

T.R.

**GEBZE TECHNICAL UNIVERSITY
ENERGY TECHNOLOGIES INSTITUTE**

**HOLD TIME EFFECT on CRACK PROPAGATION LIFE of
INCONEL 718 TURBINE DISC**

TUĞBA KÖSTERİT

**A THESIS SUBMITTED FOR THE DEGREE OF MASTER OF
SCIENCE**

**DEPARTMENT OF APPLIED PROPULSION SYSTEM
DESIGN& ENGINEERING FOR AEROSPACE TECHNOLOGIES**

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THESIS SUPERVISOR
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GEBZE

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SUMMARY

Disc is one of the most life critical component in gas turbine engines. It carries high energy and it cannot be contained if it bursts. One of the most important factors that will create catastrophic failure is the crack propagation on the disc. It can cause disc burst. The aim of this study is to show the hold time parameter effect on crack growth. It is thought to have a significant effect on the crack propagation rate. This study has been investigated in order to make precise crack propagation analysis for disc part, which is a critical part in gas turbine engines. First of all, the hold time test results for Inco718 material, which is widely used as a disc material, were examined in detail. Afterwards, an analysis model representing real engine operating conditions was established for a disc geometry with axial symmetry. Temperature and stress data which are obtained from these analysis results, the crack propagation life of the disc has been calculated with an in-house crack calculation tool. Examined test results and analysis studies showed that high temperature and longer hold time values have an important role in crack growth rate.

Key Words: Crack Propagation, Hold Time Effect, Inconel 718

ÖZET

Disk, gaz türbinli motorlardaki en kritik bileşenlerden biridir. Yüksek enerji taşır ve infilak halinde kontrol altına alınamaz. Katastrofik hata yaratacak en önemli faktörlerden biri disk üzerindeki çatlak ilerlemesidir. Disk infilakına neden olabilir. Bu çalışmanın amacı, yüksek sıcaklıkta ve sabit yük altında bekleme süresi parametresinin çatlak ilerlemesi üzerindeki etkisini göstermektir. Çatlak yayılma hızı üzerinde önemli bir etkiye sahip olduğu düşünülmektedir. Bu çalışma, gaz türbinli motorlarda kritik bir parça olan disk parçası için hassas çatlak ilerleme analizi yapmak amacıyla gerçekleştirilmiştir. Öncelikle disk malzemesi seçenekleri içinden yaygın olarak kullanılan Inco718 malzemesinin yüksek sıcaklıkta ve sabit yük altında bekleme süresi test sonuçları detaylı olarak incelenmiştir. Daha sonra eksenel simetriye sahip bir disk geometrisi için gerçek bir gaz türbinli motor çalışma koşullarını temsil eden bir analiz modeli oluşturulmuştur. Bu analiz sonuçlarından elde edilen sıcaklık ve gerilme verileri kullanılarak diskin çatlak ilerleme ömrü şirket içi bir çatlak hesaplama aracı ile hesaplanmıştır. İncelenen test sonuçları ve analiz çalışmaları, çatlak büyüme hızında yüksek sıcaklık ve daha uzun bekleme süresi değerlerinin önemli bir role sahip olduğunu göstermiştir.

Anahtar Kelimeler: Çatlak ilerlemesi, Bekleme Süresi Etkisi, Inconel 718

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SYMBOLS AND ABBREVIATIONS

<u>Abbreviations and Acronyms</u>	<u>Explanations</u>
Σ	: Summation
σ	: Normal Stress
F	: Normal Force
A	: Area
$\sigma_x, \sigma_y, \sigma_z$	: Normal Stresses on planes x, y, z
L, l	: Length
ϵ, e	: Strain
ϵ_t	: True Strain
ϵ_e, ϵ_n	: Engineering, Nominal Strain E Young's Modulus
$\sigma_1, \sigma_2, \sigma_3$	: Principal Stresses
σ_m	: Mean Stress
σ_a	: Alternating Stress
$\sigma_{min}, \sigma_{max}$	: Min, Max Stress
$\Delta\sigma$	: Stress Range
R	: Stress Ratio
N	: Number of Cycles
a	: Crack Length
ΔK	: Stress Intensity Factor Range
C, m	: Paris' Law Parameters
Y	: Parameter of The Geometry
a0, ac	: Initial, Critical Crack Lengths

Abbreviations

S-N	: Nominal Stress - Number of Cycles
Ansys	: Ansys Classic FE Software
RPM	: Revolutions per Minute
UG	: Unigraphics Cad Software

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1. INTRODUCTION

1.1. Gas Turbine Engines

Gas turbine engine is a type of internal combustion engine. It is used in aircrafts to thrust and power. It usually consists of an inlet compressor, combustion chamber and turbine components [1].

A gas turbine is defined as a power plant that produces power and energy according to its capacity. Over the years, its use in the energy sector has become more widespread and has an important place in the industry. Gas turbines are especially prominent in use in the aviation sector. They are used to provide the necessary power by providing the design criteria and requirements for the engines used in aviation.

With the development of the aviation and energy sector over the years, different types of gas turbine engines were designed in the last century. In order to increase the power of aircrafts, especially in aviation, many engine types such as turboprop, turbofan, turbojet and turboshaft were developed in accordance with gas turbines information and technologies. These developments have led to strong competition in the aircraft technologies market. This contributes to the development of more powerful but less costly engines.

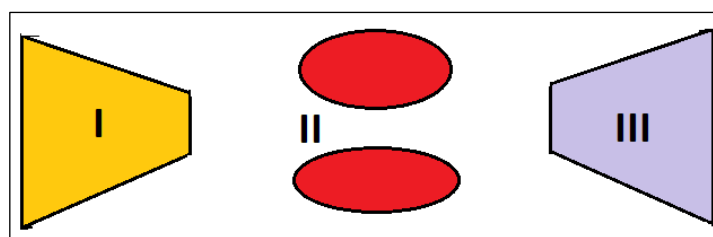


Figure 1.1: Gas turbine engine main components

Gas turbine consists of three main modules. These are as follows

- I) Compressor Module: Compressor takes in air and compresses it
- II) Combustion Chamber: Combustion chamber takes high pressure air and allows it to burn with fuel
- III) Turbine Module: The turbine is driven by exhaust gases and drives the compressor

1.2. Gas Turbine Engine Types

There are many different types of gas turbine engines in aviation.

Turbojet Engine: Turbojet engine has the simplest structure among gas turbine engines. The compressor module takes and compresses the air and air reaches high pressure. This high-pressure air comes to the combustion chamber and the combustion chamber mixes this high-pressure air with the fuel, allowing it to burn. These high energy burning gases reach the turbine and it makes the turbine rotate by hitting the turbine blades. The energy obtained from this rotating turbine is used in the rotation of the compressor. These hot gases passing through the turbine provide the thrust to the engine. They are preferred in airplanes and rockets. They are not be used in commercial airplanes due to their high fuel consumption. There is an image of the turbojet engine and the engine structure is shown in below.

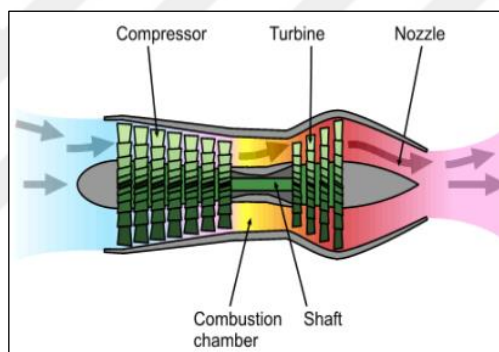


Figure 1.2: Turbojet engine

Turboprop Engine: Turboprop engine drives turbine and is defined as a propeller that creates thrust. This is because exhaust gases are used to rotate the propeller. They have less thrust than a turbojet engine. Exhaust gases provide about 5% of the thrust while most of it from torque conversion, it is obtained by connecting the propeller to the gearbox and converting it from high speed but low torque value to low speed but high torque value. They are not efficient at very high speeds; they are preferred in slow speed aircraft and these are generally cargo aircrafts. There is an image of the turboprop engine structure is shown in below.

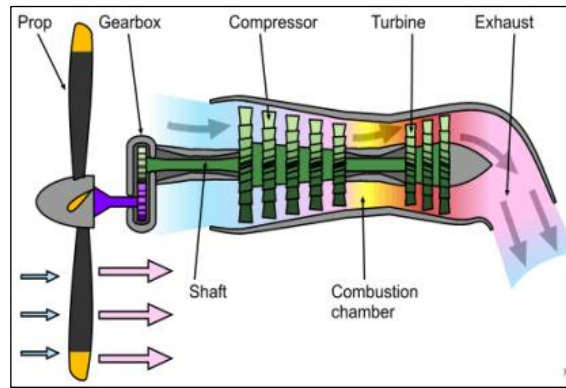


Figure 1.3: Turboprop engine

Turbofan engine is the most used engine type in civil aviation. In the engine where the turbojet engine is used as the core, the engine is converted into a turbofan engine by adding a fan to the front part of the engine. The fan sucks the bypass air, which is unburned air, using the path outside the core engine. Turbofan engine has an extra module called low pressure turbine. This module is located in the engine to drive the fan. Turbofan engines are efficient engines at low speeds and their fuel consumption is not very high. There is an image of the turbofan engine and the engine structure is shown in below.

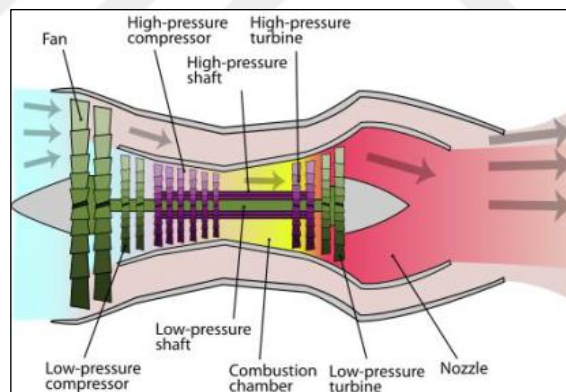


Figure 1.4: Turbofan engine

Turboshaft engine has propeller and it is similar with turboprop engines. It is a type of motor that is not used at high speed but is efficient. They are preferred in places where high speed is not needed. Generally, these platforms are helicopters [9].

There is an image of the turboshaft engine structure is shown in below.

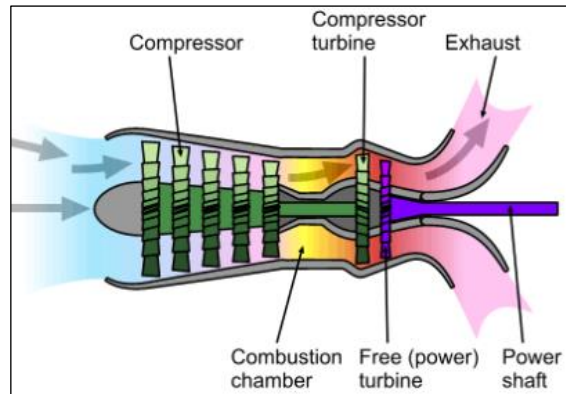


Figure 1.5: Turboshaft engine

1.3. Gas Turbine Engine Working Principal

Gas turbine engine main working principal is according to Brayton cycle. In the Brayton cycle principle, air is used as the working fluid. The air is compressed by the compressor. Fuel is sprayed into the air inside and energy is released by the combustion effect. The high-pressure gas that has this energy goes to the turbine; unused energy, if a turbojet engine produces thrust directly or is known as a power turbine, which is an independent turbine that can be connected to a fan, propeller [1].

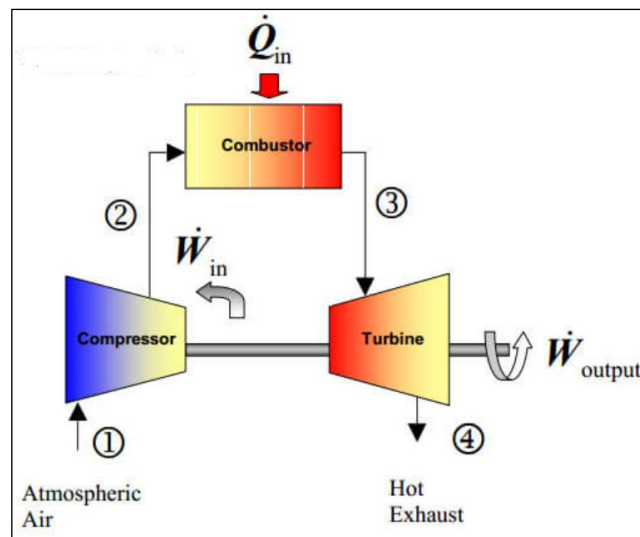


Figure 1.6: Basic Brayton cycle

1.4. Turbine Discs

Gas turbines have major components and modules. One of them is turbine module. Turbine has significant component which are discs and blades. Disc is one of the most life critical components in engine. It has some important roles in engine turbine module. They locate the blades in gas path and rotate them at a specific and high angular velocity. They act as a component in torque path and they are exposed to high stress and high temperature. It carries high energy and it cannot be contained if it bursts. This energy comes from cyclic loads, thermal loads and centrifugal loads due to the aircraft engine working system [2].

The disc as a critical part has burst risk and this can cause catastrophic failure in the engine because it cannot be contained. Therefore, the discs are designed to meet certain criteria when designing. The most important of these are burst margin, overspeed capability, low cycle fatigue life limit and crack propagation life criteria [3].

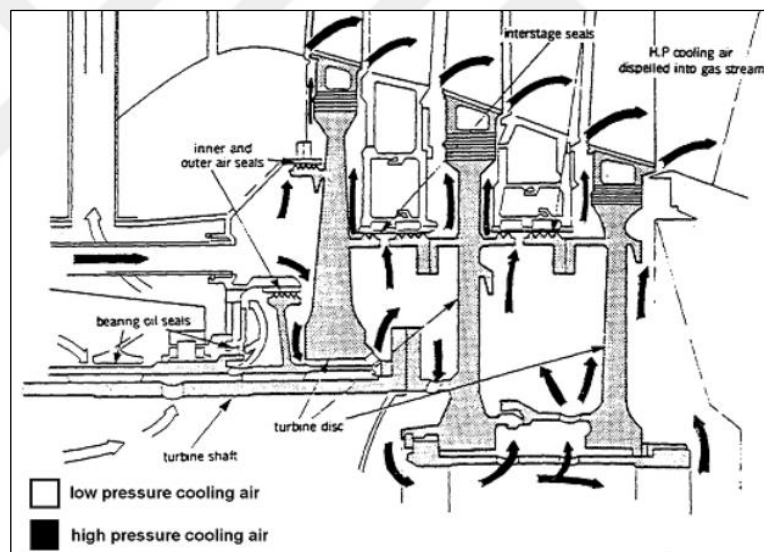


Figure 1.7: Disc geometries on gas turbine engine cross section [4]

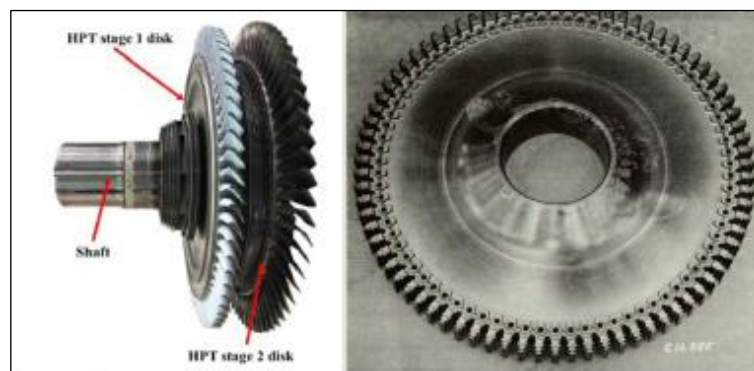


Figure 1.8: High pressure turbine disc geometry examples

The engine manufacturer shall show the authority that it maintains the integrity of the rotor and that discs burst will not occur in a possible danger. One of the most important factors that will create this crucial risk is the initiation of crack on the disc and the propagation of the crack. Crack propagation analyses, calculations, data used and test outputs are important in terms of ensuring flight safety. In the certification processes after the design and production phase, it is necessary to show that the crack propagation analysis and calculations have been verified to show that the discs will not burst because of crack. The sensitivity of the calculations significantly affects the number of engine tests and the cost for the engine validation and certification phase [10].



Figure 1.9: Airbus Qantas A380-842-disc burst [10]

1.5. Material Selection

The turbine discs are exposed to very severe conditions and for this reason nickel-based super alloy materials are chosen during the design as it is desired to be durable. Nickel based super alloys are developed for specific usage such as rotor disc components. These materials provide disc parts durable and high-performance properties. Turbine disc parts have harsh environments and high temperature conditions, these causes high stress levels. Hence, disc materials evolved high performance nickel-based alloys.

Turbine disc shall meet main design criteria such as burst, creep, fatigue crack growth and life limits. Nickel based super alloys were developed in order to provide high material performance for these design criteria. Alloy contents were increased to

improve material properties. Manufacturing processes has been changed according to material complexity. This caused production difficulties; therefore, various manufacturing methods were developed. For example, with the increase in the alloy content, the ingot metallurgy method, which is the first preferred processing method, has been changed to the powder metallurgy method. The difficulties of these methods still remain and material engineers continue to work on it.

Gas turbine engine design changes and the aerospace industry will require materials and processes that can be used in cost effective methods for machining this nickel based super alloys [5]. Several nickel-based alloy materials are used in the production of gas turbine engine discs. There are some nickel-based materials known as turbine disc material that can withstand the harsh conditions that the disc is exposed to. Inconel 718 material is one of the materials used in these main materials.

Inconel 718 is an important alloy in the manufacture of gas turbine engine discs because it has defect tolerance property, high temperature condition resistance and it is good and high strength material. Inconel 718 material is generally produced in cast and forged alloy form and used as a turbine disc material in aviation [16].

1.6. Mechanical Property

In order to understand the basic formulations, basic mechanical terms are explained in terms of material. The response of the material to the forces it is exposed to shows the mechanical properties of the material. These materials response to the forces may be deformations along with the fails. Material mechanical factors cause deformation or fail in the material, when necessary, conditions are met. For this reason, all factors affecting the material behaviour should be considered to prevent the failure.

Strength is a property that indicates the mechanical strength capacity of the material under load. However, the boundary features are not clearly defined. Strength property can be defined in percent of stress as the required limit for cracking, yield overshoot, or the limit at which the material loses its function.

In the strength test, a force is applied to the sample used for the test and the sample tries to stretch by breaking the bonds inside the material with the effect of this force. An internal reaction occurs against this tendency to fracture in the sample, called

stress. The applied force is distributed as normal stress on the normal surface and this stress is called resistance per unit area.

$$\sum F = 0 \quad (1.1)$$

$$F - \sigma A = 0 \quad (1.2)$$

$$\sigma = \frac{F}{A} \quad (1.3)$$

The normal stress happens when applied force on the perpendicular direction of the area and the force producing the shear stress is parallel to the surface area. To define stress, it is necessary to know two basic elements and they are the direction of the force and the direction normal to the force. Normal stresses are used in the definition of shear stress. There are tensor stresses for normal stress, notation as follows.

$$\sigma_{ij} = \begin{bmatrix} \sigma_{xx} & \sigma_{yx} & \sigma_{zx} \\ \sigma_{xy} & \sigma_{yy} & \sigma_{zy} \\ \sigma_{xz} & \sigma_{yz} & \sigma_{zz} \end{bmatrix} \quad (1.4)$$

While performing the tensile test on the material specimen, when F force is applied to the sample, the length of the sample becomes longer. If the increase in force is dF and the sample length is L, then the amount of increase in the sample size is dL. Normalized increase for L is expressed as follows.

$$d\varepsilon = \frac{dl}{l} \quad (1.5)$$

Integration of this expression from initial value L_0 to current value L, true strain is obtained as follows.

$$\varepsilon = \int \frac{dL}{L} = \ln\left(\frac{L}{L_0}\right) \quad (1.6)$$

The engineering strain expression included in the engineering calculations is as follows.

$$\varepsilon_n = \varepsilon_e = \frac{\Delta l}{l_0} = \frac{l_1}{l_0} - 1 \quad (1.7)$$

$$e = \frac{\Delta l}{l_0} \quad (1.8)$$

For small strains in metals during the elastic deformation, there is not much difference between the engineering strain and true strain. However, in terms of plastic deformation, there is a non-negligible difference between the engineering strain and true strain. In elastic deformations relation between true strain and engineering strain is given.

$$\epsilon_t = \ln(1 + \epsilon_e) \quad (1.9)$$

Robert Hooke conducted several studies in 1678 to investigate the relation between strain and stress. Along with these, it is assumed that there is a relation between stress and strain for metals in the elastic region. The region where this relationship is valid is called Hookean Solid. Then, it is called as a Hooke's Law. The simplest form of this law is expressed.

$$E = \frac{\sigma}{\epsilon} \quad (1.10)$$

E is Young Modulus. It comes from first principal and changes according to ingredients of the material, structure of the material and element bonding behaviour. Heat and mechanical treatments can affect it limited.

The stress in which shear stress disappear while normal stress occurs is called principal stress. There are three axes on three-dimensional body forms and normal stresses occur on these three main axes. These stresses are $\sigma_1, \sigma_2, \sigma_3$ stresses. These are can be expressed where I_1, I_2, I_3 are defined as follows.

$$\sigma_p^3 - I_1 \sigma_p^2 - I_2 \sigma_p - I_3 = 0 \quad (1.11)$$

$$I_1 = \sigma_{xx} + \sigma_{yy} + \sigma_{zz} \quad (1.12)$$

$$I_2 = \sigma_{yz}^2 + \sigma_{zx}^2 + \sigma_{xy}^2 - \sigma_{yy} \sigma_{zz} - \sigma_{zz} \sigma_{xx} - (\sigma_{xx} \sigma_{yy})^2 \quad (1.13)$$

$$I_3 = \sigma_{xx} \sigma_{yy} \sigma_{zz} + 2\sigma_{yz} \sigma_{zx} \sigma_{xy} - \sigma_{xx} \sigma_{yz}^2 - \sigma_{yy} \sigma_{zx}^2 - \sigma_{zz} \sigma_{xy}^2 \quad (1.14)$$

Another basic stress used in strength comparison is von Misses stress. This stress is calculated using the principal stresses in all directions. In the design controls, the yield stress of the material is compared by checking this von Misses stress.

Designed part Von Misses stress value should be lower than the yield stress of the part material. Basic Von Misses stress formula is shown considering principal stresses [11].

$$\sigma_v = \left[\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2} \right]^{1/2} \quad (1.15)$$



2. FRACTURE MECHANICS

2.1. History and Definition of Fracture Mechanics

Fracture is a problem that human beings will face as long as there is human made product. These problems can actually cause more dangerous consequences today than in previous centuries, because technology is getting more and more complex and this can only make us worse. For example, major plane crashes would not have been possible without modern aviation.

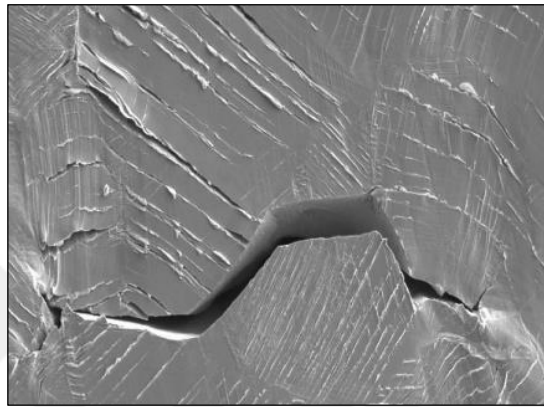


Figure 2.1: Structural fracture example

Over time, developments in the field of fracture mechanics have contributed to solving some problems for the dangers and complexity of technology. In this process, in the fracture area understanding of the deterioration process of materials and their ability to prevent such failures have increased significantly. With the Second World War, there were further developments in this field and the studies still continue today.

These catastrophic failures contributed to the developments in the field of fracture mechanics and significantly improved the engineering. Unfortunately, these events can result in loss of life and great economic damage for countries.

Most structural failures have common causes. At the beginning of these, there are issues such as improper design, ignoring certain requirements during the design, unsuitable material selection, inability to make production methods with the necessary sensitivity, and lack of appropriate technology. In addition to all these, the possibility of human error is inevitable in works that touch human hands. Poor manufacturing, analysis and engineering errors can also cause major failures [8].

Fracture is the breaking of a part into two or more parts under the influence of various forces. It can be defined as separation as well. Fracture Mechanics, describes the fracture and it is a science that deals with macro and micro aspects using its basic principles in the examination of structures, fracture, material life and it is very important for gas turbine parts security. Hence, fracture mechanics is an important and main branch which controls the integrity of a structure for crack and damage tolerance.

During World War II the Liberty Ship the damage caused by the rupture was shown in figure 2.2.a, and in figure 2.1.b, damage as a result of breaking during a flight (1988). Today, fracture can be seen in different structures under mechanical, thermal and displacement loads. The fact that many similar damages occur as a result of this clearly shows the importance of fracture mechanics. Therefore, fracture mechanics is one of the most important research topic which has an important place in aviation[7].



(a)

(b)

Figure 2.2: Examples of fracture (a) Liberty Ships World War II, 1941-1945

(b) Aloha airlines flight 243 April 28, 1988

2.2. Fracture Mechanics

In the production processes of structural parts, there can be initiation of crack and damage in the parts. Such crack and damage are considered to already exist in the part before the part is loaded. Hence, when the part exposed to the load these crack or damage which is in the part will propagate with the effect of the load. This situation is of great importance for the life of the part because crack propagation may cause to a catastrophic failure. In order to prevent this, crack propagation life calculations are made with the fracture mechanics method.

Fracture mechanics examines how much the crack propagation rate in the material will be, what kind of tendency the material behaviour will be. A crack propagation in the material may be stable at a non-high rate, but may also grow unsteadily with suddenly. In this direction, materials are divided into ductile material and brittle material. While fracture is slow and controlled in ductile materials, fracture is more sudden and uncontrolled in brittle materials.

In the basic strength approach, an evaluation and part design are made by comparing the yield strength of the material with the stress value resulting from the application of load on the part. There are basically three main variables to be examined in the case of proceeding by considering the fracture situation during the design. These are the fracture toughness of the material, the stress value to which the material is exposed, and the size of the crack in the material. Numerical calculations are made by using these variables in crack propagation calculations. In some cases, they are also used to find the unknown variables if one is not known, besides its known values. There is a triangle formed by these three basic variables in fracture mechanics, this is called the fracture mechanics triangle [8].

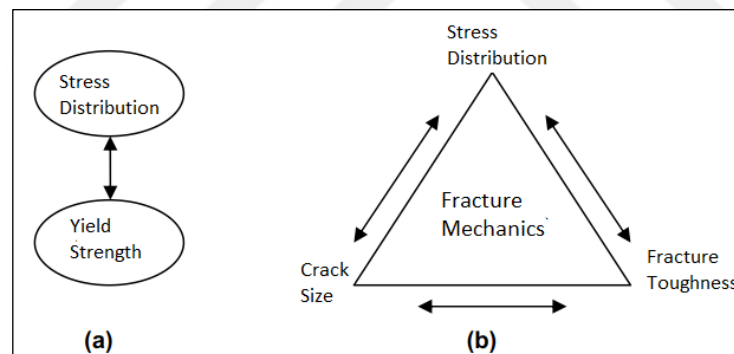


Figure 2.3: a) Basic strength approach b) Fracture mechanics triangle

2.2.1. Fracture Control Mechanism

Crack and defect which are in material reduce part strength and part life because of the crack growth. The strength of the part decreases during crack propagation and it exceeds the service load of the material. This situation results in fracture of the structure. Fracture is prevented by keeping part on the safe side which is provided by controlling structure strength considering the material strength.

Cracks which are on the structure should be controlled by calculating crack propagation life value in order to prevent fracture. It should be kept under control

before fail, that's why crack propagation life is calculated. It should be known that what will be critical failure crack size. Therefore, the relation between crack sizes and material strength should be calculated. According to this, the crack propagation life in the part should be calculated.

To make all these calculations, first of all critical locations of the structure should be determined. Then, crack propagation analysis is made for life calculation. This is called damage tolerance analysis. Damage tolerance analysis has three main steps, these are data evaluation, analysis and requirement check.

The main aim in damage tolerance assessment that the structure should continue its operation safely with cracks and dents. Crack or notch cleaning process is repairing part or if it has uncontrollable crack, changing part. If the structure crack propagation life still not met requirement, part design or material can be made higher resistance. Periodic inspection is possible for critical locations to prevent failure. Inspection intervals can be determined according to calculated crack propagation life and cost. In short, an audit of damage tolerance, design damage is allowed if it can be kept under control with the program.

The mathematical tool in damage tolerance assessment is fracture mechanism. It examines crack initiation, crack propagation and the effect of material strength of crack.

2.2.2. Ductile Fracture and Brittle Fracture

When examined microscopically, the breaking of particles and the breaking of bonds between atoms cause the cohesion force between atoms to disappear.

In ductile fracture, there are particles in the structure of metal materials. Often these particles become components of elements from the alloy in the metal. While the purpose of adding some elements in alloy metals is to increase the strength of the part, in some cases it is to facilitate the manufacture. In the fracture phase, the particles begin to break in the region where the first large particles are located, and a gap begins to form at the crack tip. Fracture occurs when the cavities formed by small particles merge. In ductile fracture, the fracture surface appears opaque grey due to discontinuities because the surface absorbs light.

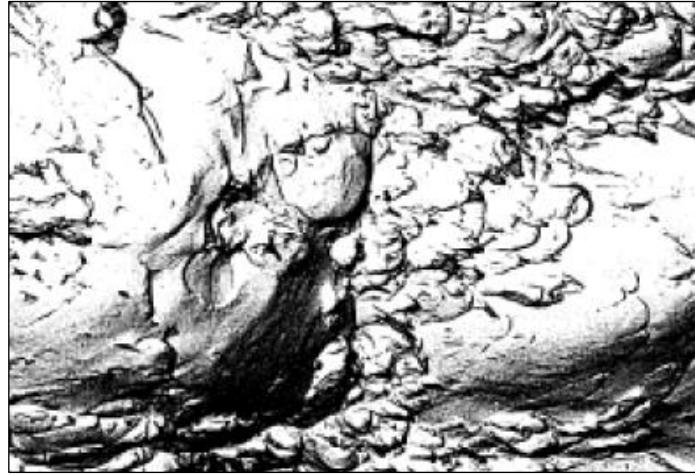


Figure 2.4: Ductile fracture surface of aluminium alloy

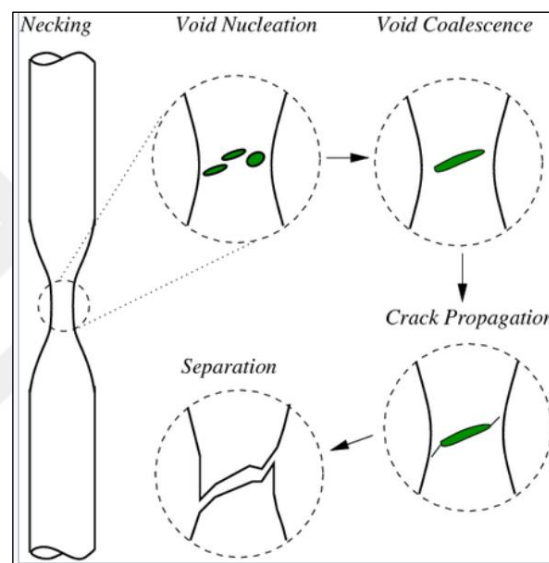


Figure 2.5: Schematic representation of the steps in ductile fracture

In brittle fracture, fracture type is generally cleavage crack. Cleavage fracture has a crystalline or granular appearance because this type of fracture occurs in a plane within each grain. In cleavage crack type, fracture occurs by separation in different atomic planes. During crack propagation, the parting surface has light reflective properties, so in brittle fracture, the surface is bright immediately after fracture. Afterwards, this shine will be temporary as oxidation will occur with oxygen contact on the surface [12].

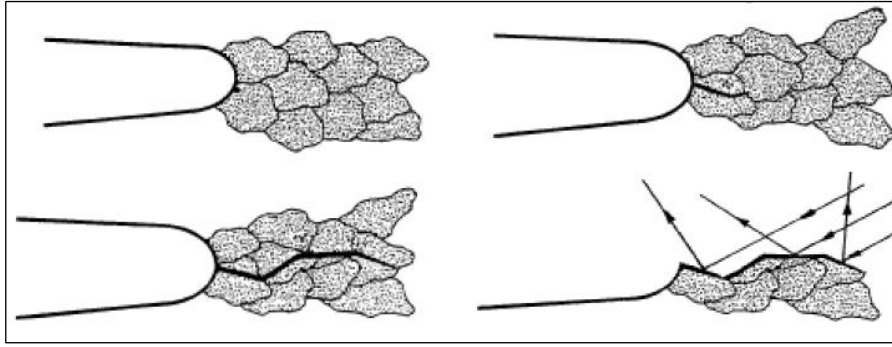


Figure 2.6: Mechanism of cleavage crack type - brittle fracture

2.3. Fatigue Fracture Failure on Structures

2.3.1. Fatigue Stress Cycle Information

Structures exposed different cyclic stresses. Fully reversed cycle is one of them and it is used in tests. Moreover, there is different cycle which is irregular cycle. It has no regular loading. It is just exposed to random stress loading. Another cycle is repeated stress cycle. It has max stress ($\sigma_{\max}$), min stress ($\sigma_{\min}$) and mean stress (σ_m) values. The repeated cycle is shown in below. Stress load is repeated in cycle and minimum stress is zero.

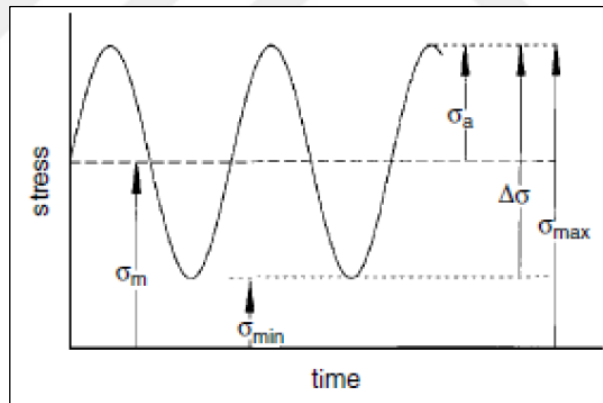


Fig 2.7: Cyclic stress loading

σ_m is mean stress. It is expressed in equation in below.

$$\sigma_m = (\sigma_{\max} + \sigma_{\min}) / 2 \quad (2.1)$$

σ_a is stress amplitude. It is expressed in equation in below.

$$\sigma_a = (\sigma_{\max} - \sigma_{\min}) / 2 \quad (2.2)$$

$\Delta\sigma$ is stress range. It is expressed in equation in below.

$$\Delta\sigma = (\sigma_{\max} - \sigma_{\min}) = 2\sigma_a \quad (2.3)$$

R is ratio value which is min and maximum stress ratio value. It is expresses in equation in below.

$$R = \sigma_{\min} / \sigma_{\max} = (\sigma_m - \Delta\sigma/2) / (\sigma_m + \Delta\sigma/2) \quad (2.4)$$

A is amplitude ratio value which is the ratio of stress amplitude and mean stress.

$$A = \frac{\sigma_a}{\sigma_m} = \frac{1-R}{1+R} \quad (2.5)$$

2.3.2. Loading and Modes of Fractures

Loading in structures can be in the form of single loading or multiple loading. In single load, load is carried by one part. This part should be designed for the required life to withstand the load it will be subjected to. It should not fail during its operating life. Single loading is not a preferred type of loading in aviation part design, but in some specific designs, it may be necessary to perform a single loading. In such cases, a safety factor should be used. The landing gear of airplanes can be an example of this type of loading situation. In this case there is no extra part to carry load. Therefore, the life durability of the parts which expose to high loads for long hours should be designed according to their life requirement.

In multiple loading, there can be another part which carries the loads. Inspection interval has also importance for this type of loading. Hence, in multiple loadings, the inspection period should be adjusted to intervene before the crack reaches critical failure sizes. The size of the crack that can be detected using known NDT test methods depends on the location of the crack and the test method used in crack detection. For instance, in the non-destructive test method with the Eddy Current method, the hole around 0.2 mm in other places 0.1 mm is accepted the initial size of the crack.

Critical areas where fracture can initiate on the part under loads. We can sort as follows.

- High load transfer connections
- High stress intensity locations

- After the main loaded part is damaged, secondary loaded part analysis
- High load spectrum intensity
- Low static limit
- Areas prone to damage in the event of an accident
- Fatigue tests for parts

In addition to these, the material can tear in different ways according to the direction of loading. There are three types of fracture modes depending on different loading conditions. These are shown in figure as follows.

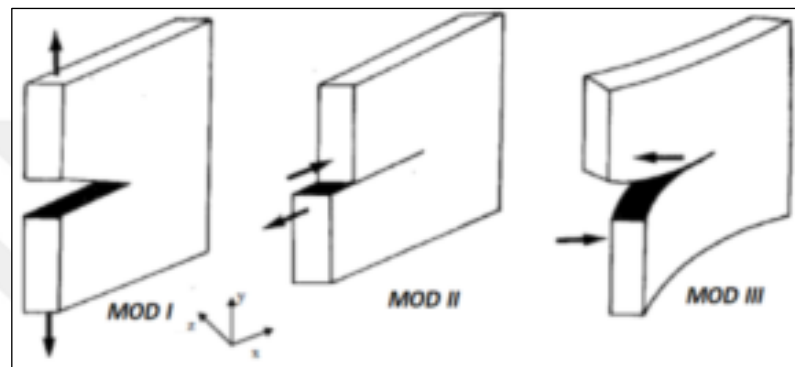


Figure 2.8: Modes of fracture

- Mod I: Opening mode (the most common type)
- Mod II: Sliding mode
- Mod III: Tearing mode

In opening mode (mode I), tensile stress is applied on part and crack plane is pulled apart in y axis direction. Mod II is sliding mode. In the sliding mode, body exposes to shear stress which is parallel to the crack plane. Crack surface sliding in x axis direction. Mod III is tearing mode which is caused from shear stress in z axis direction. In general, crack propagation occurs as a superposition of these modes, called mixed mode.

2.3.3. Stress Intensity Factor

The presence of sharp corners, discontinuities and notch effects in the structures cause stress concentration. Stress concentration is of great importance in estimating crack propagation life in the structure and means that the average stress value in the part is less than the stress value in structure's small region.

When we examine the effect of notch in the structure, the discontinuities in the structure affect the load flow on the part. Hence, the load flow lines do not move in the direction they should go and deviate from the way, and the load flow lines tighten in certain regions. With the tightening of the load flow lines, stress concentration occurs in these regions. If the part where the notch effect is seen has a blunt geometry, the region under the influence of the flow lines will be larger. As a result of this large area, the unit stress concentration per total area will have a lower value than the smaller affected area geometries.

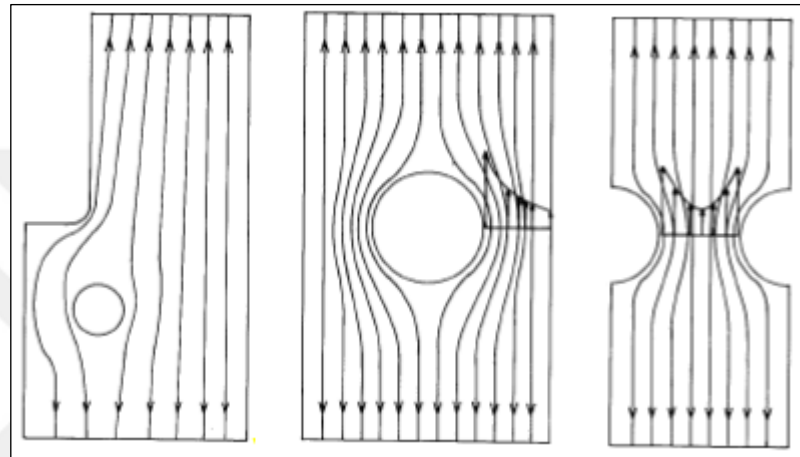


Figure 2.9: The notch effect of load flow lines

In summary, sharp notches cause high regional stresses. Blunt notches are lower cause regional tensions. The stress values (σ_l) in areas with sharp notches are higher than the nominal stress (σ_{nom}) of the part values.

Theoretical stress concentration factor (k_t) obtained by the ratio of the local stress value and nominal stress value. The regional stress value formula is given below;

$$\sigma_l = k_t \sigma_{nom} \quad (2.6)$$

In this formula, the nominal stress is not always defined in the same way. In some cases, uniformly distributed stress across the entire section away from the notch effect and in some cases the average stress is used. However, regional stresses are the same for both cases. Using different nominal stress values, stress causes the concentration factors to change.

Stress in the case of notch with elliptical geometry the concentration factor can be found by using following equation.

$$k_t = 1 + 2 \frac{b}{a} \quad (2.7)$$

The crack radius in an elliptical crack is found by the equation below.

$$\rho = a^2 / b \quad (2.8)$$

In these equations a and b are crack sizes which shown in Figure 2.10.

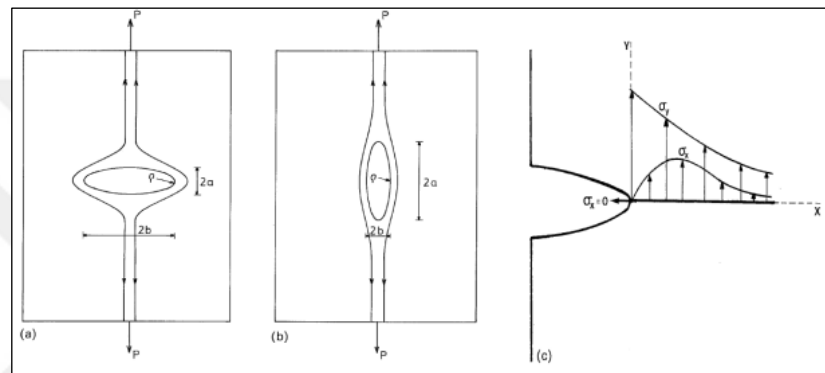


Figure 2.10: In an elliptical notch

- a) High stress concentration
- b) Low stress concentration
- c) Stress free crack surfaces [12]

2.3.4. Fatigue Crack Growth

The fatigue fracture process consists of three main phases; crack initiation, crack propagation, and fracture. First, a fatigue induced crack initiation occurs on the surface of the part. After the initial crack reaches a long grain size, stage II occurs which is propagation and the crack begins to propagate throughout the part. Crack propagation rate at this second phase considering the propagation rate per cycle at the stage, it is higher than others. Finally, in the last cycle a static failure occurs. This means that the net cross section decreased enough [13].

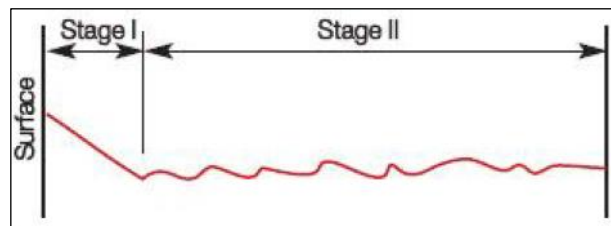


Figure 2.11: Fatigue crack growth first two stages

Fatigue crack growth mostly starts in areas of high stress concentration, such as areas with notch effects, sharp corners or free surfaces. In some cases, the crack starts from the inner surface. It starts in the inner region where the interior of a carburized surface layer or internal inhomogeneities exist.

Phase one, which is the crack initiation stage, usually covers a small part of crack propagation and fracture phases. If the nucleation process in the crack is not very fast, many loadings may be required for propagation. In general, the crack formed in the first stage occurs at an angle of 45 degrees with respect to the loading direction.

After a certain distance, a crack propagation orientation changes to sustain cracking. This change of orientation occurs from a crack propagating with a single slip to a multiple slip. In phase two, crack propagation plane direction depends on that whether stress state is plane stress or plane strain based. There is an important feature for fatigue crack. In stage two, when the electron microscopic scanning is applied, it shows that this feature is fatigue striations. The crack propagation direction is normal to the direction of the maximum tensile stress, and the striations indicate the successive position of the crack in propagation. Each of the striations come from a single cycle. As a result, it is possible in stage two to find the fatigue crack growth rate that is the difference between the two fatigue lines. In stage two fatigue crack, plastic blunting stimulates crack growth. It is shown in below.

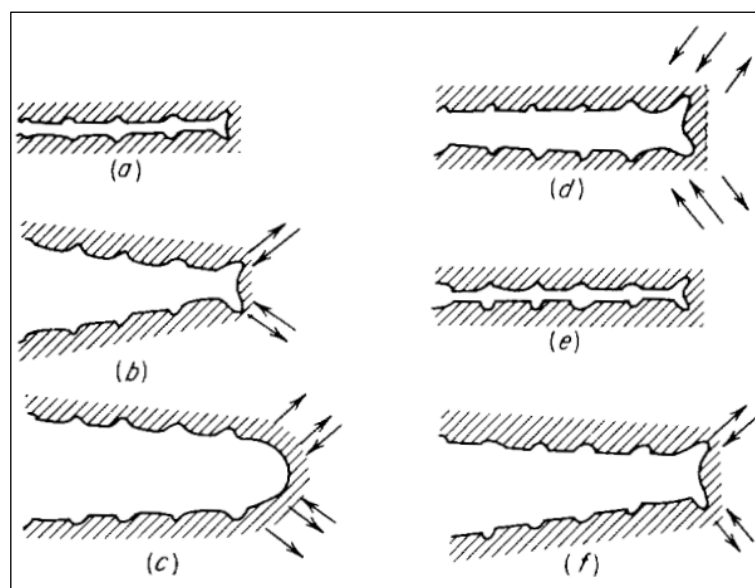


Figure 2.12: Plastic blunting process fatigue striations

At first, crack initiate with sharp tip. When load is applied on structure, in the crack tip region, which starts with the notch effect, the concentrates along slip plane at 45 degrees to the crack plane. Afterwards, the crack expands and reaches the maximum sizes it can reach. It grows longer by plastic shearing then after tip becomes blunter. As the load changes, the compression effect reverses the slip direction in the end region. Different crack faces create new crack by crushing. The crack planes are forced to flip inward to form a new sharp crack tip [14].

To summarize it again, fatigue crack growth has three stages. It can be seen on the chart according to life cycle versus crack length.

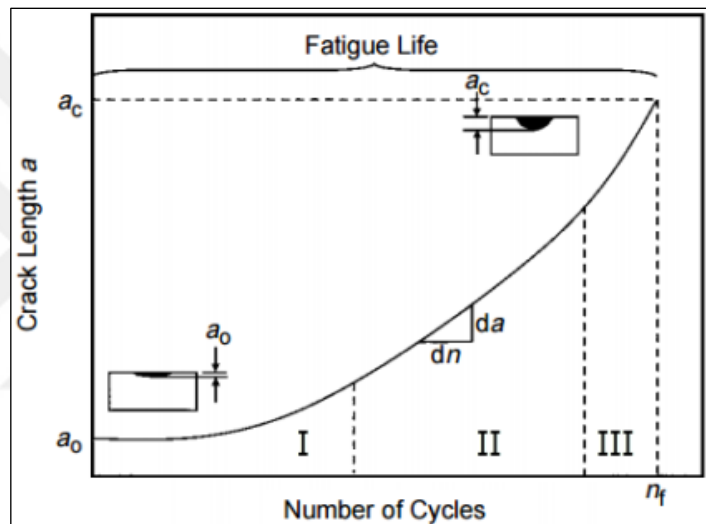


Figure 2.13: Crack length and cycle relation

Stage I: In stage one, crack propagate along slip planes, then its direction changes as normal to tensile stress. The crack does not propagate fast at this first stage.

Stage II: In stage two, the crack plane and direction change as normal to max principal stress direction and it grows fast.

Stage III: In stage three, fracture failure occurs and cross section is not enough to endure the applied load anymore.

The existence of defects such as notches, dents or cracks in the structure may cause important failure in the working cycle phase. In addition, any crack formation on the free surface can also cause failure as a result of fatigue.

The growth stages of the crack and life relation can be seen in detail below.

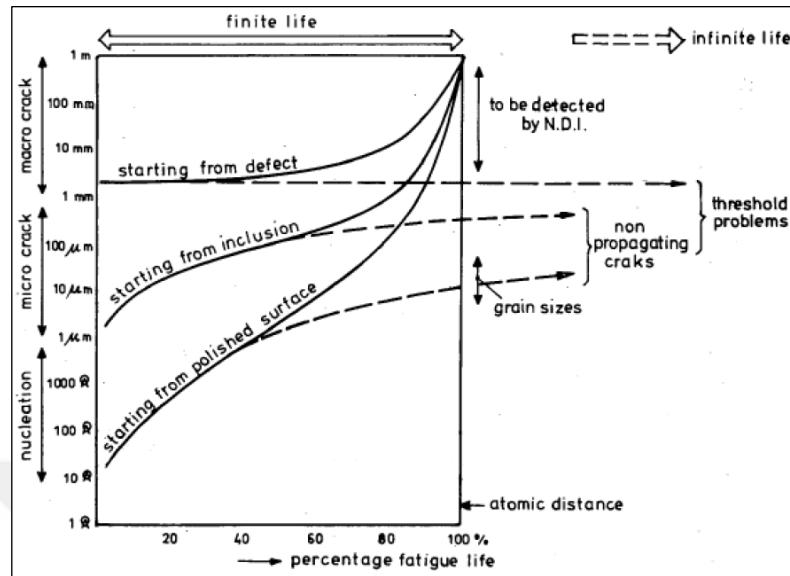


Figure 2.14: The growth stages of the crack and life relation

2.3.5. Linear Elastic Fracture Mechanics

In linear elastic fracture mechanics, evaluations are made by assuming that the part already has defects. In the crack calculations, it is accepted that there is an initial crack size of a_0 and this crack size is assumed to reach the a_c size with the propagation of the crack as a result of the loads that the structure is exposed. When the crack initiates, the propagation of the crack is slow in the first stage. In the later stages, as the crack grows, the rate of crack propagation increases and the crack propagate rapidly. It can be seen from Figure 2.13 which shows crack length, stress and cycle related to each other.

In the past, very important studies have been done by Paris and Erdogan on the crack propagation rate. As a result of all of these, Paris explained in an article written in 1961 that the stress density factor which called K has a significant effect on the crack propagation rate.

K is stress intensity factor and Paris and Erdogan used aluminium panel which has crack on the center in their test about crack growth, they founded that there is a relationship between crack growth rate and stress intensity factor K and also the crack propagate direction is parallel to the crack length. As a result of, it is a function of K as follows.

$$\frac{da}{dN} = f(\Delta K) \quad (2.9)$$

The stress intensity factor difference is

$$\Delta K = K_{\max} - K_{\min} \quad (2.10)$$

The Paris-Erdogan equation explains power law relationship between the crack growth rate in cyclic loading and the range of the stress intensity factor can be seen in figure 2.15. According to this graph, it is shown that there is a linear relationship between crack growth and the stress intensity factor range. It is expressed as a Paris – Erdogan equation in below.

$$\frac{da}{dN} = C (\Delta K)^m \quad (2.11)$$

- a: The crack size
- N: The number of cycles
- C – m: The material parameters which come from tests

If these three regions are investigated separately, the crack growth rate decreases with decreasing ΔK . The crack reaches the crack threshold value known as K_{th} in this region I. If it does not reach this value, no growth is seen in the crack.

In the region II, the crack growth rate is stable and it depends on Paris – Erdogan equation. $\log(da/dN)$ and $\log(\Delta K)$ have linear relationship. Fatigue crack growth in this area II is stable and there is macroscopic crack due to environmental influence. The crack propagation of the microstructure and the mean stress in the region II effect on behaviour is less than in Region I.

In the region III, the crack grows rapidly and $K_{\max}$ value reaches K_c value. The local static fracture modes are valid in this region. In this region, the crack propagation rate increases so much that it becomes unstable and the crack propagation life is shortened by fatigue. This region is affected by microstructure and environment. It is controlled by the fracture toughness K_c that depends on it.

- ΔK : Threshold stress intensity factor
- K_c : Fracture toughness

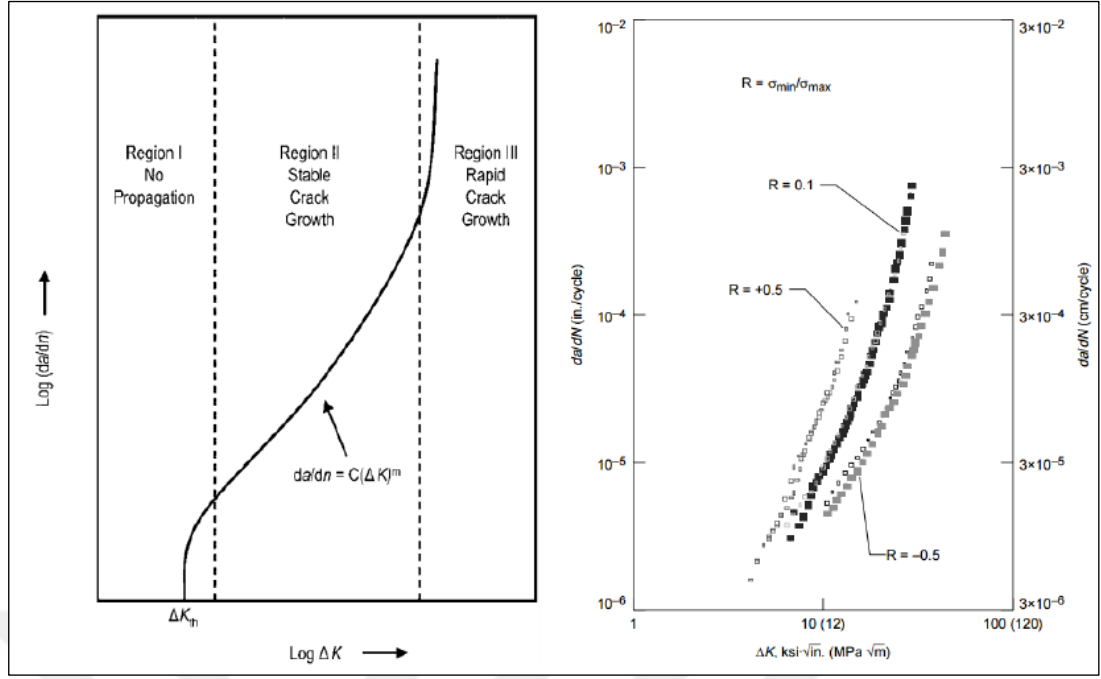


Figure 2.15: The growth stages of the crack and life relation

The crack growth rate is linear in region II, the cycle numbers to reach failure can be found according to the Paris- Erdogan equation. Basic equations describing the crack propagation mechanism in general are the following in equations.

$$dn = \frac{da}{C(\Delta K)^m} \quad (2.12)$$

$$nf = \int_0^{nf} dn = \int_{a_0}^{ac} \frac{da}{C(\Delta K)^m} \quad (2.13)$$

ΔK is formulated based on $\Delta\sigma$ in below.

$$\Delta K = Y\Delta\sigma\sqrt{\pi a} \quad (2.14)$$

- Y: Coefficient which depends on geometry of crack
- $\Delta\sigma$: Stress range of loading

if $\Delta\sigma$ is accepted as a constant, Y will be dependent to crack size. It can be iterated as follows to obtain the cycle number to reach failure.

$$nf = \frac{1}{C\pi^{m/2}(\Delta\sigma)^m} \int_{a_0}^{ac} \frac{da}{Y^m a^{m/2}} \quad (2.15)$$

In region II, R ratio value can affect some metal crack growth behaviours. It is called that mean load effect. Paris-Erdogan equation does not consider this.

There is another equation for da/dn which belongs to Forman.

$$\frac{da}{dn} = \frac{C(\Delta K)^m}{(1-R)K_C - \Delta K} \quad (2.16)$$

There are some important factors affecting the crack propagation rate, the main ones are as follows.

- Crack initial sizes
- Stress ratio
- Material sizes (Width and thickness)
- Temperature
- Environmental effects
- Loading frequency
- Crack orientation
- Producer effect

Initial crack sizes are effective on crack propagation life. The large crack sizes make growth faster than when its sizes are small.

Stress ratio is effective on crack growth rate. If the stress ratio R is increased, the crack growth rate in the structure will also increase, and conversely, if the stress ratio value decreases, this rate will decrease.

It can be seen from Figure 2.16 in below.

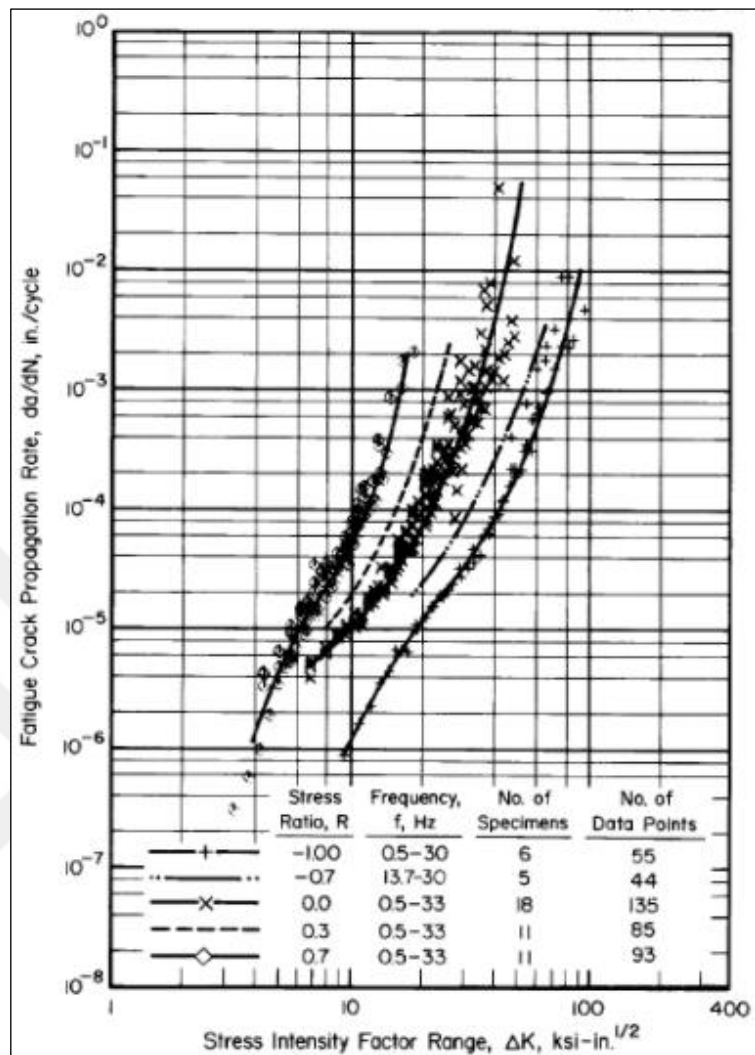


Figure 2.16: The crack growth rate – R ratio relation

As the thickness increases, the crack growth rate increases. The reason is plane in thin piece stress is the occurrence of plane strain in thick parts.

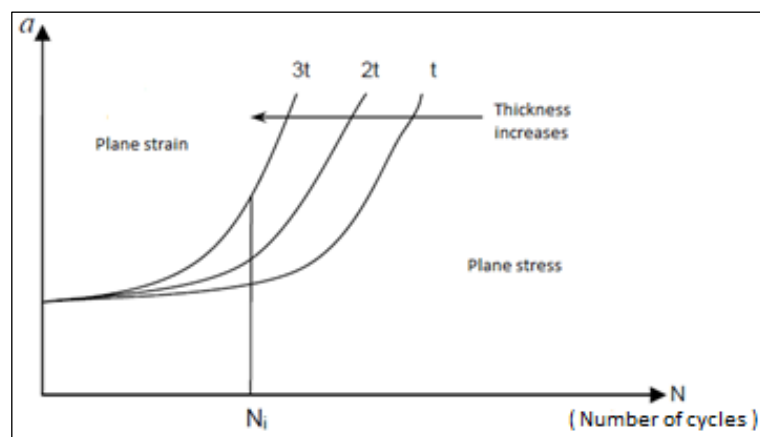


Figure 2.17: Thickness effect on crack propagation

Temperature has a linear relationship between crack growth. Rate of being affected by temperature depends on the material properties. It is shown in figure in below.

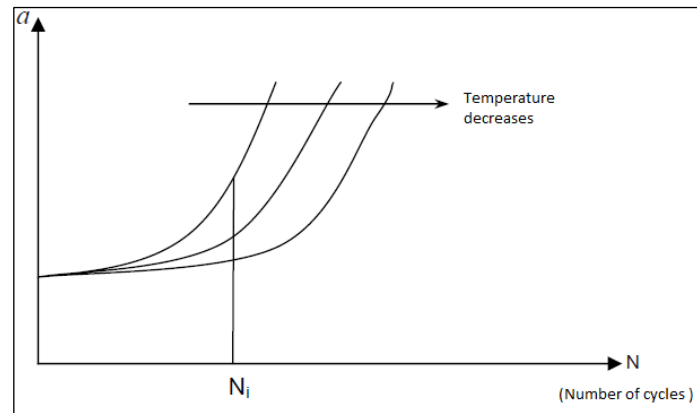


Figure 2.18: Temperature effect on crack propagation

Environment is one of the other important effects on crack propagation. Humid and salty environments cause an increase in crack propagation rate. In addition, the formation of a corrosion effect at the crack tip has an increasing effect on crack propagation.

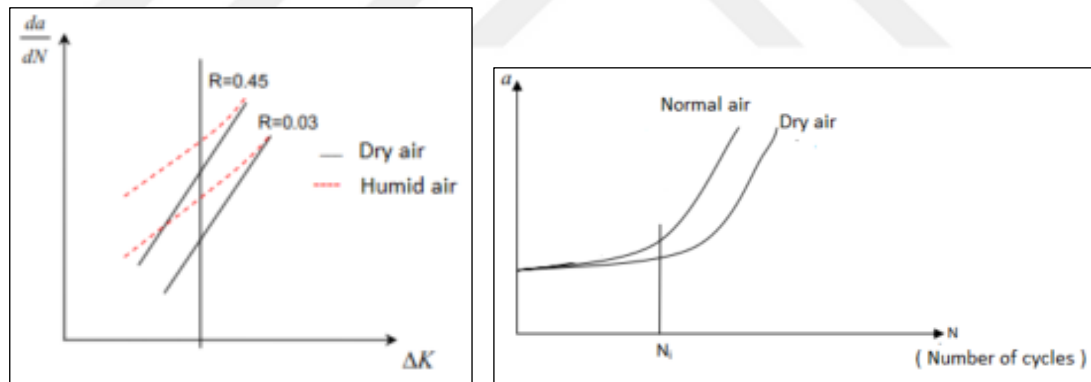


Figure 2.19: Different environment effect on crack growth

As mentioned above, corrosion also has a significant effect on crack propagation. In corrosive environment, the crack propagates more slowly around the threshold value. But then it increases the crack propagation rate. Moreover, the frequency effect is more effective in corrosive environments. As the frequency decreases, the corrosion effect on the crack surface increases. It can be seen in below the effect of corrosive environment.

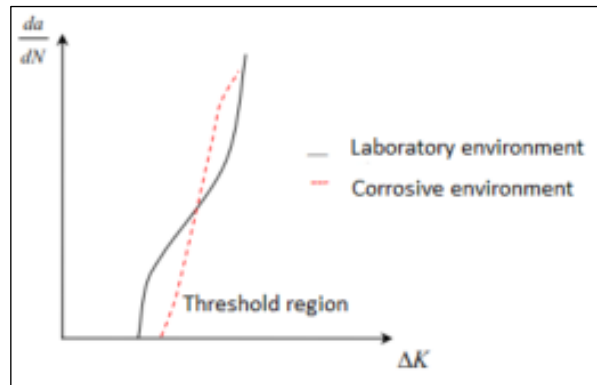


Figure 2.20: Corrosive environment effect on the crack propagation rate

Since the crack surface will be more exposed to the corrosive environment as the frequency decreases, decreasing the frequency has the effect of increasing the crack propagation rate.

Another important effect is crack orientation. There are material directions in casting and forging materials according to the way they are manufactured. For instance, in the centrifugal pouring method, material direction occurs in the radial direction. Thus, the centrifugal casting is radially and it is very resistant to spreading cracks.

Different manufacturers effect is also important for crack propagation rate because manufacturing conditions and methods will be different and they will not have the same quality, therefore this may cause different crack propagation rates [15].

3. TIME DEPENDENT CRACK GROWTH

3.1. Time Dependent Crack Growth Definition

Complying with the required life requirements in gas turbine engine design is critical for flight safety. In addition to this, there are many research and development activities in order to provide all the safety requirements for the gas turbine engines. The engine manufacturers give a great importance to this safety critical issue. Specific maintenance intervals are planned to prevent situations that may cause catastrophic failure in the engine. In determining these maintenance intervals, the material, design and therefore the life of the parts are effective.

Although some fatigue crack growth-based researches have been studied extensively and in detail, the crack propagation under the hold time is also of great importance for gas turbine parts which expose to high temperature.

There different loading situations and are there can be seen different crack growth behaviour under these loading types. It has been shown in below;

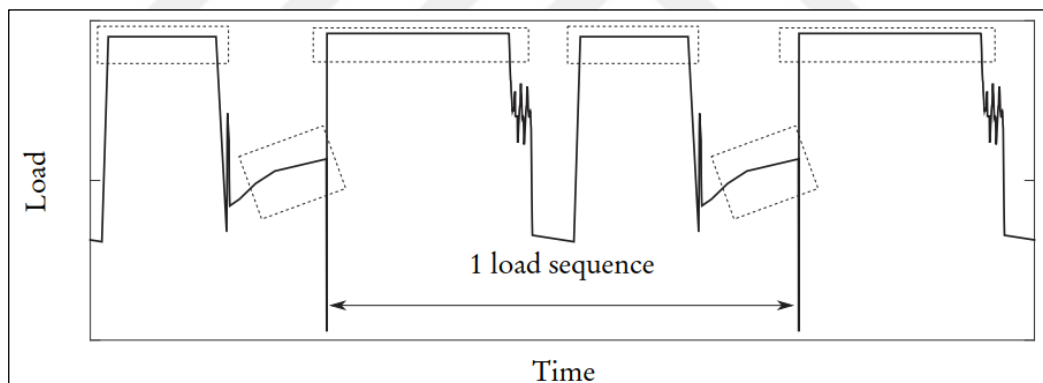


Figure 3.1: Cyclic loading and hold times (static loading)

Investigation and knowledge of crack growth behaviour under such loading types in gas turbine parts which expose to high temperatures and extreme conditions will provide more reliable results in crack propagation life calculations and will contribute to the determination of better maintenance intervals. It can also contribute to reducing extra maintenance costs [16].

The hold (dwell) time effect can be called the investigation of time-dependent crack propagation behaviour in nickel-based super alloys at high temperature and under static load. In fact, this is time dependent crack growth type and there is no need

for fatigue effect for this growth. The crack propagates only with the effect of static loading. This type of crack propagation behaviour has similarity with the corrosion induced crack propagation seen in steels.

This type of crack growth has the crack path which is often inter granular. It is shown in laboratory tests that time dependent crack growth needs localized creep and oxygen at crack tip plastic zone area. In addition to that, it has sensitivity to over peak stresses which are higher than its dwell time stress.

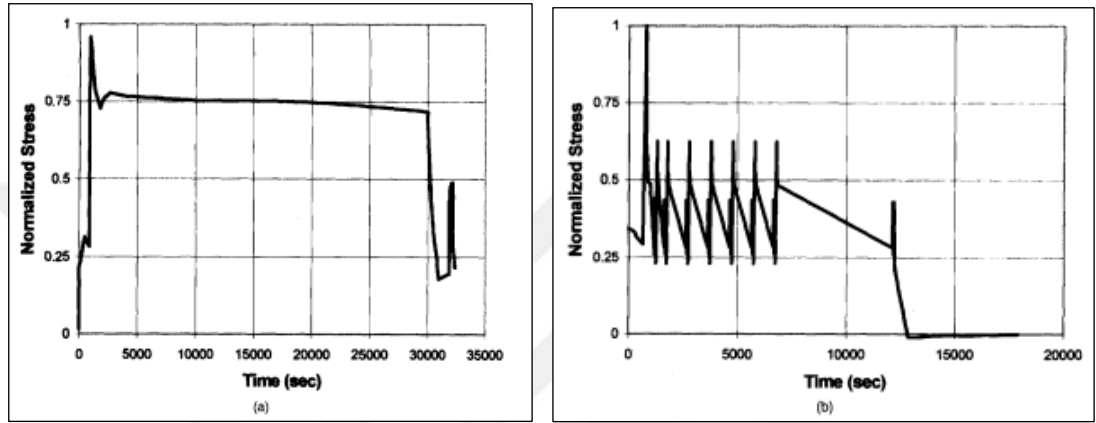


Figure 3.2: An examples of an aircraft representative missions

In the most of the mission profiles of gas turbine engines, engine parts can be subjected to cyclic loadings and also static loadings at high temperature conditions many times. In such cases, different crack growth behaviours can be seen.

The hold time effect can increase the crack propagation rate significantly at high temperature conditions in materials commonly used in gas turbine engines. Low-alloyed steel, Inconel 100, Inconel 718, 706, 783, Udimet720 and Waspaloy can be given as an example to these materials.

As a result of the studies on crack growth modelling, there is a linear superposition model proposed by Wei and Landes. In time dependent crack growth, this model is used for Ni based super alloys. Time dependent crack propagate model is shown in below.

$$\Delta a_{mission} = \Delta a_{cyclic} + \Delta a_{td} \quad (3.1)$$

$$\Delta a_{td} = \int \left(\frac{da}{dt} \right) dt \quad (3.2)$$

The static crack growth rate is expressed according to Paris-Erdogan equation as follows.

$$\frac{da}{dt} = AK^n \quad (3.3)$$

If it is accepted that at maximum loading K is constant, time dependent crack growth can be expressed;

$$\Delta a_{td} = AK^n \Delta t \quad (3.4)$$

- Δa_{cyclic} : Cyclic loading fatigue crack growth increase
- Δa_{td} : Time dependent crack growth increase
- $\Delta a_{mission}$: The crack growth increase for mission
- $\frac{da}{dt}$: Static loading crack growth rate

The final expression for mission can be seen in below [18,19].

$$\Delta a_{mission} = (da/dN)_{cyclic} \times (1cycle) + AK^n \Delta t \quad (3.5)$$

3.2. Experimental Study About Time Dependent Crack Growth

There are important experimental studies about hold time effect on crack growth. In order to see the effect of dwell time on the crack propagation at high temperatures for Inco718 material, which is widely used in aviation engine parts, some dwell time tests were carried out for 450 C, 500 C, 550 C and 650 C. While the tests are being planned, it has been adjusted to be performed without including the dwell time and then including the dwell time to see the difference clearly. The tests were carried out at different high temperatures and with different hold times. With these different temperatures and different dwell times, the impact factors on crack propagation can be observed quantitatively and comparatively better. In addition, the growth rate of the crack under this high temperature and hold time effects and how the material structure changes and how it is damaged can also be examined [20]. As it is known, gas turbine engines are mainly used in the aviation industry to achieve high efficiency, and in order to achieve this efficiency as high as possible, the engine is exposed to very high gas temperatures. This leads to the need for engine part designs that can withstand these high gas temperatures [21].

For example, jet engines, which also have an important place in aviation, are exposed to higher temperature gas in order to reach higher speeds and reach a wider range compared to other engines. In this case, the loads on the engine will also be much higher. When all these are taken into consideration, high temperature in a gas turbine engine means more efficiency, higher thrust, therefore less fuel requirement and lower cost. Since critical parts in the engine, such as discs, are subject to loading at high temperatures, these situations are among the main factors limiting the design when designing a gas turbine engine. Super alloys are known for their resistance to high temperatures and their superiority in many aspects in terms of strength. For this reason, these super alloys are used for the production of parts in the hot zone in gas turbine engines. Inco718 material is an important nickel-based super alloy used for critical parts such as discs, which are among these super alloys and exposed to high temperatures in aviation. It has high temperature resistance. Despite this, hot zone parts work on the engine at values close to the maximum load limits they can carry and the maximum temperature they can bear. For such parts, the life criterion is very important, and the existence of some uncertainties while making total life calculations causes an over conservative design in the part design, which causes extra costs. For this reason, in crack propagation perspective the more uncertain crack propagation life calculation methods are, the better and more cost-effective design can be made. In the laboratory experiments, it has been observed that the dwell of some materials at high temperatures under a certain high load is a very important factor in the crack growth [23]. The cyclic loading condition that the parts are exposed to causes deterioration in the physical structure of the material, which is called cyclic plastic deformation [24]. Moreover, if the dwell occurs under this loading condition at a sufficiently high temperature, this dwell effect causes a time dependent effect at high temperature, called creep deformation, in the material structure of the part [25]. When the material is exposed to high temperature, besides the deterioration of its mechanical properties, another condition that may occur is the change in its microstructure, oxidation and grain boundary embrittlement. Hence, the fatigue resistance of the material decreases and the resistance of the material for crack propagation decreases. In the test approach, it is accepted that cyclic loading and dwell time loading should be in the same order. Because it has been seen that this is possible for real gas turbine engine loading conditions.

3.2.1. Experimental Study Details

In the test phase, a Kb type test sample made of Inconel 718 material was used and a semi elliptical surface crack model was formed on this sample [21].



Figure 3.3: A Kb test specimen

High temperature values of 450 C, 550 C, 550 C and 650 C under isothermal condition were determined as temperature. At these temperatures, firstly, normal cyclic loading, then hold time under cyclic loading and finally both tests were carried out. While these tests were being made, different hold times were applied, where the effect could be seen according to the temperature. Detailed results will be mentioned in the following pages. The main purpose of these tests is to see how the dwell time has an effect on the crack propagation behaviour with temperature.

There can be given more information about the In718 material used in the test. The test sample material Inco718, is a nickel based super alloy and a polycrystalline material with a high content of Fe and Cr. The composition of the Inco718 material can be seen in detail in the table below.

Table 3.1: Composition of elements for Inco718 material

Composition of elements for Inconel 718								
Element	Ni	Cr	Mo	Nb	Al	Ti	Fe	C
Weight%	Balance	19.0	3.0	5.1	0.5	0.9	18.5	0.04

The material was obtained in the form of a bar with a diameter of 25.4 mm. The applied processes are respectively, in accordance with the AMS 5664 standard, after 1 hour annealing at 945 C, aging processes at two different temperatures as 8 hours at 718 C and 8 hours at 621 C. To represent the turbine discs, the line intercept method was used by estimating that the grain size is approximately 10 microns [21].

To give detailed information about the experimental method, the Kb type specimen used in the test has the dimensions of 4.3 x 10.2 mm. To represent the semi elliptical surface crack, an initial notch with a depth of 0.075 mm was created by applying the EDM (electro discharge machining) method. Before starting the crack propagation tests under high temperatures and hold times, the specimen was pretested with a R ratio of 0.05 at room temperature. The purpose of this pre-tests is to create a semi elliptical crack, and as a result of the test, a semi elliptical crack with a depth of about 0.2 mm was obtained and tests are completed when the crack length reaches 2.5 mm. MTS servo hydraulic machine was used in the tests [27]. Many different tests were performed. Some of these tests are baseline tests that are not included in the hold time. These tests were done at three high temperatures which were 450°C, 550°C and 650°C. Furthermore, hold time tests were also carried out. For the hold time tests, unlike the previous tests, it was made for two high temperature values which were 550 C and 650 C. In the hold time tests, the dwell times were applied as 90 seconds and 2160 seconds. In order to see the embrittlement volume in the material, that is, the damaged zone and its size, separate tests were carried out in the form of a block test and the dwell times were applied in different blocks. The details of these mentioned block tests can be seen better in the figure below;

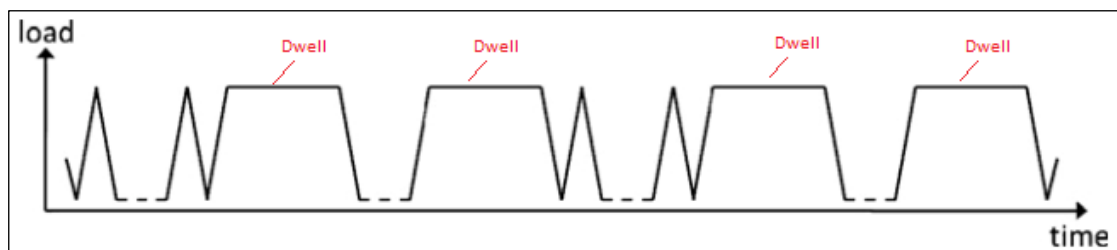


Figure 3.4: Load and time profiles for block tests

As a result of these tests, it was observed that the rate of crack growth increases as the temperature and dwell time increase. In addition to this information, important information about the fracture mode was obtained. Although the type of crack growth in the baseline tests is trans granular, in the hold time tests this crack growth is of inter granular type.

3.2.2. Experimental Study Result Comparisons

Comparative graphics of the baseline tests can be seen in below. Looking at the graph, basic test data for 500 °C and trend lines for 450 °C, 550 °C and 650 °C are seen without hold time effect. It is understood from the data of this test results that the crack propagation rate increases as the temperature increases. When the same tests were conducted with 2160s dwell time, a similar situation was observed again. Temperature has an increasing effect on the crack propagation rate, da/dN - ΔK charts can be seen in below:

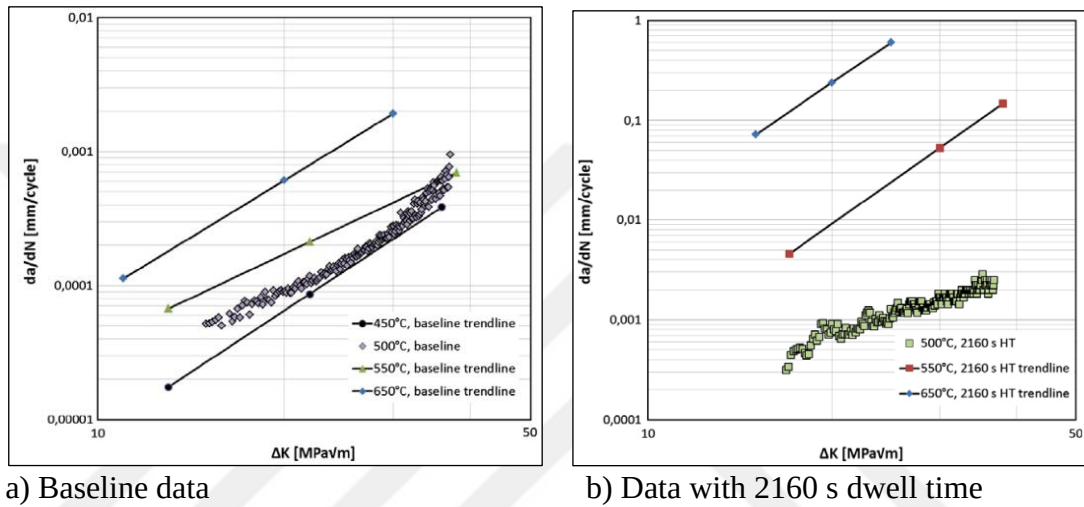


Figure 3.5: da/dN - ΔK charts for baseline tests without hold time and with 2160 s hold time

In another test series, the hold time effect was examined. For this, a test was carried out with a dwell time of 21600 seconds at 550 C, and the test trend lines for dwell time of 90 seconds and 2160 seconds were added to the chart in below, including the baseline test result, comparatively. When the results are examined, it can be seen that the crack propagation rate increases as hold time increases.

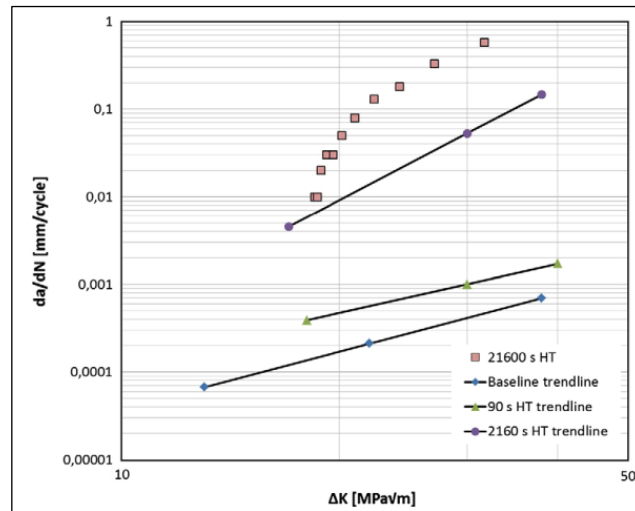
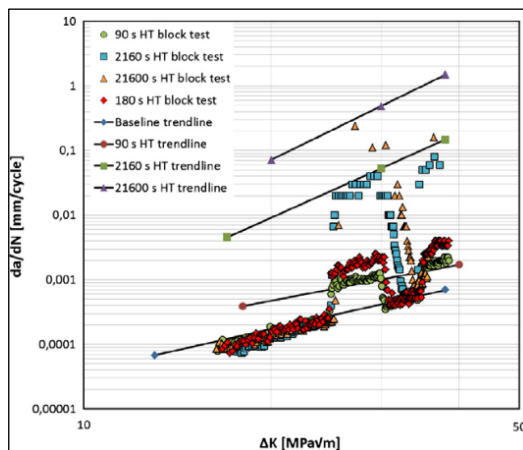
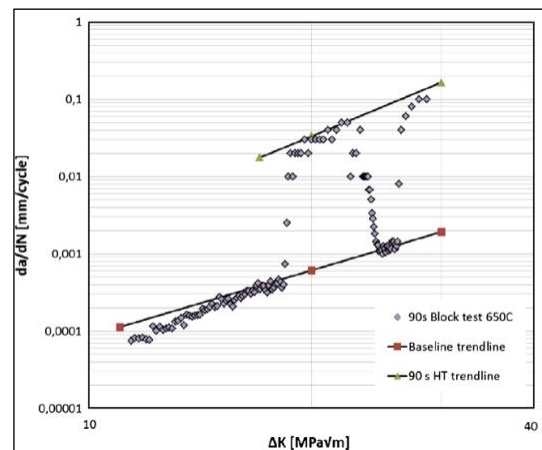


Figure 3.6. da/dN - ΔK charts for baseline test and different hold times at 550 C

Some block tests were carried out at different hold times for high temperatures of 650 C and 550 C. The hold time block was applied in the tests and as a result, it was seen that the block effect greatly increased the crack propagation rate. At the same time, the crack propagation rate increases during the dwell time application period. When the hold time was applied during the baseline test, a transient transition behaviour was observed in the crack propagation rate. When the hold time effect is active, the crack propagation rate increases. Block test results can be seen in below



a) 650 C block tests



b) 550 C block tests

Figure 3.7: da/dN - ΔK charts for block tests at 650 C and 550 C

To see what the amount of crack growth changes during cyclic loading and during the hold time, a comparison study was made by taking the hold time 90 sec at 650C. It was observed that the main factor in the growth of crack length at this temperature and hold time was the cyclic loading part. When the same comparison was made for 2160 s at 650 °C, a different result was obtained. The effect of high

temperature and high dwell time is more dominant in crack growth than cyclic loading. It can be seen on comparison charts in below.

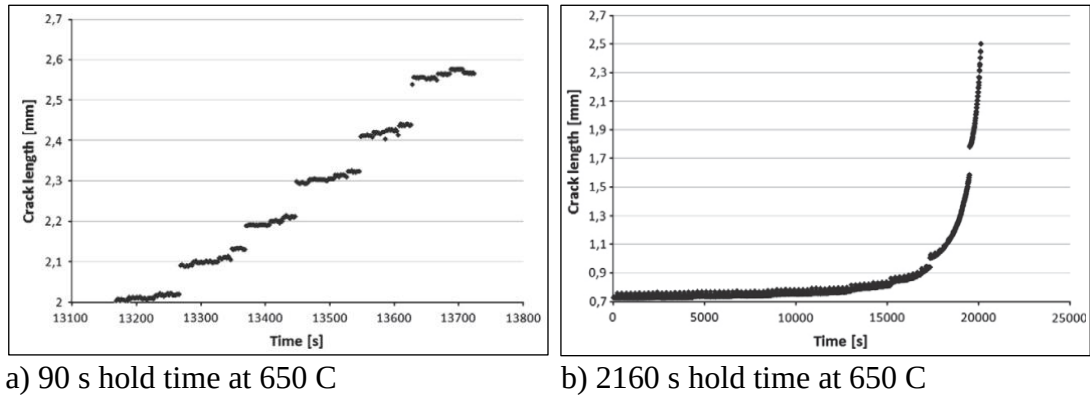


Figure 3.8: Crack length change depends on time at 650C with different hold times

In order to see numerically the effect of cyclic loading and hold time on crack growth, a separation study was carried out. Firstly, two separation studies were carried out at 550 C high temperature for 2160 seconds and 21600 seconds hold times. Then, for 650 C, 90 seconds hold time values were separated. The relevant results can be seen in the graphs below for each temperature and hold time values.

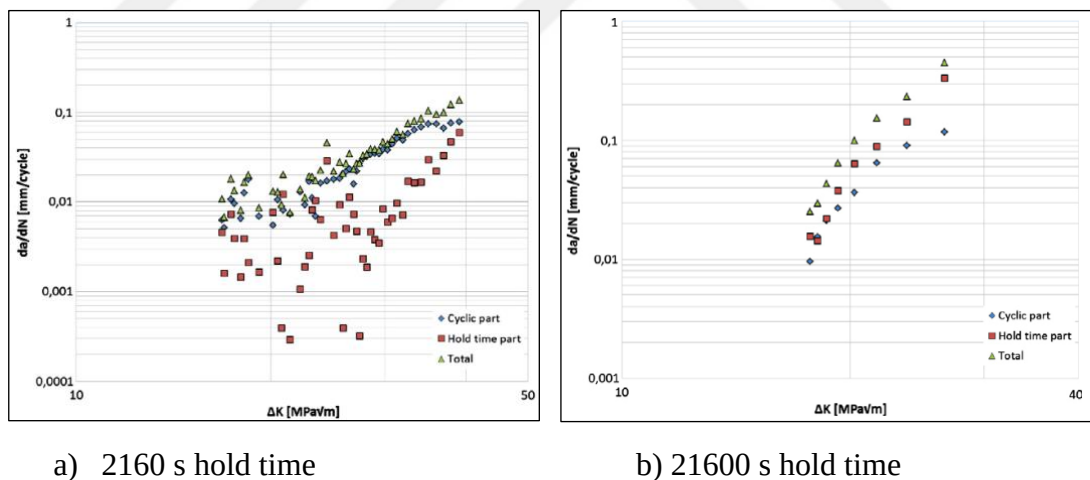


Figure 3.9: Separation study at 550 C for different hold times

As can be seen in Figure 3.8.a, cyclic loading is more effective in crack propagation for 2160 s hold time at 550 °C. As for a 21600 s hold time at 550 C, the effect on crack propagation is almost the same in terms of cyclic loading and hold time.

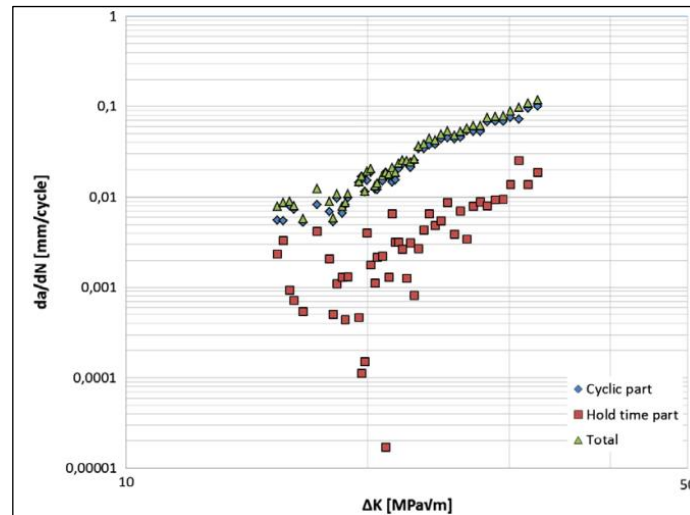


Figure 3.10: Separation study at 650 C for 90 s hold time

In the study conducted for 650 C and 90 seconds hold time, it can be seen that cyclic loading is more effective than hold time in crack propagation due to the short duration and retardation effect. However, as the dwell time increases, the effect of dwell time on crack propagation becomes more significant. Another important point to be noted is that the dwell time becomes more effective as the tests continue [20].

Crack growth usually occurs inter granular during the effect of hold time. Planar slip occurs in the grains which are located around the crack tip. This can also be seen in the figure below. The increase in the amount of slip during crack propagation causes more oxygen effect on these regions [28].



Figure 3.11: Picture of planar slip in the grain surrounding the crack tip at 550 C with 90 s hold time

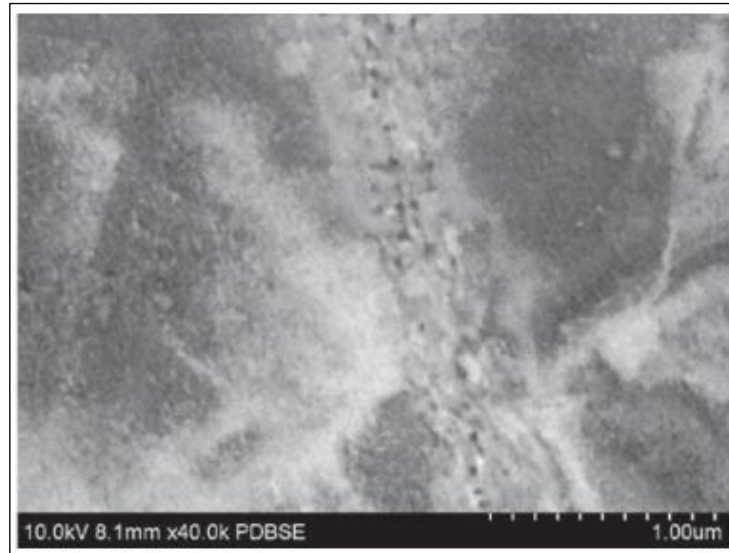


Figure 3.12: The damage zone by the oxide particles along the grain boundary at 550 C with 90 s hold time

4. ANALYSIS STUDY ON TURBINE DISC FOR TIME DEPENDENT CRACK GROWTH

4.1. Analysis of Crack Propagation Model

In order to represent discs which are known as critical parts in gas turbine engines, high pressure turbine disc geometry was used. The analysis which is used in the calculations was performed as a 2D analysis on the ANSYS software program, since the geometry is axisymmetric. Geometry was design using by UNIGRAPHICS software program as a 2D model. Dead weight which is considered in analysis calculated from blade weight, disc dovetail geometry till live rim border and wedge factor effect for 2D analysis. Wedge factor is an adder to over blade radial loading and tangential loading on disc blade contact pressure faces.

4.1.1. Model Information

Disc geometry details and regions can be seen in Figure 4.1.

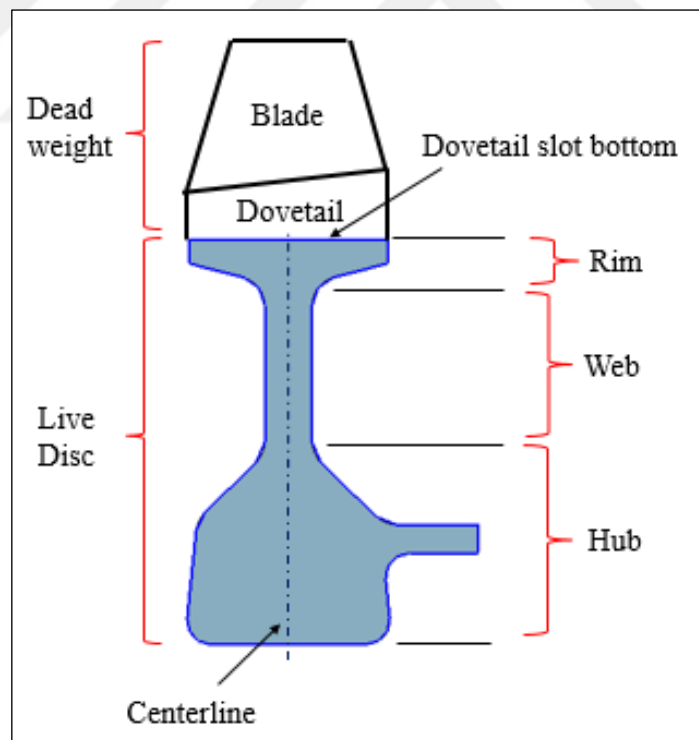


Figure 4.1: Disc geometry details and regions

After the model was created, boundary conditions were given to represent the real conditions. In addition to the boundary conditions, the dead weight which is carried by the live disc region was also added on the disc model.

Boundary conditions can be seen in Figure 4.2.

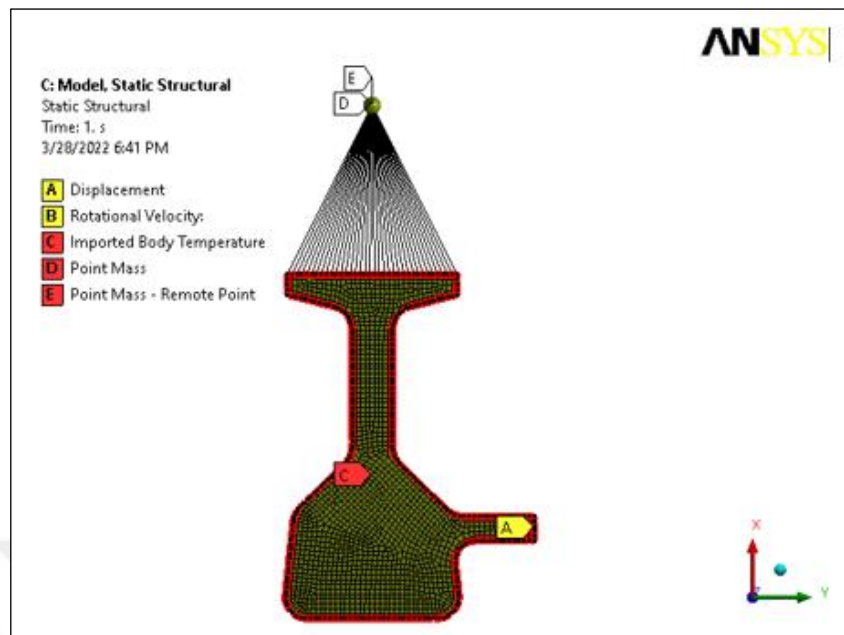


Figure 4.2: Boundary conditions on the analysis model

To represent the operating conditions of the disk 16000 RPM velocity was given which is the angular rotational speed of the disk around the Y-axis in coordinates. Displacement boundary condition was given as $Y = 0$, $X = \text{Free}$ on disc arm edge. Body temperature and dead weight which are blade and dovetail geometries were given as well. Disc and blade materials were selected same Inconel 718. There are 52 blades on the disc.

4.1.2. Dead Weight Calculation

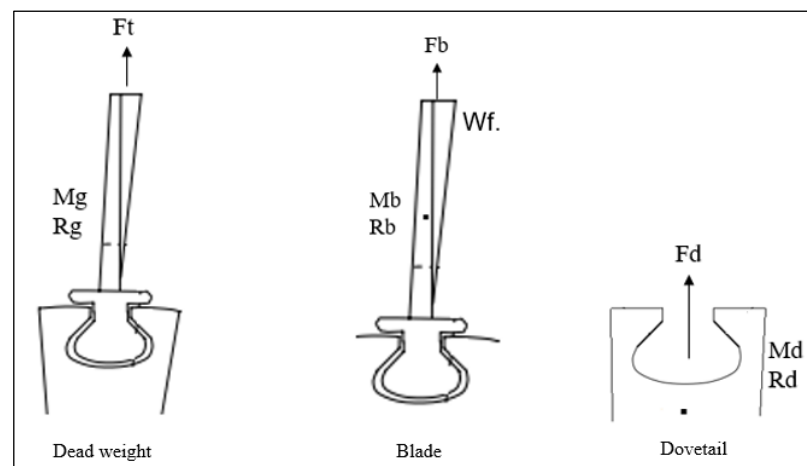


Figure 4.3: Force, weights and locations on representative model of dead weight

$$F_t = F_b \times W_f + F_d \quad (4.1)$$

$$F_t = M_g \times R_g \times w^2 \quad (4.2)$$

$$M_g = (M_b \times R_b \times W_f + M_d \times R_d) / R_g \quad (4.3)$$

M_g is dead weight; M_b is blade weight and M_d is dovetail weight. R is Cg radial location of parts. W is rotation speed of parts. W_f is wedge factor for 2D analysis.

Table 4.1: Dead weight calculation values

Blade weight (1/52)	R blade	Dovetail weight (1/52)	R dovetail	Wedge factor	Blade number
0.025 kg	115.17 mm	0.0090 kg	98.29 mm	1.04	52

According to equation 4.2 and equation 4.3

$$M_{g \text{ total}} = M_g \times \text{Blade number} \quad (4.4)$$

Table 4.2: Dead weight calculation results

Mg Total Dead weight	Dead weight R location
1.77 kg	113.536 mm

4.1.3. Stress Results

Analysis was completed according to these conditions. Von misses stress and maximum principal stress results can be seen in below.

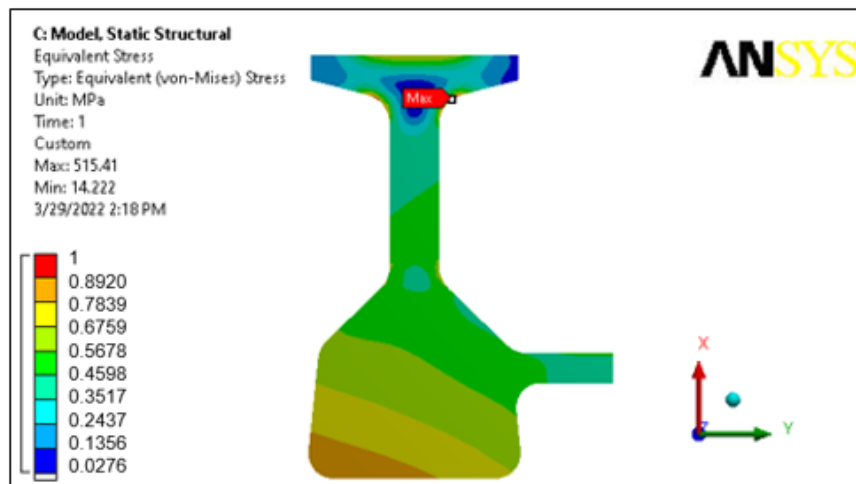


Figure 4.4: Von Misses stress result of disc

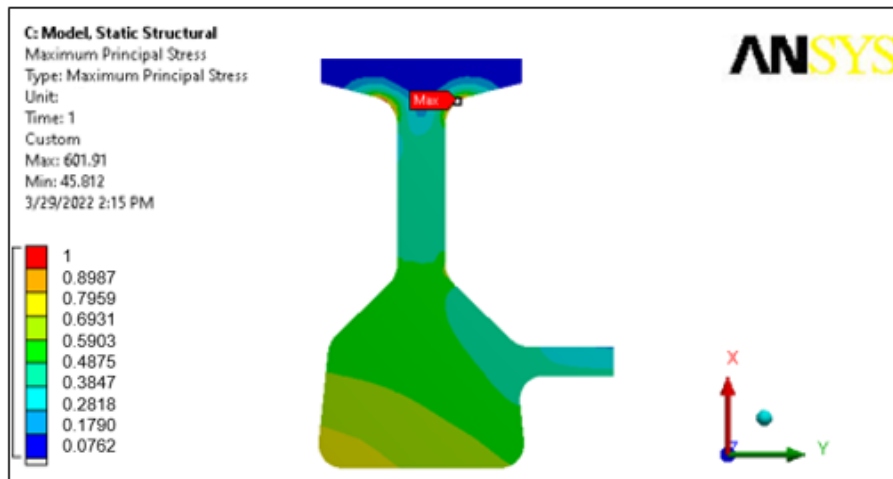


Figure 4.5: Max principal stress result of disc

According to the results of the analysis, crack propagation calculations were made using an in-house software for the disc bore region and the region with the maximum stress, based on the max principal stress values. Before the calculations, the crack propagation plane was determined perpendicular to the principal stress and the stress gradient values in 1D were taken from the analysis model.

4.1.4. Crack Type Information

Semi elliptical surface crack type was used as crack type in calculations. It can be seen in Figure 4.6.

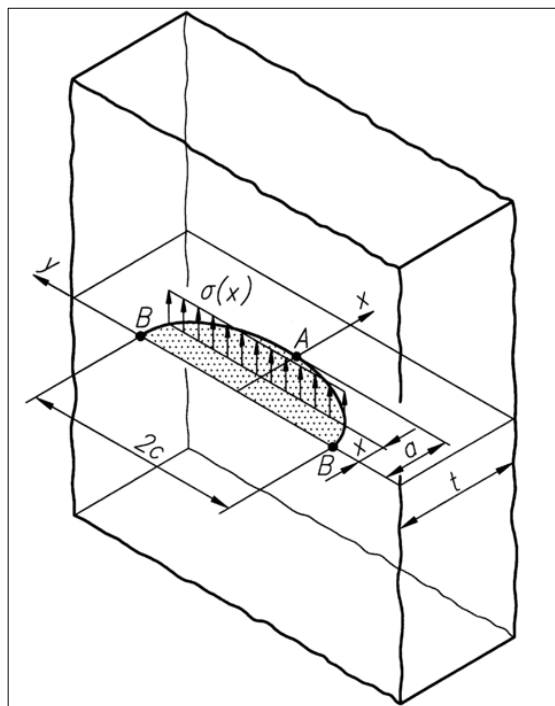


Figure 4.6: Semi elliptical surface crack type

In this crack type, $2c$ is the crack width, a is crack the length and t is the thickness of material. Firstly, baseline condition crack propagation lives were calculated. Baseline condition does not have any hold time, it is pure cyclic. To see the high temperature effect at the constant hold time, crack propagation calculation was made for 550°C and 645°C with 90s hold time. 550°C location is disc's bore region, 645°C is for max principal stress region (rim fillet). Results can be seen on Figures 4.7 and 4.8 which shown crack length vs. number of cycles for these two temperatures.

4.2.1. Result Comparison Study

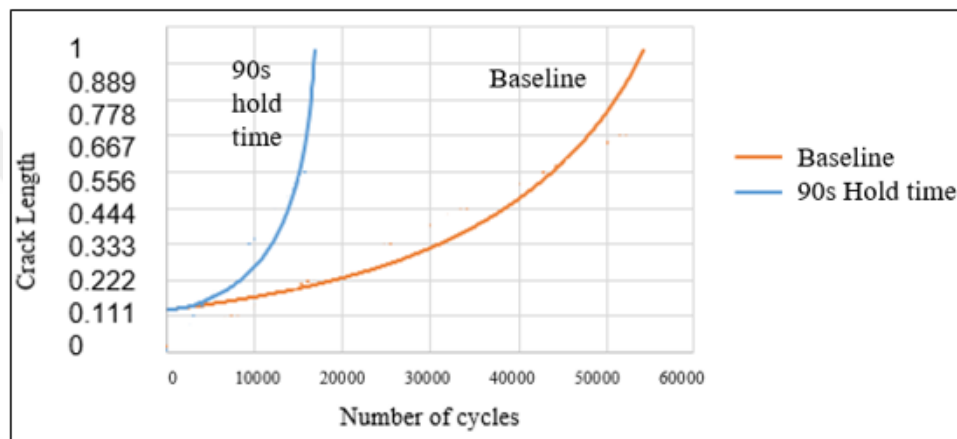


Figure 4.7: Crack length vs. cycle results for baseline and 90s hold time at 645°C

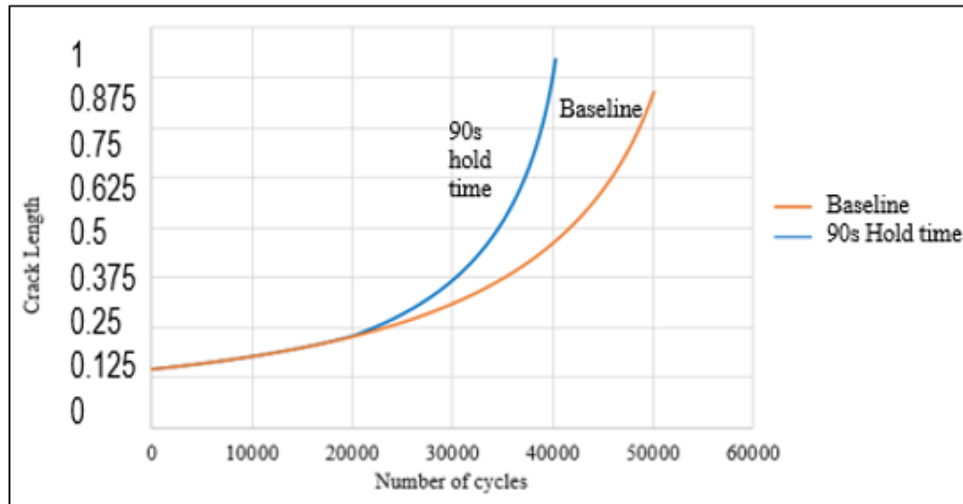


Figure 4.8: Crack length vs. cycle results for baseline and 90s hold time at 550°C

Both rim fillet and bore crack propagation lives are reduced with hold time. With higher temperature, the reduction is worse. It can be understood from these

results that temperature is a major factor that increases crack growth rate (for constant dwell time).

To see different hold time effect at the constant high temperature two different dwell time crack propagation calculations were made. Temperature was taken as 645°C, and dwell times are 90s, 120s and 150s.

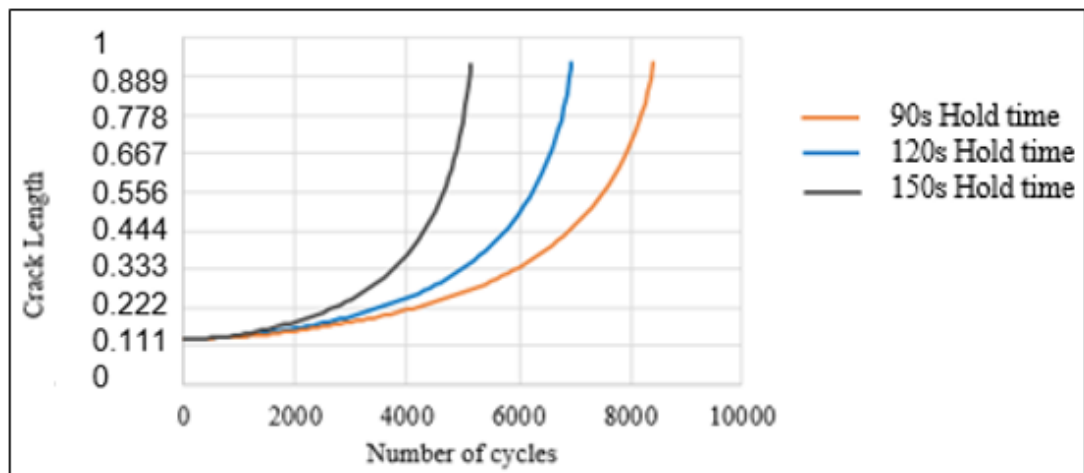


Figure 4.9: Crack length vs. cycle results for 90s - 120s - 150s hold times at 645°C

It can be seen in Figure 4.9 that; crack propagation rate increases as the high temperature dwell time increases. Hence, dwell time value is also critical in terms of crack propagation at high temperatures for critical components such as discs.

5. RESULTS

The effect of hold time on crack propagation was investigated for a disc with Inconel 718 material, which is one of the most critical parts in a gas turbine. Based on the analysis results, first of all, crack propagation life for the bore max stress region and disc's max principal stress region which is web to rim fillet region of the disc were calculated without including the hold time effect. These regions are the regions with high temperatures of 550°C and 645°C, which are known to have a hold time effect. Afterwards, crack propagation life calculations were made using an in-house tool at 90s hold time for both temperatures. In order to see the effect of temperature, the reduction in crack propagation lives are compared. When the results are examined, it can be seen that the temperature increase significantly increases the growth rate of the crack during the hold time. This can be risky for hot zone parts in gas turbine engines. Finally, to examine the effect of the dwell time at constant temperature, crack propagation life calculations for the 645°C region at three different hold time values were made. In the comparison study conducted for these three different hold times, it was understood that the prolongation of the hold time at high temperature increases the crack growth rate very quickly. As a result of all these studies, it is necessary to obtain as clear results as possible when determining the crack propagation life of critical parts such as discs exposed to high temperatures and high loads. The hold time effect is one of the most important factors for high temperatures and has the potential to cause dramatic effects on the crack growth rate. Completed crack propagation life calculations without at sufficient maturity can take the disc parts to the burst, which is a catastrophic failure for the engine.

6. DISCUSSION

It has been seen in the study that the dwell time in crack propagation is an important parameter for Inco718 material. This study can be similarly investigated for different critical parts and materials. Since the blades on the engine are exposed to very high temperatures, similar operation can be made for the blades. Likewise, a study can be made for different nickel based super alloys commonly used in gas turbine engines by changing different parameters for hold time.



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BIOGRAPHY

Tuğba KÖSTERİT Kocaeli’de doğdu. İş hayatına havacılık sektöründe mekanik tasarım mühendisi olarak başladı. Şu anda kıdemli tasarım mühendisi olarak çalışmaya devam etmektedir.