

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

AFTERBURNER LINER
LOW CYCLE FATIGUE LIFE COMPUTATION

BARAN CİN

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF ENERGY TECHNOLOGIES
APPLIED PROPULSION SYSTEM DESIGN AND
ENGINEERING FOR AEROSPACE TECHNOLOGIES
PROGRAM

ADVISOR: ASST. PROF. SALİH ÖZEN ÜNVERDİ

JULY 2025

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GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

ART YAKICI GÖMLEKLERİNDE DÜŞÜK ÇEVİRİM
YORULMA ÖMÜR HESAPLAMASI

BARAN CİN

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*To my
Family*

ABSTRACT

Military aircraft gas turbine engines operate under extreme thermal and mechanical conditions during afterburner use. The afterburner liner, a critical component of the engine's hot section exposed to severe operating conditions such as rapid thermal transients, high temperatures, and cyclic mechanical loads, must be resistant to low-cycle fatigue (LCF) damage. Reliable prediction of low-cycle fatigue (LCF) life is crucial for ensuring structural integrity, minimizing the risk of failure, and optimizing maintenance planning.

This thesis presents a comprehensive investigation into the low-cycle fatigue (LCF) life estimation of afterburner liners, employing experimental testing, finite element analysis (FEA), and strain-based fatigue prediction methods. Emphasis is placed on the effect of effusion cooling holes, which, while enhancing thermal protection, introduce significant stress concentrations that diminish fatigue-life. Furthermore, the damage-accelerating effect of thermal hold times—prolonged exposure to high temperatures—through creep-fatigue interaction has been experimentally demonstrated.

Thermo-mechanical FEA simulations are conducted to capture the stress-strain response of the liner under representative engine conditions. Critical regions prone to crack initiation are identified, and fatigue life is estimated based on strain-based models. The results demonstrate that both the geometric effects of effusion cooling holes and operational factors like hold-time at elevated temperatures significantly reduce component life.

This research provides a comprehensive framework for assessing the fatigue behavior of afterburner liners, contributing to improved design strategies, more accurate life prediction, and safer, more efficient engine operation.

Keywords: Low Cycle Fatigue, Afterburner Liner, Effusion Cooling, Fatigue Life Prediction, Structural Integrity, Gas Turbine Engines

ÖZET

Askeri uçakların gaz türbinli motorları art yakıcı kullanımında son derece zorlu ısı ve mekanik koşullar altında çalışırlar. Hızlı ısı geçişler, yüksek sıcaklıklar ve çevrimsel mekanik yükler gibi zorlu çalışma koşullarına maruz kalan motor sıcak bölümünün kritik bileşeni art yakıcı gömleği düşük çevrimli yorulma (LCF) hasarına mukavim olmalıdır. Yapısal bütünlüğün sağlanması, arıza riskinin en aza indirilmesi ve bakım planlamasının optimize edilmesi için güvenilir LCF ömür tahmini büyük önem taşımaktadır.

Bu tez çalışmasında, art yakıcı gömleklerinin düşük çevrimli yorulma (LCF) ömrü; deneysel testler, sonlu elemanlar analizi (FEA) ve gerinim tabanlı yorulma ömrü tahmin yöntemleri kullanılarak kapsamlı bir şekilde incelenmiştir. Çalışmanın odak noktalarından biri, termal korumayı artırmalarına rağmen önemli gerilme yığılmalarına yol açarak yorulma ömrünü olumsuz etkileyen efüzyon soğutma deliklerinin etkisidir. Ayrıca, ısı bekleme sürelerinin (yüksek sıcaklıklarda uzun süreli çalışmanın) sürünme-yorulma etkileşimi yoluyla hasarı hızlandırıcı etkisi de deneylerle belirlenmiştir.

Temsili motor koşulları altında yapılan termo-mekanik FEA simülasyonlarıyla gömlek üzerindeki gerilme-gerinim tepkisi analiz edilmiş, çatlak oluşumuna yatkın kritik bölgeler belirlenmiş ve gerinim esaslı modellerle yorulma ömrü tahmin edilmiştir. Elde edilen sonuçlar hem efüzyonla soğutma deliklerinin geometrik etkilerinin hem de yüksek sıcaklıklarda bekleme süresi gibi operasyonel faktörlerin bileşen ömrünü önemli ölçüde azalttığını göstermektedir.

Bu araştırma, art yakıcı gömleklerinin yorulma davranışının değerlendirilmesine yönelik kapsamlı bir çerçeve sunmakta; bu sayede gelişmiş tasarım stratejilerine, daha doğru ömür tahminlerine ve daha güvenli, daha verimli motor işletimine katkı sağlamaktadır.

Anahtar Kelimeler: Düşük Çevrimli Yorulma, Art Yakıcı Gömleği, Efüzyonla Soğutma, Yorulma Ömrü Tahmini, Yapısal Bütünlük, Gaz Türbinli Motorlar

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LIST OF SYMBOLS AND ABBREVIATIONS

σ_a	: Alternating Stress
A	: Area
ε_e	: Elastic Strain
S_e	: Endurance Limit
ε_e	: Engineering Strain
ε'_f	: Fatigue Ductility Coefficient
c	: Fatigue Ductility Exponent
K_f	: Fatigue Notch Factor
S'_f	: Fatigue Strength
σ'_f	: Fatigue Strength Coefficient
b	: Fatigue Strength Exponent
f	: Fatigue Strength Fraction for 10^3 Loading Cycles
σ_{tf}	: Fatigue Stress
F	: Force
δt	: Hold Time Per Cycle
L_0	: Initial Length
K	: Kelvin
L	: Length
α	: Material Constant
σ_{max}	: Maximum Stress
σ_m	: Mean Stress
mm	: Milimeter
σ_{min}	: Minimum Stress
σ	: Normal Stress
$\sigma_x, \sigma_y, \sigma_z$	: Normal Stresses on planes x, y, z
r	: Notch Radius
q	: Notch Sensitivity
N	: Number of Cycles
N_f	: Number of Cycles to Failure
ε_p	: Plastic Strain
ν	: Poisson's Ratio
I_1, I_2, I_3	: Principal Axes
$\sigma_1, \sigma_2, \sigma_3$	: Principal Stresses
s	: Second
τ	: Shear Stress
A	: Stress Amplitude Ratio
K_t	: Stress Concentration Factor
σ_r	: Stress Range
R	: Stress Ratio
ε	: Strain
ε_a	: Strain Amplitude
σ_v	: The von Mises Stress
ε_t	: True Strain
S_{ut}	: Ultimate Tensile Strength
E	: Young's Modulus

ANN	: Artificial Neural Networks
ANSYS WB	: Ansys Workbench Finite Element Software
APS	: Atmospheric Plasma Spraying
ASTM	: American Society for Testing and Materials
CAD	: Computer Aided Design
CMC	: Ceramic Matrix Composites
ECI	: Eddy Current Inspection
EDM	: Electrical Discharge Machining
FE	: Finite Element
FEA	: Finite Element Analysis
FEM	: Finite Element Model
FGM	: Functionally Graded Material
FPI	: Fluorescent Penetrant Inspection
HCF	: High Cycle Fatigue
HPC	: High Pressure Compressor
HPT	: High Pressure Turbine
IGV	: Inlet Guide Vane
IRP	: Intermediate Rated Power
LCC	: Life Cycle Cost
LCF	: Low Cycle Fatigue
LPT	: Low Pressure Turbine
LPB	: Low Plasticity Burnishing
LSP	: Laser Shock Peening
MAC	: Modal Assurance Criteria
MIMO	: Multiple Input, Multiple Output
MISO	: Multiple Input, Single Output
NDT	: Nondestructive Testing
NRIFSD	: Non-Recoverable In-flight Shut Down
NSMS	: Non-interference Stress Measurement System
OMC	: Organic Matrix Composite
PDF	: Probability Density Function
SG	: Strain – Gauge
SN	: Specimen Number
S-N	: Nominal Stress – Number of Cycles
SWT	: Smith-Watson-Topper
TBC	: Thermal Barrier Coating
TC	: Thermocouple
TMF	: Thermomechanical Fatigue

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1. INTRODUCTION

The dream of the sky has haunted mankind's imagination since antiquity. The mythological figure Icarus, who made wings of feathers and wax to fly to the sun, symbolizes the relentless effort of human beings to conquer the sky. In the 17th century, Hezarfen Ahmet Celebi's attempt to cross the Bosphorus by jumping from the Galata Tower is one of the oldest examples of this passion and effort.

This dream has become a reality with modern aviation and has been especially accelerated by the development of gas turbine engines. These engines, which stand out with their efficiency, reliability, and thrust-to-weight characteristics, form the backbone of civil and military aviation. Among other engines, the turbofan and turbojet engines with afterburners stand out due to their ability to provide thrust boost during critical flight phases such as takeoff, combat maneuvers, and supersonic flight. In addition to the capabilities gained through afterburner, it is essential to meet the critical reliability and safety requirements of gas turbine engines. Therefore, it is crucial to understand and mitigate fatigue, one of the most critical damage mechanisms in aerospace engines, at the design stage to ensure long-term structural integrity.

1.1. The Evolution of Gas Turbine Engines

Modern gas turbine engines for aircraft propulsion are sophisticated machines consisting of many integrated sub-components and interfaces. In recent years, the complexity of the design of gas turbine engines has improved significantly in a positive sense. They now serve applications ranging from small auxiliary power units (APUs) producing shaft power to advanced vectored thrust engines used in modern military fighter aircraft.

The development of gas turbine engines was primarily driven by the need for air superiority in military missions. To maintain this superiority, engines need to be lightweight, compact, and capable of providing thrust to achieve higher aircraft speeds. The concept of using a gas turbine to create a hot jet stream and thereby generate thrust was first conceived by Sir Frank Whittle in 1929. This concept led to Sir Frank Whittle receiving a patent the following year. The idea then became of commercial interest

and led to the founding of a company in 1935. This company's prototype engine made its first run in 1937. The potential was recognized in 1939 by the British Air Ministry, which supported the development of a test aircraft that made its first flight on May 15, 1941. This was the beginning of the jet age [1]. A diagram of the components and thermodynamic states along the gas path of a single-spool turbojet engine is presented in **Figure 1.1**.

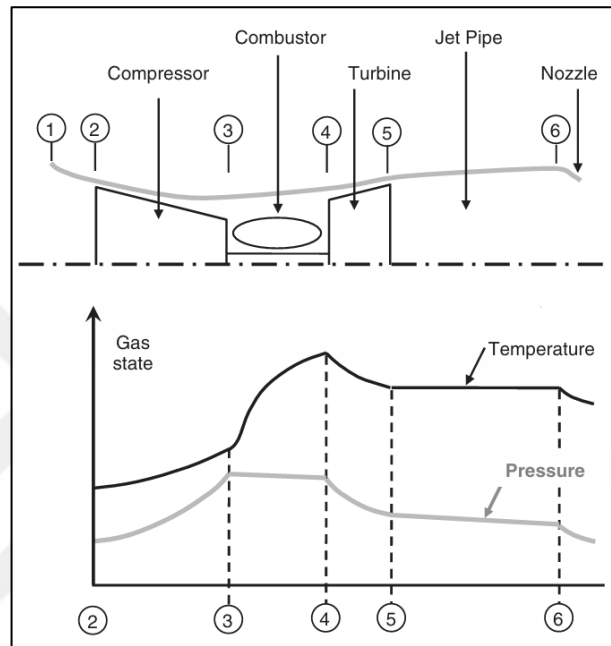


Figure 1.1: Components and gas path thermodynamic state profile of a typical turbojet engine [1].

The process of evolution and development of engines has progressed from simple systems to more complex systems that have been developed because of aviation and military needs. There are various types of engines in operation today. The reason for this variety is that the engine type changes depending on the application. For example, the requirements of a short-range passenger aircraft are significantly different from those of a supersonic fighter jet. In this context, different engine types are preferred by comparing the specifications for both aircraft. Therefore, modern engines are varied due to requirements [2].

The components of a single-shaft or single-spool turbojet engine are shown in **Figure 1.2**. The diffuser decreases the velocity and increases the pressure of the incoming air. The compressor elevates the air pressure and density and moderately increases its temperature. Injected fuel burns with the compressed air in the combustor resulting in

high temperature and specific volume combustion products. The turbine extracts part of the energy of the combustion products to drive the compressor which is on the same shaft. Finally, nozzle accelerates the hot, expanded gases at moderate pressure to produce thrust.

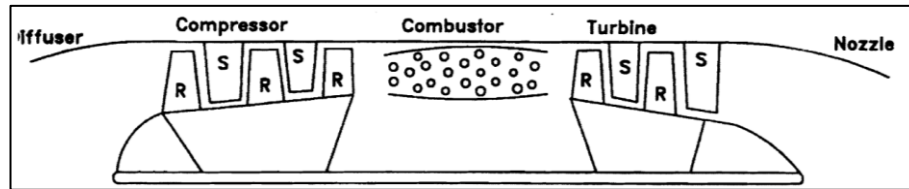


Figure 1.2: Components of a single-shaft or single-spool turbojet engine [2].

The components of a single-shaft or single-spool turbojet engine with afterburner are shown in Figure 1.3. An afterburner can be applied to a single- or twin-spool turbojet engine. A twin-spool turbojet engine with consecutive low- and high-pressure compressors driven by low- and high-pressure turbines by means of a hollow and a considerably faster rotating concentric solid shaft, respectively, has better off-design operating characteristics. Afterburner generates additional thrust and acceleration in military fighter aircrafts by increasing velocity of the gases at exhaust nozzle due to their elevated temperature and specific volume.

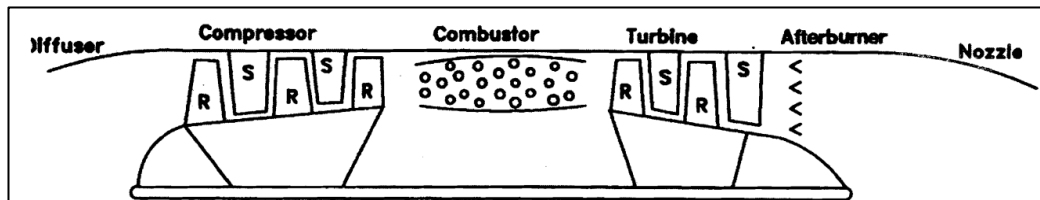


Figure 1.3: Components of a single-shaft or single-spool turbojet engine with afterburner [2].

The components of a turbofan engine with a mixer are shown in **Figure 1.4**. Diffused and slightly compressed air by fan is split into core and secondary streams. The secondary air bypassed around a two-spool turbojet engine through a duct is mixed with the turbine exhaust gases in a mixer before the mixture being accelerated through the nozzle to produce thrust with better fuel economy. The fan and first few stages of the low-pressure compressor are driven by the low-pressure turbine, while the high-pressure compressor is driven by the high-pressure turbine. Commercial and military aircraft use high- and lighter low-bypass ratio turbofan engines, respectively.

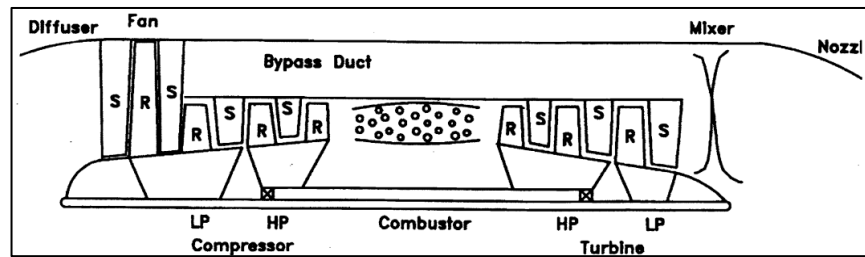


Figure 1.4: Components of a turbofan engine with a mixer [2].

The components of a turbofan engine with a mixer and afterburner for rapid thrust increase are shown in **Figure 1.5**. The afterburner is located downstream of the mixer where combustion with a large amount of air increases thrust significantly.

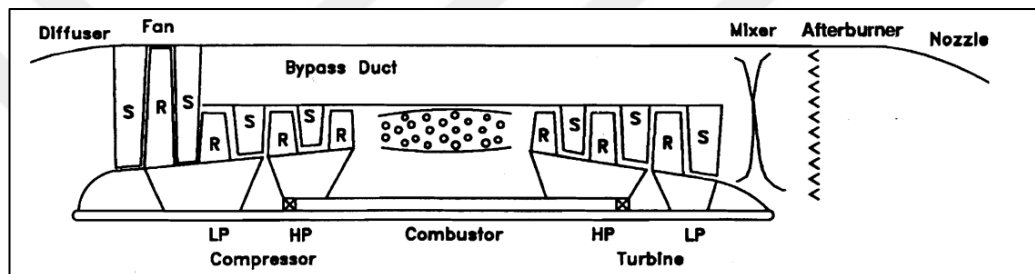


Figure 1.5: Components of a turbofan engine with a mixer and afterburner [2].

The components of a ramjet engine are shown in **Figure 1.6**. Ramjet without a self-propelled takeoff capability is used in very high-speed applications. The diffuser significantly increases the pressure of the incoming high-speed air. Then, high temperature combustion products of the fuel-air mixture are accelerated and leave the engine through the nozzle, producing thrust.

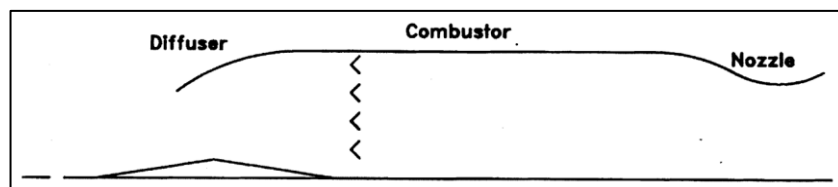


Figure 1.6: Components of a ramjet engine [2].

1.2. The Role of Afterburners in Modern Aviation

Thrust generation is essential to move an aircraft through the air, and most modern fighter aircraft achieve this with low bypass turbofan engines or turbojet engines integrated with afterburners. Supersonic flight requires overcoming a massive increase in drag close to the speed of sound. An afterburner must be added to the core engine as a means of achieving the necessary thrust to reach supersonic speeds. The afterburner injects additional fuel directly into the hot exhaust gases, allowing them to be re-combusted and thus generating more thrust. **Figure 1.7** depicts a modern fighter jet with its afterburner engaged.



Figure 1.7: A Modern Fighter Jet with Afterburner Activated [3].

The afterburner consists of fuel injectors, flame holders, and a liner housed within an elongated nozzle section. When activated, fuel is injected and mixed with air, which is then ignited and stabilized by the flame holders to produce additional thrust. However, this method results in higher fuel consumption and is less efficient than the combustion that occurs in the engine's core. When the afterburner is not in use, the engine operates like a basic turbojet or turbofan.

The thrust equation is typically analyzed by aerodynamicists in terms of two components. The subscripts of the first and second terms—*gross thrust* and *ram drag*—"e" and "0," denote conditions at the nozzle exit and the engine inlet, respectively. For clarity, the engine's thrust is called *net thrust*. According to the thrust

equation, net thrust is obtained by subtracting ram drag from gross thrust [4]. **Figure 1.8** presents the $F = m_e V_e - m_0 V_0$ thrust equation.

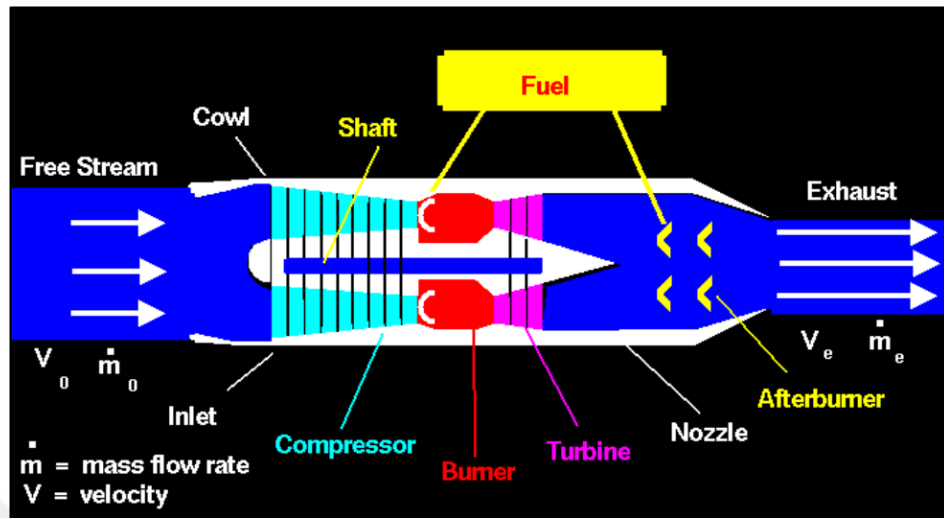


Figure 1.8: The Thrust Equation [4].

1.2.1. Understanding Afterburner Liners

Figure 1.9 shows a typical afterburner equipped with fuel spray bars, a torch igniter, flame holders, a screech/cooling liner, and a variable area nozzle. The afterburner liner serves two primary purposes: acting as a cooling barrier and enhancing combustion stability. As a cooling liner, it protects the afterburner from extreme temperatures by distributing a layer of cooler air along its length. Like the combustion chamber liner, it shields the outer casing from high thermal loads. Additionally, like a screech liner, it helps suppress intense pressure oscillations associated with combustion instabilities and rapid fluctuations in heat release. To minimize the risk of screech-related damage, a dense array of small holes is incorporated into the forward section of the liner. By carefully selecting the diameter and distribution of these holes, the system's acoustic response can be shifted away from harmful resonant frequencies [5].

It defines the volume in which the combustion process occurs and serves several key functions:

- Protects the outer casing from high temperatures
- Acts as a cooling-oriented heat shield
- Damps combustion instabilities

- Resists thermo-mechanical loads

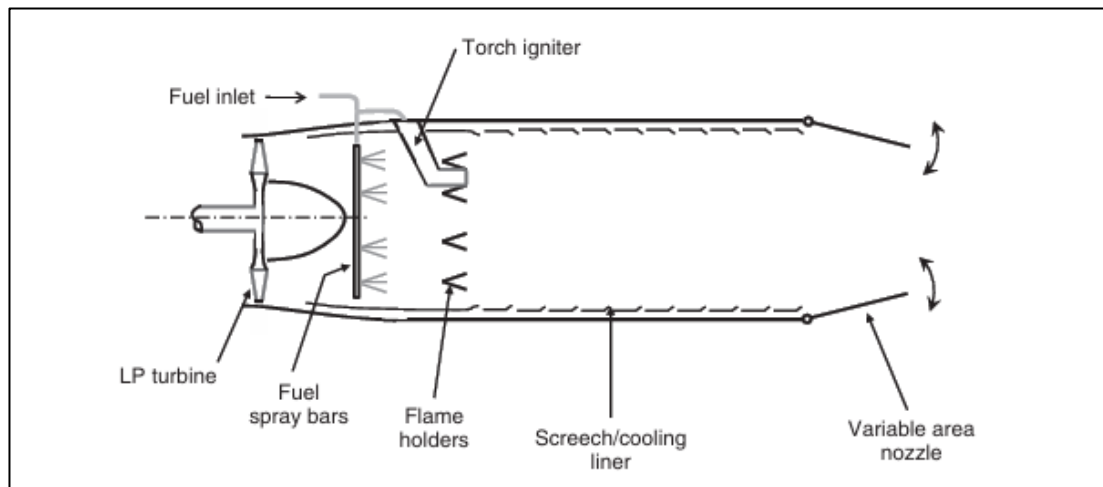


Figure 1.9: Typical Afterburner Arrangement [1].

1.3. Fatigue in Gas Turbine Engine Components

Fatigue refers to the gradual and localized structural deterioration that occurs in a material when it is repeatedly subjected to varying stresses and strains at specific locations. Over time, this repeated loading can result in the initiation of cracks and potentially lead to complete failure [6]. **Figure 1.10** provides a summary of key aspects of fatigue design procedures. The first column outlines major design considerations, including layout and geometry, joints, material selection, material surface conditions, and production variables. The second column presents essential information for stress analysis, such as stress distributions, stress concentration factors (K_t), stress intensity factors (K), secondary bending, S–N (cyclic stress amplitude (alternating stress)–number of loading cycles) curves, fatigue crack growth properties (da/dN) in relation to the stress intensity range (ΔK) and the cyclic stress intensity ratio (R), fracture toughness, and the effects of surface conditions and production variables on fatigue life. The third column describes fatigue performance predictions, including fatigue limit, crack initiation life, fatigue crack growth, and final failure, all based on fatigue loads and dynamic response stress spectra in a specified environment.

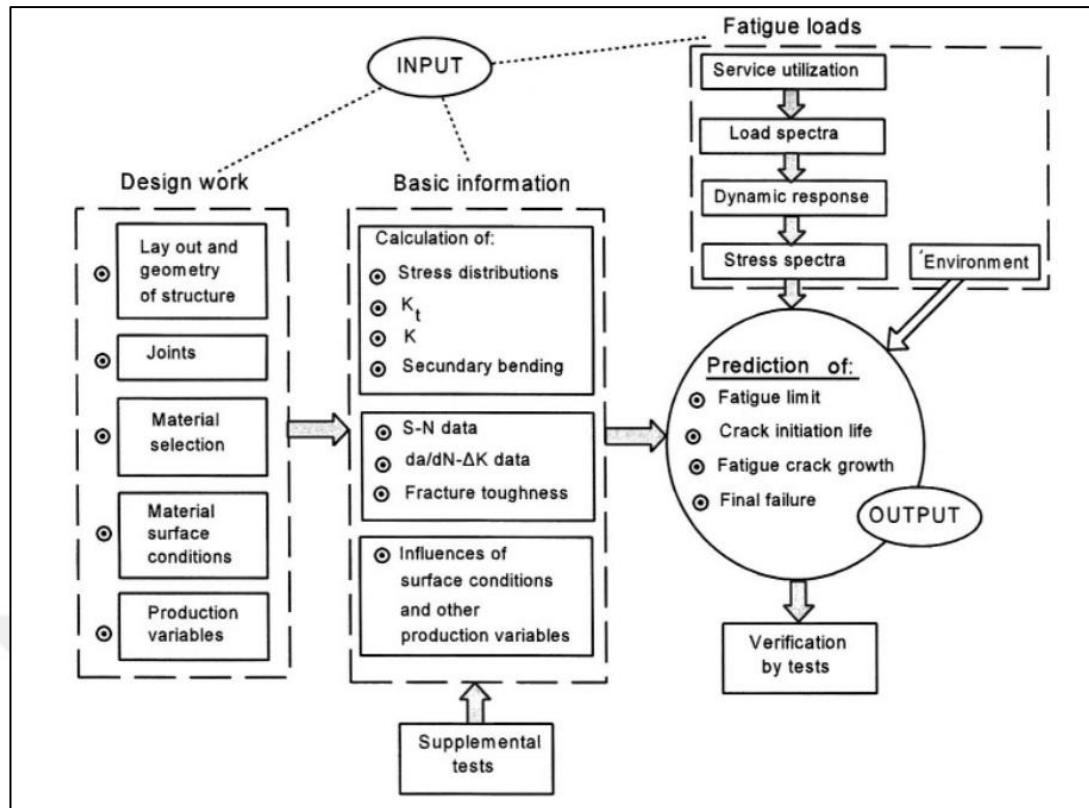


Figure 1.10: Investigation of Various Aspects of Fatigue of Structures [15].

1.3.1. Fatigue Related Aviation Accidents

Fatigue failure mechanisms have been a critical factor in many aviation accidents, particularly in gas turbine engine components subjected to repeated thermal and mechanical load cycles. Such fatigue failures can result in catastrophic engine events with serious safety consequences. The following section discusses several major aviation accidents attributed to low cycle fatigue (LCF) and underscores the importance of accurate fatigue life prediction and robust inspection protocols in preventing such incidents.

United Airlines Flight 232 suffered a catastrophic failure on July 19, 1989, due to the failure of its General Electric CF6-6 engine, type 2. The failure was caused by a fatigue crack initiated by a metallurgical defect in the fan disk material. Under low-cycle fatigue (LCF) conditions, the crack propagated with each flight cycle, ultimately resulting in the complete disintegration of the fan disk. The fan disk, where the LCF crack originated, is a critical load-bearing component. Its failure led to the loss of all three hydraulic systems, rendering the aircraft nearly uncontrollable. The flight crew

managed to land the aircraft using differential thrust control. Remarkably, 185 of the 296 people on board survived. The accident investigation emphasized the importance of ensuring material integrity during manufacturing and implementing strict LCF inspection protocols for engine components [7]. **Figure 1.11** shows the inspection history of the accident fan disk.

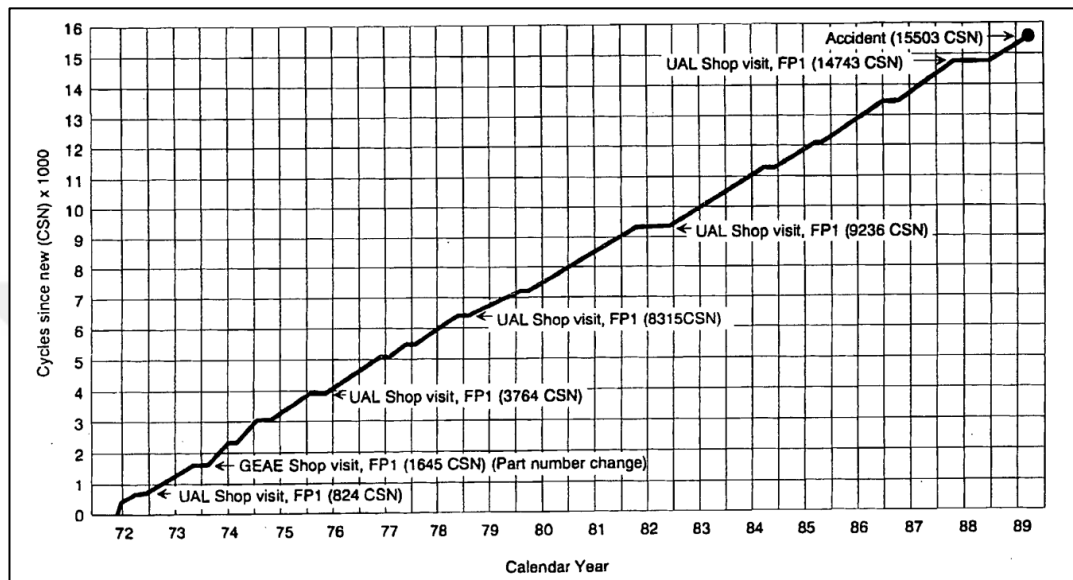


Figure 1.11: Inspection History of Accident Fan Disk [7].

Qantas experienced an uncontained engine failure involving a Rolls-Royce Trent 900 engine shortly after takeoff from Singapore on November 4, 2010. The failure was initiated by a fracture in an oil supply pipe, which led to an internal oil fire within the engine. This fire caused thermomechanical fatigue (TMF) in the turbine disk, ultimately resulting in low-cycle fatigue (LCF) failure. Therefore, the turbine disk ruptured, causing extensive damage to the engine and surrounding aircraft systems. Despite the severity of the failure, the flight crew managed to land the aircraft safely. The accident investigation revealed that the turbine disk was subjected to unexpected thermal and mechanical loads, which accelerated LCF crack growth. This incident underscored the need for accurate fatigue life prediction models that consider the combined effects of thermal and mechanical stresses. It also highlighted the importance of monitoring thermomechanical fatigue cycles to ensure component integrity throughout their design life [8].

On April 17, 2018, Southwest Airlines experienced a catastrophic in-flight engine failure caused by a fractured fan blade on a CFM56-7B24 engine. The failure was

attributed to an undetected low-cycle fatigue (LCF) crack in the dovetail root of the fan blade. This crack propagated over time due to cyclic mechanical loading during normal engine operations, such as engine start-up, shutdown, and power transitions, within the aircraft's flight envelope. The LCF-induced failure caused extensive engine damage and resulted in significant structural harm to the airframe. A piece of engine debris breached the fuselage, leading to cabin depressurization and the fatal injury of a passenger. The investigation revealed that the fatigue crack was present before the last overhaul in 2012 but was missed during the fluorescent penetrant inspection (FPI). Following a similar engine failure in 2016, the manufacturer developed an eddy current inspection (ECI) technique to improve detection of such cracks [9].

1.3.2 Life Computation

In a gas turbine engine, the failure of a single component can result in the loss of control over that part during operation. Such a failure not only compromises the function of the affected component but can also lead to damage to surrounding parts and potentially the aircraft itself. Therefore, it is essential to determine a safe operating life for these components, which is the primary objective of life cycle analysis.

In the aerospace industry, there are two primary approaches to life analysis: the commercial approach and the military approach. The commercial approach assumes that cracks are not permissible and relies on low-cycle fatigue (LCF) properties to predict failure. In contrast, the military approach assumes that defects or cracks may already be present in components and focuses on crack propagation behavior to predict the remaining useful life.

The importance of fatigue life analysis is further underscored by lessons learned from operational experience, which continue to drive advancements in materials, inspection methods, and analytical tools. This proactive approach helps ensure that components operate safely within their defined life limits, thereby preventing failures and enhancing overall engine performance and reliability [10]. The flow chart in **Figure 1.12** summarizes the life analysis process.

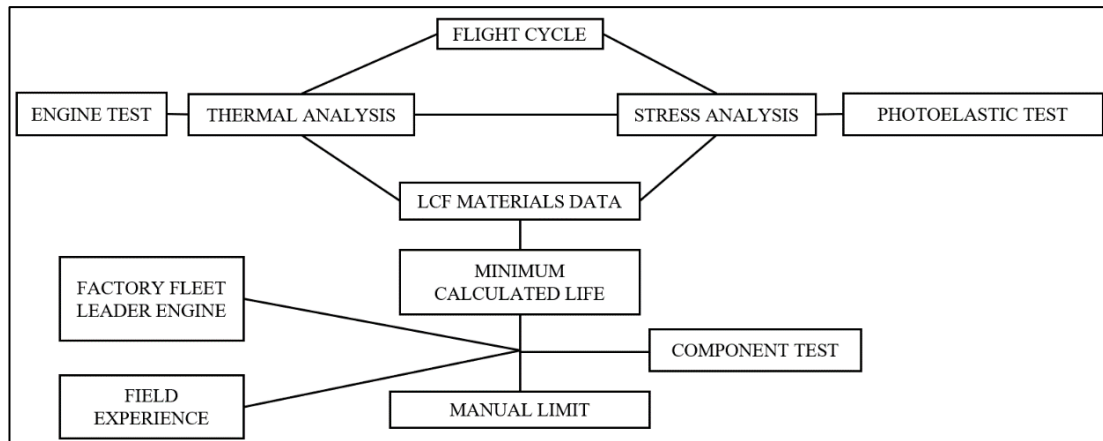


Figure 1.12: Life Analysis Flowchart [10].

1.3.3 Cycle Counting

A cycle in fatigue loading refers to the variation in load, under constant amplitude conditions, from the minimum load to the maximum load and back to the minimum load [11].

Cycle counting is a technique used to simplify non-uniform load-time data by identifying how frequently specific amplitude ranges occur. The definition of a "cycle" can vary depending on the counting method employed. Common approaches for extracting these counts include level-crossing, peak-based, simple range, range-pair, and rainflow techniques. These methods can be applied to time-dependent data such as force, stress, strain, torque, acceleration, or displacement, enabling structured analysis of fluctuating load profiles. **Figure 1.13** illustrates the basic fatigue loading parameters.

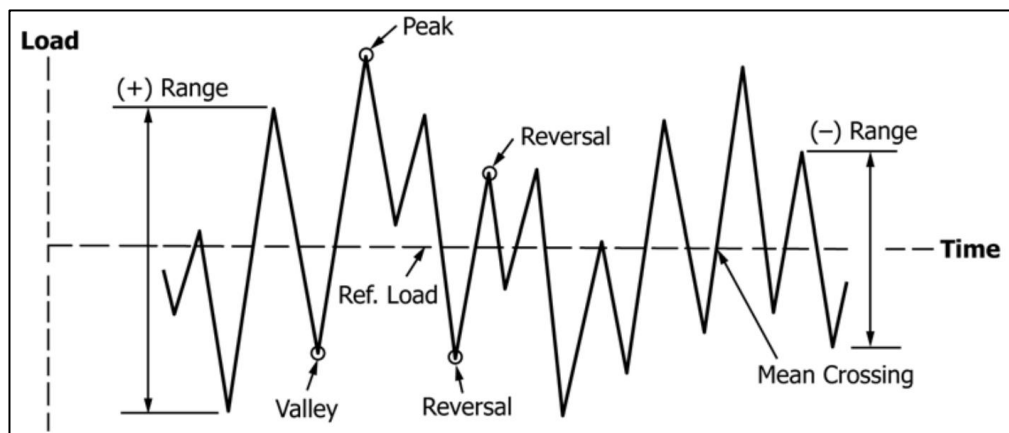


Figure 1.13: Fatigue Loading Parameters [11].

2. PURPOSE OF THE STUDY

The primary objective of this study is to investigate the low-cycle fatigue (LCF) behavior of afterburner liners under cyclic loading conditions, with particular emphasis on the effects of strain accumulation, hold time, and effusion cooling hole geometry on fatigue life. Given the extreme operational environment of afterburner liners—including high temperatures, thermal gradients, and mechanical stresses—it is essential to accurately assess their fatigue resistance and failure mechanisms.

This research provides a comprehensive evaluation of the fatigue performance of afterburner liners through experimental testing, finite element analysis (FEA), and empirical fatigue life prediction models. Experimental characterization includes tensile tests, hysteresis loop measurements, and thermal fatigue testing to establish the material's mechanical properties and cyclic stress-strain behavior. Numerical modeling involves finite element simulations to predict stress-strain distributions and validate computational fatigue models against experimental results. Additionally, empirical fatigue life prediction methods, such as Morrow's equation and the Smith-Watson-Topper (SWT) model, are applied to assess their accuracy in estimating the lifespan of afterburner liners under real-world conditions.

Hold time in low-cycle fatigue (LCF) testing refers to a deliberate dwell period during which strain or stress is held constant at a specific point in the loading cycle, typically at peak tensile or compressive levels. This pause simulates creep and other time-dependent damage mechanisms prevalent in high-temperature environments, such as gas turbine blades and afterburner liners. Sustained loads at elevated temperatures induce creep deformation, accelerated grain boundary weakening, void formation, and oxidation-assisted cracking. Incorporating hold times in fatigue tests captures these creep-fatigue interactions, which accelerate damage accumulation and cause premature failure beyond that predicted by fatigue alone. Hold time intensifies strain localization, promotes intergranular crack initiation, and markedly reduces fatigue life, which decreases—often nonlinearly—as dwell duration increases.

A key aspect of the study is evaluating the influence of hold time on creep-fatigue interactions and analyzing the impact of effusion cooling hole geometry on local stress

concentrations and fatigue crack initiation. By systematically addressing these factors, the study contributes to the development of more fatigue-resistant afterburner liners, enhances the accuracy of fatigue life prediction methods, and provides insights to guide future advancements in aerospace propulsion systems. The findings support the optimization of material selection, cooling hole configurations, and operational parameters, ultimately leading to increased service life and reduced maintenance costs for high-performance jet engines.

2.1. Structural Integrity in Design

Ensuring structural integrity is essential for preventing critical failures over a component's intended service life. This depends primarily on meeting both static strength and durability requirements.

The static strength criterion ensures that a component can withstand the maximum loads it may experience within a loading cycle. During the design phase, this condition is typically verified through testing, using standard material properties and idealized geometric dimensions. However, such assessments do not account for imperfections like pre-existing flaws or damage accumulated during service, and therefore may not fully reflect real-world load-bearing performance.

Therefore, inferences about service life requirements are made by considering factors such as duration of use and damage mechanisms occurring during operation. This involves evaluating the rate of damage accumulation and assessing the remaining strength of the component. A service life test essentially determines the safe operating time of the part, incorporating multiple opportunities for inspection and maintenance to minimize the risk of catastrophic failure during its operational lifespan [12].

2.2. Mechanical Behavior of Materials

This section presents key terminology from the field of mechanics of materials and summarizes the fundamental equations relevant to the analysis.

Strength refers to an inherent property of a material or structural element. It is influenced by the choice of material as well as the processing and treatment methods used. This property becomes embedded in the component due to the material's specific characteristics and the manufacturing techniques applied during production. Strength

can be described as the level of stress at which a specific event or material response takes place such as reaching the proportional limit, yielding at 0.2% offset, or undergoing fracture. Often, these stress levels correspond to the point at which the material or component can no longer perform its intended function.

Stress is a characteristic of the state at a particular point within a structure, depending on factors such as geometry, temperature, load, and the manufacturing process [13].

σ represents the normal stress, which is the force per unit area that is uniformly distributed over a normal section of the material (Equation 2.3).

$$\sum F = 0 \quad (2.1)$$

$$F - \sigma A = 0 \quad (2.2)$$

$$\sigma = \frac{F}{A} \quad (2.3)$$

Shear stress is generated by a force applied parallel to the surface, while normal stress is caused by an external force applied perpendicular to the surface. Stress is represented by two subscripts: the first indicates the direction normal to the surface, and the second indicates the direction of the applied force. Normal stress is represented by using the same subscript twice. In contrast, shear stress, denoted by τ , uses different subscripts to indicate the directions of both the surface and the applied force.

The three-dimensional stress tensor is presented below:

$$\sigma_{ij} = \begin{bmatrix} \sigma_{xx} & \sigma_{yx} & \sigma_{zx} \\ \sigma_{xy} & \sigma_{yy} & \sigma_{zy} \\ \sigma_{xz} & \sigma_{yz} & \sigma_{zz} \end{bmatrix} \quad (2.4)$$

In a tensile test, the length of the specimen increases as the applied force (F) increases. The incremental change in length, dl , is directly related and proportional to the corresponding increase in force, dF . Equation (2.5) presents the normalized increase in length.

$$d\varepsilon = \frac{dl}{l} \quad (2.5)$$

True strain is derived by integrating infinitesimal changes in length over the current length from the initial length, L_0 , to the current length, L , as described in Equation (2.6):

$$\varepsilon = \int dL/L = \ln(L/L_0) \quad (2.6)$$

A simplified form of strain, known as *engineering strain*, is commonly used in many engineering applications. It is defined as follows:

$$\varepsilon_n = \varepsilon_e = \frac{\Delta l}{l_0} = \frac{l_1}{l_0} - 1 \quad (2.7)$$

$$e = \frac{\Delta L}{L_0} \quad (2.8)$$

For strains less than 0.005—which are commonly observed in metals during elastic deformation—engineering strain and true strain are nearly identical. However, as the material transitions from elastic to plastic deformation, the difference between engineering and true strain becomes more significant. The relationship between engineering strain and true strain during elastic deformation can be expressed by Equation (2.9).

$$\varepsilon_t = \ln(1 + \varepsilon_e) \quad (2.9)$$

The relationship between stress and strain in metals was first formulated by Robert Hooke in 1678 based on experimental observations. This relationship is expressed by the equation shown in (2.10). In the elastic region, stress and strain are proportional in metals, as defined by Hooke's Law.

$$E = \frac{\sigma}{\varepsilon} \quad (2.10)$$

Young's modulus, denoted by E and also called the modulus of elasticity or elastic modulus, indicates the stiffness of a material. While generally stable, the value of Young's modulus can be influenced to a limited degree by thermal and mechanical processing.

The ratio of stress to strain defines Young's modulus in uniaxial tension, where the applied force is aligned with the direction of the stress. Although the loading is uniaxial, it also induces lateral strains, as shown in Equation (2.11). Poisson's ratio, denoted by ν , characterizes the lateral contraction of an isotropic material in two perpendicular directions when it is subjected to tensile or compressive loading along a third axis. For a general state of stress $(\sigma_x, \sigma_y, \sigma_z)$, the lateral strain contributions due to σ_y and σ_z are expressed by Equation (2.12), while the axial strain caused by σ_x is given by Equation (2.13).

$$e_y = e_z = -\nu e_x \quad (2.11)$$

$$e_x = -\frac{\nu \sigma_y}{E} \quad \text{and} \quad e_x = -\frac{\nu \sigma_z}{E} \quad (2.12)$$

$$e_x = \frac{\sigma_x}{E} \quad (2.13)$$

For a general 3D state of stress in an isotropic linear elastic material, Hooke's law for normal strain in the x-direction is given by:

$$e_x = (1/E)[\sigma_x - \nu(\sigma_y + \sigma_z)] \quad (2.14)$$

Principal stresses are the normal stresses that occur when shear stresses are entirely absent. They represent the dominant stress components acting on a material. For any given stress state, a coordinate system (1, 2, 3) can be defined such that the normal stresses along these directions—denoted as σ_1 , σ_2 , and σ_3 —are the principal stresses. These are the three roots of the characteristic equation (2.15) of the stress tensor, given by:

$$\sigma_p^3 - I_1 \sigma_p^2 - I_2 \sigma_p - I_3 = 0 \quad (2.15)$$

where, the stress invariants are defined as:

$$I_1 = \sigma_{xx} + \sigma_{yy} + \sigma_{zz} \quad (2.16)$$

$$I_2 = \sigma_{yz}^2 + \sigma_{zx}^2 + \sigma_{xy}^2 - \sigma_{yy}\sigma_{zz} - \sigma_{zz}\sigma_{xx} - \sigma_{xx}\sigma_{yy} \quad (2.17)$$

$$I_3 = \sigma_{xx}\sigma_{yy}\sigma_{zz} + 2\sigma_{yz}\sigma_{zx}\sigma_{xy} - \sigma_{xx}\sigma_{yz}^2 - \sigma_{yy}\sigma_{zx}^2 - \sigma_{zz}\sigma_{xy}^2 \quad (2.18)$$

The von Mises stress, commonly used in design and failure analysis, is calculated from the principal stresses. It provides a scalar value representing an equivalent uniaxial

stress and is used in yield criteria for ductile materials. For a component to remain in the elastic region, the von Mises stress must be less than the yield strength of the material. The von Mises stress incorporates all three principal stresses and is defined as:

$$\sigma_v = \left[\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2} \right]^{1/2} \quad (2.19)$$

2.3. Fatigue

Fatigue refers to the localized and progressive structural changes that take place in a material exposed to cyclic loading conditions. These repeated stress and strain fluctuations at specific sites can eventually initiate cracks or cause complete failure after a sufficient number of cycles [6].

Figure 2.1 illustrates the crack initiation phase, crack growth period, final failure, and the factors influencing each stage during fatigue life. The crack initiation and the crack growth periods and the final failure are the key factors that determine fatigue life until failure [14]. Differentiating between the crack initiation and crack propagation phases is essential, as surface conditions often have minimal influence on the propagation stage but can significantly affect crack initiation. Distinct fatigue life estimation techniques are applied to each phase. For predicting the onset of cracking, the stress concentration factor K_t plays a particularly important role. The stress intensity factor K is used to model crack growth behavior, while fracture toughness K_{Ic} is critical for assessing the final failure stage.

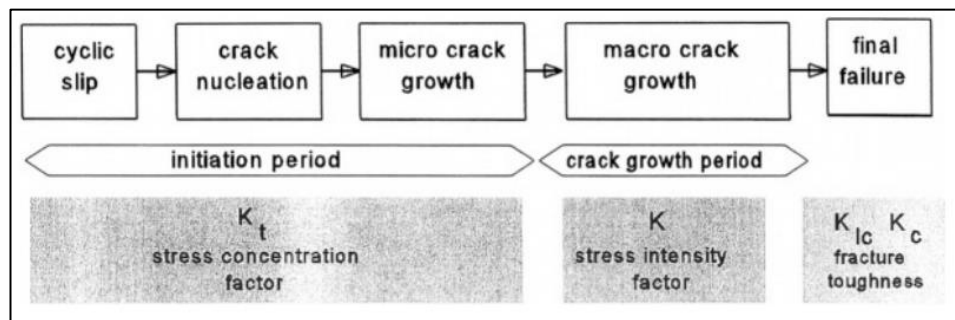


Figure 2.1: Phases of Fatigue Life and Associated Influencing Factors [15].

2.3.1 Cyclic Stress Behavior

Different types of cyclic stresses exist, such as fully reversed cycles, repeated stress cycles, and irregular cycles. Fully reversed cycles are those in which the maximum and minimum stresses are equal in magnitude but opposite in sign. Repeated stress cycles involve a nonzero mean stress, with distinct maximum and minimum stress values that are not necessarily equal or opposite. Irregular cycles involve random or non-periodic loading, often occurring during real-world operational conditions.

A schematic of cyclic stress is presented in **Figure 2.2**.

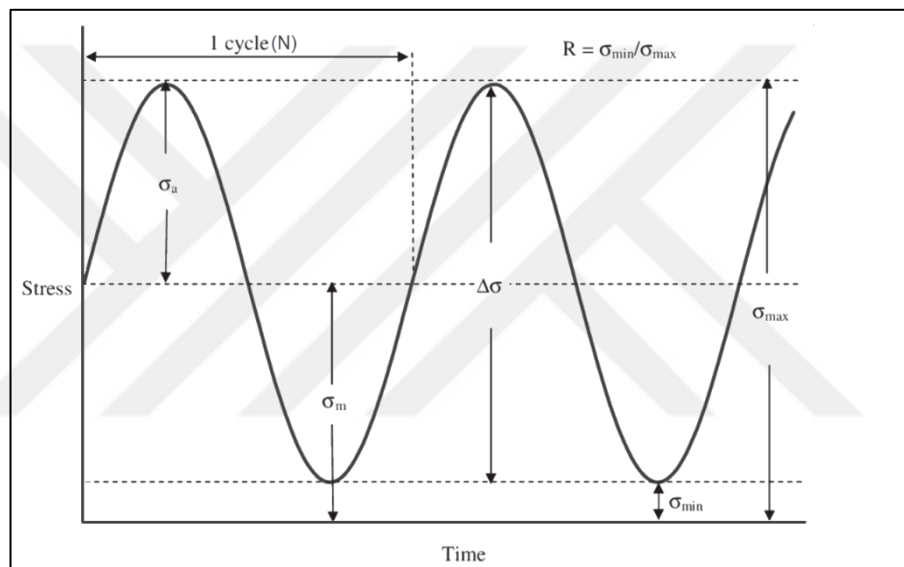


Figure 2.2: Schematic of Cyclic Stress.

Cycle (N): A cycle, also known as a period or load repetition, is the basic unit of stress fluctuation applied to a component. It consists of a full sequence of loading and unloading that repeats over time.

Minimum Stress (σ_{min}): Minimum stress is the lowest stress value a structure experiences during a loading cycle. It can be either tensile or compressive, depending on the applied loading conditions.

Maximum Stress (σ_{max}): Maximum stress refers to the highest stress value a structure experiences during a loading cycle. Tensile stress is indicated by positive (+) values, while compressive stress is represented by negative (−) values.

Mean Stress (σ_m): Mean stress represents the average stress within a loading cycle and is calculated using the following equation:

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \quad (2.20)$$

Alternating Stress (σ_a): Alternating stress, also known as cyclic stress amplitude, is defined as half the difference between the maximum and minimum stress in a loading cycle. It represents the magnitude of stress variation around the mean stress during cyclic loading.

$$\sigma_a = \left| \frac{(\sigma_{max} - \sigma_{min})}{2} \right| \quad (2.21)$$

Stress Range (σ_r): The difference between the maximum and minimum stress values in a loading cycle is known as the stress range.

$$\sigma_r = \sigma_{max} - \sigma_{min} \quad (2.22)$$

Stress Ratio (R): The stress ratio represents the loading condition and is defined as the ratio of the minimum stress to the maximum stress within a cycle.

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad (2.23)$$

Two common loading conditions used in fatigue testing and endurance limit determination are fully reversed loading ($R = -1$) and pulsating loading ($R = 0$). In fully reversed loading, the applied load oscillates symmetrically between equal tensile and compressive values, meaning there is no mean stress component. In contrast, pulsating loading is characterized by a minimum stress of zero, resulting in a purely tensile loading cycle.

The definitions provided in this section, along with the different loading conditions based on various R ratios, are visually represented in **Figures 2.3 and 2.4 [16]**.

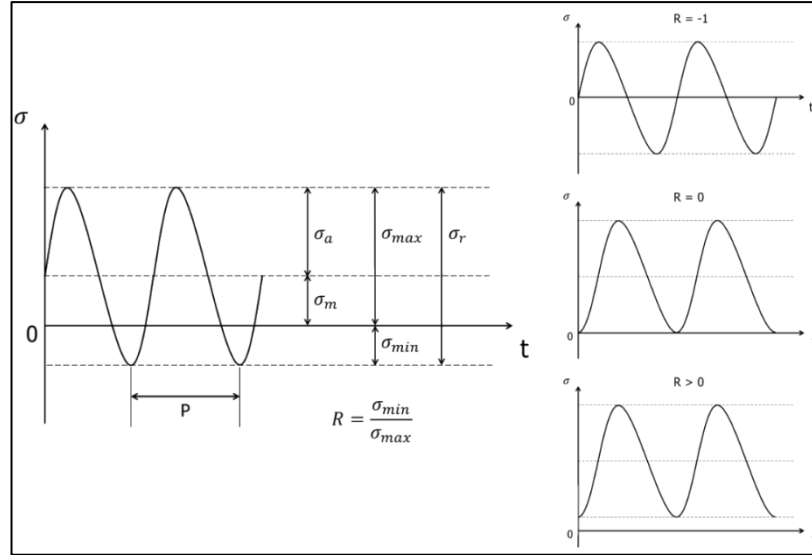


Figure 2.3: Definition of Stress Parameters for Cyclic Loading [16].

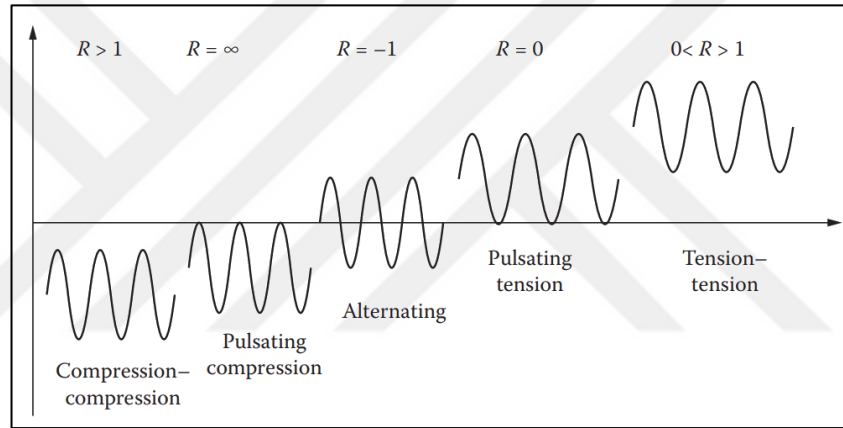


Figure 2.4: Stress Cycles [16].

Stress Amplitude Ratio (A): The stress amplitude ratio quantifies the intensity of cyclic loading on a material. It is defined as the ratio of the alternating stress (σ_a) to the mean stress (σ_m) within a loading cycle and is typically expressed as a percentage. This ratio plays a crucial role in fatigue life prediction, as it indicates the relative level of stress the material experiences in each cycle.

Materials subjected to a higher stress amplitude ratio generally exhibit shorter fatigue lives due to increased stress levels, which accelerate crack propagation and lead to premature failure. Conversely, materials with a lower stress amplitude ratio tend to have longer fatigue lives, as they are subjected to less severe cyclic stresses.

$$\text{Stress Amplitude Ratio (A)} = \frac{\sigma_a}{\sigma_m} = \frac{1 - R}{1 + R} \quad (2.24)$$

2.3.2 S-N Curves

Before the microstructural mechanisms of the fatigue process were fully understood, engineers developed empirical methods to evaluate fatigue and design components accordingly. One of the most important concepts that emerged from this approach is the S-N diagram. In this diagram, the vertical axis (S) represents the cyclic stress amplitude (also known as alternating stress), while the horizontal axis (N) represents the number of loading cycles. Since failure at low stress levels often requires millions of cycles, the N-axis (abscissa) is typically plotted on a logarithmic scale. **Figure 2.5** presents S-N curves for both smooth and notched specimens.

The endurance limit (σ_e) (also called the fatigue limit) is the maximum cyclic stress amplitude that a material can withstand for an infinite number of loading cycles without failing due to fatigue. The designer typically sizes the structure with an appropriate safety factor to ensure that the cyclic stress amplitude remains below *the endurance limit* (σ_e) when cyclic loads are expected. To define the S-N curve in a statistically reliable way, it is necessary to test the fatigue life of many specimens. However, obtaining a precise S-N curve is both expensive and time-consuming [17].

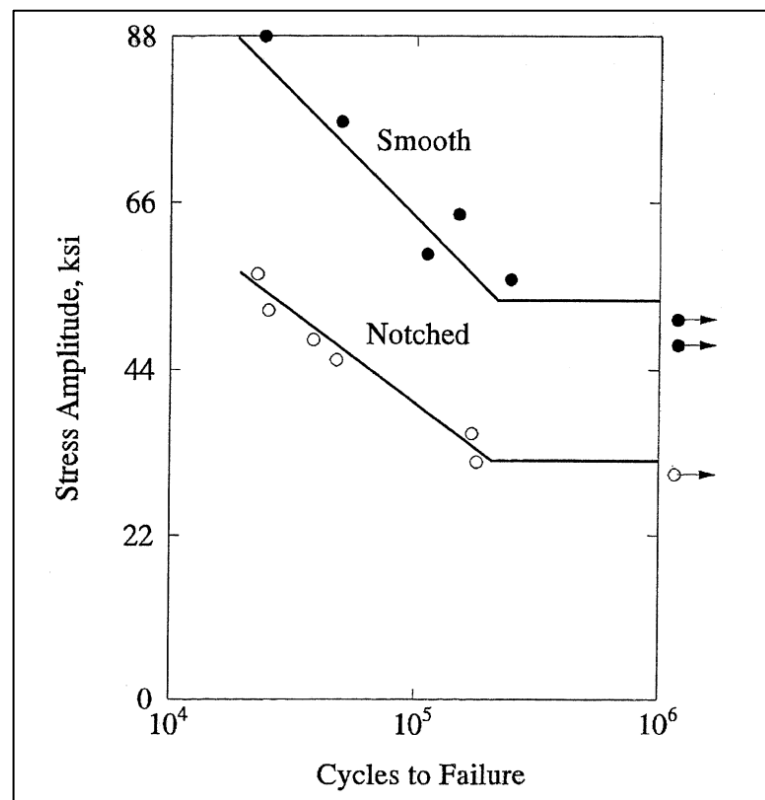


Figure 2.5: S-N Curves for Smooth and Notched Specimens [18].

2.3.3 LCF vs. HCF

High Cycle Fatigue (HCF) and Low Cycle Fatigue (LCF) are often distinguished by their frequency and duration characteristics.

HCF typically occurs under relatively low stress amplitudes at high loading frequencies—often exceeding 1000 Hz—and involves a very high number of cycles, typically ranging from 10,000 to over 1,000,000. The material response in HCF is primarily elastic. In a standard stress-life (S-N) curve, also known as a Wöhler diagram, HCF corresponds to the right-hand side of the plot, where the number of cycles becomes so large that collecting statistically robust data can be challenging. The failure mechanism in HCF involves the initiation and gradual growth of microcracks over a long period, ultimately leading to fracture.

In contrast, LCF occurs under relatively high stress or strain levels and often results in plastic (permanent) deformation. The loading frequency for LCF is typically low, usually between 0.001 Hz and 10 Hz, depending on application and test conditions. LCF typically involves fewer than 10,000 cycles and corresponds to the left-hand side of the S-N curve. Due to significant plastic strain, LCF is often analyzed using the strain-life (ϵ -N) approach, which captures cyclic plasticity effects. The failure mechanism in LCF is characterized by rapid crack initiation and growth caused by large cyclic strains. A widely used analytical model for LCF is the Coffin-Manson relation, which relates the plastic strain amplitude to the number of cycles to failure.

Alternatively, HCF and LCF can also be differentiated by their testing methods: HCF is generally evaluated under load-controlled conditions, whereas LCF is assessed under strain-controlled conditions. However, this distinction is not always definitive, as some applications may blur the boundary between the two.

Figure 2.6(a) presents an S-N curve—also known as a stress-life curve or Wöhler diagram—which plots maximum stress (S) against the number of cycles to failure (N). This curve is obtained for a constant stress ratio R and is commonly used in low-cycle fatigue (LCF) analysis.

Figure 2.6(b) shows a Goodman diagram, which plots alternating stress versus mean stress. It includes a straight line drawn radially outward from the origin, representing

a constant stress ratio R , and a constant life curve corresponding to 10^7 cycles, typically used in high-cycle fatigue (HCF) analysis.

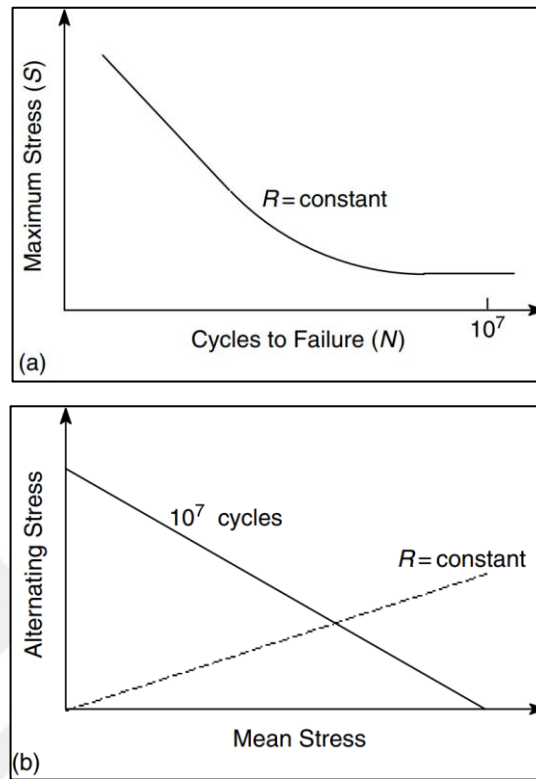


Figure 2.6: Representative Fatigue Diagrams: (a) S–N Curve Illustrating LCF Behavior, (b) Goodman Diagram for HCF [19].

2.3.4 Factors Affecting Fatigue Life

Fatigue life is influenced by various factors that modify the standard stress-life behavior observed in fully reversed axial or bending loading of small, clean, unnotched specimens. These factors can lead to significant variations in fatigue life for the same material under different conditions.

One of the most critical factors affecting fatigue behavior is the type of loading. The fatigue life of a component can vary significantly depending on whether it is subjected to axial tension, bending, torsion, or a combination of multiple loading modes. Additionally, the intensity, frequency, and nature of the applied load—whether constant or fluctuating—also influence fatigue performance [20].

Another crucial factor influencing fatigue life is the **material's microstructure**. Grain size and structure play a significant role in determining how a material responds to

cyclic loading. At ambient temperatures, materials with finer grain sizes generally exhibit higher fatigue limits compared to those with coarser grains. However, at elevated temperatures—within the creep range of metals—materials with larger grain structures often demonstrate superior fatigue resistance [21].

Manufacturing processes significantly influence the fatigue performance of materials. Techniques such as forging, rolling, and extrusion align the grain structure, imparting direction-dependent properties. While this alignment tends to improve fatigue resistance along the grain orientation, it may reduce strength in directions perpendicular to it. Moreover, imperfections introduced during processing can act as localized stress raisers, facilitating crack initiation.

Surface modification methods—such as heat treatment, case hardening, surface coating, plating, and various forms of cold or hot working—also impact fatigue life. Another important factor is **residual stress**, which remains in a component even in the absence of external loads. Compressive residual stresses at the surface generally enhance fatigue resistance, whereas tensile residual stresses may accelerate failure [21].

The **size effect** also influences fatigue behavior. In unnotched bending scenarios, specimens with a diameter or thickness below 10 mm typically exhibit consistent S-N fatigue behavior, showing minimal variation in response. However, for larger specimens, fatigue resistance tends to decrease [20].

Additionally, component design can introduce localized stress concentrations that significantly affect fatigue life. A well-known historical example is the fatigue failure of early commercial aircraft caused by sharp-cornered window designs. These corners created stress concentrations, which led to crack initiation and eventual failure. Modern aircraft now incorporate rounded window designs to mitigate this risk.

Surface conditions are also critical to fatigue resistance, as a large proportion of fatigue failures initiate at the surface. Surface imperfections—such as scratches, dents, and machining marks—act as initiation points for cracks. Notches, in particular, significantly affect stress distribution by increasing localized stresses. The **theoretical stress concentration factor (K_t)** quantifies the degree to which stress is amplified in these regions. High localized stresses can exceed the material's threshold for crack initiation, thereby accelerating fatigue failure [22].

Environmental factors also play a significant role in fatigue life. Material degradation in corrosive environments often manifests as pitting or surface roughness, both of which act as stress concentrators and serve as crack initiation sites. Areas experiencing fatigue slip activity are particularly vulnerable, as minor electrochemical potential variations between the surface and interior of slip bands accelerate corrosion.

The frequency of loading cycles also affects fatigue life. The relationship between frequency and S-N behavior is complex, as it involves interactions between temperature, corrosion, strain rate sensitivity, and frequency effects. Elevated test frequencies can lead to specimen heating due to internal hysteresis damping, which may obscure the material's actual fatigue behavior at ambient temperatures. This effect is particularly pronounced in lower-strength metals, where increased temperatures further reduce fatigue resistance [20].

Fatigue behavior is highly sensitive to the combined effects of these factors, making it essential to carefully consider them in engineering applications to optimize fatigue performance and ensure component reliability. By understanding the interplay of these variables, engineers can enhance fatigue resistance through material selection, design improvements, and manufacturing optimizations [16].

2.4. Life Computation Methods

Different methods are used to analyze the fatigue behavior of structural components, depending on material properties, expected failure mechanisms, and the type of loading. This section provides guidance on selecting the appropriate fatigue life prediction method.

The strain-life method is most suitable for metallic structures that are largely defect-free, where crack initiation is the primary concern. It is particularly effective in evaluating short-life, low-cycle fatigue conditions dominated by plastic deformation. This method helps identify crack initiation points, assess different materials and surface conditions, and is best applied to isotropic, ductile metals with symmetrical cyclic stress-strain behavior.

In contrast, the stress-life method is appropriate for high-cycle fatigue problems where plastic deformation is minimal. Based on S-N data, it is useful in cases where modeling

crack initiation or growth is impractical—such as in composites, welds, and non-metallic materials. It is commonly used when extensive S-N data already exists or when fatigue analysis is required by regulatory bodies. This method is also effective for spot weld analysis and evaluating fatigue due to random vibrations.

Lastly, the linear elastic fracture mechanics (LEFM) method is applied to structures that are pre-cracked or expected to develop cracks during service or manufacturing, such as welds. It is used to predict crack growth, optimize test programs by avoiding unnecessary testing, and develop inspection plans with appropriate intervals. This method also provides a means of estimating the remaining life of a component after crack initiation.

Selecting the correct fatigue analysis method is crucial for ensuring component reliability and durability, reducing testing efforts, and optimizing maintenance strategies.

2.4.1 Stress-Life Method

Since the early 1800s, the stress-based approach has been the standard method for fatigue calculations and related designs. This method, also known as the S–N approach, differs from other fatigue evaluation methods in that it is governed by cyclic stresses and is typically applied under high-cycle fatigue (HCF) conditions [23].

The S–N approach evaluates fatigue damage based on fatigue strength, which is typically defined in terms of the number of load cycles a material can endure. When a component withstands a number of cycles exceeding a certain threshold, this threshold is referred to as the endurance limit. If a material's fatigue strength exceeds the endurance limit, it is considered to have infinite fatigue life. The relationship between fatigue strength and the number of cycles is commonly represented using the S–N curve.

$$S'_f = \frac{(f S_{ut})^2}{S_e} N^{(-\frac{1}{3} \log(\frac{f S_{ut}}{S_e}))} \quad (2.25)$$

S'_f : Fatigue strength

N : Number of fully reversed cycles

f : Fatigue strength fraction for 10^3 loading cycles

S_{ut} : Ultimate tensile strength

S_e : Endurance limit

The fatigue strength coefficient, S'_f , and the endurance limit, S_e , in Equation 2.25 apply specifically to fully reversed loading conditions under standardized testing environments. However, actual service conditions often differ from these idealized settings. To account for such variations, correction factors are applied to adjust fatigue parameters to real-world applications. For example, when the applied load is not fully reversed, the influence of mean stress must be considered—this adjustment is often visualized using design tools such as **Figure 2.7**.

In cases involving variable loading, fatigue damage accumulates over time. This cumulative effect is typically assessed using Miner's Rule. The stress-life (S–N) approach is especially suitable for fatigue analysis when the material behavior remains within the elastic range.

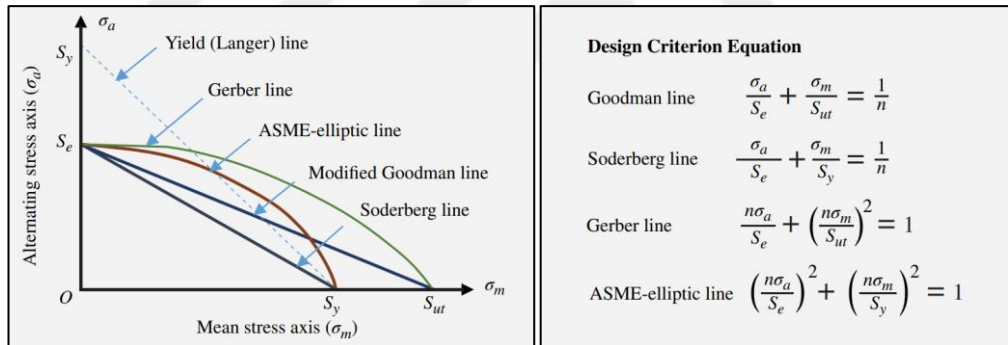


Figure 2.7: Stress-Life Approach in Fatigue Evaluation [24].

2.4.2 Strain-Life Method

The strain-based approach to fatigue analysis is widely used due to its ability to account for both elastic and plastic deformation, particularly under low-cycle fatigue (LCF) conditions. Unlike stress-based methods—better suited for high-cycle fatigue (HCF), where plastic deformation is minimal—the strain-based approach provides a more accurate representation of material behavior under cyclic loading, especially when local plasticity is significant.

Strain is a critical parameter in fatigue analysis because it can be directly measured and has been shown to correlate strongly with fatigue life. This is especially relevant

in components subjected to large stress ranges, such as gas turbine engine parts, where both thermal and mechanical loading cycles cause significant strain variations. For example, while gas turbines operate under relatively stable stress conditions during steady-state operation, they experience substantial stress changes during startup and shutdown. These variations can result in local strains exceeding the yield strain, making stress-based analysis difficult. In such cases, the strain-based approach simplifies fatigue prediction by focusing on strain as the primary variable.

Fatigue damage in materials progresses through cyclic plastic deformation, which leads to crack initiation and subsequent propagation. The strain-life method, also known as the $\varepsilon - N$ method, is based on the fundamental observation that total strain amplitude—rather than stress amplitude—governs fatigue life.

Extensive strain-life fatigue data have been published for various engineering alloys. These datasets are typically obtained from small, polished, unnotched axial specimens subjected to fully reversed, constant-amplitude strain cycles. Testing typically ranges from 10 to 10^6 cycles to failure, with loading frequencies between 0.1 Hz and 10 Hz. During testing, the material exhibits stable hysteresis loops, which can be decomposed into elastic and plastic strain components. **Figure 2.8** schematically presents a strain-life fatigue curve on logarithmic scales, with total strain amplitude plotted on the vertical axis and the number of cycle reversals to failure, $2N_f$, on the horizontal axis. The total strain amplitude has been decomposed into elastic and plastic strain components based on the steady-state hysteresis loops:

$$\varepsilon_a = \varepsilon_e + \varepsilon_p \quad (2.26)$$

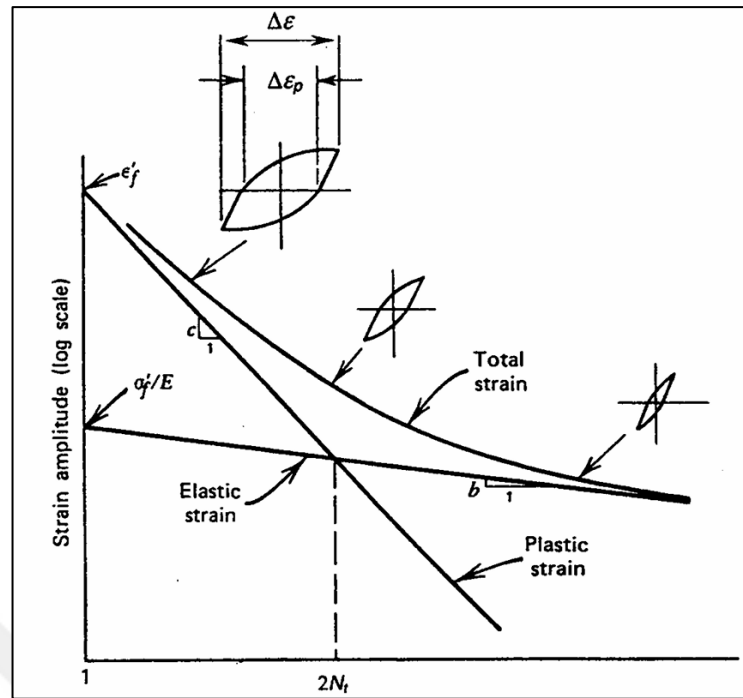


Figure 2.8: Strain-Life Curves Showing Total, Elastic, and Plastic Strain Components [20].

Both elastic and plastic curves are approximated by straight lines. At high strains or short lifetimes, plastic strain dominates, while at low strains or longer lifetimes, elastic strain prevails, as shown by the straight-line curves and hysteresis loop sizes in **Figure 2.8**.

The strain-based approach provides a comprehensive and reliable method for estimating the fatigue life of materials and components subjected to cyclic loading. Through experimental data, empirical models, and analytical formulations, the strain-life approach enables accurate fatigue assessments, particularly for notched components and structures experiencing complex loading histories [20].

Life Prediction Models

Various empirical methods are used in fatigue life prediction. While the Goodman, Gerber, and Soderberg models are typically used in the stress-life method, the Morrow and Smith-Watson-Topper (SWT) approaches are widely applied in the strain-life method.

Morrow Approach

Morrow suggested that the effect of mean stress could be incorporated by modifying the elastic component of the strain-life curve. The Morrow equation is given by:

$$\varepsilon_a = \frac{\sigma'_f - \sigma_f}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c \quad (2.27)$$

This model captures both elastic and plastic strain contributions and explicitly accounts for the influence of tensile mean stress on fatigue life. This correction aligns well with observed behavior: the impact of mean stress is significant at low levels of plastic strain but diminishes at higher plastic strain levels [12].

Smith-Watson-Topper (SWT) Model

The SWT model incorporates mean stress effects by using the maximum stress in the fatigue cycle. It defines the fatigue damage parameter as the product of the maximum tensile stress ($\sigma_{max} = \sigma_f + \sigma_a$) and the total strain amplitude (ε_a^t) given by $\sigma_{max} \varepsilon_a^t$.

$$\sigma_{max} \varepsilon_a^t = \frac{(\sigma'_f)^2 (2N_f)^{2b}}{E} + (\sigma'_f \varepsilon'_f) (2N_f)^{(b+c)} \quad (2.28)$$

2.5. Stress Concentration Factors

According to research, nearly all fatigue-induced fractures originate from stress concentration zones at structural discontinuities such as holes, notches, cracks, flaws, and scratches. In these regions, stresses are significantly higher than in the surrounding material due to the local concentration of stress caused by these discontinuities. This phenomenon is known as the notch effect or stress concentration. To understand it fully, one must examine the relationship between stress concentration and the geometric characteristics of structural discontinuities [25].

The theoretical stress concentration factor (K_t) is defined as the ratio of the peak stress at the discontinuity (e.g., at the root of a notch or hole) to the nominal stress that would exist in the absence of the discontinuity:

$$K_t = \frac{\sigma_{peak}}{\sigma_{nominal}} \quad (2.29)$$

Figure 2.9 illustrates the stress distribution in a prototype notched component subjected to uniaxial tension for stress concentration analysis.

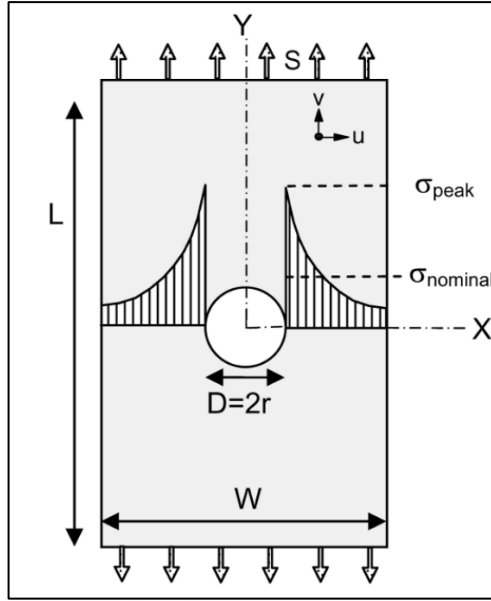


Figure 2.9: A prototype of a notched part used for stress concentration analysis [15].

Fatigue limit (also called the endurance limit) of a specimen is the maximum stress amplitude a material can withstand for an essentially infinite number of loading cycles without experiencing fatigue failure. The fatigue notch factor for normal stress is denoted by K_f . It is defined as the ratio of the fatigue limit of an unnotched specimen to that of a notched specimen under the same loading conditions (axial or bending):

$$K_f = \frac{\text{Fatigue limit of unnotched specimen}}{\text{Fatigue limit of notched specimen}} = \frac{\sigma_f}{\sigma_{tf}} \quad (2.30)$$

The fatigue stress σ_{tf} for a member with holes can be calculated using:

$$\sigma_{tf} = \frac{\sigma_f}{K_f} \quad (2.31)$$

The fatigue notch factor K_{tf} for a perforated element can be estimated using:

$$K_{tf} = q(K_t - 1) + 1 \quad (2.32)$$

Here, K_t is the theoretical stress concentration factor, and q is the notch sensitivity of the component. The notch sensitivity q can be determined using:

$$q = \frac{1}{1 + \alpha/r} \quad (2.33)$$

where, α is a material-dependent constant, and r refers to the notch root radius ($0 \leq q \leq 1$). If the material is fully notch-sensitive ($q = 1$), then $K_f = K_t$. If the material is not notch-sensitive at all ($q = 0$), then $K_f = 1$ — the notch has no effect on fatigue.

Stress concentration factors can be estimated using standard elasticity formulas, empirical graphs from the literature, finite element analysis (FEA), photoelastic testing, or strain gauge measurements. **Figure 2.10** presents the stress concentration factors $K_{t\infty}$ for a circular hole inclined at 45° to the surface of an infinite plate, under various biaxial tensile loading conditions, as a function of the plate thickness-to-hole radius ratio.

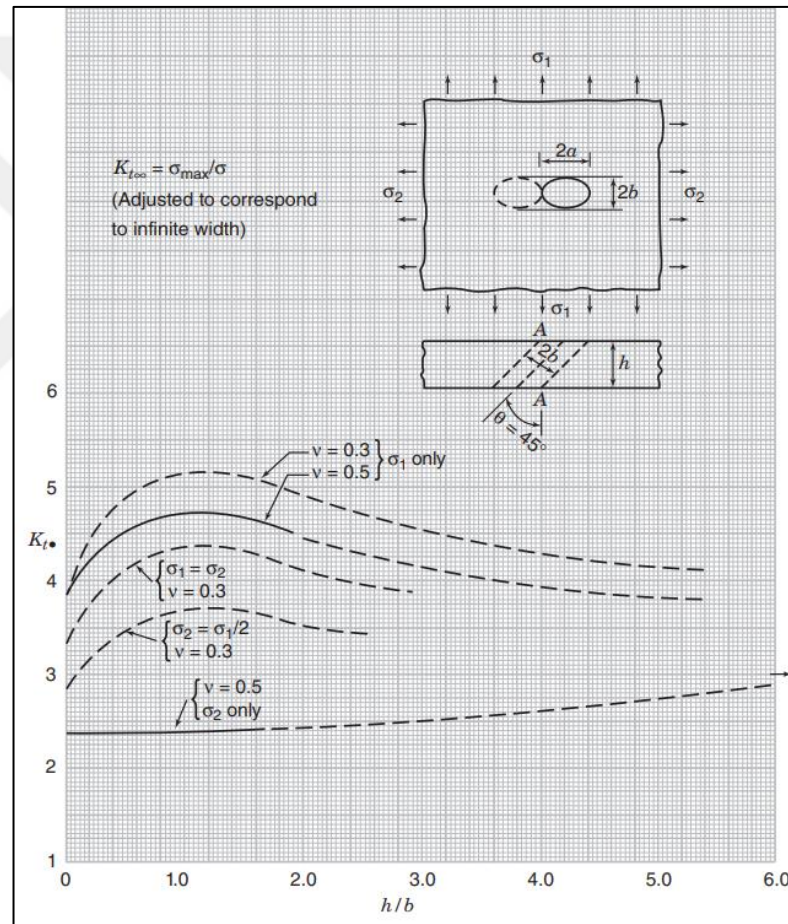


Figure 2.10: Stress concentration factors $K_{t\infty}$ for a 45° inclined circular hole in an infinite plate under various tensile loading conditions. (Adapted from McKenzie and White, 1968; Leven, 1970; Daniel, 1970; Ellyin, 1970) [24].

Figure 2.11 shows the geometry of an elliptical hole in an infinite plate, the coordinate system, and normal stress variation along the principal axes under biaxial tension.

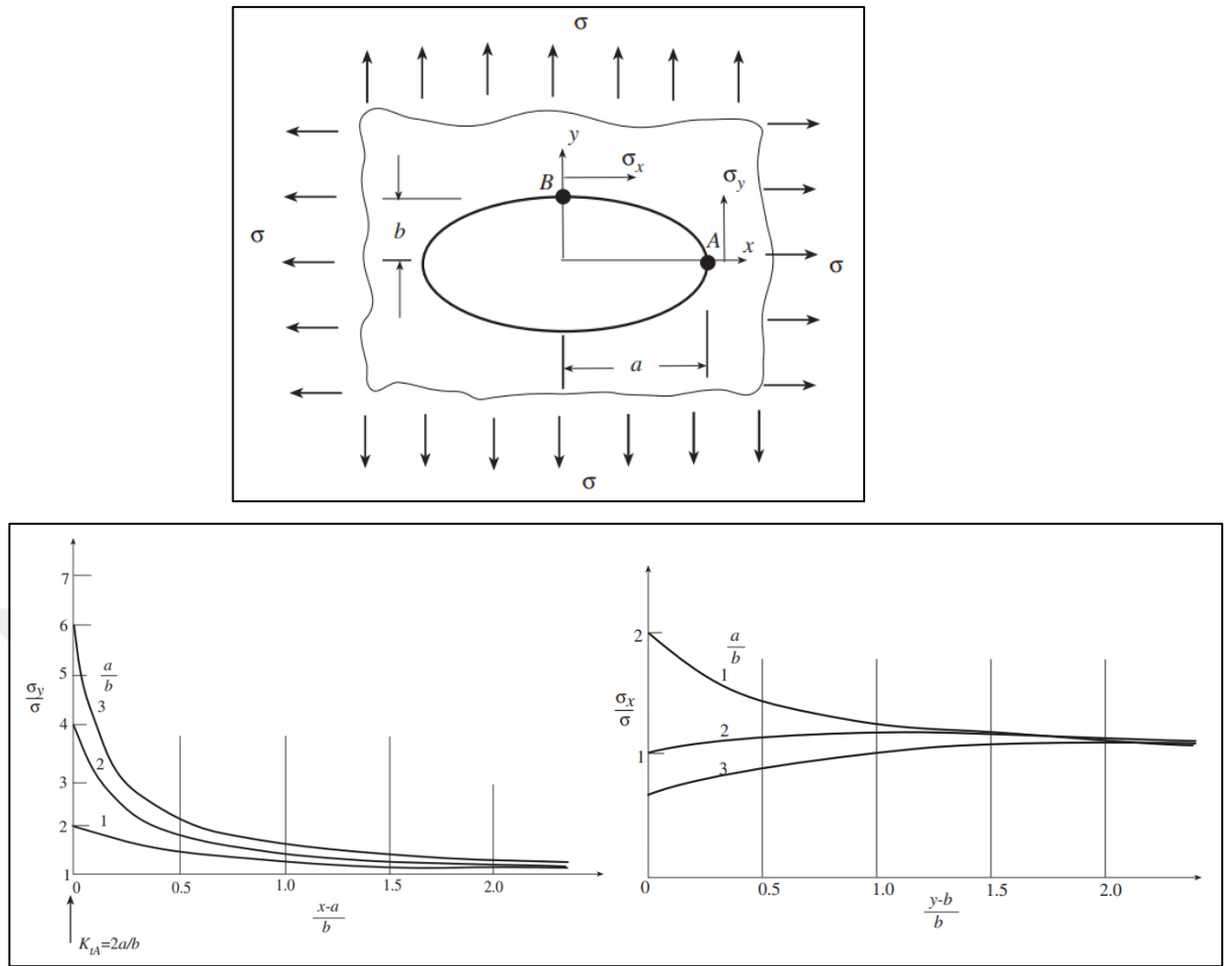


Figure 2.11: Normal Stress Distribution along Principal Axes of an Elliptical Hole under Biaxial Tension [24].

Effusion cooling is an advanced liner cooling technique widely employed in the combustion chambers and afterburner sections of modern gas turbine engines [26]. The effusion cooling holes are produced using laser drilling, which enables effective thermal management. This process involves drilling thousands of small holes at an angle to the liner surface [26]. A close-up view of a component with laser-drilled effusion cooling holes, which act as stress concentrators, is shown in **Figure 2.12**.



Figure 2.12: Component with Effusion Cooling Holes [27].

2.6. Fatigue Tests

Fatigue tests are conducted for various purposes. In engineering practice, the objectives often include evaluating the fatigue properties of materials, joints, and structural elements, or comparing different design alternatives. In contrast, research-oriented fatigue testing typically focuses on understanding fatigue phenomena and the influence of related variables.

Numerous examples of fatigue tests exist in literature, and their number continues to grow. These tests utilize different loading conditions, specimen environments, and testing equipment. Correctly identifying and planning these variables is critical. As the saying goes: “*Experiments never lie, but you should ask the right question!*”. Figure 2.13 presents a flat-sheet metal fatigue test specimen with a rectangular cross-section subjected to uniaxial loading.

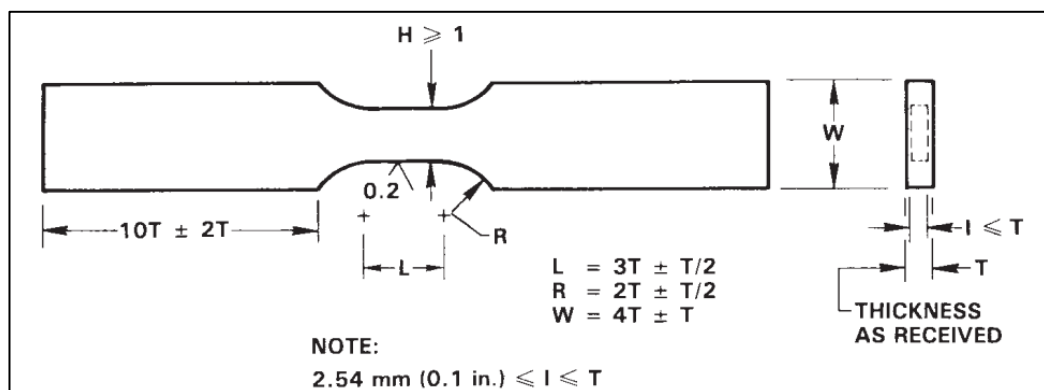


Figure 2.13: Flat-Sheet Fatigue Specimen with Rectangular Cross Section [28].

To minimize scatter in test results, careful attention must be paid to the fatigue test specimens themselves. The geometry and manufacturing method of all specimens should be identical. Whenever possible, the manufacturing process should be closely monitored.

Modern fatigue testing machines are typically equipped with standard grips that simplify the installation of specimens—especially when their ends are flat. Accurate alignment of the specimen's central axis with the machine's loading axis is essential. This alignment should be verified for each new specimen, ideally using strain gauges for precise measurement.

Fatigue test planning should include tables specifying the number of specimens to be tested under each condition. When generating an S–N curve, testing usually starts at a high stress amplitude to induce failure or run-out.

Fatigue life evaluations are often based on unnotched specimens. However, such tests provide limited information regarding the material's sensitivity to stress concentrations. Therefore, the use of notched specimens is recommended, as they offer deeper insights into comparative studies. Ideally, fatigue testing should simulate actual operating conditions. The most realistic assessment of fatigue life is achieved when testing is conducted on the actual part in service-like conditions. Nevertheless, simple notched and unnotched tests still provide valuable information about component fatigue life [15]. Figure 2.14 illustrates the effect of a sharp notch on the S–N behavior of a test specimen.

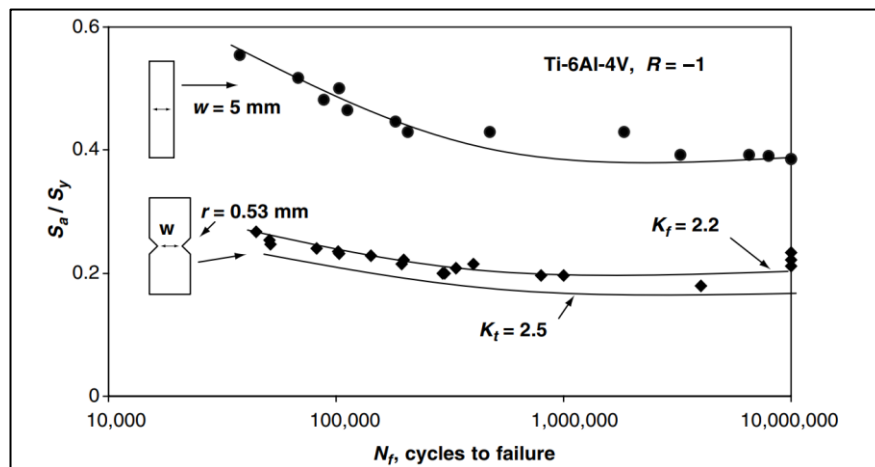


Figure 2.14: Effect of a Sharp Notch on the S–N Behavior of a Test Specimen [23].

Fatigue life is commonly characterized by a material's stabilized response to cyclic loading. In constant strain–amplitude-controlled testing, the stress–strain behavior typically stabilizes after an initial phase of rapid hardening or softening. This transient phase spans a relatively small number of cycles and accounts for only a minor portion of the total fatigue life. The hysteresis loop shown in **Figure 2.15**, representing the cyclically stabilized stress–strain response and defined by the total strain range ($\Delta\varepsilon$) and total stress range ($\Delta\sigma$), characterizes the combined elastic and plastic deformation of the material under cyclic loading and unloading. This loop is typically observed at the midpoint of the specimen's fatigue life [23].

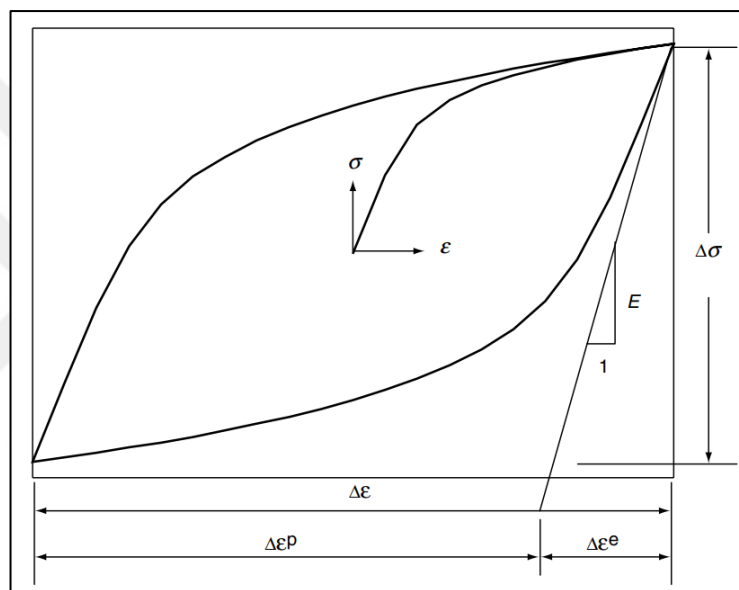


Figure 2.15: Hysteresis Loop [23].

The **transient cyclic response** of a material refers to how its deformation resistance evolves under repeated loading. When subjected to fully reversed strain-controlled loading, a material may exhibit cyclic hardening, softening, stabilization, or a combination of these behaviors.

Figures 2.16 and **2.17** illustrate transient cyclic hardening and softening, respectively. In cyclic hardening, the stress required for each successive strain reversal increases with the number of cycles. In contrast, cyclic softening is marked by a progressive decrease in stress over time. In both cases, the rate of change diminishes, and the material eventually reaches a stable condition. Once this steady state is achieved, the stress amplitude remains nearly constant until fatigue cracking initiates.

In the **local strain-life method**, this transient behavior is typically represented by the stabilized cyclic response, as the initial transient phase accounts for only a small fraction of the overall fatigue life.

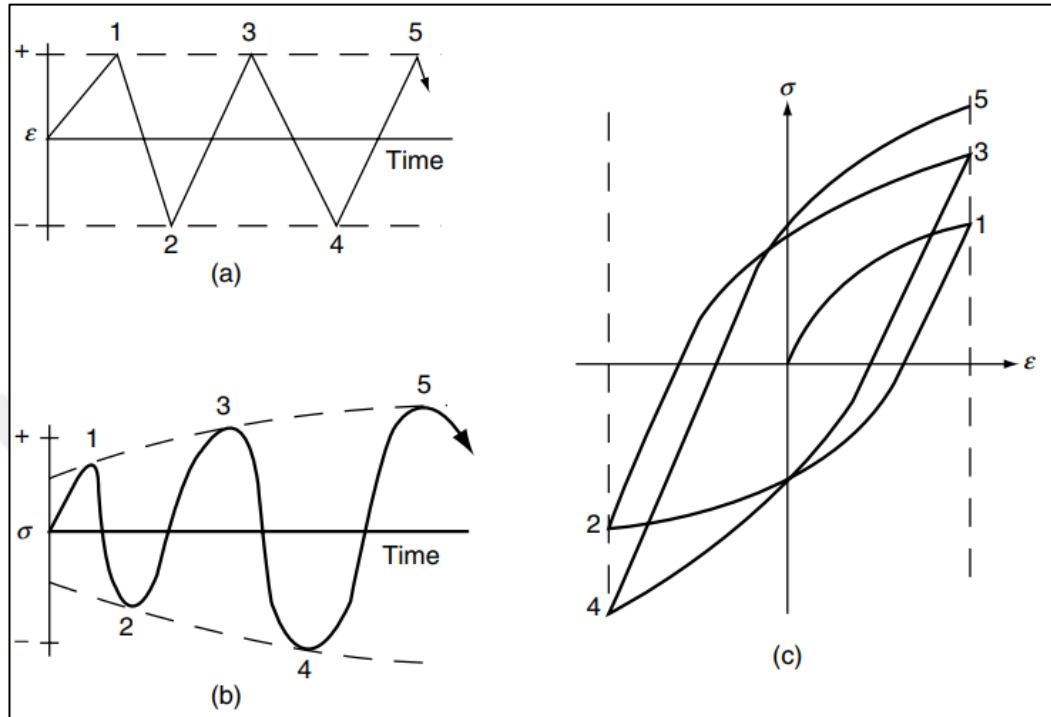


Figure 2.16: Transient Cyclic Hardening [23].

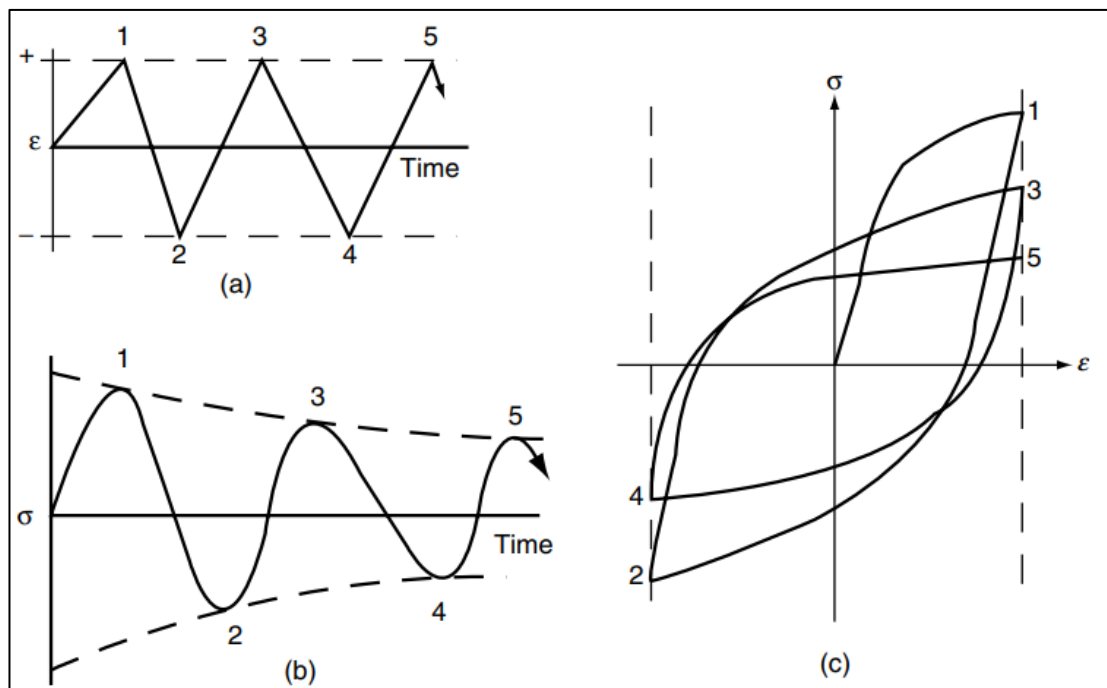


Figure 2.17: Transient Cyclic Softening [23].

This time-dependent behavior is generally associated with the stability of the dislocation substructure within the material's crystal lattice. Typically, materials with low initial dislocation densities—such as aluminum alloys—exhibit cyclic hardening. Conversely, harder materials like steel are more prone to cyclic softening [23].



3. EXPERIMENT

In this chapter, the planning of the test setup, the application of stress concentration factors to the test specimens, the execution of the tests, and the finite element analysis of these tests are explained.

Due to the company's confidentiality policy and commitment to information security, material testing data is considered proprietary. Sharing or disclosing this data to external stakeholders requires prior approval from the company. Therefore, in this section, material data and critical outputs have been normalized to ensure confidentiality.

3.1. Low Cycle Fatigue (LCF) Test

In this thesis, low-cycle fatigue (LCF) tests were conducted using a tensile specimen with the geometric parameters illustrated in **Figure 2.13**. A photograph of a fatigue specimen subjected to tensile testing is presented in **Figure 3.1**.



Figure 3.1: A Fatigue Specimen Subjected to Tensile Test.

Strain-controlled low-cycle fatigue (LCF) tests were performed using a servo-hydraulic machine, with total strain (elastic + plastic) as the primary control parameter. A high-precision high-temperature extensometer measured strain directly, and a closed-loop control system used real-time feedback to adjust the actuator, maintaining the desired strain amplitude and waveform. This ensured consistent loading conditions despite changes in material properties due to hardening, softening, or damage. All tests were conducted under isothermal conditions, with temperature kept constant throughout the experiments.

To examine fatigue–creep interaction, dwell (hold) time tests were also conducted as part of this study. For components such as afterburner liners that operate at high temperatures, fatigue–creep interaction is both critical and complex, and it must be thoroughly investigated. **Figure 3.2** illustrates the influence of hold time on the low-cycle fatigue (LCF) life of a test specimen subjected to uniaxial loading with a trapezoidal waveform, across various total strain amplitudes.

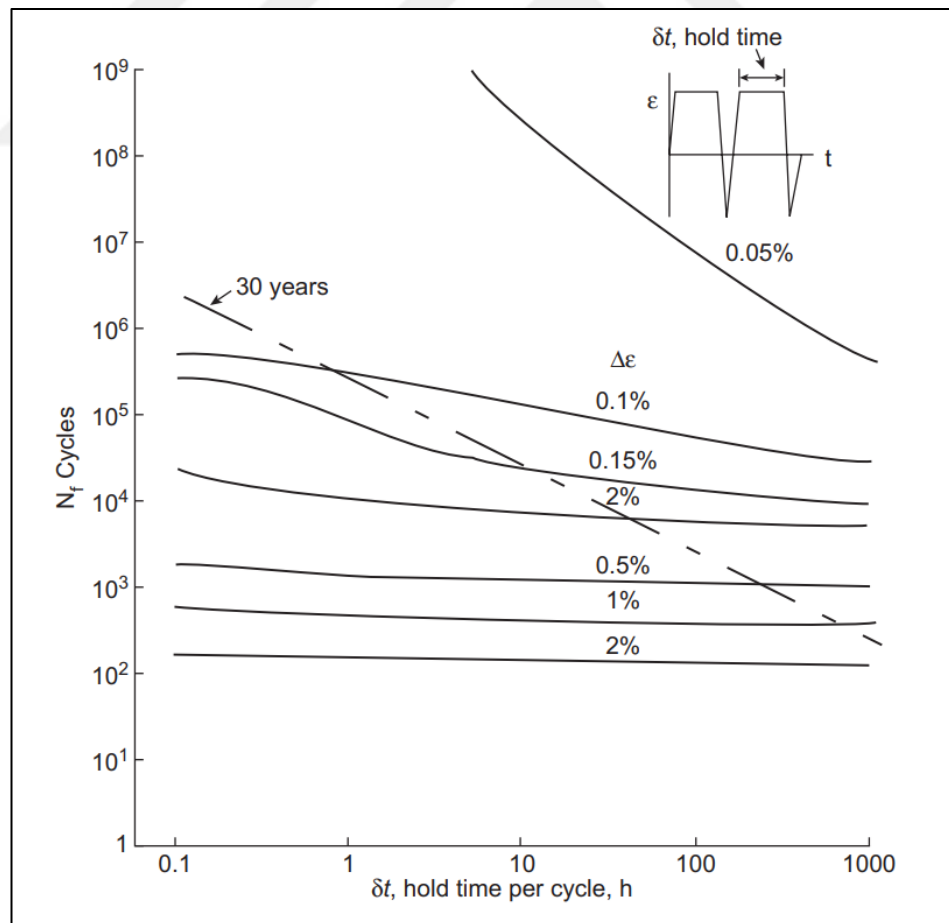


Figure 3.2: Hold-Time Tensile Test [18].

Electrical Discharge Machining (EDM) was employed to drill angled effusion cooling holes through the full thickness of the test specimens, thereby introducing stress concentration factors. **Figure 3.3** presents CAD views of the LCF test specimen with an angled effusion cooling hole and its longitudinally sectioned half.

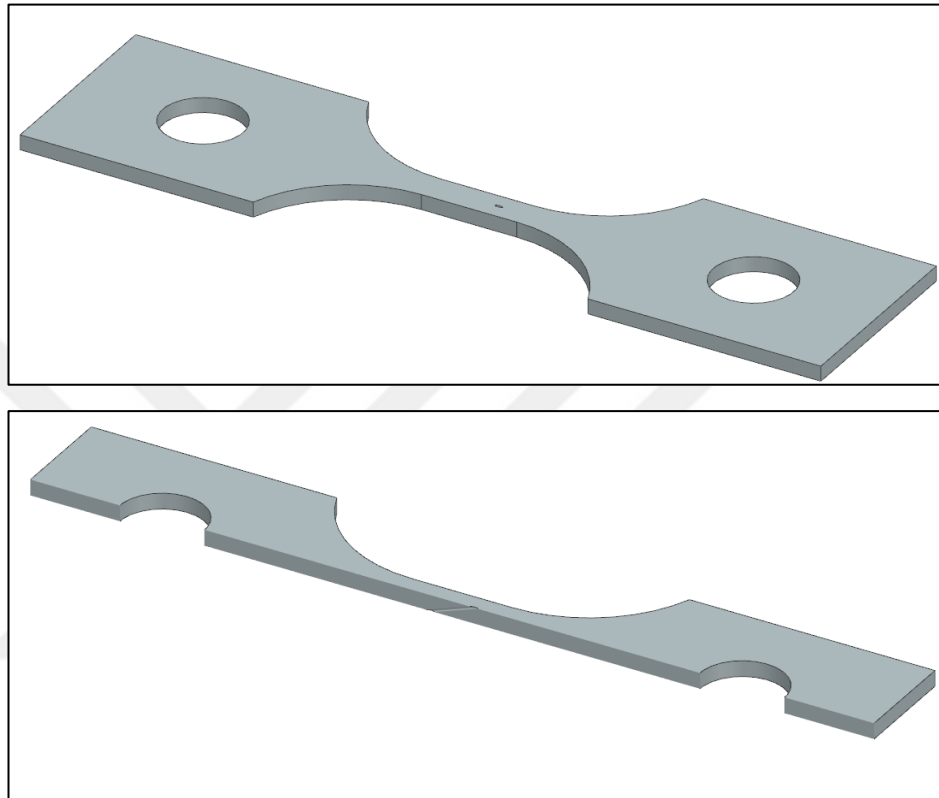


Figure 3.3: Perspective CAD views of the LCF Test Specimen with an Inclined Effusion Cooling Hole and its Longitudinal Section.

The selection of suitable materials for afterburner liners is critical due to the extreme thermal, mechanical, and oxidative environments in which these components operate. Among the high-performance superalloys commonly evaluated for such applications, Alloy 188 (also known as Hastelloy X-188 or Haynes 188) is generally preferred over Alloy 625 (commonly referred to as Inconel 625). This preference is primarily due to Alloy 188's superior high-temperature strength, creep resistance, and oxidation behavior. Composed primarily of cobalt, Alloy 188 maintains mechanical integrity at temperatures reaching up to 1095 °C, aligning well with the thermal demands typical of afterburner operation.

In contrast, nickel-based Alloy 625 exhibits excellent corrosion resistance and weldability, making it an attractive option for components exposed to aggressive chemical or marine environments. However, it is better suited to lower-temperature sections of the exhaust system or applications where cost and corrosion resistance are prioritized over high-temperature performance. Alloy 625 begins to exhibit a decline in strength and oxidation resistance beyond 980 °C, which limits its effectiveness in thermally intensive regions of the engine.

Therefore, due to its elevated thermal performance and stability under cyclic thermal loads, Alloy 188 remains the material of choice for afterburner liners, whereas Alloy 625 may still be used effectively in adjacent structural or support components operating under less extreme conditions.

Figure 3.4 presents images of Alloy 188 and Alloy 625 test specimens featuring effusion cooling holes.



Figure 3.4: Alloy 188 and Alloy 625 Test Specimens with an Effusion Cooling Hole.

Microstructural analysis via optical microscopy was conducted on EDM-drilled specimens, with one specimen examined for each material. **Figure 3.5** illustrates the test specimens subjected to microstructural examination.



Figure 3.5: Test Specimens Examined for Microstructural Analysis.

The recast layer is a thin surface region formed on test specimens during the Electrical Discharge Machining (EDM) process. This layer comprises material that has melted due to the intense heat generated by the EDM spark and subsequently solidified rapidly on the specimen surface. The recast layer can significantly influence crack initiation and propagation, as it typically exhibits distinct microstructural features—such as residual stresses, micro-cracks, and altered hardness—relative to the base material. High-magnification optical microscopy facilitates the detection of micro-cracks following metallographic preparation. Additionally, residual stresses can be quantified through analysis of diffraction peak shifts in X-ray Diffraction (XRD) data, while hardness variations across the recast layer and into the base material can be measured with fine spatial resolution using microhardness testing (e.g., Vickers or Knoop) or nanoindentation techniques.

Figures 3.6 and **3.7** show the recast layer thickness measurements of effusion cooling holes in Alloy 188 and Alloy 625 test specimens, respectively. These measurements were performed to minimize manufacturing-related variability that could influence Low Cycle Fatigue (LCF) test results. The maximum recast layer thickness was approximately 50 μm for Alloy 188 and 34 μm for Alloy 625.

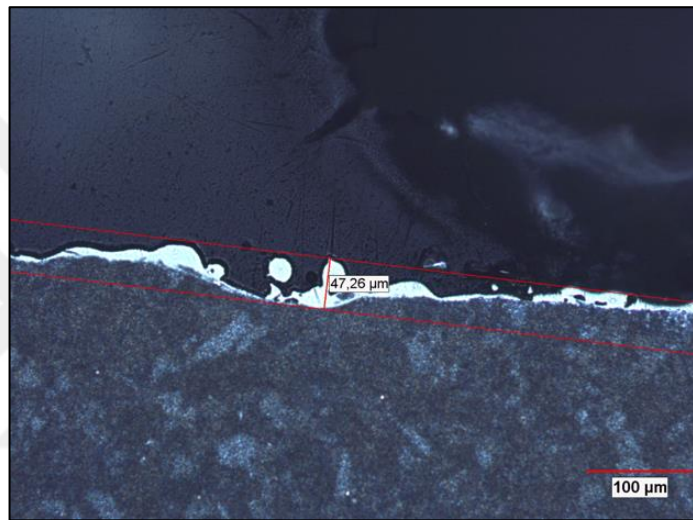
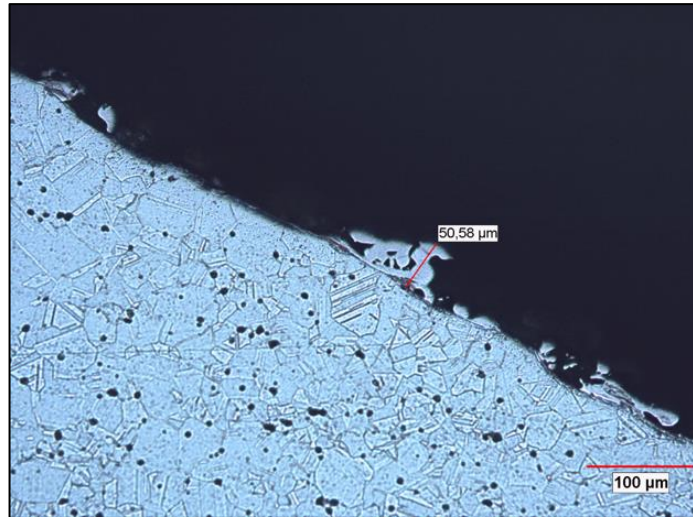


Figure 3.6: Recast Layer Thickness Measurement on Alloy 188 Test Specimen.

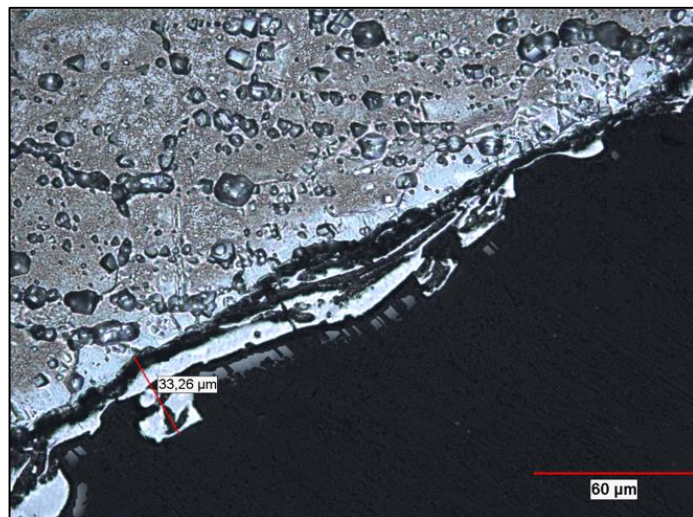




Figure 3.7: Recast Layer Thickness Measurement on Alloy 625 Test Specimen.

Table 3.1: Low Cycle Fatigue (LCF) Test Matrix

	Material	Specimen Form	Test	Temperature
1	Alloy625	Sheet	Strain Controlled LCF	1250 K
2	Alloy625	Sheet + Hole	Strain Controlled LCF	1250 K
3	Alloy188	Sheet	Strain Controlled LCF	1250 K
4	Alloy188	Sheet + Hole	Strain Controlled LCF	1250 K
5	Alloy188	Sheet + Hole	Hold Time+ Strain Contr. LCF	1250 K

The LCF test matrix is presented in **Table 3.1**. Strain-controlled LCF tests were designed for two different materials. For the Alloy 188 test specimen, a hold-time condition was included to evaluate the effect of creep. All tests in this phase of the study were conducted isothermally at a temperature of 1250 K.

The experiments were conducted under strain-controlled conditions. For both perforated and non-perforated specimens, strain at the specimen center was measured using strain gauges. The waveform, amplitude, and frequency of the alternating strain—critical parameters in low-cycle fatigue (LCF) testing—were held constant across all specimens.

In strain-controlled LCF tests with a dwell period, a cyclic strain waveform is applied, and the peak tensile strain is held constant at elevated temperature during the dwell period to simulate creep–fatigue interaction. This hold-time condition was employed to investigate its effect on the fatigue life of the Alloy 188 test specimen.

LCF tests were conducted for each condition in the test matrix using the specified parameters. Testing continued until specimen fracture, allowing the determination of

LCF life. **Figure 3.8** shows two test specimens following fracture at the conclusion of the LCF tests.

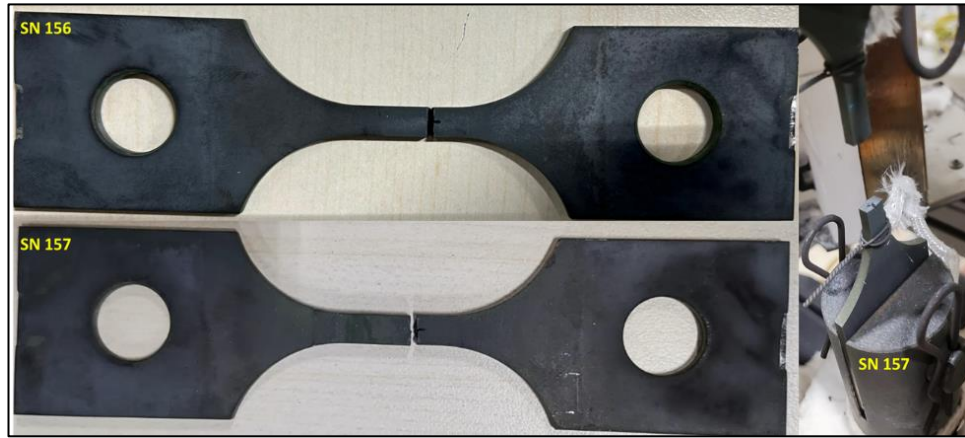


Figure 3.8: Fractured Test Specimens Following LCF Testing.

Table 3.2: LCF Test Specimens

Specimen	Material	Form	Test	Normalized Strain	Cycle
SN100	Alloy625	Sheet+Effusion Hole	Strain Controlled LCF	0.875	325
SN101	Alloy625	Sheet+Effusion Hole	Strain Controlled LCF	0.250	110
SN102	Alloy188	Sheet+Effusion Hole	Strain Controlled LCF	0.125	1100
SN103	Alloy188	Sheet+Effusion Hole	Strain Controlled LCF	0.750	360
SN104	Alloy188	Sheet+Effusion Hole	Strain Controlled LCF	0.250	350
SN105	Alloy188	Sheet+Effusion Hole	Strain Controlled LCF	0.125	800
SN106	Alloy188	Sheet+Effusion Hole	Strain Controlled LCF	0.800	175
SN107	Alloy188	Sheet+Effusion Hole	Strain Controlled LCF+Hold time	0.750	110
SN108	Alloy188	Sheet+Effusion Hole	Strain Controlled LCF+Hold time	0.875	85
SN109	Alloy188	Sheet+Effusion Hole	Strain Controlled LCF +Hold time	0.125	440

Table 3.2 summarizes the strain-controlled uniaxial LCF test conditions and results for ten tensile specimens with effusion cooling holes (SN100–SN109), enabling comparison with non-holed specimens tested under identical conditions. A hold-time was applied to three specimens to evaluate dwell fatigue. The table lists normalized strain levels—total strain amplitudes (elastic + plastic) applied symmetrically in tension and compression during strain-controlled fatigue tests—and the corresponding cycles to crack initiation for each specimen to maintain confidentiality.

Figures 3.9 to 3.18 present the stress–strain hysteresis loops for specimens SN100 to SN109, in the order listed in **Table 3.2**. The plots are based on in-situ measurements, with cycle progression indicated by color shading, from darker to lighter tones as cycles increase.

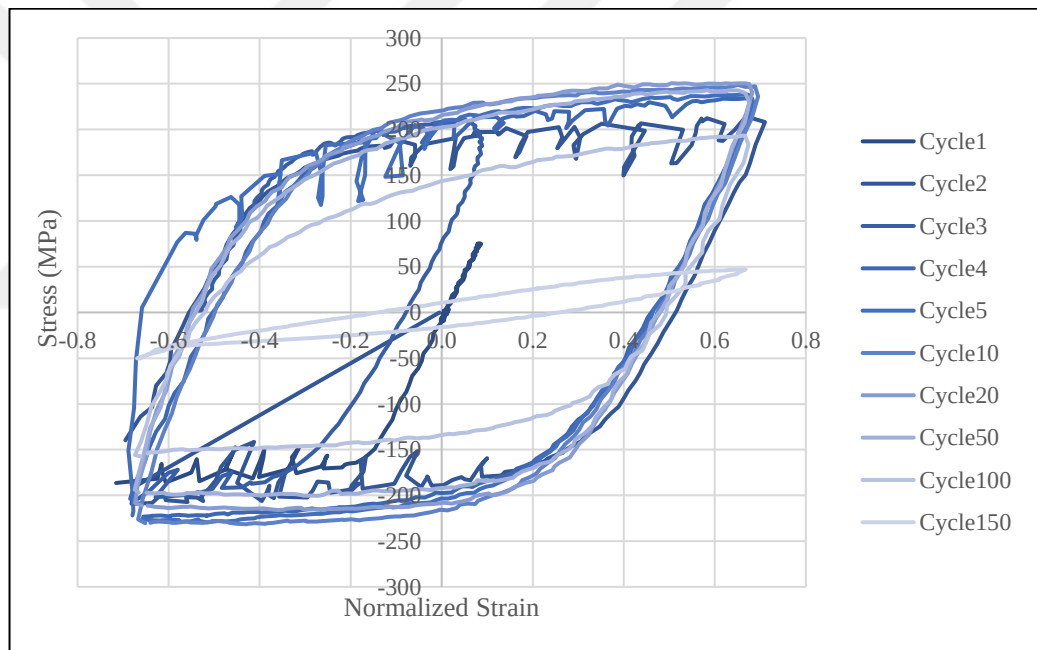


Figure 3.9: Stress–Strain Hysteresis Loop of Specimen SN100 (Alloy 625 Sheet with an Effusion Cooling Hole under Strain-Controlled LCF Testing at a Normalized Strain of 0.875).

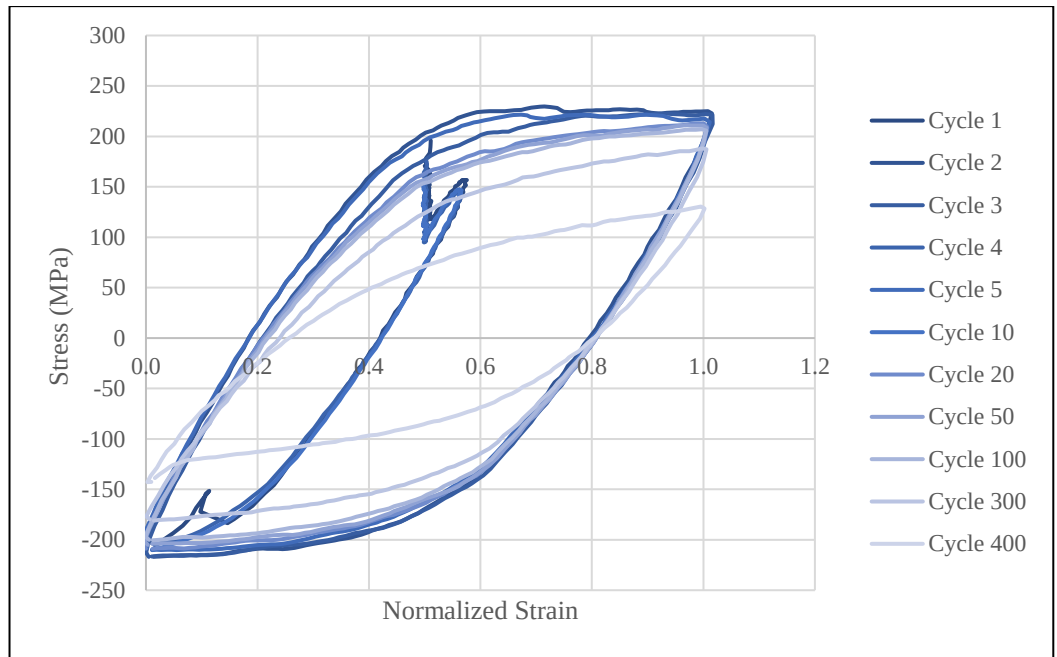


Figure 3.10: Stress–Strain Hysteresis Loop of Specimen SN101 (Alloy 625 Sheet with an Effusion Cooling Hole under Strain-Controlled LCF Testing at a Normalized Strain of 0.250).

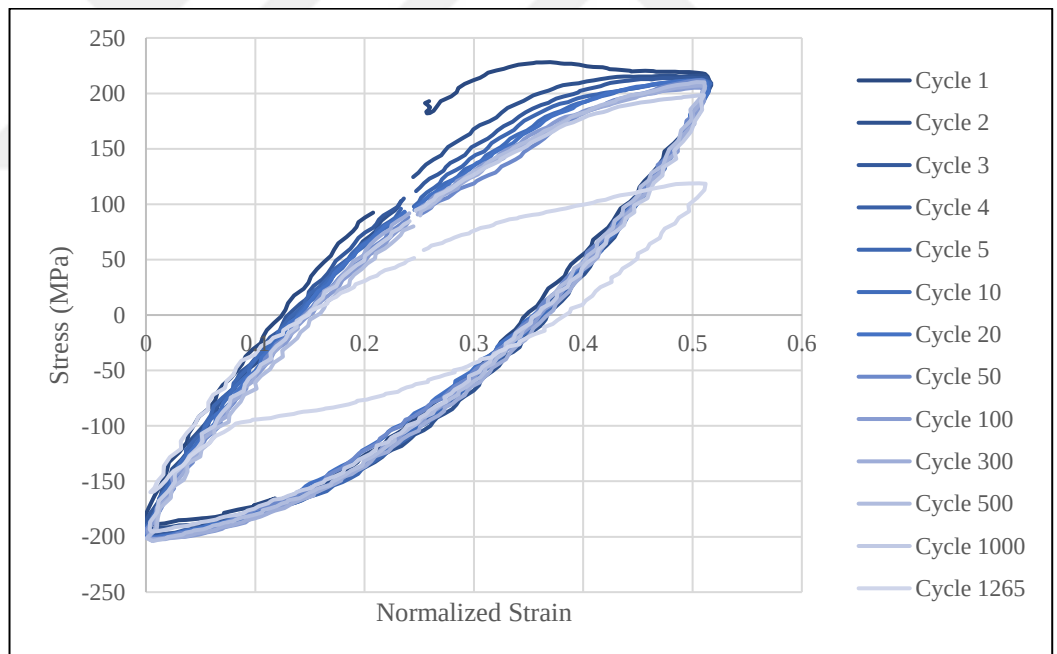


Figure 3.11: Stress–Strain Hysteresis Loop of Specimen SN102 (Alloy 188 Sheet with an Effusion Cooling Hole under Strain-Controlled LCF Testing at a Normalized Strain of 0.125).

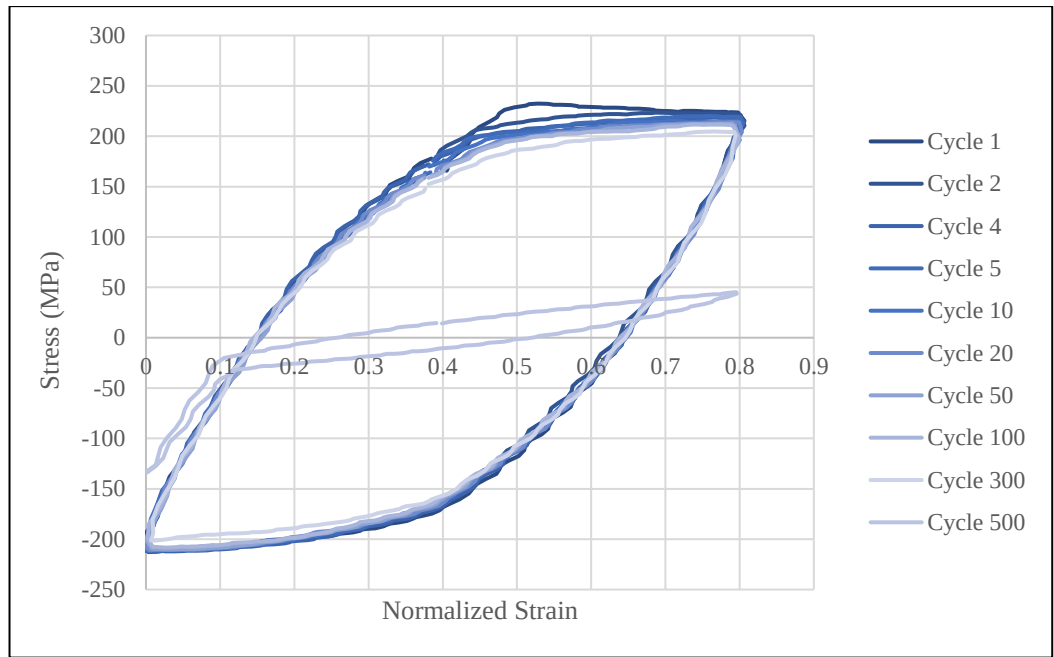


Figure 3.12: Stress–Strain Hysteresis Loop of Specimen SN103 (Alloy 188 Sheet with an Effusion Cooling Hole under Strain-Controlled LCF Testing at a Normalized Strain of 0.750).

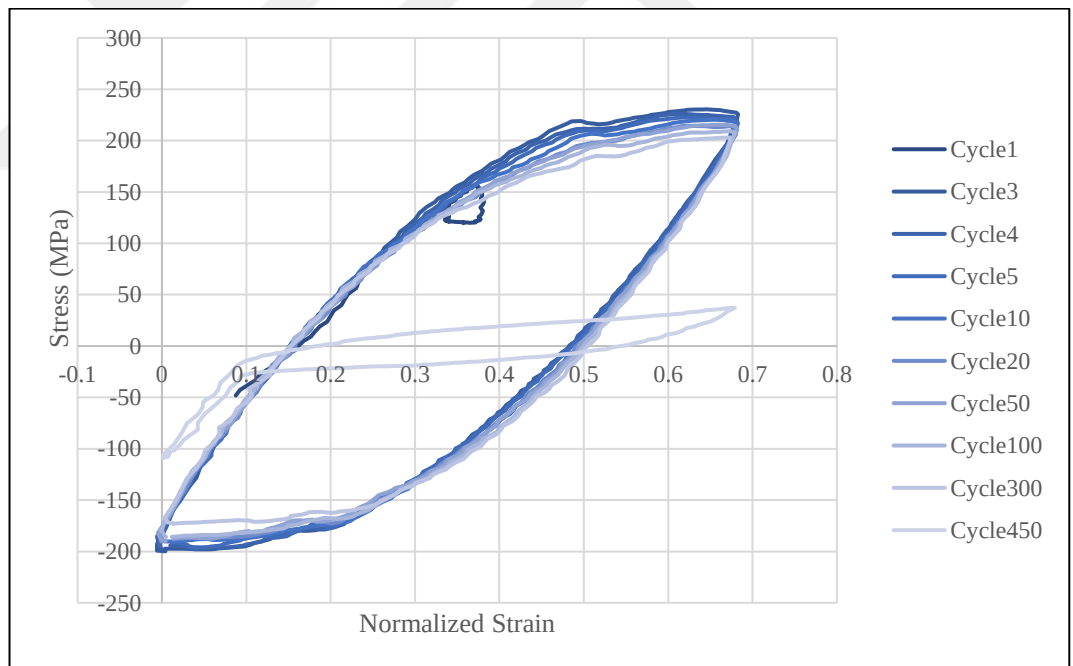


Figure 3.13: Stress–Strain Hysteresis Loop of Specimen SN104 (Alloy 188 Sheet with an Effusion Cooling Hole under Strain-Controlled LCF Testing at a Normalized Strain of 0.250).

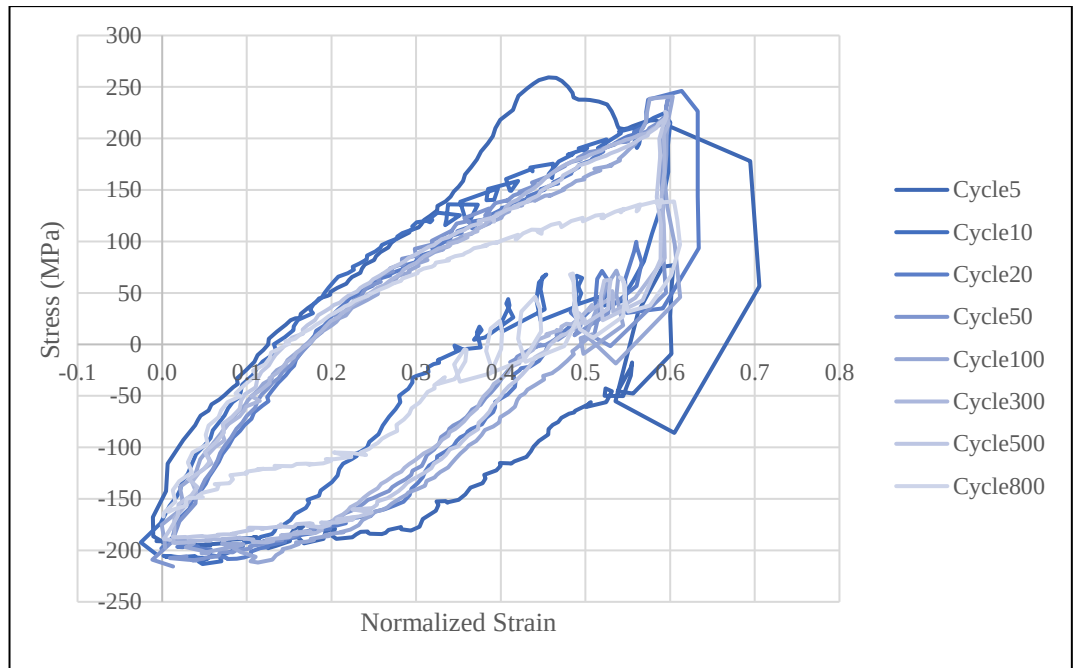


Figure 3.14: Stress–Strain Hysteresis Loop of Specimen SN105 (Alloy 188 Sheet with an Effusion Cooling Hole under Strain-Controlled LCF Testing at a Normalized Strain of 0.125).

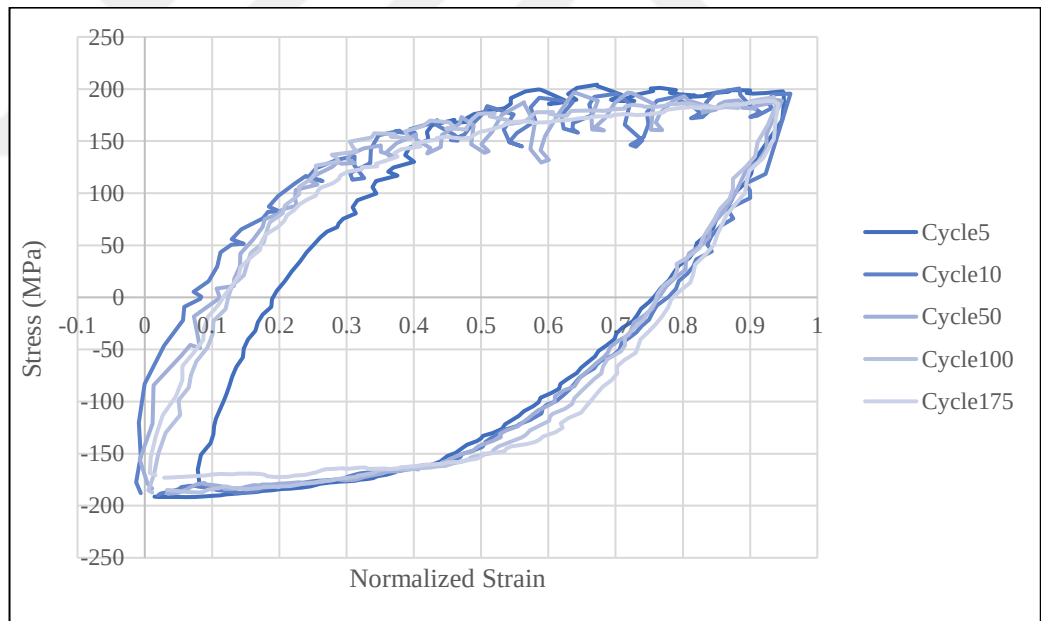


Figure 3.15: Stress–Strain Hysteresis Loop of Specimen SN106 (Alloy 188 Sheet with an Effusion Cooling Hole under Strain-Controlled Low-Cycle Fatigue Testing at a Normalized Strain of 0.800 with Hold Time).

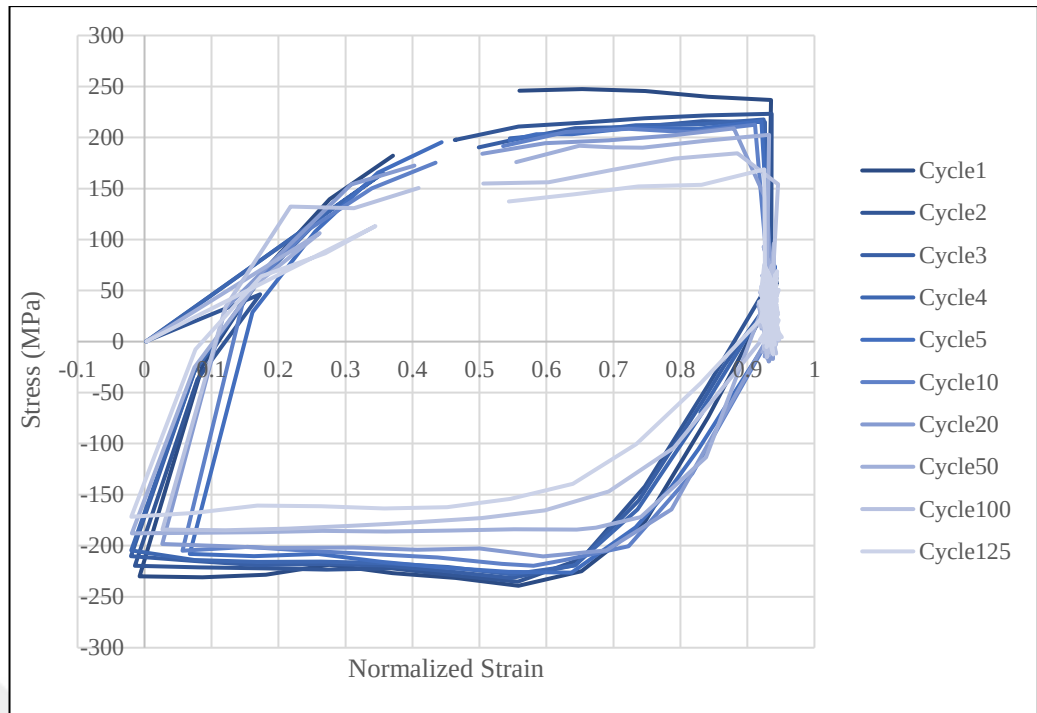


Figure 3.16: Stress–Strain Hysteresis Loop of Specimen SN107 (Alloy 188 Sheet with an Effusion Cooling Hole under Strain-Controlled Low-Cycle Fatigue Testing at a Normalized Strain of 0.750 with Hold Time).

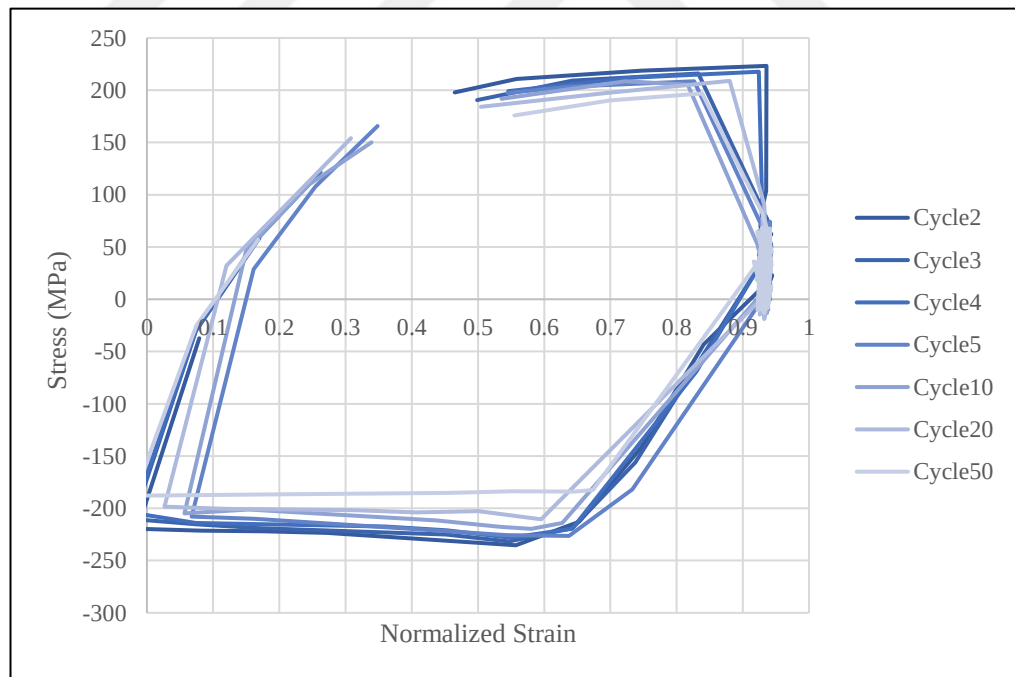


Figure 3.17: Stress–Strain Hysteresis Loop of Specimen SN108 (Alloy 188 Sheet with an Effusion Cooling Hole under Strain-Controlled Low-Cycle Fatigue Testing at a Normalized Strain of 0.875 with Hold Time).

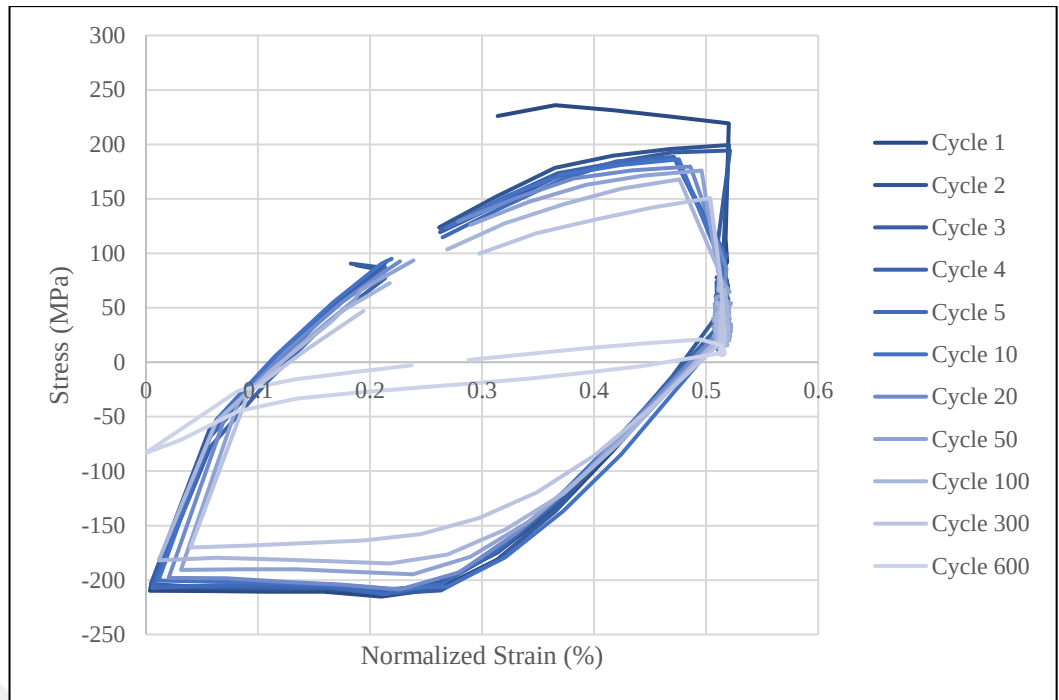


Figure 3.18: Stress–Strain Hysteresis Loop of Specimen SN109 (Alloy 188 Sheet with an Effusion Cooling Hole under Strain-Controlled Low-Cycle Fatigue Testing at a Normalized Strain of 0.125 with Hold Time).

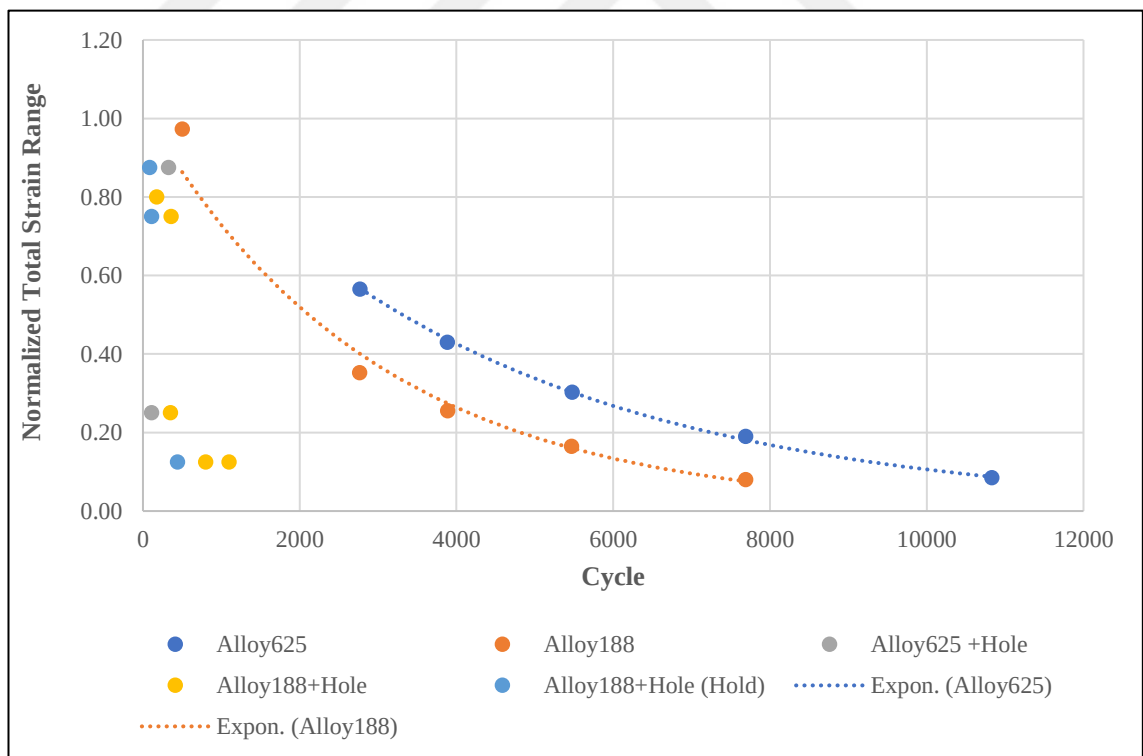


Figure 3.19: Normalized Total Strain Range vs. Fatigue Life (Cycles) for LCF Test Specimens.

Figure 3.19 presents the normalized total strain range versus fatigue life (cycles) for specimens with effusion cooling holes, without holes, and with hold-time exposure, for both Alloy 625 and Alloy 188.

3.1.1. Finite Element Analysis of the LCF Test Specimen

This section presents the geometric modifications, meshing strategy, and the boundary and loading conditions employed in the finite element (FE) model of the low-cycle fatigue (LCF) test specimen.

Meshing was performed in ANSYS Workbench (WB), a process that requires careful consideration. An excessively fine mesh can lead to prohibitively high computational costs, while an overly coarse mesh may compromise simulation accuracy by failing to capture critical geometric features and stiffness variations. To balance these trade-offs, a non-uniform mesh was adopted, with finer elements applied in regions requiring higher resolution.

The **SOLID185** element, a three-dimensional, 8-node brick element with three translational degrees of freedom per node, was used in this analysis. It supports a wide range of material and geometric nonlinearities, including plasticity, hyperelasticity, stress stiffening, creep, large deformations, and large strains. Its mixed formulation capability allows for accurate modeling of nearly incompressible elastoplastic and fully incompressible hyperelastic materials [29]. The SOLID185 homogeneous structural solid element is illustrated in **Figure 3.20**.

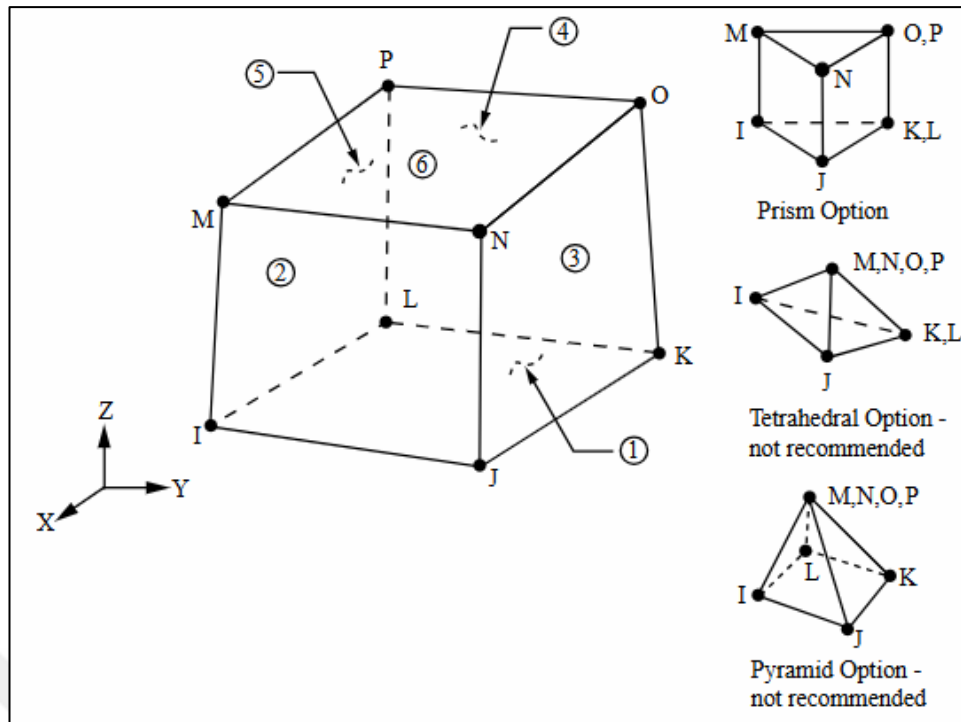
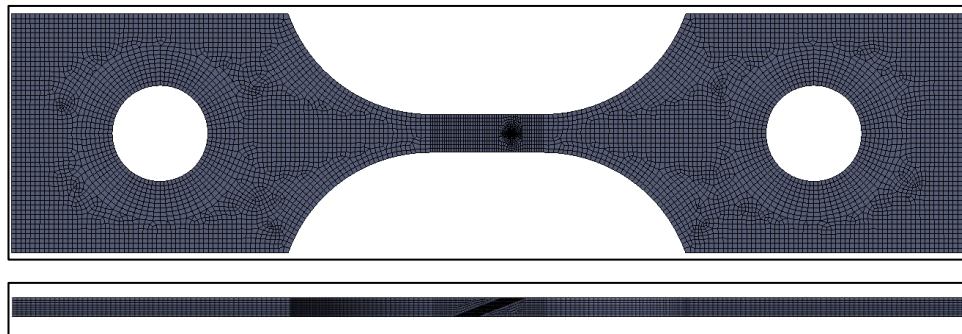


Figure 3.20: SOLID185 Homogeneous Structural Solid Element (adapted from [29]).

The meshed finite element model is illustrated in Figure 3.21, comprising 72,246 nodes and 61,468 elements.



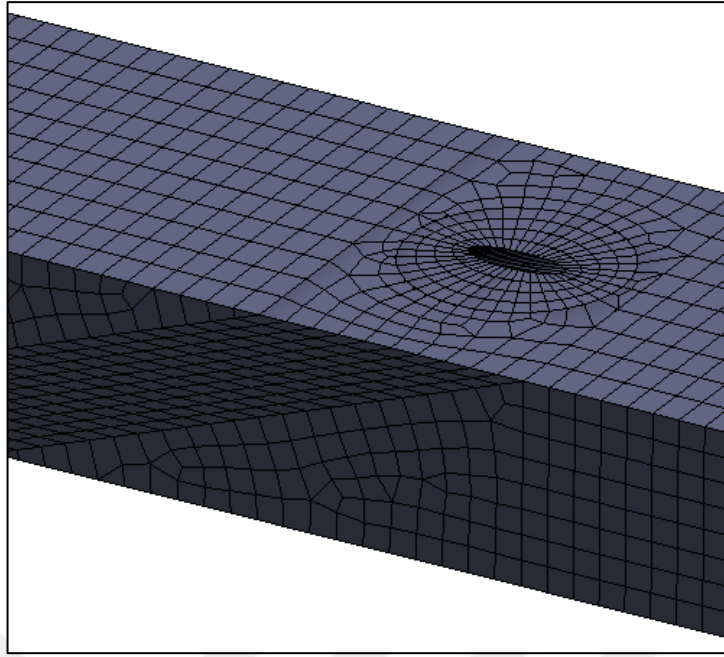


Figure 3.21: Finite Element Mesh of the Model.

To replicate the experimental conditions in the finite element (FE) model, appropriate boundary conditions were applied to the tensile specimen. Since the test was conducted under isothermal conditions, a uniform temperature of 1250 K was applied across the entire specimen, as shown in **Figure 3.22**. Remote displacement accurately replicates the uniform loading and resulting deformation applied to the gripped surfaces by the testing machine during the strain-controlled low-cycle fatigue (LCF) test within the finite element model. This approach mitigates the risk of artificial stress concentrations that could arise from non-uniform or point loading. Additionally, standard Earth gravity was applied to simulate the specimen's orientation and support conditions, consistent with the physical test setup.

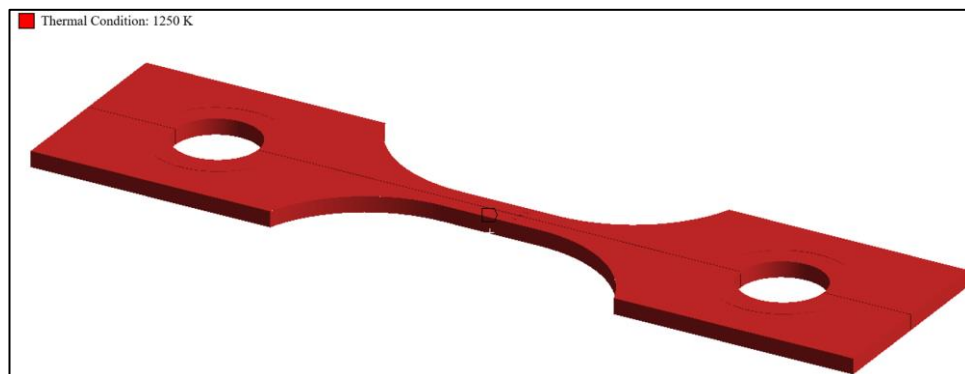


Figure 3.22: Uniform Temperature of 1250 K Applied to the Finite Element Model.

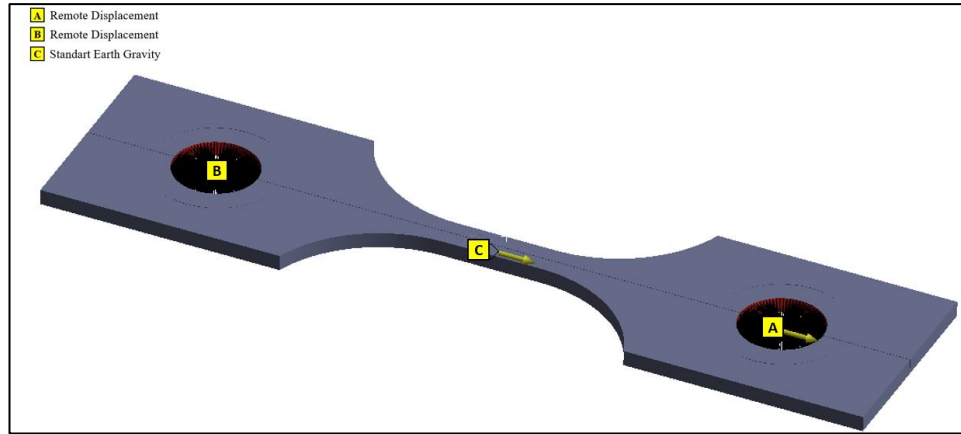
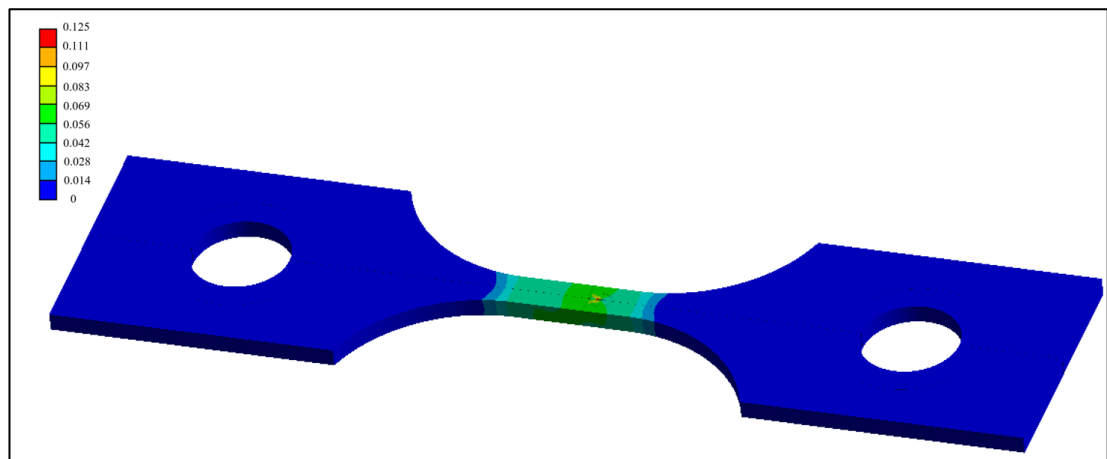


Figure 3.23: Applied Boundary Conditions in the Finite Element Model.

This finite element analysis (FEA) was conducted for the case in Row 4 of the test matrix presented in **Table 3.1**. The simulation replicated the strain levels measured in the tensile direction during the testing of specimen SN102, as detailed in **Table 3.2**. Correspondingly, the stress and strain results were normalized.

The equivalent total strain and stress distributions, calculated by the FEA model for the LCF test specimen SN102, are shown in **Figures 3.24** and **3.25**, respectively. The simulated maximum elastic, plastic, and total strains per cycle for test specimen SN102 are depicted in **Figure 3.26**. The simulated stress-strain hysteresis loop for test specimen SN102 is presented in **Figure 3.27**.



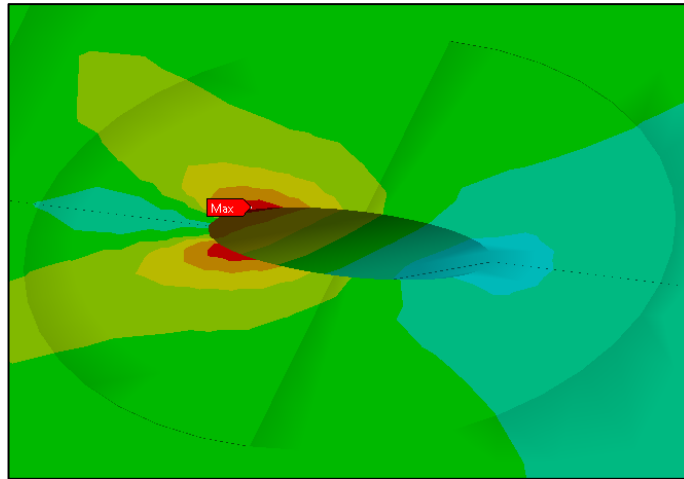


Figure 3.24: Equivalent Total Strain Distribution Calculated by the FEA Model for LCF Test Specimen SN102.

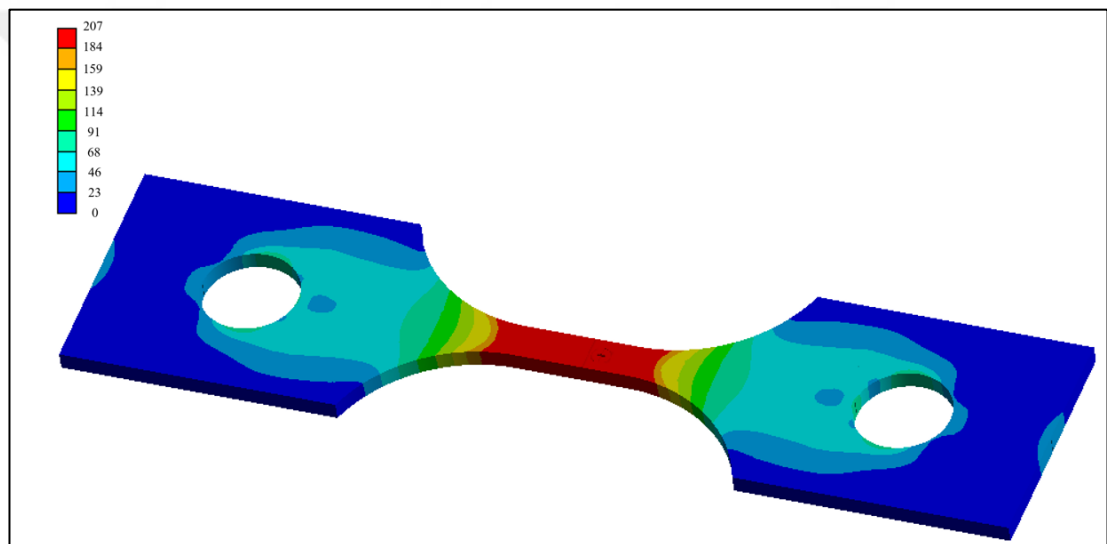


Figure 3.25: Equivalent Stress Distribution Calculated by the FEA Model for the LCF Test Specimen SN102.

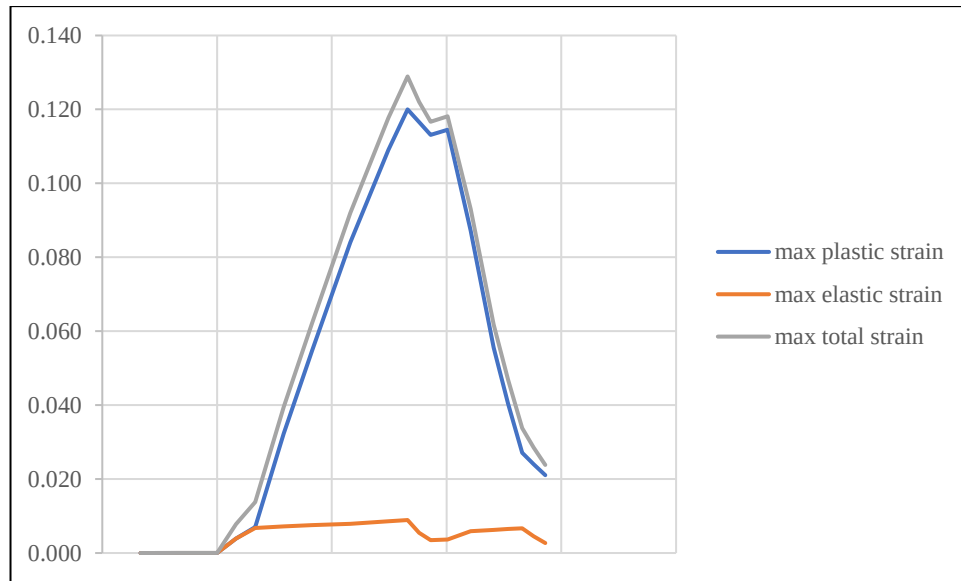


Figure 3.26: Simulated Maximum Elastic, Plastic, and Total Strains per Cycle for Test Specimen SN102.

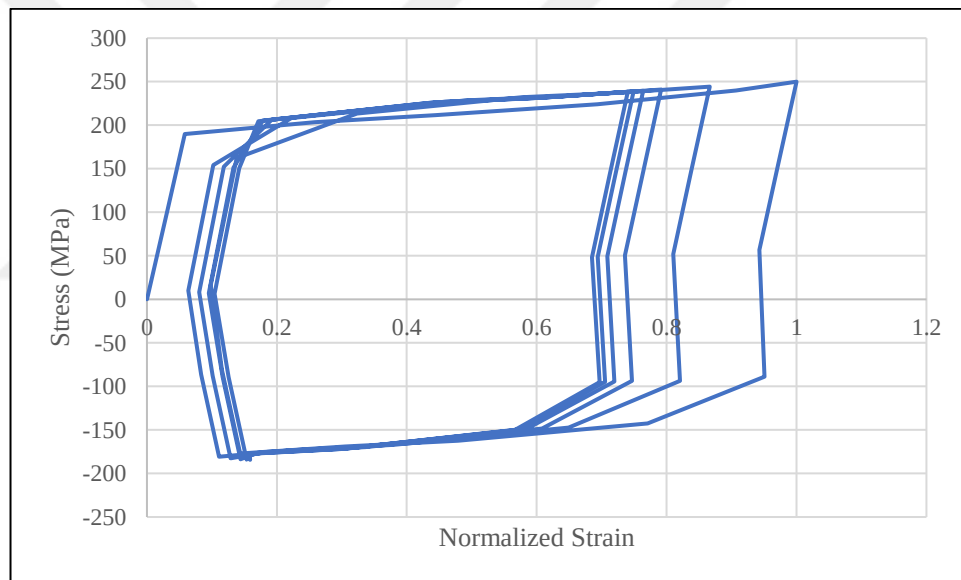


Figure 3.27: Simulated Stress-Strain Hysteresis Loop for Test Specimen SN102.

3.2. Thermal Fatigue Test

This study seeks to assess the fatigue life of the liner component under representative operating conditions. A specialized test rig was employed to subject the liner to cyclic thermal loading, replicating the thermal stresses experienced during service. The experimental setup closely emulated real-world operating environments, allowing for a comprehensive evaluation of the effects of cyclic thermal loads on both the thermo-mechanical durability and microstructural evolution of the component.

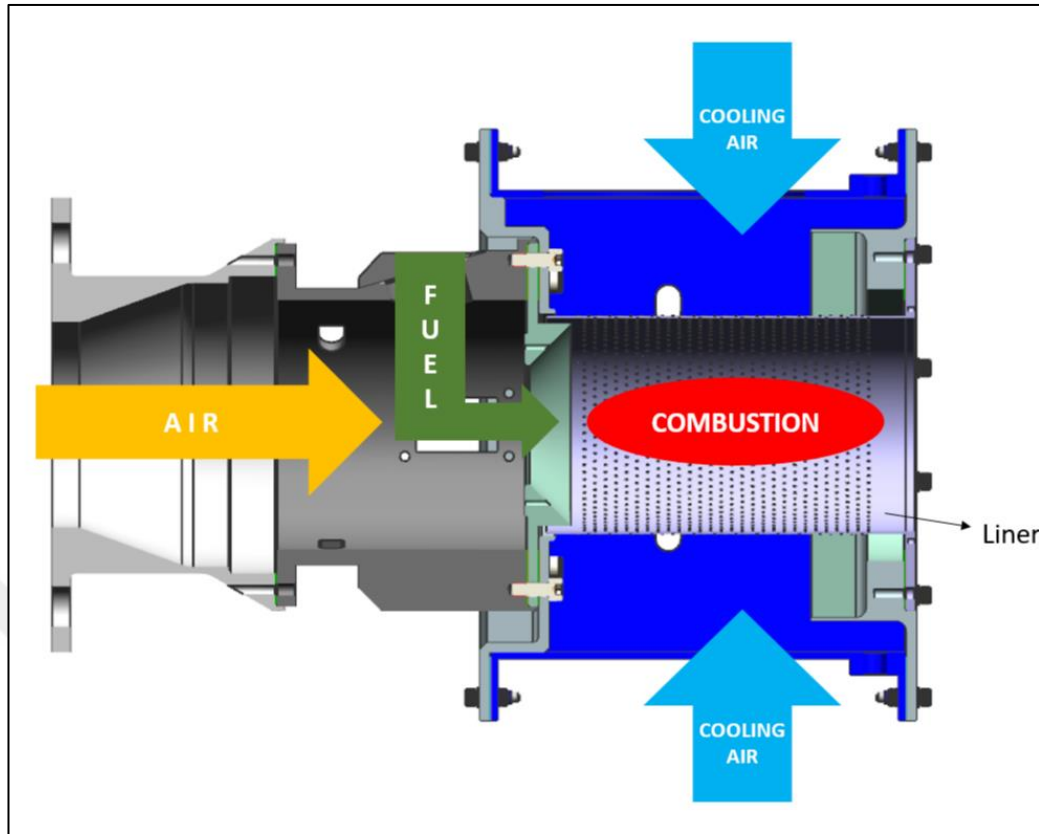


Figure 3.28: Schematic Diagram of the Experimental Test Rig.

Figure 3.28 illustrates a schematic of the test rig, which is equipped with three inlets: a hot air inlet, a fuel inlet, and a cooling air inlet. Within the system, the incoming air is mixed with the fuel, and the resulting fuel-air mixture undergoes combustion within the liner. Ignition is initiated via a torch at the exit side, which is exposed to the atmosphere. This ignition method was selected to maintain the circumferential symmetry of the liner's operating conditions, eliminating the need for an igniter port on the specimen and, thereby, preventing any potential indirect impact on fatigue life assessment. Cooling air is introduced through dedicated inlets to facilitate thermal cycling within the liner and regulate its temperature to the desired levels. During testing, thermal load is controlled by adjusting the flow rates and temperatures of the hot air, fuel, and cooling air.

The liner used in this test rig, designed to simulate the afterburner liner of an aircraft, incorporates effusion cooling holes that induce localized stress concentrations. A **Thermal Barrier Coating (TBC)** was applied using the **Atmospheric Plasma Spraying (APS)** technique. Subsequently, the effusion cooling holes were drilled after

the TBC application to replicate the actual manufacturing sequence. **Figure 3.29** presents an image of the specimen with the applied thermal barrier coating.



Figure 3.29: Test specimen featuring the applied Thermal Barrier Coating [27].

Instrumentation was utilized to monitor the liner throughout the test. Thermocouples and strain gauges were employed to measure the metal temperature and strain, respectively. The locations of these measurement devices are depicted in **Figure 3.30**.

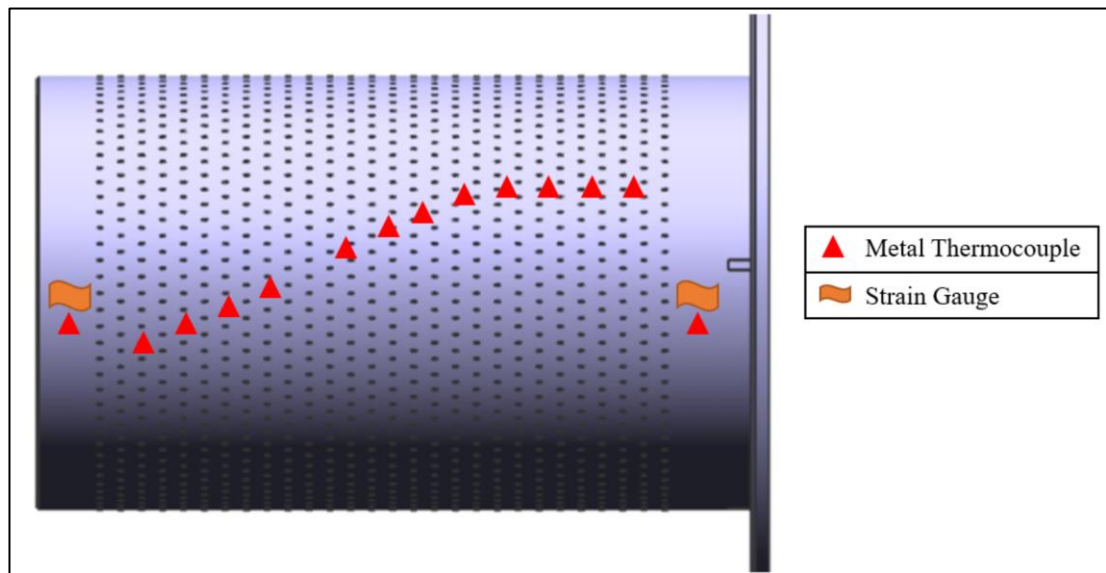


Figure 3.30: Instrumentation Arrangement on the Test Specimen.

Metal temperature measurements were conducted along the axial length of the liner. Strain gauges were strategically placed near the effusion cooling holes on both the

anterior and posterior surfaces of the specimen. The exact locations and orientations of the strain gauges are illustrated in **Figure 3.31**.

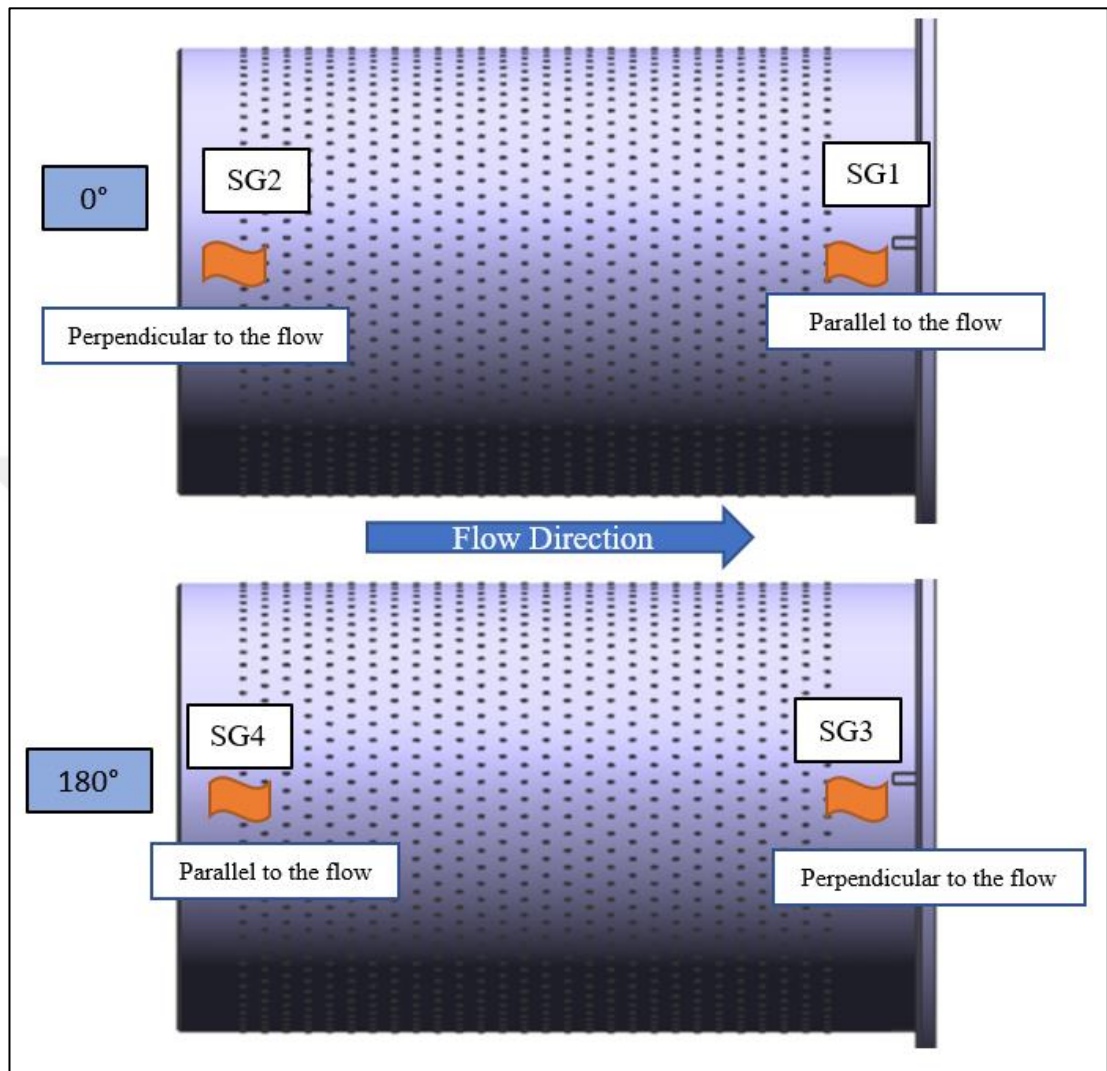


Figure 3.31: Strain gauge measurement locations and orientations.

The afterburner liner tested in this rig experiences a maximum metal temperature of 1100 K. During the cooling phase, the temperature decreases to approximately 650 K. The heating interval, from the minimum to the maximum temperature, lasts 160 seconds, followed by a cooling period of approximately 80 seconds, during which the temperature returns to 650 K. As a result, each thermal cycle has a total duration of 240 seconds. This thermal cycling was maintained continuously throughout the entire test duration. **Figure 3.32** presents the temperature profile across nine consecutive test cycles.

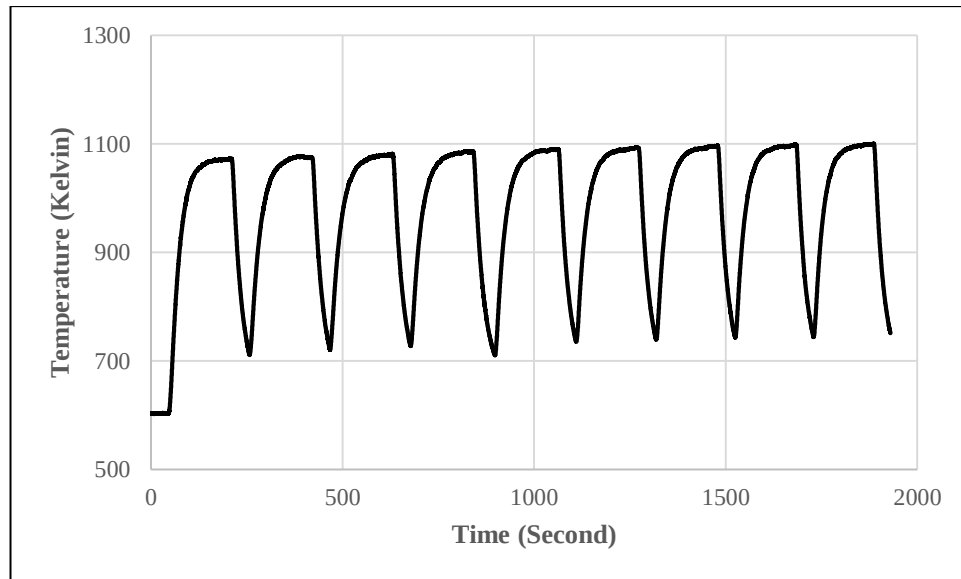


Figure 3.32: Liner Temperature Variation During Nine Thermal Cycles of the Fatigue Test.

The specimen underwent 750 thermo-mechanical fatigue cycles, with continuous data acquisition carried out by the instrumentation throughout the test.



Figure 3.33: Test Execution Using the Experimental Setup.

Upon completion of the test, the specimen underwent visual inspection and microstructural analysis. Additionally, post-processing of the instrumentation data was carried out.

The uniaxial strain gauge used in this study is schematically depicted in **Figure 3.34**. Time-dependent strain and temperature measurements, recorded at selected locations as indicated in **Figures 3.30** and **3.31**, are presented in **Figures 3.35** through **3.40**.

$$\text{Elongation (\%)} = \frac{L_1 - L_0}{L_0} \times 100 \quad (3.1)$$

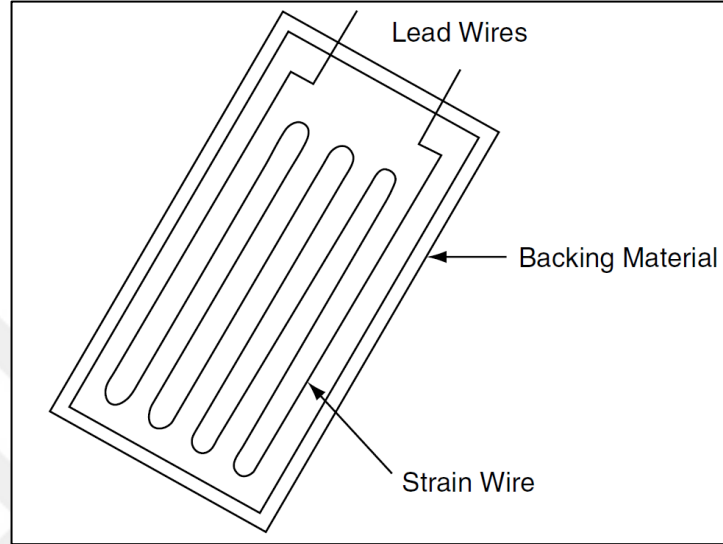


Figure 3.34: Typical Uniaxial Strain Gauge.

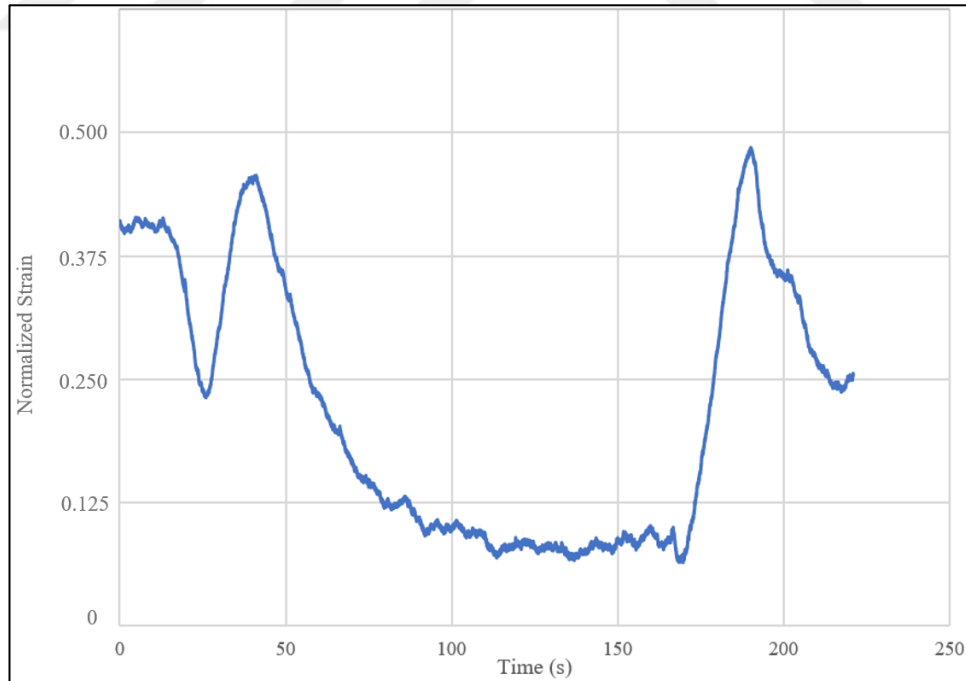


Figure 3.35: Normalized Strain History During a Thermal Cycle Measured by Strain Gauge 1.

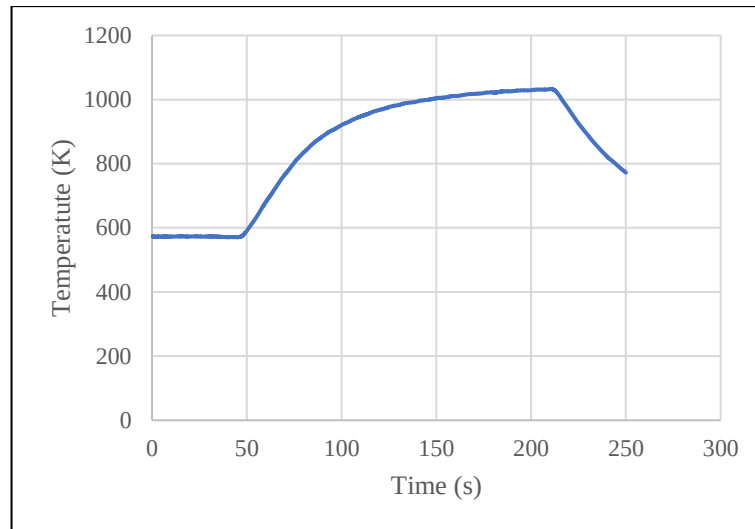


Figure 3.36: Temperature History During a Thermal Cycle Measured by Thermocouple 1.

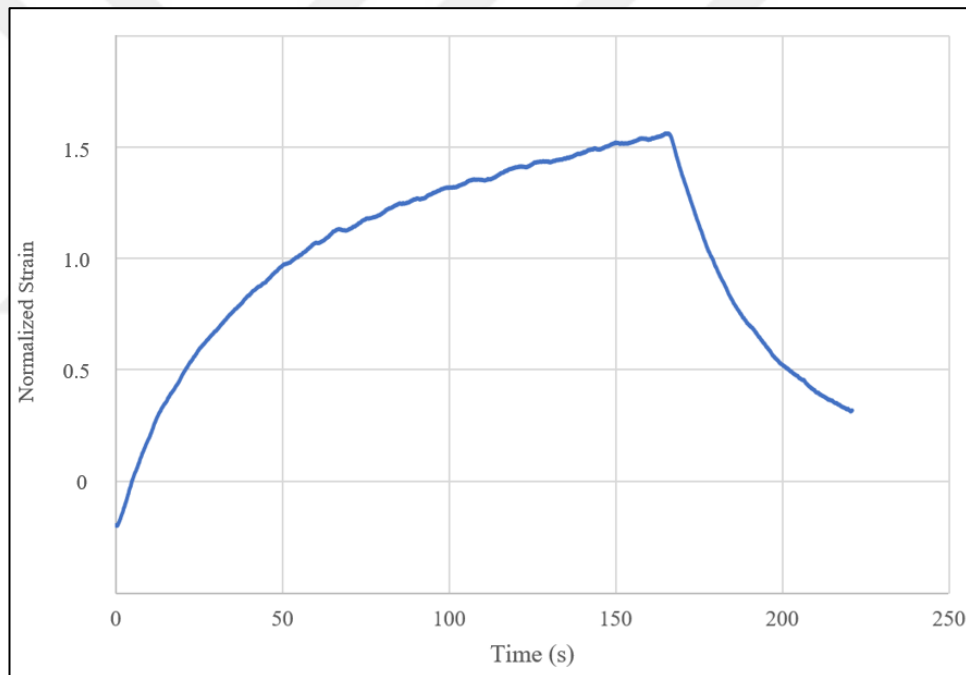


Figure 3.37: Normalized Strain History During a Thermal Cycle Measured by Strain Gauge 2.

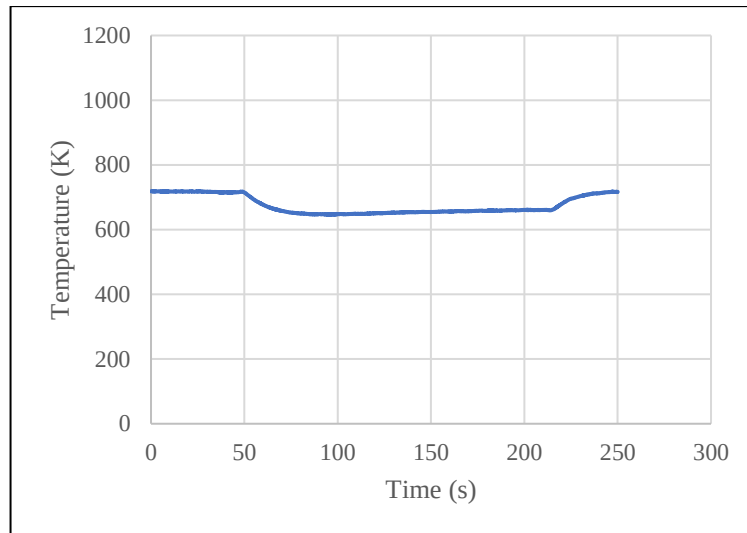


Figure 3.38: Temperature History During a Thermal Cycle Measured by Thermocouple 2.

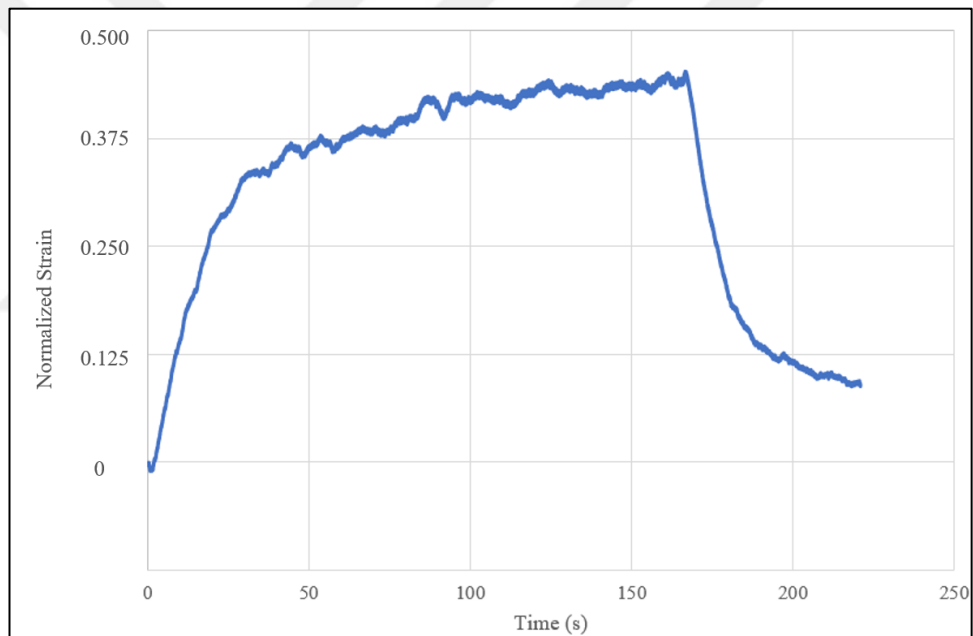


Figure 3.39: Normalized Strain History During a Thermal Cycle Measured by Strain Gauge 3.

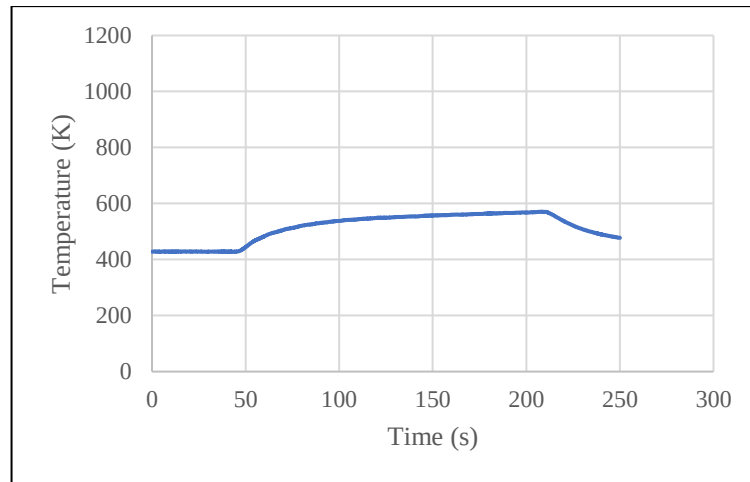


Figure 3.40: Temperature History During a Thermal Cycle Measured by Thermocouple 3.

4. RESULTS

The objective of this chapter is to provide a comprehensive and in-depth assessment of both experimental and numerical investigations conducted on the afterburner liner material. The experimental program comprises uniaxial tensile testing, cyclic loading for hysteresis loop characterization, thermal fatigue testing, and strain gauge measurements. Collectively, these methods yield a robust dataset that enhances the understanding of the material's low-cycle fatigue (LCF) behavior under complex thermo-mechanical loading conditions representative of realistic engine environments.

The experimental results are systematically compared with numerical simulations to evaluate the accuracy, reliability, and limitations of current fatigue life prediction methodologies. This comparative analysis not only serves to validate the computational models but also identifies discrepancies arising from modeling assumptions and simplifications, thereby providing insights for improving predictive capabilities.

This chapter also examines the applicability of two widely utilized empirical fatigue life prediction models—the Morrow model and the Smith-Watson-Topper (SWT) model. The predictive performance of these models is assessed through direct comparison with experimental fatigue life data, enabling a critical evaluation of their effectiveness in capturing the fatigue response of the material under the test conditions.

In addition, the influence of hold time—periods of sustained exposure to elevated temperatures during thermal cycling—is investigated to understand its effect on fatigue life. This aspect is particularly significant for components subjected to variable thermal loads, where phenomena such as creep-fatigue interaction and oxidation-driven degradation can accelerate failure mechanisms.

The study further considers the impact of effusion cooling holes, which are integral to the thermal management of the liner. These geometric features are known to induce localized stress concentrations, thereby influencing the initiation and propagation of fatigue cracks. Their effects are analyzed through both experimental findings and numerical simulations to assess their role in the overall fatigue performance of the component.

By integrating mechanical loading, thermal cycling, empirical model validation, hold time effects, and the influence of geometric discontinuities, this chapter aims to advance current fatigue life prediction techniques and support the development of more resilient design and maintenance strategies for afterburner liners in high-performance gas turbine engines.

The stress–strain curves obtained from the tensile tests exhibit a clearly defined elastic region, where stress and strain follow a linear relationship in accordance with Hooke’s Law. This is followed by a transition into the plastic deformation region, during which the material undergoes irreversible microstructural changes. Beyond the onset of plasticity, the material experiences strain hardening, characterized by an increased resistance to deformation as the applied stress is distributed over a greater volume. Ultimately, the material reaches its fracture point, at which it can no longer withstand additional loading and fails.

The experimentally obtained cyclic loading results revealed a softening behavior, which directly affects the material’s fatigue resistance by inducing further hardening or softening over time. Hysteresis loop measurements were performed under strain-controlled cyclic loading to evaluate the material’s response, offering insights into cyclic hardening, softening, and energy dissipation during repeated deformation. These loops characterize the stress–strain relationship over successive cycles and provide critical information about the material’s ability to accommodate cyclic loading.

The experimental data indicates that the material exhibits cyclic softening over the course of the fatigue test. This behavior is evidenced by the progressive change in the shape and size of the hysteresis loops, which initially show substantial plastic deformation and gradually stabilize after a certain number of cycles. The cyclic softening observed in two test specimens is depicted in **Figure 4.1**. Cyclic hardening, reflected by an increase in peak stress over time, is typically associated with microstructural mechanisms such as dislocation accumulation and phase transformation. In contrast, cyclic softening is marked by a decrease in peak stress, which may result from mechanisms including microcrack initiation, void formation, or phase degradation. The behavior illustrated in **Figure 2.17** corresponds to the stress–strain hysteresis loops presented in **Chapter 3**.

The stress–strain hysteresis loops of the LCF test specimens illustrate the stabilized cyclic response, indicating that the material reaches a steady-state condition after a certain number of cycles. This stabilized behavior is critical for defining the fatigue limit and enabling reliable fatigue life predictions.

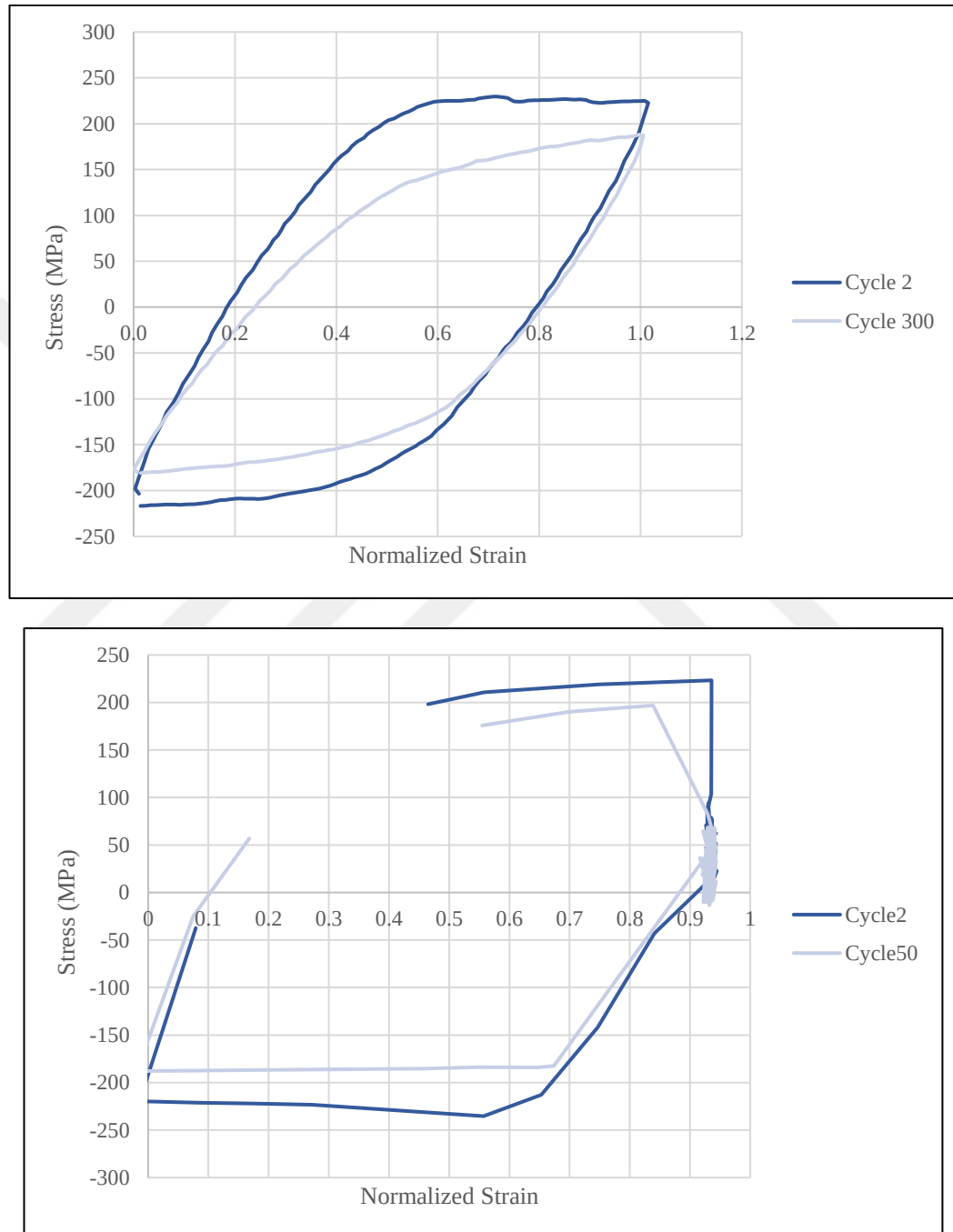


Figure 4.1: Cyclic Softening Response Demonstrated by Two Test Specimens.

Table 4.1: Fatigue Test Results for Specimens with Effusion Cooling Holes

Specimen	Test	Cycle	Normalized Strain
SN100	Strain Controlled LCF	325	0.875
SN101	Strain Controlled LCF	110	0.250
SN102	Strain Controlled LCF	1100	0.125
SN103	Strain Controlled LCF	360	0.750
SN104	Strain Controlled LCF	350	0.250
SN105	Strain Controlled LCF	800	0.125
SN106	Strain Controlled LCF	175	0.800
SN107	Hold time+ Strain Controlled LCF	110	0.750
SN108	Hold time+ Strain Controlled LCF	85	0.875
SN109	Hold time+ Strain Controlled LCF	440	0.125

Thermal fatigue tests were conducted to replicate the severe temperature fluctuations experienced by the afterburner liner during engine operation. The component was subjected to repeated thermal cycling, simulating the thermal conditions characteristic of various flight phases, including takeoff, cruise, and landing. The primary objective of these tests was to investigate the influence of thermally induced stresses on local strain distribution and their contribution to fatigue failure.

Strain gauges were installed at specific locations on the specimen to monitor real-time strain evolution throughout the thermal cycles. These gauges were positioned as close as possible to the effusion cooling holes, without obstructing them. The normalized maximum strain values measured at locations 1, 2, and 3, along with the corresponding cycle counts from the afterburner thermal cycle fatigue tests, are presented in **Table 4.2**. The measurements reveal substantial thermal expansion and contraction during each cycle, leading to high alternating stresses that significantly contribute to accelerated fatigue damage.

Table 4.2: Measured Normalized Strain and Cycle Counts in Fatigue Tests

Location	Normalized Strain (ϵ)	Cycle Count
1	0.485	>750
2	1.515	>750
3	0.413	>750

The thermal fatigue test was conducted for a total of 750 cycles. The test specimen at various stages of the cycling process is shown in **Figures 4.2** through **4.5**.



Figure 4.2: Test Specimen After the 60th Cycle.



Figure 4.3: Test Specimen After the 320th Cycle.



Figure 4.4: Test Specimen After the 600th Cycle.



Figure 4.5: Test Specimen After the 750th Cycle – Final Condition.

No crack initiation was observed during the test, as confirmed by microstructural analysis. A microstructural examination of an effusion cooling hole in the test specimen is presented in **Figure 4.6**. These results suggest that the component's thermal fatigue life exceeds 750 cycles under the tested thermal strain conditions.

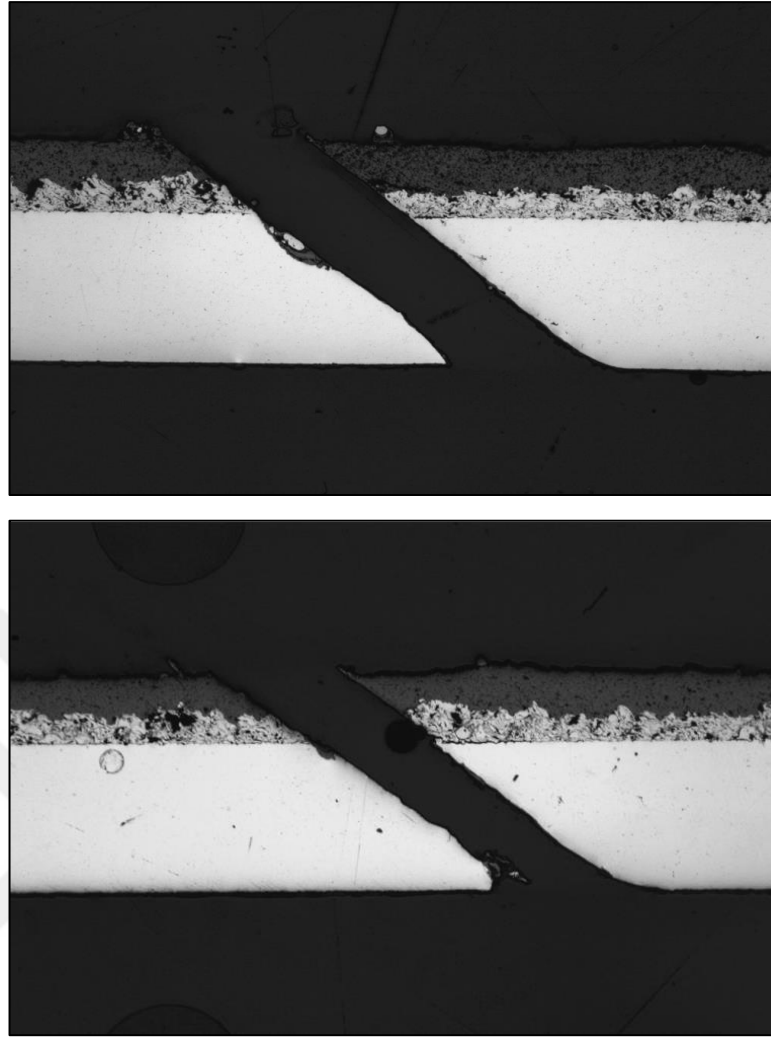


Figure 4.6: Microstructural Examination of the Test Specimen.

A detailed examination of strain evolution reveals the development of localized plasticity, which plays a critical role in governing the material's fatigue behavior. Areas subjected to higher strain amplitudes are more susceptible to early crack initiation, underscoring the need for further optimization in both material selection and component design.

Finite Element Analysis (FEA) was conducted to replicate the experimental conditions and predict fatigue life through advanced numerical simulations. The computational model was developed with the following key features:

- Temperature-dependent material properties
- Nonlinear plasticity behavior
- Refined mesh topology for enhanced spatial resolution in regions of high stress and strain gradients

Table 4.3 compares the strain predicted by FEA with that measured experimentally for the SN102 case.

Table 4.3: Comparison of Experimental and FEA-Predicted Strain

Specimen	Normalized Experimental Strain (ϵ)	Normalized FEA Strain (ϵ)
SN 102	0.125	0.875

The significant percentage error between the strain predicted by FEA and the experimental data indicates weak agreement between the two approaches. This discrepancy may be attributed to simplified boundary conditions, material anisotropy, or unaccounted-for surface imperfections in the simulation.

For test specimens **SN100** to **SN106**, the normalized strain values and the corresponding predicted fatigue life cycles, as calculated using the **Morrow** and **Smith-Watson-Topper (SWT)** mean stress correction methods—both of which modify the basic strain-life equation—are presented in **Table 4.4**. The predicted fatigue life values were subsequently compared with experimental low-cycle fatigue (LCF) results. Both models generally overestimated fatigue life relative to the experimental observations. However, the analysis indicated that the Morrow model significantly overpredicted fatigue life, whereas the SWT model, which accounts for the combined effects of maximum stress and alternating strain amplitude, demonstrated better agreement with the experimental data.

Further refinements in **mean stress correction methods** and **damage accumulation models** could improve the predictive accuracy of these empirical approaches.

Table 4.4: Strain–Life Predictions Based on the Morrow and Smith–Watson–Topper (SWT) Models

Specimen	Normalized Strain	Cycle (Morrow)	Cycle (SWT)
SN100	0.875	106122	68380
SN101	0.250	191361	114999
SN102	0.125	700507	146368
SN103	0.750	274305	75989
SN104	0.250	559489	125149
SN105	0.125	700507	146368
SN106	0.800	258501	72887

Figure 4.7 illustrates the Low Cycle Fatigue (LCF) life as a function of imposed strain amplitude, estimated using the Morrow and Smith-Watson-Topper (SWT) methods for Alloy 188 and Alloy 625 test specimens. The Alloy 188 specimens demonstrate longer fatigue lives compared to the Alloy 625 specimens for the same applied strain amplitude. The Morrow method consistently overestimates fatigue life, while the Smith-Watson-Topper (SWT) method yields predictions that are more consistent with the experimental observations.

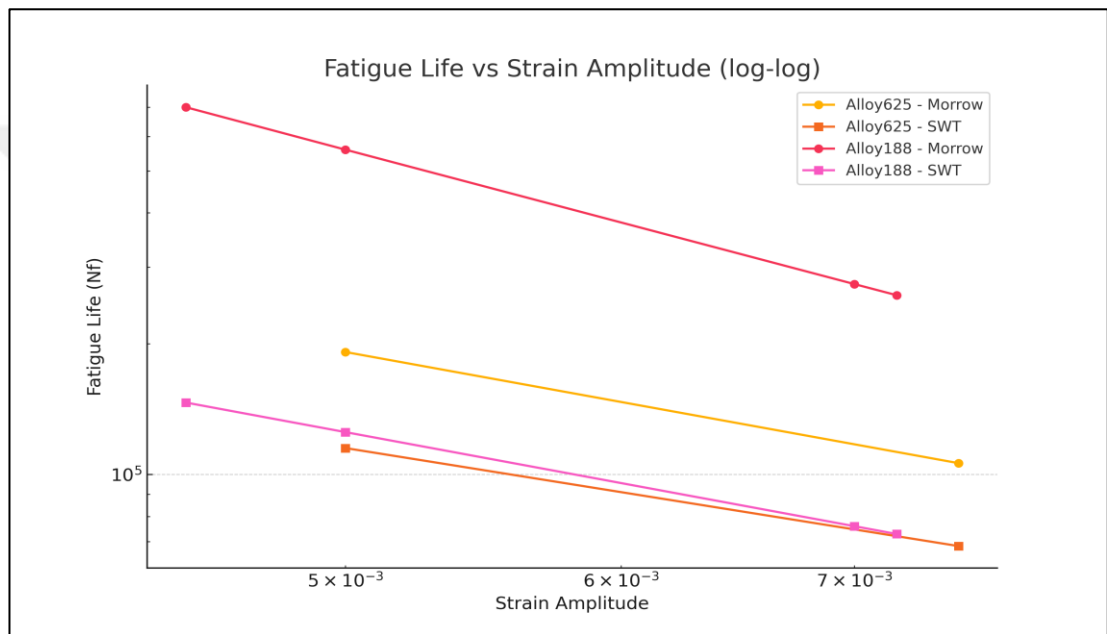


Figure 4.7: Fatigue Life as a Function of Strain Amplitude, as Predicted by the Morrow and Smith–Watson–Topper (SWT) Methods.

4.1. Conclusion

This study provides a comprehensive analysis of the low-cycle fatigue (LCF) behavior of afterburner liners by integrating experimental testing, finite element analysis (FEA), and empirical fatigue life prediction methods. The results offer valuable insights into the influence of thermal and mechanical cyclic loading conditions on fatigue damage accumulation, with particular emphasis on the effects of thermal hold time and effusion cooling holes on fatigue crack initiation.

Figure 4.8 illustrates the relationship between the total strain range and fatigue life cycles for effusion-cooling-hole-drilled specimens, encompassing both those

subjected to thermal hold time at elevated temperatures and those without, all tested under comparable strain levels within the low-cycle fatigue (LCF) regime. The graph clearly shows that specimens subjected to thermal hold time experience a marked reduction in fatigue life. Notably, when comparing specimens at equivalent strain levels, the presence of thermal hold time leads to an approximately 60% decrease in fatigue life.

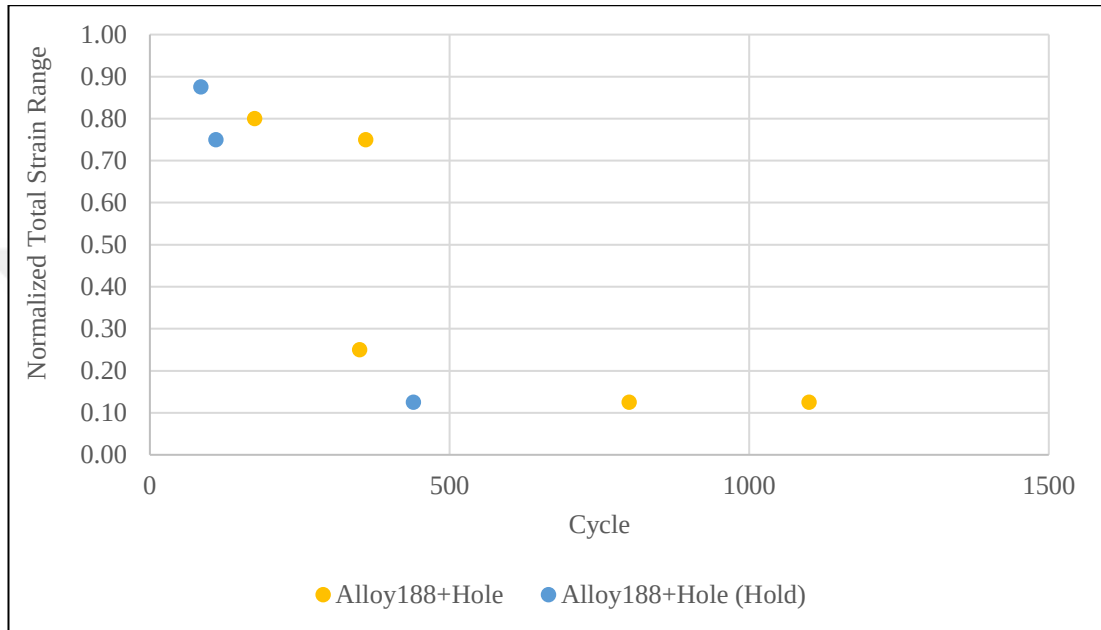


Figure 4.8: Effect of Thermal Hold Time on the Low-Cycle Fatigue Life of Alloy 188 Specimens Containing Effusion Cooling Holes.

Figure 4.9 presents the relationship between total strain range and fatigue life cycles for Alloy 188 specimens subjected to isothermal low-cycle fatigue (LCF) testing. A comparison between specimens with and without effusion cooling holes reveals that the former are positioned further to the left on the graph, indicating a reduction in fatigue life. This suggests that the inclusion of effusion cooling holes accelerates fatigue damage. Furthermore, the fatigue life of specimens with effusion cooling holes is further compromised when a thermal hold time at elevated temperatures is applied.

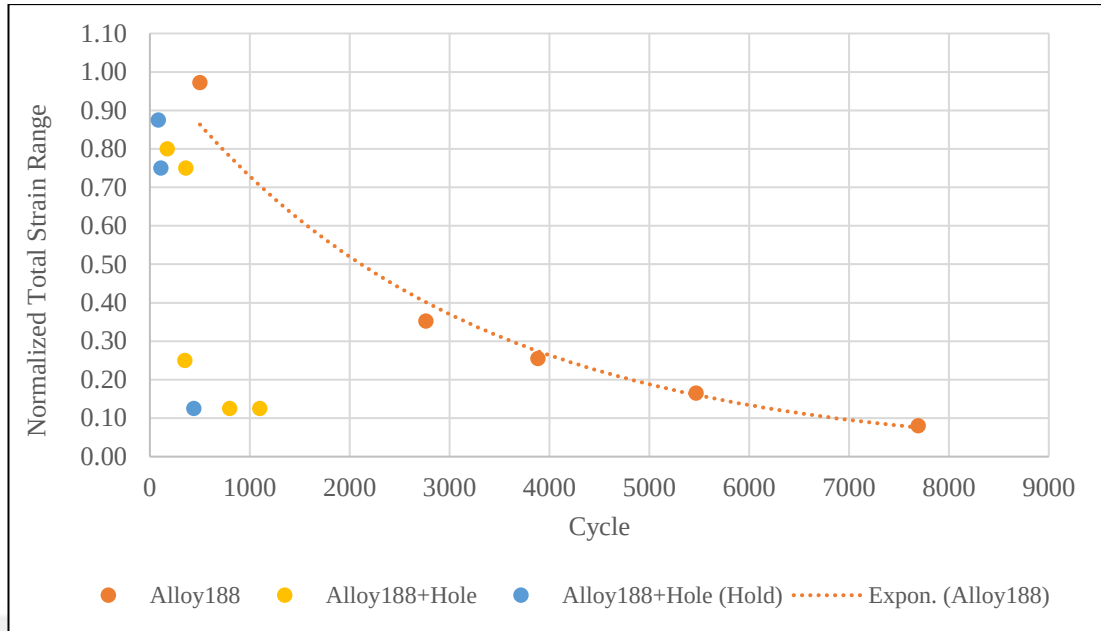


Figure 4.9: Influence of Effusion Cooling Holes and Thermal Hold Time on the Low-Cycle Fatigue Life of Test Specimens.

Hysteresis loop analysis revealed that the material exhibited cyclic softening, which substantially diminished its fatigue resistance. When combined with strain gauge measurements, the results confirmed that localized strain concentrations, induced by thermal cycling, played a pivotal role in fatigue failure. Thermal fatigue testing further indicated that the regions most susceptible to damage were those exposed to high thermal gradients, particularly near effusion cooling holes and geometric discontinuities, where stress localization resulted in early crack initiation. These findings underscore the significant impact of thermal expansion and contraction cycles on fatigue degradation in afterburner liners, emphasizing the critical importance of enhanced thermal management in their design.

The comparison between finite element analysis (FEA) results and experimental strain measurements revealed moderate agreement, though some discrepancies were observed. While the numerical simulations successfully captured the overall stress-strain distribution, the differences between computational and experimental data suggest that improvements in boundary conditions, material modeling, and plasticity behavior are required to enhance predictive accuracy. Furthermore, the empirical Morrow and Smith-Watson-Topper (SWT) models were used to estimate fatigue life based on strain-life relationships. Both models tended to overestimate fatigue life in comparison to the experimental results, highlighting the limitations of traditional

empirical approaches in accounting for the complex interactions of thermo-mechanical fatigue.

The study further investigated the influence of hold (dwell) time at elevated temperatures during thermal cycles, identifying it as a significant factor contributing to the acceleration of fatigue damage. Experimental results demonstrated that prolonged hold times at elevated temperatures substantially reduced fatigue life, highlighting the critical role of high-temperature creep-fatigue interactions in material degradation. These findings indicate that future fatigue life prediction methodologies for afterburner liners should incorporate the effects of high-temperature creep-fatigue interactions into low-cycle fatigue (LCF) life analyses.

Another key focus of the study was the impact of effusion cooling holes on fatigue life. Although these holes are intended to enhance thermal management, they were found to serve as stress concentrators, thereby accelerating the initiation of fatigue cracks. Specimens containing effusion cooling holes exhibited an approximate 70% reduction in fatigue life compared to solid specimens, underscoring the need to optimize hole geometry, spacing, and orientation to achieve an effective balance between cooling efficiency and structural durability.

In summary, this research demonstrates that a comprehensive approach—integrating computational modeling, empirical fatigue prediction, and experimental validation—is essential for accurately assessing the fatigue behavior of afterburner liners. While offering valuable insights into the underlying mechanisms of fatigue failure, the study also highlights opportunities for improvement in modeling accuracy, material selection, and design optimization to enhance component reliability. The findings support the development of an integrated fatigue analysis framework that accounts for high-temperature creep effects, oxidation phenomena, and multi-axial stress states—factors critical to the design of next-generation, fatigue-resistant afterburner liners for high-performance aerospace propulsion systems.

4.2. Recommendations for Future Research

While this study has provided a comprehensive understanding of low-cycle fatigue (LCF) behavior in afterburner liners, several critical areas warrant further investigation to refine fatigue life prediction methodologies, optimize component design, and explore alternative material solutions. Discrepancies observed between finite element

analysis (FEA) predictions and experimental results, coupled with the limitations inherent in empirical fatigue life models, indicate that future research should prioritize enhancing computational accuracy, broadening experimental validation, and leveraging advanced material technologies to improve fatigue performance.

A primary avenue for future work lies in the refinement of computational modeling techniques. Although the FEA simulations conducted herein effectively captured the overall stress–strain response, further advancements are required to incorporate multiaxial fatigue modeling, which is essential for accurately simulating the synergistic effects of thermal and mechanical stresses in afterburner liners. The development and integration of more sophisticated high-temperature creep–fatigue interaction models will also be indispensable, as experimental evidence demonstrated that sustained exposure to elevated temperatures accelerates material degradation. Moreover, incorporating oxidation and environmental degradation phenomena into computational frameworks will facilitate more realistic fatigue life predictions under actual operational conditions.

Beyond computational enhancements, additional experimental investigations are necessary to deepen understanding of fatigue damage mechanisms at the microstructural scale. Advanced characterization methods, such as scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD), should be employed to elucidate crack initiation and propagation pathways in fatigued specimens. Furthermore, fracture mechanics-based fatigue crack growth studies are recommended to quantify crack propagation rates under varying loading and temperature regimes, thereby providing critical data for life extension strategies. The development of an in-situ high-temperature fatigue testing apparatus, equipped with digital image correlation (DIC) for strain mapping, would enable real-time monitoring of strain evolution, facilitating more accurate fatigue life assessments under service-like conditions.

Another significant research direction involves the optimization of afterburner liner design. Given that effusion cooling holes have been identified as primary sites for stress concentration and fatigue crack initiation, systematic refinement of their geometry, spacing, and orientation is essential to enhance both cooling effectiveness and structural integrity. Employing topology optimization techniques can yield optimal material distributions, resulting in lighter yet more fatigue-resistant

components. Additionally, the use of functionally graded materials (FGMs), characterized by gradual variations in material properties through the liner thickness, presents a promising strategy to mitigate thermal stress concentrations and prolong component life.

Advances in data science and artificial intelligence offer further opportunities to improve fatigue life prediction through machine learning-based models that integrate experimental data with computational fatigue simulations. Training artificial neural networks (ANNs) on comprehensive datasets—including material properties, fatigue test results, and FEA outputs—can generate highly accurate and adaptive predictive tools. Probabilistic approaches, such as Bayesian inference, can be employed to quantify uncertainties in fatigue predictions, thereby enhancing the reliability of damage tolerance assessments in aerospace applications.

Finally, the exploration of alternative material solutions remains a promising path toward improving afterburner liner durability. The development of advanced superalloys with enhanced high-temperature creep and oxidation resistance could substantially extend service life under extreme operating conditions. Additionally, ceramic matrix composites (CMCs) and thermal barrier coatings (TBCs) warrant investigation as potential technologies for increasing oxidation resistance and mitigating thermal fatigue damage. Integrating these advanced materials into aerospace components could lead to significant improvements in performance and longevity.

In conclusion, future research should adopt a holistic approach that integrates experimental techniques, computational modeling, and data-driven methodologies to develop the next-generation, fatigue-resistant afterburner liners. By combining optimized material selection, advanced fatigue modeling, and AI-based predictive analytics, it will be possible to enhance afterburner durability, cooling efficiency, and operational safety—ultimately extending service life and improving the overall performance of aerospace propulsion systems.

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BIOGRAPHY

Baran Cin earned his degree in Aeronautical Engineering from the Department of Aeronautics and Astronautics at the University of the Turkish Aeronautical Association in February 2021. He is currently employed in the aviation industry as a Mechanical Design Engineer, specializing in gas turbine engines, and has four years of professional experience in this field.



PUBLICATIONS AND PRESENTATIONS FROM THESIS

Poster presentation titled “*Low Cycle Fatigue of Afterburner Liners*”, presented within the scope of the Applied Propulsion System Design & Engineering for Aerospace Technologies Master of Science program in the Department of Energy Technologies, at the 9th Graduate Research Symposium organized by the Graduate School of Gebze Technical University, held on May 26–27, 2025.



APPENDICES

APPENDIX-A: STRAIN-LIFE COMPUTATION PYTHON CODE

```
import numpy as np
import pandas as pd
from scipy.optimize import fsolve
import matplotlib.pyplot as plt

def solve_fatigue_life(strain_amplitudes, sigma_f_prime, epsilon_f_prime, b, c, E,
sigma_m, sigma_max):
    results = []
    for epsilon_a in strain_amplitudes:
        def morrow_eq(logN):
            Nf = 10**logN
            return ((sigma_f_prime - sigma_m) / E) * (2 * Nf)**b + epsilon_f_prime * (2
* Nf)**c - epsilon_a

        def swt_eq(logN):
            Nf = 10**logN
            return (sigma_f_prime**2 / E) * (2 * Nf)**(2 * b) + sigma_f_prime *
epsilon_f_prime * (2 * Nf)**(b + c) - (sigma_max * epsilon_a)

        logN_morrow = fsolve(morrow_eq, 3)[0]
        logN_swt = fsolve(swt_eq, 3)[0]
        Nf_morrow = 10**logN_morrow
        Nf_swt = 10**logN_swt
        results.append([epsilon_a, Nf_morrow, Nf_swt])
    return results

def get_user_inputs():
    print("Enter the following material fatigue parameters:\n")
```

```

sigma_f_prime = float(input("Fatigue Strength Coefficient ( $\sigma_f$ ): "))
epsilon_f_prime = float(input("Fatigue Ductility Coefficient ( $\epsilon_f$ ): "))
b = float(input("Fatigue Strength Exponent (b): "))
c = float(input("Fatigue Ductility Exponent (c): "))
E = float(input("Young's Modulus (E): "))
sigma_m = float(input("Mean Stress ( $\sigma_m$ ): "))
sigma_max = float(input("Maximum Stress ( $\sigma_{max}$ ): "))

strain_input = input("Enter strain amplitudes separated by commas (e.g. 0.0045, 0.005): ")
strain_amplitudes = [float(val.strip()) for val in strain_input.split(",")]

return sigma_f_prime, epsilon_f_prime, b, c, E, sigma_m, sigma_max, strain_amplitudes

def run_fatigue_analysis_user():
    sigma_f_prime, epsilon_f_prime, b, c, E, sigma_m, sigma_max, strain_amplitudes = get_user_inputs()
    results = solve_fatigue_life(strain_amplitudes, sigma_f_prime, epsilon_f_prime, b, c, E, sigma_m, sigma_max)

    df = pd.DataFrame(results, columns=["Strain Amplitude", "Morrow Nf", "SWT Nf"])
    print("\nFatigue Life Results:")
    print(df)

# Plotting
plt.figure(figsize=(10, 6))
plt.plot(df["Strain Amplitude"], df["Morrow Nf"], marker='o', label="Morrow")
plt.plot(df["Strain Amplitude"], df["SWT Nf"], marker='s', label="SWT")
plt.xscale("log")
plt.yscale("log")
plt.xlabel("Strain Amplitude")
plt.ylabel("Fatigue Life (Nf)")

```

```

plt.title("Fatigue Life vs Strain Amplitude")
plt.grid(True)
plt.legend()
plt.tight_layout()
plt.savefig("User_Fatigue_Life_Plot.png", dpi=300)
plt.show()

# Export to Excel
with pd.ExcelWriter("User_Fatigue_Life_Results.xlsx", engine='xlsxwriter') as
writer:
    df.to_excel(writer, sheet_name="Fatigue Life Results", index=False)
    workbook = writer.book
    worksheet = writer.sheets["Fatigue Life Results"]
    worksheet.insert_image("F7", "User_Fatigue_Life_Plot.png")

print("\n✔ Results and plot saved to 'User_Fatigue_Life_Results.xlsx'")

if __name__ == "__main__":
    run_fatigue_analysis_user()

```