Stress Analysis of Welding Seam of Throttling Flowmeter Used in Power Plant Boiler

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Abstract. To reveal the stress distribution characteristics of throttling flowmeter used in power station boiler under different working conditions, two methods are used to calculate and analyze this kind of flowmeter. The welding seam of throttling flowmeter was calculated by finite element method based on Ansys software, and the stress distribution characteristics under different working conditions were obtained. The results show that there is a large peak stress between the root of the welding seam and the circumferential short joint of the throttle. Based on ASME "Load and Resistance Factor Design" limit analysis method, the results show that throttle flowmeter is easy to crack and fatigue failure when pressure load and temperature load change. The analysis results of the two methods are consistent with the problems in practical application.

Keywords: Throttling flow meter · Safety performance · Stress analysis · Limit analysis · Crack

1 Introduction

Simple structure, easy installation, low cost, and series products, throttling flowmeter is widely used in the flow measurement of power station boilers. For a long time, throttling flow meter as a kind of measuring instrument, the related research and the existing standard mainly pay attention to its measurement characteristic.

For testing the use of flow meters in vacuum piping systems, Maqsood et al. [1] found an expanded uncertainty for leakage rate of 8% for the stated testing conditions and he designed a simple and compact primary orifice plate flowmeter. Sood et al. [2] focused on smart side of flowmeter and derived a prototype which is composed of a microcontroller, a flow sensor, and a GPS sensor. To improve the accuracy of flowrate measurement, Li et al. [3] designed a portable and integrated type flowmeter, whose welding neck flanges is designed for the connecting

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flanges. This structure weakened the distribution of connecting flanges and meet the demand of test. A finite element analysis of pressure drops in orifice meter by Gohil et al. [4] shows that is some permanent pressure loss depending on the shape of obstruction, diameter ratio, and the fluid's properties. Dhumalm et al. [5] investigated the effect of various geometric features on the pressure loss characteristics of multi-holed orifices. Moreover, a simple model to calculate the pressure loss coefficient of multi-holed orifices was presented. They also analysed, designed, and calculated the discharge variations in single-holed, 4-holed, 5-holed and 7-holed orifice flow meters. By applying a new Lab VIEW technique, Faraj et al. [6] simplified orifice plate sizing calculation, which provides valuable help for engineers. During welding process, Mvola et al. [7] illustrated that ternary shielding gas (Ar+CO2+O2) is widely used in various position as a result of the extensive metal transfer modes including short circuit, spray and pulsed spray. It slightly improves the arc stability compared to Ar/CO2. Tamizhinian et al. [8] established an effective deposition technique on austenitic stainless-steel orifice plate component. The successful crack free weld deposition process parameters include localized weld bordering, usage of clamping fixture, thermal insulation and 14-h and 18-h cooling after first- and second-layer weld deposition, respectively. Ravindra et al. [9] developed Load and Resistance Factor Design criteria for steel building structures from first order (second moment) probabilistic principles, provide a foundation of good engineering practice.

Luo [10] analyzed the inspection method of ISA 1932 nozzle steam flowmeter. Because of its special structure, conventional ultrasonic inspection is not suitable for non-destructive inspection of steam flowmeter, the application of TOFD and phased array detection in this type of flowmeter is analyzed.

According to the structure size of flowmeter, Qian [11] put forward the detection method of sector scan by using phased array technology, in which the oblique probe is mainly used to detect the defects in the middle and lower parts of the weld, the straight probe is mainly used to detect the defects in the upper part of the weld. This method can successfully detect four kinds of common flow meter welding defects including non-fusion, non-penetration, crack and gas hole.

Lin [12] carried out ultrasonic testing on shell welds of orifice flowmeter and considered that TOFD ultrasonic testing has great technical advantages.

In order to solve the problem that it is difficult for a single probe to complete the detection of flowmeter in A-type pulsed ultrasonic testing, Xia [13] developed a "Flowmeter weld ultrasonic testing simulation and analysis software", the k-value combination of probe can be screened out intuitively, efficiently and accurately, and the detection of flowmeter weld can be achieved by using different k-value combination of probe.

Synthesize the previous statements, although throttling flowmeter used in power plant boiler is used in the environment of high temperature and high pressure, there is a lack of relevant research on the safety performance of throttling flowmeter [14,15]. According to the structure of the throttling flowmeter, the corresponding mathematical model is established in this paper, the weld stress is collected and analyzed, and the safety condition of the throttling flowmeter is analyzed systematically.

To ascertain the safety of throttling flow meters commonly used in power plant boilers, nine throttling flowmeters (Fig. 1) were selected for dissection, non-destructive testing, scanning electron microscopy (SEM), energy spectrum analysis and experimental study of mechanical properties. It was found that there were cracks and other defects in the welds of 9 throttling flow meters. The rate of defects was 100%. Different defect characteristics of flowmeters are shown in Fig. 2. SEM Fig. 2(d) shows the existence of fatigue striations on the fracture surface, indicating the existence of alternating stress. In this paper, the welding seam stress analysis of $\Phi 273 \times 20$ mm standard orifice flowmeter is carried out to obtain the stress distribution characteristics under different working conditions, which provides a theoretical basis for improving the reliability of the flowmeter.

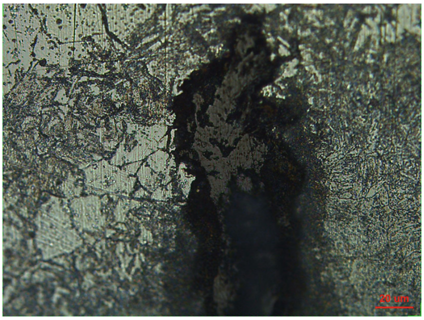
Fig. 1. Throttle flowmeter.

2 Physical Models and Material Properties

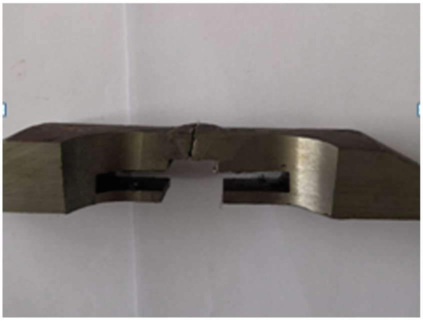
2.1 Physical Models

The $\Phi 273 \times 20$ mm standard orifice flowmeter (hereinafter referred to as orifice flowmeter) is a kind of throttling flowmeter, as shown in Fig. 3. The main pressure bearing parts include the front measuring tube 6, the back measuring tube 1, the short connection of positive annular chamber 5, the short connection of negative annular chamber 2 and the orifice plate 3. The materials of the front and back measuring tubes 4, the short connection of positive annular chamber and the short connection of negative annular chamber are all 12Cr1MoG, and the orifice plate is 1Cr18Ni9Ti. The design pressure of the orifice flowmeter is 9.8 MPa and the design temperature is 540 °C. According to GB/T 2624.2-2006, the structure is in the form of annular chamber corner tap. 7 is the process pipe, I is the tap weld, II is the flow meter manufacture butt weld.

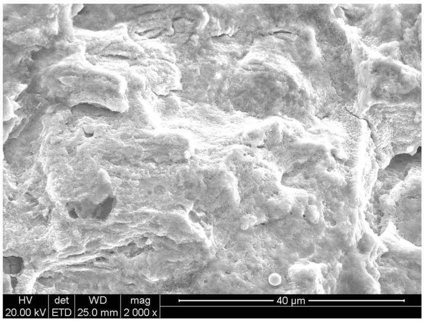
(a) Macrograph of crack



(b) Crack metallograph



(c) Fracture at crack



(d) Fatigue striation at fracture

Fig. 2. Defect characteristics of flowmeter.

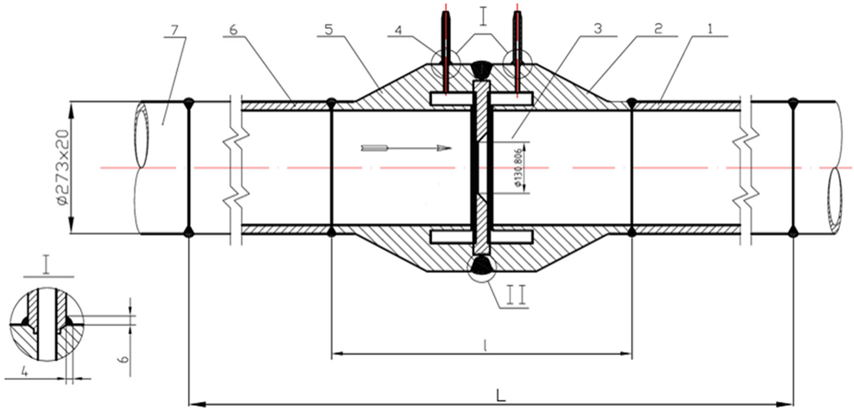


Fig. 3. Assembly drawing of $\Phi 273 \times 20\,\mathrm{mm}$ standard orifice flowmeter

2.2 Material Properties

According to GB150-2011, the main components of orifice flowmeter are 12Cr1MoG and 1Cr18Ni9Ti. The modulus of elasticity at different temperatures is shown in Table 1, the yield strength at different temperatures is shown in Table 2, and the average coefficient of linear expansion at different temperatures is shown in Table 3. The allowable stresses of 12Cr1MoG and 1Cr18Ni9Ti at 540 °C are Sm1 = 68.2 MPa and Sm2 = 63.4 MPa, respectively. The allowable stress, which is less than 1.5 times of the material's stress intensity under the working condition, is taken as the qualified standard.

Table 1. Elastic modulus of materials at different temperatures

Temperature (°C) Elastic modulus (MPa)	20	100	150	200	250	300	350	400	450	500	550
12Cr1MoG	204	200	197	193	190	186	183	179	174	169	164
1Cr18Ni9Ti	195	189	186	183	179	176	172	169	165	160	156

Table 2. Yield strength of materials at different temperatures

Temperature (°C) Yield strength (MPa)	20	100	150	200	250	300	350	400	450	500	550
12Cr1MoG	255	230	215	200	190	176	167	157	150	142	134
1Cr18Ni9Ti	210	174	156	144	135	127	123	120	117	114	111

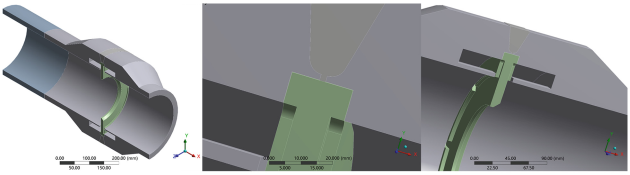
Table 3. Average linear expansion coefficient of materials at different temperatures

Temperature (°C) Average linear expansion coefficient ($\alpha/10^{-6}$ mm/mm°C)	20	50	150	250	350	450	550
12Cr1MoG	10.76	11.12	11.88	12.56	13.24	13.93	14.42
1Cr18Ni9Ti	16.28	16.54	17.06	17.42	17.79	18.19	18.58

3 Stress Analysis Modelling

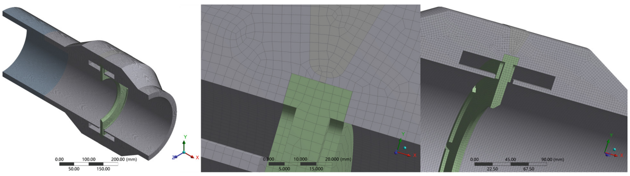
3.1 Mathematical Models

The stress analysis uses Ansys software (version:18.2) to carry on the finite element stress computation to the bearing pressure component. The software meets ASME and JB4732-1995(2005) requirements. Using SolidWorks software to build a three-dimensional model, as shown in Fig. 4. According to the actual working condition of the orifice flowmeter, the design temperature is 540 °C inside and the external environment temperature is 20 °C. The distribution of the temperature field of the orifice flowmeter is obtained, then introduced into the stress field. The internal pressure load is the design pressure of the flowmeter, one end is fixed, and the other end is restrained by the load. Considering the symmetry of structure and load, the 1/2 model is established. The model uses a 3D isoparametric element (solid186) provided by Ansys, which is used for 3D modeling of the structure. The element is defined by 20 nodes, each node has 3 degrees of freedom, x, y and z directions respectively. According to the size given in the design drawing of the flowmeter, the model includes the connection of the measuring tube, throttle, voids and welds. The principle of this model is consistent with Zhen [16]'s simulation of residual stresses in aluminum alloy welds and Chiocca [17]'s testing model of residual stresses in pipe-to-plate welds. In these two published papers, the authors have obtained the variation characteristics of stress and other parameters by using numerical simulation method. The calculation method in this paper is consistent with the numerical calculation method in these two papers, so the results obtained based on the numerical calculation method are reliable. A 0.1 mm gap between the orifice plate and the short joint of the front and back annular chamber is reserved and is calculated as friction contact problem. The welding seam is calculated according to the material of 1Cr18Ni9Ti. There are 603016 cells and 2580182 nodes in the orifice flowmeter model. The discretized finite element grid is shown in Fig. 5.



(a) Internal structure of flowmeter (b) Joint of weld and orifice (c) Weld seam

Fig. 4. Computational model of orifice flowmeter



(a) Mesh of flowmeter (b) Local mesh at joint of weld and orifice (c) Mesh at weld

Fig. 5. Finite element mesh diagram of orifice flowmeter model

3.2 Loads Calculation

The orifice flowmeter is analyzed according to two working conditions: working condition 1(no temperature load working condition), the design pressure and temperature are 9.8 MPa and 20 °C respectively; working condition 2 (with temperature load working condition), the design pressure and temperature are 9.8 MPa and 540 °C respectively.

3.3 Boundary Conditions

The X, Y, and Z directions of the end of the pipe are restricted to ensure that the rigid body displacement does not occur. Symmetric constraints on the plane of symmetry. The internal pressure is applied on the inner surface of the structure, and the equivalent axial tensile stress caused by the internal pressure is applied on the end face of the pipe on the side without displacement. The temperature is applied in a uniform temperature field. The boundary condition diagram is shown in Fig. 6.

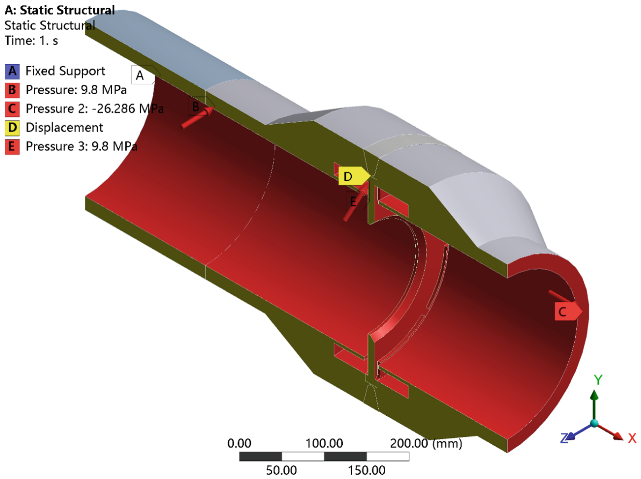


Fig. 6. Boundary conditions of orifice flowmeter model

4 Stress Analysis

The stress intensity cloud diagram of the orifice flowmeter under working condition 1 is shown in Fig. 7. The results show that the maximum stress strength is 69.635 MPa at the root of the weld joint of the positive and negative annular chamber and the orifice plate. The stress intensity cloud diagram of orifice flowmeter under working condition 2 is shown in Fig. 8. The results show that the maximum stress strength is 1179.1 MPa at the root of the weld joint of the positive and negative annular chamber and the orifice plate. The maximum equivalent stress of each section is selected along the axial direction of the orifice flowmeter to obtain the stress distribution, as shown in Fig. 9. The stress distribution shows that the stress intensity is relatively low at the weld without temperature load, indicating that the primary stress is at a relatively low level. But after applying the temperature load, the stress intensity level at the weld is obviously increased because of the dissimilar steel welding. After the temperature load is applied, the thermal stress is amplified by the stress in the root

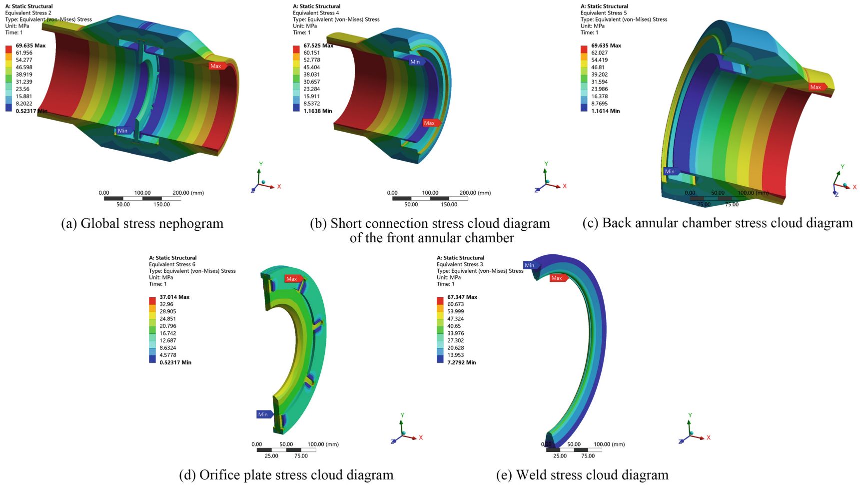


Fig. 7. Stress distribution diagram of orifice plate flowmeter under working condition 1

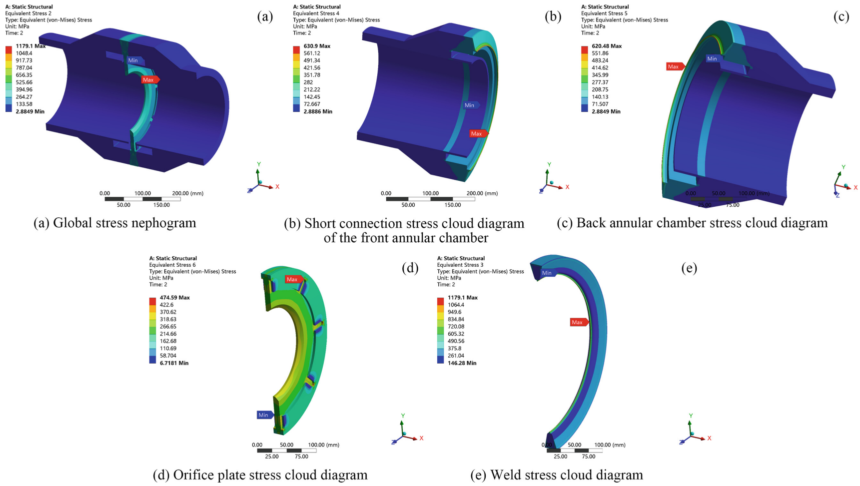


Fig. 8. Stress distribution diagram of orifice plate flowmeter under working condition 2

of the weld seam. The ratio of maximum stress intensity of working condition 1 and 2 is 20.42 times, so the fatigue failure caused by alternating temperature load must be considered in the design of orifice flowmeter.

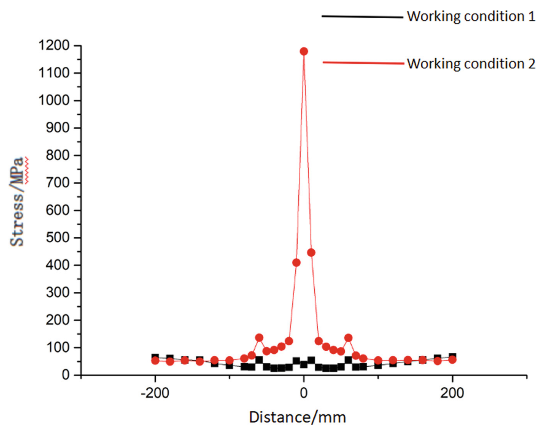


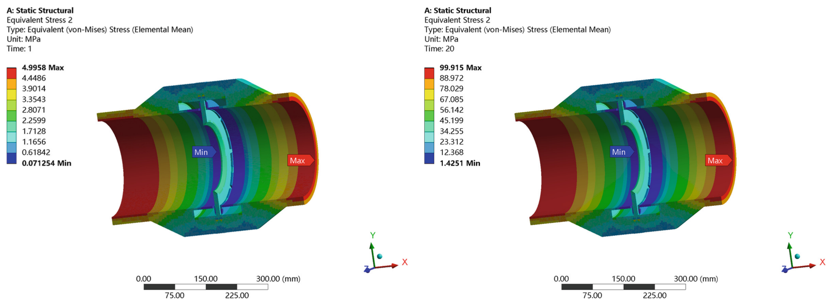
Fig. 9. Axial distribution of stress intensity of orifice flowmeter

The maximum stress intensity of orifice flowmeter is 69.635 MPa, less than 1.5 times of allowable stress. The results show that the primary stress of the flowmeter meets the requirements of the design specification. It is difficult to distinguish the secondary stress from the peak stress due to the maximum stress intensity occurs at the stress concentration. Considering the limitation of stress classification method and avoiding misjudgement, the strength of orifice flowmeter was evaluated by ASME limit analysis method of "Load and Resistance Factor Design".

AYSYS bi-linear isotropic reinforced material model was selected. The elastic modulus of 12CR1MoVG is 1.65 × 105 MPa, the tangent modulus is 1.196 × 102 MPa, and the yield strength is 136.8 MPa. The elastic modulus, tangent modulus, and yield strength of 1Cr18Ni9Ti are 1.568 × 105 MPa, 1.462 × 102 MPa and 111.6 MPa respectively. According to ASME VIII Part 2, the load combination and load coefficient of limit analysis are obtained. The load factor for this analysis is 1.5. The pressure of limit analysis method is 14.7 MPa. In the calculation, load increment proportional loading is adopted, which is divided into 20 steps, as Table 4 shown. Figure 10 shows the stress intensity cloud diagrams for the first and 20th load steps.

Table 4. Load for each load step within limit analysis

Load step	Pressure (MPa)	Load step	Pressure (MPa)
1	0.735	11	8.085
2	1.470	12	8.820
3	2.205	13	9.555
4	2.940	14	10.290
5	3.675	15	11.025
6	4.410	16	11.760
7	5.145	17	12.495
8	5.880	18	13.230
9	6.615	19	13.965
10	7.350	20	14.700



(a) Load step 1 (b) Load step 2

Fig. 10. Cloud diagram of stress intensity

Figure 11 shows the relationship between load and displacement in the 20-step load step calculation. The load and displacement are linear, with the maximum deformation 0.14957 mm, maximum stress intensity 99.915 MPa, which occurs on the measuring pipeline. A convergent finite element solution is obtained in 20th load steps. After considering the load coefficient, the calculation process has not met the limit load of the structure, nor has plastic collapse occurred. Therefore, the orifice flowmeter will not collapse when it is subjected to a finite number of design loads. However, when working under the condition of alternating pressure load and temperature load, it is easy to produce crack and fatigue failure. The result is consistent with the practical application of orifice flowmeter.

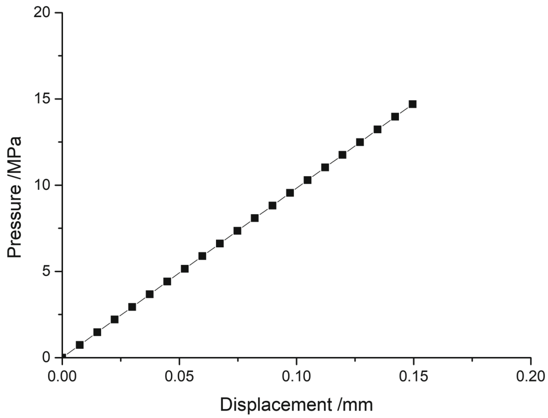


Fig. 11. Relationship between load and displacement during calculation

5 Conclusions

Through stress analysis of welding seam under working condition when manufacturing orifice flowmeter, we can derive that the throttling flowmeter with the same structure has the following problems:

without considering the temperature load, the maximum stress intensity of the structure is less than 1.5 times the allowable stress when the throttling flowmeter is subjected to design pressure, that is, the primary stress of the structure is less than 1.5 times the allowable stress. Under the condition of considering the temperature load, a large peak stress appears at the root of the welding seam of the short joint annular chamber and throttling parts when throttling flowmeter is subjected to the design pressure.

using the limit analysis method of ASME "Load and Resistance Factor Design", the typical structure of throttling flowmeter was analysed. The analysis shows that the limit load and the plastic collapse of the structure have not been found in the calculation process, and the load and displacement are linear. Therefore, the throttling flowmeter will not collapse when it is subjected to a finite number of design loads. However, the throttling flowmeter is prone to crack and fatigue failure under the condition of alternating pressure load and temperature load.

both stress analysis shows that the throttle flowmeter with a typical structure can work under the condition of high temperature and high pressure (for example, design pressure is 9.8 MPa, design temperature is 540 °C), and large stress appears at the root of the welding seam between the front and back annual chamber and the throttles, and serious defects such as cracks will appear after long-term operation. The defects such as cracks were found in the welds of the in-service throttling flowmeter, which proved the above analysis. Therefore, there are some problems with the structure of the throttling flowmeter, which is widely used in utility boilers, and it needs to be adjusted.

In this paper, the stress state and existing problems of the welding seam of throttling flowmeter are analyzed systematically for the first time, and the results are consistent with the weld inspection results and the serious defects of the throttling flowmeter in service. These throttling flowmeters are widely used in high-temperature and high-pressure pipelines of power plant boilers and need to be replaced urgently, at the same time, It is suggested to avoid throttling parts and to eliminate the sudden change of structure at the weld.

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