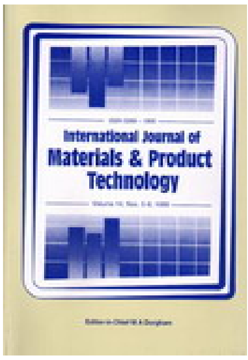

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# Study on damage fatigue test method of metal materials for rotating machinery

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**Abstract:** In order to solve the problem that the existing metal material damage fatigue test methods can not accurately test the compression and shear properties of materials, a new metal material damage fatigue test method for rotating machinery is proposed in this paper. The calculation model of mechanical characteristics of metal materials based on impact load is established to calculate the yield moment and the damage fatigue degree of metal test materials. The smaller size Q235 steel material on rotating machinery is selected as the experimental object and the damage fatigue test is designed. The experimental results show that the overall height of the three-dimensional morphology of the fatigue surface is low, and becomes uneven when the number of tensile times increases. It is proved that the damage fatigue test of the proposed method is more accurate and can predict the life and strength of steel under damage.

**Keywords:** rotating machinery; metallic materials; damage fatigue; impact load; cyclic load.

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## 1 Introduction

Under the action of cyclic load, the strength of metal materials of rotating machinery will gradually weaken, resulting in material fracture. Fatigue failure will cause the machinery to fail to operate and affect the working efficiency (Shanyavskiy and Soldatenkov, 2020). During the maintenance of rotating machinery faults, it is found that most of the faults are caused by fatigue of metal materials, resulting in damage to parts and components, resulting in the failure of normal operation of the machinery (Salimi et al., 2019). Fatigue life has important reference value for the service life of metal materials. The load cycle can be used to consider the damage fatigue bearing range of metal materials (Main et al., 2019; Salimi et al., 2020). Therefore, it is of great significance to clarify the damage fatigue properties of metal materials of rotating machinery.

Wu et al. (2019) propose to test the damage fatigue of metal materials by constructing a fatigue propagation model. This method integrates various factors of fatigue cracks of metal materials, constructs a phenomenological model of fatigue crack propagation, and proposes a fatigue crack propagation model based on uniaxial tensile properties by using low cycle and ultra-high cycle fatigue crack propagation data. It plays a certain role in the analysis of material damage and fatigue performance, but for the integration of fatigue cracks in metal materials, the material consumption is large and the data are scattered. Sun et al. (2020) propose a metal material damage fatigue test method based on finite element. This method extracts the boundary potential information in the form of finite element simulation, analyses the electrical impedance imaging and electrical characteristics of metal materials, obtains the impedance detection method of metal material fatigue damage, locates the fatigue damage location of metal materials, and effectively reduces mechanical faults, however, it has a long experimental cycle and cannot provide damage results quickly. Wenhan et al. (2018) adopt the metal material damage fatigue test method of nonlinear acoustic method, which believes that with the deepening of fatigue degree, the dislocation density also increases, which will lead to the generation of microcracks in the later stage of fatigue. The mechanism of acoustic nonlinear effect in different fatigue damage stages is different. The mechanism of nonlinear effect is described by dislocation model and microcrack model, and the damage fatigue simulation results are obtained. However, the simulation process of this method is time-consuming.

Because the above two methods can not accurately test the compression and shear properties of materials, and the detection cycle is long and the data are scattered, the traditional methods are not suitable for the damage fatigue test of rotating machinery. Therefore, a damage fatigue test method for metal materials of rotating machinery is proposed in this paper. The overall research scheme of this method is:

1. According to the structure and material characteristics of rotating machinery, the calculation model of mechanical characteristics of metal materials under impact load is constructed, the influencing factors of ultimate fatigue of metal materials are extracted, and the damage fatigue degree of metal test materials is calculated.

2. Based on the damage fatigue results obtained from the above calculation, the smaller size Q235 steel notch material in rotating machinery is selected as the experimental object, and the damage fatigue test experiment of metal materials in rotating machinery is designed.

## 2 Damage fatigue analysis of metal materials in rotating machinery

### *2.1 Calculation model of mechanical characteristics of metal materials based on impact load*

The host structure of rotating machinery meets the main functions of rotating machinery, and its structure is reliable, the process is reasonable and the total cost meets the design requirements of rotating machinery. Since the core requirements of rotating machinery are bearing capacity and compression shear capacity, the main structure of rotating machinery at this stage meets the following structural design principles: try to meet the compression shear test function, strength and stiffness, meet the use requirements, and have the characteristics of low cost and small weight. Therefore, the designed rotating machinery for compression shear experiment meets the application requirements more and more. According to the structure and material characteristics of rotating machinery, the calculation model of mechanical characteristics of metal materials under impact load is established. Assuming that the action speed of impact load is v, the dynamic balance equation of metal material at any time point is:

$$\begin{cases} F = m \cdot g \cdot \cos\alpha \\ mv = m \cdot g \cdot \sin\alpha - f_{\text{friction}} \\ v = g \cdot \sin\alpha - g \cdot \sin\alpha \cdot r \cdot \cos\alpha \end{cases} \tag{1}$$

In the formula: F represents the force perpendicular to the rotating machinery; $m \cdot g$ represents the quality of metal materials; $\alpha$ represents the angle of the force; v represents acceleration; $f_{\text{friction}}$ represents friction; r is the coefficient of friction.

According to the force value of the above impact load, the element model of the mechanical characteristics of metal materials is constructed. The model is essentially a structural model of rotating machinery, so it will not be described repeatedly. Based on this, the material model is established. The impact load force is simulated by the rigid body material model, and then the mechanical characteristics of metal materials are determined according to the degrees of freedom of the rigid body (Kravchuk et al., 2019; Owoeye et al., 2019). By constructing a multi-linear elastic-plastic material model, the stress curve related to strain rate is obtained (Wang et al., 2020; Zou et al., 2021). Considering the relationship between strain rate and yield stress, it is described by Cowper Symonds calculation method:

$$q_{\text{Yield stress}} = \left(1 + \frac{u}{x}\right) \cdot \left(q'_{\text{Yield stress}} + s_{\text{Plastic strain}}\right) \tag{2}$$

where u is the effect rate; x is the strain rate parameter; $q'_{\text{Yield stress}}$ is yield stress (Portone et al., 2019); $s_{\text{Plastic strain}}$ is the hardening function.

Three strength theories are obtained:

$$\begin{cases} F < q_{\text{Yield stress}} \\ F - r \cdot \left(q'_{\text{Yield stress}} + s_{\text{Plastic strain}}\right) \le q_{\text{Yield stress}} \\ \frac{1}{2} F + u \cdot q_{\text{Yield stress}} \le q_{\text{Yield stress}} \end{cases} \tag{3}$$

The four sets of inequalities in the equations are the expressions of the first, second, third and fourth strength theory respectively. So far, based on the actual situation of impact load, the calculation model of mechanical characteristics of metal materials has been constructed.

## *2.2 Extraction of influencing factors of ultimate fatigue of metal materials*

According to the above model, the mechanical characteristics of metal materials under impact load are analysed, and the influencing factors of ultimate fatigue of metal materials in this process are extracted. According to the simplicity of the nonlinear finite element calculation method (Abuodeh et al., 2021), the metal material joints on rotating machinery are analysed by single factor analysis method, and then the bearing capacity of the joints is analysed by this method.

Firstly, it is assumed that the material width ratio of rotating machinery is the factor affecting the ultimate fatigue of materials. According to the requirements of the basic design code of rotating machinery, it is considered that the width ratio of metal materials is an important factor affecting the normal service limit state and bearing capacity limit state of rotating machinery. Therefore, set the ratio to 0.1, 0.2, 0.3 and 0.4, respectively, compare the hysteretic performance at different connection positions (Mahdavifar et al., 2019; Zhang et al., 2021), and verify the performance of metal materials at different nodes. Assuming that the width ratio is C, the yield moment and bearing capacity data of different joints are shown in Table 1.

**Table 1** Effect of C on yield moment and bearing capacity

| *Parameter* | *01* | *02* | *03* | *04* |
|---|---|---|---|---|
| $\alpha$ | 0.010 | 0.013 | 0.158 | 0.011 |
| $m_1$ | 1.42 | 6.41 | 1.35 | 9.27 |
| $m_2$ | 20.6 | 7.15 | 0.78 | 11.40 |
| $m_2/m_1$ | 1.579 | 1.527 | 0.224 | 1.129 |
| r | 5.19 | 3.11 | 0.85 | 3.60 |
| E | 0.247 | 1.229 | 0.457 | 1.274 |

In Table 1, $\alpha$ represents the yield angle; $m_1$ and $m_2$ represent the yield moment and bearing capacity respectively, $m_2/m_1$ is the strength to flexion ratio; r is the ductility model; E is accumulated energy consumption. However, it should be noted that the above parameters are analogue values. Firstly, the skeleton curve and bending capacity of rotating machinery are analysed.

According to the calculation data in Table 1, when $\alpha = 0.01$, the elastic stiffness of the joint increases significantly. At that time, $\alpha = 0.013$, the stiffness of the joint domain changes little; At that time, the stiffness of the joint domain is significantly improved to reach the failure before yield. At this time, there is $m_2 < m_1$ between the yield moment $m_1$ and the bearing capacity $m_2$. The ductility and energy dissipation effect of metal materials are analysed. According to the data in Table 1, when $\alpha = 0.011$, the ductility coefficient of the joint is reduced by about 43%, while the cumulative energy consumption is increased by nearly 114%, and the equivalent viscous damping coefficient of the joint under impact load is increased.

When $\alpha = 0.01$ the joint ductility coefficient increases by about 8.2%, and the cumulative energy consumption exceeds 32%. When $\alpha > 0$, the joint buckled in plane, so the ductility and energy dissipation capacity decreased. Combined with the comparison of two aspects of flexural hysteretic properties, the influencing factors of ultimate fatigue of metal materials are obtained.

## *2.3 Calculating the yield moment of metal test material damage fatigue*

According to the effect of the above influencing factors on the ultimate fatigue of metal materials, the yield bending moment is calculated and the flexural ultimate fatigue of metal materials is measured. For ordinary joints, there are many kinds of models used to analyse the bending moment. According to the above research results, the bending moment of metal joints is obtained by using the curve expression of three parameter power function:

$$Q = G \cdot \omega_n \Big/ \left(1 + \frac{\omega_0}{\omega_1}\right) \tag{4}$$

where Q represents the bending moment of metal joint; G represents the elastic initial rotational stiffness of the i<sup>th</sup> node; $\omega_n$ represents the node rotation angle when the radius is r; $\omega_0$ represents the reference value of the plastic rotation angle of the joint; $\omega_1$ represents the actual value of the plastic rotation angle of the joint; n represents the curve shape fitting parameter. The greater the value of n, the sharper the curve.

Given the three parameter power function of the metal joint, there are three variables to calculate the initial rotational stiffness in the weak axis direction of the metal joint:

$$G = 0.75248 \times 100A \cdot w \cdot k \cdot h / d \tag{5}$$

where A represents the elastic modulus of metal material; w is the flange width of the material; k is the thickness of the material; d is the section height of the material; H represents the distance from the central node of the material to the outer edge of the metal edge; a, b, c and d are the corresponding constant parameters, which can be calculated from Table 1.

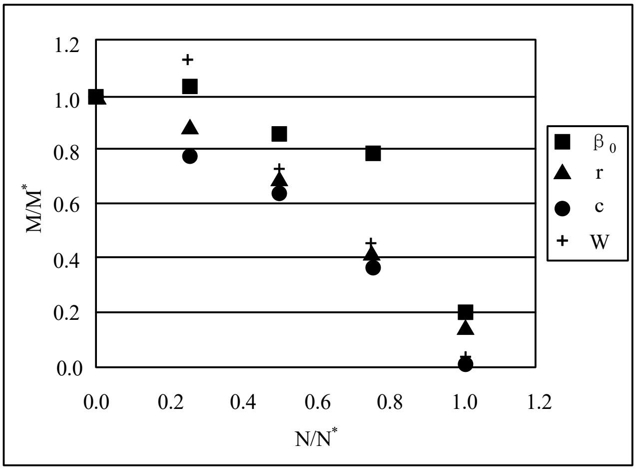
The yield moment of metal joints can be calculated according to the above formula. Draw the ultimate fatigue measurement diagram of metal materials according to the calculation results, and the fatigue measurement diagram is shown in Figure 1.

In Figure 1, N is the axial ultimate fatigue of the joint, and M is the impact load bending moment. According to the ideal analysis results in Table 1, two groups of joint limit fatigue limiting conditions with different conditions are obtained. The expression of the condition is:

$$\begin{cases} \dfrac{N}{N'} + \dfrac{M}{M'} \le 1 \\ \left(\dfrac{N}{N'}\right)^2 + \left(\dfrac{M}{M'}\right)^{1.5} \le 1 \end{cases} \tag{6}$$

According to the ideal measurement results in Figure 1, N′ is the ultimate fatigue of the joint when bearing the axial force alone, and M′ is the bending moment loaded by the joint when bearing the composite force, in a scattered distribution state.

**Figure 1** Ideal measurement diagram of ultimate fatigue of metal materials under impact load



Therefore, repeated testing and analysis are carried out according to the above process to obtain the ultimate fatigue measurement results of metal material joints of rotating machinery under composite stress:

$$\left(\frac{N}{N'}\right)^{1.3} + \left(\frac{M}{M'}\right) \leq 1 \tag{7}$$

So far, according to the above steps, the measurement task of ultimate fatigue of rotating machinery materials under impact load is realised.

## 3 Experimental study on damage fatigue test of metal materials in rotating machinery

In order to verify the actual use effect of the measurement technology in this study, a comparative test is proposed. The proposed measurement method is used as the experimental group and the traditional measurement method is used as the control group to compare the differences of different measurement technologies. In order to make the experimental test results meet the accuracy and authenticity test requirements, the same type of rotating machinery is selected as the basic test condition, and the measurement technology is used to measure the ultimate fatigue of two metal materials with different damage degrees under different impact loads. Q235 steel specimens in rotating machinery are selected for fatigue tensile test. The three-dimensional shape image of the sample surface is collected by 3D profilometer, and the change law of the three-dimensional shape image of the surface is analysed. The salsa multi band polarisation camera and electro-hydraulic servo fatigue experimental machine are selected to build the image acquisition platform of surface polarisation characteristics in metal fatigue process, and the correlation between polarisation characteristic parameters Stokes parameters and image texture characteristic parameters with the degree of fatigue damage is studied. This experiment mainly studies the change law of three-dimensional surface morphology of Q235 specimen under different fatigue damage degrees.

Mtest5000-f-k tensile in-situ tester and Keyence VR-3000 profile measuring instrument are selected to build a three-dimensional morphology acquisition system for the sample surface in the process of fatigue damage. By collecting the three-dimensional morphology of the sample surface under different cycles, the change law of the surface morphology is analysed.

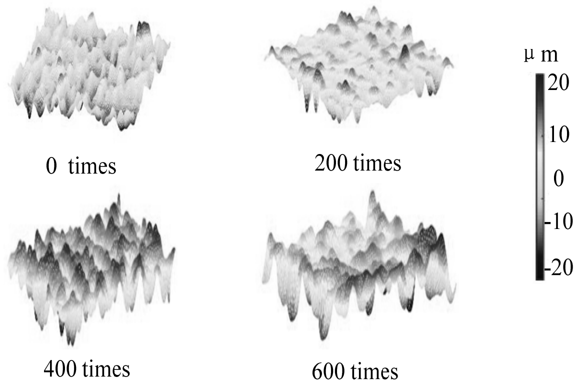
Mtest5000-f-k tensile in-situ tester produced by experimental equipment Co., Ltd. is selected to carry out the tensile fatigue test of Q235 sample. The machine can complete the tensile, bending and other fatigue behaviours of the sample, with the maximum static test force of 5000N and the maximum dynamic test force of 1,000 N. The experimental machine is mainly composed of tensile fatigue module, tensile fixture, dynamic controller, piezoelectric ceramic controller, servo system, encoder, load sensor, displacement sensor and computer control software. The host of the tensile in-situ tester adopts horizontal structure, the driving mechanism adopts DC servo motor and grating ruler closed-loop control, and the sample is clamped on the tensile fixture during the experiment. The load is applied by DC servo motor, reducer, worm gear and other components. The parameters such as stress, strain, loading waveform and displacement can be easily controlled by computer control software.

The VR-3000 profile measuring instrument from Keyence is used to collect and analyse the surface morphology of the sample. The measurement range is from ten micrometres to millimetres, and the measurement area is from 0 to 200 × 100 × 50 mm, with high measurement accuracy. Based on the principle of grating projection, the 3D profilometer can quickly and accurately obtain the concave convex fluctuation and shape features of the target surface, and save the target surface morphology information in the form of height image.

## *3.1 Three-dimensional morphology change of fatigue surface of steel*

A large number of studies show that the surface micro morphology will change continuously and irreversibly in the fatigue crack initiation stage and propagation stage. In this paper, the surface of Q235 sample undergoing different cycles (0, 200, 400 and 600) under the same conditions is measured by 3D profiler, and the three-dimensional morphology is drawn. The three-dimensional morphology of the sample under different cycles is shown in Figure 2.

**Figure 2** Three-dimensional morphology of sample under different cycles



0 times

200 times

400 times

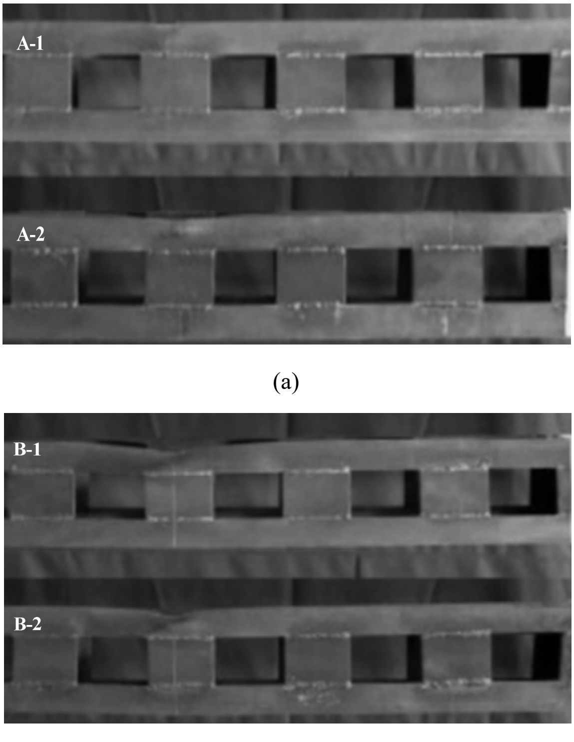
600 times

As can be seen from Figure 2, the surface of the sample without cyclic load tension is relatively uniform, there are few prominent peaks and valleys, and the overall height is also low. With the increase of cycle times, the sample surface becomes messy, the number of peaks and valleys increases, the height of peaks increases, the depth of valleys deepens, and the surface becomes uneven, indicating that the ‘invasion’ and ‘extrusion’ effects are becoming stronger and stronger. Therefore, the external cyclic load in the fatigue process will lead to the change of the micro morphology of the material surface, and the macro performance is that the material surface becomes rough.

## *3.2 Ultimate fatigue test of metal specimens*

According to the above experimental test requirements, two groups of different metal material specimens are prepared, of which the first group is completely normal without any bending. The second group of specimens have bending problems. Two groups of test pieces are shown in Figure 3.

**Figure 3** Metal material specimen prepared in the experiment, (a) normal specimen (b) slightly deformed specimen

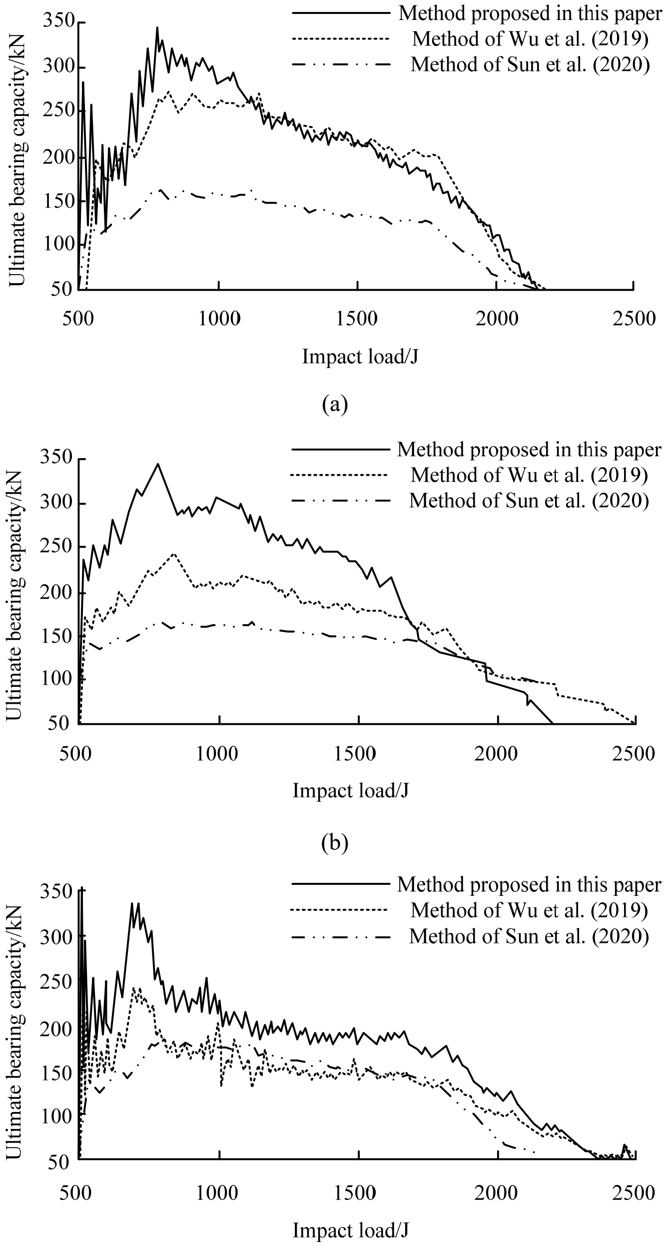


(a)

(b)

Taking A-1 and B-1 as the test conditions of the experimental group and A-2 and B-2 as the test conditions of the control group, three groups of different impact load forces are set. The ultimate fatigue measurement task of metal materials of rotating machinery is carried out by using the proposed measurement technology and traditional measurement technology, respectively. According to the two groups of experimental test results, specific experimental conclusions are obtained.

**Figure 4** Ultimate fatigue test results of normal specimens under different impact loads, (a) ultimate fatigue test results under 1,000 J impact load (b) ultimate fatigue test results under 1,500 J impact load (c) ultimate fatigue test results under 2,000 J impact load



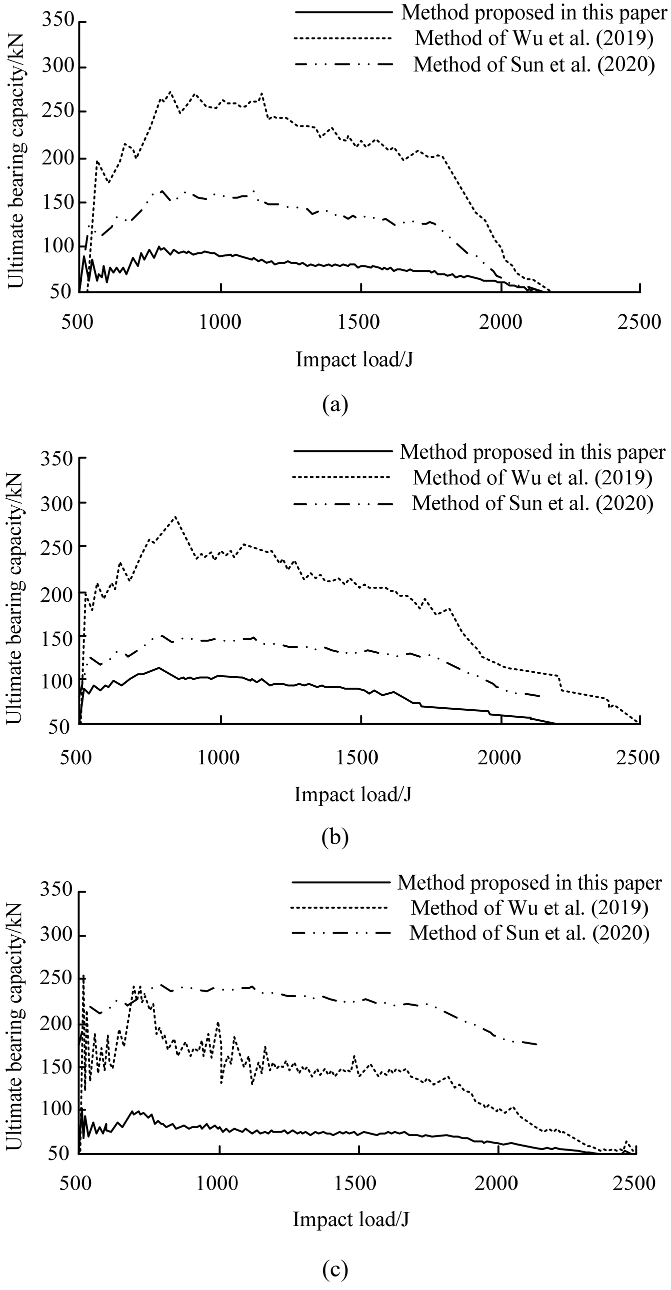
(a)

(b)

(c)

It is known that when the impact load reaches a certain value, the maximum measured value of the ultimate fatigue of the specimen is obtained. The ultimate fatigue test results of normal specimens of metal material A under different impact loads are shown in Figure 4.

**Figure 5** Ultimate fatigue test results of deformed specimens under different impact loads, (a) ultimate fatigue test results under 1,000 J impact load (b) ultimate fatigue test results under 1,500 J impact load (c) ultimate fatigue test results under 2,000 J impact load



According to the test results in Figure 4, the bearing capacity measurement results of the experimental group and the control group are highly similar, indicating that the accuracy of the two measurement techniques is guaranteed. The ultimate fatigue of metal specimens was measured by the two measurement techniques when the impact loads were 934 J, 1,432 J and 1,925 J, respectively. When the impact load increases, because the ultimate fatigue of the metal material specimen exceeds the maximum value, the performance of the metal material specimen decreases, so the value of ultimate fatigue becomes smaller and smaller until the metal material specimen completely loses its service performance and the ultimate fatigue decreases to 0.

It is known that the deformation problem of metal material specimen B has occurred, so its ultimate fatigue has been greatly reduced. Then take metal material B as the experimental test condition to test the ultimate fatigue of the deformed metal specimen under the same impact load. The ultimate fatigue test results of deformed specimens of metal material B under different impact loads are shown in Figure 5.

According to the limit fatigue test results in Figure 5, it is found that the limit fatigue measurement values obtained by the control group measurement technology are highly similar to the test results in the previous stage. The bearing capacity measurement curve measured by the experimental group technology decreased significantly, which is the same as the basic situation of deformed specimens B-1 and B-2. Based on the above test results, it can be seen that the measurement technology in this study has higher accuracy, and the basic properties of metal materials can be identified from the initial stage of measurement.

According to the above limit fatigue test results of deformed specimens, taking the accuracy of maximum load test and the effectiveness of steel material strength prediction results as experimental comparison indexes, this method is compared with Wu et al. (2019) and Sun et al. (2020).

### *3.3 Maximum load test accuracy*

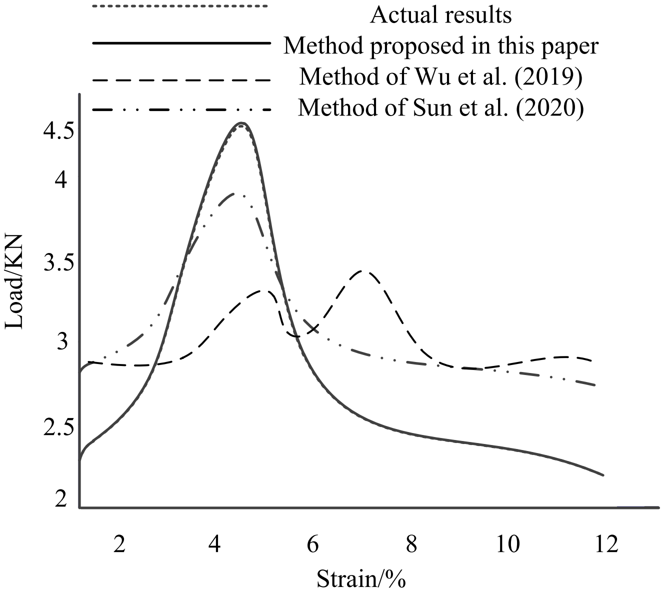
The maximum load of steel specimen is tested by this method, Wu et al. (2019) method and Sun et al. (2020) method respectively, and the actual maximum load of steel specimen is compared with the calculation results of traditional method. The comparison results of maximum load test accuracy of steel materials under different methods are shown in Figure 6.

It can be concluded from Figure 6 that the maximum load of steel specimen calculated by this method is consistent with the actual maximum load of steel specimen, which is mainly because when designing this method, the calculation model of mechanical characteristics of metal materials based on impact load is constructed, and the damage fatigue degree of metal test materials is calculated by yield moment. Therefore, the accuracy of the prediction model in this paper to calculate the maximum strength load of steel materials under fatigue load is guaranteed.

### *3.4 Comparison of effectiveness of strength prediction results of steel materials*

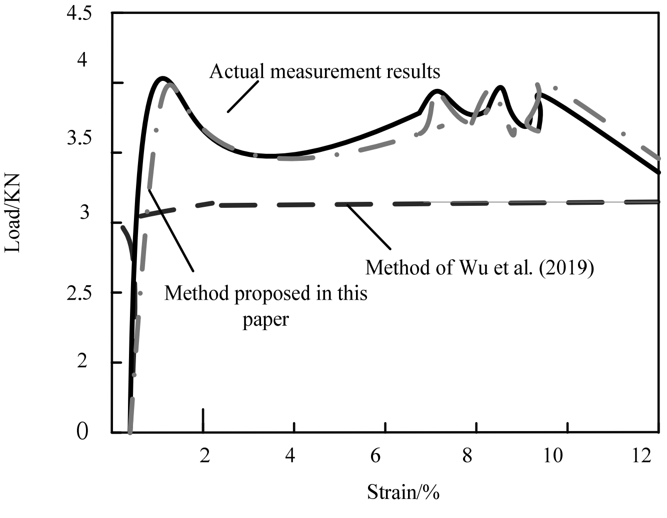
The strength of steel material under fatigue load is tested by this method, Wu et al. (2019) method and Sun et al. (2020) method, respectively, and the actual measured strength of steel material under fatigue load is compared with the predicted strength results of the other two methods. The comparison results of fatigue test results of steel materials with different methods are shown in Figure 7.

**Figure 6** Comparison of maximum load test accuracy of steel materials under different methods



According to Figure 7, the method in this paper has good fatigue prediction effect of steel materials. This is because the influencing factors of ultimate fatigue of metal materials are extracted based on the calculation model of mechanical characteristics of metal materials based on impact load, so as to ensure the data validity of strength prediction of steel materials under fatigue load.

**Figure 7** Comparison of fatigue test results of steel materials with different methods



## 4 Conclusions

In order to solve the defect that the existing damage fatigue test methods for metal materials of rotating machinery cannot accurately test the compression and shear properties of materials, a damage fatigue test method for metal materials of rotating machinery is proposed. The performance of the method is verified from both theory and experiment. The test results verify that the proposed method can test the performance change of steel under cyclic load tension. When the number of load tension increases, the performance change is obvious, and the fatigue surface is uneven. The experimental results show that the maximum load test results of the proposed method are basically consistent with the actual results, close to 100%, and this method can accurately predict the life and strength of steel under damage, which provides a reliable basis for related fields.

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