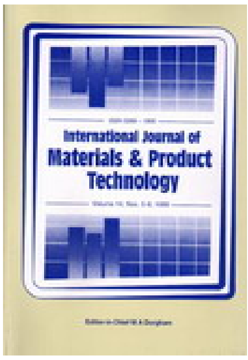

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Fatigue life estimation of metal materials based on finite element analysis

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Abstract: The fatigue life of metal materials determines the application performance of metal materials. A fatigue life estimation method of metal materials based on finite element analysis is proposed. The finite element model of metal materials is constructed through the steps of material property setting, mesh generation, etc. The influence mechanism of stress concentration degree, metal material size, and other factors is analysed; the fatigue damage evolution process of metal materials is simulated using a finite element model; the cyclic stress-strain characteristics of metal materials are extracted; the current fatigue damage accumulation state of metal materials is identified; and the estimation results of fatigue life of metal materials are obtained from two aspects of crack formation life and crack growth life. The experimental results show that the estimation error of this method is reduced by about 9.17 h, and the running speed is significantly improved.

Keywords: finite element analysis; metal materials; fatigue life estimation; cyclic stress-strain characteristics; crack formation life; crack growth life.

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1 Introduction

Metallic materials refer to those materials that are shiny, plastic, conductive and thermal conductive. They are mainly divided into three types, namely, ferrous metal, non-ferrous metal and special metal materials. Ferrous metals are mainly steel materials, while nonferrous metals refer to all metals and their alloys except iron, chromium and manganese. Special metal materials can be divided into two categories: structural and functional. These materials include amorphous metal, including quasicrystals, microcrystals, nanocrystals, etc. (Liu and Chen, 2022). The metal product industry is mainly engaged in construction metal products, metal tools, containers and packaging containers, stainless steel and similar daily metal products, as well as shipbuilding and ocean engineering. With the progress of society and the development of science and technology, metal materials have been used more and more in industry, agriculture and people's life. Metal products work under alternating loads in the actual application process, and fatigue of metal materials occurs under the action of long-term repeated stress. When fatigue accumulates to a certain amount, it will directly affect the service life of metal materials. Therefore, it is necessary to estimate the fatigue life of metal materials.

Generally, the greater the pressure, the shorter the life of the metal material. In order to ensure the application safety of metal products, it is necessary to estimate the fatigue life of the metal materials used to produce metal products, select the optimal metal materials, and timely repair and replace the metal products in the late life. At present, the more mature methods for estimating the fatigue life of metal materials mainly include: the method for estimating the fatigue life of metal materials based on strength degradation, the method for estimating the fatigue life of metal materials based on infrared thermal imaging, and the method for estimating the fatigue life of metal materials based on quantitative pre corrosion damage analysis. However, most of the above methods are only for one metal material, when it is applied to the estimation of fatigue life of various metal materials, there are obvious problems such as large estimation errors.

Fatigue is one of the common causes of metal material failure. Understanding the fatigue life of metal materials can help predict and prevent material failure during use, thereby ensuring the safety of engineering structures, equipment, or products. Finite element analysis can simulate the stress and strain situations of metal materials under actual working conditions, including complex load histories and stress fluctuations. Compared to traditional experimental methods, finite element analysis has stronger flexibility and controllability, and can more realistically and accurately reproduce the fatigue performance of metal materials in practical use. So this article proposes a fatigue life estimation method of metal materials based on finite element analysis. This method provides a flexible, accurate, and controllable method to study and optimise the fatigue performance of metal materials, providing important technical means for engineering practice and material science fields. The main research content is as follows:

1 Construct a finite element model of metal materials through steps such as setting material properties and meshing. Analyse the influence mechanism of factors such as stress concentration and metal material size.

2 Based on the analysis of the impact mechanism, a finite element model is used to simulate the fatigue damage evolution process of metal materials, extract the cyclic stress-strain characteristics of metal materials, identify the current cumulative state of fatigue damage of metal materials, and estimate the fatigue life of metal materials from two aspects: crack formation life and crack propagation life.

3 The effectiveness of this method was thoroughly verified through experiments.

2 Fatigue life estimation method of metal materials

The finite element model corresponding to the metal material is constructed, under which the fatigue evolution process of the metal material is analysed. Combined with the stress and strain properties of the current metal material, the corresponding life stage of the current metal material is determined. By analysing the influencing factors of the metal material fatigue, the fatigue life estimation results are obtained. Figure 1 shows the basic operation process of the fatigue life estimation method of optimised design metal materials.

In the process of fatigue life estimation of metal materials, it is necessary to comprehensively consider the material properties, material loads and other factors, and obtain accurate fatigue life estimation results from two aspects of crack formation life and crack growth life.

2.1 Construction of metal material finite element model

Construct a finite element model of metal materials through steps such as setting material properties and meshing. Compared with other types of finite element models, constructing finite element models for metal materials has the following advantages and characteristics:

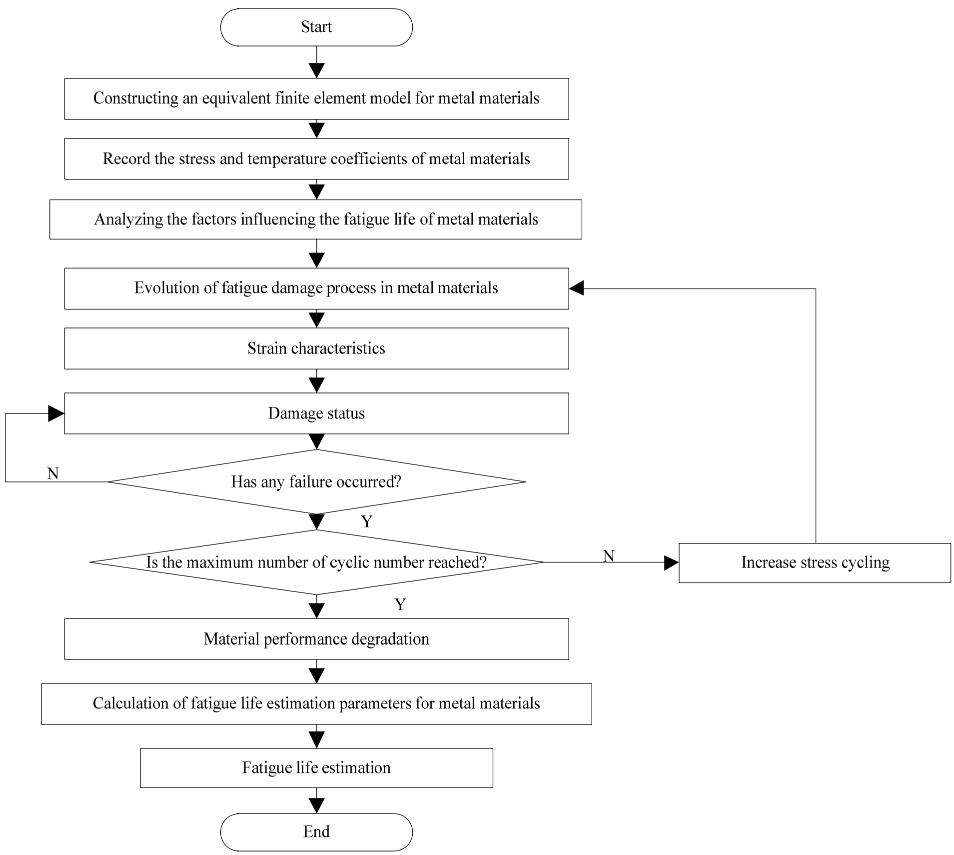
1 Material property settings: the mechanical properties of metal materials can usually be obtained through experimental testing to obtain accurate material parameters, such as elastic modulus, yield strength, etc. Therefore, when constructing a finite element model of metal materials, real material properties can be used as inputs to more accurately simulate the behaviour of metal materials under different stress conditions.

2 Grid division: metal materials have typical continuity and uniformity, and can be divided through regular or automatically generated grids, and refined as needed. Compared to other types of finite element models, the mesh division of metal materials is relatively simple, easy to understand and operate, and can ensure the accuracy and stability of the calculation results.

3 Fatigue life estimation: the specific fatigue life assessment of metal materials is an important engineering requirement. The finite element model can estimate the fatigue life of metal materials by utilising their actual stress-strain distribution. By combining experimental data and simulation results, it is possible to better analyse the fatigue performance of metal materials under cyclic loading and conduct reliable life estimation.

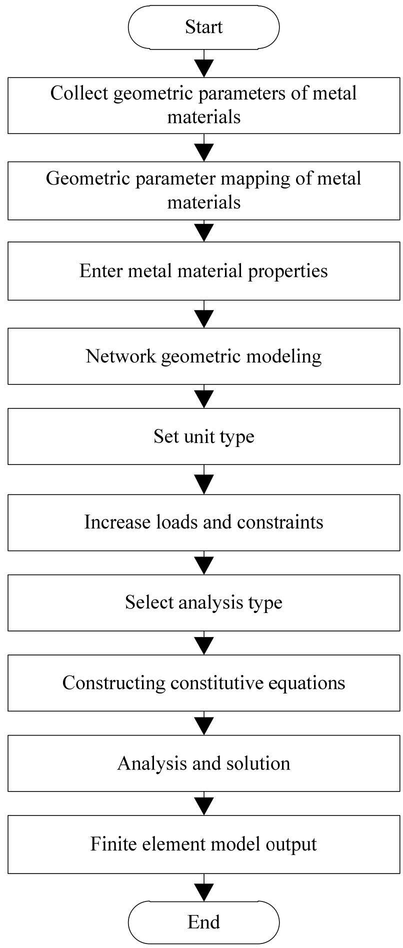
In summary, constructing a finite element model of metal materials has advantages in material attribute settings and mesh generation, which can more accurately simulate the mechanical behaviour and fatigue life of metal materials.

Figure 1 Flowchart of metal material fatigue life estimation



The basic idea of finite element method is to decompose a continuous problem into a finite set composed of several elements, and connect them according to a certain rule. The field function (Pei and Wang, 2022) to be solved in the whole solution area is determined by piecewise expression of the assumed approximation function in each element. The field function values in each element are obtained by interpolation method, and then the field function values in the whole region are obtained. The construction process of metal material finite element model is shown in Figure 2.

Figure 2 Flowchart of metal material finite element model construction



In the process of building the finite element model, it is necessary to determine the geometric characteristics of the object, obtain the geometric data of the actual metal materials, and obtain the corresponding physical model through mapping. The discretisation of metal material objects is to assume that a continuous elastic body is decomposed into several finite size elements, which are connected by hinges only at specific joint points. The boundary of the mesh is discretised. At the original boundary, the displacement at the boundary and the constraint conditions of each node at the discrete boundary are replaced by the displacement and boundary conditions at the original boundary. The discretisation method is used to decompose the original continuous system into a set of finite elements (Burghardt et al., 2021) connected only with nodes. The displacement of any point in the metal material can be expressed by the displacement of the node:

$$\Delta x = [W]\{s\}^e \tag{1}$$

In formula (1), $[W]$ and $\{s\}^e$ represent the node displacement of the shape function matrix and element respectively. According to the properties of metal materials, set the constitutive relationship of materials in the finite element model, and the specific setting results are as follows:

$$\varepsilon = \frac{\vartheta}{E} + \left(\frac{\vartheta}{K}\right)^{\tau} \tag{2}$$

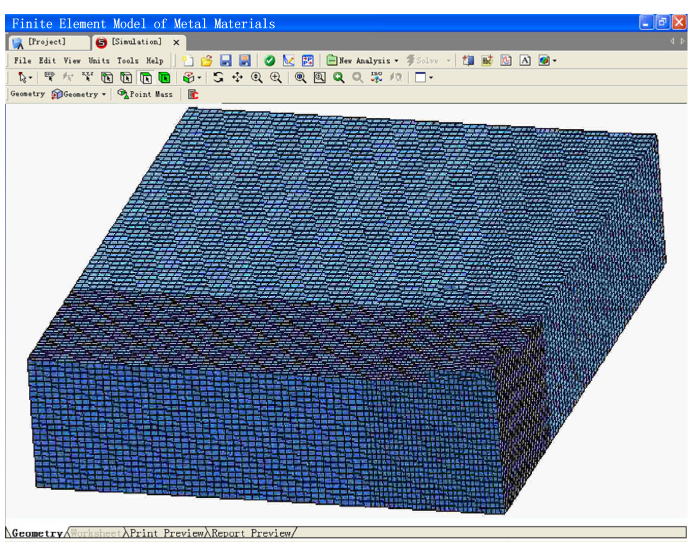
In formula (2), E is the cyclic strength coefficient, K is the cyclic strain hardening index, ϑ is the yield strength, τ represents the elastic coefficient of metal material. The element strain is determined using the geometric equation of elasticity:

$$B = [A_{strain}] \cdot \varepsilon \cdot \Delta x \tag{3}$$

In formula (3), A_{strain} represents the unit strain loss.

Substitute the calculation results of formulas (1) and (2) into formula (3) to obtain the element strain of each node in the metal material. During the evolution of fatigue damage process of actual metal materials, the fatigue damage and displacement of materials are reflected according to the displacement of metal materials. The displacement finite element method takes the node displacement as an unknown number and the node displacement as an unknown number. In the finite element analysis, the initially constructed finite element model is meshed. The number of meshes directly affects the accuracy of the numerical solution and the calculation scale (Hong et al., 2021). These two aspects need to be considered comprehensively in the process of selecting the number of grids. In order to ensure the accuracy of the calculation, the size of the unit needs to be controlled at about 4 mm. Grid density refers to dividing different grids into different sizes according to the distribution characteristics of the calculation data. The results of metal material finite element model construction are shown in Figure 3.

Figure 3 Construction results of metal material finite element model (see online version for colours)



2.2 Factors affecting fatigue life of metal materials

Based on the above finite element model, the influence mechanism of stress concentration degree, metal material size and other factors is analysed, so as to lay a solid foundation for subsequent analysis.

Factors affecting the fatigue life of metal materials include: stress concentration degree, metal material size, load condition, service temperature, etc. The calculation formula of stress concentration degree coefficient is as follows:

$$\gamma_{Stress\ concentration} = \frac{F_{\max}}{F_{theory}} \tag{4}$$

In formula (4), $F_{\max}$ and F_{theory} respectively represent the maximum local stress and theoretical stress value (Azar et al., 2021) at the stress concentration position in the metal material. The influence relationship between stress concentration degree coefficient and fatigue life is as follows:

$$Q = \frac{1}{\gamma_{Stress\ concentration}} \cdot F \tag{5}$$

In formula (5), F is the stress value (Lei et al., 2022) applied on the metal material. The relationship between the size coefficient of metal material workpiece and its influence on the fatigue life of metal material can be expressed as:

$$\begin{cases} \gamma_{size} = \dfrac{u_{gap}}{u_{s\tan dard}} \\ Q = \dfrac{1}{\gamma_{size}} \cdot F \end{cases} \tag{6}$$

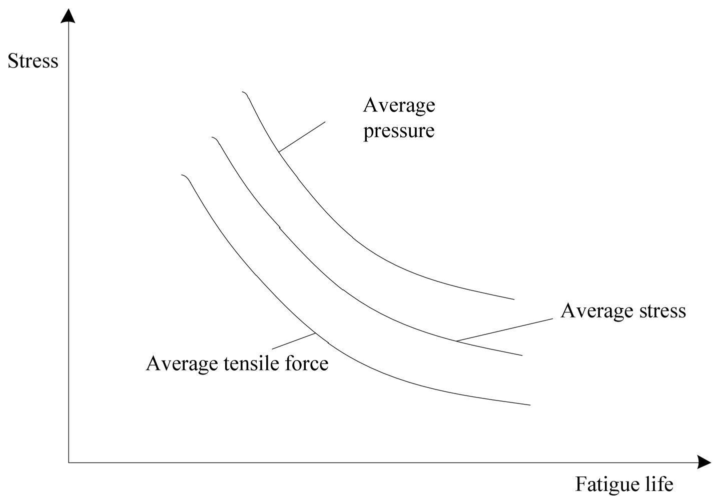
In formula (6), γ_{size} is the size coefficient of the metal material workpiece, u_{gap} and $u_{standard}$ indicate the fatigue limit of notched specimen and standard specimen respectively. The influence factors of load state on fatigue life include: loading frequency, average stress, etc. (Jang and Khonsari, 2021). The influence of average stress on fatigue life is shown in Figure 4.

The equivalent symmetrical cyclic stress amplitude is calculated as follows:

$$\begin{cases} A = \beta_{pressure} + \omega\beta_{pulling} \\ \omega = \dfrac{\alpha_{limit}}{F_{fracture}} \\ F_{fracture} = q_{limit} + 300 \end{cases} \tag{7}$$

In formula (7), variables $\beta_{pressure}$ and $\beta_{pulling}$ are the pressure and tension values applied to the metal material, α_{limit} is the fatigue limit of the material, $F_{fracture}$ is the true fracture stress, q_{limit} is the strength limit of metal materials. According to the above way, the influence mechanism of other factors on the fatigue life of metal materials can be obtained.

Figure 4 Schematic diagram of the effect of average stress on fatigue life

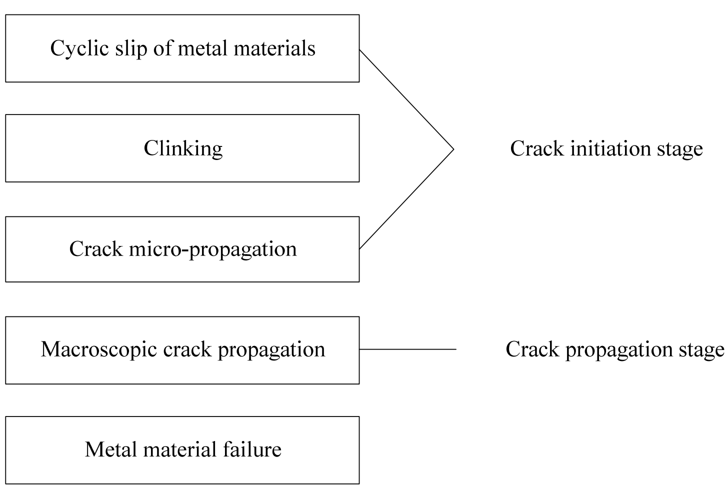


2.3 Evolution of fatigue damage process of metal materials based on finite element analysis

Combined with the analysis results of influencing factors, the finite element model is used to simulate the fatigue damage evolution process of metal materials, so as to lay a solid foundation for the subsequent extraction of stress-strain characteristics.

Through the coupling of temperature field and stress field of metal materials, the fatigue damage evolution process of metal materials (Wang and Geng, 2022) was simulated with the finite element model as the research object. The fatigue damage evolution stage of metal materials is shown in Figure 5.

Figure 5 Fatigue damage evolution stage of metal materials

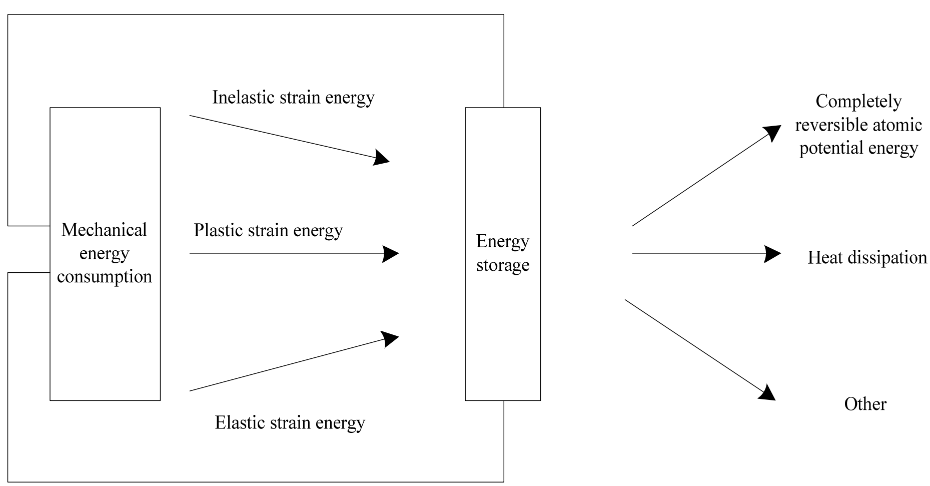


The metal material structure is deformed due to heating. When the deformation is limited by its physical structure by many factors, it cannot produce obvious deformation, but there is a trend of deformation. At this time, the generated force is thermal stress (Nashed et al., 2022). Thermal stress passes through three forms of conduction, convection and radiation. In metal materials, different fluids with different temperatures will generate heat transfer during mutual movement. Thermal radiation refers to the process of heat exchange between objects through electromagnetic energy. The processes of heat conduction, heat convection and heat radiation inside metal materials can be expressed as:

$$\begin{cases} \rho = -k_{heat\ conduction}\left(\dfrac{dT}{dx}\right) \\ y_{burial} = k_{heat\ transfer}\left(T_{solid} - T_{environment}\right) \\ \mu_{Heat\ flux} = \mu_{radiation} S_{radiation} k_{shape} T_{solid} \end{cases} \tag{8}$$

where $k_{heat\ conduction}$ is the thermal conductivity of the metal material, ρ is the heat flux around the metal material, y_{burial} is the Newton cooling equation satisfied by thermal convection, $k_{heat\ transfer}$ is the convective heat transfer coefficient, T_{solid} and $T_{environment}$ respectively corresponding to the surface temperature of metal materials and ambient temperature, $\mu_{Heat\ flux}$ and $\mu_{radiation}$ are heat flux and emissivity, $S_{radiation}$ is the radiation surface area, k_{shape} is the shape coefficient of the thermal radiation surface, that is, the metal material surface (Hattingh et al., 2022). In the case of considering the stress field, the energy dissipated by the metal material in the form of heat cannot be spontaneously transformed into useful mechanical work in the process of cyclic loading. Figure 6 shows the energy consumption structure in the fatigue damage process of metal materials.

Figure 6 Schematic diagram of energy consumption structure of metal material during fatigue damage process



Mechanical energy consumption mainly consists of elastic deformation, plastic deformation and anelastic internal friction. The elastic strain energy only reflects the instantaneous recovery deformation of the material lattice, and does not affect the damage. Considering the hysteresis characteristics of the material, it has conditional reversible characteristics. Under the condition of high cycle fatigue, the static elastic internal friction effect of materials is the main factor affecting their fatigue damage (Omrani et al., 2021). Under the low cycle fatigue load, the microstructure of the material will appear irreversible distortion, which will transform it into large-scale plasticity, and plastic deformation will lead to the change of the microstructure of the material. This project focuses on the law of low cycle fatigue energy consumption of metal materials, in which plastic deformation energy is an important factor leading to low cycle fatigue damage of metal materials. The deformation energy is consumed in a variety of ways, most of which are in the form of heat energy, a few in the form of sound energy, and some in other ways. The other is stored by the change of material microstructure (Jian et al., 2022). The total failure energy consumption during fatigue damage of metal materials can be expressed as:

$$Z = C + R + Z_{kinetic\ energy} + Z_{other} \tag{9}$$

Among C and R are respectively the total stored energy and heat dissipation energy of metal materials, $Z_{kinetic\ energy}$ and Z_{other} are respectively kinetic energy of metal materials and other forms of energy consumption under cyclic load. Under the synergetic effect of stress load, temperature and energy consumption, metal materials generate cracks of different degrees, thus completing the evolution of metal material fatigue damage process.

2.4 Extraction of cyclic stress-strain characteristics of metal materials

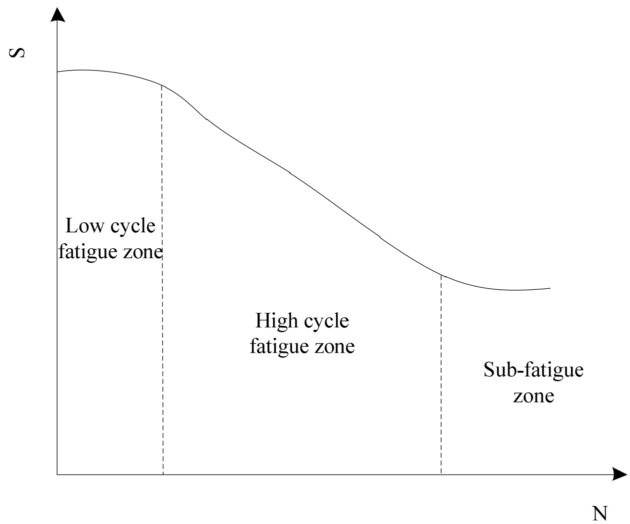
Extract the cyclic stress-strain characteristics of metal materials based on the evolution analysis results of fatigue damage process. The innovation in extracting the cyclic stress-strain characteristics of metal materials lies in the use of innovative experimental design and measurement techniques. Through analysis and simulation, the behaviour patterns of metal materials under cyclic loading are revealed, and influencing factors are explored to provide a deep understanding and accurate prediction of the cyclic behaviour of metal materials. The S-N curve of metal materials reflects the cyclic stress-strain characteristics of the material. The S-N curve refers to the relationship between the external load and fatigue life of the material, and is a performance curve for predicting the fatigue life and fatigue strength of metal materials (Sanaei and Fatemi, 2021), as shown in Figure 7.

The S-N curve of metal materials can be expressed in the form of exponential function, and the function expression is as follows:

$$\lg N = a + bS \tag{10}$$

Among a and b all are metal material coefficients, S represents the stress-strain parameters. According to the above method, the extraction results of the stress-strain characteristics of metal materials can be obtained, that is, the change law of fatigue damage of metal materials.

Figure 7 Cyclic stress strain characteristic curve of metallic materials



2.5 Identify the current cumulative state of fatigue damage of metal materials

The cumulative state of fatigue damage of current metal materials is identified according to the extraction results of cyclic stress-strain characteristics of metal materials. Fatigue damage is a comprehensive parameter, which includes a variety of damages in materials. The damage variable in the continuous damage mechanics of metal materials can be quantified as:

$$\gamma_{damage} = \frac{V_{damage}}{V_{refer\ to}} \tag{11}$$

In the above formula, V_{damage} and $V_{refer\ to}$ respectively represent the volume of the damaged part in the metal material and the total volume of the metal material. The metal material consists of the damaged part and the undamaged part. Assuming that the material of the damaged part has no bearing capacity, according to the volume distribution rate, the equivalent Young's modulus of the metal material can be obtained as follows:

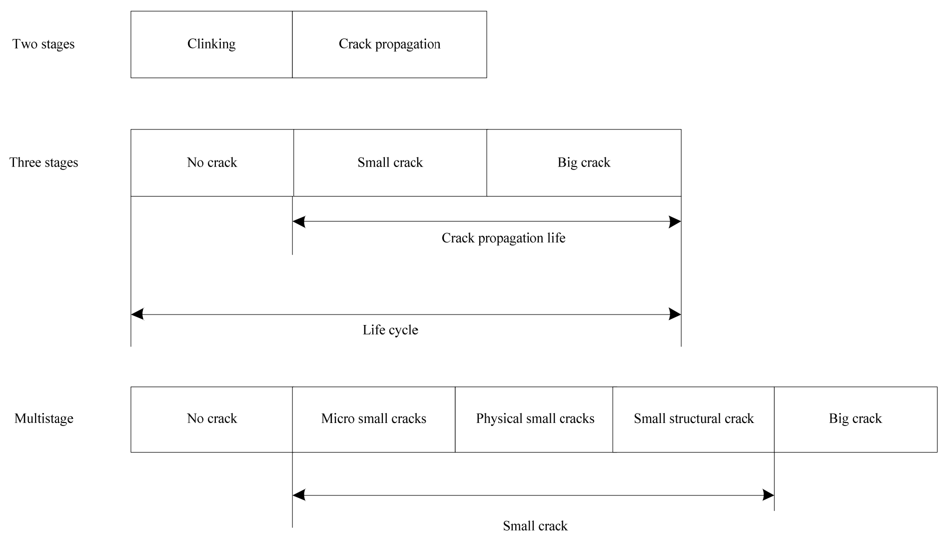
$$\sigma = E(1 - \gamma_{damage}) \tag{12}$$

After the introduction of equivalent stress, the amount of deformation of the material or the amount of strain in the undamaged state can be calculated without considering the degradation of the material constant (Tchemodanova et al., 2021). By solving the equivalent Young's modulus of metal materials, the identification results of the current cumulative state of fatigue damage of metal materials are obtained.

2.6 Realise fatigue life estimation of metal materials

This article uses a finite element model to simulate the fatigue damage evolution process of metal materials, extract the cyclic stress-strain characteristics of metal materials, identify the current cumulative state of fatigue damage of metal materials, and obtain the estimation results of metal material fatigue life from two aspects: crack formation life and crack propagation life. This can effectively improve the accuracy of metal material fatigue life estimation. Under the finite element model of metal materials, comprehensive consideration of stress, strain, temperature field and other factors, combined with the influence mechanism of factors affecting the fatigue of metal materials, the estimation results of current fatigue life of metal materials (Al-Karawi, 2021) are obtained. Figure 8 shows the fatigue life diagram of metal materials.

Figure 8 Schematic diagram of fatigue life of metal materials



In the actual process of estimating the fatigue life of metal materials, the properties, geometric dimensions, boundary conditions, stress calculations, specified periods, etc. of metal materials are read from the finite element model. On this basis, the maximum and minimum stresses of different composite components in different axes are analysed by using the finite element method. The fatigue failure criteria are used to judge the failure of each laminated plate unit. If there is no failure, judge whether the specified maximum number of cycles has been reached. If so, take the specified maximum number of cycles as its fatigue life and stop the program. If the requirements cannot be met, the hardness, strength and other indicators of the material shall be degraded by the gradual degradation method, and on this basis, the cycle amount shall be increased to continue the next cycle (Muhammad et al., 2021). If a component in the laminate fails, the parameter of the failed component will be degraded by using the material mutation degradation method to judge whether the hole edge structure of the laminate is completely damaged; if the hole edge structure of the laminated plate is not completely damaged, repeat the above cycle again, and continue to judge whether there is any new component failure, until the end of this cycle, add another cycle to reduce the residual stiffness and residual strength of the composite component again, so as to carry out the next cycle; when it is judged that the hole edge structure of the laminated plate has been completely damaged, the current cycle times are taken as the fatigue life of the hole edge of the laminated plate, and the calculation is terminated (Larsen et al., 2021). The fatigue life estimation results of metal materials are obtained from two aspects of crack formation life and crack growth life. The estimation results can be expressed as:

$$T_{tired} = T_{form} + T_{form} \tag{13}$$

Among, T_{form} and T_{form} are the estimation results of crack initiation life and crack propagation life are shown respectively. The estimation formula of the above variables is as follows:

$$\begin{cases} T_{form} = \sum_{i=1}^{m} T_i \\ T_{form} = \int_0^{l_{Instability}} \dfrac{dl_{Instability}}{k_{material} k_{toughness}} \end{cases} \tag{14}$$

In the above formula, T_i is the fatigue life of the metal material within the i^{th} characteristic length, m is the number of feature lengths, $l_{Instability}$ is the critical buckling length, $k_{material}$ and $k_{toughness}$ are correspond to the crack growth rate coefficient and fracture toughness coefficient (Lacombe et al., 2021) of metal materials respectively. Finally, the estimation result of formula (14) is substituted into formula (13) to get the final estimation result of fatigue life of metal materials (Alshareef et al., 2022; Kumar et al., 2022).

3 Experimental analysis

3.1 Experimental scheme

In order to test the estimation performance of the fatigue life estimation method of metal materials based on finite element analysis, performance test experiments are designed. The quantitative test results of performance are obtained through the calculation of the estimated performance test indicators. By comparing with the traditional estimation methods, the advantages of the optimal design method in estimating performance are reflected. The main factors affecting the estimation of fatigue life of metal materials include the following:

1 Loading conditions: the loading method, amplitude, frequency, and load ratio have a significant impact on the fatigue life of metal materials. Different load conditions can lead to different strength, plastic strain, and fracture behaviour, thereby affecting fatigue performance.

2 Material properties: the microstructure, grain size, grain boundary characteristics, alloy composition, and hardening mechanism of metal materials can all affect their fatigue behaviour. The fatigue life of different materials varies greatly.

3 Surface and defects: surface processing and defects such as cracks, internal pores, particle inclusions, etc. can serve as fatigue initiation points or propagation paths, significantly affecting fatigue life.

4 Environmental factors: environmental temperature, humidity, corrosive media, and atmosphere also have an impact on the fatigue life of metal materials. Some environmental factors such as corrosion and hydrogen embrittlement can increase the fatigue sensitivity of materials.

To improve the accuracy of experimental results, the following measures can be taken:

1 Control sample preparation: ensure that the preparation quality and size of the sample meet the requirements, and avoid the impact of factors such as strategy and thermal effects on the performance of the sample.

2 Accurate measurement data: advanced measurement equipment and technology are used to accurately measure key parameters such as stress, strain, load, and displacement, improving the reliability of experimental data.

3 Multiple data validation: verify the consistency and stability of experimental results through repeated experiments or testing under different load conditions, and increase the credibility of the data.

4 Calibration and comparison: compare with known fatigue life data, calibrate experimental results, in order to better evaluate and predict the fatigue life of metal materials.

By implementing the above measures, the accuracy and reliability of experimental results can be improved, providing more accurate data and prediction for the fatigue life estimation of metal materials.

In order to ensure the reliability of the experimental results, ten groups of experiments are set up in this experiment. The metal materials estimated by each group are different. The initial data of the metal material workpiece is set by means of corrosion, notch setting, etc. According to the setting of the initial state of the material, combined with the setting of the temperature field and stress field, the theoretical value of the fatigue life of the metal material is determined. That is, the comparison standard data of fatigue life estimation accuracy. In order to reflect the advantages of the optimisation design method in estimating performance, three traditional material fatigue life estimation methods are set as the comparison methods of experiments, and the optimisation design algorithm method and three experimental comparison methods are simultaneously executed to obtain the corresponding metal material workpiece fatigue life estimation results. Through the comparison with the set theoretical value, the relevant estimation results are obtained.

This experiment tests the estimation accuracy and the operation performance of the estimation method. The test index of the estimation accuracy is the estimation error, and the numerical result of this index is:

$$\varepsilon = T_{tired} - T_{set} \tag{15}$$

Among T_{set} is to set the fatigue life of metal materials, the larger the estimation error of the fatigue life of metal materials calculated, the better the estimation accuracy of the corresponding method. In addition, the test index of the operation performance of the estimation method is set as the estimation speed, and the test results of this index are as follows:

$$v = \frac{n_{task}}{\Delta t} \tag{16}$$

In the above formula, n_{task} is the estimated task amount of fatigue life of metal materials, Δt is to estimate the execution time of the task. It is calculated that the larger the estimated rate index value is, the better the operation performance of the corresponding method is.

3.2 Experimental analysis

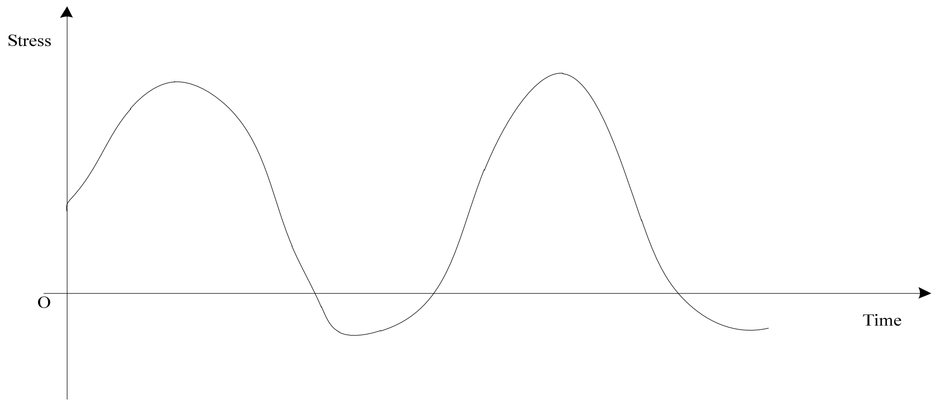
The basic structure and fatigue life settings of the initially prepared metal material workpiece are shown in Table 1.

Table 1 Metal material workpiece structure and fatigue life setting table

Workpiece number	*Metallic material*	*Workpiece length (mm)*	*Workpiece width (mm)*	*Workpiece thickness (mm)*	*Crack formation life (h)*	*Crack propagation life (h)*	*Fatigue life (h)*
1	Copper alloy	235	180	20	1,680	1,150	2,830
2	Iron	185	160	40	2,050	1,580	3,630
3	Aluminium alloy	220	170	30	1,870	1,740	3,610
4	Gold copper	245	185	25	2,320	2,010	4,330
5	Stainless steel	180	175	35	2,560	1,840	4,400
6	Magnesium alloy	190	200	40	1,970	1,960	3,930
7	Titanium	200	195	30	2,025	1,430	3,455
8	Red copper	210	190	20	2,280	1,520	3,800
9	A3 steel	225	165	35	2,170	2,105	4,275
10	40 chromium	255	180	25	1,960	2,070	4,030

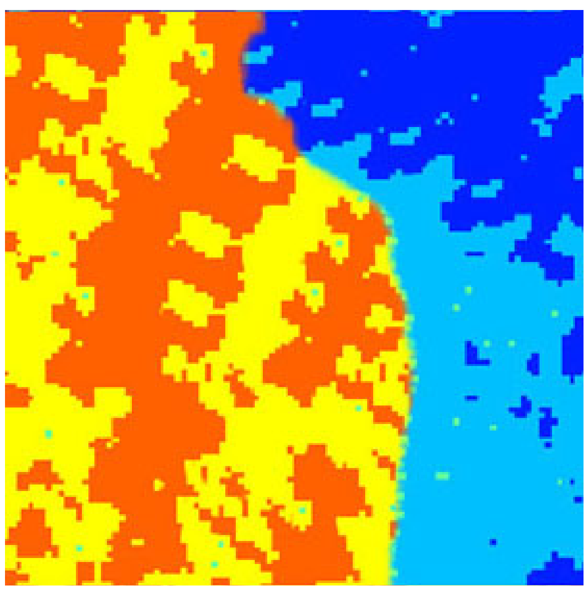
The electro-hydraulic servo fatigue testing machine is selected as the hardware support. The maximum load of the testing machine is ±300 KN, and the maximum displacement is ±80 mm. The main body of the host is composed of a complex frame, a servo actuator, a servo valve, a sensor and a hydraulic control system of the host. It can conduct fatigue tests such as tensile and torsional tests on samples. Place the prepared metal material workpiece on the operating platform, and use the pressure equipment to apply the corresponding stress. Figure 9 shows the cycle of stress application.

Figure 9 Waveform diagram of stress field setting of metal material workpiece



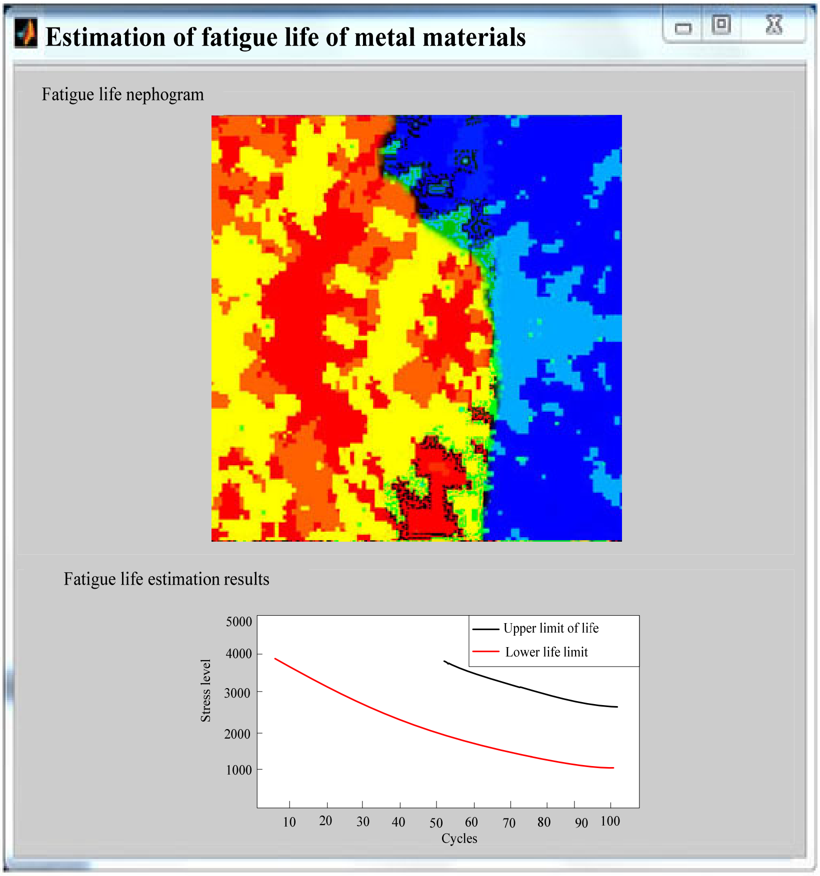
Set the temperature field of the metal material workpiece according to the above method, and the setting result is shown in Figure 10.

Figure 10 Schematic diagram of temperature field setting of metal material workpiece



Under the established finite element model, through the steps of fatigue process evolution and damage state identification, the estimation results of metal material fatigue life are obtained. Figure 11 shows the estimated output result of fatigue life of no. 1 metal material workpiece.

Figure 11 Fatigue life estimation results of metal material workpieces



Similarly, the fatigue life estimation results of all metal material workpieces set in the experiment can be obtained. The comparative estimation methods set up in this experiment specifically include: the fatigue life estimation method of metal materials based on strength degradation, the fatigue life estimation method of metal materials based on infrared thermography, and the fatigue life estimation method of metal materials based on quantitative pre corrosion damage analysis. Repeat the above operations to obtain the fatigue life estimation results output by the comparative method. Through the statistics of relevant data, the test results reflecting the precision performance of fatigue life estimation of metal materials by the above methods are obtained, as shown in Table 2.

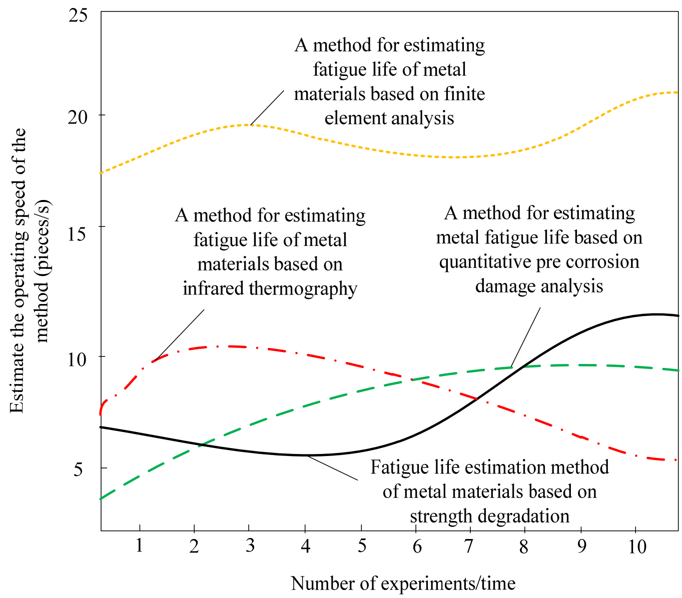
Through the calculation of formula (13), the total estimation results of the fatigue life of metal materials output by four estimation methods are obtained. The total estimation results and the data in Table 1 are substituted into formula (16), and the average estimation error sum of the three estimation methods is calculated to be 17 h, 14 h and 10 h, respectively. However, the average estimation error of the metal material fatigue life estimation method based on finite element analysis in the optimised design is 4.5 h, The reason for the low average estimation error of this method is that it uses a finite element model to simulate the fatigue damage evolution process of metal materials, extract the cyclic stress-strain characteristics of metal materials, identify the current cumulative state of fatigue damage of metal materials, and obtain the estimation results of fatigue life of metal materials from two aspects: crack formation life and crack propagation life.

Table 2 Data sheet of metal material fatigue life estimation accuracy performance test

Workpiece number	*Fatigue life estimation method of metal materials based on strength degradation*		*A method for estimating fatigue life of metal materials based on infrared thermography*	
	Crack formation life (h)	*Crack propagation life (h)*	*Crack formation life (h)*	*Crack propagation life +(h)*
1	1,695	1,120	1,690	1,125
2	2,070	1,560	2,065	1,565
3	1,835	1,710	1,845	1,715
4	2,300	2,025	2,305	2,020
5	2,575	1,825	2,570	1,830
6	1,995	1,935	1,990	1,940
7	2,060	1,410	2,055	1,415
8	2,295	1,530	2,290	1,525
9	2,185	2,125	2,185	2,120
10	1,975	2,045	1,970	2,050
Workpiece number	*A method for estimating metal fatigue life based on quantitative pre corrosion damage analysis*		*A method for estimating fatigue life of metal materials based on finite element analysis*	
	Crack formation life (h)	*Crack propagation life (h)*	*Crack formation life (h)*	*Crack propagation life (h)*
1	1,685	1,130	1,680	1,155
2	2,055	1,570	2,055	1,580
3	1,855	1,725	1,870	1,740
4	2,310	2,015	2,315	2,005
5	2,565	1,835	2,560	1,840
6	1,985	1,945	1,970	1,965
7	2,040	1,420	2,020	1,430
8	2,285	1,505	2,280	1,515
9	2,180	2,115	2,170	2,100
10	1,965	2,055	1,955	2,070

In addition, through the calculation of formula (17), the test results of four methods to estimate speed are obtained, as shown in Figure 12.

Figure 12 Comparison curve of running speed test of metal material fatigue life estimation method (see online version for colours)



From Table 2, it can be intuitively seen that the operating speed of the fatigue life estimation method for metal materials based on strength degradation varies between 6.2 pieces/s and 12.3 pieces/s. The operation speed of the metal material fatigue life estimation method based on infrared thermal imaging varies between 6.3 pieces/s and 7.8 pieces/s. The operation speed of the metal fatigue life estimation method based on quantitative corrosion damage analysis varies between 2.5 pieces/s and 8.3 pieces/s. The operation speed of the metal material fatigue life estimation method based on finite element analysis varies between 17.4 pieces/s and 19.6 pieces/s. Compared with three traditional metal material fatigue life estimation methods, The optimisation design method runs faster and can quickly obtain accurate life estimation results. The main reason is that this method constructs a finite element model of metal materials through steps such as material attribute setting and mesh division, and uses this model to obtain relevant fatigue life results of metal materials. Therefore, this method has the advantage of high transportation speed.

4 Conclusions

Metal materials are important materials in industrial production, and their performance directly determines the performance and application value of industrial products. In this study, finite element analysis technology was used to estimate the fatigue life of metal materials. The experimental results show that the estimation error of this method is reduced by about 9.17 h, and the operating speed varies between 17.4 pieces/s and 19.6 pieces/s. It can obtain more accurate estimation results, providing effective reference for the selection of metal materials in industrial production processes. However, the number of metal material samples set up in this experiment is relatively small, and the authenticity and reliability of the obtained results have slightly decreased. Therefore, further supplementation of the experimental data is needed in future research work.

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