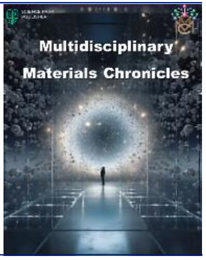
Multidisciplinary Materials Chronicles, 2024, Vol. 1, Iss. 1, 49-61

DOI: 10.62184/mmc.jmmc110020245

Review Article

SCIENCE PARK
PUBLISHER



Multidisciplinary Materials Chronicles

Fundamental Drivers of Metal Fatigue Failure and Performance

Moustafa M. Mohammed*

Mechanical Department, Faculty of Technology and Education, Beni-Suef University, Beni Suef, 62511, Egypt

Received: 25, 07, 2024; Accepted: 05, 08, 2024; Published: 09, 09, 2024

Abstract

Understanding fatigue behavior is critical for ensuring the safety and reliability of various engineering components and structures. Fatigue-related failures have historically led to catastrophic events, including aviation accidents and infrastructure collapses, resulting in significant economic and reputational damage. This study delves into the fatigue processes, focusing on crack initiation, growth mechanisms, the impact of microstructure, stress concentrations, surface finish, mean stress, frequency, and environmental conditions on fatigue life. It also explores fatigue principles, stress cycles, S-N curves, fatigue limits, and the stages of crack formation and propagation. By comprehensively analyzing fatigue behavior, engineers can design safer components, optimize materials, and extend product lifespans, thus facilitating technological advancements, predictive maintenance, and risk reduction across industries such as aerospace, automotive, and biomedical sectors.

Keywords: Fatigue Behavior, Cyclic Loading, Crack Initiation, Crack Propagation, S-N curve, Fatigue Limit, High-Cycle Fatigue (HCF), Low-Cycle Fatigue (LCF)

1. Introduction

Fatigue behavior in materials is a critical concern in engineering, as it significantly influences the longevity and reliability of components subjected to cyclic loading. The phenomenon of fatigue involves the initiation and propagation of cracks under repeated stress cycles, which can eventually lead to catastrophic failure without prior warning [1–3]. This unpredictable nature of fatigue-induced failures has historically resulted in severe accidents and substantial economic losses, particularly in high-stakes industries such as aerospace, automotive, and infrastructure.

Understanding the mechanisms of fatigue is essential for predicting the service life of components and for developing strategies to mitigate failure risks. Key factors influencing fatigue behavior include the material's microstructure, the presence of stress concentrators, surface finish, mean stress, frequency of loading, and environmental conditions [4, 5]. These variables interplay to affect the initiation and growth of fatigue cracks, making it imperative to comprehend their roles to improve material performance and safety.

The study of fatigue behavior encompasses several aspects: the fatigue stress cycle, the S-N curve, the existence of fatigue limits, and the fracture mechanisms under cyclic loading [6–8]. The fatigue stress cycle includes parameters such as maximum and minimum stress, mean stress, and stress amplitude, which are crucial for characterizing fatigue loading. The S-N curve, or Wöhler curve, illustrates the relationship between stress amplitude and the number of cycles to failure, providing valuable insights into material endurance under cyclic loading. The concept of a fatigue limit, where materials can withstand infinite cycles without failure below a certain stress threshold, is particularly significant for designing durable components [9,10].

Additionally, the fracture mechanisms in fatigue involve stages of crack nucleation, growth, and eventual failure. Microstructural features, such as grain boundaries and dislocations, play a pivotal role in these stages. Understanding these mechanisms aids in identifying the factors that contribute to fatigue resistance and in developing materials with enhanced durability.

This paper aims to delve into the intricacies of fatigue behavior, exploring the fundamental principles and mechanisms that govern fatigue life in materials. By gaining a comprehensive understanding of fatigue processes, engineers can design more reliable and longer-lasting components, ultimately enhancing safety and performance across various applications.

2. Importance of understanding fatigue behavior

A thorough comprehension of fatigue behavior is crucial for various reasons. Firstly, fatigue-related failures, which can occur without prior warning, have historically resulted in catastrophic events, including aviation accidents and infrastructure collapses. The economic implications are also significant; unforeseen fatigue failures can lead to costly repairs, unexpected downtimes, and legal challenges [11]. Comprehending the fatigue process, including crack initiation, growth mechanisms, and impact of microstructure, is key to accurately predicting component fatigue life [2, 12, 13]. Knowledge of how factors like stress concentrations, surface finish, mean stress, frequency, and environment influence fatigue life is essential.

Fatigue-related failures, occurring unexpectedly, have historically led to catastrophic events like aviation accidents and infrastructure collapses, causing significant economic losses and reputational damage. Understanding fatigue processes, including crack initiation and growth, is crucial for predicting component life accurately [3]. Factors such as stress concentrations, surface finish, mean stress, frequency, and environmental conditions significantly affect fatigue life [14]. By comprehending fatigue behavior, engineers can design safer components, optimize materials, and extend product lifespans. This knowledge facilitates technological advancements, predictive maintenance, and risk reduction across industries like aerospace, automotive, and biomedical sectors. Fatigue analysis plays a pivotal role in ensuring structural integrity and safety standards.

3. Fatigue principle

3.1. Fatigue stress cycles

In fatigue testing, the term "Fatigue Cycle" refers to the smallest repetitive portion of a stress-time or strain-time cycle [15]. It is also called a stress, load, or strain cycle. The determination of the load cycle in fatigue testing involves considering various parameters, as presented in Figure 1 including the maximum stress (σ_{max}), minimum stress (σ_{min}), steady or mean stress (σ_m), stress amplitude, also referred to as alternating stress (σ_a), range of stress (σ_r) in a fatigue cycle, stress ratio (R), and amplitude ratio (A) [16, 17]. The amplitude ratio is calculated as

$$\boldsymbol{A = \frac{\sigma_a}{\sigma_m} = \frac{\sigma_{max}-\sigma_{min}}{\sigma_{max}+\sigma_{min}} = \frac{1-R}{1+R}}$$

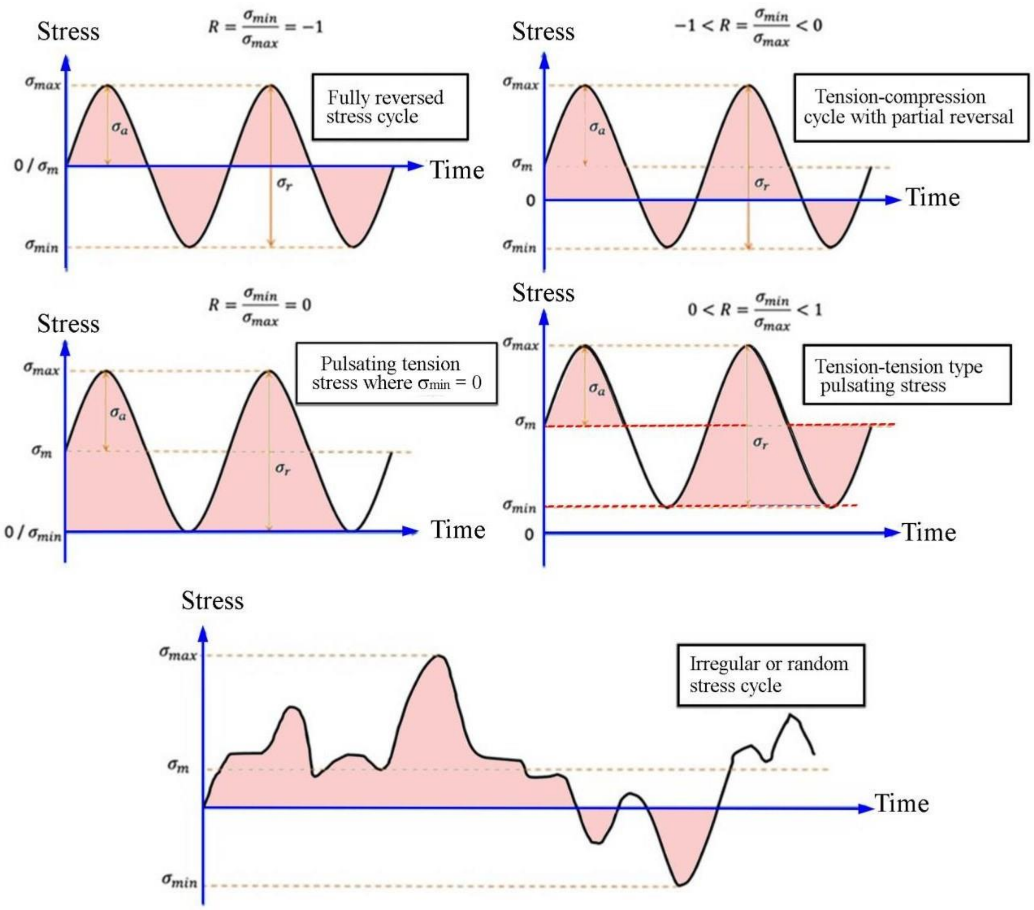


Figure 1. Illustration of common stress cycle configurations encountered in fatigue testing [18].

The time-dependent stress cycles, depicted in Figure 1 can be observed in the materials' fatigue performance. Figure 1 displays sinusoidal stress variations with different stress ratios that are typical in rotating and reciprocating machine components. Nonetheless, fatigue loading often involves a complicated stress cycle with irregular/random stress variation. An airplane wing subjected to storm-induced unexpected overloads may experience this irregular or random stress cycle. This type of stress can also be detected in intermittently working machinery due to natural vibrations with varying amplitudes through beginning and stopping. To analyze fatigue design, it is necessary to simplify the random stress cycle. This is usually achieved by dividing the actual stress cycle into several simplified sinusoidal variations, ensuring that each set contains the same number of oscillations with similar mean stress and stress amplitude [19].

Fatigue stress cycles can involve tension, compression, or shear stresses induced by axial, shearing, flexural, or torsional loading, or a combination of two of them. According to the ASTM Manual of Fatigue Testing, there are over thirty fatigue testing devices based on the load type and the way of its application [18]. The fatigue samples are loaded by applying a constant maximum load, moment, or maximum displacement or strain [20]. Fatigue cycles can be classified into two primary categories [21]:

1. High-cycle fatigue, also called “stress-controlled fatigue,” involves conducting fatigue tests using a prescribed cycle of fixed load or stress limits. This type of fatigue generally occurs with high-stress cycle numbers, (> 10^4 cycles).
2. Low-cycle fatigue, termed “strain-controlled fatigue,” involves conducting fatigue tests using a prescribed set of elastic and plastic strain limits within each cycle. This type of

fatigue usually occurs at low numbers of stress cycles (< 10^3 cycles).

3. Ultra-low cycle fatigue. This section highlights the unique characteristics of ULCF, such as its occurrence under large cyclic loads leading to complete ductile fracture and the distinct mechanisms involved, which are different from those in HCF and LCF.
4. Ultra-high cycle fatigue (UHCF), which refers to the phenomenon of fatigue failure that occurs at extremely high numbers of cycles, typically exceeding 10^7 or even 10^9 cycles. Unlike traditional HCF, which typically involves fatigue failure at lower numbers of cycles (e.g., 10^4 to 10^6 cycles), UHCF occurs under conditions of very low stress amplitudes and is often associated with components subjected to high-frequency loading or vibrations. The mechanisms governing UHCF differ from those of conventional fatigue, with factors such as material microstructure, surface conditions, and environmental influences playing significant roles. UHCF is characterized by the initiation and propagation of microstructural defects, such as microcracks, grain boundary cracking, and surface- initiated cracks, which gradually propagate over a large number of cycles until catastrophic failure occurs.

Worthy to note that high-cycle fatigue has gained engineering significance because it accounts for the vast common fatigue failures during service (> 10^4 cycles). The smooth and well-prepared surfaces of fatigue samples are essential to prevent stress concentrations and minimize tensile residual stresses. Although fatigue properties are a significant cause of safety failures in industries such as automotive and aerospace, they have not received adequate attention because of the complexity and time-consuming nature of fatigue testing, which requires numerous well- prepared specimens [21, 22].

Table 1 reveals the fatigue stress ratio (R) and amplitude ratio (A) associated with the fatigue loading modes. Lerch and Halford [23] studied the influence of control mode (strain and stress- controlled) and R-ratio at both R = 0 (zero-tension load) and R = -1 (fully reversed) on the fatigue performance of MMC samples. According to their results, it is found that loading condition affects damage mode. For instance, for R = 0, transverse fiber cracking is the dominant damage mechanism, and there is practically little cracking observed in the matrix. Whereas, for R = 1, transverse fiber cracking was uncommon during tension-compression loading, and the matrix was severely damaged. Both strain and stress-controlled conditions yield the same findings.

Table 1. The values corresponding to the fatigue stress ratio (R) and amplitude ratio (A) associated with the fatigue loading modes [23].

R values	Amplitude ratio (A)	Mode of fatigue loading
R = -1	∞	Completely reversed stress (tension-compression)
-1 < R < 0	> 1	Tension- compression fatigue
R = 0	1	Zero-tension load
0 < R < 1	< 1	Tension- tension
R = 1	0	static

3.2. S-N curve and fatigue properties

The S-N curve, commonly called the fatigue curve or Wöhler curve, describes the material fatigue properties [24]. The S-N curve can be applied only for high-cycle (stress-controlled) fatigue, usually more than 10^4 cycles. A series of fatigue samples are tested under identical conditions at different stress levels to establish the S-N curve. For each stress level, the samples are tested until a fracture occurs. Then, the stress amplitude (S) and the cycle numbers (N) at fatigue fracture are determined, and these obtained values of the S and N act for one point on the S–N curve [25]. Although the stress amplitude changes in each sample in a tested series, the mean stress remains constant. The S-N curve in Figure 2 (a) displays the correlation between S and N for two categories of metals: non-ferrous metals like aluminum and titanium alloys (curve A) and ferrous metals like steel (curve B).

The S-N curve for ferrous metals highlights the endurance limit or fatigue limit (σ_L), a specific stress level below which fatigue failure does not occur [26]. This is evident in the horizontal segment of the curve at increasing values of N. The fatigue limit, typically much lower than the yield strength, serves as a threshold below which fatigue failure is not expected, despite cycle numbers [27]. In contrast, nonferrous metals like aluminum, copper, and magnesium alloys lack a fatigue limit [28]. Their S-N curve never flattens out, exhibiting a decreasing trend and the absence of a distinct lower stress limit, making it challenging to identify a "safe" stress level for these materials.

In addition to the fatigue limit, fatigue properties such as fatigue strength can be determined from the S-N curve, as depicted in Figure 2 (a). Dynamically stressed components do not necessarily need a fatigue-limit design for economic purposes. In most cases, parts will only be subjected to stress cycles up to the number specified by their service life [16]. For instance, milling cutters are not designed to last indefinitely; instead, they are typically designated with a specific number of load cycles that they must endure without sustaining damage [29, 30]. This predetermined strength is now known as fatigue strength rather than the fatigue limit. Thus, the fatigue strength represents the stress amplitude that a material can endure under a specific mean stress for a given number of load cycles without encountering any fatigue damage.

Figure 2(b) illustrates the influence of strain aging on the fatigue limit. Strain aging refers to the phenomenon where materials undergo changes in their mechanical properties due to the interaction of dislocations with interstitial atoms (such as carbon or nitrogen) over time, particularly at elevated temperatures. This interaction can increase the strength and hardness of the material, thereby elevating the fatigue limit. The S-N curve in Figure 2(b) demonstrates how strain aging can result in a higher fatigue limit compared to materials that have not undergone strain aging.

The differences in the shapes of the S-N curves in Figure 2(a) and 2(b) are thus attributed to these underlying high-cycle fatigue mechanisms. The presence of a distinct fatigue limit in Figure 2(a) is indicative of materials that can endure cyclic stresses indefinitely below this limit. In contrast, the increased fatigue limit shown in Figure 2(b) displays the impact of strain aging, which enhances the material resistance to cyclic loading by impeding dislocation movement and reducing the rate of crack initiation and propagation.

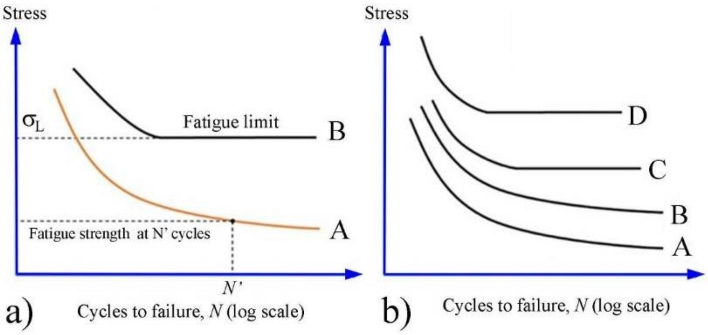


Figure 2. (a) Schematic illustrating the differentiation between the fatigue strength and fatigue limit, (b) Schematic illustrating the influence of strain aging on the fatigue limit [18].

3.3. Existence of fatigue limit

The existence or non-existence of a fatigue limit is a subject of ongoing debate. Canteli et al. [31] addressed this issue in their paper and proposed that various aspects of fracture mechanics must be considered. However, the reasons why certain materials have a fatigue limit are unknown, and there are many hypotheses regarding this important question. One of these hypotheses is associated with the stacking fault energy (SFE). Fatigue damage accumulates to cause fatigue failure.

Assuming flawless samples without defects or notches, fatigue damage initiates through the localized plastic strain, which can result in intergranular or transgranular microcracks. Grain boundaries can hinder the growth of these microcracks, and a material's SFE is a crucial factor in determining whether or not microcracks can surpass these barriers. With high SFE materials such as Al, Zn, and Mg, for instance, dislocations can easily traverse slip and overcome impediments, which is the same goes with microcracks. SFE can affect the structure of dislocations, but it does not directly impact crack growth. Then, the microcracks can easily propagate to form macrocracks, eventually resulting in fatigue failure [31].

Awatani et al. [32] studied the impact of SFE on fatigue crack growth through dislocation patterns. They declared that dislocation could transfer through cell boundaries in metals with high SFE, lessening crack growth rates. On the other hand, in materials with very low SFE, i.e., titanium and steel alloys, slip is limited, and crack growth is faceted in the case of low imposed load/strain amplitude. Thus, microcracks can be impeded by obstacles like grain boundaries, preventing the formation of macrocracks. Consequently, when the accumulated fatigue damage is inadequate to induce failure, the material will display a distinctive break on the S-N curve known as a fatigue limit. Another hypothesis ascribed the appearance of the fatigue limit to a metallurgical phenomenon called "strain aging", which can occur in some materials but not in others. Strain aging is a phenomenon were solute atoms trap dislocations, causing an increase in yield stress. This means that greater stresses are required to release these dislocations and produce deformation in materials like steel that exhibit strain aging [33].

It was reported that interstitial elements in materials determine a fatigue limit [34, 35]. For more clarification, if we considered a pure metal, the S-N curve would decrease gradually as the number of cyclic cycles increases (curve A) in Figure 2 (b). Suppose adding a solute element to the pure metal forms a solid solution. The S-N curve will be shifted to curve B (Figure 2 (b)) because of the solid solution strengthening. Suppose a sufficient number of interstitial elements are added to the pure metal. In that case, the interstitials can strengthen additional alloy through strain aging. The fatigue limit (curve C in Figure2 (b)) results from the equilibrium between the localized strengthening by strain aging and the fatigue failure induced through applied stress at a specific limiting stress since strain aging is relatively independent of applied stress. Worthy to note that the strain aging increases with higher fatigue temperatures or a higher number of interstitial elements. Curve D in Figure 2 (b) illustrates this augmented strain aging by showing that the fatigue limit is increased and an earlier onset of the horizontal 'knee' compared to curve C (Figure 2 (b)), as demonstrated by the reduced number of stress cycles.

Wilson [36] provided evidence suggesting that strain aging can result in the development of a fatigue limit in mild steel. Also, Nakagawa and Ikai [37] investigated the influence of strain aging on the fatigue limit. They demonstrated that the fatigue limit occurs when dislocation multiplication, work hardening, and strain aging reach a state of equilibrium at the maximum stress level. The S-N curve for most nonferrous metal slopes steadily downward with increasing cycle numbers. It never gets horizontal, so these metals lack a real fatigue limit. Thus, it is practically common to define the fatigue properties of the material by considering the fatigue strength at a specific number of cycles. Usually, the fatigue test is terminated for practical considerations at low stress. The fatigue limit for these materials is commonly expressed as the stress at which failure happens at a rate of roughly 10^8 or $5x10^8$ cycles [38].

4. Fracture fatigue mechanism

Understanding the fracture mechanism in fatigue necessitates understanding the development of fatigue fracture. Fatigue fractures occur when stress is applied, removed, and reapplied cyclically. This repetitive process can continue for millions of cycles until the fatigue fracture reaches a critical point, leading to material failure [38].

4.1. Stages of crack formation

The fatigue failure process involves three main stages, which include: crack nucleation, crack growth and propagation, and eventually fatigue failure. The following is a brief discussion of these three stages.

4.1.1. Crack nucleation

Crack nucleation is a failure process that happens at the initial stage of fatigue. As a result of surface irregularities such as roughness, small cracks, and other imperfections, no material surface can be considered completely smooth at a microscopic level [2, 39–41]. These defects can act as heterogeneous sites for initiating crack formation, i.e., microscopic notches, resulting in the buildup of triaxial stresses that exceed the uniaxial nominal stresses. The yield point is, therefore, locally exceeded at these defects, resulting in microscopic deformations. During fatigue, metals undergo deformation by slipping on the same atomic planes and the same crystallographic directions [42].

Under fatigue conditions, the formation of slip lines and the gradual accumulation of small slip lines frequently occur within the initial few thousand stress cycles, leading to the development of cyclic slip bands. These tiny slips move back and forth within a slip band, producing ridges called slip-band extrusions and grooves or notches, known as slip-band intrusions, which exacerbate crack formation. Zhang et al. [43] confirmed that the slip bands formed during fatigue loading are crucial in initiating and growing cracks, as illustrated in Figure 3 depicting the fatigue crack initiation and propagation process in a nickel-based superalloy loaded to failure.

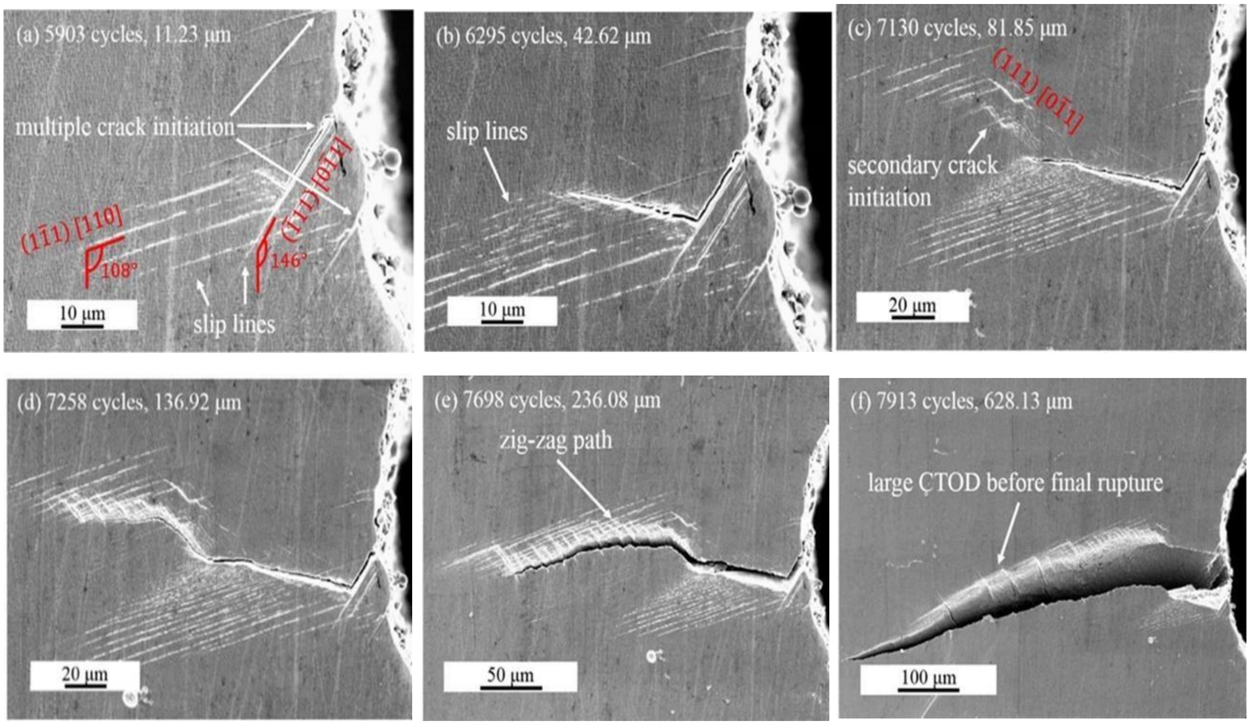


Figure 3. Scanning electron microscopy images of fatigue-crack initiation and growth in nickel- based superalloys [43].

4.1.2. Crack growth and its propagation

This stage can be divided into two distinct steps: crack growth, characterized by the initial propagation of the crack along slip planes at an extremely slow rate on the order of nanometers per cycle [44]. During this phase, the fatigue crack extends gradually, spanning a few grain diameters until it reaches a critical length at which the stress field surrounding the crack tip becomes dominant. Figure 4 (a) shows a schematic depiction of the fatigue failure crack growth through the three main fatigue stages. The mechanical characteristics of the material and the applied stress level could define the critical size of the fatigue crack [45]. After reaching the critical length, the second step starts crack propagation perpendicular to the applied principal tensile stress direction at a rate of microns per cycle, significantly faster than the rate in step 1. The crack propagation step typically results in a pattern of ripples or fatigue striations, invisible to the naked eye [46]. It can only be seen under magnification; see Figure 4 (b).

The distance between these striations, often referred to as fatigue striation spacing, provides a measure of the crack growth rate per stress or strain cycle. Each striation represents the incremental advancement of the crack front during successive loading cycles. The presence of striations signifies the progressive movement of the crack front as it propagates through the material under cyclic loading conditions.

Fatigue crack propagation involves a cyclic process of plastic blunting and re-sharpening of the crack front, as depicted schematically in Figure 5 (a-f). During each loading cycle, the crack tip undergoes plastic deformation, resulting in the blunting of the crack and the formation of plastic zones around the crack tip. Subsequent unloading allows for crack closure, but residual plastic deformation remains. Upon reapplication of the load, the crack tip re-sharpens as it advances further into the material, forming new fatigue striations [46, 47].

This cyclic process of crack blunting and re-sharpening continues throughout the fatigue life of the material, leading to gradual crack propagation. The observation and analysis of fatigue striations provide valuable insights into the mechanisms of fatigue crack growth and are instrumental in predicting the fatigue life of structural components and materials.

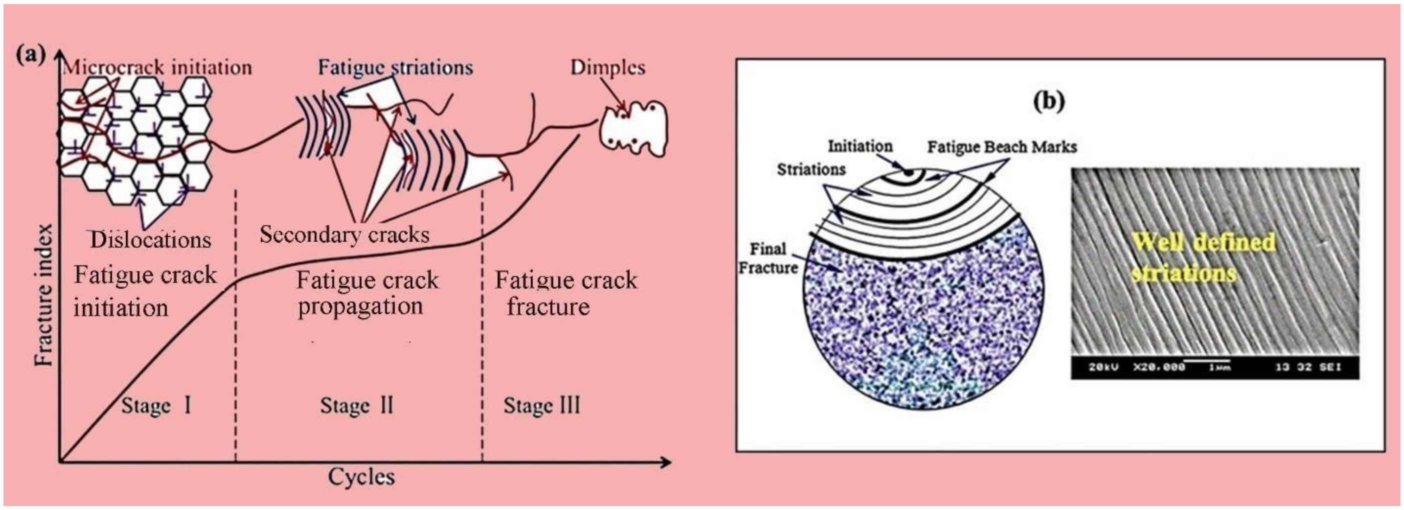


Figure 4. (a) Schematic illustrating the stages of the fatigue failure process [45], and (b) typical fatigue striations appeared in the fracture surface of Al alloy [46, 47].

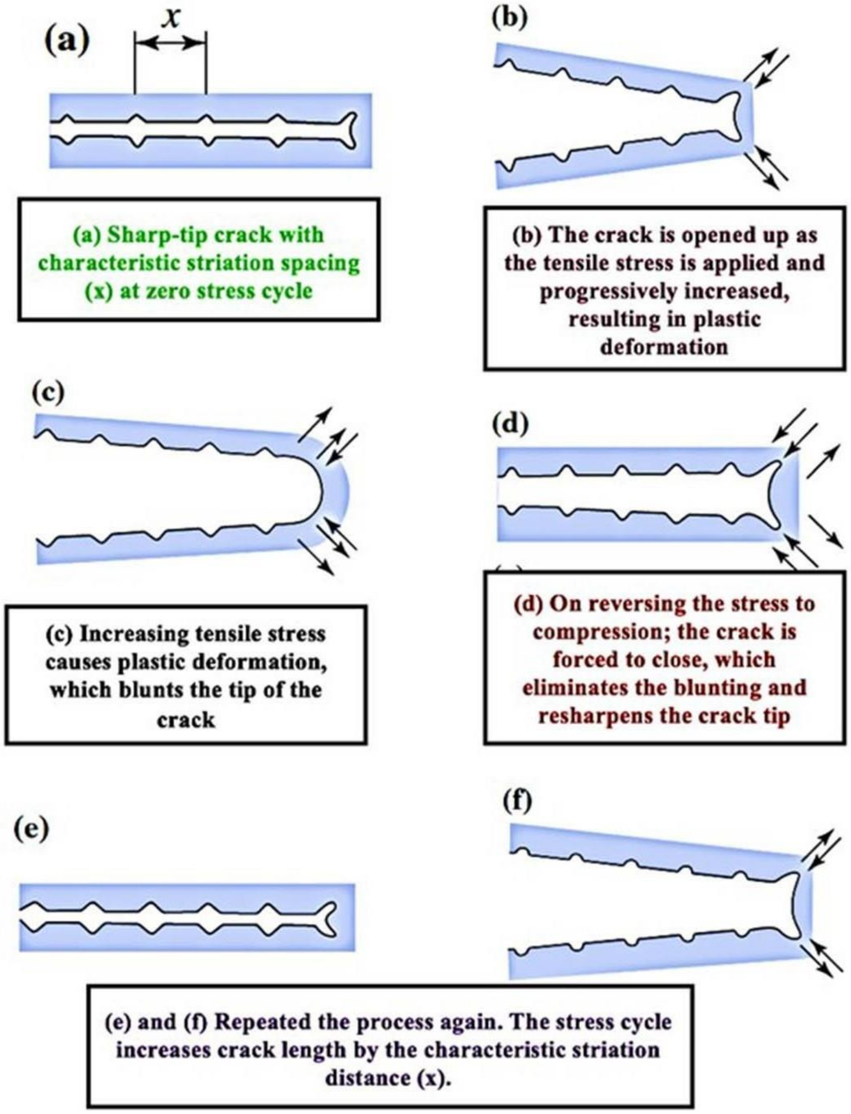


Figure 5. The stages of fatigue crack propagation [18].

4.1.3. Fatigue failure

In this stage, fatigue failure would occur if the crack developed in the second stage (growth and propagation stage) continues to grow due to existing sufficient energy. The ultimate mode of failure, which is a catastrophic fracture, can either be ductile or brittle or a combination of both, depending on various factors like the material type, thickness, applied stress, temperature applied stress, etc. Fatigue failures often happen unexpectedly and suddenly, without prior warning. Fatigue-induced fractures in damaged parts consistently display smooth surfaces without evidenceof plastic deformation. Recent research studies for additional clarification on the stages of fatigue failure are found elsewhere [48–51].

4.2. Fatigue striations and beach marks

The presence and appearance of fatigue striations and beach marks are highly dependent onthe type of material being analyzed. For instance, materials like aluminum and aluminum alloys tend to exhibit the formation of striations [46, 52]. On the other hand, steel may display cleavage as a dominant fracture mechanism [19, 53]. Regardless of the material, the formation of striations is typically attributed to the combination of cyclic stress, plastic strain, and stress frequency acting simultaneously. Typical fatigue striations, see Figure 4 (b) can appear in the material during the second stage, in which crack propagation occurs due to the cyclic progress of the crack with each load change. When the stress intensity level exceeds significantly or non-uniform dynamic stress is applied, these fatigue striations can convert into beach marks (shown in Figure 4 (b)) which becomevisible to the naked eye, unlike fatigue striations. These marks appear as concentric rings in the fatigue zone and resemble the tide marks seen on a beach. Beach marks are oriented normally to the orientation of the crack propagation direction. The main difference between fatigue striations and beach marks is that fatigue striations are only visible at a microscopic level. In contrast, beach marks are visible at a macroscopic level. Various components, for example, the automobile drive shafts, are rarely exposed to uniform dynamic stress; hence, such a multistage load is typically encountered in practice. Since the fatigue test is often a uniform dynamic load (a single-stage load with constant stress amplitude and not a multi-stage load), no beach marks can be detected on the fracture surface [54].

5. Conclusion

This study highlights the critical importance of understanding fatigue behavior in engineering materials to prevent unforeseen failures, such as those in aviation and infrastructure, which lead to significant economic and safety impacts. The research emphasizes the mechanisms of crack initiation and growth, the role of microstructural features, and the influence of stress parameters on fatigue life. Analyzing S-N curves reveals that certain materials have a fatigue limit,which is crucial for designing components to endure cyclic stresses below this threshold. Understanding the stages of fatigue fracture, from crack nucleation to propagation and failure, is essential for mitigating fatigue-related failures. The insights from this study aid in designing safercomponents, optimizing material selection, and extending product lifespans across various industries. This knowledge facilitates technological advancements, predictive maintenance, and risk reduction, ensuring structural integrity and safety. Future work should focus on advancing fatigue testing methods, exploring new materials with enhanced fatigue resistance, and developingmore accurate predictive models for fatigue life.

Conflicts of Interest

The author declares no conflict of interest.

Author Information

Corresponding Author: Moustafa M. Mohammed*

E-mail: moustafa.mahmoud@techedu.bsu.edu.eg

References

[1] W. Abd-Elaziem, M. Khedr, Ammar.H. Elsheikh, J. Liu, Y. Zeng, T.A. Sebae, M.A. Abd El- Baky, M.A. Darwish, W.M. Daoush, X. Li, Influence of nanoparticles addition on the fatigue failure behavior of metal matrix composites: Comprehensive review, Eng. Fail. Anal. 155 (2024) 107751. https://doi.org/10.1016/j.engfailanal.2023.107751.

[2] J.C. Newman, Fatigue and crack-growth analyses under giga-cycle loading on aluminum alloys, Procedia Eng. 101 (2015) 339–346. https://doi.org/10.1016/j.proeng.2015.02.041.

[3] P. Chen, C. Lee, S.-Y. Wang, M. Seifi, J.J. Lewandowski, K.A. Dahmen, H. Jia, X. Xie, B. Chen, J.-W. Yeh, C.-W. Tsai, T. Yuan, P.K. Liaw, Fatigue behavior of high-entropy alloys: A review, Sci. China Technol. Sci. 61 (2018) 168–178. https://doi.org/10.1007/s11431-017- 9137-4.

[4] A. Pramanik, A.R. Dixit, S. Chattopadhyaya, M.S. Uddin, Y. Dong, A.K. Basak, G. Littlefair, Fatigue life of machined components, Adv. Manuf. 5 (2017) 59–76. https://doi.org/10.1007/s40436-016-0168-z.

[5] I. Koutiri, E. Pessard, P. Peyre, O. Amlou, T. De Terris, Influence of SLM process parameters on the surface finish, porosity rate and fatigue behavior of as-built Inconel 625 parts, J. Mater. Process. Technol. 255 (2018) 536–546. https://doi.org/10.1016/j.jmatprotec.2017.12.043.

[6] T. Sakai, A. Nakagawa, N. Oguma, Y. Nakamura, A. Ueno, S. Kikuchi, A. Sakaida, A review on fatigue fracture modes of structural metallic materials in very high cycle regime, Int. J. Fatigue. 93 (2016) 339–351. https://doi.org/10.1016/j.ijfatigue.2016.05.029.

[7] U. Zerbst, M. Madia, M. Vormwald, H.Th. Beier, Fatigue strength and fracture mechanics – a general perspective, Eng. Fract. Mech. 198 (2018) 2–23. https://doi.org/10.1016/j.engfracmech.2017.04.030.

[8] C.M. Sonsino, Course of SN-curves especially in the high-cycle fatigue regime with regard to component design and safety, Int. J. Fatigue. 29 (2007) 2246–2258. https://doi.org/10.1016/j.ijfatigue.2006.11.015.

[9] I. Marines, X. Bin, C. Bathias, An understanding of very high cycle fatigue of metals, Int. J. Fatigue. 25 (2003) 1101–1107. https://doi.org/10.1016/S0142-1123(03)00147-6.

[10] A. Sharma, M.C. Oh, B. Ahn, Recent advances in very high cycle fatigue behavior of metals and alloys—A review, Metals. 10 (2020) 1200. https://doi.org/10.3390/met10091200.

[11] D. Chan, J. Mo, Life cycle reliability and maintenance analyses of wind turbines, Energy Procedia. 110 (2017) 328–333. https://doi.org/10.1016/j.egypro.2017.03.148.

[12] P. Juijerm, I. Altenberger, Fatigue performance enhancement of steels using mechanical surface treatments, J. Met. Mater. Miner. 17 (2007) 59-65.

[13] Z. Xu, S. Wang, L. Gao, X. Qiao, Y. Cui, Fatigue life analysis model of crankshaft under uncertain working conditions based on physical-data collaboration, J. Eng. Res. (2023). https://doi.org/10.1016/j.jer.2023.12.002.

[14] J. Fan, B. Chen, Z. Gao, C. Xiang, Mechanisms in failure prevention of bio-materials and bio-structures, Mech. Adv. Mater. Struct. 12 (2005) 229–237. https://doi.org/10.1080/15376490590928598.

[15] Y. Furuya, Y. Shimamura, M. Takanashi, T. Ogawa, Standardization of an ultrasonic fatigue testing method in Japan, Fatigue Fract. Eng. Mater. Struct. 45 (2022) 2415–2420. https://doi.org/10.1111/ffe.13727.

[16] M. Kamal, M.M. Rahman, Advances in fatigue life modeling: A review, Renew. Sustain. Energy Rev. 82 (2018) 940–949. https://doi.org/10.1016/j.rser.2017.09.047.

[17] R.E. Smallman, A.H.W. Ngan, Chapter 15 - Creep, Fatigue and fracture, in: R.E. Smallman, A.H.W. Ngan (Eds.), Mod. Phys. Metall. Eighth Ed., Butterworth-Heinemann, Oxford, 2014: pp. 571–616. https://doi.org/10.1016/B978-0-08-098204-5.00015-8.

[18] A. Bhaduri, Mechanical properties and working of metals and alloys, Springer, 1st ed. (2018). ISBN-13: 978-9811072086 2018.

[19] J.F. Barbosa, J.A.F.O. Correia, R.C.S.F. Júnior, A.M.P.D. Jesus, Fatigue life prediction of metallic materials considering mean stress effects by means of an artificial neural network, Int. J. Fatigue. 135 (2020) 105527. https://doi.org/10.1016/j.ijfatigue.2020.105527.

[20] X. Pei, P. Dong, S. Xing, A structural strain parameter for a unified treatment of fatigue behaviors of welded components, Int. J. Fatigue. 124 (2019) 444–460. https://doi.org/10.1016/j.ijfatigue.2019.03.010.

[21] M. Zimmermann, Diversity of damage evolution during cyclic loading at very high numbers of cycles, Int. Mater. Rev. 57 (2012) 73–91. https://doi.org/10.1179/1743280411Y.0000000005.

[22] B. Pyttel, D. Schwerdt, C. Berger, Very high cycle fatigue – Is there a fatigue limit?, Int. J. Fatigue 33 (2011) 49–58. https://doi.org/10.1016/j.ijfatigue.2010.05.009.

[23] B. Lerch, G. Halford, Effects of control mode and R-ratio on the fatigue behaviour of a metal matrix composite, Mater. Sci. Eng. A. 200 (1995) 47–54. https://doi.org/10.1016/0921-5093(95)07005-2

[24] S. Zhou, X. Wu, Fatigue life prediction of composite laminates by fatigue master curves, J. Mater. Res. Technol. 8 (2019) 6094–6105. https://doi.org/10.1016/j.jmrt.2019.10.003.

[25] Y. Murakami, T. Takagi, K. Wada, H. Matsunaga, Essential structure of S-N curve: Prediction of fatigue life and fatigue limit of defective materials and nature of scatter, Int. J. Fatigue. 146 (2021) 106138. https://doi.org/10.1016/j.ijfatigue.2020.106138.

[26] S. Suresh, Fatigue of materials, Cambridge university press, 2nd ed (1998). ISBN-13- 978-0521578479.

[27] M. Baboria, P. Devi, M. Baboria, P. Devi, A critical assessment of fatigue behaviour of ferrous alloys by empirical correlation of multifactor S-N curves, World J. Adv. Res. Rev. 16 (2022) 722–730. https://doi.org/10.30574/wjarr.2022.16.2.1226.

[28] J. Małecka, T. Łagoda, K. Głowacka, S. Vantadori, Influence of plastic deformations on both yield strength and torsional fatigue life of non-ferrous alloys, Fatigue Fract. Eng. Mater. Struct. 46 (2023) 2080–2095. https://doi.org/10.1111/ffe.13982.

[29] F. Gong, J. Zhao, Y. Jiang, H. Tao, Z. Li, J. Zang, Fatigue failure of coated carbide tool and its influence on cutting performance in face milling SKD11 hardened steel, Int. J. Refract. Met. Hard Mater. 64 (2017) 27–34. https://doi.org/10.1016/j.ijrmhm.2017.01.001.

[30] A. Laamouri, F. Ghanem, C. Braham, H. Sidhom, Influences of up-milling and down-milling on surface integrity and fatigue strength of X160CrMoV12 steel, Int. J. Adv. Manuf. Technol. 105 (2019) 1209–1228. https://doi.org/10.1007/s00170-019-04280-2.

[31] A. Fernández-Canteli, S. Blasón, B. Pyttel, M. Muniz-Calvente, E. Castillo, Considerations about the existence or non-existence of the fatigue limit: implications on practical design, Int. J. Fract. 223 (2020) 189–196. https://doi.org/10.1007/s10704-019-00413-6.

[32] J. Awatani, K. Katagiri, K. Koyanagi, A study on the effect of stacking fault energy on fatigue crack propagation as deduced from dislocation patterns, Metall. Trans. A 10 (1979) 503–507. https://doi.org/10.1007/bf02697078.

[33] G.E. Dieter, Mechanical metallurgy, McGraw-Hill New York, 1961. ISBN: 07-016890-3

[34] J.C. Levy, G.M. Sinclair, An investigation of strain aging in fatigue, Illinois University at Urbana Champaign, 1954. Ad. No. 37257

[35] H.A. Lipsitt, G.T. Horne, The fatigue behavior of decarburized steels, Proc Am Soc Test Mater 57(1957) 587.

[36] D.V. Wilson, Effects of microstructure and strain ageing on fatigue-crack initiation in steel, Met. Sci. 11 (1977) 321–331.

[37] T. Nakagawa, Y. Ikai, Strain ageing and the fatigue limit in carbon steel, Fatigue Fract. Eng. Mater. Struct. 2 (1979) 13–21.

[38] F.C. Campbell, Fatigue and fracture: understanding the basics, ASM International, 2012. ISBN: 978-1-61503-976-0

[39] M. Skorupa, A. Skorupa, Experimental results and predictions on fatigue crack growth in structural steel, Int. J. Fatigue 27 (2005) 1016–1028. https://doi.org/10.1016/j.ijfatigue.2004.11.011.

[40] M. da Fonte, L. Reis, M. de Freitas, Fatigue crack growth under rotating bending loading on aluminium alloy 7075-T6 and the effect of a steady torsion, Theor. Appl. Fract. Mech. 80 (2015) 57–64. https://doi.org/10.1016/j.tafmec.2015.05.006.

[41] J.C. Newman, K.F. Walker, Fatigue-crack growth in two aluminum alloys and crack-closure analyses under constant-amplitude and spectrum loading, Theor. Appl. Fract. Mech. 100 (2019) 307–318.

https://doi.org/10.1016/j.tafmec.2019.01.029.

[42] H.J. Gough, Crystalline structure in relation in failure of metals-especially by fatigue, American Society for Testing Materials, 1933.

[43] L. Zhang, L.G. Zhao, A. Roy, V.V. Silberschmidt, G. McColvin, In-situ SEM study of slip- controlled short-crack growth in single-crystal nickel superalloy, Mater. Sci. Eng. A 742 (2019) 564–572. https://doi.org/10.1016/j.msea.2018.11.040.

[44] H.A. Padilla, B.L. Boyce, A Review of Fatigue Behavior in Nanocrystalline Metals, Exp. Mech. 50 (2010) 5–23. https://doi.org/10.1007/s11340-009-9301-2.

[45] Z. Gao, S. Yang, X. Meng, Z. Wang, Z. Peng, Study on fatigue crack growth of electron beam selective melting of titanium alloy, Mater. Res. Express 8 (2021) 096521. https://doi.org/10.1088/2053-1591/ac2444.

[46] I. Salam, W. Muhammad, N. Ejaz, Fatigue crack growth in an aluminum alloy-fractographic study, in: IOP Conf. Ser. Mater. Sci. Eng., IOP Publishing 146 (2016) 012010. https://doi.org/10.1088/1757-899x/146/1/012010.

[47] N. Perez, Fatigue Crack Growth, in: Fract. Mech., Springer, Cham, 2017: pp. 327–372. https://doi.org/10.1007/978-3-319-24999-5_9.

[48] M.D. Chapetti, Fracture mechanics for fatigue design of metallic components and small defect assessment, Int. J. Fatigue 154 (2022) 106550. https://doi.org/10.1016/j.ijfatigue.2021.106550.

[49] J. Pelleg, Cyclic deformation in oxides, carbides, nitrides: alumina, magnesia, yttria, SiC, B4C and Si3N4, Cham, Switzerland : Springer ,2022.

[50] A.A. Shanyavskiy, A.P. Soldatenkov, Metallic materials fatigue behavior: scale levels and ranges of transition between them, Int. J. Fatigue 158 (2022) 106773. https://doi.org/10.1016/j.ijfatigue.2021.106550.

[51] J. Kang, Q. Wang, Z. Wang, Z. Han, R. Xin, X. Jiao, Fatigue fracture mechanism of T92/HR3C dissimilar metal weld joints at elevated temperature, Mater. Charact. 190 (2022) 112081. https://doi.org/10.1016/j.matchar.2022.112081.

[52] S.M. El-Katatny, A.E. Nassef, A. El-Domiaty, W.H. El-Garaihy, Fundamental analysis of cold die compaction of reinforced aluminum powder, Int J Eng Tech Res 3 (2015) 180–184. ISSN: 2321-0869,

[53] N. Xiao, W. Hui, Y. Zhang, X. Zhao, Y. Chen, H. Dong, High cycle fatigue behavior of a low carbon alloy steel: The influence of vacuum carburizing treatment, Eng. Fail. Anal. 109 (2020) 104215. https://doi.org/10.1016/j.engfailanal.2019.104215.

[54] I. Varfolomeev, S. Moroz, D. Siegele, K. Kadau, C. Amann, Study on fatigue crack initiation and propagation from forging defects, Procedia Struct. Integr. 7 (2017) 359–367. https://doi.org/10.1016/j.prostr.2017.11.100.