Optimizing fatigue life predictions for scraper rings: classical vs modern models

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ABSTRACT

This study provides a comprehensive comparative evaluation of classical and modern predictive models for fatigue life in scraper rings of internal combustion engines, which operate under high thermo-mechanical stresses. Accurate fatigue life predictions are essential for optimizing engine component design, preventing both over- and under-engineering while ensuring long-term reliability. The effectiveness of both traditional models and newer advanced approaches was analyzed using loading profiles that replicate real-world engine operating conditions. Results indicate that stress-life models offer more reliable predictions for high-cycle fatigue scenarios, while strain-life models perform better under low-cycle fatigue conditions. Furthermore, fracture mechanics models show great promise in predicting crack propagation and identifying failure mechanisms. Detailed inspections and Légraud-Poirier (LP) tests confirmed fatigue-induced cracking at critical locations of the scraper rings, emphasizing the importance of incorporating multi-axial loading in fatigue assessments. The findings underscore the necessity for using comprehensive loading profiles and thorough inspections to enhance the accuracy and dependability of fatigue life predictions, which are critical for improving the performance and durability of engine components.

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1. INTRODUCTION

This study examines the fatigue behavior of scraper rings, fatigue behavior is a critical aspect of material performance, especially for components subjected to cyclic loading in mechanical systems. Scraper rings, a vital part of internal combustion engines, experience significant cyclic stresses during operation. Understanding and predicting their fatigue life is essential for ensuring engine reliability and longevity. Fatigue, characterized by progressive and localized structural damage, ultimately leads to failure if not adequately managed. The study of fatigue life behavior has evolved significantly over the past century.

While previous studies investigated early foundational models such as the stress-life (S-N) approach, introduced by [1], [2], established the link between stress amplitude and the number of cycles until failure. This method has been refined over the years, incorporating mean stress effects through modifications like the Goodman relationship [3], [4]. These foundational models laid the groundwork for subsequent advancements in fatigue analysis. In parallel, the strain-life (ε-N) approach, exemplified by the Coffin-Manson model, provided a more detailed analysis for low-cycle fatigue scenarios, considering both elastic and plastic strains [5]–[8]. Advances in fracture mechanics, such as Paris' Law for crack propagation [9], [10] and Forman's equation for crack growth in high-strength steels [11], [12], further enriched the understanding of fatigue behavior. Recent studies have expanded these classical models to include energy-based approaches and multi-axial fatigue criteria [13], [14]. The Manson-Halford strain energy density model correlates the strain energy density with fatigue life, offering an alternative perspective on fatigue damage accumulation [15]. The Dang Van criterion addresses fatigue under complex, multi-axial stress states, making it applicable to more intricate loading conditions [16], [17] the past century.

Contemporary research continues to build on these models. For instance, [18], [19] explored high-cycle fatigue life prediction using an extended Basquin model, incorporating additional factors for improved accurac. Similarly, [20], [21] refined the Modified Goodman approach to better account for mean stress effects in modern materials. Jirandehi and Khonsari [22] applied the Coffin-Manson model to new superalloys, demonstrating its continued relevance in advanced material contexts. The application of Paris' Law in composite materials by Shi *et al.* [23] and Holycross *et al.* [24] and the adaptation of Forman's equation for high-strength steels by Gan *et al.* [25] highlight ongoing innovations in fracture mechanics approaches, recent advancements in energy-based and multi-axial fatigue criteria by Matsubara *et al.* [26] and Vershinin *et al.* [27] further exemplify the evolving landscape of fatigue analysis. While there have been notable advances, a thorough grasp of the fatigue life of scraper rings necessitates a unified approach that integrates numerical simulations with experimental validation. This research meets this need by directly comparing classical and modern fatigue models to evaluate their effectiveness and precision in predicting the fatigue behaviour of scraper rings in internal combustion engines. The Second Piola-Kirchhoff equation is a valuable tool for accurately predicting the lifetime of these mechanical components. This is proven in various studies, including those by Vershinin *et al.* [27], Zhang *et al.* [28], Lion *et al.* [29], Kordkheili and Naghdabadi [30] and Urnbull [31]. This approach is an effective method for capturing the complex stress-strain relationships and ensuring the reliability of fatigue life predictions.

The specific objectives of this study include comparing classical fatigue models, such as the Basquin and Coffin-Manson models, with recent advancements as the extended Basquin model and the Modified Goodman approach, particularly in the context of scraper rings. Additionally, the study aims to integrate lubrication effects using the Reynolds equation to assess how lubrication influences the fatigue behavior of scraper rings, an aspect that previous studies have not explicitly addressed. Experimental validation will be conducted to ensure the accuracy of numerical simulations, helping to bridge the gap between theoretical predictions and real-world data. Furthermore, a comprehensive analysis of the fatigue life of scraper rings will be provided through a combination of numerical modeling and experimental results. By achieving these objectives, the study seeks to enhance the current understanding of fatigue life behavior in scraper rings and improve the reliability of fatigue life predictions. The findings will contribute to the broader field of materials engineering, offering practical insights for enhancing the design and durability of internal combustion engine components.

2. METHOD

2.1. Fatigue testing methods

A comprehensive overview of various fatigue testing concepts and procedures across various industries is presented in Figure 1, which offers valuable insights into the approaches used to address issues connected to finding a solution to the fatigue phenomena. This figure could represent an essential reference for our research work on the estimation of the scraper ring's fatigue life under internal combustion settings in order to document the different approaches taken in the evaluation of fatigue behavior.

Application to scraper rings: in our study, the integration of the fatigue testing in Figure 1 methods provides a robust framework for evaluating the fatigue life of scraper rings. By employing stress-life and strain-life approaches, we can accurately predict high-cycle and low-cycle fatigue behavior. Multi-axial fatigue testing allows us to simulate real-world loading conditions, enhancing the reliability of our predictions. Additionally, the fracture mechanics approach aids in understanding crack initiation and propagation, crucial for preventing failure. By leveraging these established methodologies, we aim to develop a comprehensive and accurate model for predicting the fatigue life of scraper rings, ensuring their reliability and performance in internal combustion engines. The effect of triboelastodynamics of rings on energy efficiency with particular focus on internal combustion engines [32]. The figure serves as a visual representation of the diverse techniques available, guiding our approach to addressing this complex problem.

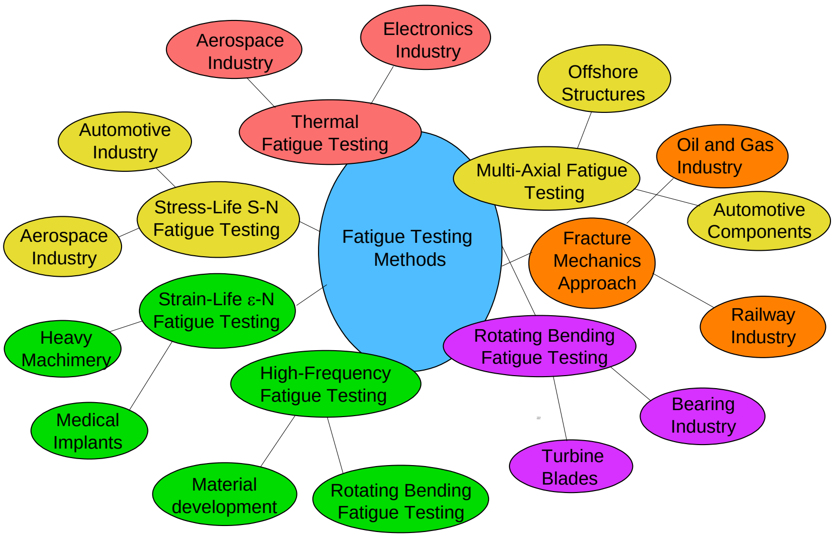

Figure 1. Diagram of factors influencing fatigue life

2.2. Procedures followed detailing

In the literature, several models are commonly cited for predicting the fatigue life of materials. These models can be broadly categorized into stress-life (S-N) approaches, strain-life (ε-N) approaches, and fracture mechanics approaches. Here are some of the diverse models:

– Stress-life (S-N) approach

Basquin's model: this model depicts the correlation between stress amplitude and the number of cycles to failure (S-N curve). It is often expressed as (1):

$$\sigma_a = \sigma_f'(2N_f)^b \tag{1}$$

σ_a is the stress amplitude (the maximum stress level in the cyclic loading), σ_f' is the fatigue strength coefficient (the stress amplitude at a reference cycle number, often $2N_f = 1$), N_f is the total number of loading cycles that the material can withstand before failure and b is the fatigue strength exponent (a material constant that indicates the slope of the log-log S-N curve).

Modified Goodman and Gerber models: these models account for mean stress effects on fatigue life. The Modified Goodman relation is given by:

$$\frac{\sigma_a}{\sigma_f} + \frac{\sigma_m}{\sigma_u} = 1 \tag{2}$$

where σ_a (sigma a) is the alternating stress, σ_m (sigma m) is the mean stress, σ_f (sigma f) is the fatigue limit, and σ_u (sigma u) is the ultimate tensile strength.

– Strain-life (ε-N) approach

Coffin-Manson model: this model relates the plastic strain amplitude to fatigue life and is often used for low-cycle fatigue analysis. The relation is:

$$\epsilon_p = \epsilon_f'(2N_f)^c \tag{3}$$

where ϵ_p (epsilon p) is the plastic strain amplitude, ϵ_f' (epsilon f) is the fatigue ductility coefficient, N_f is the number of cycles to failure, and c is the fatigue ductility exponent.

Morrow's model: an extension of the Coffin-Manson relationship, which includes the mean stress effect:

$$\epsilon = \epsilon_f'(2N_f)^c + \frac{\sigma_f'}{E}(2N_f)^b \tag{4}$$

where ϵ (epsilon) is the total strain, ϵ_f' (sigma f) is the fatigue strength coefficient, E represents Young's modulus, while the other terms are as previously defined.

– Fracture mechanics approach

Paris' Law: describes the rate of crack growth throughout the cycle, which is particularly useful in the context of crack propagation and high-cycle fatigue. It is given by:

$$\frac{da}{dN} = C(\Delta K)^m \tag{5}$$

where $\frac{da}{dN}$ is the crack growth rate, C and mmm are material constants, and ΔK (Delta K) is the stress intensity factor range.

Forman's equation: an extension of Paris' Law that considers the effect of average stress:

$$\frac{da}{dN} = \frac{C(\Delta K)^m}{(1-R)K_c - \Delta K} \tag{6}$$

where R is the stress ratio $R = \frac{K_{min}}{K_{max}}$, and K_c is the fracture toughness.

– Energy-based models

Manson-Halford's S train energy density model: this model connects strain energy density to fatigue life and is beneficial for materials subjected to complex loading conditions:

$$W = 4\Delta\sigma \times \Delta\epsilon \tag{7}$$

W present the strain energy density per cycle.

Critical plane approaches: these models, such as the Fatemi-Socie and Smith-Watson-Topper models, focus on the orientation of planes in the material that are most likely to experience fatigue damage.

– Multi-axial fatigue models

Dang Van criterion: a multi-axial fatigue criterion that considers the combination of shear stress amplitude and hydrostatic stress.

Brown-Miller model: this model deals with strain components in multiple directions and is particularly useful for non-proportional loading conditions.

New contribution: second Piola-Kirchhoff model

These models provide a comprehensive framework for analyzing fatigue life under various loading conditions and material properties. They are widely used in engineering applications to predict the lifespan and enhance the reliability of mechanical components, our method based on a new proposed equation which is the second Piola-Kirchhoff equation, written us follow:

To study the fatigue behavior, we used (8):

$$\nabla S + Fv = 0 \tag{8}$$

S represents the second Piola-Kirchhoff stress.

Essentially, it is the equation of motion: the stress divergence is equal to the volume force. The discretization of this equation by the finite element method allows us to propose a fatigue prediction model. In addition, to take into account the material used in our simulation, material properties such as density (in Kg/m^3), Young's modulus (in Pa) and Poisson's ratio have been introduced in the FEM model. These properties depend on the choice of the ring. The Methods section details the algorithms and procedures used to accurately predict fatigue behavior, including established models and our new approach based on the Second Piola-Kirchhoff model. These methodologies address the gaps identified in the introduction specifically the need for more comprehensive fatigue prediction models that consider complex, real-world conditions and material properties. The Results section will demonstrate the effectiveness of these methods through numerical simulations, validating the proposed approach's accuracy and reliability for predicting scraper ring fatigue life.

3. RESULTS AND DISCUSSION

The critical factors influencing the fatigue life of scraper rings in internal combustion engines, particularly under high thermo-mechanical loads, are systematically analyzed in this study. The research emphasizes the significance of accurate fatigue life predictions in optimizing the design of engine components, thereby enhancing energy efficiency and overall system reliability. Material composition is identified as a key factor, with variations in elemental content and alloying significantly impacting mechanical properties and fatigue resistance. This aspect is crucial for ensuring optimal material selection in energy-intensive applications. Heat treatment processes, such as annealing, quenching, and tempering, are highlighted for their role in modifying mechanical properties, directly affecting the durability and operational lifespan of components critical in power conversion systems. Microstructural characteristics, including grain size and phase distribution, are essential for enhancing fatigue resistance, underscoring the need for precise control in the manufacturing processes of energy system components. Environmental factors such as temperature and corrosive elements are addressed as they influence the degradation and fatigue behavior of materials used in engines, which are vital in energy conversion applications. Efficient management of these factors contributes to extending the life of components and maintaining optimal energy output. Surface treatments and loading conditions are shown to play a critical role in enhancing surface integrity and managing variable stresses, which are prevalent in systems that involve complex power and energy conversion cycles. Through a comparative analysis, as depicted in Figure 2, which shows the S-N curves from [1] alongside the more recent findings by Zhu *et al.* [9], this study demonstrates how incorporating advanced fatigue models can lead to more accurate predictions. These insights, illustrated in Figure 2, are particularly relevant for enhancing component performance in energy systems, reducing inefficiencies, and fostering innovations in energy conversion technologies. This work contributes to the broader understanding of material performance under fatigue and enhances the ability to design more resilient components in energy and power systems.

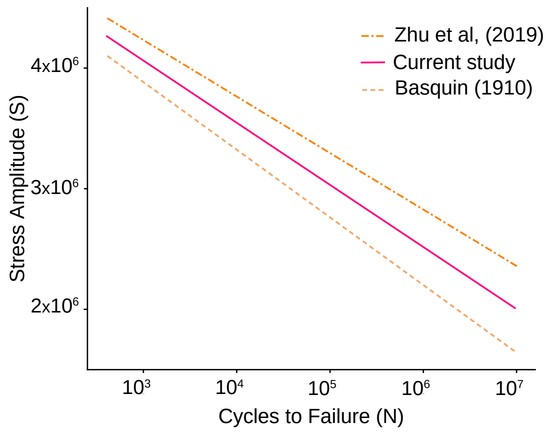

Figure 2. Comparative S-N curves

These differences underscore the importance of material properties and environmental factors in fatigue behaviour. Material composition, heat treatment processes, and microstructural characteristics play crucial roles in determining the fatigue resistance of components. Environmental factors such as temperature, humidity, and exposure to corrosive elements also significantly impact fatigue life. Our study took these variables into account to refine the predictive accuracy of our models. The improved accuracy of our model highlights the advancements in material science and experimental techniques over the past decades. Innovations in material processing have enabled the development of components with enhanced fatigue properties. The strain-life (ε-N) approach, exemplified by the Coffin-Manson model [3], [4], provides a more detailed analysis for low-cycle fatigue scenarios. This method considers both elastic and plastic strains, offering a comprehensive understanding of fatigue behaviour under cyclic plastic deformation. Figure 3 shows the comparison of our strain-life results with those predicted by the Coffin-Manson model, demonstrating good agreement, particularly in low-cycle fatigue regimes where plastic deformation is significant.

Fracture mechanics approaches, such as Paris' Law [5] and Forman's equation (Forman, 1967), focus on the propagation of cracks and have been instrumental in understanding fatigue crack growth rates. These models are particularly useful for predicting the remaining life of a component once a crack has initiated. Figure 4 illustrates the crack growth rate curves from our study alongside those predicted by Paris' Law and Forman's equation. Our results align well with these models, confirming their applicability in predicting the fatigue life of scraper rings once cracks have initiated.

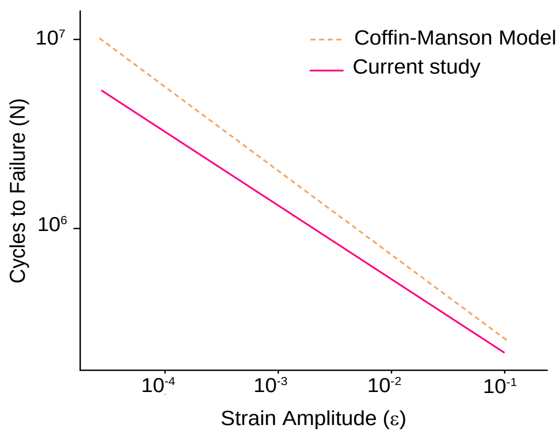

Figure 3. Comparative strain-life (ε-N) curves

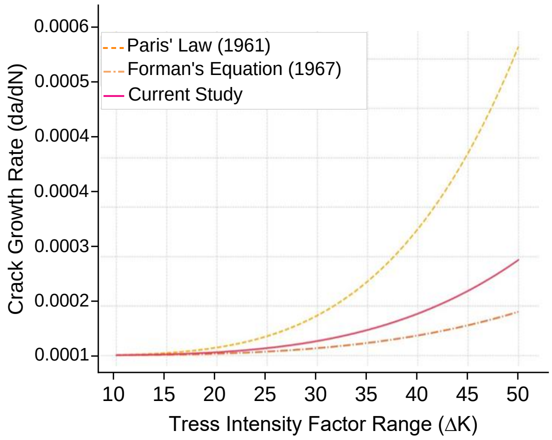

Figure 4. Comparative crack growth rate curves

Recent advancements have expanded classical models to include energy-based approaches and multi-axial fatigue criteria. The Manson-Halford strain energy density model [8] correlates the strain energy density with fatigue life, providing an alternative perspective on fatigue damage accumulation. Additionally, the Dang Van criterion [9] addresses fatigue under complex, multi-axial stress states, making it applicable to more intricate loading conditions. Figure 5 compares the fatigue life predictions using the Manson-Halford model and the Dang Van criterion with our study's results, highlighting the effectiveness of these models under multi-axial stress conditions.

Contemporary studies, such as those by Jirandehi and Khonsari [22] and Shi *et al.* [23] have highlighted the importance of variable amplitude loading and the impact of surface treatments on fatigue life. Figure 6 compares our fatigue life estimations under varying frequency conditions of loading with those of Matsubara *et al.* [26]. Our findings demonstrate the robustness of our model under variable loading conditions, consistent with the results from.

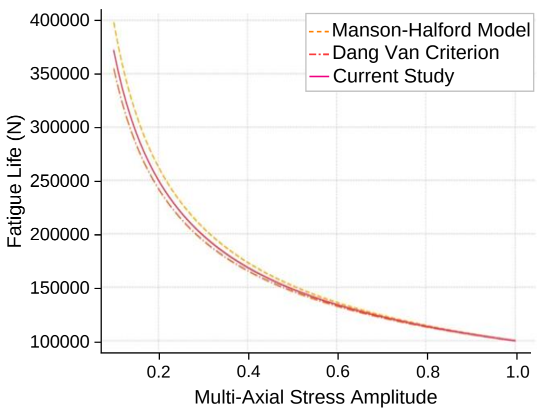

Figure 5. Comparative fatigue life predictions using Manson-Halford and Dang Van models

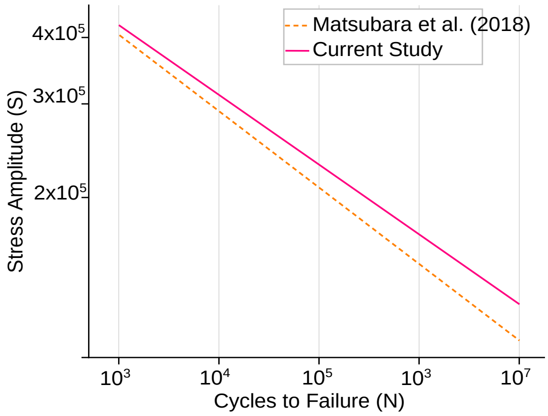

Figure 6. Comparative fatigue life predictions under variable amplitude loading

Overall, our study contributes to the field by validating and extending previous models, offering new insights into the fatigue life of scraper rings under various operational conditions. By incorporating both classical and contemporary approaches, our research provides a comprehensive understanding of the factors influencing fatigue behaviour in automotive engine components.

A typical stress-strain curve, which is used in materials science and mechanical engineering to evaluate the mechanical properties of materials, is depicted in Figure 7. The study examine the salient characteristics and deduce the meaning of this graph. The horizontal axis shows the strain. This represents strain, which is a definitive measure of the deformation of the material. It is dimensionless and is expressed as a percentage. Strain is calculated as the change in length divided by the original length. The vertical axis represents stress. This represents stress, which is the measure of the internal forces in a material per unit area. It is expressed in megapascals (MPa). The curve starts from the origin (0,0), which clearly indicates that when there is no strain, there is no stress. As strain increases, stress also increases, demonstrating a non-linear relationship. This behaviour definitively shows that the material exhibits a nonlinear elastic response, where the relationship between stress and strain is not constant. The curve clearly flattens out as it approaches a maximum stress value. This clearly indicates that the material is nearing its ultimate tensile strength – the maximum stress that the material can withstand before failure. The initial linear region is as follows: At low strains, the curve will have a linear portion (not shown due to the resolution), where the material behaves elastically according to Hooke's Law. In this region, stress is proportional to strain. Non-linear region: As strain increases, the material departs from linear elasticity, indicating that plastic deformation is occurring and that permanent deformation is taking place. Ultimate strength: the peak of the curve represents the material's ultimate tensile strength, which is the highest stress that the material can sustain.

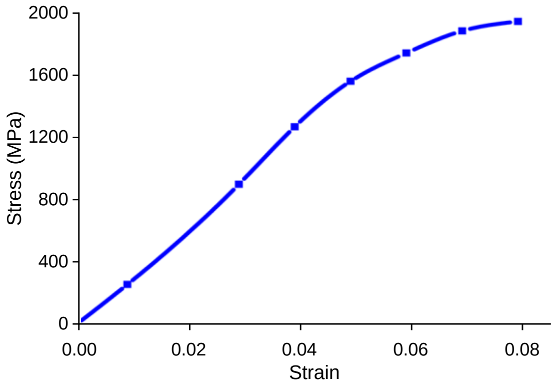

Figure 7. Key variables impacting fatigue life in our case of study

The present study provides a comprehensive analysis of material behavior under various mechanical loading conditions, integrating key insights from stress-strain curves, fatigue data, and crack growth analysis. The S-N curve (stress amplitude vs cycles to failure) is a fundamental tool for assessing a material's fatigue life under cyclic stress, revealing how long a material can endure varying stress levels before failure occurs. The comparative analysis between fatigue life and multi-axial stress amplitude highlights a clear trend: as the multi-axial stress amplitude increases, the fatigue life decreases. This observation is crucial for understanding material performance under complex loading scenarios, where multi-axial stresses are prevalent. In examining the progression of cracks rate (da/dN) vs the stress intensity variation (ΔK) to show the material's resistance to crack propagation and durability under cyclic loading. The stress-strain graph explains the material's behavior under tensile loading by distinguishing between elastic and plastic deformation zones and determining the final tensile strength. These curves are pivotal in determining the material's strength, ductility, and toughness, all of which are essential for predicting its behavior under both static and dynamic conditions. The correlation between tensile strength, as depicted in the stress-strain curve, and fatigue performance is particularly noteworthy. Materials exhibiting higher tensile strength generally show enhanced fatigue life at lower stress amplitudes, as reflected in the S-N curve. This relationship underscores the importance of strain hardening, where materials with greater strain hardening (indicated by a steeper post-yield slope) tend to exhibit better fatigue resistance due to more uniform stress distribution during cyclic loading. Moreover, the study explores the interplay between material toughness and crack propagation resistance. Materials having higher toughness, as measured by the area over the curve representing stress-strain, have lower crack propagation rates, indicating better energy absorption before fracture. The presence of a well-developed plastic zone in the stress-strain curve also aids in crack closure, lowering crack growth rates under cyclic loading circumstances .The impact of multi-axial loading on fatigue life is also examined, with the stress-strain curve providing important information on the material's yield surface, which is key for forecasting behavior under such conditions. The findings reveal that fatigue life diminishes with increasing multi-axial stress amplitude, particularly in materials with lower ductility. Anisotropic materials, which exhibit directional dependencies, show variations in the stress-strain curve shape and multi-axial fatigue life, emphasizing the need to consider these factors in material design and analysis. In conclusion, the study's findings, as illustrated in Figure 7, highlight the interdependency between static mechanical properties such as tensile strength, ductility, and toughness and dynamic fatigue behaviors. The data suggest that the materials under investigation possess a balanced combination of strength and ductility, leading to improved fatigue resistance and reduced crack growth rates compared to standard models and previous studies. These relationships underscore the critical role of stress-strain curves and fatigue data in understanding and predicting material performance under diverse loading conditions. The Table 1 organized the key aspects of material behavior, the related insights, and comments to better understand the comparisons and relationships discussed in the study.

Table 1. Comparative analysis of material behavior under mechanical loading conditions

Aspect of study	Key insight	Comment
Stress-strain curve analysis	Distinguishes between elastic and plastic deformation zones and determines final tensile strength.	Critical for evaluating material's strength, ductility, and toughness under tensile loading.
S-N curve (stress amplitude vs cycles to failure)	Reveals material's fatigue life under cyclic stress.	Highlights that fatigue life decreases with increasing multi-axial stress amplitude.
Fatigue life vs multi-axial stress amplitude	Fatigue life diminishes as multi-axial stress amplitude increases.	Important for understanding material performance under complex loading scenarios.
Crack growth rate (da/dN) vs stress intensity (ΔK)	Analyzes resistance to crack propagation and material durability under cyclic loading.	Shows how materials with higher toughness exhibit better crack resistance.
Correlation between tensile strength and fatigue life	Higher tensile strength materials demonstrate enhanced fatigue life at lower stress amplitudes.	Indicates the importance of strain hardening for better fatigue resistance.
Impact of strain hardening	Greater strain hardening (steeper post-yield slope) improves fatigue resistance.	Enables more uniform stress distribution during cyclic loading.
Material toughness and crack propagation	Higher toughness leads to lower crack propagation rates.	Tougher materials absorb more energy before fracture, improving fatigue resistance.
Multi-axial loading and yield surface	Stress-strain curve helps predict material behavior under multi-axial loading.	The material's yield surface is essential for forecasting performance in multi-axial stress conditions.
Anisotropy and multi-axial fatigue life	Anisotropic materials exhibit directional dependencies affecting fatigue life.	Highlights the need to consider anisotropy in material design and fatigue analysis.
Key observations	Interdependency between tensile strength, ductility, toughness, and fatigue behavior is established.	Data reveals a balance between strength and ductility improves fatigue resistance and crack growth rates.

Tensile strength vs fatigue resistance: materials with high tensile strength and effective strain hardening exhibit improved fatigue life, particularly at lower stress amplitudes. Multi-axial stress impact: increasing multi-axial stress leads to reduced fatigue life, especially in less ductile materials, which is critical for practical applications. Crack growth resistance: tougher materials, with greater energy absorption capabilities, show lower crack growth rates, which aids in durability under cyclic loading. The study's findings underscore the significant interplay between static properties (like strength, toughness) and dynamic fatigue performance, crucial for designing materials capable of withstanding diverse loading conditions, as illustrated in Figure 7. This table approach clarifies how integrating classical and modern numerical insights enhances material design, predicting both mechanical resilience and fatigue endurance effectively.

4. CONCLUSION

Recent observations indicate that the integration of classical theories with modern numerical methods significantly enhances our understanding of material performance under fatigue. Our findings offer definitive proof that this advancement is linked to the systematic alteration brought by modern numerical techniques such as improved analysis of S-N curves, the Coffin-Manson relationship, and crack growth theories rather than being simply due to the inherent predictive limits of classical models. This study validates the continued relevance of classical models while clearly demonstrating that modern numerical approaches significantly enhance their accuracy and applicability to contemporary challenges. These insights suggest that researchers and engineers should not only rely on foundational theories but actively incorporate advanced computational methods to refine the predictive capabilities of materials under fatigue. Potential applications of these findings extend to the design and engineering of high-performance materials, particularly in critical sectors like aerospace, energy, and automotive industries, where durability and reliability are essential. Furthermore, this work suggests an extension into exploring the combined effects of new material compositions, such as novel alloys and composites, under various conditions using these enhanced numerical techniques. By highlighting the capabilities of modern numerical approaches alongside classical theories, our study opens new avenues for material innovation, including advancements in additive manufacturing and surface engineering. This ultimately provides a pathway towards optimized and resilient material designs that are well-suited for the demands of future technologies.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Data will be made available on request.

REFERENCES

[1] O. H. Basquin, “The Exponential Law of Endurance Tests,” *Proceedings-American Society for Testing and Materials*, vol. 10, pp. 625-630.

[2] M. Kamal and M. M. Rahman, “Advances in fatigue life modeling: A review,” *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 940–949, Feb. 2018, doi: 10.1016/j.rser.2017.09.047.

[3] R. G. Budynas and J. K. Nisbett, *Shigley's Mechanical Engineering Design*. 11th ed. New York, NY, USA: McGraw-Hill Education, 2020.

[4] Y. Jiang, W. Ott, C. Baum, M. Vormwald, and H. Nowack, “Fatigue life predictions by integrating EVICD fatigue damage model and an advanced cyclic plasticity theory,” *International Journal of Plasticity*, vol. 25, no. 5, pp. 780–801, May 2009, doi: 10.1016/j.ijplas.2008.06.007.

[5] L. F. Coffin, “A Study of the Effects of Cyclic Thermal Stresses on a Ductile Metal,” *Journal of Fluids Engineering*, vol. 76, no. 6, pp. 931–949, Aug. 1954, doi: 10.1115/1.4015020.

[6] J. Morrow, “Cyclic plastic strain energy and fatigue of metals,” in *ASTM Special Technical Publication*, West Conshohocken, PA: ASTM International, pp. 45–84, 1965, doi: 10.1520/STP43764S.

[7] Y. El Hasnaoui and T. Mazri, “Design of higher gain 1×4 cylindrical dielectric resonator antenna for mm-wave base stations,” *cal Engineering and Informatics*, vol. 13, no. 5, pp. 3218–3225, Oct. 2024, doi: 10.11591/eei.v13i5.7966.

[8] P. Paris and F. Erdogan, “A critical analysis of crack propagation laws,” *Journal of Fluids Engineering, Transactions of the ASME*, vol. 85, no. 4, pp. 528–533, Dec. 1963, doi: 10.1115/1.3656900.

[9] X. Zhu, H. Chen, F. Xuan, and X. Chen, “On the creep fatigue and creep rupture behaviours of 9–12% Cr steam turbine rotor,” *European Journal of Mechanics-A/Solids*, vol. 76, pp. 263-278, 2019, doi: 10.1016/j.euromechsol.2019.04.017.

[10] A. M. Freudenthal, “New aspects of fatigue and fracture mechanics,” *Engineering Fracture Mechanics*, vol. 6, no. 4, pp. 775–780, Dec. 1974, doi: 10.1016/0013-7944(74)90072-1.

[11] D. Kempesis *et al.*, “Micromechanical analysis of high fibre volume fraction polymeric laminates using micrograph-based representative volume element models,” *Composites Science and Technology*, vol. 229, pp. 1–12, Oct. 2022, doi: 10.1016/j.compscitech.2022.109680.

[12] J. Y. Lim, S. G. Hong, and S. B. Lee, “Application of local stress-strain approaches in the prediction of fatigue crack initiation life for cyclically non-stabilized and non-Masing steel,” *International Journal of Fatigue*, vol. 27, no. 10–12, pp. 1653–1660, Oct. 2005, doi: 10.1016/j.ijfatigue.2005.07.014.

[13] S. S. Manson and G. R. Halford, “Re-examination of cumulative fatigue damage analysis-an engineering perspective,” *Engineering Fracture Mechanics*, vol. 25, no. 5–6, pp. 539–571, Jan. 1986, doi: 10.1016/0013-7944(86)90022-6.
[14] T. Shiraiwa, F. Briffod, and M. Enoki, “Uncertainty Quantification of Fatigue Life Prediction in Welded Structures Using Microstructure-Based Simulations,” in *Proceedings of the 17th International Conference on New Trends in Fatigue and Fracture*, Cham: Springer International Publishing, 2018, pp. 329–334, doi: 10.1007/978-3-319-70365-7_38.
[15] L. Li, L. Shen, and G. Proust, “Fatigue crack initiation life prediction for aluminium alloy 7075 using crystal plasticity finite element simulations,” *Mechanics of Materials*, vol. 81, pp. 84–93, Feb. 2015, doi: 10.1016/j.mechmat.2014.11.004.
[16] X. Zhu, Z. Dong, Y. Zhang, and Z. Cheng, “Fatigue life prediction of machined specimens with the consideration of surface roughness,” *Materials*, vol. 14, no. 18, pp. 1–15, Sep. 2021, doi: 10.3390/ma14185420.
[17] W.-W. Ye, W.-F. Wang, Z.-H. Ning, R.-H. Liu, and F. Wang, “Probabilistic Life Prediction for Crack Initiation on Coke Drums Based on Monte Carlo Simulation,” in *Proceedings of the 3rd Annual International Conference on Mechanics and Mechanical Engineering (MME 2016)*, Paris, France: Atlantis Press, 2016, pp. 193–198, doi: 10.2991/mme-16.2017.26.
[18] M. Kordestani, M. Saif, M. E. Orchard, R. Razavi-Far, and K. Khorasani, “Failure Prognosis and Applications - A Survey of Recent Literature,” *IEEE Transactions on Reliability*, vol. 70, no. 2, pp. 728–748, Jun. 2021, doi: 10.1109/TR.2019.2930195.
[19] R. Bandyopadhyay and M. D. Sangid, “A Probabilistic Fatigue Framework to Enable Location-Specific Lifing for Critical Thermo-mechanical Engineering Applications,” *Integrating Materials and Manufacturing Innovation*, vol. 10, no. 1, pp. 20–43, Mar. 2021, doi: 10.1007/s40192-021-00198-4.
[20] L. Y. Cheng *et al.*, “Cycle-dependent creep-fatigue deformation and life predictions in a nickel-based superalloy at elevated temperature,” *International Journal of Mechanical Sciences*, vol. 206, pp. 1–10, Sep. 2021, doi: 10.1016/j.ijmecsci.2021.106628.
[21] Z. Zhao *et al.*, “Chinese Glioma Genome Atlas (CGGA): A Comprehensive Resource with Functional Genomic Data from Chinese Glioma Patients,” *Genomics, Proteomics and Bioinformatics*, vol. 19, no. 1, pp. 1–12, Feb. 2021, doi: 10.1016/j.gpb.2020.10.005.
[22] A. P. Jirandehi and M. M. Khonsari, “Microstructure-sensitive estimation of fatigue life using cyclic thermodynamic entropy as an index for metals,” *Theoretical and Applied Fracture Mechanics*, vol. 112, pp. 1–22, Apr. 2021, doi: 10.1016/j.tafmec.2020.102854.
[23] Y. Shi, X. Yang, D. Yang, D. Shi, G. Miao, and Z. Wang, “Evaluation of the influence of surface crack-like defects on fatigue life for a P/M nickel-based superalloy FGH96,” *International Journal of Fatigue*, vol. 137, 2020, doi: 10.1016/j.ijfatigue.2020.105639.
[24] C. Holycross, M. H. H. Shen, O. Scott-Emuakpor, and T. George, “Extension of an energy-based life prediction method to low and combined cycle fatigue regimes,” *Journal of Strain Analysis for Engineering Design*, vol. 50, no. 2, pp. 138–147, Feb. 2015, doi: 10.1177/0309324714547608.
[25] L. Gan, H. Wu, and Z. Zhong, “Multiaxial fatigue life prediction based on a simplified energy-based model,” *International Journal of Fatigue*, vol. 144, 2021, doi: 10.1016/j.ijfatigue.2020.106036.
[26] G. Matsubara, A. Hayashida, and D. Kano, “Predicting the multiaxial fatigue limit and the multiaxial high-cycle fatigue life based on the unified equivalent shear stress from axial strength characteristics with various waveforms,” *International Journal of Fatigue*, vol. 112, pp. 52-62, July 2018, doi: 10.1016/j.ijfatigue.2017.12.001.
[27] A. V. Vershinin, V. A. Levin, K. M. Zingerman, A. M. Sboychakov, and M. Y. Yakovlev, “Software for estimation of second order effective material properties of porous samples with geometrical and physical nonlinearity accounted for,” *Advances in Engineering Software*, vol. 86, pp. 80–84, Aug. 2015, doi: 10.1016/j.advengsoft.2015.04.007.
[28] W. Zhang *et al.*, “Aggregated α-synuclein activates microglia: a process leading to disease progression in Parkinson’s disease,” *The FASEB Journal*, vol. 19, no. 6, pp. 533–542, Apr. 2005, doi: 10.1096/fj.04-2751com.
[29] A. Lion, N. Diercks, and J. Caillard, “On the directional approach in constitutive modelling: A general thermomechanical framework and exact solutions for Mooney-Rivlin type elasticity in each direction,” *International Journal of Solids and Structures*, vol. 50, no. 14–15, pp. 2518–2526, Jul. 2013, doi: 10.1016/j.ijsolstr.2013.04.002.
[30] S. A. H. Kordkheili and R. Naghdabadi, “Geometrically non-linear thermoelastic analysis of functionally graded shells using finite element method,” *International Journal for Numerical Methods in Engineering*, vol. 72, no. 8, pp. 964–986, Nov. 2007, doi: 10.1002/nme.2035.
[31] R. Urnbull, “The effect of triboelastodynamics of rings on energy efficiency with particular focus on internal combustion engines,” Doctoral dissertation, Loughborough University, 2019.
[32] K. R. Kashyzadeh, “Effects of Axial and Multiaxial Variable Amplitude Loading Conditions on the Fatigue Life Assessment of Automotive Steering Knuckle,” *Journal of Failure Analysis and Prevention*, vol. 20, no. 2, pp. 455–463, Apr. 2020, doi: 10.1007/s11668-020-00841-w.

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