

Article

A Fatigue Life Prediction Model of Aluminum Alloy Considering Crack Initiation

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Abstract

In high-cycle fatigue, the majority of fatigue life is spent in the crack initiation stage. However, current models fail to accurately capture the fatigue life consumed in the crack initiation stage, resulting in discrepancies in predictions. Here, we propose a fatigue life prediction model based on the crack tip plastic zone, combined with a multi-stage crack growth approach. To quantify the crack initiation life, a modified Tanaka–Mura model is developed by incorporating the effects of localized plastic deformation at the crack tip. The proposed model demonstrates good agreement with experimental observations. Furthermore, a reliability-based fatigue evaluation framework is established by introducing a fatigue safety factor formulation. The results show that the safety factor decreases with increasing applied stress levels, attributed to the reduced standard deviation and lower scatter of fatigue life at higher stresses. The findings provide a practical and physics-informed methodology for fatigue life and safety assessment of aluminum alloy components under complex cyclic loading conditions.

Keywords: fatigue life prediction; crack initiation model; crack tip plastic zone; safety factor; reliability analysis

1. Introduction

Fatigue crack initiation plays a pivotal role in the overall fatigue failure process, particularly under high-cycle fatigue conditions, where failure typically occurs after 10^4 to 10^7 loading cycles [1–5]. In many engineering applications, components are subjected to alternating stresses well below their static strength limits, making fatigue the dominant failure mode. As such, accurate prediction of fatigue life under cyclic loading has become a crucial area of research for ensuring safety, reliability, and cost-effectiveness in structural design [6–8].

Traditional *S-N* curve-based models rely heavily on empirical fitting and often fail to explicitly account for critical microstructural factors and loading condition variability [9,10]. To address these shortcomings, Tanaka and Mura [11] proposed a crack initiation life model based on dislocation theory, establishing for the first time a quantitative relationship between grain size and fatigue life. Building on this foundation, Chan et al. [12] extended the theory to incorporate the influence of slip bands and inclusions, refining the fatigue response equation with more representative parameters. Further advancements were made by Sangid et al. [13], who proposed a microstructure-sensitive model integrating grain boundary characteristics, the energetic stability of slip bands, and their statistical



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distributions [14]. This work offered a more detailed understanding of how factors such as grain size distribution, crystallographic orientation, and boundary misorientation affect fatigue crack nucleation [15]. These developments marked a significant shift toward the use of microstructural mechanics and crystallographic data in fatigue life assessment. In parallel, Fan et al. [16] proposed a hybrid approach combining a Z-parameter-based physical model with neural network algorithms to predict fatigue life in the very high cycle fatigue (VHCF) regime. This framework effectively captured the effects of defect size, spatial location, and stress amplitude during the crack initiation phase. Moreover, it demonstrated superior predictive accuracy compared to conventional empirical methods, especially in scenarios involving internal defects and small cracks.

Fatigue failure is a complex and progressive phenomenon that typically comprises two distinct stages: crack initiation and crack growth. Once the crack exceeds a critical threshold length, it enters the growth phase, which itself can be divided into short crack and long crack propagation regimes [17–20]. While the behavior of long cracks is relatively well understood and can be effectively predicted using established models such as the NASGRO equation, short crack growth remains a significant challenge due to its complex and often material-specific nature [21]. In fact, the short crack growth phase frequently constitutes the majority of the total fatigue life, making its accurate prediction crucial for reliable fatigue assessment [22–24]. Various models have been proposed to address this issue; however, many require extensive material-specific parameters that are difficult to obtain in practice. To alleviate this challenge, the equivalent initial flaw size (EIFS) methodology has gained widespread acceptance [25,26]. The central idea of EIFS is to introduce a hypothetical initial crack size that enables fatigue life predictions to align closely with experimental observations, thereby bridging the gap between theory and real-world performance [27].

In parallel, the accurate determination of fatigue safety factors is of paramount importance in ensuring structural reliability in engineering applications. Traditional approaches often rely on empirical margins and do not fully capture the complexities of actual service conditions, such as variable loading environments and material degradation, which can lead to either overly conservative designs or unforeseen failures [28–32]. Recognizing these limitations, recent research has shifted toward data-driven and probabilistic methods that enhance the scientific robustness of safety assessments. Li et al. [33] employed generative adversarial networks and feature extraction to enhance safety factor prediction under limited data. Baro et al. [34] introduced probabilistic safety factors using Weibull-based stress-strength analysis to account for uncertainty. Building on this, Su et al. [35] proposed a Bayesian backward propagation method for fatigue failure updating in orthotropic steel decks, while Kakaie et al. [36] applied Bayesian updating and fracture mechanics to evaluate the fatigue reliability of corroded pipelines. Xu et al. [37] further combined response surface models with dynamic Bayesian networks to update fatigue reliability of deepwater risers. Despite these advances, many proposed methods remain computationally intensive and challenging to implement in routine design workflows. Consequently, there is a growing need for practical, quantitative approaches that integrate fatigue test data, reliable predictive models, and statistical evaluation frameworks to provide engineers with a more balanced and implementable safety factor design methodology.

In response to these ongoing challenges, the present study proposes a novel fatigue life prediction framework that accounts for the evolution of the plastic zone at the crack tip within a multi-stage crack growth process. By incorporating the plastic zone development, the model more accurately captures the transition from microstructural crack initiation to stable crack growth. Additionally, this work introduces a probabilistic fatigue safety factor evaluation method that synthesizes experimental fatigue test results

and statistical variability analysis to provide a more realistic and service-oriented safety margin estimation.

Together, these innovations aim to bridge the gap between theoretical fatigue modeling and engineering application, ultimately contributing to safer and more efficient structural component design.

2. Theory Background

2.1. Crack Initiation Model

To estimate the fatigue crack initiation life under different stress levels, Tanaka and Mura proposed a model based on the accumulation of dislocation dipoles [11]. This model quantitatively describes the relationship between crack initiation life and various microstructural and macroscopic material parameters as follows:

$$(\Delta\tau - 2k)^2 N_i = \frac{4\mu W_s}{\pi(1-\nu)d} \quad (1)$$

where N_i is the number of cycles required for crack initiation, $\Delta\tau$ is the shear stress range, k is the dislocation friction stress, μ is the shear modulus, W_s is the fracture energy per unit area of the slip band, ν is the Poisson's ratio, and d is the grain size.

To improve the applicability of this model to cracks initiated by both slip bands and inclusions, Chan et al. introduced an optimized model [12]:

$$n_c = 0.05 \left(\frac{d}{bh} \right) \sqrt{\frac{cW_{eq}}{d\mu}} \quad (2)$$

$$W_{eq} = 2d\gamma_s \quad (3)$$

$$c = n_c b \quad (4)$$

$$c = 0.005 \left(\frac{d}{h} \right)^2 \left(\frac{\gamma_s}{\mu} \right) \quad (5)$$

where n_c is critical number of dislocations, b is the Burgers vector coefficient, c is the crack length, W_{eq} is the equivalent dislocation strain energy within the slip band, and h is the width of the slip band. γ_s is the surface energy of the crack.

Based on Equations (1)–(5), the crack initiation life can be expressed as:

$$(\Delta\tau - 2k)N_i^{1/2} = \left[\frac{8\mu^2}{0.005\pi(1-\nu)} \right]^{1/2} \left(\frac{h}{d} \right) \left(\frac{c}{d} \right)^{1/2} \quad (6)$$

In polycrystalline materials, fatigue crack initiation is influenced by the relationship between the macroscopic applied stress amplitude $\Delta\sigma$ and the shear stress range on the slip plane $\Delta\tau$, characterized by the Taylor factor M . To better align with experimental data, the model can be further corrected by introducing a fitting parameter α , yielding:

$$(\Delta\sigma - 2Mk)N_i^\alpha = \left[\frac{8M^2\mu^2}{0.005\pi(1-\nu)} \right]^{1/2} \left(\frac{h}{d} \right) \left(\frac{c}{d} \right)^{1/2} \quad (7)$$

The W_s can be expressed as:

$$W_s = \frac{\Delta K_{th}^2}{2E} \quad (8)$$

where K_{th} is threshold stress intensity factor range and E is modulus of elasticity.

To account for corrections to the S - N curve, Yang et al. [38] proposed a model that introduces a fitting factor β , leading to:

$$N_i = \beta \frac{9 \times 10^{11} G W_s}{(\Delta\sigma - \sigma_w)^2 a_0} \quad (9)$$

$$\beta = \begin{cases} \frac{l}{a_0} \left(1 + \frac{\sigma_s}{A\Delta\sigma} \right)^{\left[\frac{\sigma_s}{B(\Delta\sigma - \sigma_w)} \right]}, & \Delta\sigma \leq 0.525\sigma_s \\ \frac{l}{a_0}, & \Delta\sigma > 0.525\sigma_s \end{cases} \quad (10)$$

where G is shear modulus, σ_w is fatigue limit, a_0 is initial flaw size/inclusion size, l is characteristic length, and σ_s is yield strength of material under Yang model.

As reviewed above, the Chan model, although comprehensive, requires multiple additional parameters, limiting its convenience in engineering applications. The Yang model also involves multiple empirical coefficients.

In contrast, the model proposed in this study requires fewer fitting parameters while incorporating the effects of the plastic zone near the crack tip, thus providing improved predictive accuracy with enhanced engineering applicability.

2.2. Safety Factor Model

The material safety factor, as a key indicator for evaluating the safety margin of materials under load, plays a crucial role in engineering applications [32,39]. In current engineering practice, the safety factor is generally defined as shown in Equation (11):

$$SF = \frac{\sigma_s}{[\sigma]} \quad (11)$$

where σ_s is ultimate stress; $[\sigma]$ is allowable stress.

For different types of materials, the ultimate stress exhibits distinct forms and meanings. For example, in plastic materials, when the applied stress reaches a certain threshold, significant plastic deformation occurs. This threshold is referred to as the yield strength, which is commonly taken as the ultimate stress for plastic materials. Once yielding occurs, deformation becomes irreversible, potentially altering the geometry of the structure and compromising its intended functionality.

In contrast, brittle materials do not exhibit an evident plastic deformation stage. Their deformation remains minimal until fracture occurs. Therefore, the ultimate stress for brittle materials is typically defined as the tensile strength σ_b , i.e., the stress value at fracture.

However, this conventional approach is often unsuitable for complex service conditions, where materials may still fail at stress levels below the allowable stress. To address this, a fatigue factor is introduced into the safety factor calculation.

Assume a set of equations, as expressed in Equation (12):

$$y = g(x_1, x_2, \dots, x_n) \quad (12)$$

where y is the dependent variable and $x_1, x_2, \dots, x_n$ are the independent variables.

Taking fatigue life as an example, y is typically selected as the fatigue life, while the primary independent variable is the stress level. The above formulation can then be transformed into an equation suitable for fatigue life, as given in Equation (13), which retains the same meaning:

$$y = N = g(\sigma) \quad (13)$$

where N is the fatigue life and σ is the stress level.

Assuming that y or its logarithmic form follows a normal distribution [40], its probability density function (PDF) is given in Equation (14), and its cumulative distribution function (CDF) is given in Equation (15). The reliability can be calculated using Equation (16):

$$f(y) = \frac{1}{s\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{y-\mu}{s}\right)^2\right], -\infty < y < +\infty \quad (14)$$

$$F(y) = \int_{-\infty}^y \frac{1}{s\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{y-\mu}{s}\right)^2\right] dy \quad (15)$$

$$R(y) = 1 - F(y) = 1 - \int_{-\infty}^y f(a) da \quad (16)$$

where $f(y)$ is the probability density function, s is the standard deviation, μ is the sample mean, $F(y)$ is the cumulative distribution function, $R(y)$ is the reliability function, and y is the upper limit of integration.

In this formulation, a specific upper integration limit μ_p is introduced, corresponding to the standard normal distribution function for a given failure probability, enabling the derivation of a fatigue life curve equation with a specified reliability:

$$y_1 = g(x_1, x_2, \dots, x_n) + \mu_p \times s \quad (17)$$

where μ_p is the specific upper integration limit and s is the standard deviation.

From Equation (17), a safety factor formula incorporating specific dependent and independent variables can be obtained, as expressed in Equation (18). Taking x_i as an example, by keeping the dependent variable in Equations (12) and (17) and other independent variables constant while varying only x_i , two distinct values, x_i and x'_i , can be determined. Reliability is then linked to the safety factor by combining Equations (11), (12) and (17), leading to the fatigue life safety factor equation (Equation (18)), which enables calculation of the safety factor for a given reliability and working stress:

$$SF = \frac{x_i}{x'_i} \quad (18)$$

where x_i is the fatigue strength and x'_i is the working stress at the specified reliability. Notably, x_i and x'_i in Equation (18) are the independent variables in Equations (12) and (17), obtained while maintaining constant fatigue life as the dependent variable. For instance, the safety factor at a given reliability is derived from the mean trend line and the fatigue life curve at that reliability (see in Figure 1). Two stress values corresponding to the specified reliability are determined, and the safety factor is defined as the ratio of these two stresses. The relevant fatigue test data used in this study are obtained from the literature [40], and the experimental work itself is not included in this paper.

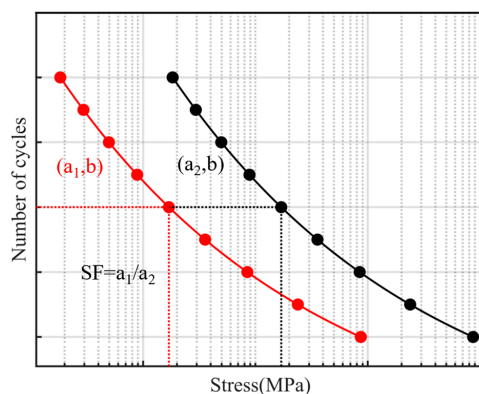


Figure 1. Safety factor at a given reliability.

3. Results and Discussion

3.1. Fatigue Life Prediction Model Considering the Crack Tip Plastic Zone

Figure 2 presents the S - N data for 6082 aluminum alloy, fitted using Basquin's law (Equation (19)) to describe the fatigue life behavior.

$$\sigma = a(2N_f)^b \quad (19)$$

where a is fatigue strength parameter and b is fitting parameter.

If the traditional method is adopted, where the fatigue strength at 10^7 or 10^8 cycles is defined as the fatigue limit σ_f , the resulting fatigue strength values σ_f would be 152.1 MPa and 130 MPa, respectively. However, as shown in Figure 2, the S - N curve continues to decrease monotonically within the range of 10^6 to 10^9 cycles [41]. Therefore, we define the fatigue strength at a cycle count of 10^9 as the fatigue limit σ_f , which is found to be 103.8 MPa. This refined limit is particularly significant for preventing fatigue failure, a critical risk that initiates below elastic limits.

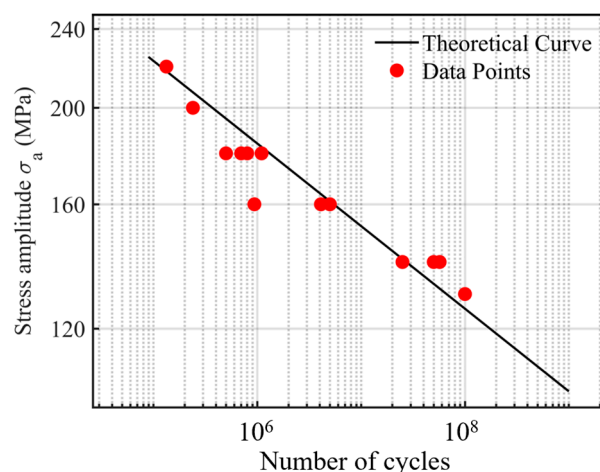


Figure 2. S - N curve of 6082 aluminum alloy.

Fatigue life is typically divided into three stages: crack initiation, short crack growth, and long crack growth. Current mainstream models generally fail to systematically consider the damage evolution mechanism during the crack initiation stage. Traditional theoretical models are often based on idealized assumptions, either assuming instantaneous crack formation in defect-free materials or focusing solely on the fracture mechanics behavior during the macro crack growth stage. This simplification in theory has led to a lack of in-depth understanding of the microcrack nucleation mechanism and its stable growth during the early stages, particularly the significant plastic deformation generated in localized regions of the material under cyclic loading and its cumulative damage effect on fatigue life, which has not been effectively quantified [1,42].

In practical materials, especially ductile materials, the crack tip, as shown in Figure 3a, undergoes plastic deformation, which consumes additional energy. The plastic zone not only affects the stress–strain distribution but may also dominate the crack initiation location, path, and growth rate. Neglecting the effect of plastic energy dissipation during the crack initiation phase can lead to deviations in fatigue life predictions [43,44]. To incorporate the influence of the crack tip plastic zone into fatigue life prediction, we introduce the crack tip plastic zone. Based on the Dugdale–Barenblatt model in Figure 3b [45,46], the modified stress intensity factor range can be expressed as:

$$\Delta K_{eff} = \Delta K_{th} \sqrt{1 + \frac{r_p}{a}} \quad (20)$$

where a is the crack length, and the plastic zone size r_p is approximated as:

$$r_p = \frac{\pi}{8} \left(\frac{\Delta K_{th}}{\sigma_y} \right)^2 \quad (21)$$

Substituting into the original formula, the modified fracture energy can be expressed as:

$$W_s = \frac{\Delta K_{eff}^2}{2E} = \frac{\Delta K_{th}^2}{2E} \left[1 + \frac{\pi}{8a} \left(\frac{\Delta K_{th}}{\sigma_y} \right)^2 \right] \quad (22)$$

where σ_y is the yield stress.

The modified fracture energy W_s in Equation (22) explicitly incorporates the contribution of the plastic zone at the crack tip. Physically, this energy term quantifies the dissipated energy per unit area due to plastic deformation under cyclic loading. This aligns with the energy dissipation framework proposed by Kassapoglou [43], where fatigue crack initiation is driven by the accumulation of local plastic strain energy. The parameter ΔK_{eff} captures the shielding effect induced by the plastic zone, and the correction term Equation (22) effectively accounts for microstructural constraints such as grain size and yield strength. As such, Equation (22) provides a physics-based representation of crack tip energy dissipation, bridging macroscopic fracture mechanics with microscale plasticity mechanisms [47].

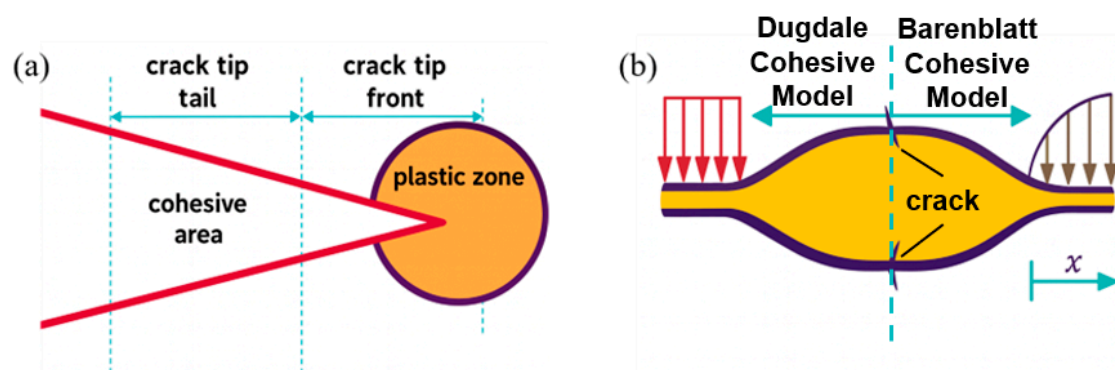


Figure 3. Comparative schematic of crack tip structure and Dugdale–Barenblatt model: (a) Detailed crack tip structure showing tail, front and plastic zone; (b) Dugdale–Barenblatt theoretical model.

Combining Equations (1) and (22) yields the formula for crack initiation life.

$$(\Delta\sigma - 2Mk)N_i^\alpha = \left[\frac{2M^2\Delta K_{th}^2}{\pi d [1-\nu]^2} \right]^{\frac{1}{2}} \left[1 + \frac{\pi}{8a} \left(\frac{\Delta K_{th}}{\sigma_y} \right)^2 \right]^{\frac{1}{2}} \quad (23)$$

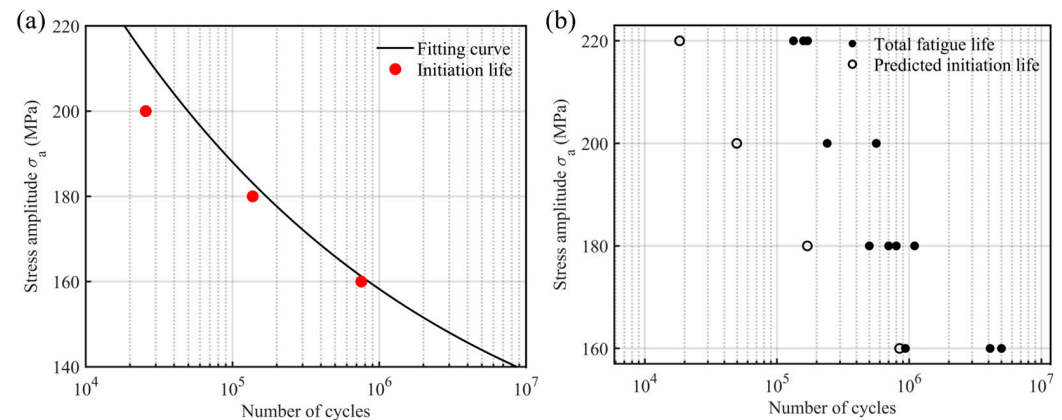
where $\Delta\sigma$ is the loading stress range and M is the Taylor factor, which is generally 2, $2Mk$ represents the fatigue limit.

In this study, we assume that the crack initiation phase ends and the crack growth phase begins when the crack length reaches one grain size, i.e., $a = d$. The other parameters can be obtained by fitting experimental data.

Parameters within the equation were calibrated by fitting experimental crack initiation life data; their values are listed in Table 1. The resulting crack initiation life curve, calculated using Equation (23), is shown in Figure 4a. This curve demonstrates good agreement with the experimental results, with improved fitting accuracy observed at higher fatigue lives. Figure 4b illustrates the relationship between the predicted crack initiation life and the total fatigue life. Analysis of this figure indicates a substantial increase in crack initiation life as stress decreases. Additionally, crack initiation constitutes a progressively larger fraction of the total life at lower stresses, ultimately dominating near the fatigue limit.

Table 1. Parameters of the crack initiation model of 6082.

$d/\mu\text{m}$	μ/MPa	ν	σ_y/MPa	$\Delta K_{th}/\text{MPa}\cdot\text{m}^{1/2}$	$a/\mu\text{m}$	α
15.12	27,000	0.3	325	1.1	15.12	0.22

**Figure 4.** Prediction of fatigue crack initiation life: (a) parameter fitting, (b) crack initiation life.

Fatigue crack growth life typically consists of two parts: short crack growth life and long crack growth life. Experimental results indicate that the short crack growth life accounts for the majority of the total crack growth life in 6082 aluminum alloy.

Therefore, predicting the fatigue life during the short crack growth phase is highly complex. However, studies have found that short crack growth is highly sensitive to microstructural features. To address this issue, Li et al. [27] have applied the equivalent initial flaw size (EIFS) method to predict the short crack growth life.

The crack growth rate curve obtained through experiments can be used to predict the crack growth life. In this study, the Nasgro equation is employed to obtain the crack growth rate curve:

$$\frac{da}{dN} = C \left(\Delta K_{eff} \right)^m \frac{\left(1 - \frac{\Delta K_{th}}{\Delta K} \right)^p}{\left(1 - \frac{K_{max}}{K_{IC}} \right)^q} \quad (24)$$

where C , m , p and q are the parameters obtained through fitting, da/dN is the crack growth rate, ΔK_{eff} is the effective stress intensity factor range, ΔK_{th} is the threshold stress intensity factor, ΔK is the stress intensity factor range, K_{max} is the maximum stress intensity factor, and K_{IC} is the fracture toughness.

The effective stress intensity factor range ΔK_{eff} can be obtained using the following equation:

$$\Delta K_{eff} = \left(\frac{1-f}{1-R_{eff}} \right) \Delta K \quad (25)$$

where R_{eff} is the effective stress ratio, which can be obtained using the following equation:

$$f = \frac{K_{max}}{K_{op}} = \begin{cases} \max(R_{eff}, A_0 + A_1 R_{eff} + A_2 R_{eff}^2 + A_3 R_{eff}^3) & R_{eff} \geq 0 \\ A_0 + A_1 R_{eff} & -2 \leq R_{eff} < 0 \\ A_0 - 2A_1 & R_{eff} < -2 \end{cases} \quad (26)$$

$$A_0 = \left(0.825 - 0.34\alpha + 0.05\alpha^2 \right) \left[\cos \left(\frac{\pi \sigma_{max}}{2\sigma_{av}} \right) \right]^{1/\alpha} \quad (27)$$

$$A_1 = (0.415 - 0.071\alpha) \frac{\sigma_{max}}{\sigma_{av}} \quad (28)$$

$$A_2 = 1 - A_0 - A_1 - A_3 \quad (29)$$

$$A_3 = 2A_0 + A_1 - 1 \quad (30)$$

where A_0 , A_1 , A_2 , and A_3 are the relevant coefficients in the Nasgro equation, σ_{max} is the maximum load stress, and σ_{av} is the flow stress. Under the approximate plane strain condition, it is assumed that $\sigma_{max}/\sigma_{av} = 0.3$ and $\alpha = 3$ [48].

Typically, the Nasgro equation is only applicable for predicting the long crack growth life. Therefore, to predict the short crack life, the EIFS method can be employed to extend the Nasgro equation from the long crack phase to the short crack phase [27]. The EIFS method involves selecting a crack length such that the short crack growth zone is equivalent to a portion of the long crack growth zone. This approach effectively circumvents the challenges associated with predicting the life of short cracks. As illustrated, the core of the EIFS method is to identify an appropriate initial crack size that equates the areas of S_1 and S_2 , as depicted in Figure 5, thereby ensuring that the predicted crack growth life using the equivalent method aligns with the actual observed crack growth life.

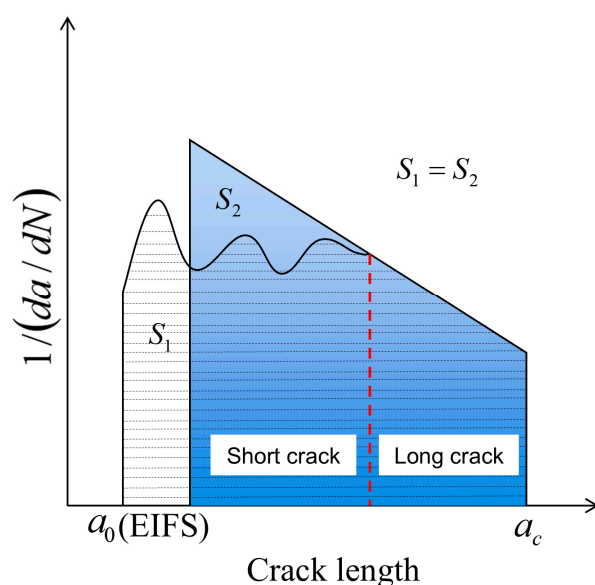


Figure 5. Schematic diagram of the EIFS method principle.

The EIFS-related parameters can be obtained using the following equation:

$$\Delta K = F\Delta\sigma\sqrt{\pi a} \quad (31)$$

$$a_0 = \frac{1}{\pi} \left(\frac{\Delta K_{th}}{F\Delta\sigma_f} \right)^2 \quad (32)$$

$$a_f = \frac{1}{\pi} \left(\frac{K_{IC}}{F\sigma_a} \right)^2 \quad (33)$$

where F is the geometric correction factor and $\Delta\sigma_f$ is the fatigue limit.

The crack growth life can be calculated using the following equation:

$$N_f = \int_{a_0}^{a_f} \frac{\left(1 - \frac{K_{max}}{K_{IC}}\right)^q}{C \left(\Delta K_{eff}\right)^m \left(1 - \frac{\Delta K_{th}}{\Delta K}\right)^p} da \quad (34)$$

The crack growth-related parameters are listed in Table 2. As shown in Figure 6a, the fitted crack growth rate curve indicates that the experimental data points exhibit typical characteristics of the Paris regime, where the crack growth rate (da/dN) shows

an approximately linear relationship with the stress intensity factor range (ΔK) in a semi-logarithmic coordinate system, and da/dN increases significantly as ΔK increases. The fitted curve matches the experimental data well, indicating that the crack growth model accurately describes the fatigue crack growth behavior of the material. The fitted crack growth life is shown in Figure 6b, where the curve exhibits a nonlinear decline, and the data points are uniformly distributed, suggesting that the experimental data is consistent and exhibits regularity. Figure 6 demonstrates that the Nasgro equation provides a good fit for the crack growth rate and crack growth life of 6082 aluminum alloy. The fatigue initiation life and crack growth data for 6082 aluminum alloy are taken from the literature [40].

Table 2. Parameters of the crack growth model of 6082.

$K_{IC}/\text{MPa}\cdot\text{m}^{1/2}$	$\Delta K_{th}/\text{MPa}\cdot\text{m}^{1/2}$	p	q	C	m
20.0	1.1	0.93	0.72	9.25457×10^{-11}	4.059

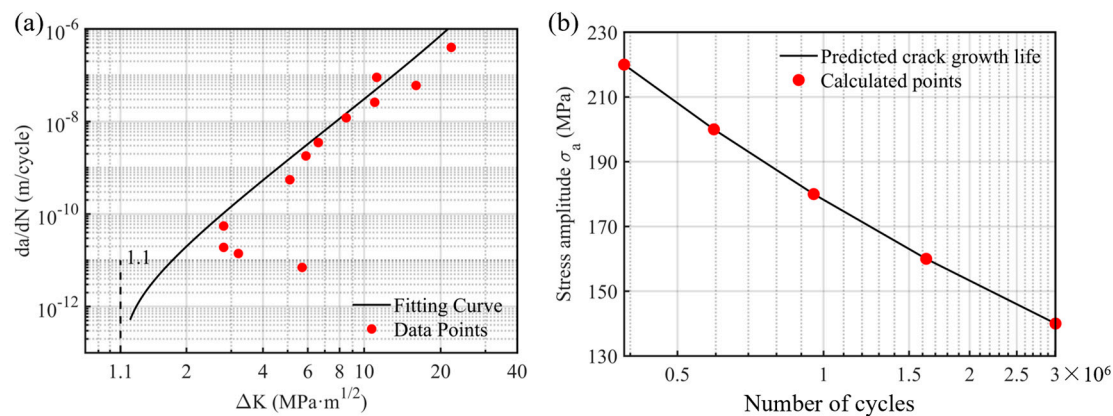


Figure 6. Fatigue Crack Growth Behavior and Life Prediction: (a) crack growth rate; (b) crack growth life prediction.

The total fatigue life can be obtained using Equations (23) and (34), as shown in Equation (35):

$$N = \left[\frac{\sqrt{\frac{2M^2\Delta K_{th}^2}{\pi d(1-\nu)^2}} \cdot \sqrt{1 + \frac{\pi}{8a} \left(\frac{\Delta K_{th}}{\sigma_y} \right)^2}}{\sigma_a - 2Mk} \right]^{1/\alpha} + \int_{a_0}^{a_f} \frac{\left(1 - \frac{K_{max}}{K_{IC}}\right)^q}{C(\Delta K_{eff})^m \left(1 - \frac{\Delta K_{th}}{\Delta K}\right)^p} da \quad (35)$$

Equation (35) is shown in Figure 7a. By comparing the predicted fatigue life of 6082 aluminum alloy with the experimental data, the results indicate that the fitted curve can accurately describe the material's fatigue life evolution, validating the applicability of the model. It was also observed that the prediction error increased in the high-stress region, which may be due to the scatter of the experimental data and deviations in the fitting parameters [49]. Another explanation is that the small-scale yielding (SSY) assumption is less valid at high stress levels. When the stress amplitude approaches the yield strength, large-scale plastic deformation accelerates damage beyond the model's linear expectations. Additionally, multiple crack initiation and coalescence at high stresses can further reduce the total life. Our single-crack framework does not account for these interactions. Therefore, the model is most effective in the HCF regime where SSY conditions are strictly met. Furthermore, based on the model calculations, the proportion of microcrack initiation life and crack growth life under varying stress levels is illustrated in Figure 7b. It can be

observed from the figure that at high stress levels, the crack growth phase dominates the total fatigue life. However, as the applied stress decreases, the proportion of microcrack initiation life gradually increases. This trend highlights the growing significance of the initiation phase under low-stress conditions, indicating the necessity to consider both stages comprehensively in fatigue life assessments across different loading scenarios.

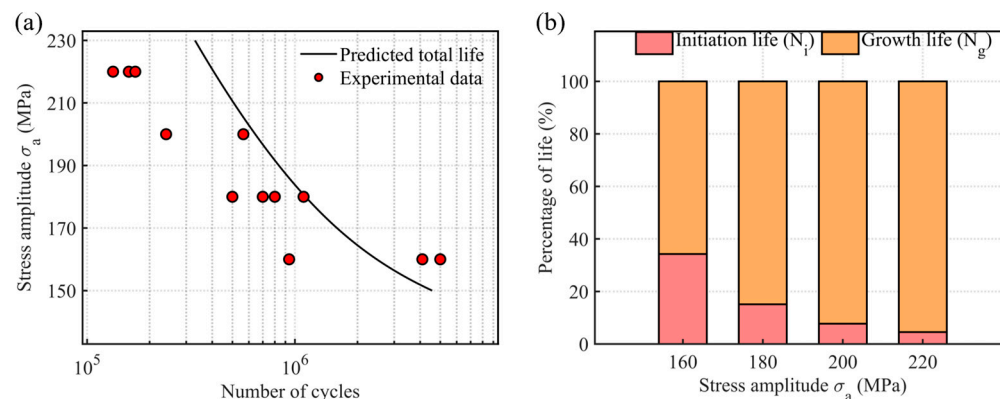


Figure 7. Total fatigue life prediction: (a) Comparison of predicted total life with experimental fatigue life. (b) The proportions of crack initiation life and crack growth life under different loading stresses.

3.2. Safety Factor Model Based on Reliability

This section applies the previously established fatigue life model to compute safety factors and analyze reliability under various stress conditions. The analysis yields the material's safety factor corresponding to a specified reliability level and the associated required fatigue strength. Extensive studies have demonstrated that the logarithm of fatigue life conforms to a normal distribution. Accordingly, the logarithmic fatigue life equation in Equation (36) is employed. By incorporating the target reliability, the lower bound stress in Equation (37) is subsequently derived. Combining Equations (36) and (37) yields the safety factor in Equation (38).

$$\lg(N) = \lg \left\{ \left[\frac{\sqrt{\frac{2M^2 \Delta K_{th}^2}{\pi d(1-\nu)^2}} \cdot \sqrt{1 + \frac{\pi}{8a} \left(\frac{\Delta K_{th}}{\sigma_y} \right)^2}}{\sigma_1 - 2Mk} \right]^{1/\alpha} + \int_{a_0}^{a_f} \frac{\left(1 - \frac{K_{max}}{K_{IC}}\right)^q}{C(\Delta K_{eff})^m \left(1 - \frac{\Delta K_{th}}{\Delta K}\right)^p} da \right\} \quad (36)$$

$$\lg(N) = \lg \left\{ \left[\frac{\sqrt{\frac{2M^2 \Delta K_{th}^2}{\pi d(1-\nu)^2}} \cdot \sqrt{1 + \frac{\pi}{8a} \left(\frac{\Delta K_{th}}{\sigma_y} \right)^2}}{\sigma_2 - 2Mk} \right]^{1/\alpha} + \int_{a_0}^{a_f} \frac{\left(1 - \frac{K_{max}}{K_{IC}}\right)^q}{C(\Delta K_{eff})^m \left(1 - \frac{\Delta K_{th}}{\Delta K}\right)^p} da \right\} + \mu_p \times s \quad (37)$$

$$SF = \frac{\sigma_1}{\sigma_2} \quad (38)$$

where σ_1 and σ_2 represents the stress level, μ_p is the upper integration limit corresponding to the desired reliability, and s is the standard deviation.

Experimental data reveal substantial variations in the scatter of fatigue life across different stress levels. To characterize the relationship between life scatter and the applied stress, this study proposes a log-linear model, expressed as:

$$\lg s = A + B\sigma \quad (39)$$

where A and B are regression coefficients determined by fitting standard deviations of fatigue life obtained from grouped fatigue tests at various stress levels. The resulting standard deviation curve is illustrated in Figure 8.

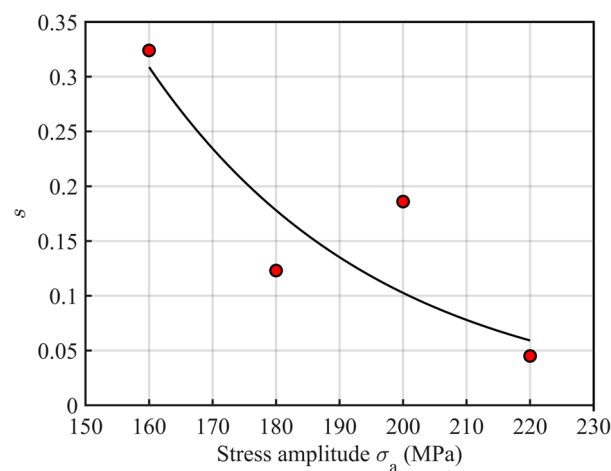


Figure 8. Effect of stress level on the dispersion of fatigue life.

As shown in Figure 8, the standard deviation of fatigue life generally decreases with increasing stress level and exhibits notable fluctuations across the stress range. Using a constant standard deviation for all calculations may result in inaccuracies across different stress levels. Therefore, the fitted curve effectively captures the stress-dependent variation in the fatigue life standard deviation.

This reduction in variability at higher stress levels is due to a change in the fatigue mechanism. At lower stresses, the crack initiation phase dominates the total life. This phase is highly sensitive to random microstructural features like grain orientation. Therefore, the data shows significant scatter. At higher stresses, cracks initiate almost immediately. The life is then dominated by the crack growth phase. Macroscopic mechanical driving forces control crack growth, which is less sensitive to microscopic randomness. As a result, the fatigue life becomes more deterministic and less variable.

The variation of the safety factor with respect to stress level under different reliability levels is presented in Figure 9a, covering the range of 160–220 MPa. At a fixed reliability level, the safety factor decreases as the applied stress increases. This trend is attributed to the fact that higher stress levels correspond to smaller fatigue life standard deviations and reduced data scatter, thereby resulting in a lower safety factor. Conversely, for a fixed stress level, the safety factor increases with higher reliability requirements. For example, at 160 MPa, the safety factor is 1.13 for 80% reliability, increasing to 1.28 for 95% reliability.

When a safety factor of 1.25 is required, Figure 9a shows that this value exceeds the safety factor range corresponding to 95% reliability. This implies that a safety factor of 1.25 is more conservative than necessary for 95% reliability, potentially leading to overdesign and increased manufacturing costs. Additionally, the intersection between the safety factor curve for 99% reliability and the 1.25 threshold occurs at 181 MPa. Thus, for stress levels below 181 MPa and under 99% reliability, the proposed method yields more stable safety factors.

Figure 9b further illustrates the relationship between reliability and stress level. At a given safety factor, reliability increases with increasing stress. As described in the previous chapter, at a fixed reliability level, higher stress results in a smaller safety factor and thus a narrower safety margin. Conversely, under a constant safety factor, higher stress levels correspond to higher reliability, while lower stress levels yield lower reliability.

These findings indicate an inverse relationship between safety factor and stress at a given reliability and between reliability and stress at a given safety factor.

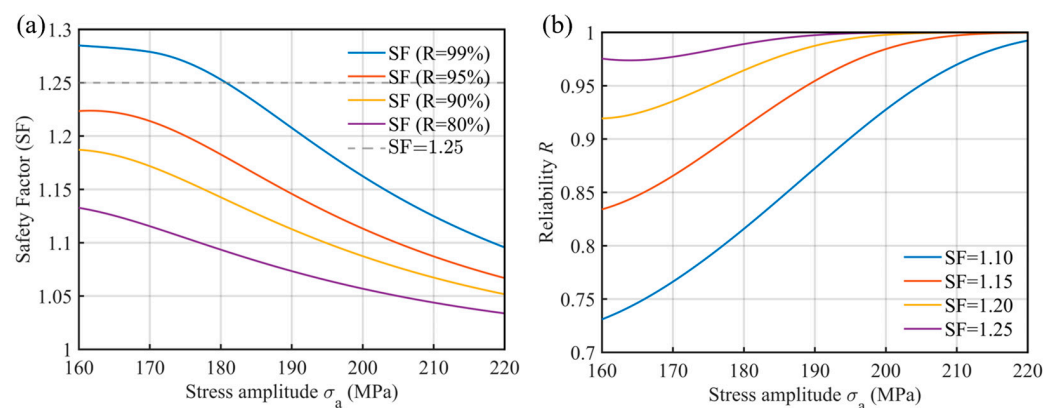


Figure 9. Correlation between reliability and safety factor: (a) safety factors at various stress levels for a given reliability, (b) reliability at various stress levels for a given safety factor.

To further illustrate the effect of data scatter, a representative case with 95% reliability and a safety factor of 1.2 is selected; analogous conclusions can be drawn for other combinations. The relationship between stress level and temperature under different standard deviations (i.e., $0.8s$, s , and $1.2s$) is depicted in Figure 10a. Larger standard deviations result in higher required safety factors due to increased data scatter, which shifts the 95% reliability curve further from the mean. Consequently, a larger margin is necessary to maintain the same reliability level.

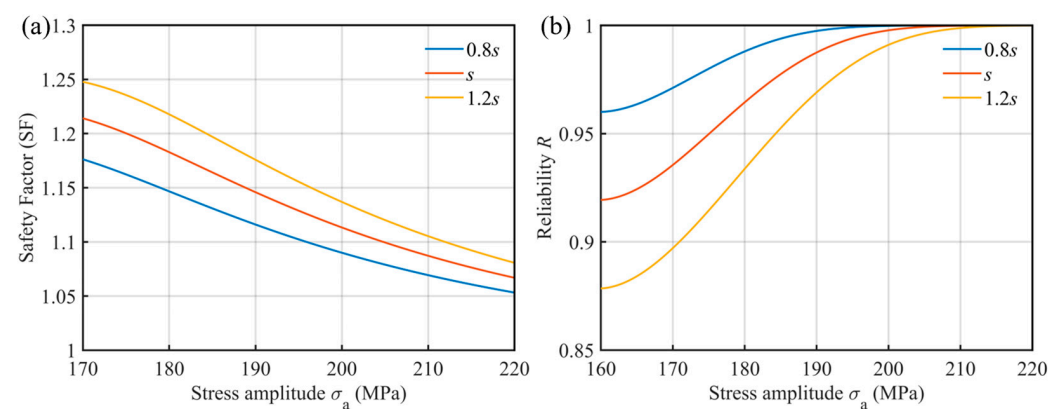


Figure 10. Effect of standard deviation on safety factor and reliability: (a) safety factors as a function of stress level at various standard deviations, (b) reliability factors as a function of stress level at various standard deviations.

Similarly, Figure 10b shows the relationship between stress level and reliability for various standard deviations (i.e., $0.8s$, s , and $1.2s$). For higher standard deviations, the reliability decreases. This is due to increased data scatter, which causes a greater proportion of fatigue life data to fall below the threshold defined by a given safety factor. Therefore, lower reliability is expected under conditions of higher standard deviation.

The proposed reliability-based framework differs from established engineering standards like Eurocode 3 or IIW recommendations. These standards typically apply a constant partial safety factor. They also assume that the fatigue life scatter is the same for all stress levels. However, our experimental data proves that the standard deviation changes with stress. Our model captures this dynamic scatter. At lower stresses, the model provides a higher safety factor to cover the large uncertainty. At higher stresses, it reduces the safety

factor to avoid overdesign. This approach makes the fatigue assessment more efficient than traditional fixed-factor methods.

4. Conclusions

In this study, a crack initiation life prediction method based on the plastic zone at the crack tip was proposed, and a multi-stage crack model was adopted to predict the fatigue life. Subsequently, an analytical framework incorporating both safety factors and reliability was established to investigate their interrelation and examine the influence of standard deviation on the results. The main conclusions are summarized as follows:

- (1) The S-N curve of the 6082 aluminum alloy shows a continuously decreasing trend in the tested regime. The proposed multi-stage model captures this fatigue behavior continuously.
- (2) The modified model provides a reasonable estimation of the fatigue life for 6082 aluminum alloy, particularly in the HCF regime. However, the prediction becomes non-conservative at high stress levels. This is attributed to the breakdown of the small-scale yielding assumption and the accelerated damage caused by large-scale plasticity as the stress approaches the yield limit.
- (3) For a given reliability level, the safety factor decreases with increasing stress level. This is attributed to the lower standard deviation and reduced scatter in fatigue life under higher stress, thereby reducing the required safety margin. Conversely, at a constant stress level, the safety factor increases with higher reliability requirements.
- (4) For a given safety factor, reliability increases with increasing stress levels. At the same time, under a specific reliability requirement, higher stress levels correspond to smaller safety factors (i.e., lower safety margins). When the safety margin (i.e., safety factor) is fixed, higher stress levels yield higher reliability, whereas lower stress levels yield lower reliability. The variations of safety factors at various stress levels for a given reliability and the reliability at various stress levels for a given safety factor exhibit opposite trends.
- (5) Standard deviation has a significant influence on both reliability and safety factors. Under a fixed reliability level, an increase in standard deviation results in a higher safety factor, whereas under a fixed safety factor, increasing the standard deviation leads to a decrease in reliability.

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References

1. Kedir, Y.A.; Lemu, H.G. Prediction of Fatigue Crack Initiation under Variable Amplitude Loading: Literature Review. *Metals* **2023**, *13*, 487. [\[CrossRef\]](#)
2. Kim, D.; Jiang, R.; Sinclair, I.; Reed, P. Microstructural influences on fatigue crack initiation and early propagation in Ni-based superalloy. *Mater. Sci. Technol.* **2022**, *38*, 1081–1094. [\[CrossRef\]](#)

3. Sharma, A.; Oh, M.C.; Ahn, B. Recent Advances in Very High Cycle Fatigue Behavior of Metals and Alloys—A Review. *Metals* **2020**, *10*, 1200. [[CrossRef](#)]
4. Talebi, N.; Ahlström, J.; Ekh, M.; Meyer, K.A. Evaluations and enhancements of fatigue crack initiation criteria for steels subjected to large shear deformations. *Int. J. Fatigue* **2024**, *182*, 108227. [[CrossRef](#)]
5. Wu, Y.; He, W.; Ma, H.; Nie, X.; Liang, X.; Pan, J.; Wang, S.; Shang, M.; Cheng, L. Titanium alloy materials with very high cycle fatigue: A review. *Materials* **2024**, *17*, 2987. [[CrossRef](#)]
6. Li, M.; Gao, J.; Zhou, J. A combined high and low cycle fatigue life prediction model for wind turbine blades. *Appl. Sci.* **2025**, *15*, 1173. [[CrossRef](#)]
7. Teng, Z. Thermo-based fatigue life prediction: A review. *Fatigue Fract. Eng. Mater. Struct.* **2023**, *46*, 3121–3144. [[CrossRef](#)]
8. Zhang, L.; Jiang, B.; Zhang, P.; Yan, H.; Xu, X.; Liu, R.; Tang, J.; Ren, C. Methods for fatigue-life estimation: A review of the current status and future trends. *Nanotechnol. Precis. Eng.* **2023**, *6*, 025001. [[CrossRef](#)]
9. Golahmar, A.; Niordson, C.F.; Martinez-Paneda, E. A phase field model for high-cycle fatigue: Total-life analysis. *Int. J. Fatigue* **2023**, *170*, 107558. [[CrossRef](#)]
10. Pilgar, C.M.; Fernandez, A.M.; Segurado, J. Microstructure sensitive fatigue life prediction model for SLM fabricated Hastelloy-X. *Int. J. Fatigue* **2023**, *168*, 107372. [[CrossRef](#)]
11. Tanaka, K.; Mura, T. A dislocation model for fatigue crack initiation. *J. Appl. Mech.* **1981**, *48*, 97–103. [[CrossRef](#)]
12. Chan, K.S. A microstructure-based fatigue-crack-initiation model. *Metall. Mater. Trans. A-Phys. Metall. Mater. Sci.* **2003**, *34*, 43–58. [[CrossRef](#)]
13. Sangid, M.D.; Maier, H.J.; Sehitoglu, H. A physically based fatigue model for prediction of crack initiation from persistent slip bands in polycrystals. *Acta Mater.* **2011**, *59*, 328–341. [[CrossRef](#)]
14. Yang, B.; Peng, X.; Huang, C.; Wang, Z.; Yin, D.; Fu, T. Strengthening and toughening by partial slip in nanotwinned diamond. *Carbon* **2019**, *150*, 1–7. [[CrossRef](#)]
15. Yang, B.; Tong, K.; Huang, C.; Qi, Z.; Yin, D.; Wei, Q.; Zhao, Z.; Peng, X.; Hu, N. Strengthening effects of penetrating twin boundary and phase boundary in polycrystalline diamond. *Diam. Relat. Mater.* **2021**, *117*, 108436. [[CrossRef](#)]
16. Fan, J.-L.; Zhu, G.; Zhu, M.-L.; Xuan, F.-Z. A data-physics integrated approach to life prediction in very high cycle fatigue regime. *Int. J. Fatigue* **2023**, *176*, 107917. [[CrossRef](#)]
17. Xu, N.; Fu, Z.; Wang, Y.; Shen, X. Study on the short fatigue crack initiation and propagation behavior of 42CrMo. *Adv. Mech. Eng.* **2022**, *14*, 16878132221119928. [[CrossRef](#)]
18. Singh, R.; Singh, V.P.; Mahobia, G.S. On the transition of short cracks into long fatigue cracks in reactor pressure vessel steels. *MATEC Web Conf.* **2018**, *165*, 13001. [[CrossRef](#)]
19. Chapetti, M.D.; Gubeljak, N.; Kozak, D. Intrinsic fatigue limit and the minimum fatigue crack growth threshold. *Materials* **2023**, *16*, 5874. [[CrossRef](#)]
20. Yang, X.; Zhang, C.; Wu, P.; Xu, A.; Ju, P.; Yang, D.; Dong, Z. A multi-scale model for predicting physically short crack and long crack behavior in metals. *Materials* **2024**, *17*, 5163. [[CrossRef](#)]
21. Hussain, K. Short fatigue crack behaviour and analytical models: A review. *Eng. Fract. Mech.* **1997**, *58*, 327–354. [[CrossRef](#)]
22. Yang, B.; Zhao, Y. Experimental research on dominant effective short fatigue crack behavior for railway LZ50 axle steel. *Int. J. Fatigue* **2012**, *35*, 71–78. [[CrossRef](#)]
23. Hu, Y.N.; Wu, S.C.; Wu, Z.K.; Zhong, X.L.; Ahmed, S.; Karabal, S.; Xiao, X.H.; Zhang, H.O.; Withers, P.J. A new approach to correlate the defect population with the fatigue life of selective laser melted Ti-6Al-4V alloy. *Int. J. Fatigue* **2020**, *136*, 105584. [[CrossRef](#)]
24. Guo, X.; Liu, X.; Long, G.; Zhao, Y.; Yuan, Y. Data-driven prediction of the fatigue performance of corroded high-strength steel wires. *Eng. Fail. Anal.* **2023**, *146*, 107108. [[CrossRef](#)]
25. Li, C.; Xie, L.; Zhao, H.; Song, J.; Zhao, Z. A transition size of dividing crack initiation and propagation phases and the fatigue total life prediction approach. *J. Fail. Anal. Prev.* **2019**, *19*, 1380–1388. [[CrossRef](#)]
26. Xiang, Y.; Lu, Z.; Liu, Y. Crack growth-based fatigue life prediction using an equivalent initial flaw model. Part I: Uniaxial loading. *Int. J. Fatigue* **2010**, *32*, 341–349. [[CrossRef](#)]
27. Li, H.; Zhang, J.; Hu, L.; Su, K. Notch fatigue life prediction of micro-shot peened 25CrMo4 alloy steel: A comparison between fracture mechanics and machine learning methods. *Eng. Fract. Mech.* **2023**, *277*, 108992. [[CrossRef](#)]
28. Martinez-Puente, E.; Zarketa-Astigarraga, A.; Martinez-Agirre, M.; Zabala, A.; Esnaola, J.A.; Muniz-Calvente, M.; Llavori, I.; Penalba, M. Benchmarking of spectral methods for fatigue assessment of mooring systems and dynamic cables in offshore renewable energy technologies. *Ocean Eng.* **2024**, *308*, 118311. [[CrossRef](#)]
29. Elahi, S.A.; Sofiani, F.M.; Chaudhuri, S.; Balbin, J.A.; Larrosa, N.O.; De Waele, W. A numerical study on fatigue strength degradation due to pitting corrosion of S355 structural steel in a marine environment. *Eng. Fail. Anal.* **2025**, *177*, 109669. [[CrossRef](#)]

30. Tridello, A.; Niutta, C.B.; Rossetto, M.; Berto, F.; Paolino, D.S. Fatigue design curves for industrial applications: A review. *Fatigue Fract. Eng. Mater. Struct.* **2025**, *48*, 1001–1021. [\[CrossRef\]](#)
31. Hwang, I.-S.; Kim, J.-H.; Im, W.-T.; Jeung, H.-H.; Nam, J.-S.; Shin, C.-S. Analyzing safety factors and predicting fatigue life of weak points in an electrically driven, multi-purpose cultivation tractor. *Agriculture* **2024**, *14*, 416. [\[CrossRef\]](#)
32. Maljaars, J.; Leonetti, D.; Hashemi, B.; Snijder, H.H. Systematic derivation of safety factors for the fatigue design of steel bridges. *Struct. Saf.* **2022**, *97*, 102229. [\[CrossRef\]](#)
33. Li, J.; Liu, S.; He, H.; Li, L. A novel framework for gear safety factor prediction. *IEEE Trans. Ind. Inform.* **2019**, *15*, 1998–2007. [\[CrossRef\]](#)
34. Baro-Tijerina, M.; Piña-Monárrez, M.R.; Villa-Covarrubias, B. Stress-strength Weibull analysis with different shape parameter β and probabilistic safety factor. *Dyna* **2020**, *87*, 28–33. [\[CrossRef\]](#)
35. Su, Y.-H.; Ye, X.-W.; Ding, Y.; Chen, B. Data-driven fatigue failure probability updating of OSD by Bayesian backward propagation. *Struct. Control Health Monit.* **2024**, *2024*, 2353457. [\[CrossRef\]](#)
36. Kakaie, A.; Guedes Soares, C.; Ariffin, A.K.; Punurai, W. Fatigue reliability analysis of submarine pipelines using the Bayesian approach. *J. Mar. Sci. Eng.* **2023**, *11*, 580. [\[CrossRef\]](#)
37. Xu, L.; Hu, P.; Li, Y.; Qiu, N.; Chen, G.; Liu, X. Improved fatigue reliability analysis of deepwater risers based on RSM and DBN. *J. Mar. Sci. Eng.* **2023**, *11*, 688. [\[CrossRef\]](#)
38. Yang, Y.-F.; Hu, H.-Y.; Min, L.; Sun, Q.-T.; Song, M.; Zhu, M.-L.; Wen, J.-F.; Tu, S.-T. Failure mechanism and life correlation of Inconel 718 in high and very high cycle fatigue regimes. *Int. J. Fatigue* **2023**, *175*, 107764. [\[CrossRef\]](#)
39. Brahma, A.; Ferguson, S.; Eckert, C.; Isaksson, O. Margins in design—Review of related concepts and methods. *J. Eng. Des.* **2024**, *35*, 1193–1226. [\[CrossRef\]](#)
40. Zhang, J.; Li, H.; Guan, J.; Zhang, J.; Xue, Y. Fatigue fracture mechanism and life prediction of two Al-Si-Mg alloys used in catenary cantilever system. *Eng. Fail. Anal.* **2025**, *169*, 109207. [\[CrossRef\]](#)
41. Deng, H.; Li, W.; Sakai, T.; Sun, Z. Very high cycle fatigue failure analysis and life prediction of Cr-Ni-W gear steel based on crack initiation and growth behaviors. *Materials* **2015**, *8*, 8338–8354. [\[CrossRef\]](#) [\[PubMed\]](#)
42. Pinz, M.; Weber, G.; Stinville, J.C.; Pollock, T.; Ghosh, S. Data-driven Bayesian model-based prediction of fatigue crack nucleation in Ni-based superalloys. *npj Comput. Mater.* **2022**, *8*, 39. [\[CrossRef\]](#)
43. Kassapoglou, C. Determination of energy dissipation during cyclic loading and its use to predict fatigue life of metal alloys. *Fatigue Fract. Eng. Mater. Struct.* **2023**, *46*, 3667–3679. [\[CrossRef\]](#)
44. Li, B.; Chen, C.; Qin, Z.; Xue, H. An energy-CP-combined model for predicting the fatigue life of polycrystalline materials under high cycle and very high cycle fatigue. *Eng. Fract. Mech.* **2023**, *291*, 109564. [\[CrossRef\]](#)
45. Dugdale, D.S. Yielding in steel sheets containing slits. *J. Mech. Phys. Solids* **1960**, *8*, 100–104. [\[CrossRef\]](#)
46. Barenblatt, G.I. The mathematical theory of equilibrium cracks in brittle fracture. *Adv. Appl. Mech.* **1962**, *7*, 55–129. [\[CrossRef\]](#)
47. Yang, B.; Peng, X.; Zhao, Y.; Yin, D.; Fu, T.; Huang, C. Superior mechanical and thermal properties than diamond: Diamond/lonsdaleite biphasic structure. *J. Mater. Sci. Technol.* **2020**, *48*, 114–122. [\[CrossRef\]](#)
48. Forman, R.G.; Mettu, S.R. Behavior of surface and corner cracks subjected to tensile and bending loads in Ti-6Al-4V alloy. In *Fracture Mechanics: 22nd Symposium*; ASTM STP 1131; NASA: Washington, DC, USA, 1992; pp. 519–546. Available online: <https://ntrs.nasa.gov/citations/19910009960> (accessed on 8 May 2026).
49. D’Antuono, P. An analytical relation between the Weibull and Basquin laws for smooth and notched specimens and application to constant amplitude fatigue. *Fatigue Fract. Eng. Mater. Struct.* **2019**, *43*, 991–1004. [\[CrossRef\]](#)

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