ISSN: 2414-1895 DOI: 10.6919/ICJE.202405_10(5).0012

Fatigue Strength Mechanics of Beam of Mining Hydraulic Gyratory Crusher

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Abstract

The beam of a certain type of hydraulic gyratory crusher of PXZ series was taken as the research object. Firstly, through theoretical and experimental research, determine the stress load condition of the beam. Then, the crossbeam analysis model is established, the stress distribution of the crossbeam in the working process is analyzed by finite element calculation, the cause of the strength failure of the crossbeam is analyzed from the stress aspect, and finally the fatigue crack propagation life of the crossbeam is calculated. The calculation results show that there is stress concentration at the four corners of the beam hub, and the stress amplitude reaches the crack initiation threshold. Theoretically, the cause of the crack in the beam hub is explained, and the crack propagation life of the beam is less than one month, and the work needs to be stopped immediately. The research in this paper has certain guiding significance for the design and use of hydraulic gyratory crusher beams.

Keywords

Hydraulic Gyratory Crusher; Finite Element Models; Fatigue Cracks; Strength Analysis.

1. Introduction

Large hydraulic gyratory crusher is an important production equipment for heavy industries such as mining, chemical industry, building materials, cement, etc., and is widely used in mining and aggregate industries. It is characterized by continuous crushing, high production efficiency, stable equipment operation, low energy consumption, uniform particle size, etc. Due to the complex load conditions during the operation of the crusher, various failure problems may occur in its internal components, including surface wear, friction failure, and overload failure. As one of the important components of the hydraulic gyratory crusher, the beam bears its own weight, material impact and large dynamic load force in long-term work, and the beam has a very serious impact once it fails, and its maintenance and replacement needs large-scale equipment to assist in cooperating, consuming a lot of manpower and material resources, reducing productivity or stopping production, causing huge economic losses to the enterprise. In order to ensure that the crusher is safer and more reliable during operation, the failure mechanism of the beam structure is analyzed to reduce the maintenance cost of the crusher and guide the engineering practice.

During the disassembly and inspection of the faulty hydraulic gyratory crusher, cracks were found at the four corners of the beam hub. In practical engineering applications, failure can be caused by a combination of factors, including unreasonable structural design, operating loads, and complex environmental conditions. In this paper, the failure of the beam of the large hydraulic gyratory crusher is analyzed in depth according to the actual working conditions. Firstly, the structural composition of the large hydraulic gyratory crusher and the stress of the crusher beam are analyzed. Then, the operator of the hydraulic gyratory crusher. The operating conditions of the hydraulic gyratory crusher were studied in depth, and the finite element model of the large rotary crusher was established. On this basis, the static strength finite element analysis of the hydraulic gyratory crusher was carried out. Then, the failure mechanism of the beam was studied and analyzed, and the fatigue crack propagation life prediction calculation was carried out on the beam. The failure mechanism of the beam was comprehensively discussed.

2. Crusher Beam Load Calculation

2.1 Crusher Working Principle and Structural Analysis

The hydraulic gyratory crusher is mainly composed of parts such as fixed cone and moving cone, wherein the fixed cone is composed of upper and lower parts, and is bolted together, the lower part is connected with the machine base, the upper part is connected with the beam, and the crushing space (i.e. crushing cavity) is formed between the fixed cone and the moving cone(B. Lang and S. Lang 2009; Qin, Shen, and Zhang 2021). When the ore is fed from the top, the ore that is located at the moving cone is crushed by the action of extrusion and bending, and the part that is in the moving cone retreats from the fixed cone, the ore that has been broken is discharged under the action of its own gravity. In the normal working process of the hydraulic gyratory crusher, the beam as one of the key parts of the hydraulic gyratory crusher, mainly provides a supporting point for the upper end of the moving cone, and the upper end of the moving cone is inserted into the center hole of the beam (Xu 2008; Zheng et al. 2013). A cross-sectional view of the connection between the beam and the spindle is shown in Fig.1.

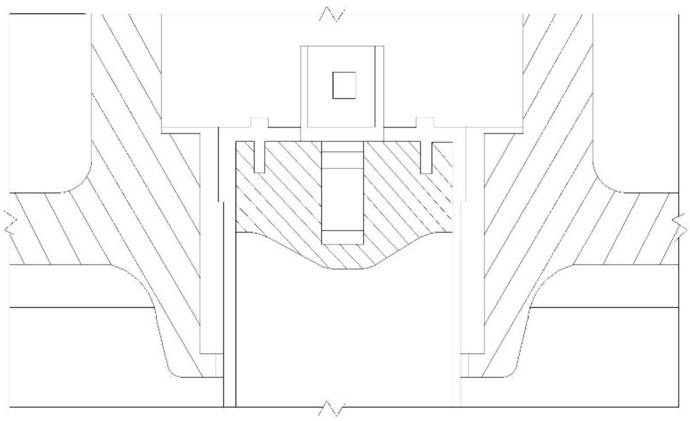

Fig. 1 Cross beam and the main axis of the connection profile.

2.2 Beam Force Analysis

The main force of the crusher beam is as follows: (1) the force (crushing force, friction force, gravity, etc.) on the beam is the main force of the beam; (2) the weight of the beam itself; (3) the residual tensile stress that the beam bushing (taper sleeve) produces on the cross beam when it is matched with the interference of the cross beam. (4) The frictional force at the crossbeam on the moving cone is negligible to the crossbeam. (5) The impact force of the material on the fracture position. In this article, only the crushing force on the beam is considered.

2.3 Field Load Measurement and Calculation of Beam

The hydraulic gyratory crusher was shut down due to failure, and it was found that cracks appeared in the outer radius of the center hub of the beam during the maintenance process, all of which were external cracks, with a total of four parts. After the tapered sleeve was removed, no cracks were found in the inner hole of the beam. The parameters of the moving cone and the measured data of field experiments are shown in Table 1.

Table 1. Related parameters of crushing a motor cone.

Self-weight of spindle(G1)	Angle of the moving cone (α)	Static Load Pressure(p1)	Working peak pressure (pmax)
45508kg	19.23°	1.33MPa	4.5MPa

The crushing force (sometimes referred to as the extrusion force) of the hydraulic gyratory crusher is calculated mainly based on the measured oil pressure value(Cheng and Yu 2018). The oil cylinder is installed at the bottom of the crusher base, and there are three thrust friction discs above the piston in the oil cylinder body to support the downward load of the moving cone. When the crusher is working, the hydraulic oil pushes the piston and the moving cone to the working position, which can be changed by controlling the amount of oil in the oil cylinder. Change the top and bottom positions of the cone (Cong 2008).

The crusher cylinder provides the vertical support force of the self-weight of the crushing cone, and according to this principle, the crushing force of the crushing cone can be calculated by changing the oil pressure value of the oil cylinder. The external force of the automatic cone that the beam is subjected to is the transverse component of the crushing force. The calculation diagram of the crushing force of the material in the crushing chamber when the moving cone is moving is shown in Fig. 2.

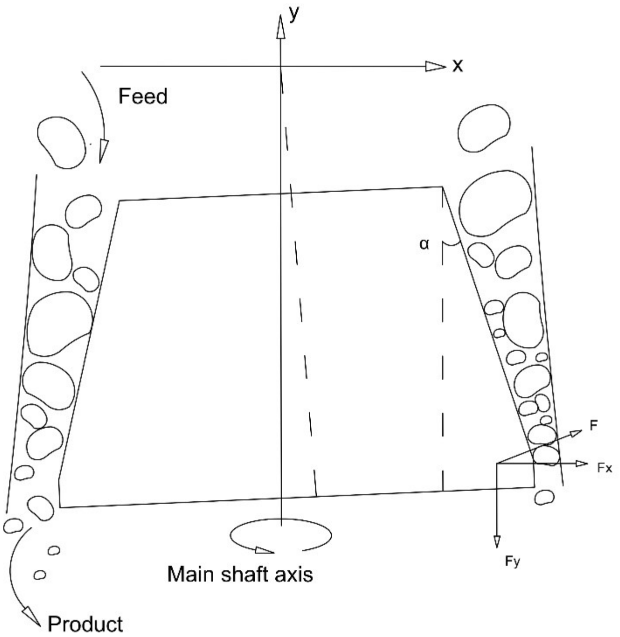

Fig. 2 Decomposition diagram of cone crushing force.

According to the principle of force balance, the equivalent load pressure of the hydraulic cylinder can be obtained from the following formula:

$$G_2 = (p_{max} \times G_1)/P_1 \tag{1}$$

ISSN: 2414-1895
DOI: 10.6919/ICJE.202405_10(5).0012

In the formula (1), P1 is the static pressure of the hydraulic cylinder, Pmax is the peak pressure of the hydraulic cylinder, and G1 is the self-weight of the spindle.

The crushing force F on the moving cone is:

$$\mathrm{F} = ((G_2 - G_1) \times 10)/\sin\alpha \tag{2}$$

In the formula (2), α is the dynamic cone angle.

The force on the beam load is:

$$F_x = F \times \cos\alpha \tag{3}$$

Substituting the relevant parameters in Table 1 into formulas (1)–(3), it can be found that the force on the beam is F_x = 310.9 t.

3. Static Analysis of Beams

In order to determine whether the failure of the beam is insufficient strength, a static strength analysis of the beam is required. This section calculates and analyzes the stress distribution of the beam in the actual working condition. Considering the factors such as material inhomogeneity, load type, manufacturing defects and other factors of the beam (Yu 2007), and at the same time in order to ensure that the beam can work safely and reliably under the condition of unscientific human operation and plastic deformation, the safety factor is taken 2.5 when designing. The allowable stress expression for the beam is:

$$[\sigma_{\mathrm{b}}] = \sigma_s/2.5 \tag{4}$$

In the formula (4), the σs yield strength of the beam material is 270MPa, and the allowable stress [σb] is 108MPa.

3.1 Establish the Model.

According to the design parameters of the crusher beam structure, combined with the structural characteristics and deformation characteristics of the hydraulic gyratory crusher beams, the finite element software is used in this section to carry out the numerical simulation calculation of the crusher beam. In the finite element beam model, the material properties are first set. The crusher beam is made of ZG270-500, and the specific parameters are shown in Table 2. In terms of finite element discretization, the free method is used, and the element size is set to 0.02m, and a total of 2336002 elements and 3465701 nodes are generated. The beam model is shown in Fig. 3.

Table 2. Crusher beam material parameter table

Material	modulus of elasticity	tensile strength	yield strength	density	Poissonratio
ZG270-500	2.1×10^5 MPa	500MPa	270MPa	7.85×10^3 g/cm^3	0.3

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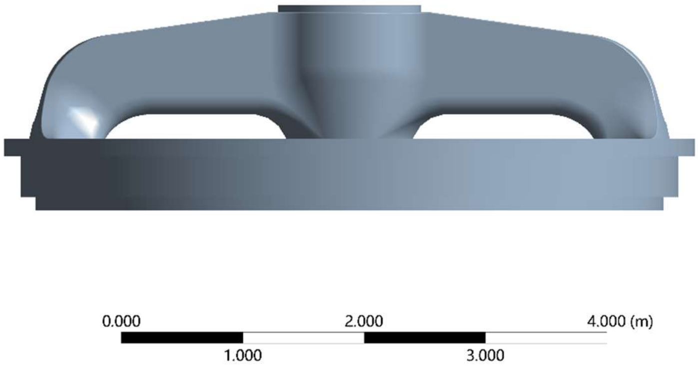

Fig.3 Model diagram of the beam of the hydraulic gyratory crusher.

3.2 Assuming Condition

Considering the actual working conditions in the hydraulic gyratory crusher, under the premise of not affecting the accuracy of the calculation results, the following assumptions are made in the finite element analysis of the cross beam: (1) The whole cross beam is regarded as a continuum; (2) Taking the crushing force as a local uniform distribution force; (3) As a large-scale heavy equipment, the beam has a gravity acceleration of $9.8\mathrm{m/s^2}$.

3.3 Constraints and Load Conditions

In the finite element analysis of the beam, the corresponding constraints and loads are imposed according to the motion state of the model. The cross beam of the crusher is fixed on the crushing cavity at the upper part of the crusher, so the displacement of the base surface of the cross beam is constrained in all directions. According to the theoretical analysis results in the second section, the load on the cross beam is loaded on the corresponding surface of the cross beam bushing, and three working conditions of parallel, vertical, and 45-degree angles between the load and the cross beam are calculated. Fig. 4 is a schematic diagram of the load and boundary constraints of the relevant cross beam, in which the arrow direction is the load loading direction and the yellow area is the displacement constraint position.

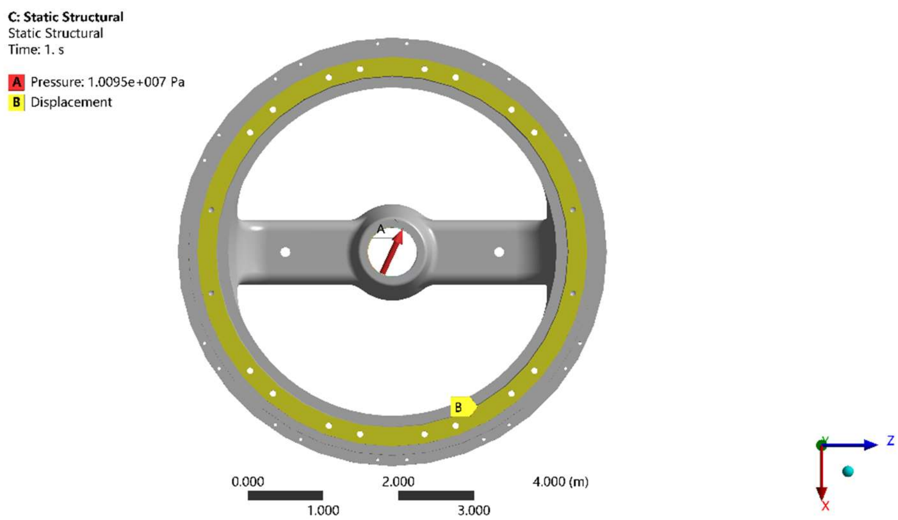

Fig. 4 Schematic diagram of boundary constraint loads.

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3.4 Solution and Analysis of Results

Combined with the actual operation of the crusher, there are three working conditions when the spindle runs in the beam hub, the first working condition is that the load is parallel to the beam, the second condition is that the load is perpendicular to the beam, and the third condition is that the load is at an angle of 45 degrees to the beam. The finite element calculation of the beam model was performed under three operating conditions. After finite element solving, the maximum and minimum principal stress contours of the beam under three working conditions are shown in Figure 5-10. The variation of the overall stress magnitude and amplitude of the beam under the three working conditions is shown in Table 3. The calculated stress amplitude at the fillet at the junction of the beam hub and the beam arm is shown in Table 4.

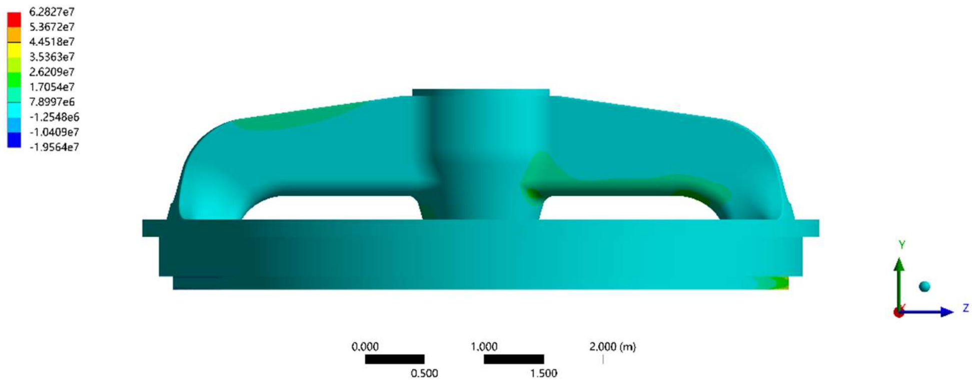

Fig. 5 Maximum principal stress nephogram of working condition I.

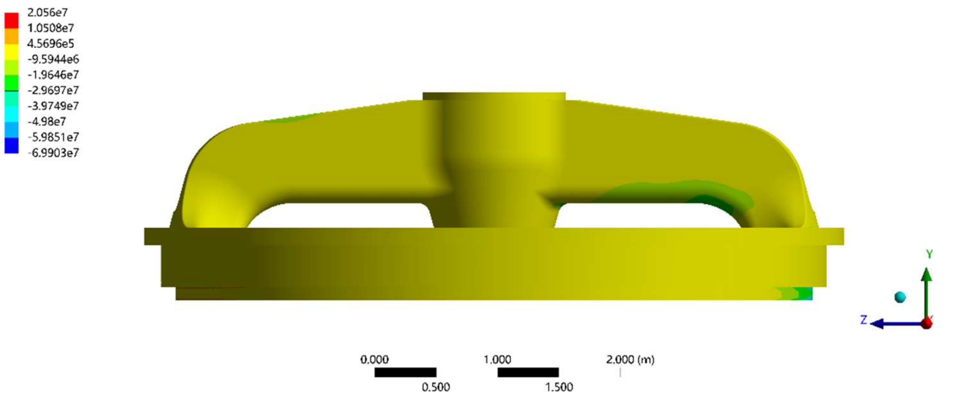

Fig.6 Minimum principal stress nephogram of working condition I.

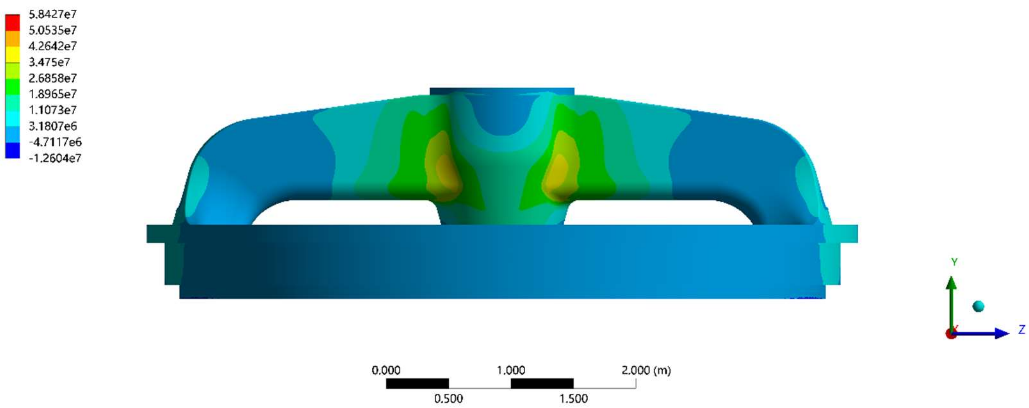

Fig.7 Maximum principal stress nephogram of working condition 2.

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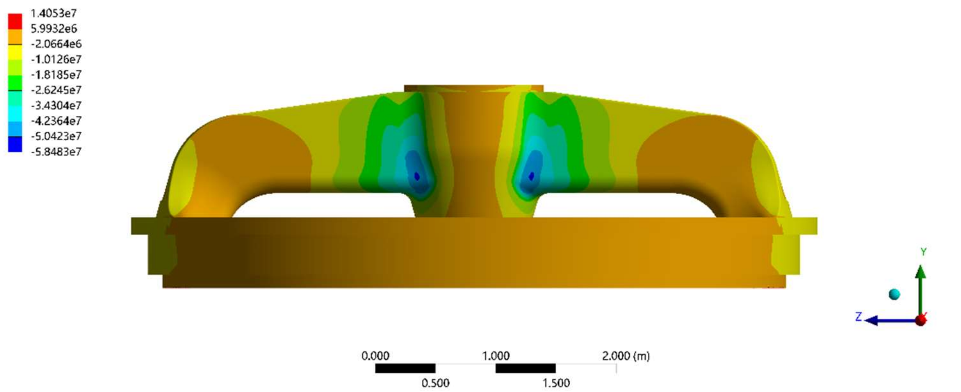

Fig.8 Minimum principal stress nephogram of working condition 2.

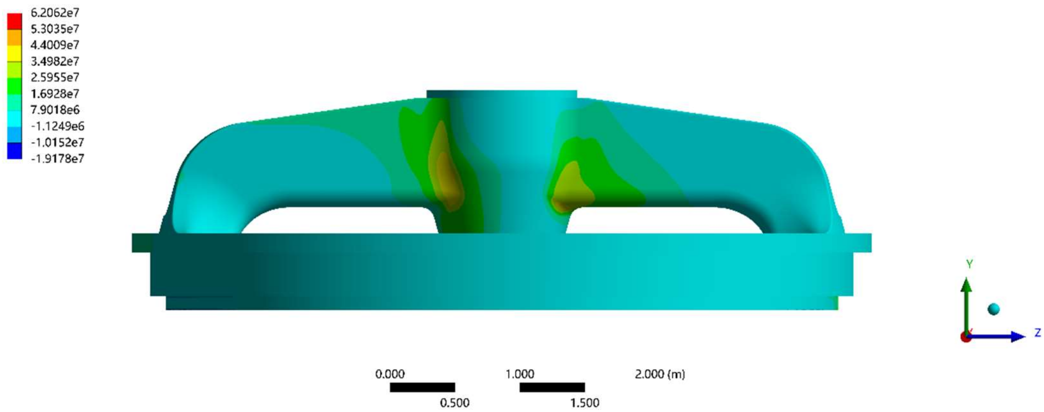

Fig.9 Maximum principal stress nephogram of working condition 3.

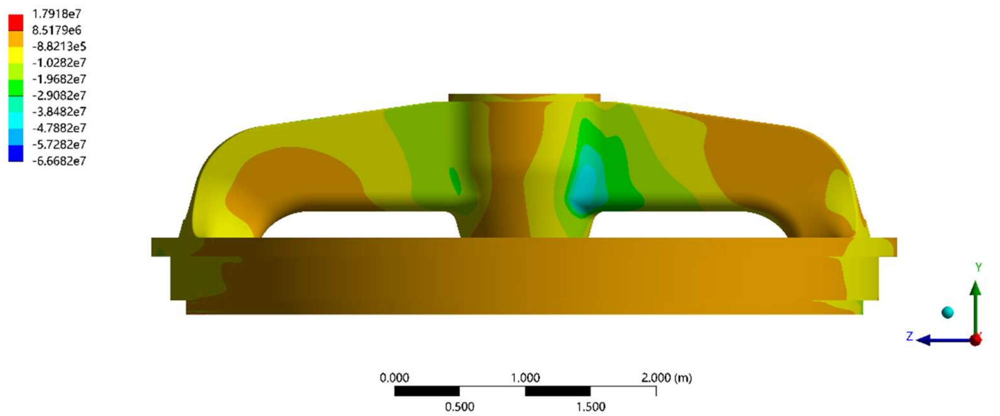

Fig.10 Minimum principal stress nephogram of working condition 3.

Table 3. Calculation of beam stresses for different operating conditions.

Operating condition	Maximum principal stress (MPa)		Minimum principal stress (MPa)		Stress amplitude (MPa)
	Max	Min	Max	Min	
Operating condition 1	62.8	-19.6	20.6	-69.9	132.7
Operating condition 2	58.4	-12.6	14.1	-58.5	116.9
Operating condition 3	62.1	-19.2	17.9	-66.8	128.9

Table 4. Calculated stress amplitude at the corner of the junction between the beam hub and the beam arm.

Operating condition	Maximum principal stress (MPa)	Minimum principal stress (MPa)	Fatigue amplitude(MPa)
Operating condition 1	20.6	-1.8	113.6
Operating condition 2	46.2	-62.2	
Operating condition 3	51.4	-59.0	

The calculation results show that the stress at the junction fillet of the crusher beam hub and the beam arm is large, and the stress concentration phenomenon occurs. However, the maximum tensile stress is 62.8 MPa, and the maximum compressive stress is 69.9 MPa, which does not exceed the allowable stress of 108 MPa, so the structure will not have static strength failure.

4. Fatigue Analysis

Stress fluctuations are necessary conditions for fatigue crack initiation(Qu, He, and Liu 2010). After the initial crack occurs in the beam, the crack tip will inevitably cause a stress set, and the local stress must be too large (the average stress does not necessarily exceed the yield limit of the material itself) (He and Wang 2012; Shi, cai, and Bao 2014; Wu et al. 2019; Ye et al.2022). According to the theory of linear elastic fracture mechanics, fatigue crack propagation is divided into three stages: the first stage is the initiation stage of fatigue cracks, the second stage is the crack steady-state propagation stage, and the third stage is the crack propagation instability stage, wherein the crack steady-state propagation stage is the main stage of fatigue crack propagation (Xiong et al. 2009; Zang and Yao 2014). The crack begins to expand under the fatigue cyclic dynamic load (Liu et al. 2017), and its crack propagation reaches the fatigue fracture failure threshold, which is the actual service life of this beam (Meng, Li, and Zhou 2007).

Fatigue amplitude is an important parameter to evaluate the fatigue performance of a material or structure, which directly affects the fatigue life of the material. Under cyclic loading, the fatigue life of a material or structure is related to factors such as stress amplitude and average stress. According to the experimental study of this project, according to the safety factor of 2.5 in the fatigue life analysis, when the fatigue amplitude exceeds 40%, the structure will produce fatigue cracks.

From the analysis results in Table 4, it can be seen that during normal operation, the initial crack will occur at the junction fillet of the beam hub and the beam arm under cyclic fatigue load. The position of the maximum stress of the beam is consistent with the actual position of the beam crack. According to the fatigue damage theory and the definition of fatigue failure, the beam will produce fatigue failure under cyclic load.

4.1 Fatigue Crack Propagation Life Calculation

When calculating the fatigue crack growth life of the beam, the initial crack size a0 and the critical crack size ac of the member should be determined first. According to the theory of linear elastic fracture mechanics, the critical crack size is expressed by Formula (5).

$$a_C = {K_C}^2/(\pi f^2 {\sigma_{max}}^2) \tag{5}$$

In formula (5), K_C is the fracture toughness value of the material; f is the component shape, crack size, and shape coefficient of related materials; and σ_{max} is the maximum cyclic stress of the member.

In the steady-state crack growth stage, the relationship between the amplitude ΔK of the fatigue crack stress intensity factor and the fatigue crack growth rate da/dN can be expressed by the Pairs formula.

$$da/dN = C(\Delta K)^m \tag{6}$$

$$\Delta K = K_{max} - K_{min} = f\Delta\sigma\sqrt{\pi a} \tag{7}$$

In formulas (6)–(7), a is the crack length; $\Delta\sigma$ is the stress amplitude at the crack (MPa); C and m are crack propagation constants. ΔK is the amplitude of the stress intensity factor ($N \cdot mm^{-2/3}$), ($\Delta K = K_{max} - K_{min}$).

By integrating dN in the range $[a_0, a_c]$, we can get the expression of the number of stress cycles N experienced by structural cracks (Sun and Yuan 2011):

$$N_c = \begin{cases} \frac{2}{C\left(f\Delta\sigma\sqrt{\pi}\right)^m (m-2)}\left(\frac{1}{a_0^{0.5m-1}} - \frac{1}{a_c^{0.5m-1}}\right), m \neq 2 \\ \frac{1}{C\left(f\Delta\sigma\sqrt{\pi}\right)^m}\ln\left(\frac{a_c}{a_0}\right), \qquad m = 2 \end{cases} \tag{8}$$

Based on the fatigue life calculation formula, the fatigue crack life of the beam is calculated. Firstly, determine the basic data: $a_0 = 0.01$ mm; $\sigma_{max} = 51.4$ MPa; $\Delta\sigma = 113.6$MPa ;The material is ZG270-500 steel, and its fracture toughness is 43.4MPa $\cdot$ m$^{1/2}$.

According to the specification (Guide to methods for assessing the acceptability of flaws in metallic structures 2013), C is 5.21×10^{-1} MPa $\cdot$ mm (regardless of steel corrosion), and M is 3.0. The reference (Ni, Li, and Wang 2006) takes the value f= 1.12. The amplitude expression of the stress intensity factor is $\Delta K = 1.12\sigma_{max}\sqrt{\pi a}$.

Substituting the relevant values into formula (5), the critical crack size $a_c = 181$mm is obtained; the fatigue crack propagation life is calculated by formula (8), and $N_c = 3322296$ cycles.

The crusher is known to work for 8 hours a day, and the N=332229 beam continues to work after the appearance of microcracks, and the remaining life of the structure is only one month. The theoretical calculation value is large relative to the normal life value of the beam, and the durability of the beam may be negatively affected by the fact that the quality of the beam itself is not considered in the calculation, including the inhomogeneity of the material, internal defects, or residual stresses introduced during the manufacturing process.

4.2 Fatigue Strength Calculation

The main failure mode of the beam is fatigue failure, and the number of cycles required for fatigue fracture failure at a certain position depends on the stress fluctuation of the beam and the properties of the material itself. The finite element simulation calculation of the beam model is selected first. Take the S-N curve that determines the beam material. For a specific material, its fatigue failure is determined by the S-N curve of the material, and the S-N curve is obtained by the method of fatigue testing on the material. Due to the limited experimental conditions, fatigue testing of the material was not possible, so an approximate S-N curve was fitted based on the performance parameters of the beam material itself and ANSYS (see Figure 11). Considering the material properties of the beam, the Goodman theory was selected to correct the average stress, and finally, the fatigue calculation under cyclic stress at the junction of the beam hub and the beam arm was completed.

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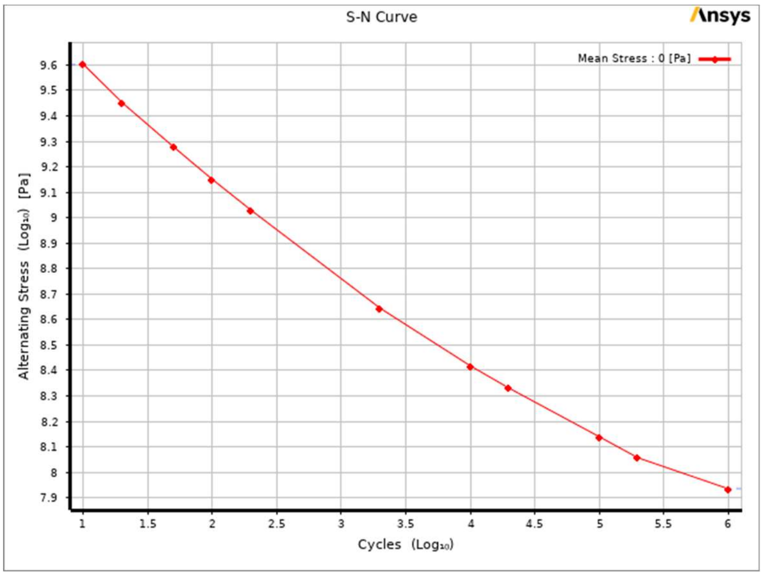

Fig. 11 S-N curves of the material.

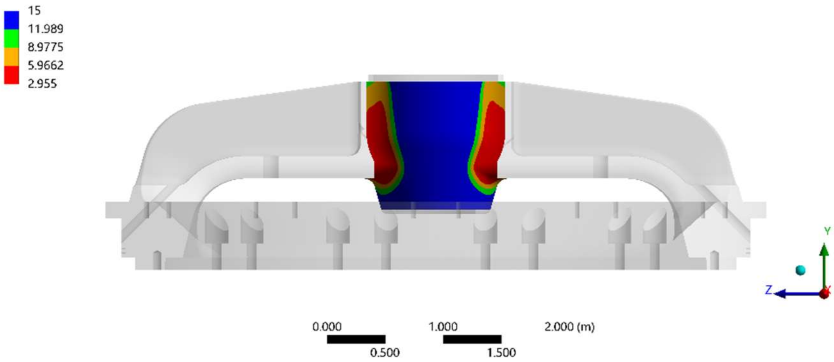

Fig. 12 Contour of the safety factor of the beam.

The fatigue analysis module in the finite element software was used to analyze the fatigue of the beam, and the safety factor of the beam was obtained (as shown in Fig. 12). The minimum safety factor value is concentrated in the beam hub, where the minimum value of the safety factor is 3.0, combined with the crack propagation life cycle value here, indicating that the fatigue strength of the beam is not enough. So it is necessary to stop the beam work immediately and repair or replace it.

5. Conclusion

In this paper, the following research was carried out on the beam of a hydraulic gyratory crusher:

(1) Through the study of the working condition of the on-site hydraulic gyratory crusher, the failure position of the crusher and the force of the crusher beam were measured.

(2) established the finite element calculation model of the cross beam, calculated the stress area distribution of the cross beam in normal operation, pointed out that the stress at the junction fillet of the cross beam hub and the cross beam arm is larger, and the possible failure position of the cross beam is near the fillet at the junction of the cross beam arm and the cross beam hub.

(3) According to the theory of linear elastic fracture mechanics, the fatigue fracture analysis of the beam was carried out, and the fatigue life of the beam crack propagation was calculated by the Paris formula. The finite element software was used to analyze the fatigue life of the beam to obtain the specific safety factor. for Useful technical information was provided for the design of the beams of the PXZ series hydraulic gyratory crusher.

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