum external axial compressive stress is 426.8 MPA and the maximum circumferential stress is 144 MPA. The pressure level is significantly reduced by post-weld heat treatment, but the pressure gradient is also significantly reduced after stress redistribution. However, the maximum external axial and circumferential stresses are still in the weld and heat affected zone. Maximum axial compressive stress 161.3 MPA, maximum circumferential stress 75.5 MPA. Because post-weld heat treatment can reduce the welding residual stress in the more obvious weld seam and heat-affected zone, the redistribution of post-weld stress can reduce the pressure of residual stress gradient. To learn more about the stress distribution of welded joints and the heat-affected zone of welds perpendicular to the inner and outer reference paths P1 and P2, high residual stress areas can be obtained in the heat-affected zone or in the welded zone. Moreover, the axial and circumferential residual stresses in the weld seam and heat-affected zone are significantly reduced by post-weld heat treatment. High tensile residual stress at welded joints often leads to failure of welded joints under harsh conditions (high temperature, high pressure, corrosion, etc.), such as mode IV cracks and stress corrosion cracks in heat affected zone. At high temperature, the creep strain of welded joints will also be affected by the residual stress when there is a higher residual stress, and the creep strain at the high stress position will increase.

3.4. Equivalent Stress Distribution of Welded Joints.

The experimental results show that when the creep damage process is dominated by the structure coarsening mechanism and there are few voids, it is appropriate to take Von-Mises stress as the equivalent stress of failure under multiaxial stress. The maximum equivalent stress of welded joints occurs in the weld seam and heat affected zone, which is also due to the maximum axial and circumferential equivalent stress at the weld seam. The Mises stress distribution in the outer weld of straight pipe is relatively uniform, ranging from 145 MPa to 188 MPa, while the Mises stress in the local position of inner wall is relatively low, about 50 MPa. If the creep damage process is dominated by microcracks and voids, the failure is controlled by the maximum principal stress. But in most cases, this stress and the maximum principal stress contribute to the failure of high temperature components. According to the fracture stress theory of bone points, the maximum principal stress is a component of equivalent fracture stress that causes failure of high temperature components, which is a good example. The maximum principal stress of the joint is 192.4 MPa at the weld and heat affected zone of the inner wall, while the principal stress of the outer wall is low, almost zero.

4. Conclusion

Through the research, we have a better understanding of the stress in the welded joint of the pressure equipment, and have a thorough analysis of the effective ways to eliminate the stress in the pressure vessel.

4.1. The axial and circumferential stresses of the weld seam and thermal effect of T91 steel are the highest.

In as-welded condition, the stress gradient of weld and base metal is higher, the axial and circumferential stress of inner wall is tensile stress, and the axial and circumferential stress of outer wall is compressive stress. After post-weld heat treatment, the welding residual stress level of the welded joint is obviously reduced, the maximum reduction range is 60%. After heat treatment, the welding residual stress level is reduced to less than 190 MPa, and the maximum reduction is about 50 MPa.

4.2. The maximum principal stress is one of the main reasons to control the failure of high temperature welded structures.

Through the analysis of the maximum principal stress of the component, the equivalent stress level of the weld and heat affected zone is still higher than that of the base metal, which is one of the reasons for the first failure of the welded joint.

4.3. Significance of residual stress analysis of welded joints.

By analyzing the residual stresses of these welded joints, it can be regarded as one of the reasons for the complex loads that high temperature components bear during service, which lays a mechanical foundation for creep damage analysis and life prediction of welded joints.

5. Reference

[1] Wang Jianhua. Welding numerical simulation technology and its application [M]. Shanghai: Shanghai Jiaotong University Press, 2009.
[2] Cai Zhipeng. Research and application of numerical simulation of welding deformation for large structures [D]. Ph.D. Dissertation, Beijing: Tsinghua University, 2001.
[3] Chen Xiaodong. Solutions for eliminating welding residual stress in pressure vessels [J]. Material Engineering, 2003 (6): 15.
[4] Zhang Guodong, Xue Jilin, Zhou Changyu. Welding process optimization of high temperature pipeline based on orthogonal experimental design. Journal of Welding, 2008, 29 (11): 53-56.
[5] Lu An-li, Shi Qingyu, Zhao Haiyan, et al. Several key technical problems in the field of welding process simulation and their preliminary study [J]. China Mechanical Engineering, 2000, 11 (1-2): 201-205.