Fatigue Life Analysis of Key Equipment in High Temperature Reactor Considering Nuclear Irradiation

Chen Qing¹, Jiangpeng Liu², Jianyong Gao¹ and Jie Geng³, *
¹Suzhou Nuclear Power Research Institute, Shenzhen, 518033, PR China
²Huaneng Shandong Shidao Bay Nuclear Power Co., Ltd, Weihai, 264312, PR China
³School of Reliability and Systems Engineering, Beihang University, Beijing, 100191, PR China

*Corresponding author

Abstract. The key equipment of high-temperature gas-cooled reactors is always exposed to nuclear irradiation, while the influence of nuclear irradiation on equipment fatigue life is one of the targets to be studied. Based on the expansion mechanism of fatigue cracks of fracture mechanics, combined with actual material parameters, the critical parts of the equipment, the position and time of occurrence of the working tolerance limit are pre-critically analyzed, and the fatigue life model under the influence of nuclear irradiation are corrected to calculate the influence of nuclear radiation on fatigue life which has certain guiding significance for the estimation of fatigue life of key equipment in high temperature gas cooled reactor.

Keywords: High temperature gas cooled reactor; nuclear irradiation; fatigue life.

1. Introduction

The equipment is subjected to a certain external pressure both in normal operation and when accidents occur. These loads have a great influence on the service life. Thus it is necessary to take detailed calculation and analysis on the fatigue life of the key equipment of the high temperature gas cooled reactor[1]. For the life analysis of important components and structures in the nuclear industry, the traditional method uses the safety factor method, based on meeting the requirements of use and mechanical properties, use engineering design experience to make the product as reliable as possible. However, this method cannot answer the reliability and the probability of failure of the system. So, generally, introduces a safety factor greater than 1 to avoid failures of the mechanical product. The idea of its relatively conservative design leads to oversize, overweight, and increased cost.

While the idea of reliability design is that from the perspective of reliability, factors that lead to the failure of mechanical products can be summarized as “stress” and “strength”[2], and failure occurs when the stress is greater than the strength. In practical engineering, stress is a random variable affected by various factors such as external load, temperature, humidity, etc. [3], and has a certain distribution law. Similarly, the intensity is also a random variable with a certain distribution law. Thus, provides the basis for studying the mechanical structure using the reliability design method.

Mechanical structural reliability is the ability of a mechanical structural product to perform specified functions under specified conditions and within a specified time. Its characteristics are: using stress and strength as random variables, using probability and statistical methods, to quantitatively answer product failure probability and reliability, reflecting the influence of external load and structural changes on the structure. Usually use reliability (failure probability), failure distribution function, failure rate, mean
time between failure, average maintenance time, mean operation hours between failure, availability, etc. to reflect the level of reliability. In addition, reliability and fatigue life is often used to characterize mechanical structural reliability, which is a reliability performance index that combines reliability with life.

The fatigue life analysis method based on fracture mechanics recognizes the existence of initial defects of structural parts, which meets the actual situation of the structure.

In the evaluation of the residual fatigue life of the structure with the traditional linear elastic fracture mechanics method, the parameters are considered as deterministic quantities [4]. However, due to subjective and objective factors, these parameters have great uncertainties [5], such as material performance uncertainty, randomness of applied loads, uncertainty of crack shape simplification, and uncertainty of crack size caused by nondestructive testing [6,7]. This paper introduces the method of probability and statistics to fracture mechanics, meanwhile, considers the influence of irradiation, which is more in line with the actual situation of the equipment of the verification system during operation.

2. Fatigue Life Model Considering Nuclear Irradiation

The residual fatigue life assessment based on probabilistic fracture mechanics is a method to evaluate the residual fatigue life of the structure by considering the random parameters as statistics with a certain statistical distribution.

In practical engineering, it is rare for components to be subjected to constant amplitude stress, in most cases, the member is subjected to variable amplitude stress. Under variable amplitude loading, there are interactions between different load cycles, so the load sequence affects the fatigue crack growth life. Generally, for the sake of simplicity, the effect of the load sequence is not considered. The Paris formula applies to constant amplitude stress, generally, use Miner criterion to convert the variable amplitude stress into the corresponding equivalent normal amplitude stress, and then the residual fatigue life of the member is obtained.

Fatigue crack growth life as follows:

\[
N_c = \frac{2}{(m-2)C(\alpha\Delta \sigma_e \sqrt{\pi})^m} \left(a_0^{1-m/2} - a_c^{1-m/2}\right)
\]  

(1)

There are 6 parameters in equation (1). Considering these parameters as random variables, the fatigue crack growth life can be written as a function of 6 random variables:

\[
N_c = (C, m, \alpha, \Delta \sigma_e, a_0, a_c)
\]  

(2)

Generally, for simplicity, \( \alpha \) is taken as a constant (\( \alpha = 1 \)) in actual engineering. Then, there are only 4 independent variables in the fatigue crack growth life evaluation formula.

Calculate the logarithm of the quantity of the formula (1)

\[
\lg N_c = \lg \frac{2}{(m-2)C(\alpha \sqrt{\pi})^m} - \lg C - m \lg \Delta \sigma_e + \lg \left(a_0^{1-m/2} - a_c^{1-m/2}\right)
\]  

(3)

In the fatigue crack propagation calculation, it is generally considered that the equivalent normal amplitude stress \( \Delta \sigma_e \) follows a lognormal distribution with a standard deviation of about 2% of the mean. According to the experimental data in the literature, take the average, get the fatigue crack propagation parameters \( C \) and \( m \), and \( C \) follow the lognormal distribution; Generally, \( a_0 = a_c \), so \( \lg \left(a_0^{1-m/2} - a_c^{1-m/2}\right) \) approximately equal to \( \left(1 - \frac{m}{2}\right) \lg a_0 \) the large-scale statistical result of the initial crack by non-destructive testing, which is considered to be 0.05 mm-0.5mm, which also obeys
the lognormal distribution, it is known that the fatigue crack growth life of the member also obeys the lognormal distribution, and the mean and standard deviation can be obtained. The statistical results of large-scale data of non-destructive testing show initial cracks \( a_0 \) are considered to be 0.05mm-0.5mm, which also follows the lognormal distribution. Thus, it is known that the fatigue crack growth life of the members also follows the lognormal distribution, and the mean \( \mu_{\text{lg} N_c} \) and standard deviation \( \sigma_{\text{lg} N_c} \) can be obtained. Given a level of reliability \( P_r \), \( u_p \) can be found in the table ( \( u_p \) is the “standard normal offset” associated with reliability \( P_r \)), then the logarithmic extended lifetime at this level of reliability is

\[
\lg N_c = \mu_{\text{lg} N_c} + u_p \sigma_{\text{lg} N_c}
\]

(4)

\[
N_c = 10^{u_p + u_p \sigma_{\text{lg} N_c}}
\]

(5)

Then the adjustment calculation is taken under the condition of nuclear irradiation. The Russian specification defines the radiation attenuation coefficient \( \varphi_F \) according to the weakening of the material properties by neutron irradiation. The stress amplitude \( \varphi_1 \) for fatigue evaluation is amplified from the cyclic stress amplitude \( \varphi_0 \) without neutrons by \( \varphi_F \).

\[
\varphi_1 = \varphi_0 / \varphi_F
\]

(6)

Where the specific value \( \varphi_F \) is to be determined, and the selection is 0.6, 0.65, 0.7, 0.75, and 0.8 for calculation.

3. Fatigue Life Calculation Based on Probability Fracture Mechanics

The wear law of the equipment is related to the type of components, the load, the environmental conditions, the working conditions, and the failure mechanism. Take multiple simulations with efficient center composite design and record the maximum stress point, maximum stress value, load spectrum and nominal stress spectrum in each simulation to carry out the fatigue life calculation of the equipment. We applied the solid mechanics simulation and analysis module of COMSOL finite element software to create a three-dimensional finite element simulation environment, this key equipment contains three working conditions including stationary state, accelerating upwards and accelerating downwards, and the necessary material parameters are as shown in Fig 1.

Table 1. Material parameters values.

| Material         | Density(g/cm\(^3\)) | Modulus of Elasticity(GPa) | Poisson Ratio |
|------------------|---------------------|-----------------------------|--------------|
| Alloy625(20°C)   | 8.44                | 208                         | 0.28         |
| Alloy625(600°C)  | 8.44                | 174                         | 0.31         |
| Incoloy800(20°C) | 7.94                | 196.5                       | 0.339        |
| Incoloy800(600°C)| 7.94                | 157.7                       | 0.373        |
| B\(_4\)C(20°C)   | 2.52                | 234                         | 0.18         |
| B\(_4\)C(600°C)  | 2.52                | 210                         | 0.20         |

The mechanical simulation analysis of key equipment is as following Fig.1, after inputting necessary characters, including temperature, pressure and load, the Stress distribution was shown, in which the red part shows the critical area, and then the critical area should be concentrated. After the simulation, the maximum equivalent stress of working conditions are obtained, as shown in Table 2.
Figure 1. Mechanical simulation analysis of key equipment.

Table 2. Dangerous part simulation results.

| Working condition | Maximum equivalent stress (Pa) |
|-------------------|--------------------------------|
| still             | 1.45E07                        |
| rise              | 1.63E07                        |
| down              | 9.75E06                        |

According to the actual working conditions and fatigue life calculation requirements, in the following calculation of the life, take "still---rise----still----down----still" as one time, reliability take 16 sets: 0.90, 0.91, 0.92, 0.93, 0.94, 0.95, 0.96, 0.97, 0.98, 0.99, 0.999, 0.9999, 0.99999, 0.999999, 0.9999999, 0.99999999, the fatigue life results under difficulty irradiation coefficient are as shown in Table 3.

Table 3. Inner rod reliability - life calculation results.

| No. | Reliability (probability) Pr | No irradiation | Irradiation coefficient % |
|-----|------------------------------|----------------|--------------------------|
|     |                              |                | 0.6 | (0.65) | (0.7) | (0.75) | (0.8) |
| 1   | 0.90                         | 76849829       | 9954859 | 13712111 | 18444441 | 24307624 | 31469017 |
| 2   | 0.91                         | 71768938       | 9296698 | 12805541 | 17224996 | 22700537 | 29388457 |
| 3   | 0.92                         | 66629195       | 8630914 | 11888471 | 15991425 | 21074835 | 27283799 |
| 4   | 0.93                         | 61401619       | 7953752 | 10955728 | 14736774 | 19421351 | 25143174 |
| 5   | 0.94                         | 56046555       | 7260076 | 10000239 | 13451526 | 17727543 | 22950344 |
| 6   | 0.95                         | 50506779       | 6542473 | 9011791 | 12121945 | 15975310 | 20681877 |
| 7   | 0.96                         | 44693707       | 5789467 | 7974580 | 10726771 | 14136634 | 18301499 |
| 8   | 0.97                         | 38455868       | 4981440 | 6861579 | 9229651 | 12163604 | 15747185 |
| 9   | 0.98                         | 31490477       | 4079167 | 5618763 | 7557913 | 9960448 | 12894947 |
| 10  | 0.99                         | 22982533       | 2977078 | 4100713 | 5515953 | 7269383 | 9411053 |
| 11  | 0.999                        | 9508355        | 1231679 | 1696551 | 2282065 | 3007496 | 3893550 |
| 12  | 0.9999                       | 4598348        | 595654 | 820471 | 1103633 | 1454459 | 1882965 |
| 13  | 0.99999(5)                   | 2447370        | 317024 | 436678 | 587385 | 774104 | 1002167 |
| 14  | 0.999999(6)                  | 1391776        | 180286 | 248331 | 334035 | 440219 | 569915 |
| 15  | 0.9999999(7)                 | 831428         | 107700 | 148350 | 199548 | 262981 | 340459 |
| 16  | 0.99999999(8)                | 516135         | 66858 | 92093 | 123876 | 163254 | 211351 |

Note: "Still---rise----still----down----still" is recorded as 1 time.

Probability-life approximation fitting expressions and curves as following Fig.2.

4. Conclusion
This paper adopts the linear fatigue-based cumulative damage theory widely used in engineering, regards the equipment operation as the cyclic condition under constant amplitude stress or variable amplitude stress, and constructs the fatigue life model. Further, with reference to the empirical data from relevant Russian literature, define the radiation attenuation coefficient according to attenuation of material properties based on neutron irradiation, give coefficients to the parameters of the relevant model in analysis, and correct the fatigue life model to recalculate the fatigue life of the equipment.
According to the different set values of the irradiation coefficient, it can be seen that the nuclear irradiation has a great influence on the life of key equipment.

![Figure 2. Probability-life approximation fitting curves](image)

When carrying out the analysis of key equipment, the influence of nuclear irradiation on the equipment should be fully considered in order to obtain more objective data.

Acknowledgement
The research was financially supported by the Major Project of National Science and Technology -High-temperature Reactor Demonstration Engineering Reliable Operation Technology Research Project, Operation Reliability Key Equipment Support Sub-project (Grant No.2018ZX06906012).

References
[1] Fuller Robert W, Shamsaei Nima, Simsiriwong Jutima: Fatigue life predictions for irradiated stainless steels considering void swellings effects (2016)
[2] Wang Lu, Shang De Guang, Ren Chong Gang: Effect of temperature induced by laser irradiation processing on fatigue damage repairing for copper thin film (2013)
[3] Fabritsiev, S.A., Pokrovsky, A.S: Effect of neutron irradiation on low-cycle fatigue of GlidCopAl251G alloy for ITER applications(2003)
[4] Guo, Yu-Bo, Shang, De-Guang, Liu, Xiao-Dong: Recovery of Fatigue Damage and Life Prediction by Laser Irradiation Healing Treatment for Copper Film(2015)
[5] Zuo, J.H., Wang, Z.G., Han, E.H: The effect of ion irradiation on the tensile and fatigue properties of Ti-6Al-4V alloy(2010)
[6] Jiang, S.N., Xu, L.Q., Zheng, P.F: Evaluation of hardening behavior under synergistic interaction of He and subsequent H ions irradiation in vanadium alloys (2018) Reference to a chapter in an edited book:
[7] Chopra O.K., Stevens G.L.: Effect of Light Water Reactor Water Environments on the Fatigue Life of Reactor Materials (2017)