Fatigue Reliability Analysis of Tunnelling Boring Machine Cutterhead with Cracks

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Abstract :

The cutterhead of tunnel boring machine is a large-scale metal welding structure, which is prone to problems such as wear and cracking during the tunnelling process. For the issue, the fatigue crack propagation rate model of cutterhead under different reliability was established, based on the damage tolerance of cutterhead. Its dangerous position of cutterhead failure was determined by using finite element method. According to the fatigue load spectrum, the fatigue propagation life of cutterhead under different reliability was calculated, the main factors affecting the reliability of cutterhead were analyzed and the engineering experiment is carried out. The results show that three dangerous positions of the cutterhead failure are the junction of the split plane, the maximum deformation of the block and the central cutter seat. The load stress amplitude and initial crack size are the main factors affecting the crack propagation life and the reliability of cutterhead. With the increase of load stress amplitude and initial crack size of cutterhead, the fatigue crack propagation life of cutterhead decreases and the reliability is worse. When the initial crack size of cutterhead is greater than 0.5mm, the fatigue crack propagation life of cutterhead decreases obviously. The research results provide a scientific basis for crack detection, life prediction and reliability evaluation of cutterhead structure.

Key words : Tunnel boring machine (TBM) ; cutterhead ; fatigue reliability ; crack propagation ; damage tolerance

0 Introduction

Tunnel boring machine (TBM) is a kind of large tunnel construction equipment, with the characteristics of safe, efficient and rapid construction, it has been widely used in various tunnel construction[1-3]. Cutterhead is one of the key components of TBM, which bears the functions of tunnel excavation, supporting face and slag discharging, and its reliability is very important. The structure of TBM is shown in Figure 1(a). During the process of tunnelling, the cutterhead is subjected to huge propulsion force and rotating torque from the driving system, at the same time, it also bears large vibration and impact when it acts on the rock face. Therefore, the wear and crack of cutterhead are the main failure forms. The crack of cutterhead gradually expand under the action of alternating load, which will cause the TBM shutdown and the cutterhead repaired. But if the cutterhead fracture will cause a major safety accident. So, it is of great significance to analyze the fatigue reliability of the cutterhead and study the crack propagation life and reliability of the cutterhead structure with cracks. It is helpful to improve the TBM construction efficiency, formulate a scientific maintenance cycle of the cutterhead, and ensure the construction safety of the TBM.

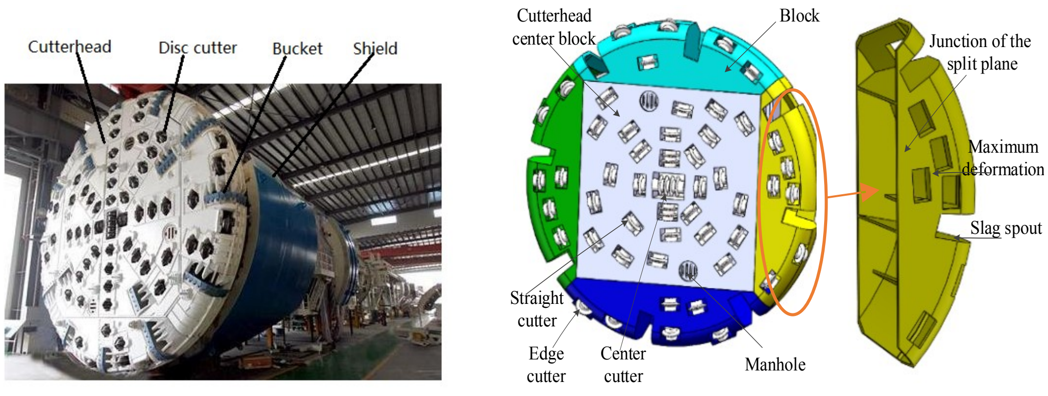
In recent years, scholars have carried out a lot of research on the structural strength and fatigue performance of TBM cutterhead. Cheng Yongliang et al. [4] established a cutterhead calculation model considering key parameters such as cutters layout, opening and cutterhead body design, proposed corresponding geological adaptability design method of TBM cutterhead, and carried out engineering verification. Xia Yimin et al. [5] established the cutterhead performance evaluation system, and proposed a comprehensive performance evaluation method of cutterhead based on fuzzy mathematics and evaluation theory. And it was verified by an engineering example. Sunwei et al. [6] put forward a set of TBM cutterhead crack location prediction and analysis method based on the crack failure zone division of cutterhead crack failure area. Through the stress distribution of TBM cutterhead, combined with the statistical results of crack failure, the crack location of TBM cutterhead is estimated, and the parameters required for calculating the fatigue crack life of cutterhead are analyzed, which provides the basis for calculating the fatigue life of TBM cutter head. Huo Junzhou et al. [7] established the optimization model of coupling layout of cutter group and cutterhead support structure, proposed the coupling design method of cutter adaptive layout and cutterhead structure based on multi subsystem co evolution. The feasibility and effectiveness of the proposed coupling optimization model and its solution method are proved by engineering verification. Lin et al. [8] aimed at the structural cracking problem caused by impact and vibration of TBM cutterhead, established the equivalent dynamic model of TBM host with cutterhead by using the lumped mass method, analyzed the dynamic response characteristics of the host. It was concluded that the multi-directional vibration of the cutter head was more severe than that of other components, and the vibration was the same as the external excitation The trend of change. Rohola Hasanpour et al. [9] presents an application of artificial neural network (ANN) and Bayesian network (BN) for evaluation of jamming risk of the shielded tunnel boring machines (TBMs) in adverse ground conditions such as squeezing grounds. Wen Liu et al. [10] proposed a systematic method by integrating exploratory factor analysis (EFA) and structural equation model (SEM) to examine the risk factors for the safety of metro construction. It was found that safety was profoundly influenced by the risks associated with the launching and arrival of tunnel boring machine (TBM) and the risks during tunnel excavation that involved special procedures and conditions. In contrast, the risks pertaining to shaft construction did not have a statistically significant impact on safety. Anil Kumar Agrawal et al. [11] established the reliability model of the TBM system. The reliability analysis using markov modelling was carried out for an EPBTBM (earth pressure balance tunnel boring machine), being used in an irrigation tunnel, considering its suitability to analyze a continuous production system. Accordingly, the failure and repair rates of the different subsystems were critically analyzed and variability was fixed. Maximum availability can be obtained by increasing reliability and maintainability of the equipment.

The above researches mainly focus on the mechanical properties, load characteristics, structural design and optimization of cutterhead, and the reliability analysis of cutterhead with cracks has been not carried out. Therefore, this paper aiming at the problem of fatigue crack propagation and reliability of cutterhead with cracks, the finite element model of TBM cutterhead is established to analyze the stress-strain state of cutterhead and to determine the damage tolerance of cutterhead firstly. Secondly, based on fracture mechanics theory, the fatigue crack propagation life prediction of cutterhead with crack is realized. Finally, the factors influencing the fatigue reliability of cutterhead are analyzed. The analysis provides a theoretical basis for the safety evaluation of TBM cutterhead.

1 Cutterhead structure and damage tolerance determination

1.1 Cutterhead structure of TBM

Cutterhead is installed at the front end of TBM. It is a large-scale metal structure, which is usually made for a specific project under some standard constraints. Its structure mainly includes cutterhead body, disc cutter, scraper, water spray system, etc. The cutterhead structure is shown in Figure 1(b).



(a) (b)

Fig.1. Cutterhead Structure of TBM

The structure of TBM cutterhead studied in this paper is square in the middle, which is composed of five parts, as shown in Figure 1. The cutterhead diameter is 7 930 mm, the central block and the split block are connected as a whole by welding or bolt connection. There are 49 single edge disc cutters and 4 double edge disc cutters on the cutterhead panel which size are 17-inch . According to the different distribution positions, the disc cutter can be divided into front cutters and edge cutters. There are 8 groups of slag chutes arranged evenly around the cutterhead, and two manholes are set for the maintenance of the cutterdead. The cutterhead is made of high strength structural steel Q345D, and its physical parameters are shown in Table 1.

Tab 1 Physical parameters of Q345D material

Serial numbe	performance index	numerical value
1	Density	7 850 kg/m^3
2	Elastic modulus	210 GPa
3	Poisson's ratio	0.3
4	yield strength /f_y	345 MPa
5	Ultimate tensile strength /f_u	500 MPa
6	Fracture threshold value /ΔK_{th}	6.59 MPa·m$^{1/2}$
7	fracture toughness / K_{IC}	198.3 MPa·m$^{1/2}$

In the process of TBM tunnelling, the load is very complex and difficult to calculate. In this paper, the cutterhead thrust is defined as the resultant force required to complete the rock breaking of the disc cutter. The force acting on dozens of disc cutters constitutes the cutterhead load. The force model of the cutterhead is shown in the figure 2.

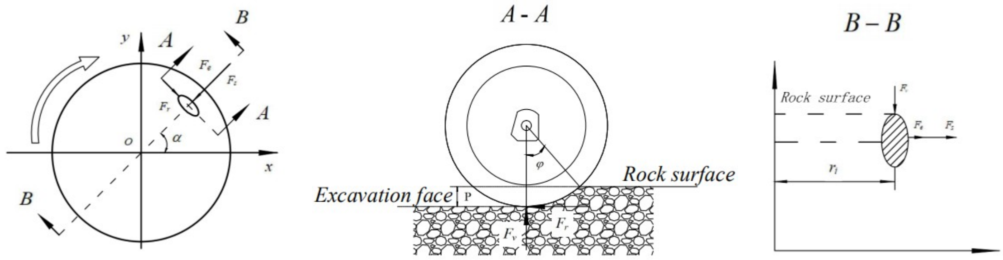


Fig.2. Force model of cutterhead

1.2 Finite element analysis and damage tolerance determination of cutterhead

1.2.1 Finite element analysis of cutterhead

The static analysis of cutterhead is carried out by ANSYS software. Tetrahedral elements are used to divide the mesh, the finite element model of cutterhead has 181064 elements and 333417 nodes after meshing. The boundary conditions are set as follows: the fixed constraint is added to the cutterhead flange, the vertical force F_n and rolling force F_r are added at the cutter seat, and the lateral force is ignored. The CSM model is used to calculate the vertical force F_n and rolling force F_r of disc cutter. The CSM model is shown in formula (1) and calculation parameters are shown in Table 2.

$$\begin{cases} F_n = C_1 \dfrac{RT\varphi}{1+\psi} \sqrt[3]{\dfrac{S\sigma_c^2\sigma_t}{\varphi\sqrt{RT}}} \cos\dfrac{\varphi}{2} \\ F_r = C_1 \dfrac{RT\varphi}{1+\psi} \sqrt[3]{\dfrac{S\sigma_c^2\sigma_t}{\varphi\sqrt{RT}}} \sin\dfrac{\varphi}{2} \end{cases} \quad (1)$$

Where, C_1 is the dimensional coefficient, $C_1 \approx 2.12$, R is the radius of disc cutter, T is the width of disc cutter tip, φ is the contact angle between disc cutter and rock, ψ is the distribution coefficient of tip pressure, $\psi = -0.2{\sim}0.2$, S is the cutter spacing, σ_c is the compressive strength of rock, σ_t is the shear strength of rock.

Tab 2 Disc cutter parameters of CSM model

Serial number	Calculation parameters	numerical value
1	Disc cutter radius/ R	216 mm
2	Penetration /h	6 mm
3	Cutter blade width/T	10 mm
4	Ψ	0.1
5	C_1	2.12
6	cutter spacing /S	100 mm

Generally, the shear strength of rock is about one tenth of its compressive strength [12]. According to the geological parameters of TBM excavation, it can be divided into four common rock grades, namely 40 MPa, 80 MPa, 120 MPa and 150 MPa. According to formula (1) and Tab 2, the load of disc cutter under the four rock grades is calculated, and the results are shown in Tab

3.

Tab 3 Rock parameters and predicted value of disc cutter

Load rating	Rock compressive strength/σ_c	Vertical force/F_n	Rolling force/F_r
1	150 MPa	142.00 kN	16.852 kN
2	120 MPa	113.60 kN	13.482 kN
3	80 MPa	75.734 kN	8.988 kN
4	40 MPa	37.867 kN	4.494 kN

The boundary condition is set as level 1 load and the finite element analysis of the cutterhead is carried out. The results are shown in figure 3.

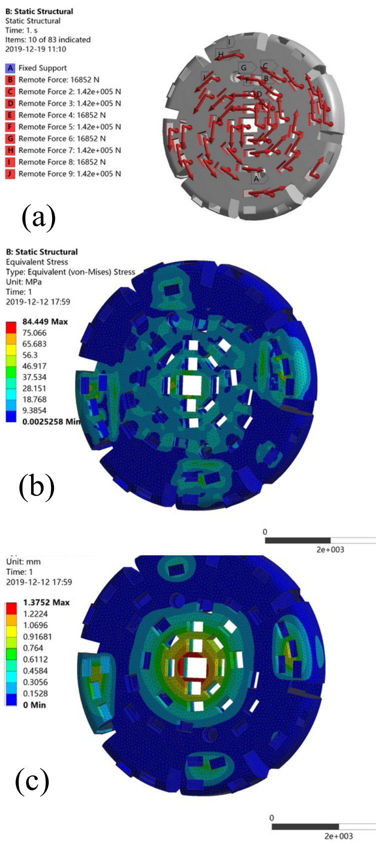


Fig. 3. Cutterhead boundary conditions and finite element analysis results

It can be seen from Fig.3 that the maximum stress of cutterhead is 84.449 MPa, which is located at the maximum deformation of cutterhead block. The maximum deformation of cutterhead is 1.375 mm, which is located in the center of cutterhead. Because the stress of cutterhead structure is far lower than the yield strength of material, the cutterhead structure has a higher safety factor. According to the statistical data of TBM cutterhead in service, it is found that TBM cutterhead is easy to fail at the welding seam of the central cutterhead, the joint surface of the cutterhead split, the maximum deformation of the block and the slag discharge plate [6]. Because the failure form of the slag discharge plate is mainly wear, based on the static analysis results, this paper analyzes the fracture of other three important parts, whidh are the joint surface of the cutterhead split, the maximum deformation of the block and the central cutter seat.

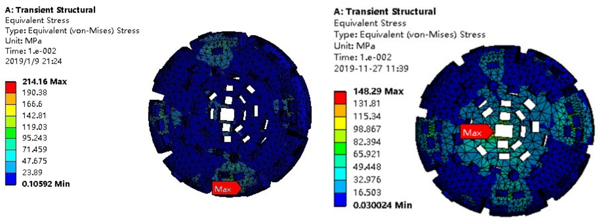
1.2.2 Damage tolerance determination of cutterhead

The damage of TBM cutterhead is the slow propagation of surface cracks [13-14], which involves an important problem of determining the damage tolerance depth of the cutterhead. The methods to determine the damage tolerance size are usually empirical method [14] and formula method [15]. In this paper, formula method is used to calculate the critical crack size of the cutterhead, the formula is:

$$a_c = \frac{1}{\pi}\left(\frac{K_{\mathrm{IC}}}{\alpha n \sigma_{\max}}\right)^2 \qquad (2)$$

Where, α is the crack shape factor, which is taken as 1 [14], n is the safety factor, taken as 2, $\sigma_{\max}$ is the maximum stress value of cutterhead structure (MPa), K_{IC} is the fracture toughness, which can be determined according to the GB/T2038-1991, and the K_{IC} of Q345D is $6270.80 MPa \cdot mm^{1/2}$.

In order to accurately predict the damage tolerance size of the cutterhead, the transient dynamic analysis of the cutterhead is carried out. The level 1 and 4 of disc cutter loads are applied respectively. The transient response of the cutterhead is shown in figure 4.



(a) Level 1 load (b) Level 4 load

Fig. 4. Cutterhead transient analysis result

As shown in Fig. 4 (a), the maximum stress value of cutterhead is 214.16 MPa, which is located at the maximum deformation of block. The damage tolerance in the depth direction of cutterhead crack is calculated as follows:

$$a_c = \frac{1}{\pi}\left(\frac{6270.80}{1\times 2\times 214.6}\right)^2 = 67.95\,\mathrm{mm} \qquad (2a)$$

As shown in Fig. 4 (b), the maximum stress value of cutterhead center is 148.29 MPa. The damage tolerance values of the center block of cutterhead along the crack depth direction are as follows:

$$a_c = \frac{1}{\pi}\left(\frac{6270.80}{1\times 2\times 148.29}\right)^2 = 142.30\,\mathrm{mm} \qquad (2b)$$

The initial crack size of cutterhead is generally determined according to the method of nondestructive testing (ultrasonic testing or magnetic particle testing) in engineering. Generally, the accuracy of magnetic particle testing can reach 0.5 mm and the accuracy of ultrasonic testing can reach 2 mm. In order to accurately analyze the surface crack propagation characteristics, the initial crack depth dimension a_0=0.5 mm is taken in this paper[14,15]. When the crack depth reaches the critical size, the cutterhead panel is considered to be out of service. Through analysis and calculation, the damage tolerance of this cutterhead is determined as 67.95 mm.

1.2.3 Typical load spectrum of cutterhead

The crack propagation of cutterhead is mainly controlled by stress intensity factor amplitude $\Delta K = f(\Delta\sigma)$ [16]. The fatigue crack growth life of cutterhead is the duration that the crack extends from initial fatigue crack size a_0 to the crack damage tolerance dimension a_c. According to literature [16-17], the amplitude of crack stress intensity factor is:

$$\Delta K = \alpha\Delta\sigma\sqrt{\pi a} \qquad (3)$$

Where, a is crack length (m) and $\Delta\sigma$ is crack stress amplitude (MPa).

According to formula (3), the propagation law of cutterhead crack is directly affected by stress amplitude and crack length. At the same time, the crack growth rate da/dN is determined by ΔK. Therefore, the fatigue growth life of cutterhead mainly considers the structural stress change order of coupling field and the amplitude of current crack stress intensity factor.

In the process of TBM tunneling, the rock breaking force and other load parameters are different when facing different rock strata. According to the feedback data of geological exploration and Construction Party of a diversion tunnel, about 60% of the rock uniaxial compressive strength value is greater than 150 MPa, 30% is 101-150 MPa, and 10% is less than 100 MPa. Due to the random occurrence of strata, in order to construct typical geological cutterhead load spectrum, it is necessary to synthesize the cutterhead load spectrum of TBM under different working conditions [18]. The load spectrum synthesis formula is as follows:

$$N_i = 10^6 c_i \qquad (4)$$

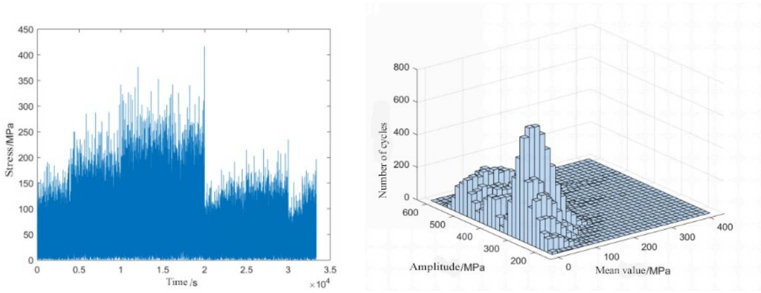
Where, N_i is the frequency of the i-th working condition in the total cumulative frequency; c_i is the ratio of the i-th working condition to the calculation cycle.

$$k_i = N_i / \sum_{j=1}^{3} n_{ij} \qquad (5)$$

Where, k_i is the extrapolation coefficient of load spectrum of the i-th working condition, and n_{ij} is the cumulative frequency of the j-th operation section in the i-th working condition.

According to the above load spectrum compilation method, matlab program is compiled to process the data of the load series, and the rain flow counting statistics of the load series obtained can obtain the load spectrum at different positions of the cutterhead, as shown in Fig. 4, Fig. 5 and Fig. 6, respectively.

Using the above method, the rain flow matrix and the composite load spectrum at the junction of the split plane of cutterhead are obtained, as shown in figure 5.

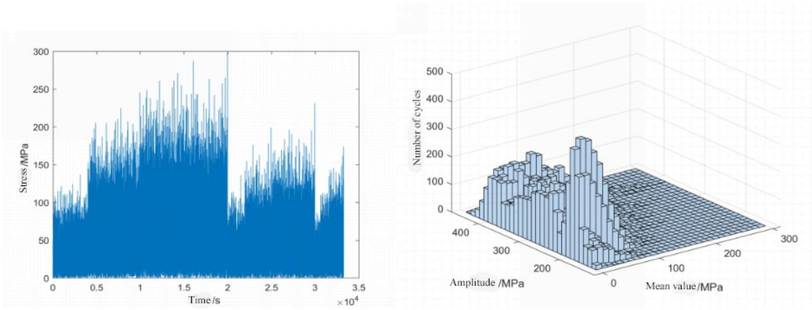


(a) Synthetic load spectrum (b) Rain-flow counting matrix

Fig. 5. Rain-flow counting results at the joint of the split face of the cutterhead

It can be seen from Fig.5, the load amplitude at the junction of the split plane is large, with the average value basically within 150 MPa, and the amplitude mainly appears around 300 MPa (about 500 frequency) and 450 MPa (about 200 frequency).

The rain-flow counting matrix and composite load spectrum at the maximum deformation of cutterhead block are shown in figure 6.

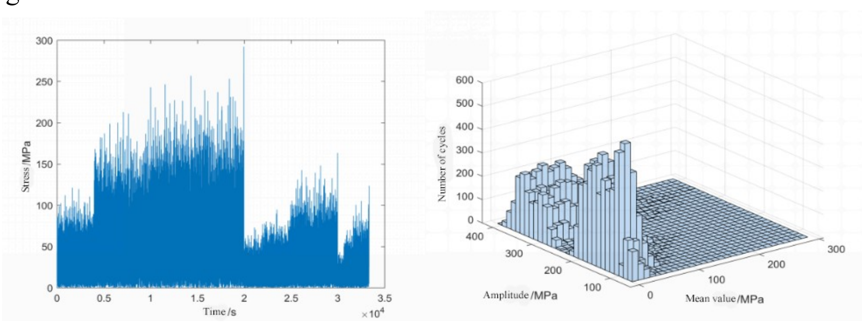


(a) Synthetic load spectrum (b) Rainflow counting matrix

Fig. 6. Rainflow counting results at the maximum deformation of the cutterhead

It can be seen from Fig.6 that the load amplitude at the maximum deformation of the cutterhead block is mainly around 200 MPa (about 400 frequency). The opportunity of load amplitude is basically equal within 200~400 MPa (about 200 frequency).

The rain-flow counting matrix and the composite load spectrum at the central cutter seat are shown in figure 7.



(a) Synthetic load spectrum (b) Rain-flow counting matrix

Fig. 7. Rain-flow counting results at the central cutter seat

It can be seen from Fig. 7, the load amplitude at the central cutter seat is around 120 MPa (about 500 frequency) and 300 MPa (about 300 frequency), and the mean value is less than 100 MPa.

According to the average load operation cycle time, each loading of the composite load spectrum is equivalent to 3.33×10^4 tunnelling cycles. According to the TBM construction data, the penetration h is about 6 mm/r, the cutterhead speed is about 6 r/min, and each typical load spectrum is equivalent to the tunnelling mileage of 19.98 m.

2 Reliability analysis of cutterhead with cracks

2.1 Determination of fatigue crack growth rate of cutterhead

In this paper, Paris formula is used to study the fatigue crack growth rate of cutterhead[19]. The curve of stable crack propagation rate $(\mathrm{d}a/\mathrm{d}N) - \Delta K$ in Paris formula presents linear relationship in double logarithmic coordinate system, as follows:

$$\mathrm{d}a/\mathrm{d}N = C(\Delta K)^m \tag{6}$$

Where, a is the crack depth dimension (m), da/dN is the crack propagation rate (m/cycle), N is the crack propagation cycle (cycle), C is the fatigue growth coefficient and m is the fatigue crack growth index. The parameters C and m directly affect the fatigue crack growth rate. Based on the fatigue crack growth test data, the fatigue crack growth rate is calculated by taking m as a constant value and lg$C$ obeying normal distribution [20-21]. The specific method is as follows: take m as the definite value, lg$C$ obeys normal distribution, that is, C obeys the single random variable theory of lognormal distribution, as follows:

$$\lg C \sim N(\mu_{\ln C}, \sigma_{\ln C}^2) \tag{7}$$

Where, $N(\mu, \sigma^2)$ is the normal distribution function of mean value μ and standard deviation σ, $\mu_{\lg C}$ is the mean value of $\lg C$, $\sigma_{\lg C}^2$ is the variance of $\lg C$.

When the parameter m obeys the normal distribution, it is recorded as follows:

$$m \sim N(\mu_m, \sigma_m^2) \tag{8}$$

Where, μ_m is the mean value of m, σ_m^2 is the variance of m.

According to the research results given in reference[22], the fatigue parameter $\lg C$ of crack propagation conforms to normal distribution, and $\lg C \sim N(-10.14, 0.342)$ is taken, the fatigue crack growth parameter $m = 2.81$. According to the 3σ criterion, the probability within the $(\mu - 3\sigma, \mu + 3\sigma)$ interval is 99.74%. For the data beyond the confidence interval, the probability of existence is less than three thousandth, which can be ignored.

The fatigue parameter lg$C$ can directly affect the crack growth rate lg(da/dN), and the fatigue crack growth rate can be expressed as[19]:

$$[\lg(\mathrm{d}a/\mathrm{d}N)]_p = \lg C_{\mathrm{R}} + m \lg \Delta K \tag{9}$$

Where, R is the different reliability.

Definition $\lg C_p = \mu_{\lg C} - \mu_p \sigma_{\lg C}$, u_p is the standard normal deviation corresponding to different reliability R, which can be obtained by referring to the corresponding manual[23], $\sigma_{\lg C} = 0.34$. Thus, the P-da/dN-lgΔK curve can be expressed as follows:

$$\left[\lg\left(\mathrm{d}a/\mathrm{d}N\right)\right]_{\mathrm{R}} = \mu_{\lg C} - u_p\sigma_{\lg C} + m\lg\left(\Delta K\right) \tag{10}$$

According to equation(10), the expression of crack propagation rate of cutterhead under different reliability can be obtained. When the reliability R=50%, the standard normal deviation u_p= 0, and the crack propagation rate formula is as follows:

$$\begin{cases}\left[\lg(\mathrm{d}a/\mathrm{d}N)\right]_{\mathrm{R}=0.5} = -10.14 + 2.81\lg(\Delta K) \\ \left[\mathrm{d}a/\mathrm{d}N\right]_{\mathrm{R}=0.5} = 7.244\times10^{-11}(\Delta K)^{2.81}\end{cases} \tag{10a}$$

When the reliability R=90%, the standard normal deviation u_p=-1.232, and the crack propagation rate formula is as follows:

$$\begin{cases}\left[\lg(\mathrm{d}a/\mathrm{d}N)\right]_{\mathrm{R}=0.9} = -9.721 + 2.81\lg(\Delta K) \\ \left[\mathrm{d}a/\mathrm{d}N\right]_{\mathrm{R}=0.9} = 1.900\times10^{-10}(\Delta K)^{2.81}\end{cases} \tag{10b}$$

When the reliability R=95%, the standard normal deviation u_p=-1.645, and the crack propagation rate formula is as follows:

$$\begin{cases}\left[\lg(\mathrm{d}a/\mathrm{d}N)\right]_{\mathrm{R}=0.95} = -9.581 + 2.81\lg(\Delta K) \\ \left[\mathrm{d}a/\mathrm{d}N\right]_{\mathrm{R}=0.95} = 2.626\times10^{-10}(\Delta K)^{2.81}\end{cases} \tag{10c}$$

When the reliability R=99%, the standard normal deviation u_p=2.326, and the crack propagation rate formula is as follows:

$$\begin{cases}\left[\lg(\mathrm{d}a/\mathrm{d}N)\right]_{\mathrm{R}=0.99} = -9.349 + 2.81\lg(\Delta K) \\ \left[\mathrm{d}a/\mathrm{d}N\right]_{\mathrm{R}=0.99} = 4.475\times10^{-10}(\Delta K)^{2.81}\end{cases} \tag{10d}$$

According to the above formula of Fatigue crack propagation rate, the Fatigue crack propagation life of cutter under different reliability can be predicted.

2.2 Calculation method for fatigue crack propagation life prediction of TBM cutterhead

Paris formula is used to estimate the Fatigue crack propagation life of cutterhead. The formula (2) is introduced into equation (5), and the expression of Fatigue crack propagation life of cutterhead is obtained as follows:

$$\mathrm{d}a/\mathrm{d}N = C\left(\alpha\Delta\sigma\sqrt{\pi a}\right)^m \tag{11}$$

For each small crack depth increment, there is Δa corresponding a satisfaction: $\mathrm{d}a/\mathrm{d}N = \Delta a/\Delta N$, every time the load acts, the stress intensity factor of the crack should be recalculated once, namely:

$$\begin{cases}a_{n+1} = a_n + \Delta a_n = \sum_1^n \Delta a_i \\ N_{n+1} = N_n + \Delta N_n = \sum_1^n \Delta N_i\end{cases} \tag{11}$$

Where, ΔN_n is the number of load cycles (cycle), a_n is the crack size at the n-th cycle (m), a_{n+1} is the crack size after ΔN_n load cycle (m), Δa_n is the increment of crack size after ΔN_n (m), N_{n+1} is the number of load cycles (cycle) corresponding to a_{n+1}.

The load spectrum and parameters required for calculation are imported into matlab program to obtain the Fatigue crack propagation life at different positions of TBM cutterhead. The rotating speed of cutterhead is ω = 6*r*/min, and the penetration is h = 6 mm/*r*. After calculation, the Fatigue crack propagation life can be converted into tunnelling mileage. The results are shown in figure 8.

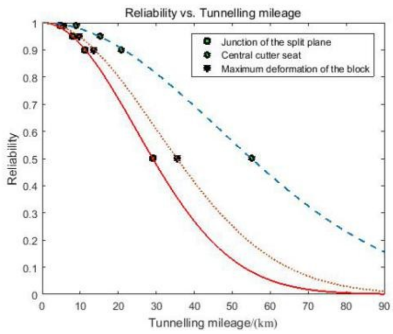


Fig. 8. Prediction of Fatigue crack propagation life of TBM cutterhead

It can be seen from Fig. 8 that the fatigue crack propagation life of TBM cutterhead with different reliability and positions is quite different. The stress at the junction of the split plane is the largest, and the stress at the central cutter seat is the smallest. With the crack growth cycle going on, the crack growth rate changes greatly with the initial small stress difference, so the gap of fatigue growth life of cutterhead structure is large. The stress amplitude is the main influence factor of crack propagation. When the reliability increases from 50% to 90%, the crack growth rate increases at the three dangerous location, which leads to the decrease of structural fatigue crack propagation life. When the reliability increases from 90% to 99%, the structural fatigue crack propagation life continues to decrease. The tunnelling mileage can be used as the basis for TBM cutterhead design, maintenance and remanufacturing through the conversion of tunnelling speed and load action times.

According to the analysis of Fig.8, the data points are close to the Weibull distribution curve of two parameters, and the expression is as follows:

$$R(L) = \exp\left[-\left(\frac{L}{\theta}\right)^{\beta}\right] \quad (L > 0) \tag{13}$$

Where, $R(L)$ is the reliability function, between 0 and 1, L is the tunnelling mileage (km), θ is the scale parameter, β is the shape parameter, and there are $\theta > 0$, $\beta > 0$.

In order to distinguish them easily, the subscripts at the junction of the split plane, the maximum deformation of block and the central cutter seat are 1, 2 and 3, respectively. The reliability function and scale coefficient are respectively recorded as $R_1(L)$, $R_2(L)$, $R_3(L)$ and θ_1, θ_2 and θ_3. The reliability functions of different positions of cutterhead are as follows:

$$\begin{aligned} R_1(L) &= \exp\left[-\left(\frac{L}{34.937}\right)^2\right] \quad L > 0 \\ R_2(L) &= \exp\left[-\left(\frac{L}{42.604}\right)^2\right] \quad L > 0 \\ R_3(L) &= \exp\left[-\left(\frac{L}{66.080}\right)^2\right] \quad L > 0 \end{aligned} \tag{14}$$

It can be seen from Fig. 8 that the fitting correlation of the curve of reliability function $R(L)$ is good, and the reliability trend declines gently. The function expression establishes the functional correspondence relation between tunnelling mileage L and reliability R. Using equation (14) and the load spectrum of the cutterhead, it is calculated that the safety tunnelling distance of the cutterhead is 29.11km when the reliability is 50%. Howere, the safety tunnelling distance of the cutterhead is 5.56km when the reliability is 99%.

3. Influencing factors of the reliability of cutterhead with cracks

In the process of TBM tunnelling, such factors as cutterhead structure, initial crack size, cutterhead load, construction environment and other factors affect the safety and reliability of cutterhead. Among them, the parameters of cutterhead load amplitude and initial crack size have great influence on the safety life of cutterhead structure, and directly affect the safe tunnelling mileage of TBM.

3.1 Safety analysis of initial crack size on TBM cutterhead with cracks

In view of the influence of different initial crack sizes on the fatigue crack propagation life of cutterhead, the life of three dangerous positions is calculated by using the cutterhead load spectrum. The figure 9 shows the calculation results of fatigue propagation life of different initial cracks at the junction of the split plane.

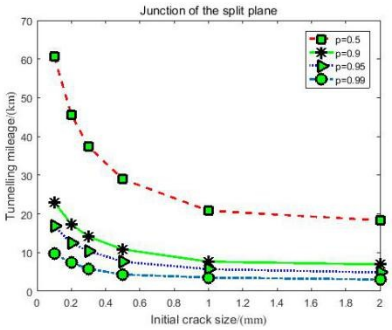


Fig. 9. Prediction of fatigue crack propagation life of different initial cracks at the junction of the split plane

It can be seen from Fig.9 that when the initial crack size is less than 0.5 mm, with the increase of initial crack size, the propagation rate gradually increases, and the fatigue crack propagation life of the cutterhead structure decreases. The initial crack size of cutterhead has a great impact on the tunnelling mileage. When the reliability is high, the fatigue crack propagation life becomes smaller. When the initial crack size is 2 mm, the crack propagation rate is relatively stable. When the cutterhead crack extends to the critical size, the structure will be broken due to insufficient strength or rapid increase of crack propagation rate. It can be seen that the initial crack size has a great influence on the fatigue crack propagation life of the structure. Therefore, improving the detection ability of the initial crack has a positive significance for predicting the fatigue crack propagation life of the structure.

Through calculation, the results of fatigue propagation life of different initial crack sizes at the maximum deformation of cutterhead block are shown in figure 10.

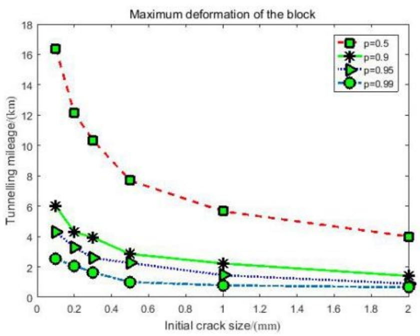


Fig. 10. Fatigue propagation life of different initial crack sizes at the maximum deformation

Compared with Fig. 9 and Fig. 10, it can be seen that the crack propagation life at the maximum deformation of the block is larger than that at the junction of the split plane. When the initial crack size is less than 0.5 mm, the fatigue crack propagation life increases greatly. When the crack size is between 0.5 mm and 1 mm, the fatigue crack propagation life changes little. When the crack size is between 1-2 mm, the fatigue crack propagation life is basically unchanged.

In the same way, the fatigue life of different initial crack sizes at the central cutter seat is obtained by calculation, and the results are shown in figure 11.

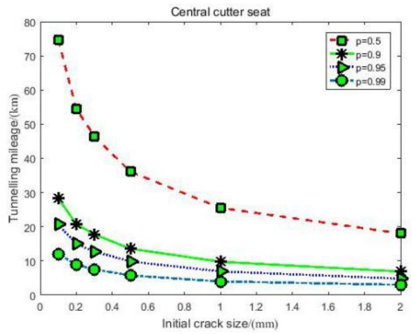


Fig. 11. Fatigue extended life of different initial crack sizes at the central cutter seat

It can be seen from Fig.11 that with the increase of the initial crack size, the tunnelling mileage of the central cutter seat is almost reduced by 75%, and the tunnelling mileage is significantly reduced to about 40% when the reliability changes from 50% to 99%. It shows that strengthening the structural reliability can significantly reduce the safe tunnelling mileage. The variation of fatigue crack propagation life with the initial crack size is the same as that at other dangerous locations. Therefore, the initial crack detection of cutterhead is recommended to be between 0.5 and 2 mm.

3.2 Safety analysis of TBM cutterhead with cracks caused by overload

The influence of overload on TBM cutterhead with cracks can be realized by giving different amplitude coefficients to the load spectrum of cutterhead under typical geological conditions[24]. In this paper, the crack propagation life is analyzed when the amplitude coefficients of the cutterhead load spectrum are 1.0, 1.2 and 1.5 respectively. The variation of tunnelling mileage of TBM cutterhead under the three amplitude coefficients of the junction of the split plane, the maximum deformation of the block and central cutter seat are shown in Fig.12, Fig.13 and Fig.14, respectively.

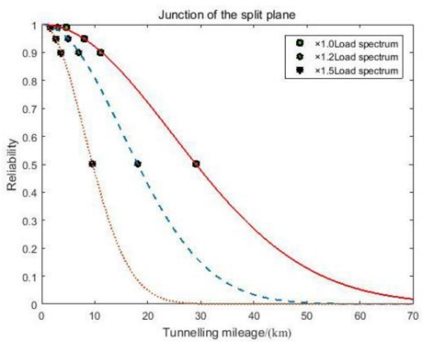


Fig. 12. Fatigue crack propagation life of different amplitudes at the junction of the split plane

It can be seen from Fig. 12 that after the fatigue crack propagation "accelerated" by the amplitude coefficient of the load spectrum, the crack propagation life at the junction of the split plane decreases significantly. When the reliability is in the range of 90%-99%, the crack propagation life still continues to decrease. Because the tunnelling mileage of crack propagation life is relatively small, the influence of load spectrum amplitude coefficient on crack propagation life is relatively small.

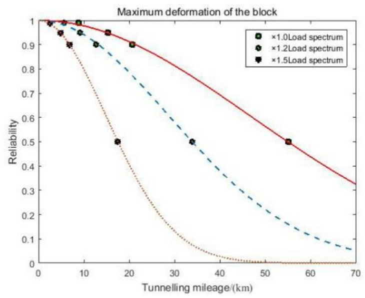


Fig. 13. Fatigue crack propagation life of different amplitudes at the maximum deformation of cutterhead

It can be seen from Fig. 13 that when the reliability is 50%, the tunnelling mileage at the maximum deformation of cutterhead decreases from 55 km to 17.5 km, indicating that the amplitude coefficient of load spectrum has a great influence on the fatigue crack propagation life. When the reliability increases to 90%, the fatigue crack propagation life basically decreases to half of that at 50% reliability. When the reliability is between 90% and 99%, the fatigue crack propagation life decreases rapidly.

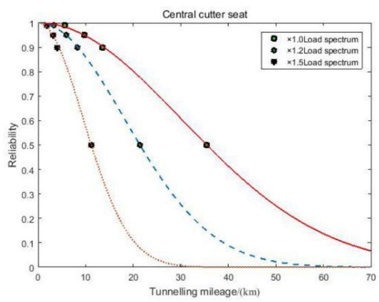


Fig. 14. Fatigue crack propagation life of different amplitudes at the center cutter seat

It can be seen from Fig. 14 that the greater the amplitude multiple of load spectrum at the cutter head center cutterhead, the faster the crack growth life decreases. When the amplitude of the load spectrum is 1.5 times of the typical load spectrum, the safe propagation life of the structure is reduced by 2/3. It can be seen that the load overload has a great influence on the fatigue crack propagation life of the central cutter seat.

The above analysis shows that the initial crack size and load amplitude have a great impact on the fatigue crack propagation life of the cutterhead. After the cutterhead is processed, the initial crack size can be determined by appropriate detection method, and the tunnelling parameters can be controlled reasonably according to geological conditions during the tunnelling process. When the rock strength of the working face is high, it is important to reduce the cutterhead load to improve the fatigue reliability of the cutterhead.

4. engineering experiment verification

The surrounding rock of TBM tunnelling section is mainly andesite, tuff and volcanic rock.Among them, the uniaxial compressive strength of nearly 70% rocks reaches or exceeds 140

MPa, and even 200 MPa in some places. The average thrust of cutterhead is about 10 500 kn. In order to verify the correctness of the theoretical analysis, the cutterhead tunnelling tracking test is carried out.

In the process of tunnel excavation, TBM cutterhead is inspected regularly, such as checking and measuring cutter wear, cutterhead panel crack and the weld crack, etc.. If there is a problem with the cutterhead, the excavation will be stopped immediately and the cutterhead will be repaired to ensure the construction safety. When the TBM was tunnelling to 5 km, it was found that there were deformation, cracking and weld cracking of cutterhead at the cutterhead center during the inspection, as shown in figure15 below.

(a) Local enlargement of cutterhead crack (b) Weld damage and crack of cutterhead

Fig. 15 the cutterhead crack location

As shown in Fig.15, cracks occurred at the cutter seat upper cutterhead due to local stress concentration. The crack propagation will gradually make this part of the structure lose its service capacity, resulting in increased vibration of the cutterhead and abnormal wear of the disc cutter. Therefore, the machine was shut down for maintenance. The crack propagation depth is about 65.3 mm, which verifies the correctness of the damage tolerance value. When the confidence level is 99%, the predicted crack growth life at the center cutterhead is 5.56 km, and the error between the predicted crack propagation life and the TBM cutterhead tunnelling distance of 5 km is 11.2%. The tracking experiment results verify the correctness of the fatigue reliability analysis method of cutterhead.

The cutterhead with cracks must be repaired and checked to be qualified before construction. The repair process of cutterhead is to repair welding groove, weld and heat preservation, eliminate welding residual stress, and the penetrant inspection is qualified. As shown in figure16.

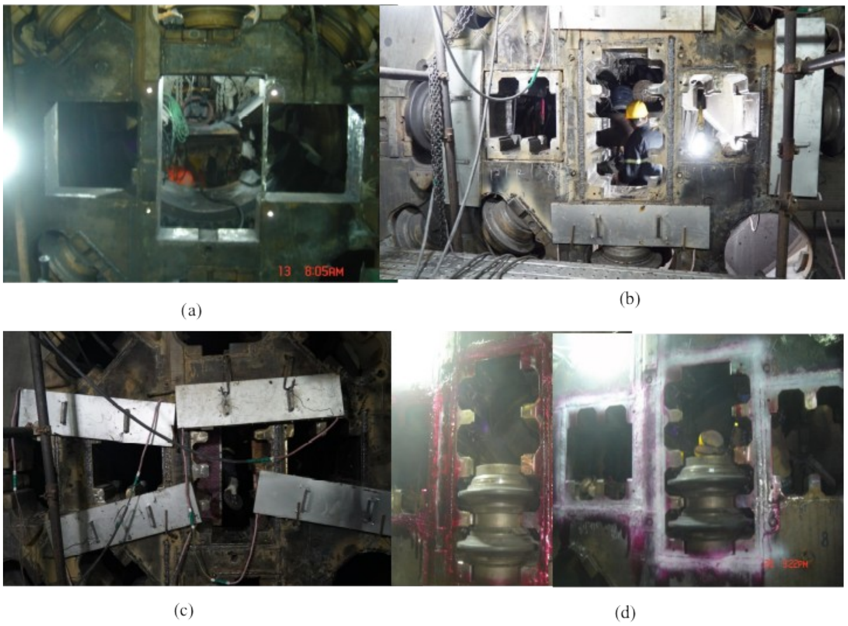


Fig.16 Repair and inspection of cutterhead crack

5. Conclusion

(1) The finite element model of TBM cutterhead is established and transient dynamic analysis is carried out. Three dangerous parts of fatigue crack propagation are obtained, which are the the junction of the split plane, the maximum deformation of the block and the central cutter seat. The load spectrum of the dangerous part of the cutterhead under typical geological conditions is obtained, and the fatigue damage tolerance of the cutterhead is determined. Using the fracture mechanics theory, the safe tunnelling mileage of the cutterhead in the diversion tunnel construction project is 5.56 km when the reliability is 99%.

(2) The fatigue reliability analysis method of the cutterhead with cracks is proposed. Based on the establishment of the fatigue crack propagation rate model of the cutterhead, the fatigue crack propagation life under different reliability is obtained. The fatigue life of dangerous parts decreases with the cutterhead reliability increases. The correctness of the fatigue reliability analysis method is verified by engineering experiments.

(3) The main factors affecting the reliability of cutterhead are analyzed. The overloading and initial crack size have great influence on the fatigue crack propagation life and reliability of cutterhead. The research results provide a scientific basis for crack detection of the dangerous parts, life prediction and reliability evaluation of TBM cutterhead structure.

Acknowledgments

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