Fatigue Life Analysis of Hydrogen Production Reactor Welds Under Thermal-mechanical-chemical Coupling

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Abstract. Hydrogen production reactor are subject to performance degradation problems in the complex environment of high temperature, high pressure and exposed to hydrogen atmosphere. The welds, being weak parts, are susceptible to fatigue damage under the influence of loads such as temperature, pressure and hydrogen penetration. In this paper, we focus on the fatigue life analysis of welds in hydrogen production reactor, taking into account the complex working conditions of thermal-mechanical-chemical coupling. Based on the Fe-safe fatigue analysis software, the stress variation of the welds under multi-field coupling was used as a cyclic load and the fatigue life was predicted using the stress-life method. Respectively, the fatigue life variation law of the weld region was studied at different temperatures, pressures, and hydrogen penetration conditions. The results show that the lowest fatigue life of the welds are concentrated in the vicinity of the fusion zone, with hydrogen penetration and temperature variations having a larger impact on the fatigue life, followed by pressure.

Keywords: Hydrogen production reactor; weld; fatigue life; multi-field coupling.

1. Introduction

Due to the continuous advancement of technology and the support of national policies, the hydrogen energy industry is rapidly developing. Many countries have incorporated hydrogen energy into their future energy strategies [1]. During hydrogen production, the hydrogen production reactor operates under prolonged high-temperature, high-pressure, hydrogen, and alternating load conditions, with fatigue failure being the primary mode of failure [2]. Simultaneously, high temperature and high pressure can lead to hydrogen infiltration into the metal, causing hydrogen embrittlement and a subsequent reduction in the material's plasticity and toughness [3], thus diminishing the reliability of the hydrogen production reactor. Being a vulnerable component of the hydrogen production reactor, the weld seam is more susceptible to fatigue damage. Therefore, investigating the weld's fatigue life under real operational conditions and analyzing the impact of various factors on fatigue life can significantly enhance the reactor's reliability.

Both domestic and international scholars have extensively researched the fatigue life of welds. Choe et al. [4] examined the impact of the weld's elastic modulus on stress concentration and the fatigue life of the pressure vessel. Their study revealed that the high elastic modulus of the weld results in a reduction in fatigue life with increasing stress concentration. Abbas et al. [5] conducted a fatigue assessment of cylindrical pressure vessels with circumferential weld misalignment under various load ratios. The results indicated that axial deviation significantly impacts the cylinder's fatigue performance, especially at higher load ratios. To assess the fatigue life of welded joints in the main steam pipeline, Shen et al. [6] conducted fatigue crack propagation tests at different temperatures. The results demonstrated that the fatigue crack growth rate in the weld at high temperatures consistently exceeds that of the base metal. Jiang et al. [7] predicted the fatigue life of 316 stainless steel welded joints under the influence of residual stress. The results revealed that residual stress primarily manifests as an increase in average stress, and the extent of this increase depends on stress redistribution. Gao et al. [8] investigated the fatigue performance of welded joints made from Q690qENH high-strength steel, and they discovered that fatigue fractures in the welded joints were due to stress concentration at the weld toe.

In this paper, the stress state of the weld of a hydrogen production reactor under the action of thermal-mechanical-chemical coupling is analyzed firstly, and then the fatigue life is predicted based on the stress-life method. At the same time, the influence of temperature, pressure, hydrogen penetration, and other factors on the fatigue life is also studied

2. Calculation Method for Fatigue Failure

The hydrogen production reactor is affected by high temperature, high pressure and hydrogen penetration in service, and the load on the weld area is variable amplitude load. Therefore, it is necessary to use Goodman method and the rain-flow counting method to deal with the load of weld [9, 10]. The stress analysis results of the weld thermal-mechanical-chemical coupling model are imported into Fe-safe as the cyclic load for fatigue life analysis and calculation.

The load on the weld of the hydrogen production reactor is asymmetric and needs to be converted using the Goodman formula.

$$S_a = S_{-1}(1-\frac{S_m}{S_b}) \tag{1}$$

Where, S_a is the converted cyclic load amplitude, S_{-1} is the fatigue limit of the material under symmetrical cyclic load, S_m is the average value of the asymmetric load, and S_b is the tensile limit load of the material.

The linear fatigue cumulative damage theory [11] assumes that under the action of constant amplitude load S_i, the failure life is N_i cycles, and the damage at cycle n_i times is defined as :

$$D_i = \frac{n_i}{N_i} \tag{2}$$

When D_i=1, the material is considered to have experienced fatigue failure. For weld fatigue, there are multiple sets of constant amplitude cyclic symmetrical loads, each group of damage is D_i, and the total damage amount is D:

$$D = \sum_{\mathrm{j=i}}^{\mathrm{k}} D_{\mathrm{i}} = \sum_{\mathrm{j=i}}^{\mathrm{k}} \frac{\mathrm{n_i}}{N_{\mathrm{i}}} \ldots i = 1,2,3,\ldots \tag{2.3}$$

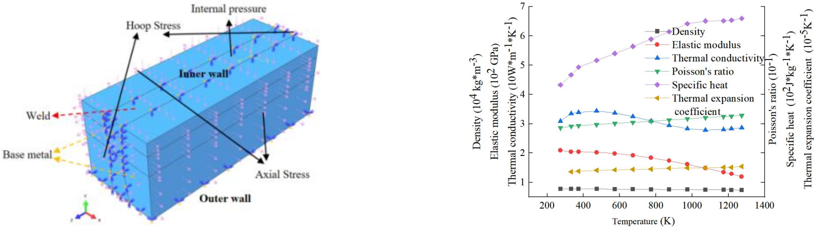
Where, k is the total number of loads obtained using the rain-flow counting method. When the sum of the damage rates of all loads equals 1, fatigue failure occurs on the weld surface.

3. Analysis of Stress and Fatigue Life in Weld Area

3.1 Simulation Analysis of Stress Under Thermal-mechanical-chemical Coupling

The material of a hydrogen production reactor is 13MnNiMoR steel, and during operation, its maximum internal pressure is 30MPa, maximum temperature is 670°C, and the outer wall is in contact with water cooling layer at 300°C. In order to study the effects of different temperature, pressure, and hydrogen penetration on the fatigue life, it is necessary to simulate the results of the stress field under different operating conditions. The temperatures were set to be 670°C, 600°C and 500°C, the pressures were 30MPa, 20MPa and 10MPa, and the hydrogen contents in the inner wall of the reactor were 0.1%, 0.075% and 0.05%, respectively. Based on the CALPHAD method, the material properties of welds with different hydrogen contents can be calculated by JMatPro [12].

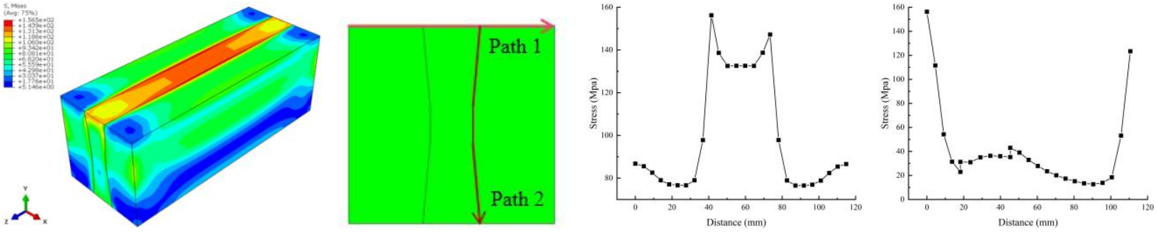
Considering the small area occupied by the weld in the hydrogen production reactor, the computational cost is too high if the whole model of the reactor is established. In order to simplify the model, part of the area of the annular weld is intercepted as the object of study. The simulation model of the weld region is shown in Fig. 1(a), which consists of two parts: the weld seam and the base material. Taking the working condition of 670℃, 30MPa and 0.1% hydrogen penetration as an example, the parameters of the simulation model are set as follows. The temperature of the inner wall is 670℃, the temperature of the outer wall is 300℃, and the pressure of the inner wall is 30 MPa. Due to the internal pressure, the weld region is also subjected to axial stress and hoop stress. By calculation, the axial stress is 62.5 MPa and the hoop stress is 125 MPa, both of which are tensile stresses. The alloy compositions of the weld and the base metal are similar, and it is assumed that the material properties of the weld and the base metal are the same, as shown in Fig. 1(b).



(a) Weld thermal-mechanical-chemical coupling model (b) Weld material properties

Fig. 1 Weld thermal-mechanical-chemical coupling model and weld material properties

The results of the stress field of the hydrogen production reactor weld under thermal-mechanical-chemical coupling are shown in Fig. 2(a). It can be found that the stresses are mainly concentrated near the fusion zone in the inner wall of the weld, and the stresses in the weld region are higher than those in the base metal region. The stress distribution around the weld is not uniform due to the stress load, while the stress distribution near the center of the weld is more uniform. Path1 and path2 are selected in the cross section at the center of the weld (Fig. 2(b)), path1 is the inner wall of the weld and path2 is the fusion zone. The results of extracting the nodal stresses on the two paths are shown in Fig. 2(c, d). From path1, it can be seen that the stresses in the weld are significantly higher than those in the base metal, and the peak stresses all appear near the fusion zone. From path2, the maximum stress appears at the inner wall. From the inner wall to the outer wall of the weld, the stress first decreases rapidly and finally increases sharply. This is mainly because the inner wall is subjected to high temperature and high pressure, and at the same time, the degree of hydrogen penetration in the inner wall of the weld is larger, and the mechanical properties of the weld are reduced, so the stress at the inner wall is the largest .The maximum stress of Path2 is at the same node as that of Path1, and the maximum stress is 156.2 MPa.

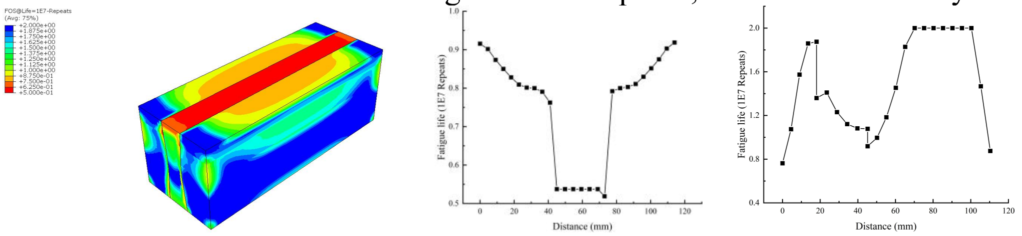


(a) Stress nephogram (b) Sath diagram (c) Path1 stress curve (d) Path2 stress curve

Fig.2 Weld stress nephogram and stress curves of different paths

3.2 Simulation Analysis of Fatigue Life

The stress field results of the hydrogen production reactor weld under thermal-mechanical-chemical coupling were imported into Fe-safe, and the Goodman algorithm was used to analyze the stress-fatigue life. The material parameters are generated by the Seeger approximation material method in the software, and the S-N curve is generated according to the ultimate tensile strength and elastic modulus of the material. The stress results of different time increments are automatically extracted by software, and the load spectrum is set to the stress results under time series. After analysis and calculation, the fatigue life cloud diagram of the weld is shown in Fig.3(a). The red area is the area with lower fatigue life. It can be found that the area with low fatigue life of the weld is mainly concentrated in the weld area, and the fatigue life of the base metal area is higher than that of the weld area. The node stress results are extracted along Path1 and Path2, as shown in Figure 3(b, c). It can be seen from path1 that the fatigue life of the weld is significantly lower than that of the base metal, and the minimum fatigue life is near the fusion zone. It can be seen from path2 that the fatigue life of the inner wall and the outer wall is low due to the influence of fatigue load. The node with the smallest fatigue life is on path1, which is 5.188E6 cycles.



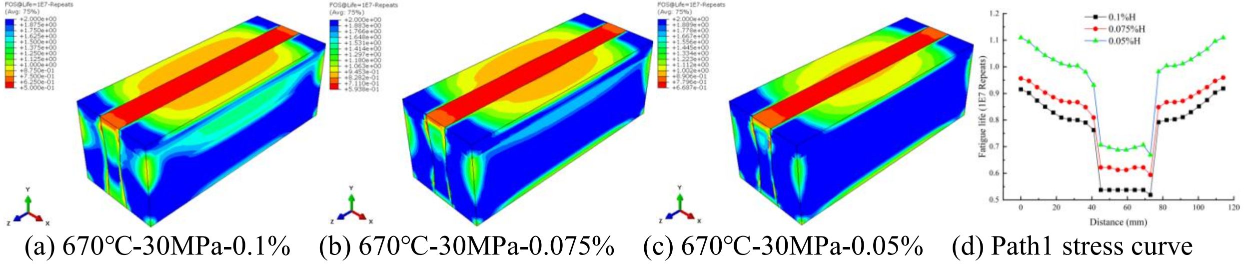
(a) Fatigue life nephogram (b) Path1 stress curve (c) Path2 stress curve

Fig.3 Weld fatigue life nephogram and fatigue life curves of different paths

4. Fatigue Life Prediction for Weld

4.1 Effect of Hydrogen Penetration on Fatigue Life

In order to study the effect of different hydrogen penetration on fatigue life, the temperature and pressure remain unchanged, only the hydrogen content of the inner wall of the reactor is changed. The temperature of 670 °C and the pressure of 30 MPa were selected, and the static analysis was carried out under different working conditions with 0.1 %, 0.075 % and 0.05 % hydrogen content in the inner wall of the reactor, and the fatigue life was analyzed by Fe-safe. The fatigue life cloud diagram under different hydrogen penetration conditions is shown in Fig.4 (a, b, c). It can be found that the areas with lower fatigue life are near the weld, which is due to the fact that the stress in the weld area is larger than that in the base metal area. With the decrease of hydrogen content in the inner wall, the minimum fatigue life of the weld model gradually increases. The node stress under different working conditions is extracted along path1, as shown in Fig.4 (d). It can be found that the stress curves under different hydrogen contents have the same change trend, and the fatigue life of the base metal area is higher than that of the weld area. With the decrease of hydrogen content in the inner wall, the fatigue life increases gradually. The minimum fatigue life is near the fusion zone. The minimum fatigue life of the inner wall hydrogen content of 0.1 %, 0.075 % and 0.05 % is 5.188E6, 5.938E6 and 6.687E6 cycles, respectively. The hydrogen content has a great influence on the fatigue life of the weld. The decrease of hydrogen penetration degree represents the decrease of hydrogen content in the weld, which reduces the risk of hydrogen embrittlement, reduces the possibility of fatigue failure of the weld, and improves the fatigue life of the weld.

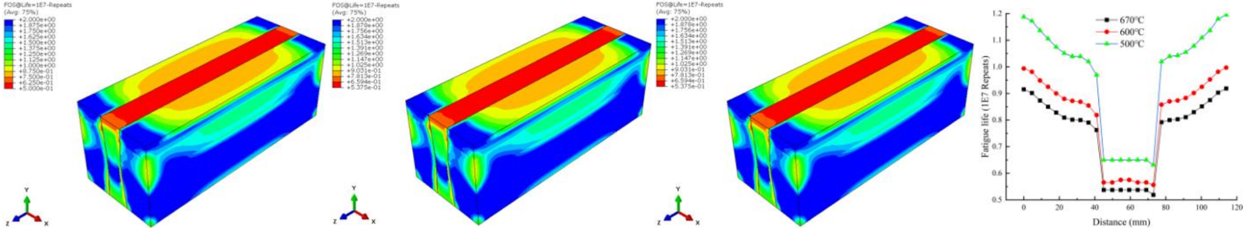


(a) 670℃-30MPa-0.1% (b) 670℃-30MPa-0.075% (c) 670℃-30MPa-0.05% (d) Path1 stress curve

Fig.4 The fatigue life nephogram and stress curve of weld under different hydrogen penetration

4.2 Effect of Temperature on Fatigue Life

In order to study the effect of different temperatures on fatigue life, the hydrogen content and pressure remain unchanged, and only the temperature of the inner wall of the reactor is changed. The hydrogen content of 0.1 % and the pressure of 30 MPa were selected to analyze the fatigue life of the reactor under different working conditions with the inner wall temperature of 670 °C, 600 °C and 500 °C. The fatigue life cloud diagram under different temperature conditions is shown in Fig.5 (a, b, c). It can be found that the minimum fatigue life of the weld model gradually increases with the decrease of the inner wall temperature. The node stress under different working conditions is extracted along path1, as shown in Fig.5 (d). It can be found that the stress curves under different temperature conditions have the same change trend, and the fatigue life of the base metal area is higher than that of the weld area. As the inner wall temperature decreases, the fatigue life gradually increases. The minimum fatigue life under the inner wall temperature of 670 °C, 600 °C and 500 °C is 5.188E6, 5.562E6 and 6.313E6 cycles, respectively. When the temperature decreases from 670 °C to 600 °C, the fatigue life of the weld increases obviously. It can be seen that the inner wall temperature has a great influence on the fatigue life of the weld. As the temperature increases, the strength of the weld will decrease. At the same time, due to the influence of hydrogen permeation, more diffused hydrogen will enter the weld, resulting in the degradation of the weld performance. The increase of temperature will increase the possibility of fatigue failure of the weld and reduce the fatigue life of the weld.

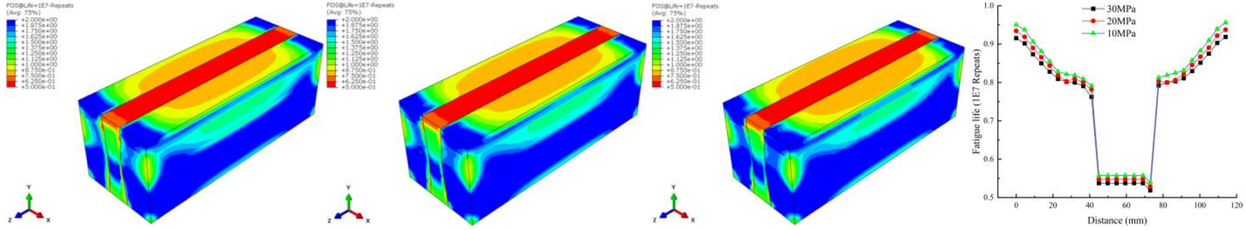


(a) 670°C-30MPa-0.1% (b) 600°C-30MPa-0.1% (c) 500°C-30MPa-0.1% (d) Path1 stress curve

Fig.5 Weld fatigue life nephogram and stress curve at different temperatures

4.3 Effect of Pressure on Fatigue Life

In order to study the effect of different pressures on fatigue life, the hydrogen content and temperature remain unchanged, and only the pressure of the inner wall of the reactor is changed. The hydrogen content of 0.1 % and the temperature of 670 °C were selected to analyze the fatigue life of the reactor under different working conditions with the inner wall pressure of 10 MPa, 20 MPa and 30 MPa. The fatigue life cloud diagram under different pressure conditions is shown in Fig.6 (a, b, c). It can be found that the minimum fatigue life of the weld model decreases with the increase of the inner wall pressure. The node stress under different working conditions is extracted along path1, as shown in Fig.6 (d). It can be found that the stress curves under different pressure conditions have the same change trend, and the fatigue life of the base metal area is higher than that of the weld area. As the inner wall pressure increases, the fatigue life gradually decreases. The minimum fatigue life under the inner wall pressure of 10 MPa, 20 MPa and 30 MPa is 5.376E6, 5.288E6 and 5.188E6 cycles, respectively. It can be seen that the inner wall pressure has little effect on the fatigue life of the weld. The increase of pressure will increase the stress of the weld, the fatigue load of the weld will increase, and the pressure will also promote hydrogen permeation to a certain extent. Therefore, the increase of pressure will slightly reduce the fatigue life of the weld.



(a) 670°C-30MPa-0.1% (b) 670°C-20MPa-0.1% (c) 670°C-10MPa-0.1% (d) Path1 stress curve

Fig. 6 The fatigue life nephogram and stress curve of weld at different pressures

5. Summary

In this paper, based on the Fe-safe fatigue analysis simulation platform, the stress-life method is used to predict the life of the weld area of the hydrogen production reactor. Simultaneously, the effects of temperature, pressure, and hydrogen penetration on the fatigue life are studied, respectively. The conclusions are as follows:

(1) The maximum stress of the weld of the hydrogen production reactor under the thermal-mechanical-chemical coupling effect appears near the fusion zone of the inner wall, and the minimum fatigue life is also near the fusion zone. The fatigue life of the weld zone is less than that of the base metal.

(2) An increase in temperature, pressure, and hydrogen penetration degree will reduce the fatigue life of the weld. Temperature and hydrogen penetration have a significant influence on the fatigue life, while the influence of pressure is relatively small. Among these factors, the fatigue life under the conditions of 670°C temperature, 30 MPa pressure, and 0.1% hydrogen penetration is the shortest, at 5.188E6 cycles.

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