International Journal of Materials Science and Technology Studies
ISSN: 3006-7693 (Print), ISSN: 3006-3744 (Online) | Volume 1, Number 1, Year 2024
DOI: https://doi.org/10.62051//ijmsts.v1n1.05
Journal homepage: https://wepub.org/index.php/IJMSTS/index

The Review of Research on Fatigue Crack Propagation in Metallic Materials

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ABSTRACT

In recent years, with the development of industry and scientific technology, the demand for materials has been increasing. Fatigue crack propagation is an important issue in the field of materials, and developing relevant theories and methods, understanding the mechanisms of fatigue cracks, and making scientific predictions on fatigue crack propagation are hot topics both domestically and internationally. Fracture mechanics, as a discipline studying the strength and propagation of cracks in materials, has developed a relatively complete theoretical system and engineering application methods over more than 100 years of continuous development. This article focuses on the effects of factors such as temperature, stress ratio, and load frequency on the fatigue crack propagation characteristics of metallic materials, and summarizes the common theories and methods of fatigue crack propagation.

KEYWORDS

Fatigue crack propagation; Fracture mechanics; Temperature; Stress ratio; Frequency.

1. INTRODUCTION

Fatigue is a localised permanent damage caused by alternating stresses. It is very common both in nature and in engineering, and fatigue crack propagation is a process of cumulative damage. With the continuous deepening of the study of fatigue, people have more and more knowledge of mechanical fatigue, the mechanism or machinery made of metal and other materials, under the action of repetitive loads, the metal structure will fail, mainly fatigue damage, and 50% to 90% of the mechanical structure will have fatigue damage failure [1,2].

Therefore, an in-depth and detailed analysis of the propagation of fatigue cracks can better prevent its occurrence. In this field, there have been more in-depth theoretical discussions at home and abroad. In the past decades, fracture mechanics has been recognised as an effective and practical method to study fatigue crack propagation. With the development of modern fracture mechanics theory and the demand for engineering practice, it has been rapidly developed. This paper describes the mechanism of the influence of temperature, load-stress ratio, frequency and other factors on fatigue crack propagation of materials in recent years and their related theories and methods.

2. FATIGUE CRACK PROPAGATION MECHANISM

Fatigue crack propagation mechanism is an important process when fatigue damage occurs in metallic materials under alternating loads. Under the action of fatigue loading, changes in microstructure and physical properties occur within the metallic material, which leads to crack initiation and expansion. The rate of crack propagation accelerates with the increase in the number of load cycles, ultimately leading to material damage. Understanding the fatigue crack propagation mechanism is important for fatigue life assessment, damage analysis and material design. The fatigue crack propagation mechanism will be introduced in the following from the material mechanics level and the microscopic level.

From the level of material mechanics, the mechanism of fatigue crack propagation mainly consists of two stages: crack initiation and crack propagation. Under fatigue loading, small elastic deformation occurs on the surface of metallic materials, forming a stress concentration zone, and when the stress in the stress concentration zone reaches the fatigue strength limit of the material, microcracks are formed, and this process is called crack sprouting. Once the crack sprouts, the stress concentration effect at the crack tip will cause the formation of plastic zone, so that the crack will further expand, this process is called crack propagation. The rate of crack expansion accelerates with the increase in the number of load cycles, which ultimately leads to the destruction of the material.

From the microscopic level, the mechanism of fatigue crack propagation mainly involves the internal lattice structure and defects in metallic materials. Under fatigue loading, microscopic deformation processes such as dislocation motion, slip, and fracture occur within the metal material. These deformation processes lead to stress concentration zones within the material, thus promoting crack initiation and propagation. In addition, there are various defects in the metal material, such as inclusions, holes, etc., which will become the point of crack initiation and expansion source, accelerating the crack expansion process.

3. COMMON THEORETICAL MODELS AND RESEARCH METHODS

In recent years, the study of fatigue crack propagation behaviour of metal materials has become a hot spot in research. With the continuous progress of science and technology, some commonly used theoretical models and research methods have emerged.

Commonly used theoretical models include linear elastic fracture mechanics model [3], elastoplastic fracture mechanics model [4] and viscoplastic fracture mechanics model. Among them, the linear elastic fracture mechanics model is mainly applicable to the study of low-strength and brittle materials, such as aluminium alloy and glass. The model considers that the crack propagation is caused by the stress intensity factor ΔK at the crack tip reaching a certain value, so the value needs to be calculated in the study and is usually solved by the finite element method or semi-analytical method. The elastic-plastic fracture mechanics model is suitable for the study of high-strength, plastic materials, such as steel, copper and so on. The model mainly considers the effects of stress intensity factor ΔK and plastic deformation at the crack tip on crack propagation, and uses the criterion method to judge whether crack propagation occurs or not. The viscoplastic fracture mechanics model is an propagation of the elastic-plastic model, taking into account the viscoplastic properties of the material and the loading rate and other factors, and is suitable for fatigue crack propagation research under high-speed loading conditions.

Commonly used research methods include experiments and numerical simulations. Experimental tests are usually carried out by fatigue tests, double propagation tests, through-hole tests, etc., to analyse the behaviour and laws of fatigue crack propagation by measuring parameters such as load and crack length. Numerical simulation, on the other hand, simulates the mechanical behaviour of the material and the crack propagation process by means of numerical calculations such as finite element method and discrete element method. This method can better simulate the various stages of fatigue crack propagation, such as initiation, propagation, joint propagation, etc., and can provide more parameters and data for the verification and correction of the theoretical model.

4. FATIGUE CRACK EXPANSION RATE

Fatigue crack propagation rate refers to the change of crack length a with the increase of the number of cycles N under fatigue loading, which is an important parameter for assessing the fatigue life of materials. Understanding the fatigue crack propagation rate can help us better understand the fatigue performance of materials, and provide a basis for the design and manufacture of reliable structural materials.

The rate of fatigue crack propagation is usually expressed as da / dN, where da is the increase in crack length and dN is the increase in the number of cycles. The fatigue crack propagation rate is related to the stress intensity factor K, which is a physical quantity proportional to the crack length, proportional to the square root of the load amplitude and inversely proportional to the toughness of the material. The greater the stress intensity factor, the faster the rate of crack expansion.

ΔK is the stress intensity factor magnitude, which can be calculated using the following equation:

$$\Delta K = K_{\max} - K_{\min} = f \Delta \sigma \sqrt{\pi a} \tag{1}$$

where $\Delta \sigma$ is the load magnitude and a is the crack length.

The rate of fatigue crack propagation can usually be expressed by the Paris formula:

$$\frac{\mathrm{da}}{\mathrm{dN}} = C(\Delta K)^{\mathrm{m}} \tag{2}$$

where C, m [5] are material constants called the crack propagation rate constant and the crack propagation index of the material, which are related to the fatigue properties of the material, respectively, and m is usually between 2 and 4.

Forman's equation [6] is another formula used to describe the rate of fatigue crack propagation which takes into account the variation of fatigue crack propagation rate at high crack lengths.Forman's equation has the form:

$$\begin{gathered} \frac{\mathrm{da}}{\mathrm{dN}} = \frac{C(\Delta K)^{\mathrm{m}}}{(1-R)K_R - \Delta K} \\ R = \sigma_{\min} / \sigma_{\max} \end{gathered} \tag{3}$$

Where C and m are material constants; K_{IC} [7] is the fracture toughness; and R is the cyclic stress ratio.

In engineering applications, fatigue tests are usually used to determine the fatigue crack propagation rate of materials in practical applications, such as the commonly used rotary bending test and tightening test. By testing the fatigue crack propagation rate of a material, the fatigue life of the material can be evaluated and the crack propagation problems that may occur in the actual use of the material can be predicted.

5. FACTORS AFFECTING FATIGUE CRACK PROPAGATION BEHAVIOUR

5.1. Effect of temperature on fatigue crack propagation behaviour

For most alloy steels, aluminium-based, niobium-based, nickel-based high temperature alloys and some titanium alloys, the steady state fatigue crack propagation process is described by the Paris equation. Based on the Paris equation, Jeglic [8] derived an Arrhenius-type relation for the crack propagation rate using the activation energy:

$$\frac{\mathrm{da}}{\mathrm{dN}} = A\exp[-\frac{\mathrm{u}\left(\Delta K\right)}{RT}] \tag{4}$$

Where A is a constant, $u(\Delta K)$ is the activation energy, R is the Boltzmann constant, and T is the absolute temperature. Since then, scholars have conducted in-depth studies on the crack propagation of alloy steel, aluminium alloy, titanium alloy and other materials under temperature change.

Teng Kui [9] determined and analyzed the fatigue crack propagation rate of 6061 aluminium alloy at room temperature, high temperature 150°C and -70°C, and derived the crack propagation law at different temperatures; meanwhile, the fatigue crack propagation law of 6061 aluminium alloy at different temperatures was investigated from the mechanical and fracture perspectives.

Using the molecular dynamics method [11], Ma Lei [10] numerically simulated the crack propagation process of Ni3Al at different temperatures. The results show that at 400 K, the main deformation mechanisms at the crack tip of Ni3Al are dislocation, slip and porosity, and there are differences in crack type, deformation characteristics and expansion rate of the initial orientation. At high temperatures from 400 K to 600 K, the crack propagation rate in Ni3Al increases with increasing temperature.

Julian Rackwitz [12] investigated the temperature dependence of fatigue crack propagation rate in Ti6Al4V alloys at different stress ratios R. It was found that lowering the test temperature from 293 K to 77 K resulted in a significant increase in fatigue crack propagation resistance, especially ΔK fatigue threshold stress intensity. And this effect is more obvious in coarse-crystal alloys. From the mechanical point of view, roughness-induced crack closure plays a key role in increasing the fatigue threshold at low temperatures and in coarse-crystal organisations.

Juan Li [13] investigated the fatigue crack propagation behaviour of TA29 titanium alloy at room temperature, 400°C, 500°C and 600°C. The results show that TA29 titanium alloy has good resistance to crack propagation at room temperature. As the test temperature increases, the C value of the Paris formula increases, the m value decreases, and the fatigue crack propagation rate increases. The fatigue fracture morphology of the fatigue crack propagation specimens was also analysed using scanning electron microscopy (SEM), and it can be found that the fracture of the fatigue crack propagation specimens at different temperatures exhibits typical pre-cracking zone, steady state propagation zone and rapid propagation zone. With the increase of temperature, the range of pre-cracked zone becomes larger, and the range of steady state expansion zone and rapid expansion zone becomes smaller.

Yu Lanlan[14] studied the fatigue crack propagation rate of TC-DT damage tolerance titanium alloy at 150°C and 25°C, and obtained the relationship between stress intensity factor and crack propagation rate. The experimental results showed that in the medium and fast expansion region, 150°C specimens, the fatigue crack expansion rate decreased.25°C specimens in the low expansion region, the critical value of the specimen is lower than 150°C. The fatigue crack expansion rate of titanium alloys was found to be lower than 150°C in the medium and fast expansion region.

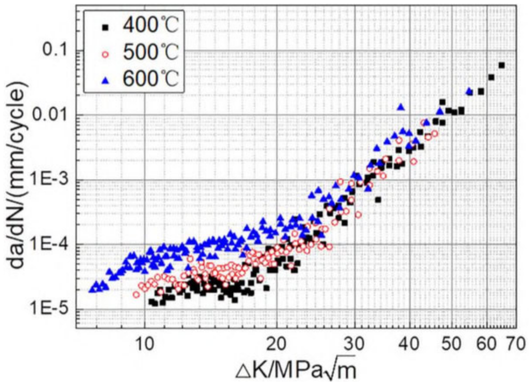

Figure 1. Fatigue crack propagation rate of TA29 alloy at different temperatures [14]

Zhang Guangping [15] investigated the effect of temperature on the fatigue-creep crack propagation behaviour of Ni3A1 (B), and the experimental results showed that the propagation rate of each waveform on the crack was significantly higher than the room temperature, 600°C, and 800°C, which indicated that the oxidative embrittlement phenomenon was larger at the crack tip of Ni3A1 (B), and it also had a stronger effect on its creep effect [16].

The results of many experiments [17-21] show that the fatigue crack propagation rate da/dN increases with increasing temperature for most metals. As da/dN increases, the effect of temperature on da/dN decreases.

5.2. Effect of load-stress ratio on fatigue crack propagation

From a large amount of literature [22-27], it can be seen that the load stress ratio R significantly affects the fatigue crack propagation, and the propagation rate of fatigue cracks under the action of high stress ratio R is faster than that of low stress R state. In calculating the stress ratio, Forman's formula is usually used to express the propagation rate of fatigue cracks. From equation (3), it can be seen that the propagation rate of fatigue cracks increases as the stress ratio R increases.

Liu Hu [28] investigated the fatigue crack propagation rate of ST12 mild steel plate under different stress ratios, which were taken as R=0.2, -0.3, -1. It was found that the crack propagation rate of ST12 mild steel increased with the increase of crack length under different stress ratios; within a certain range of the stress intensity factor, the propagation rate of the crack increased with the increase of the stress ratio.

Wang Jing [29] investigated the fatigue crack propagation rate of 15CrMo steel, a typical gas cylinder material, under the condition of simulating the actual working conditions of gas cylinders. Low-frequency corrosion fatigue tests with stress ratios of 0.1 and 0.5 were carried out in air and wet hydrogen sulphide environments with different concentrations. The results showed that the crack propagation rate in 200 ppm hydrogen sulphide environment was 27 times higher than that in air. The addition of the corrosive environment greatly accelerated the crack propagation rate of 15CrMo steel. The crack propagation rate increased exponentially with increasing H2S concentration. As the stress ratio increases, the average stress increases, the crack closure effect decreases, the crack tip opens completely, and the contact area with the corrosive medium increases, leading to an increase in the crack propagation rate.

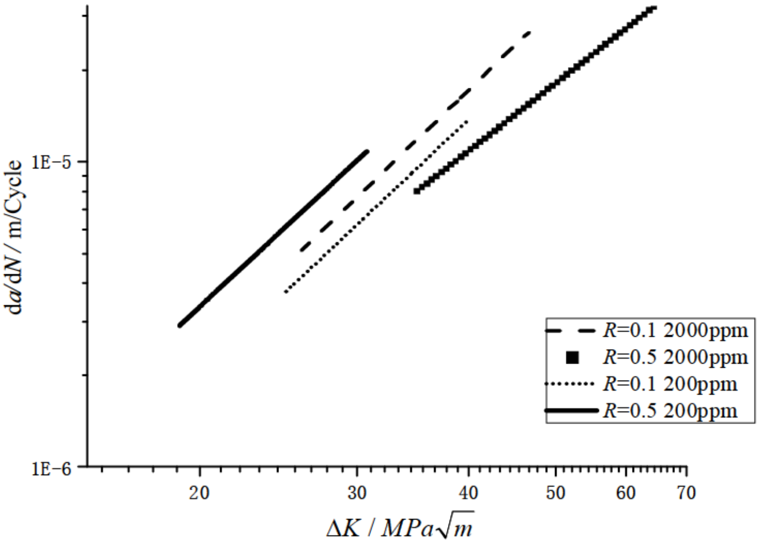

Figure 2. Curves of 15CrMo steel under different conditions [29]

Chunyan Li [30] determined the crack propagation rate of 6082T651 aluminium alloy by using a hydraulic servo fatigue testing machine and investigated the effect of different stress ratios R on the crack propagation properties and observed the fracture in the propagation zone. The results show that the crack propagation rate is significantly greater at a large stress ratio R than at a low stress ratio R. The stress ratio has a great influence on the C value of the Paris formula, but has little effect on the m value. In the stable propagation region, the fracture morphology is mainly characterised by fatigue steps, tough nests and fatigue glow [31].

J.D.M. Costa [32] investigated the effect of stress ratio R and specimen thickness B on the rate of fatigue crack propagation in CK45 steel. The results showed that the results showed that the stress ratio R and specimen thickness B both have a significant effect on the rate of fatigue crack propagation in CK45 steel. The fatigue crack propagation rate da/dN increases with the increase of R and B, while the effect of R and B on da/dN decreases with the increase of ΔK. However, da/dN is more sensitive to the change of R in the lower thickness region.

Many studies [33-40] have found that da/dN increases as the stress ratio R increases; R not only has some effect on da/dN but also on the influence threshold.

5.3. Effect of load frequency on fatigue crack propagation

In analysing the effect of cycle frequency [41,42] on metal crack propagation, scholars [43-46] have concluded that in high temperature environments, the influence of frequency can be classified into three categories: cycle-dependent, time-dependent, and cycle-time-dependent. Load frequency has an important effect on the rate of fatigue crack propagation due to material and environmental aspects.

Fu Zhenghong [47] investigated the fatigue crack propagation characteristics of alloy 690 (TT) at different loading frequencies and observed the crack propagation paths. The results show that the crack propagation rate increases with decreasing frequency at the same R. The crack expansion rate decreases with increasing R in the same frequency range. The crack expansion path is of the through-crystal type, and at low frequencies, secondary cracks appear, and secondary cracks increase when R is large.

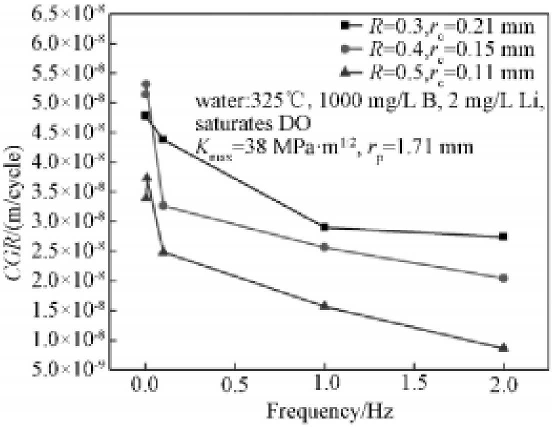

Figure 3. Trend of crack propagation rate with frequency [47]

Mukhar Sharma [48] investigated the effect of loading frequency on the fatigue crack propagation rate behaviour (FCGR) of austenitic stainless steel material of type 304L (N). The results show that FCGR increases with decreasing frequency for a range of stress intensity factors. The increase in FCGR is very significant from high frequency to low frequency.

Zheng Liu [49] investigated the effect of loading frequency and fatigue crack propagation rate of AZ91HP die-cast magnesium alloy after heat treatment. The results show that the crack propagation rate of AZ91HP-F decreases gradually with the increase of load frequency at the same R-value, while the propagation rate of AZ91HP cracks decreases gradually from T6, F and T4 states under the same load.

Many studies [50-54] found that the load frequency has almost no effect on da/dN when ΔK is small; when ΔK is larger, the effect of load frequency on Load frequency decreases, da/dN increases; with the increase of load frequency, da/dN decreases.

5.4. Effect of hydrogen on crack propagation rate

The effect of hydrogen on the mechanical properties of metals is divided into the internal effect of solid solution hydrogen, and the alteration of the microstructure of the metal by hydrogen. Hydrogen has a great influence on the plasticity of the metal, after the concentration of hydrogen exceeds 0.015%~0.02%, hydrogen will diffuse and enrich in the direction of low temperature or high stress under the effect of temperature and stress gradient, so as to make the hydride precipitate in a certain local area (crack tip or stress concentration area). Due to the generation of hydrides, tensile stresses or cracks are formed around them, which leads to a decrease in the impact toughness of the metal, thus leading to hydrogen embrittlement of the metal [55-58].

Zhang Yi-wei [59] investigated the effect of hydrogen in coal to natural gas on X80 steel spiral welded pipes in a simulated environment with a total pressure of 12 MPa and hydrogen fractions of 0, 1 vol%, 2.2 vol% , and 5 vol% to perform slow strain rate tensile tests and fatigue crack propagation rate tests, respectively. The test results show that: the hydrogen content of 5vol% below, coal gas on the domestic X80 pipeline steel strength properties of very small, but on the plastic properties have a certain effect on the fatigue crack propagation performance has a great impact on the fatigue crack propagation performance of coal gas in the fatigue crack propagation performance of the base material of the hydrogen degradation of the impact is more serious than the spiral weld.

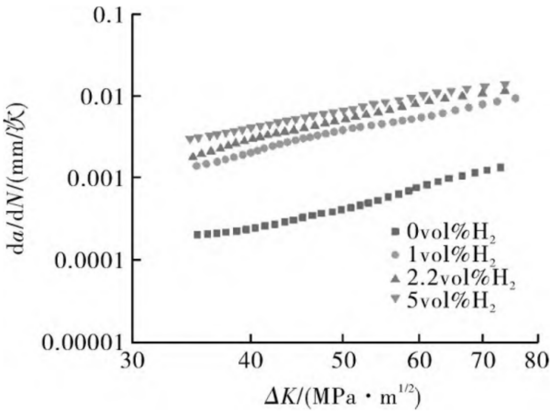

Figure 4. Fatigue Crack Expansion Rate Curve [59]

The phenomenon of hydrogen-induced delayed fracture of metals has been receiving attention because most metals are used as structural materials and therefore hydrogen-induced fracture is highly susceptible to serious accidents [60-63]. The effect of hydrogen on metallic materials is mainly reflected in the delayed fracture under static load, and there have been many research results, but most of the results are the same, it is believed that hydrogen has a great influence on the crack propagation rate of metal under static load.

6. FATIGUE CRACK PROPAGATION BASED ON FINITE ELEMENT ANALYSIS

Due to the high cost of fatigue test, time-consuming, fatigue testing machine function is single, it is difficult to achieve multi-dimensional, multi-directional alternating stress and other complex environments of fatigue test, and the experiments are often ignored the morphological correlation of the material, which leads to the bias of the test results, and does not have any guiding effect on the engineering practice. Thus, people began to use the finite element method to analyse the parts and combined with the powerful computational ability of the computer, which can obtain the data of the life, so that it can better reflect the actual situation of the project, thus greatly reducing the cost [64-67].

With the rapid development of finite element analysis technology, the reliability of its calculation results has been more and more recognized, using the finite element method to analyse a variety of engineering problems, not only can we get a more scientific solution method, but also enable us to have a more intuitive understanding of the stress and strain of the relevant engineering problems. From the crack propagation analysis based on the microscopic mechanism of metals to the fatigue life calculation based on the S-N curve, it has been widely used in the fatigue analysis of metallic materials, thus accelerating the development of fatigue analysis.

Liu Yang [68] used a finite element software and fatigue subroutine to establish the fatigue crack propagation process of a compact tensile specimen, completed the static stress analysis of the compact tensile specimen, derived the location of the maximum stress of the compact tensile specimen, and according to this location, the crack was generated in the subroutine, and through the calculation, the number of fatigue cyclic action times of the corresponding length of the crack propagation was obtained, and the local a-N curve. According to Liu Yang, this method can visualise the process of crack propagation and facilitate in-depth analysis and understanding of the fatigue mechanism.

Yatika Gori [69] investigated the fatigue crack propagation rate of AA6061-T6 aluminium alloy under different stress ratios, and used the calculation method of crack propagation and stress intensity factor to carry out finite element analysis and experimental study on the fatigue increase phenomenon of AA6061-T6 aluminium alloy. The finite element simulation results were compared with the experimental results, and the error was within 20%. Therefore, the finite element method can be used to further investigate the crack propagation of the material.

HD Wlide [70] investigated the prediction of fatigue damage in cylindrical specimens by numerical simulation of fracture mechanics. A finite element analysis model was developed for cracks in a typical cylindrical specimen used for fatigue life testing and generation of design fatigue curves. The stress intensity factor was calculated and the number of damage cycles was determined based on the Paris formula and the two-stage crack propagation relationship. The simulation results were compared with the experimental fatigue life data and showed good agreement.

7. SUMMARY

Fatigue crack propagation is an important damage mechanism in metallic materials, which is of great significance in ensuring the reliability and service life of materials. This paper reviews the fatigue crack propagation mechanism, commonly used theoretical models and research methods, factors affecting the rate of fatigue crack propagation, and fatigue crack propagation research based on finite elements.

Since the fatigue crack propagation of metallic materials is affected by a variety of factors, the existing theories and methods still have a lot of problems to be verified. Therefore, it is very important to study the test environment and internal structure of the material, which is yet to be studied in depth. In conclusion, the research on this problem is still in the stage of continuous improvement, and future research work can be carried out in the following two aspects:

(1) Previous studies have mainly focused on the study of fatigue crack propagation under a single load, however, in practice, metallic materials are often subjected to a variety of complex loads. Such as alternating loads, irregular loads and so on. The effect of these complex loads on fatigue crack propagation is often more complex and significant than a single load. Therefore, there is a need to develop a fatigue crack propagation model that can simultaneously consider the effects of multiple complex loads, in order to better study and predict the fatigue crack propagation law of metallic materials.

(2) In order to gain a deeper understanding of the mechanisms and laws of fatigue crack propagation, a method of mutual verification between experiments and numerical simulations is needed. Fatigue crack propagation simulation based on finite element is a relatively common and effective method, ABAQUS is a commonly used finite element software, and it is the future development trend to develop a set of subroutine to predict the crack propagation law based on ABAQUS. This subroutine will combine experimental data and numerical simulation results for the prediction of crack propagation rate and crack propagation life. This will be of great significance to the research and application of fatigue fracture of metallic materials, improve the fatigue strength and safety of metallic materials, and also promote the in-depth development of fatigue fracture research.

ACKNOWLEDGEMENTS

This is the place to fill in information about funds, sponsors, etc. that need to be thanked.

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