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Review article

A state-of-the-art review on fatigue life prediction methods for metal structures

WEICHENG CUI

School of Naval Architecture and Ocean Engineering, Shanghai Jiao Tong University, 1954 Huasham Road, Shanghai 200030, China

Abstract Metals are the most widely used materials in engineering structures, and one of the most common failure modes of metal structures is fatigue failure. Although metal fatigue has been studied for more than 160 years, many problems still remain unsolved. In this article, a state-of-the-art review of metal fatigue is carried out, with particular emphasis on the latest developments in fatigue life prediction methods. All factors which affect the fatigue life of metal structures are grouped into four categories: material, structure, loading, and environment. The effects of these factors on fatigue behavior are also addressed. Finally, potential problems to be resolved in the near future are pointed out.

Key words Metal fatigue · Cumulative fatigue damage theory · Fatigue crack propagation theory

1 Introduction

Fatigue is defined as a process of the cycle-by-cycle accumulation of damage in a material undergoing fluctuating stresses and strains.[1] A significant feature of fatigue is that the load is not large enough to cause immediate failure. Instead, failure occurs after a certain number of load fluctuations have been experienced, i.e., after the accumulated damage has reached a critical level.

Fatigue of metals and metal structures has been studied for more than 160 years,[2,3] and a good understanding of metal fatigue mechanisms has been achieved.[2,4–6]

Fatigue cracks usually start from the surface of a component, where fatigue damage begins as shear cracks on crystallographic slip planes. The surface shows the slip planes as intrusions and extrusions. This is stage I crack growth. After a transient period, stage II crack growth takes place in a direction normal to the applied stress. Finally, the crack becomes unstable and fracture occurs. Figure 1 shows a schematic representation of the two stages.

This two-stage process was first recognized by P.J.E. Forsyth,[7] and it was one of the most important achievements in metal fatigue in the twentieth century.[8] However, that description is too general for interesting further discussion. So other sources may be used for further details. Schijve[9] divided the process into four phases: crack nucleation, microcrack growth, macrocrack growth, and failure. Shang et al.[10] described five stages: (1) early cyclic formation and damage; (2) microcrack nucleation; (3) short crack propagation; (4) macrocrack propagation; (5) final fracture. Miller[11,12] divided the crack into three types: microstructurally small cracks, physically small cracks, and long cracks. A slightly different classification of small cracks has been proposed by Ritchie,[13] namely: microstructurally small cracks of critical microstructural dimensions, e.g., grain size; physically small cracks of the order of less than 1 mm; mechanically small cracks of the order of the plastic zone length (several millimeters); chemically small cracks of up to 10 mm.

Based on these different divisions and applications, this article recommends that the total process of fatigue failure is divided into five stages: (1) crack nucleation ($a < a_m$); (2) microstructurally small crack propagation ($a_m < a \leq a_p$); (3) physically small crack propagation ($a_p < a \leq a_l$); (4) long crack propagation ($a_l < a \leq a_c$); (5) final fractures. Here, a is the characteristic dimension of an equivalent crack in a component, a_m is the smallest crack length detectable by current technology (i.e., about 0.1 μm), a_p is the smallest crack length for physically small cracks (i.e., about 10 μm), a_l is the smallest crack length for long cracks (i.e., about 1 mm), and a_c is the critical crack length at which component fracture occurs. Obviously, these boundary divisions are subjective, and depend on the accuracy of crack-measuring

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Address correspondence to: W. Cui
(e-mail: wccui@mail.sjtu.edu.cn)
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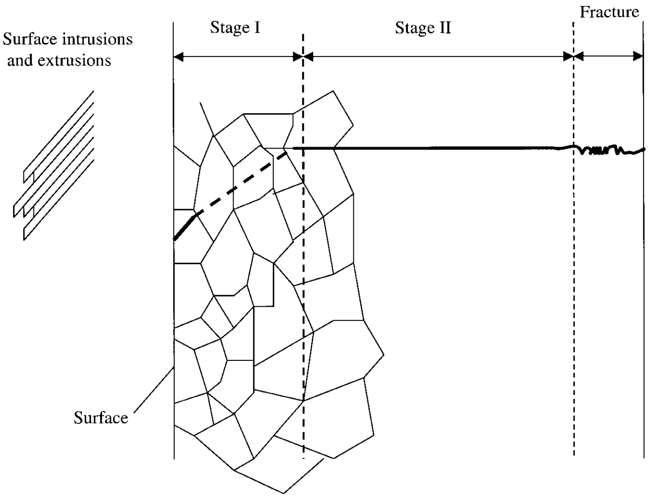

Fig. 1. Schematic representation of crack formation and growth in polycrystalline metals

systems. Traditionally, the process which occurs before long crack propagation is named "fatigue crack initiation," while long crack propagation is called "fatigue crack propagation." This division is also too rough, and could not be expected to provide an accurate prediction of fatigue life. However, it may be worth pointing out that depending on the initial crack length in a component, some of the early stages may be skipped. These five stages of the fatigue process only exist in "defect-free" metal components.

The purpose of this paper is to carry out a state-of-the-art review of metal fatigue. Since the subject is quite old and there are many published papers, it is impossible to conduct this review in a comprehensive manner. Also, many recent historical review papers are available.[3,8,14–16] Therefore, this review places particular emphasis on the latest developments in fatigue life prediction methods. All the factors which affect the fatigue life of metal structures are grouped into four categories: material, structure, loading, and environment. The effects of these factors on fatigue behavior are also addressed. Finally, potential problems to be resolved in the near future are pointed out.

2 Existing approaches to the prediction of fatigue life

Fatigue damage increases with applied cycles in a cumulative manner, which may lead to fracture. Cumulative fatigue damage (CFD) theory is the traditional theoretical framework for fatigue strength assessment (FSA). More recent work developed the fatigue crack propagation (FCP) theory based on fracture mechanics concepts. At present, these two theories are being researched and applied.

2.1 Cumulative fatigue damage theories

At the present time, cumulative fatigue damage analysis still plays a key role in predicting the life of components and structures subjected to field-load histories. Since the introduction of the damage accumulation concept[17] and the "linear damage rule,"[18] the treatment of CFD has increasingly received attention. Recent comprehensive reviews of the development of cumulative fatigue damage theories were conducted by Fatemi and Yang[14] and Yang and Fatemi.[15]

Fatigue damage is fundamentally a result of material structural changes at the microscopic level, such as dislocations of the atomic structures. While collating microscopic quantities and macroscopic experimental observations is still a long-term problem, it is reasonable to believe that microscopic parameters governing fatigue damage have an inherent relationship with macroscopic stress and strain quantities based upon the continuum mechanics concepts. These macroscopic quantities can be used to account for crack nucleation and early growth. By choosing different macroscopic quantities such as stress, strain, energy density, or a combination of these, different cumulative fatigue damage formulas have been derived.

2.1.1 Stress-based approach (S–N curve approach)

The stress-based approach was the earliest, but is still the most frequently used, approach for fatigue life prediction. In this approach, the fatigue life (number of cycles N) is related to the applied stress range ($\Delta\sigma$ or S) or the stress amplitude (σ_a). In general, a plot of the fatigue life versus the true stress amplitude for a metal gives a curve of the Basquin form[19]:

$$\sigma_a = \frac{E \cdot \Delta\varepsilon_e}{2} = \sigma_f' \cdot (2N)^b \tag{1}$$

where N is the number of cycles to failure, $2N$ is the number of load reversals to failure, σ_f' is the fatigue strength coefficient, and b is the fatigue strength exponent (the sign of b is negative).

In a component or structure, there are two types of stress concentration. One is due to the structural geometry change or discontinuity, and the other is due to welding. Depending on how the stress concentration effect is accounted for, stress-based approaches can be further divided into the nominal stress approach, the hot-spot stress approach, and the notch stress approach. Currently, the hot-spot stress approach seems to be the one most favored by ship classification societies.[20–22]

Traditional fatigue tests indicated a limit at about $N = 10^7$ cycles. If the applied stress range is lower than the limit, there will be no fatigue failure. However, recent giga-cycle fatigue tests performed on a cold-rolled steel sheet (E = 203 GPa, σ_y = 225 MPa, σ_u = 340 MPa, ρ =

7.83 g/cm[3], and HV = 95)[23] and a high-carbon chromium steel (σ_u = 2316 MPa and HV = 750–795)[24] showed that the fatigue limit does not appear until 10^9 cycles in the *S–N* curve. However the S–N curve tends to drop toward $N > 10^7$ cycles in the long-life region. This raises questions about the existence of an infinite fatigue life.[25] Thus, whether a fatigue limit exists requires further study.

If a fatigue limit is assumed to exist, then the relation expressed by Eq. 1 is only valid for the middle of the cycle. The stress amplitude is larger than the limit, but the maximum stress should not exceed the ultimate tensile strength. Recently, a new function to describe fatigue curves for both low and high fatigue regions, i.e., for the whole cycle region from tensile strength to fatigue limit, was proposed by Kohout and Vechet.[26] The function takes the form

$$\sigma(N) = \sigma_\infty \left[\frac{N + 10^7 \alpha\beta}{N + 10^7 \alpha} \right]^{-b}$$

$$\alpha = \frac{\sigma_c^{-1/b} - \sigma_\infty^{-1/b}}{\sigma_u^{-1/b} - \sigma_c^{-1/b}} \qquad \beta = \frac{\sigma_u^{-1/b}}{\sigma_\infty^{-1/b}} \tag{2}$$

where σ_u is the tensile strength and σ_∞ is the fatigue limit, and both of them can be measured accurately. σ_c is the fatigue strength at 10^7 cycles, and –b is the slope in the middle of the cycle. σ_c and *b* can be determined by the least-squares method.

Four parameters have to be determined for a complete S–N curve according to Eq. 2. In some practical situations, so much information may not be available. Wang et al.[27] proposed a simple and practical prediction method to estimate both the S–N curve and the crack growth rate curve using only the tensile strength.

2.1.2 Strain-based approach

In most practical cases of fatigue design, the critical location will be a notch in which plastic strains are imposed by surrounding elastic material. Thus, the situation will be strain-controlled, with a total strain range composed of an elastic and a plastic part.

The plastic strain resistance is best described by the Manson–Coffin relationship.[28,29]

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f' \cdot (2N)^c \tag{3}$$

where ε_f' is the fatigue ductility coefficient, and *c* is the fatigue ductility exponent (the sign of *c* is negative).

Manson and Hirschberg[28] proposed that a metal's resistance to total-strain cycling can be considered as a superposition of its elastic and plastic strain resistance. By combining Eqs. 1 and 3.

$$\frac{\Delta\varepsilon_T}{2} = \varepsilon_a = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f'}{E}(2N)^b + \varepsilon_f' \cdot (2N)^c \tag{4}$$

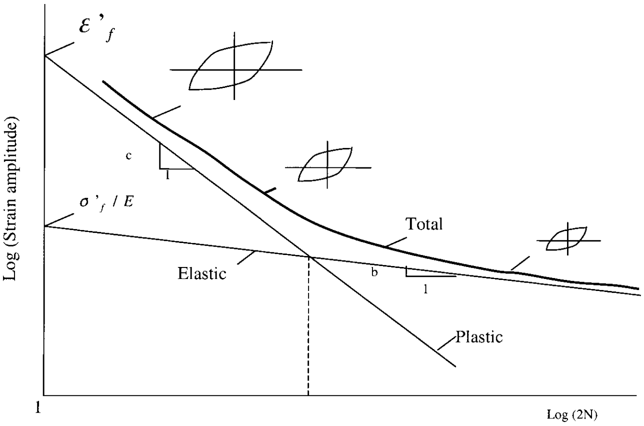

Fig. 2. Representation of elastic, plastic, and total strain resistance to fatigue loading

The total-strain life curve approaches the plastic-strain life curve in the low cycle region and the stress life curve in the high cycle region, as shown in Fig. 2.

For general low-cycle and high-cycle fatigue, the Manson–Coffin relationship (Eq. 4) has a strong curve-fit ability, but it needs to determine five material properties. Manson[30] has simplified the equation even further with his method of universal slopes, where

$$\Delta\varepsilon = 3.5 \frac{S_u}{E} (N)^{-0.1\varepsilon} + \varepsilon_f^{0.6} (N)^{-0.6} \tag{5}$$

S_u, *E*, and ε_f are all obtained from a monotonic tensile test. He assumed that the two exponents are fixed for all materials, and that only S_u, *E*, and ε_f control the fatigue behavior.

Later, the above equation was further modified by Muralidharan and Manson[31] to

$$\Delta\varepsilon = 0.0266 D^{0.115} [S_u/E]^{-0.53} N_f^{-0.56} + 1.17 [S_u/E]^{0.832} N_f^{-0.09} \tag{6}$$

where S_u is the ultimate strength of the metal, *D* is the ductility of the metal, *E* is the modulus of elasticity, and N_f is the fatigue life. A good correlation between the fatigue life predicted by this equation and the fatigue test data has been found.[31]

Based on a detailed correlation study between monotonic tensile data and constant amplitude strain-controlled fatigue properties, the following simple strain-life formula was proposed by Roessle and Fatemi[32]:

$$\frac{\Delta\varepsilon}{2} = \frac{4.25(HB) + 225}{E} (2N_f)^{-0.09} + \frac{0.32(HB)^2 - 487(HB) + 191000}{E} (2N_f)^{-0.56} \tag{7}$$

This equation uses only the hardness and the modulus of elasticity as inputs for a strain-life approximation, both of which are either commonly available, or easily measurable.

The inclusion of mean stress or mean strain effects in fatigue life prediction methods involving strain-life data is very complex. One method is to replace σ_f' with $\sigma_f' - \sigma_m$ in Eq. 5, where σ_m is the mean stress such that

$$\frac{\Delta\varepsilon}{2} = \frac{(\sigma_f' - \sigma_m)(2N)^b}{E} + \varepsilon_f'(2N)^c \tag{8}$$

where σ_m is taken as positive for tensile values and negative for compressive values. Another equation suggested by Smith et al.[33] based on strain-life test data at fracture obtained with various mean stresses, is

$$\sigma_{\max}\varepsilon_a E = (\sigma_f')^2 (2N)^{2b} + \sigma_f' \varepsilon_f' E (2N)^{b+c} \tag{9}$$

where $\sigma_{\max} = \sigma_m + \sigma_a$ and ε_a is the alternating strain. If $\sigma_{\max}$ is zero, Eq. 9 predicts infinite life, which implies that tension must be present for fatigue fractures to occur. Both Eqs. 8 and 9 have been used to handle mean stress effects.

Ong[34] calculated fatigue lives for 49 steels using published values of σ_f', ε_f', b, and c. These lives were compared with lives calculated using some of the approximation methods described above. These include the original and modified versions of the four-point correlation method, the original universal slopes method, and the Mitchell et al.[35] method. The lives covered a range from 10 to 10^7 reversals. The steels covered values of UTS from 345 MPa to 2585 MPa, and Brinell hardness values from 80 to 660. They included the steels SAE1005, SAE1015, and SAE1045.

In all cases, the correlation between the "experimental" and the "estimated" lives was poor. The modified four-point correlation method was found to be slightly better than the original universal slopes method, and to be the best of the methods studied.

In another study conducted by Park and Song,[36] six such methods were evaluated and compared. These consisted of the universal slopes and four-point correlation methods by Manson,[30] the modified universal slopes method by Muralidharan and Manson,[31] the uniform material method by Baumel and Seeger,[37] the modified four-point correlation method by Ong,[38] and the method proposed by Mitchell et al.[35] A total of 138 materials were used in the study, including unalloyed steels, low-alloy steels, high-alloy steels, aluminum alloys, and titanium alloys, with low-alloy steels providing the most data. Amongst the correlations compared, those proposed by Muralidharan and Manson,[31] Baumel and Seeger,[37] and Ong[38] yielded good predictions according to Park and Song.[36] It was concluded that the modified universal slopes method provided the best correlation.

In the study carried out by Roessle and Fatemi,[32] they also compared their simple formula, which uses only hardness and modulus of elasticity to estimate the strain-life curve, with the modified universal slopes method, and found that their simple formula resulted in somewhat better and more conservative predictions over the entire fatigue-life cycle.

2.1.3 *Energy-based approach*

A historical description of energy-based approaches is given by Fatemi and Yang.[14] In using this type of failure criteria, it was realized that an energy-based damage parameter can unify the damage caused by different types of loading such as thermal cycling, creep, and fatigue. In conjunction with Glinka's rule,[39] it is possible to analyze the damage accumulation of notched specimens or components by the energy approach. Energy-based damage models can also include mean stress and multiaxial loads, since multiaxial fatigue parameters based on strain energy have been developed.

Recently, Pan et al.[40] proposed the following fatigue-strain energy density parameter for the critical plane to predict the fatigue life of various materials under multiaxial loading:

$$W^* = \frac{\Delta\sigma_{12}}{2}\frac{\Delta\gamma_{12}}{2} + k_1 k_2 \frac{\Delta\varepsilon_{22}}{2}\frac{\Delta\sigma_{22}}{2} \tag{10}$$

where $\Delta\sigma_{12}$ and $\Delta\sigma_{22}$ are the shear and normal stress ranges in the critical plane, respectively, $\Delta\gamma_{12}$ and $\Delta\varepsilon_{22}$ are the shear and normal strain ranges in the critical plane, respectively, and k_1 and k_2 are two weight constants for strain and stress amplitudes, respectively, which are defined as:

$$k_1 = \frac{\gamma_f'}{\varepsilon_f'}, \qquad k_2 = \frac{\sigma_f'}{\tau_f'} \tag{11}$$

where σ_f' is the uniaxial fatigue strength coefficient, and ε_f' is the uniaxial fatigue ductility coefficient, τ_f' is the torsional fatigue strength coefficient, and γ_f' is the torsional fatigue ductility coefficient.

2.1.4 *Continuum damage mechanics approaches*

Continuum damage mechanics (CDM) is a relatively new subject in engineering mechanics and deals with the mechanical behavior of a deteriorating medium at the continuum scale. The general concepts and fundamental aspects of this subject were described by Kachanov.[41] Chaboche and Lesne[42] were the first to apply CDM to fatigue life prediction. For the one-dimensional case, they postulated that fatigue damage evolution per cycle can be generalized by a function of the load condition and damage state. By measuring the changes in tensile load-carrying capacity and using the effective stress concept, they formulated a nonlinear damage evolution equation as

$$D = 1 - \left[1 - r^{1/(1-\alpha)}\right]^{1/(1+\beta)} \tag{12}$$

where β is a material constant, α is a function of the stress state, and r is the damage state. This damage model is highly nonlinear in damage evolution, and is able to account for the mean stress effect. It is therefore called a nonlinear continuous damage (NLCD) model. The main features, advantages, and some deficiencies of the NLCD model are summarized by Chaboche and Lesne.[42] Based on the CDM concept, many other forms of fatigue damage equation have been developed, as described by Fatemi and Yang.[14] Basically, all these CDM-based approaches are very similar to the Chaboche and Lesne NLCD model in both form and nature. The main differences lie in the number and characteristics of the parameters used in the model, the requirements for additional experiments, and their applicability.

CDM models were mainly developed for uniaxial fatigue loading. Some difficulties arise when these models are extended to multiaxial loading. Owing to the complexity of nonproportional multiaxial fatigue problems, a three-dimensional anisotropic CDM model does not yet exist. Great efforts are still needed to obtain an appropriate generalized prediction model for cumulative fatigue damage.

2.1.5 Summary

In summary, no matter what quantities are used, fatigue criteria based on cumulative fatigue damage (CFD) theory suffer from one significant deficiency. That is, there is no consistent definition of failure. It may be when the first small detectable crack is found, or after a certain percentage decrease in load amplitude, or actual fracture. The differences in fatigue life according to these three criteria may be small or appreciable. More accurately, the following factors will affect the fatigue life:

- — quality of material processing (size and distribution of inclusions, voids, etc.);
- — procedure of material processing (annealed, quenched, tempered, etc.);
- — procedure of specimen manufacture (specimen shape, machining method);
- — quality of specimen manufacture (scratch, surface condition);
- — material properties (yield strength, ultimate strength, strain at failure, σ–ε curve);
- — geometry (length, width, thickness, diameter, transition radius, constraint effect);
- — stress state (uniaxial, multiaxial, stress ratio, mean stress);
- — effect of environment (temperature, corrosive environment).

An accurate prediction of fatigue life must take all these factors into account. To data, no CFD models are available which could consider all these influencing factors. A consequence of this is that fatigue data are subject to large scatter. However, the fuzzy definition of fatigue failure in CFD theory can be overcome through the fracture mechanics approach. Fatigue crack propagation (FCP) theory, introduced in the next section, could eliminate this deficiency.

2.2 Fatigue crack propagation theories

2.2.1 Long crack growth

The earliest theory for predicting the fatigue crack propagation length is the linear elastic fracture mechanics (LEFM) approach. The LEFM approach was first introduced by Paris et al.,[43] who equated fatigue crack growth rate to the cyclic elastic stress intensity factor range at the tip of a long crack subjected to a low value of cyclic stress, such that

$$\frac{\mathrm{d}a}{\mathrm{d}N} = A(\Delta K)^n \qquad \text{where} \qquad \Delta K = Y\Delta\sigma\sqrt{\pi a} \tag{13}$$

Here, A and n are material constants, and Y is a geometry factor depending on the loading and cracked body configuration.

Later, people found that the crack growth rate curve is not linear for all ranges of ΔK. The general crack growth rates for mode I cracks in metals are shown in Fig. 3. The sigmoidal shape of the crack growth curve in Fig. 3 suggests a subdivision into three regions. In re-

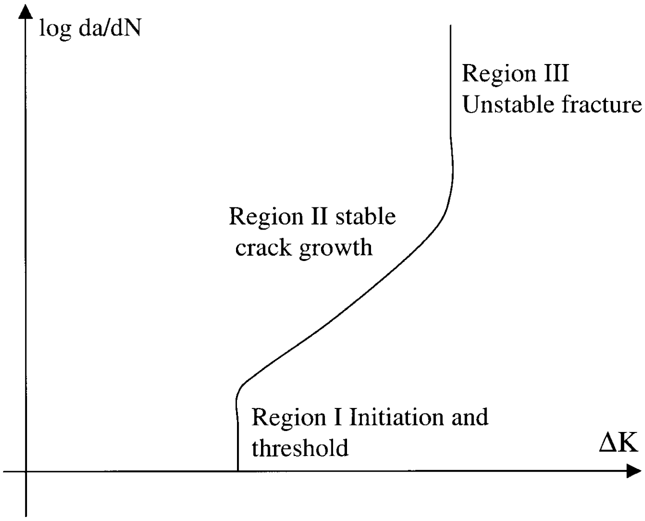

Fig. 3. Crack growth rate curve showing the three regions

gion I, the crack growth rate goes asymptotically to zero as ΔK approaches a threshold value ΔK_{th}. This means that for stress intensities below ΔK_{th}, there is no crack growth, i.e., there is a fatigue limit.

The crack growth relations in the threshold region have been proposed by Donahue et al.,[44] as

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C \cdot \left[\Delta K - \Delta K_{\mathrm{th}}\right]^{m} \tag{14}$$

Region II crack growth follows a power law, the so-called Paris–Erdogan crack growth law,[45] as given in Eq. 13.

Region III crack growth exhibits a rapidly increasing growth rate towards "infinity," i.e., ductile tearing and/or brittle fracture. This has led to the relation proposed by Forman et al.[46]

$$\frac{\mathrm{d}a}{\mathrm{d}N} = \frac{C(\Delta K)^{m}}{(1-R)K_{\mathrm{c}} - \Delta K} \tag{15}$$

where K_{c} is the fracture toughness of the material.

Relations combining the departures from power-law behavior at high and low ΔK values also exist.[47,48] The most representative one is probably the one proposed by McEvily and Groeger.[49]

$$\frac{\mathrm{d}a}{\mathrm{d}N} = A\left(\Delta K - \Delta K_{\mathrm{th}}\right)^{2}\left[1 + \frac{\Delta K}{K_{\mathrm{C}} - K_{\max}}\right] \tag{16}$$

In order to explain the effects of load ratio ($R = K_{\min}/K_{\max}$) on fatigue crack growth, Elber[50] introduced the concepts of crack closure and the effective cyclic stress intensity factor ΔK_{eff} as the dominant driving force for fatigue.

$$\Delta K_{\mathrm{eff}} = K_{\max} - K_{\mathrm{op}} \tag{17}$$

where $K_{\max}$ is the stress intensity calculated for the maximum load, and K_{op} is the stress intensity calculated for the crack-opening load. This concept was very popular in 1980s and 1990s, but it is now being challenged (e.g., Hertzberg et al.[51]). In particular, many people have agreed that the physical effects of crack closure have been greatly over-estimated in the past (e.g., Vasudevan et al.[52]). A partial crack closure model[53–55] was proposed to overcome the difficulties found in the crack closure model. The modified effective stress intensity factor range is defined as[55]

$$\begin{aligned} \Delta K_{\mathrm{effM}} &= K_{\max} - K_{\mathrm{op}}\left[1 + \left(\frac{2}{\pi} - 1\right) g\right] \\ g &= \exp\left[-\left(\frac{K_{\max}}{K_{\max\mathrm{TH}}} - 1\right)\right] \end{aligned} \tag{18}$$

where $K_{\max\mathrm{TH}}$ is the maximum SIF at the threshold for a given R ratio.

Later, Kujawski[56,57] further found that it is possible to explain the stress ratio effect even better without using the crack closure concept. He defined the following parameter as the fatigue crack driving force:

$$\Delta K^{*} = \left(K_{\max}\right)^{\alpha}\left(\Delta K^{+}\right)^{1-\alpha} \tag{19}$$

where ΔK^{+} is the positive part of the applied SIF range. Using this parameter, the threshold value can be expressed as

$$\Delta K_{\mathrm{th}}^{*} = \begin{cases} \Delta K_{\mathrm{th0}}^{*}(1-R)^{\alpha} & \text{for } R > 0 \\ \Delta K_{\mathrm{th0}}^{*}(1-R) & \text{for } R \le 0 \end{cases} \tag{20}$$

where $\Delta K_{\mathrm{th0}}^{*}$ is the threshold value corresponding to $R = 0$.

2.2.2 *Physically small crack growth*

It is widely agreed that for physically small crack growth, the elastic plastic fracture mechanics (EPFM) must be employed. The EPFM approach was first introduced by Tomkins in 1968.[8] Tomkins equated $\mathrm{d}a/\mathrm{d}N$ to crack tip decohesion (from knowledge of the cyclic stress–strain curve), and thence to the bulk plastic strain field such as occurs, for example, under high strain fatigue, thus

$$\frac{\mathrm{d}a}{\mathrm{d}N} = B\left(\Delta\varepsilon_{\mathrm{p}}\sqrt{\pi a}\right)^{m} - \Xi \tag{21}$$

where Ξ is the threshold condition in this crack regime.

Other workers established a relation between the rate of fatigue crack growth, $\mathrm{d}a/\mathrm{d}N$, and some functions of the range of the stress intensity factor, ΔK, by modifying the crack growth relation for long cracks. This was so that the constitutive relationship would be able to explain the following six phenomena: (1) anomalous fatigue crack growth; (2) fatigue crack growth under compression–compression cycling; (3) delay due to an overload; (4) two step cyclic loading; (5) the effect of mean stress on fatigue life; (6) small fatigue crack growth. McEvily et al.[58,59] proposed the following modified constitutive relationship for fatigue crack growth:

$$\begin{aligned} \frac{\mathrm{d}a}{\mathrm{d}N} = A\Bigg\{ & \Bigg[\sqrt{\pi\gamma_{\mathrm{e}}\left(\mathrm{Sec}\frac{\pi}{2}\cdot\frac{\sigma_{\max}}{\sigma_{\mathrm{y}}} + 1\right)} \\ & + Y\sqrt{\frac{\pi}{2}a\left(\mathrm{Sec}\frac{\pi}{2}\frac{\sigma_{\max}}{\sigma_{\mathrm{y}}} + 1\right)}\Bigg]\Delta\sigma \\ & - \left(1 - e^{-ka}\right)\left(K_{\mathrm{opmax}} - K_{\min}\right) - \Delta K_{\mathrm{efth}}\Bigg\}^{2} \end{aligned} \tag{22}$$

where

$$\gamma_{\mathrm{e}}\left(\frac{\Delta K_{\mathrm{effth}}}{\Delta\sigma_{\mathrm{EL}}}\right)^2 \cdot \frac{1}{\pi\left(\mathrm{Sec}\frac{\pi}{2}\cdot\frac{\sigma_{\max}}{\sigma_{\mathrm{y}}}+1\right)} \tag{23}$$

A is a material- and environment-sensitive constant (MPa)$^{-2}$, $\Delta K_{\mathrm{effth}}$ is the effective range of the stress intensity factor at the threshold level (MPa$\sqrt{\mathrm{m}}$), K_{opmax} is the maximum stress intensity factor at the opening level for a macroscopic crack (MPa$\sqrt{\mathrm{m}}$), $K_{\min}$ is the minimum stress intensity factor applied (MPa$\sqrt{\mathrm{m}}$), k is a material constant which reflects the rate of crack closure development with crack advance, Y is a geometrical factor, a is the actual crack length (m), σ_{y} is the yield strength of the material (MPa), $\Delta\sigma$ is the stress range applied (MPa), $\sigma_{\max}$ is the maximum stress applied (MPa), and $\Delta\sigma_{\mathrm{EL}}$ is the stress range of the endurance limit (MPa). A comparison with some experimental data showed that this constitutive relationship is able to explain the six phenomena concerned.

2.2.3 *Microstructurally small crack growth*

Microstructural fracture mechanics (MFM) was developed to handle crack propagation at the microcrack level. The MFM approach was first introduced by Hobson et al.[60] and later by Navarro and de los Rios.[61] The crack growth law is expressed as

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C\Delta\gamma^{\beta}\left(d-a\right) \tag{24}$$

where d is a microstructural dimension. It should be noted that Eq. 24 indicates a zero crack speed when the crack depth, a, is equal to d, and that prior to this state the crack will continuously decelerate until it either stops or continues to propagate according to an overlapping continuum mechanics description.

2.3 *Relations between CFD theories and FCP theories*

Recently, more and more people have become interested in establishing the relation between CFD theories and FCP theories.

The cornerstone for an understanding of metal fatigue is the synergism between a reversing stress (or strain) field, $\Delta\sigma$ (or $\Delta\gamma$), that induces micro- or macroplasticity, and the growth of a crack of depth a. This synergism is expressed mathematically as[8]

$$\frac{\mathrm{d}a}{\mathrm{d}N} = \mathrm{function}\left(\Delta\sigma\sqrt{a}\right) \tag{25}$$

where $\mathrm{d}a/\mathrm{d}N$ is the cyclic growth rate of the crack. This is a fundamental basis of small-crack growth (SCG) theory.

In many instances, however, the synergism represented by $\Delta\sigma\sqrt{a}$ can be undetected. These situations led, respectively, to the Basquin[19] and the Coffin–Manson equations of fatigue life endurance

$$\Delta\sigma\left[\mathrm{or}\ \Delta\varepsilon_{\mathrm{p}}\right]\cdot N_{\mathrm{f}}^{\alpha} = \mathrm{C} \tag{26}$$

where C is a constant, and $\Delta\varepsilon_{\mathrm{p}}$ is the tensile plastic strain range sustained at the critical location in a specimen, component, or structure. This is the fundamental basis of cumulative fatigue damage (CFD) theory.

However, if the fatigue crack grows from an initial defect size a_0 to a final size a_{f} according to the general expression

$$\frac{\mathrm{d}a}{\mathrm{d}N} = B\left[\Delta\sigma\left(\mathrm{or}\ \Delta\varepsilon_{\mathrm{p}}\right)\right]^{n}\cdot a^{m} \tag{27}$$

where B, m, and n are material constants, then upon integration of Eq. 27 between the limits a_0 and a_{f}, both the Basquin and the Coffin–Manson equations are derived. This is the fundamental relation between FCP theory and CFD theory. It follows that the main difficulty with the stress and strain range approaches is that no account is taken of the behavior of cracks; hence, the extent of fatigue damage between the start and the finish of the fatigue process cannot be determined.

A stricter derivation of the relation between the Palmgren–Miner rule and the crack growth law has now been given.[62,63] If the differential equation describing the crack growth process has separate variables, then the Palmgren–Miner damage accumulation rule is true. Obviously, Eq. 27 satisfies this condition, but not all crack growth relations have this property (e.g., Eqs. 23 and 24) which indicates that the Palmgren–Miner rule is not always true. The main deficiency of the Palmgren–Miner rule is that it does not take account of the load sequence effect, which could be significant in some situations.

Therefore, the crack growth approach would be more accurate for fatigue life prediction, but it is not commonly used for fatigue design in industry because of two main difficulties: (1) the initial crack size a_0 is often unknown; (2) the data of $\mathrm{d}a/\mathrm{d}N$ vs. ΔK are more expensive to obtain.

The requirement for an initial crack length a_0 causes some application difficulties, but without considering this parameter explicitly, a large scatter of fatigue lives is unavoidable. A five-fold, or even ten-fold, difference in fatigue life for identical plain specimens under well-controlled constant amplitude loading is often assumed to be natural, but a fatigue life of 2 years compared with one of 20 years is of immense importance when designing the details of a ship. This indicates that the accuracy required for practical complex structures under more complex loading is higher than that for plain specimens.

Without an ability to explain the scatter in small specimens, it is hard to increase the accuracy to predict fatigue in practical structures. One important measure to reduce the scatter in the fatigue lives tested in so-called "identical" specimens is to consider the initial crack size and distribution in great detail. As measuring systems improve, information about the initial crack size and distribution will be obtained more and more easily. To resolve the second difficulty, some methods have been proposed by Lam and Topper[64] to derive the curves of crack growth rate versus effective stress intensity factor range from effective strain fatigue life data.

3 Various factors of metal fatigue life

From the description of the fatigue mechanism given in Sect. 1, it is clear that many factors affect the fatigue life of metal structures. In this paper, these factors are grouped into four categories: (1) material factors; (2) structural factors; (3) loading factors; (4) environmental factors. We now briefly summarize the current state of knowledge about the effects of each of these factors.

3.1 Material effects

3.1.1 Basic material properties

Material type (e.g., brittle cast iron, ductile steel, aluminum, titanium) and processing conditions (e.g., reheat, cold form, hot forge, cold extrude, quenched, tempered), grain type and size, and fundamental material properties (Brinell hardness, modulus of elasticity E, yield strength at 0.2% offset YS, ultimate tensile strength S_u, percent elongation at fracture %EL, percent reduction in area %RA, true fracture strength σ_f, true fracture ductility ε_f, strength coefficient K, strain hardening exponent n; cyclic strength coefficient K', cyclic strain hardening exponent n', cyclic yield strength YS′, fatigue strength exponent b, and fatigue ductility exponent c) are all the important factors affecting the fatigue strength.

3.1.2 Effect of surface finishing

Because the initiation of microcracks is associated, in general, with a free surface, the fatigue strength of a material, particularly after a long time, as determined by testing a given batch of similar specimens, depends on the roughness and condition of the specimen surfaces created by the particular techniques used in their preparation. This effect of surface finish was extensively studied in the early days, and comprehensive experimental data were given by Frost et al.[4]

3.1.3 Fatigue limit or threshold

There are two types of fatigue threshold currently in use. One is the fatigue crack propagation threshold, which defines a loading criterion under which a crack will not grow significantly. The other is the fatigue limit, which defines a loading criterion under which significant cracks will not form.

Traditionally, most metals are thought of as having a fatigue limit at around 10^7 cycles. However, recent ultrasonic fatigue endurance tests on many alloys have shown that fatigue rupture can occur even at 10^9 cycles.[23,24] This poses questions about the existence of a fatigue limit in S–N curves.[25] However, ultrasonic fatigue crack growth test results have shown that there is very little difference between the thresholds observed at the rates of 10^{-9} and 10^{-7} mm/cycle.[65] This means that the fatigue crack growth threshold still exists. In some papers,[66,67] these two concepts are related. Thus, an inconsistency occurs. On this point, the latest opinion of Miller[8] is worth more attention. He suggested that the fatigue limits of a ferrous-based material, component, or structure can be very different in value and in nature. In an engineering structure, where defects of a length greater than 1 mm can exist, the fatigue limit should be related to the LEFM threshold condition $\mathrm{d}a/\mathrm{d}N = 0$ for long crack growth, i.e., ΔK_{th}. For a small component, designed to have no surface imperfections and so be able to sustain much higher cyclic stress levels, at which LEFM is no longer appropriate, the threshold condition $\mathrm{d}a/\mathrm{d}N = 0$ should be equated to Ξ in Eq. 21, while the fatigue limit of a material, in terms of both the cyclic stress level and the major microstructural barrier size d, see Eq. 24, is given by P in Fig. 4 for a polycrystalline metal. The fatigue limit terms ΔK_{th}, Ξ, and d are not directly related to one another, and each has to be determined experimentally.

When defining the fatigue limits of materials, components, and structures, Fig. 4 clearly shows that $\mathrm{d}a/\mathrm{d}N = 0$ is a continuous function and it is impossible to separate the two terms $\Delta\sigma\sqrt{a}$. Furthermore, any one of the

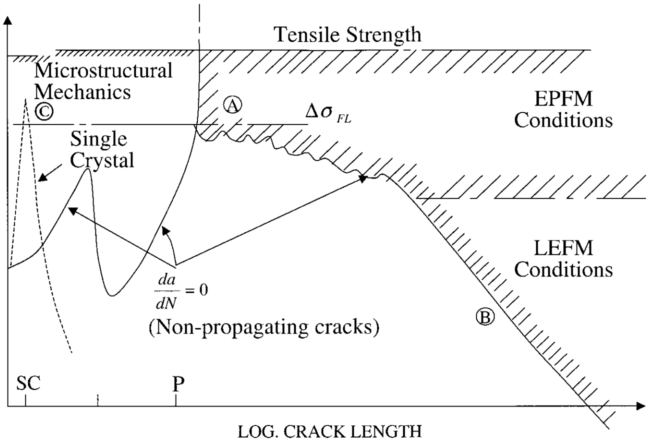

Fig. 4. The three fundamental fatigue limits of (*A*) a metal, (*B*) a structure, and (*C*) a single crystal

three fundamentally different fatigue limits should be quoted in terms of both a stress level and a non-propagating crack length. Once a microstructural barrier has been overcome, then the cyclic stress required to continue crack propagation decreases until the next barrier is approached. Once the major barrier has been overcome (the fatigue-limiting barrier of the material), crack growth will continue although the microstructural barriers ahead of the crack will continue to perturb the crack growth rate, albeit with an ever-decreasing effect. Under certain circumstances, for example corrosive environments or random loading, the three different fatigue limits of steels (material, component, structure) can be eliminated altogether, and current trends in internationally recognized engineering design codes will soon assume that no fatigue limits exist.

3.1.4 Initiation vs. propagation

It is still a commonly held view that the fatigue life of a material, component, or structure can be divided into an initiation phase and a propagation phase. This may well be true for a material that does not contain any form of defect, e.g., a 100% pure single crystal, which will require a defect to be cyclically manufactured. Some relaxation of the previously held view is now appearing in the literature, with the initiation period being subdivided into initiation plus microstructurally short crack growth phases. Nevertheless, six items of information need to be considered.[8]

1. Any kind of defect, however small, is a stress concentration (surface scratch, grain boundary, triple point, surface inclusion) which can readily give birth to a crack.
2. Fatigue cracks are frequently observed below the fatigue limits of steels, these having propagated but subsequently been arrested.
3. Micro- and macrodeformation responses in the form of the development of persistent slip bands (PSBs) can readily be observed by optical and electron microscopes since they are relatively large in comparison to initial cracks, which need only measure 0.1 × 0.1 microns but which are difficult to detect.
4. The engineering definition of an initiated crack has been decreasing steadily since the mid-nineteenth century from a length of several millimeters, to 1 mm, to $100\,\mu$m, to the size of a single grain, to a few microns (and eventually $0.1\,\mu$m or less?).
5. A crack of any size requires plasticity to grow, and should not need to wait for the establishment of a permanent slip band.
6. The introduction of the acoustic microscope can now distinguish between a slip band and a crack.

Because of these points, small crack growth (SCG) theories[8,16,68] are gradually becoming more popular. In these theories, it is assumed that the crack initiation period was zero, and that the whole lifetime was concerned with three phases of crack propagation, namely (i) a microscopic short crack propagation phase described by microstructural fracture mechanics (MFM), (ii) a physically small crack propagation phase described by elastic plastic fracture mechanics (EPFM), and (iii) a macroscopic long crack growth phase described by linear elastic fracture Mechanics (LEFM). With these theories, it can also be shown why cracks can and do propagate below any of the LEFM definitions of a threshold state. Indeed, any size of defect or fatigue crack can grow if the cyclic stress range is large enough.

3.1.5 Crack closure

Parallel to the flux about the threshold, the concept of crack closure and its significance is also under debate.[54–57,69,70]

Since Elber's discovery,[50] crack closure has been in fashion as the major mechanism of near-threshold fatigue. In many references,[68,71] this concept was greatly favored. Statements such as "crack closure has proved to be a key to the understanding of fatigue crack growth phenomena, like the effect of mean stress, threshold phenomena, short/long crack behavior, and load interaction effects" were frequently seen. Ritchie[13] listed around 15 different mechanisms of closure, which were classified as plasticity-induced, oxide-induced, roughness-induced, viscous fluid-induced, and phase transformation-induced.

However, strong criticism can also be found.[51] In particular, many people have agreed that the physical effects of crack closure have been greatly overestimated in the past.[52] A partial crack closure model[53–55] was proposed to overcome the difficulties with the crack closure model. Later, Kujawski[56,57] further demonstrated that without using the crack closure concept, it is possible to explain the stress ratio effect even better than by using the concept.

3.2 Structural effects

3.2.1 Structural geometry

It is obvious that the structural geometry decides the stress level and will affect the fatigue life. This effect has been fully accounted for in stress analysis.

3.2.2 Fabrication defects

Fatigue is mainly a local type of failure, and thus the defect geometry (size and distribution) will have a significant influence on fatigue life. Defect geometry will be greatly influenced by fabrication methods and quality control procedures. Currently, the macroscopic notch effects have been accounted for, but the micro-level defects have not yet been fully considered. This is the main reason for the wide scatter of fatigue test results.

One of the most important fabrication defects which result in fatigue are welds. Therefore, most of the existing fatigue design rules mainly concern fatigue of welded structures. One significant organization which produces fatigue design rules is the International Institute of Welding (IIW). The new IIW recommendations on fatigue of welded structures and on the assessment of weld imperfections have recently been updated.[72,73] This code contains all current fatigue assessment procedures, e.g., component testing, nominal stress, geometric (hot spot) stress and notch stress methods, and the fracture mechanics approach. The current situation concerning local approaches has recently been summarized by Radaj and Sonsino.[74]

3.2.3 Residual stresses

Fatigue damage accumulation is modeled using the stress range as the main parameter, and correcting the fatigue strength by the mean stress. Tensile mean stress reduces fatigue strength and compressive increases. In welded joints, the residual welding stresses can be regarded as mean stresses and therefore they will affect the fatigue strength. However, unlike the usual mean stress, residual stresses may have relaxation as a fatigue loading cycle. Stress peaks, tensile and compressive, affect the residual stresses in welded structures. Thus they will be changed during the fabrication and loading processes. The problems relating to residual welding stresses are[21]:

— how to model them accurately in the initial state;
— how to model their development during the lifetime of the structure;
— how to take their influence in fatigue damage accumulation into account.

3.2.4 Application of fatigue life improvement techniques

Fatigue life improvement can be achieved through various postweld treatments.[75] These include toe grinding, TIG remelting, shot peening, contouring, water-jet eroding, needle peening, spot heating, explosion treatment, plasma remelting, and hammer peening. Each employs at least one of the following strategies:

1. reduction of local stress concentration;
2. removal or neutralization of preexisting defects;
3. reduction of tensile residual stress and, by extension, the introduction of compressive residual stress.

Hammer peening results in the greatest improvement in high cycle fatigue performance of all the fatigue life improvement methods.

3.3 Loading effects

3.3.1 Mean stress effect

Fatigue tests have shown that a tensile mean stress resulted in shorter lives than a zero mean stress. A number of methods of allowing for the effect of mean stress have been reported. These include equations suggested by Goodman, Gerber, and Soderberg, and the Smith–Watson–Topper relationship. The best is probably the Smith–Watson–Topper relationship, which generally gives a good agreement with test data for many engineering materials. Kujawski and Ellyin[76] proposed a unified approach that would include all of the above approaches as special cases.

3.3.2 Variable amplitude loading

Fatigue crack growth under variable amplitude loading is usually accompanied by the load interaction phenomena, because of which the fatigue crack growth rate in a given load cycle can differ from the growth rate observed for the same cycle in constant-amplitude tests. The character and magnitude of load interaction effects depend in a complex way on loading variables, specimen geometry, material properties, microstructure, and environment. A comprehensive review of the load interaction effects during fatigue crack growth under variable amplitude loading was published by Skorupa,[77] and empirical trends were summarized. Depending on a particular combination of parameters related to the above-mentioned factors, variable amplitude load sequences of the same type can produce either retardation or acceleration in fatigue crack growth.

3.3.3 Multiaxial fatigue

Multiaxial fatigue was often treated with some equivalent stresses or other quantities. ISSC[78] listed most of them: von Mises's equivalent stress; maximum principal stress; equivalent stress based on crack opening displacement; maximum shear stress or strain; maximum shear strain and the normal strain acting on the shear plane; cyclic strain energy density. Experiments showed that a nonproportional loading history results in an order of magnitude shorter fatigue life than proportional loading when identical principal stress amplitudes are compared.

The application of fatigue damage accumulation models to welded joints is further aggravated by the true local geometry, including misalignments and defects. A book on multiaxial fatigue has recently been published by Socie and Marquis.[79] The applicability of different parameters for multiaxial fatigue was studied by Marquis et al.,[80] who proposed a modified critical plane approach.

A survey of 233 experimental biaxial constant amplitude fatigue test results from different sources was conducted by Bäckström and Marquis.[81] The results of four damage accumulation models were compared, including the hot spot, maximum principal stress range, maximum principal shear range, and critical plane approaches. The critical plane approach was found to be the most successful in resolving the experimental data on a single S–N line. However, significant scatter was still found.

3.3.4 *Frequency effects*

Many experiments[4] have shown that over the frequency range 1–200 Hz, the fatigue limit or strength after a long period of time of a material which does not heat up or whose surface is not chemically attacked during a test remains constant for all practical purposes, although there is, in fact, a slight increase with increasing test speed. At higher testing speeds, the fatigue limit continues to increase with testing speed up to frequencies of about 2 kHz, but beyond this frequency, the experimental data do not agree. There is evidence for and against a peak frequency beyond which the fatigue strength decreases with increasing frequency.

3.4 *Environmental effects*

Environmental effects on the fatigue of metals may be more severe than sharp stress concentrations or almost harmless. Quantitative fatigue life predictions are often not possible because of the many interacting factors that influence environmental fatigue behavior and the lack of significant data. Corrosion and temperature are the two main environmental factors affecting the fatigue behavior of metal structures.

3.4.1 *Corrosion*

Corrosion is defined as a physiochemical interaction between a metal and its environment which results in changes in the properties of the metal, and which often leads to an impairment of the function of the metal, the environment, or the technical system of which these form a part (ISO 8044-1986). Fatigue under a corrosive medium (known as corrosion fatigue) is a very complex problem.

Corrosion fatigue refers to the joint interaction of a corrosive environment and repeated stress. The combination of both actions together is more detrimental than either acting separately. That is, repeated stress accelerates the corrosive action, and the corrosive action accelerates the mechanical fatigue mechanisms. Corrosive environments may also be detrimental under static loads, particularly in higher strength alloys. Environmental assisted fracture under static loading is called "stress corrosion cracking."

In stress corrosion cracking, a limiting threshold value, K_{ISCC}, exists below which a crack is not observed to grow under that specific environment. This implies that repeated loads are not needed for cracks to extend if the applied stress intensity factors are above K_{ISCC}. Thus, a complex interaction exists between static and repeated loads in the presence of corrosive environments. Corrosion fatigue cracks can grow at stress intensity factors below K_{ISCC}.

Corrosion fatigue of a high-strength steel with UTS in the range 790–940 MPa was studied by Coudert and Renaudin.[82] Fatigue tests under a North Sea simulated wave-load history and cathodic protection showed improved crack growth propagation behavior compared with 50D steel. No significant hydrogen embrittlement was reported in this environment.

A considerable decrease in the fatigue strength of fillet welds due to corrosion wastage was observed by Yuasa and Watanabe.[83] The corrosion effect was studied using notched specimens of a 500 MPa-class steel by Kobayashi et al.[84] Clear differences in fatigue damage development were found as a function of notch stress relative to yield stress. Corrosion was observed to promote fatigue crack initiation for cases with a notch stress greater than yield stress. Kobayashi et al.[85] measured the corrosion rate and fatigue crack growth rate for a 500 MPa steel in synthetic seawater. Several useful findings were reported.

3.4.2 *Temperature*

At elevated temperatures, mean stress effects are extremely complex because of interactions among creep, fatigue, and environment. The linear elastic stress intensity factor K also has more limitations at elevated temperatures because of appreciable plasticity. A substantial reduction in fracture toughness can occur at low temperatures, which reduces critical crack sizes at fracture. Irradiation can reduce both fatigue resistance and fracture toughness. This is also a very important subject of research.[86]

3.4.3 *Maintenance*

Maintenance procedures also have a significant effect on the fatigue life of metal structures.

4 Unresolved problems for future attention

4.1 *Fundamental problems*

Metal fatigue has a history of more than 160 years, and much progress has been made in understanding fundamental fatigue mechanisms. By a judicious mixture of engineering judgement, testing, and calculation, and using existing fatigue life prediction methods, many fatigue failures in practical engineering structures have been successfully avoided. However, owing to the extreme difficulty of the problem, the theory of metal fatigue is far from complete. Many unsolved problems in the area of metal fatigue still exist. Schutz[3] pointed out six important examples.

1. The prediction of fatigue life under variable amplitude loading is still unsatisfactory. Neither the Palmgren–Miner calculation in its many variations nor the local-strain approach attain sufficient accuracy. The prediction of crack propagation under variable amplitude loading is better, but has not been sufficiently checked.
2. The transferability of fatigue data from small specimens to actual components or structures is completely unresolved. Many tests have shown that the damage sums to failure of actual components is much lower than those of specimens (size effect). Some concepts, such as the local-strain approach, blindly take transferability for granted, otherwise they cannot be used. This problem is, intentionally or unintentionally, passed over in silence.
3. Corrosion fatigue is another complex and unresolved problem. To date, there is no explanation of many of the effects observed. For example, why does even a few minutes in a corrosive medium have a detrimental effect which hardly increases even after several days.
4. The combination of high temperature and fatigue (creep plus fatigue) is largely unsolved.
5. Multiaxial fatigue stresses in variable amplitudes are unresolved, especially when there is no fixed correlation between the forces in different directions.
6. Another probably unsolvable problem is the scientifically and practically correct calculation of fatigue life at very low probabilities of failure. This is because the type of distribution would have to be known.

4.2 Probabilistic nature and scatter

Fatigue strengths have often been observed to show large scatter. Thus, many people have argued that fatigue strength (or life) is probabilistic in nature, and that probabilistic methods should be used. A cynical view might be that all probabilistic approaches are expressions of ignorance of one kind or another. As more detailed knowledge is acquired for a better quantitative understanding, the need for statistical treatments diminishes. Indeed, all too often statistics are applied to experimental results when basic results exist that would clarify the observed "scatter." Nevertheless, it cannot be denied that a lack of precise information exists in many practical applications where fracture is a concern. These situations are therefore candidates for probabilistic treatments.

Miller[8] requested that in the twenty-first century, serious attempts would be made to put scatter in a proper perspective, probably starting with the effects of different test variables on the three fundamental fatigue limits. Hence, for laboratory tests on materials, the scatter of microstructural variables on stage I cracks, such as grain size, barrier thickness, and strengths, now requires more detailed studies. With respect to components, the effects of slight changes in surface profiles and surface texture need to be separated, while for structures, the effect of minor variations in initial defect/crack sizes and external loading variables are very important. It needs to be recognized that a few overload cycles, and a transient change in the environment and/or temperature (including thermal shock) can have a far more serious consequence on tests to determine material behavior and stage I growth than, say, on a structure already containing a substantial stage II crack.

4.3 Computer simulation

The development of a computer simulation system to model fatigue behavior is the main purpose of fatigue research. The key problem is to establish an appropriate failure criterion under cyclic loading. Recent work shed some light in this direction.

Fujimoto and Hamada[67] proposed an inherent damage zone model to explain the fatigue properties of small-sized cracks near the fatigue limits and the crack growth threshold. The basic idea of this model is to assume that the stress at a point which is located a small distance from the crack initiation position governs the fatigue characteristics regardless of the geometric configuration of the specimen. A new fatigue crack propagation law is developed based on the inherent damage zone model. By comparison with experimental data, it is shown that this model is able to explain the propagation rate of small fatigue cracks, the effect of crack length on threshold conditions, the mechanism of nonpropagating cracks observed in notched specimens, and the necessary conditions for the occurrence of nonpropagating cracks in elliptic notches and circular holes.

Peeker and Niemi[87] proposed a new fatigue crack propagation model based on a local strain approach. If the cyclic strain is high enough, then the microcracks nucleate at microstructural defects, grow, and join together, leading to local material failure. Three existing concepts are applied in this model. The Coffin–Manson strain–life relationship is used to compute the number of load cycles to local material failure, the Ramberg–Osgood equations are used to model the cyclic nonlinear stress–strain behavior of the material, and Glinka's equivalent strain energy density (ESED) and ESED range criteria are used to compute the nonlinear stress as a function of linear elastic stress. They demonstrated that this new model is able to predict the fatigue behavior of components made of structural steel that have been subjected to any load history, have any geometry, and contain any distribution of residual stress introduced during manufacture.

5 Summary

This paper has carried out a review on metal fatigue, with particular emphasis on the latest developments in fatigue life prediction methods. These are divided into two categories: cumulative fatigue damage (CFD) theories, and fatigue crack propagation (FCP) theories. All the factors which affect the fatigue life of metal structures are grouped into four categories: material, structure, loading, and environment. The effects of these factors on fatigue behavior have also been addressed. Finally, potential problems to be resolved in future work have been pointed out.

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