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INSTITUTE OF ENERGY TECHNOLOGIES

**CREEP DAMAGE ANALYSIS AND LIFE PREDICTION OF A
SUPERALLOY TURBINE BLADE**

TÜMAY İNAL

**A THESIS SUBMITTED FOR THE DEGREE OF
MASTER OF SCIENCE IN APPLIED PROPULSION SYSTEM
DESIGN & ENGINEERING FOR AEROSPACE
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THESIS SUPERVISOR
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GEBZE
2023

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ABSTRACT

CREEP DAMAGE ANALYSIS AND LIFE PREDICTION OF A SUPERALLOY TURBINE BLADE

In gas turbine engines, the determination of the service life of components has vital importance for manufacturers and users. OEM's (major gas turbine engine manufacturers), universities and other institutions increase their research and investments on this subject day by day. Service life calculation studies of a gas turbine engine components consist of different phenomena and their interactions such as low cycle fatigue, high cycle fatigue, thermo-mechanical fatigue, creep and oxidation.

In this study, the creep damage calculation and life prediction of a turbine blade with a Ni-Based Alloy is investigated. For this purpose, firstly, material plasticity and hardening models are prepared as numerical simulations and compared with material test results. Secondly, mechanical modelling of creep behavior is prepared with finite element simulation 2d models and compared with material creep test results. In this respect, creep behavior is investigated with using of two different creep material models. The purpose of using two different creep material models is determining the plasticity effects of cyclic loads on the parts. Thus, Norton and Combined Time Hardening Material Models are selected and they are defined to the fea test specimen analysis model. % Error or material modelling accuracy is compared with test results and shown in graphics.

In the last stage of the study, 3d blade design is examined throughout a gas turbine engine mission profile. The selected creep material model is defined analyzed in fea environment. As a result of the analysis, stress and strains, permanent elongations are calculated and compared with scanned-measurement data after engine test. Creep damage calculation is completed according to engine maintenance interval.

ÖZET

BİR TÜRBİN KANADININ SÜRÜNME HASAR ANALİZİ VE ÖMÜR TAYİNİ HESAPLAMALARI

Gaz türbinli motorlarda bileşenlerin servis ömürlerinin belirlenmesi üreticiler ve kullanıcılar için hayati önem taşımaktadır. Orijinal ekipman üreticileri (büyük gaz türbin motoru üreticileri), üniversiteler ve diğer kurumlar bu konudaki araştırmalarını ve yatırımlarını her geçen gün artırmaktadır. Bir gaz türbini motor komponentinin hizmet ömrü hesaplama çalışmaları, parça değişim sürelerini belirleyerek olası kazaları önleyen farklı olgular ve bunların etkileşimlerinden oluşur.

Bu çalışmada, Nikel baz alaşımlı bir türbin kanadının sürünme olgusu ve ömür tahmini araştırılmaktadır. Bu amaçla öncelikle, malzeme plastisite ve sertleşme modelleri sayısal benzetimler olarak hazırlanarak malzeme test sonuçları ile karşılaştırılmaktadır. İkinci olarak, sürünme davranışının mekanik modellemesi sonlu elemanlar simülasyon modelleri ile hazırlanarak malzeme sürünme testi sonuçları ile karşılaştırılmaktadır. Bu bağlamda, iki farklı sürünme malzeme modeli kullanılarak sürünme davranışı kıyaslanmaktadır. İki farklı sürünme malzeme modeli kullanılmasının amacı, tekrarlı yüklerin plastisite etkilerinin parçalar üzerindeki ömür etkilerini incelemek ve karşılaştırmaktır. Böylece Norton ve Kombine Zamanla Sertleşen Malzeme Modelleri seçilerek sonlu elemanlar test numune analiz modelinde tanımlanmaktadır. % Hata oranı veya başka bir ifadeyle malzeme modelleme doğruluğu test sonuçları ile karşılaştırılarak grafiklerle gösterilmektedir.

Çalışmanın son aşamasında ise nihai olarak belirlenen sürünme malzeme modeli 3 boyutlu türbin tasarımı analiz modeline tanımlanarak sonlu elemanlar simülasyon ortamında analiz edilmektedir. Analiz sonucunda, bir motor görev profili sonunda yapı üzerinde elde edilen gerilme ve gerinimler, kalıcı uzamalar ve ömür

değerleri hesaplanarak motor testleri sonrası taranan ölçüm verileri ile karşılaştırılmaktadır.



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LIST OF ACRONYMS

A	Pre-Exponential Function
α	Back Stress
b	Exponential Material Constant in Isotropic Hardening Law
c_v	Specific Heat at Constant Volume
c_p	Specific Heat at Constant Pressure
C	Linear Hardening Modulus
$C_1, C_2, C_3, C_4, C_5, C_6, C_7$	Creep Curve Fitting Constants
ϵ_e	Elastic Strain
ϵ_p	Plastic Strain
$\bar{\epsilon}_p$	Equivalent Plastic Strain
ϵ_{vp}	Viscoplastic Strain
$\bar{\epsilon}_{vp}$	Equivalent Viscoplastic Strain
$\dot{\epsilon}_{vp}$	Viscoplastic Strain Rate
E	Elastic Modulus
h_s	Static Enthalphy
h_t	Total Enthalphy
I	Rotalphy
ν	Poisson's Ratio
S_y	Yield Strength
U	Absolute Velocity
UTS	Ultimate Tensile Strength
V	Velocity
V_θ	Tangential Velocity
w	Relative Velocity
$\dot{W}$	Rate of Work
T_{local}	Local Temperature for Time Points in Mission
$T_{local,ref}$	Reference Temperature for Selected Time Point in Mission
T_4	HPT Exit Temperature

$T_{4,ref}$	HPT Exit Reference Temperature for Selected Time Point in Mission
T_5	LPT Inlet Temperature
$T_{5,ref}$	LPT Inlet Reference Temperature for Selected Time Point in Mission
Q	Activation Energy
Q_∞	Material Constant in Isotropic Hardening Law
R	Gas Constant
R	Stress Ratio
R'	Stress Ratio for Material Data
R_e	Initial Yield Strength
σ'_{max}	Max. Corrected Stress
$\sigma_{max}, \sigma_{min}$	Min, Max Stresses
m	Walker Exponent
n	Strain Hardening Exponent
σ_{UTS}	Ultimate Tensile Stress
σ_{vm}	Von Mises Stress
k	Goodman Ratio
σ_m	Mean Stress
$\sigma_{Rupture}$	Rupture Stress
σ_a	Alternating Stress
σ'_a	Corrected Alternating Stress
$\sigma_x, \sigma_y, \sigma_z$	Normal Stress on Planes x, y, z
$\tau_{xy}, \tau_{yz}, \tau_{xz}$	Shear Stresses on Planes xy, yz, xz
$\tau_{xym}, \tau_{yzm}, \tau_{xzm}$	Mean Shear Stresses on Planes xy, yz, xz
$\tau_{xya}, \tau_{yza}, \tau_{xza}$	Alter. Shear Stresses on Planes xy, yz, xz
$\sigma_1, \sigma_2, \sigma_3$	Principal Stresses
$\sigma_{xm}, \sigma_{ym}, \sigma_{zm}$	Mean Stress on Planes x, y, z
$\sigma_{xa}, \sigma_{ya}, \sigma_{za}$	Alternating Stress on Planes x, y, z
σ_{aw}	Pseudo Alternating Stress
N	Cycle

X_i	Repetitions Respect to Damage Each of i
N_i	Damage Each of i
φ	Dynamic Recovery Constant
$\emptyset$	Yield Function



LIST OF ABBREVIATION

AnsysWB	Ansys Workbench FE Software
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CLCF	Complex Low Cycle Fatigue
COG	Center of Gravity
CTH	Combined Time Hardening
CVP	Corporate Vip Transportation
DH	Dead Heading
FEA	Finite Element Analysis
FEM	Finite Element Modeling
GBS	Grain Boundary Sliding
HCF	High Cycle Fatigue
HHH	Hot and High Hoge
HPT	High Pressure Turbine
LE	Leading Edge
LCF	Low Cycle Fatigue
LMP	Larson-Miller Parameter
LPT	Low Pressure Turbine
NGV	Nozzle Guide Vane
OEM	Original Equipment Manufacturer
PCT	Personal Cargo Transport
PT	Power Turbine
RPM	Revolution Per Minute
SAS	Secondary Air System
SWT	Smith-Watson-Topper
TE	Trailing Edge
TMF	Thermo-Mechanical Fatigue
WEM	Whole Engine Model

1. INTRODUCTION

1.1 Purpose and Structure of Thesis

Gas turbine engines are mechanical systems which are designed to evaluate thrust or shaft work. The design fundamental of a gas turbine engine aims to complete energy conversion. Gas turbine engines do this conversion according to Brayton Cycle.

In these systems, energy transformation starts with air compression in compressor module and continue in combustor module. Compressed and heated air is mixed with fuel and ignited in combustion systems. In the exit of the combustor chamber, highly energetic fluid is evaluated that is used for rotation or thrust. Thermal energy is need to be converted to kinetic energy as rotational velocity. Evaluated kinetic energy is used to generate shaft power or thrust power. Because of their high power output and high thermal efficiency, the gas turbine engines are used in a wide variety of applications from aviation to industrial systems and power generator plans to marine systems.

The gas turbine engines consist of rotational and stationary parts. Shafts, discs and blades or impellers are grouped as rotating parts of the engine while casing, frames, guide vanes, exhaust systems and fasteners are grouped in stationary parts. On the other hand, components can also be grouped as cold and hot parts. Combustor and turbine is grouped as hot parts while compressor and accessories are cold parts of the engine.

Gas turbine engine parts work in a thermal gradient environment. They are exposed to heat up and cool down cycles. According to working and environmental condition, the effect of the loads (pressure loads, thermal loads, vibrational loads etc.) change and shorten the life of the parts. Engine components exposure these loads in

every cycle and working environment become corrosive and oxidative over time. Such effects are factors that indirectly affect component life and must be taken into account in a design process.

The gas turbine engine design processes is shaped with engine requirements and failure modes. These failure modes are classified under titles as low cycle fatigue (LCF), high cycle fatigue (HCF), thermo-mechanical fatigue (TMF), creep, corrosion and oxidation. All phenomenon's effect the life management of an engine part directly. Because of that, parts are need to be designed to ensure these requirements.

If you take a closer look to the gas turbine engines, rotating parts are exposed to aero-thermal loads, centrifugal loads, vibrational loads. Turbine blades or Nozzle Guide Vanes (NGV) face with the high temperatures in a long time period. In every engine start, long-time working period and shutdown period, parts are exposed to same load types but it is called as cyclic loads anymore. Due to that, engine mission profiles are the first factor on life assessment that represent the cyclic periods especially for turbine side. In course of time, gas turbine engine gets older and nominal radial and axial gaps between stationary and rotating parts are effected. As the nominal gaps of parts changed, turbine side try to take extra cooling airs from the compressor side and the engine performance is effected. On the other hand, fracture of a turbine blade cause a revealing high kinetic energy that must be hold in engine with their casing systems. The fracture of the blade cause hazardous effect. Considering all this, cyclic loads and time factor in an engine design not only affect the part lifetime calculations, but also affect the engine performance and operating conditions of neighboring modules.

In this thesis, the main target is searching of the creep damage and its effect on a rotor blade design that consist of the permanent shape changes, alteration of the nominal gaps, stresses and total strains on parts.

Creep is a time-dependent phenomenon under mechanical load and high temperature working condition. In progress of time, creep cause some extensions or permanent deformations that change the distance between parts. As engines are getting older, radial (tip clearances) and axial gaps between NGV's and turbine blades change and that is very important to trace the chancing of the engine performance. Not only performance effect but also rubbing and disassembly of the parts, the determining of creep behavior gets an obligation in gas turbine engine design procedure.

In this respect, firstly, material plasticity and cyclic load effects are investigated with a comparison work. One single element analysis model is established in fea environment. Strain controlled material specimen test results are taken from literature tests and it is simulated in fea analysis. Loads are defined repeatedly to one single element model and cyclic load effects are examined. Analysis and test results (stresses and strains) are compared with graphics for different type of materials such as isotropic hardening, kinematic hardening and combined time hardening. The closest material type is evaluated after this comparison work in terms of material plasticity.

Secondly, creep material behavior is investigated to select the closest material model. To this end, a standard specimen test results are used in comparison work. The test specimen is modelled in 2d fea analysis model and the curve fitted creep material constants are defined for two different creep material models which are Norton and Combined Time Hardening. The curve fitting accuracy results are compared with test results to select the most realistic material behavior.

Finally, a turbine blade and disc geometry is modelled in fea environment. 3d analyses are completed according to engine mission profile to reflect the time interval effects. Besides determining the LCF behavior of the design throughout a mission profile, creep effects are searched for the geometry as total strains and permanent

deformations. As a result, the permanent deformation behavior of 3d fea analysis is compared with the scanned-measurement data after engine test. The accuracy of the mechanical modeling of the material and creep damage is investigated.

1.2 General Structure of a Gas Turbine Engine

Gas turbine engines are designed to evaluate thrust work or shaft work. To do that, high thermal energy is converted into mechanical energy from combustor chamber to turbine. A gas turbine engine consists of air intake, compressor, combustion chamber, high pressure (gas generator) and low pressure turbine (power turbine), externals and exhaust structures. In a gas turbine engine, compressor module is located before the combustion chamber. On the other hand, turbine parts are located behind the combustion chamber and exposed to high aero-thermal energy. They are used to obtain mechanical energy from highly energetic fluid, try to fulfill their functions in very different operating conditions. A typical gas turbine engine consist of air intake, compressor, combustion chamber, high and low pressure turbines and nozzle modules as it is shown in **Figure 1**. According to this, gas turbines can grouped turbo-shaft, turbojet, turbofan and turboprop engines. With respect to the customer requirements, types of compressor can change. While axial compressors are used in turbojet or turbofan engines, radial compressors are preferred to use in turboshaft due to the advantages of engine sizing and residential.

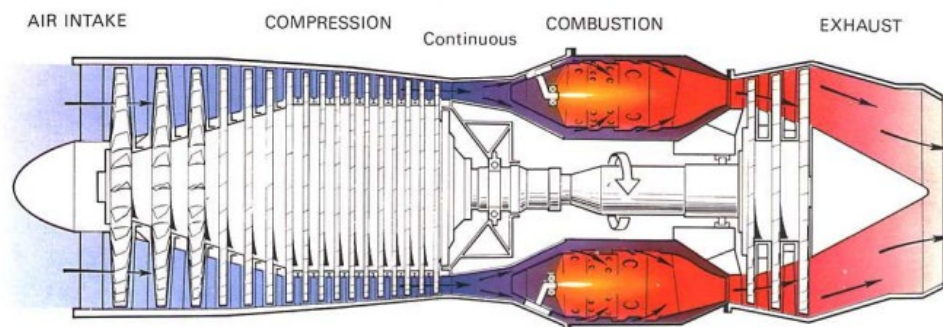


Figure 1. A Section View of a Turbojet Engine [1]

Gas turbine engines are propulsion systems and work according to Brayton Cycle as it is shown in **Figure 2**. This working cycle is similar to the four-stroke piston engine. However, combustion occurs at a constant pressure in the gas turbine engine while it occurs at a constant volume in the piston engine.

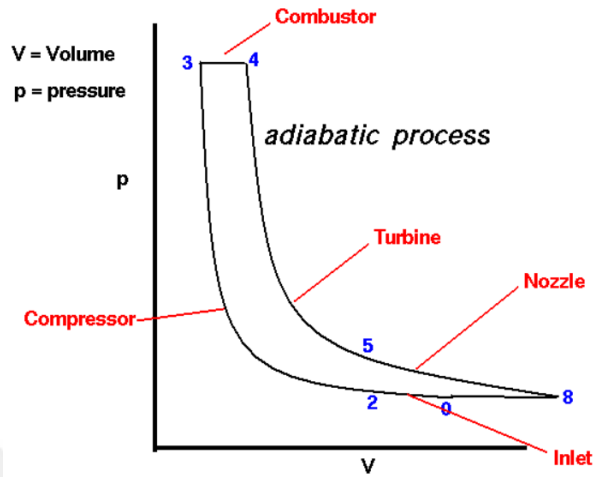


Figure 2. P-V Diagram of the Brayton Cycle [2]

In flight, the inlet slows the air stream as it is brought to the compressor face at station 2. As the flow slows, some of the energy associated with the aircraft velocity increases the static pressure of the air and the flow is compressed. Ideally, the compression is isentropic and the static temperature is also increased as shown on the plot. The compressors increase pressure and temperature isentropically to (station 3) the compressor exit. In reality, the compression is not isentropic and the compression process line leans to the right because of the increase in entropy of the flow. The combustion process in the burner occurs at constant pressure from station 3 to station 4. The temperature increase depends on the type of fuel used and the fuel-air ratio. The hot exhaust is then passed through the power turbine in which work is done by the flow from station 4 to station 5. Turbine generates work by extracting heat from the hot gas stream. The nozzle then brings the flow isentropically back to free stream pressure from station 5 to station 8. [2]

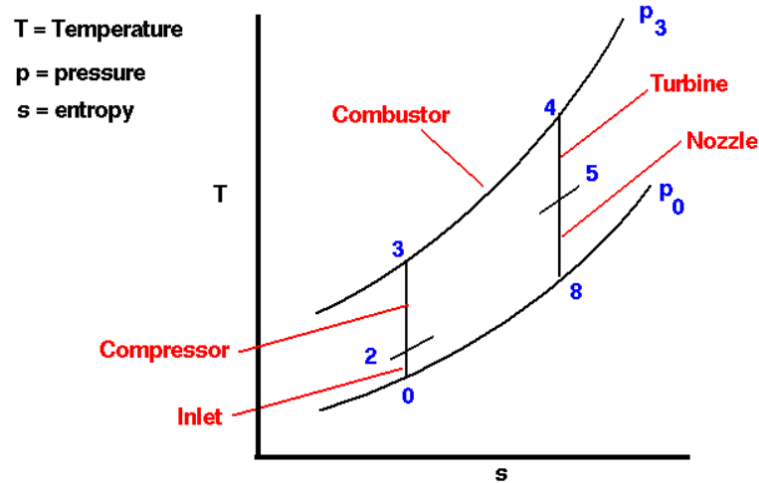


Figure 3. T-s Diagram of the Brayton Cycle [2]

As it is shown in **Figure 3** that compressors increase the air velocity with their impellers and then try to increase pressure of the air and ensure pressurized low velocity air to the combustor side. Compressors are driven by the engine turbine and are usually coupled direct to the turbine shaft.

In a turboshaft engine, high pressure turbine turns the compressor with their coupled shaft whereas power turbine tries to turn main rotor shaft of the platform. It can be concluded that compressors work across to the nature, because they are the structures which try to squeeze the air and forward to the combustor side. Air should be diffused (decelerated-raised static pressure air) from the compressor enters the combustor side. Air is mixed with fuel and ignited and this mixture of air and fuel catches fire. This provides a high temperature and high energy airflow. The fuel burns with the oxygen in the compressed air, producing hot expanding gases. This highly energetic airflow comes into the turbine parts and touches the first rotor blade or vane of the turbine. Main target is using of high energy airflow to rotate turbine blades. Airflow goes from highly energetic region to ambient. Due to that, turbines have

advantage across the nature. The thing is that turbine must be convert thermal energy to the mechanical energy while enduring the harsh environmental condition.

As it is shown in **Figure 4**, a turbine module consist of several parts which are NGV (Nozzle Guide Vanes), rotor blades and discs, shaft and bearings, sealing elements and casing or frame parts.

The design of turbine is based on aerodynamic, it is aimed to obtain optimum efficiency with suitable compressor and combustion design. In turbine module, NGV (stationary aerofoils) parts meet with the high thermal energy of the combustor side. The main target of the NGV Parts with their convergent shapes is providing a guide to the airflow and reach the accelerated airflow to the turbine blades with minimum loss.

The air coming from vanes at high speed hits the turbine blades, the energy is absorbed and blades and turbine disc and shaft rotate. It is aimed to swirl the gas flow in the direction of rotation of the blades in the design of turbine blades.

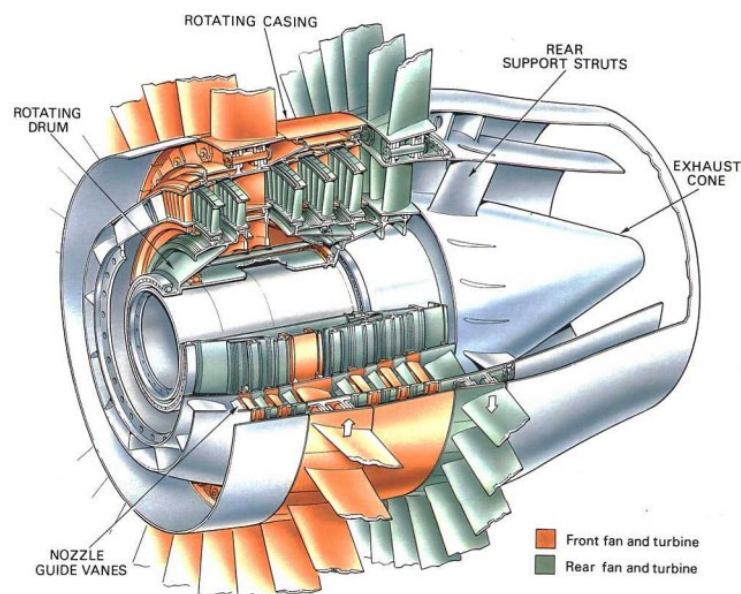


Figure 4. An Engine Section with Rotating and Stator Parts [1]

A turbine disc must rotate at high speed in a relatively cool environment, so it is subjected to big circumferential loads. High rotational velocity cause a huge centrifugal forces on blade root fillets or discs web regions. In addition to these loads, the high temperature loads also can cause stress critical locations. Turbine blades must also be resistant to fatigue and thermal shock, so that they do not fail under the influence of high frequency fluctuations in the gas conditions. Over a period of operational time, turbine blades expand. It is the effect of high temperature environment with high rotational speed. On the other hand, gas turbine engines work in long time intervals such as cruise flight regions and time is the main factor that change the general material behavior. This phenomenon is known as 'creep' and there is a finite useful life limit before failure occurs. Not only cruise regions but also the other regions such as idle or soackback cause thermal gradients that effect the life calculations directly.

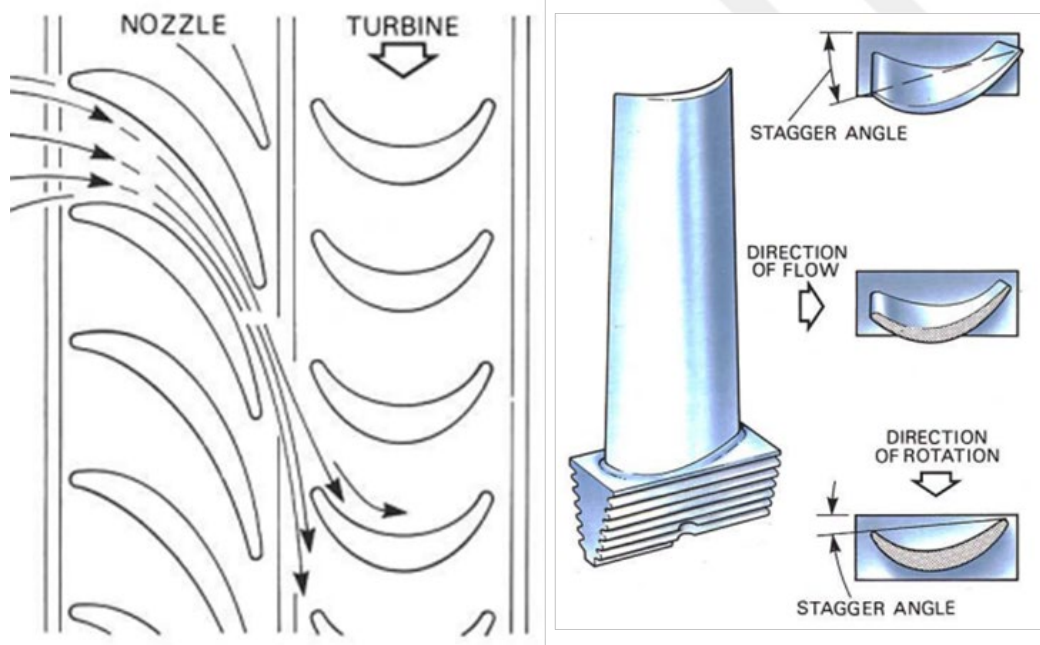


Figure 5. A View of The NGV and Turbine Blade [1]

2. THEORY OF TURBOMACHINERY

2.1 Airfoil Terminology

Airfoil is the structure that transform fluid energy to the mechanical energy. Because of that, a rotor blade design process aim is increasing the relative velocity of the gas. As it is seen in **Figure 6**, the front edge of the airfoil is called as leading edge (LE) where the air push the blade surface firstly. The gas trace the twisted shape of the blade and exit with high relative velocity. The rear edge is called as trailing edge (TE). The distance between leading and trailing edge is called as chord. The convex surface of the geometry is the suction side while the concave surface of the geometry is pressure side. The mean line is a line which separate the suction and pressure surfaces. The difference angle between the inlet angle of the air and leading edge mean line angle is called as incidence angle. The difference between exit angle and trailing edge mean line angle is deviation angle. The turbine airfoil geometries try to use all flow energy with maximum efficiency. To do that, blades are designed with optimum twisted angle to reach from an absolute velocity to high relative velocity. Because of that incidence and deviation angle is important parameters in design of airfoils.

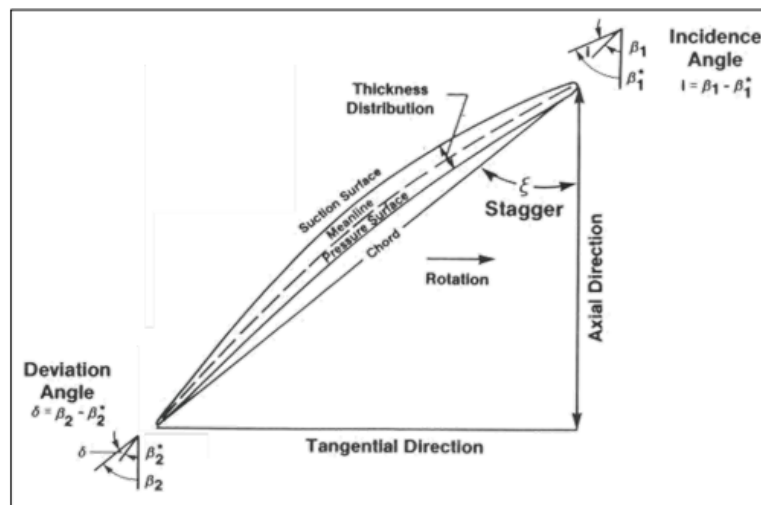


Figure 6. Airfoil Terminology [3]

As it is seen in **Figure 7**, velocity triangles show how nozzle guide vanes transfers the gas to the rotor blades. Beside that, rotor blades twist the air from leading edge to trailing edge.

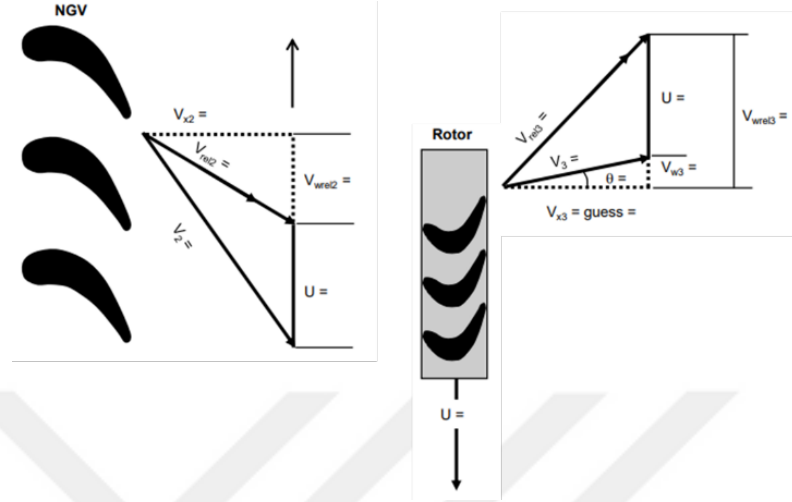


Figure 7. Velocity Triangles [2]

Airfoils have platforms which are called as hub and tip platforms. Hub, tip, leading and trailing edges and height definitions are shown in **Figure 8**. The tip definition and tip clearance control is important in a gas turbine engine design in terms of rubbing situation. Due to that, permanent deflections are need to be searched throughout a flight operation.

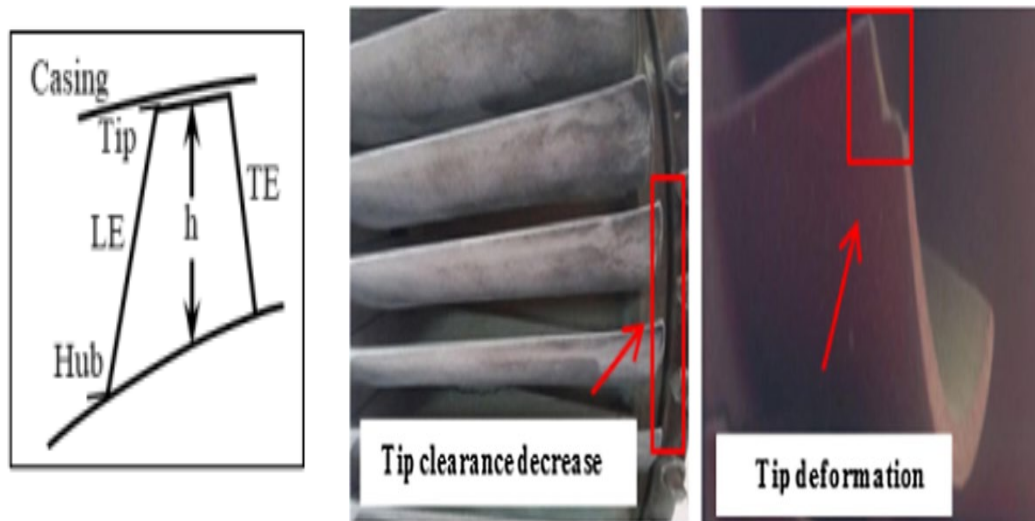


Figure 8. Airfoil definition and tip clearance notion [4]

2.2 Mechanical Structure of Airfoils

Airfoils are aerodynamically shaped parts and the design fundamental is target to evaluate energy conversion. Turbine parts are grouped into static (non-rotating) airfoils known as vanes or nozzles, and rotating airfoils known as blades. Blades are classified according to their usage area or condition. Service temperature reaches and exceeds the material melting temperature. Due to that, the cooling design is applied to the high pressure blades while power turbine blades are designed uncooled tip shrouded that is shown in **Figure 10**.

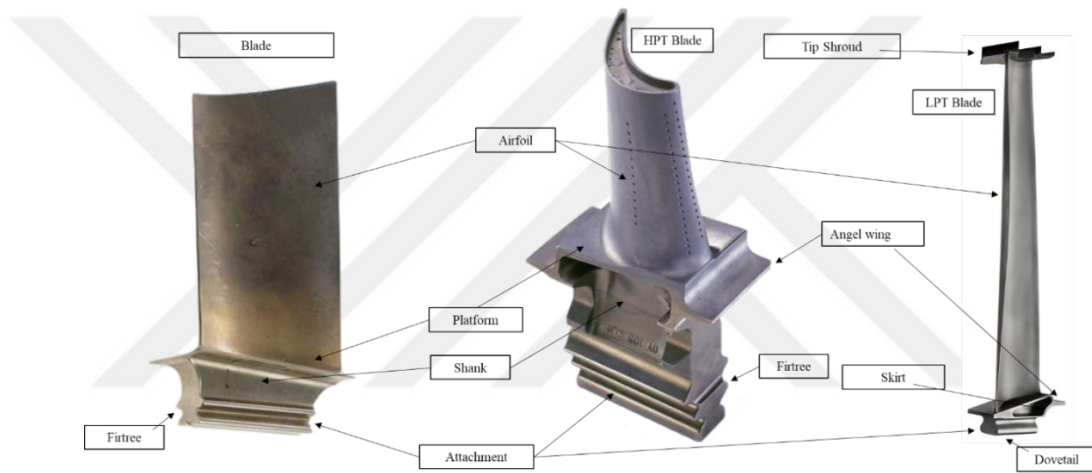


Figure 9. Blade Geometry

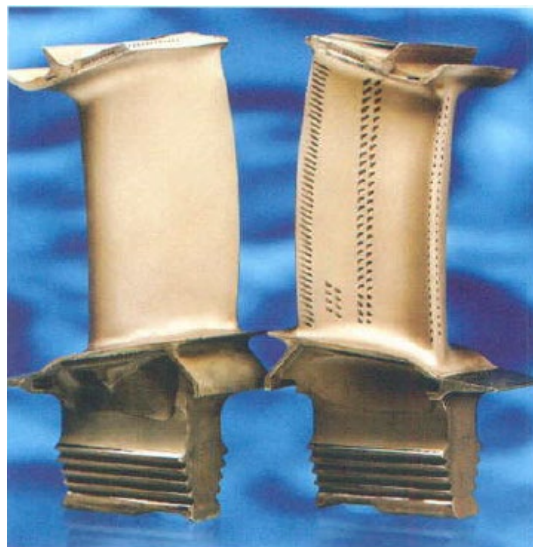


Figure 10. Cooled Blade Design [1]

2.3 General Load Distribution on Airfoil Geometry

Airfoil geometries work under compulsory aero-thermal environment. This thermal environment is composed of various loads and different physical conditions. All these loads can be grouped as aerodynamic loads, secondary air system (sas) pressure loads, thermal loads, centrifugal loads, contact or friction forces respectively which can be seen in **Figure 11**.

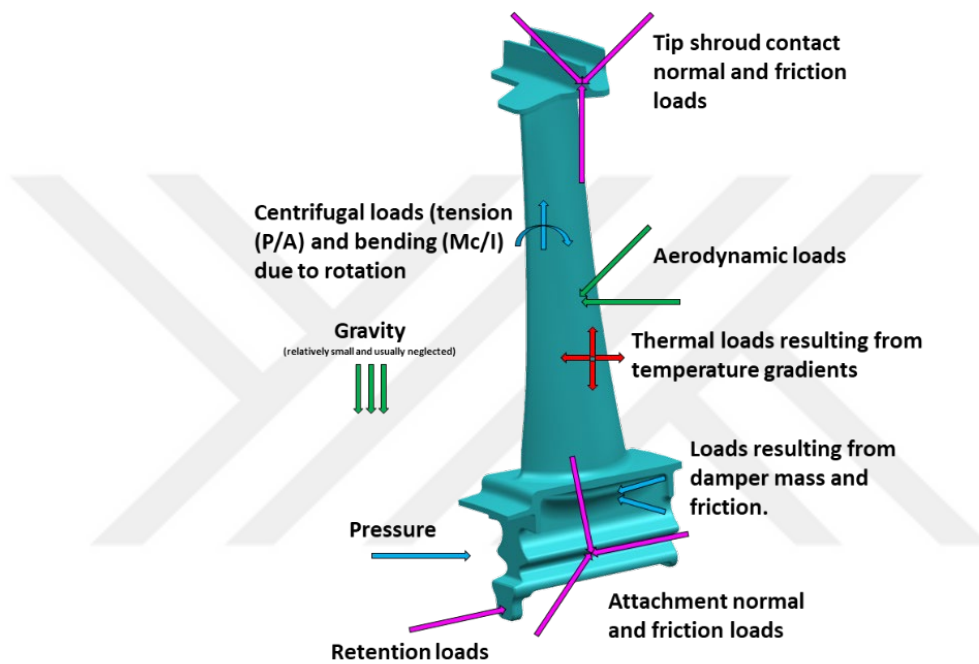


Figure 11. Load distribution on Blade Geometry

All of these forces change with time. An engine mission profile consist of ascend, descend and cruise regions which are finalized with shutdown or soackback regions. Throughout an engine mission profile, angular velocity, temperature, pressure loads and contact forces change. Huge thermal gradients are seen on parts especially in main flow region. While thermal gradients between platform and vane cause stresses, changing in rpm for rotationary parts cause tension stresses on blade-disc contact surfaces. Engine components are exposed to the heating up and cool down cycles which effect directly fatigue behavior.

2.4 Euler Turbomachinery Equation

Euler's turbomachinery equation is widely used in all types of turbomachinery. This equation, derived from the angular momentum equation determines power transfer between the fluid and the rotor blades. In pumps, fans, and compressors, the power transfer occurs into the fluid to increase its outflow rate of angular momentum over the inflow rate; in turbines, the power transfer occurs to the rotor from the fluid to decrease its outflow rate of angular momentum over the inflow rate. The power transfer to or from the fluid is simply the product of the torque and rotor angular velocity in radians per second. [5]

The aerodynamic power transfer which is the rate of work transfer as a result of the aerodynamic torque acting on the fluid control volume. The main target of the compressor is imparting work on air while turbine try to extract work from the hot gases. The main target of a turbine rotor geometry is producing work from hot gases. Due to that, turbine nozzle guide vanes accelerate the hot gases to the rotor blades. On the other hand, rotor blades increase the relative velocity of air and decrease absolute velocity. Because of that, rotor blades have more twisted shaped design with respect to the compressor blades.

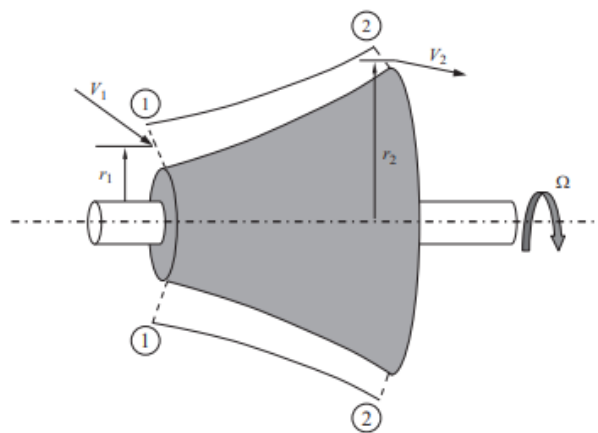


Figure 12. Flow through an axial-radial-flow turbomachinery passage between adjacent blades [5]

$$W = m (h_{t2} - h_{t1}) \quad (2.1)$$

$$(h_{t2} - h_{t1}) = (U_2 V_{\theta} - U_1 V_{\theta 1}) \quad (2.2)$$

This equation simply states that, under adiabatic conditions, the change in specific total enthalpy of the fluid flow between any two sections of a rotor equals the difference in the products of the rotor tangential velocity and flow tangential velocity at these sections. [5]

This equation further reveals that for turbines, where the work is done by the fluid, we have $h_{t2} < h_{t1}$; and for compressors, fans, and pumps, where the work is done on the fluid, we have $h_{t2} > h_{t1}$ and $U_2 V_{\theta 2} > U_1 V_{\theta 1}$. at any point in a rotor flow remains constant under adiabatic conditions (no heat transfer). This quantity is called **rothalpy** expressed as;

$$I = h_t - UV_{\theta} = h_t + \frac{V^2}{2} - UV_{\theta} = C_p T_{ts} - UV_{\theta} \quad (2.3)$$

To convert this equation into rotor frame;

$$V^2 = V_x^2 + V_y^2 + V_z^2, W^2 = W_x^2 + W_y^2 + W_z^2 \quad (2.4)$$

and $V_{\theta} = W_{\theta} + U$, where U is the local tangential velocity of the rotor.

$$I = h_s + \frac{(W_x^2 + W_r^2 + W_{\theta}^2 + 2UW_{\theta}U + U^2)}{[2 - U(W_{\theta} + U)]} \quad (2.5)$$

Euler turbomachinery equations and rothalpy definition gives us the geometric shape of the airfoils. As it is seen in the **Figure 13**, NGV's accelerate absolute velocity of hot gases and decrease total and static pressure. Accelerated hot gas enter the rotor leading edge and exit as decelerated absolute velocity and accelerated relative velocity. Total and static pressure and temperature is decreased and evaluation of the work is completed from hot gases. This process gives high rotational velocity to rotating parts and determine the load distribution on design.

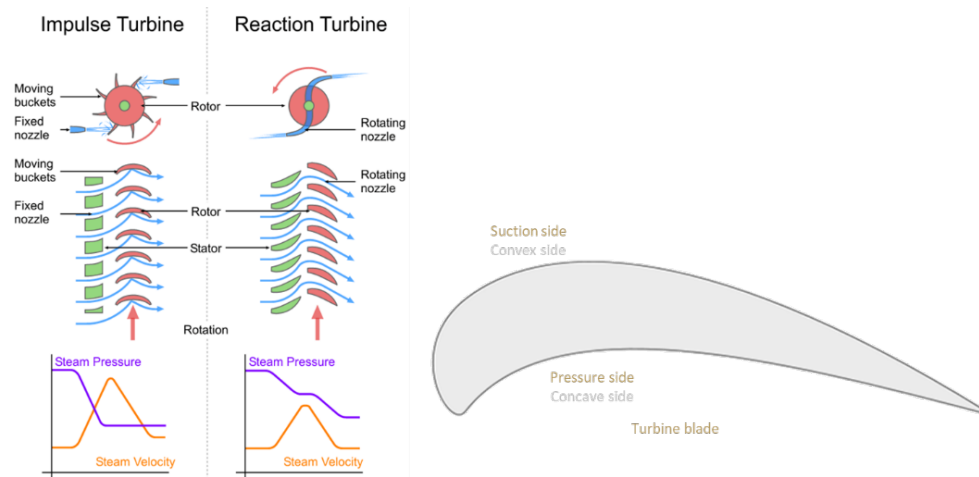


Figure 13. Basic Geometry of a Turbine Blade [6]

3. FUNDEMENTALS OF FATIGUE THEORY AND CREEP MECHANISM

3.1 Fundamentals of Fatigue Behavior

Fatigue cracks are caused by the repeated application of loads which individually would be too small to cause failure. Fatigue cracks usually initiate from the surface of a component. This is crack initiation. The crack may then propagate in a direction perpendicular to the direct stress. This is crack propagation. Finally the component is fractured. [7]

Mechanical structures are exposed to repeated loads over time that cause plastic deformations and crack initiations. While these loads directly cause plastic deformation on the part and finalized with a sudden break, they also can work within the elastic limits of the material and damage the part with very long-term repetitive loadings. This damage is called fatigue and it is classified with low cycle fatigue and high cycle fatigue. Fatigue may occur when a member is subjected to repeated cyclic loadings (due to action of fluctuating stress). The fatigue phenomenon shows itself in the form of cracks developing at particular locations in the structure. Firstly, a crack

initiated, each loading cycle initiated crack is grown in a small amount by thermal or vibration loads and it is shown in **Figure 14**.

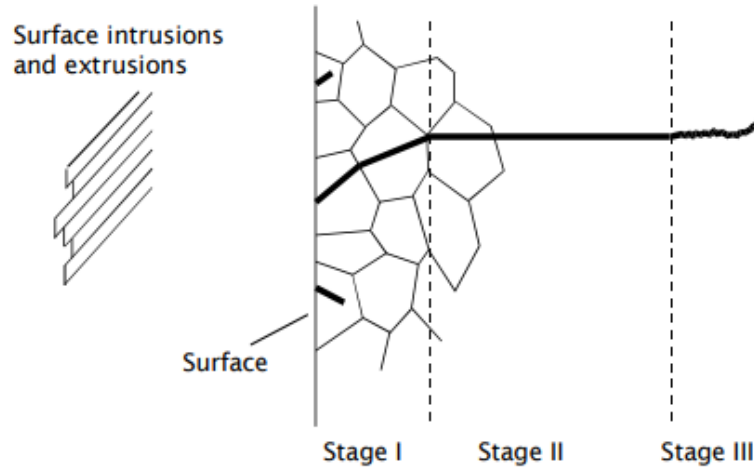


Figure 14. Three stages of Fatigue Failure [7]

The surface shows slip planes as intrusions and extrusions. This is Stage I crack growth. Stage II crack growth takes place in a direction normal to the applied stress. Finally the crack becomes unstable and fracture occurs. For many components Stage I growth occupies most of the fatigue life. [7]

In fatigue life formulations, stress level and loading conditions are often expressed with maximum stress, minimum stress, mean stress and stress amplitude.

Figure 15 shows schematically the main parameters used in fatigue theories.

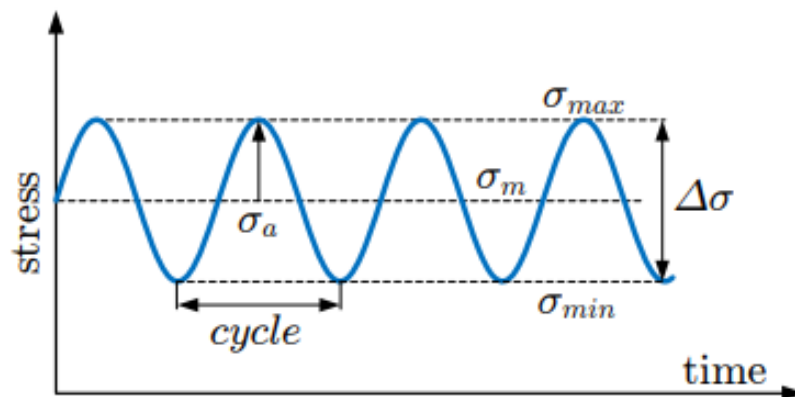


Figure 15. Stress Related Notation [8]

$\sigma_{\max}$ = Maximum Stress

$\sigma_{\min}$ = Minimum Stress

σ_a = Stress Amplitude

$$\sigma_r = \text{Stress Range} = \sigma_{\max} - \sigma_{\min} \quad (3.1)$$

$$R = \text{Stress Ratio} = \frac{\sigma_{\min}}{\sigma_{\max}} \quad (3.2)$$

$$\sigma_m = \text{Mean Stress} = 0.5[\sigma_{\max} + \sigma_{\min}] = 0.5\sigma_{\max}(1 + R) \quad (3.3)$$

$$\sigma_a = \text{Alternating Stress} = 0.5[\sigma_{\max} - \sigma_{\min}] = 0.5\sigma_{\max}(1 - R) \quad (3.4)$$

Material properties are evaluated with fatigue tests and standardized specimen geometries. Tests are completed with different loading scenarios. $R = -1$, $R = 0$, $R = 0.5$ and $R = 1$ stress ratio values are the most commonly applied stress ratios for aviation material tests. Testing for each different R ratio value means testing for each different mean stress value which is a very expensive and time consuming method. Because of the reason, $R=0$ or $R = -1$ loading scenarios are completed in material tests and empiric formulations are used for transformation of the mean stress effect.

In this respect, $R = -1$ is fully reversed loading that the test specimen is subjected to the same amount of compression and tension stress alternatingly. $R = 1$ is a static loading which means maximum and minimum stresses are equal. $R = 0$ is zero-based loading where the stress range varies between zero and positive/negative values.

Since fatigue is a highly directionally dependent phenomenon, we usually apply a directional stress component, e.g. $\sigma_x/\sigma_y/\sigma_z$ (depending on the orientation of the coordinate system) or the principal stress σ_1/σ_3 to calculate the stress amplitude, rather than a combined stress such as the Von Mises Equivalent Stress. [8]

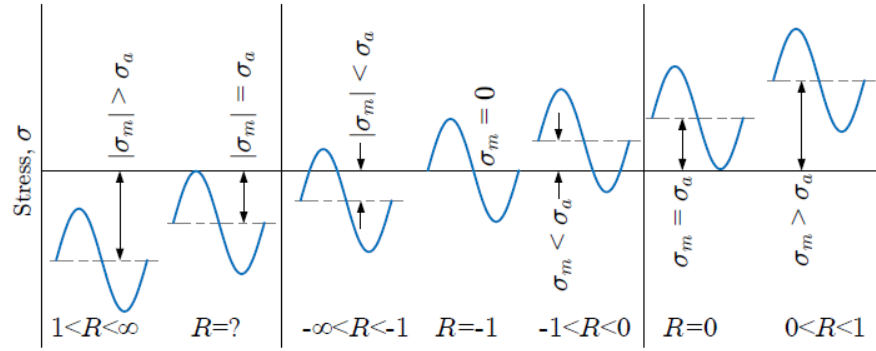


Figure 16. R - Stress Ratio [8]

3.1.1 S-N Curves and Endurance Curves

S-N curves are logarithmic graphs and obtained by material tests. Fatigue tests continue at a constant mean stress and varying stress amplitude until the specimen breaks. The reason why the tests are performed under constant average stress is that it is necessary to retest at different average stresses. Because of this difficulty, fatigue tests are often performed under fully reverse loading. The results is then interpreted as infinite life or fatigue limit that is shown in **Figure 18**. Fatigue curves are often given for $K_t = 1$ (un-notched specimens). Those curves describe the fatigue properties of a material. Actual structures are better described with S-N curves for $K_t > 1$ (notched specimens) and it is recommend to use K_t based fatigue curves for fatigue life of K_t regions. [8]

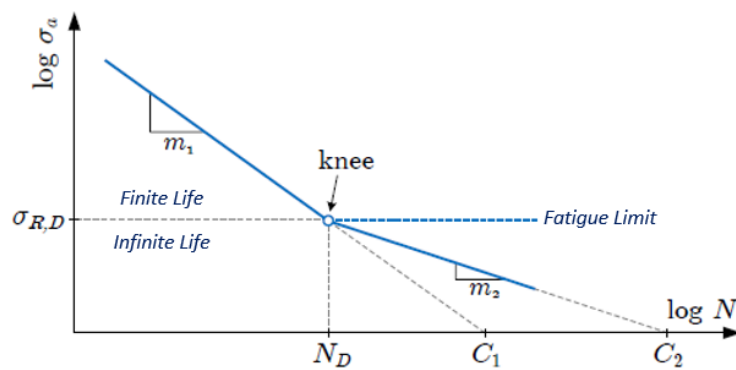


Figure 17. S-N Curve [8]

$$\sigma_a^{m_1} \cdot N = C_1 \quad (3.5)$$

$$\sigma_a^{m_2} \cdot N = C_2 \quad (3.6)$$

$$\sigma_a = \sqrt[m_1]{\frac{C_1}{N}} \quad (3.7)$$

$$\sigma_a = A \cdot N^b \quad (3.8)$$

S-N Curves are separated different regions. In low cycle fatigue region, the design is associated with high stresses (non-elastic) and relatively small number of cycles with high amplitude to failure. In a gas turbine engine, hot section components such as turbine disc, blades or nozzle guide vanes are exposed to high temperature gradients that cause high thermal stresses which result with low cycle fatigue problems. High cycle fatigue region associated with relatively low stress levels (elastic) and a large number of small amplitude cycles to failure. Blade vibration loads are an example to this small amplitude, low levels of stresses. In addition to these definitions, endurance limit corresponds the infinite life criteria, below the endurance strength and it is told about the infinite life of material.

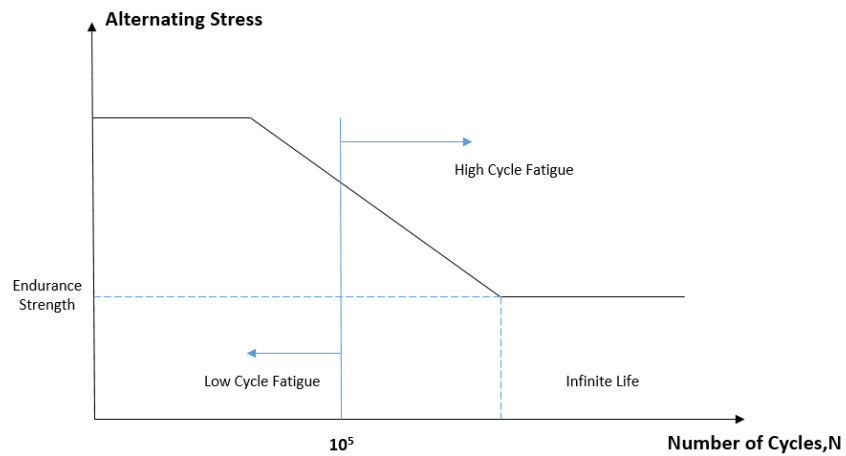


Figure 18. HCF and LCF Regions in S-N Curve

3.1.2 Mean Stress Effect in Fatigue Life

Even if the loads acting on the element are static, the stresses occurring in the section can be variable. These stresses are multi-axial and contain average stress effects. Since material fatigue tests are obtained using constant mean stress values, it is imperative to consider this difference between the actual situation and tests. Different methods such as Goodman-Haigh diagram and empirical formulations are developed to examine the mean stress effects. As it is shown in **Figure 19**, the average stress effect on the tensile side negatively affects the fatigue life and should be taken into account for ductile cast iron.

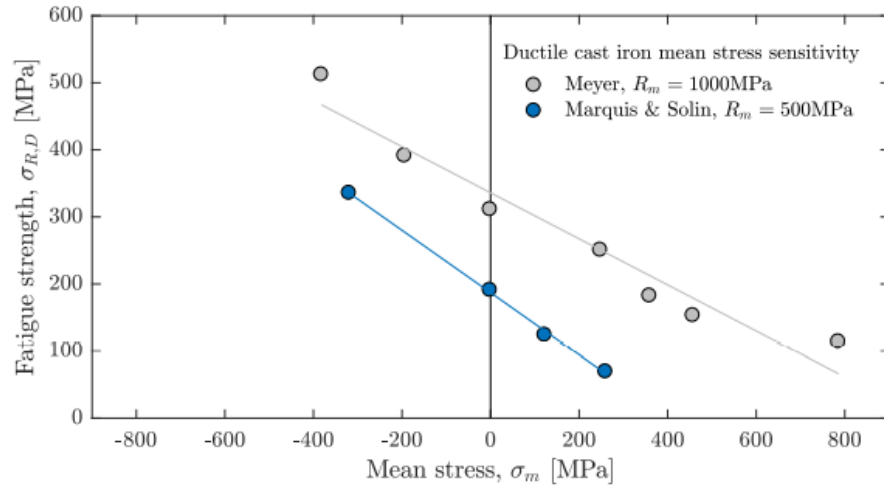


Figure 19. Mean Stress Dependency [8]

S-N Curves are improved for a defined R Ratio and some empirical formulas or methods are improved to reflect the mean stress effect in calculations. The effect of mean stress is reflected by Goodman, Gerber, Soderberg or Modified-Goodman Lines. These are shown in **Figure 20** as Haigh Diagram. Haigh diagram plots static stress in x-axis and plots oscillatory stress in y axis and drawn the line between these points. Above of the line corresponds the finite life region while below corresponds infinite life region.

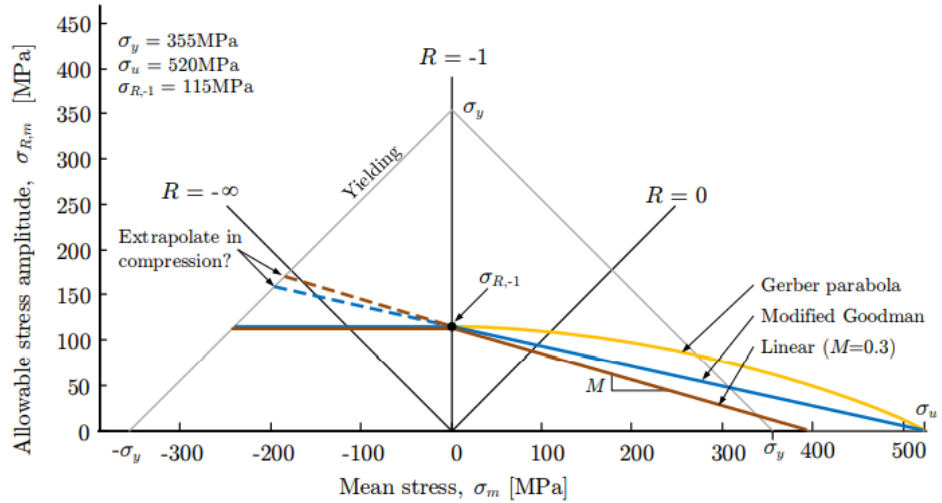


Figure 20. Haigh Diagram [8]

Goodman draws the line between alternating and tensile strength while Soderberg draws the line between alternating and yield strength which ensure more conservative behavior for fatigue calculation. For compressive mean stresses, the values are extrapolated through the correction line [8], as illustrated with dashed lines in **Figure 20**. However, to be stay in safe side, dashed lines are non used and fatigue calculations are completed with using flat line in Haigh diagram which is called as reverse or negative Goodman line.

3.1.3 Fundamental of Low Cycle Fatigue

Engine components are separated hot and cold parts, combustion chamber and turbine is called as hot parts while compressor parts are called as cold parts. Especially in turbine side, parts are exposed to high aerothermal loads and due to the heat up and cool down cycles, it may turn cyclic plastic strain on parts. When plastic strains are induced to the engine components, LCF mechanism works which is characterized by high amplitude low frequency plastic strain.

Most of the turbine parts have feature like holes and notches. These features increase the stress level and plastic strains occur. Turbine blades and vanes usually

have a configuration at the base referred to as a dove tail or fir tree. This feature is used to attach the blade to the turbine disk. As engine rotational speed increases centrifugal forces result in local plastic strains at the attachment surfaces resulting in LCF damage.

Experimentally, it is easier to measure the strain directly with a strain gauge, than measure the stress. In order to calculate fatigue damage, the corresponding stress at the same location of the measured strain is needed. The Ramberg-Osgood relationship is used to calculate the corresponding stress.

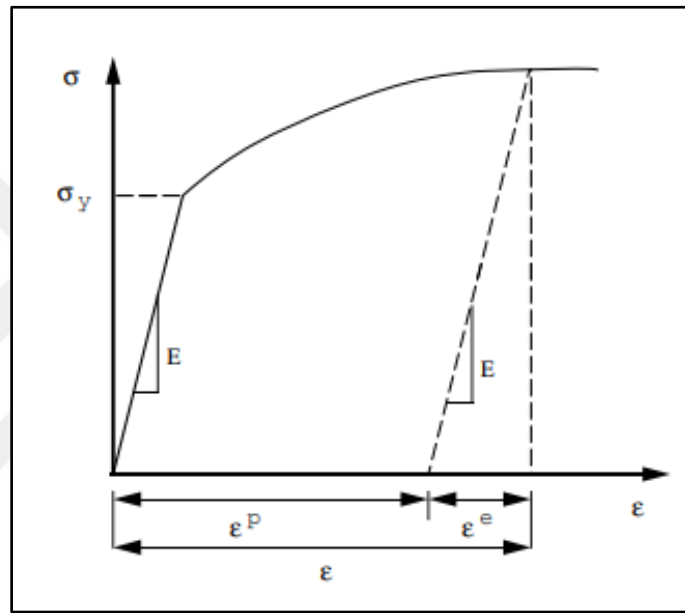


Figure 21. Stress-Strain Behavior for Monotonic Loading [7]

In crystalline materials, it is seen that the material gets stronger as the amount of strain applied to the material increases. During the tensile test, removing the load on the sample after passing the yield strength and start the test again, it is observed that the plastic deformation begins at a higher stress value, in other words, the material becomes stronger. This shows that as the amount of strain in the sample increases, some changes take place in the structure of the material, which complicates the dislocation movement.

In this regard, Ramberg-Osgood equation explains elastic and plastic behavior with power law. n is called the cyclic strain hardening exponent and the stress dimensioned material parameter K is called the cyclic hardening coefficient.

$$\epsilon = \frac{\sigma}{E} + \frac{\sigma^{1/n}}{K} \quad (3.9)$$

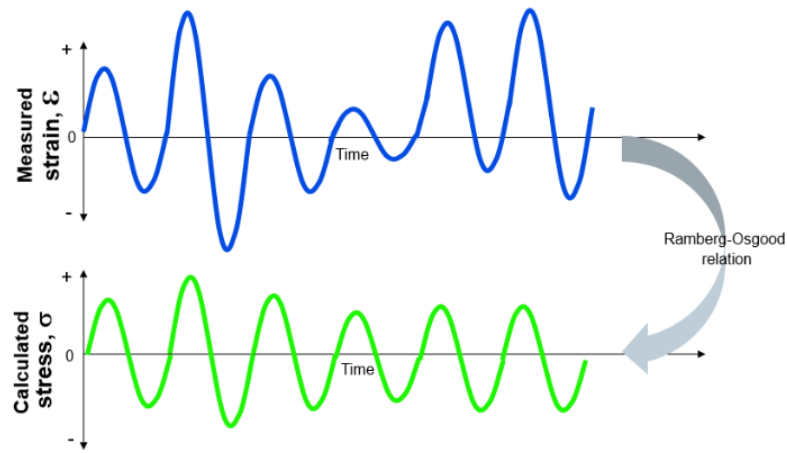


Figure 22. Strain time history and Ramberg-Osgood relation [9]

With the Ramberg-Osgood relation, corresponding stresses are evaluated for measured strain. This new stress-strain time history pair is called as local stress-strain time history. [9]

3.1.4 Coffin Manson Curve and Damage Calculation

The Coffin-Manson curve defines number of cycles versus amplitude of strain cycles of a material before failure. Coffin-Manson Equation describes the strain-life curve according to the strength ductility properties and Young Modulus of materials [9]. It contains both elastic and plastic region. Coffin-Manson is a mathematical model relating to total strain and cycles to failure. Elastic strain dominates at high cycle counts with low amplitude strain cycles while plastic strain dominates at low cycle counts at high amplitude strain cycles as it is shown in **Figure 24**.

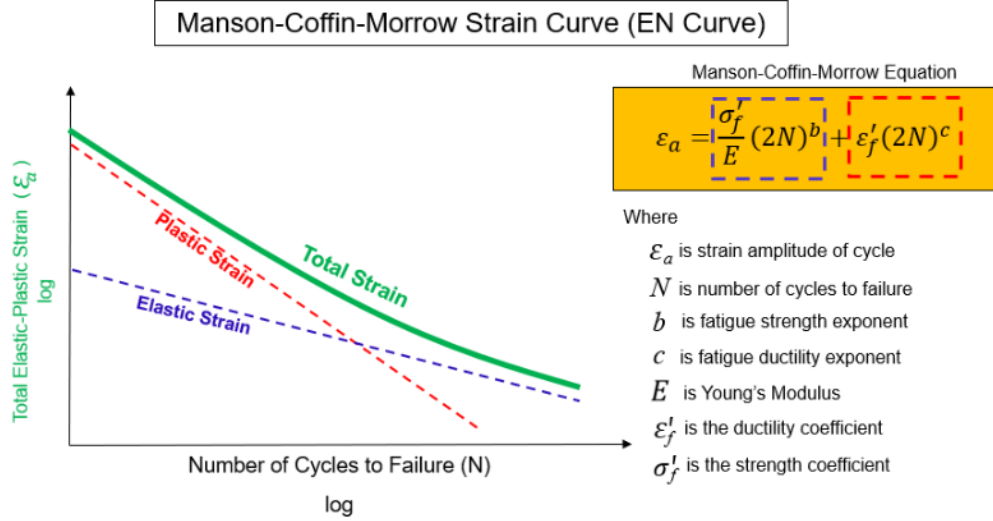


Figure 23. Coffin-Manson Equation [9]

$$\epsilon_a = \frac{\sigma_f}{E} (2N)^b + \epsilon_f (2N)^c \quad (3.10)$$

Damage can be calculated using the cycles from the time history data and compare with Coffin Manson curve. The number of strain cycles (n) at a specific amplitude in the field data are compared to the number of cycles to failure (N) the material can withstand at that same amplitude from the ϵ - N Curve. The damage (D) is calculated. [9]

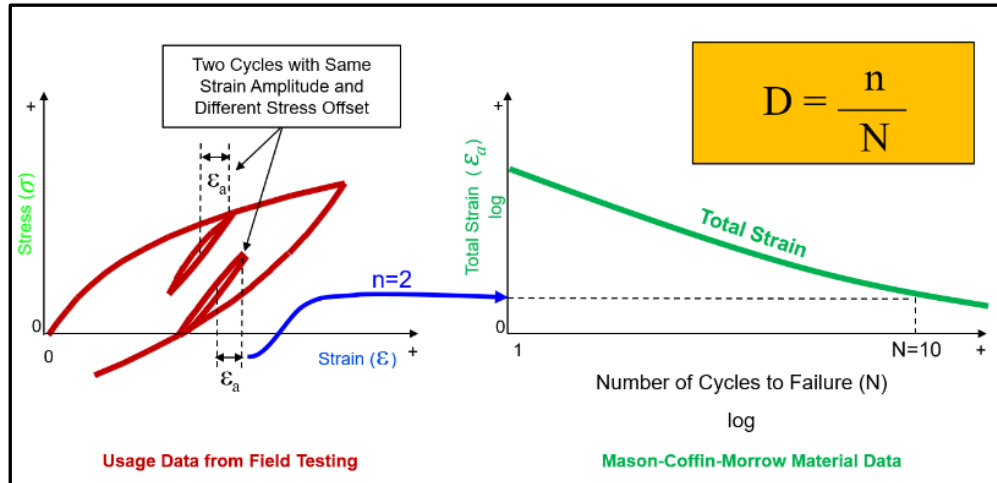


Figure 24. Damage Calculation using Coffin Manson Curve [9]

3.1.5 NASA Life Methodology

Although fatigue tests are performed by adhering to uniaxial stresses, mechanical components are exposed to multiaxial stresses. In a gas turbine engine, components have critical locations these experience significant multi-axial stress statements. These stresses consist of 3 orthogonal $\sigma_x, \sigma_y, \sigma_z$ and 3 shear stresses $\sigma_{xy}, \sigma_{yz}, \sigma_{zx}$. There is a maximum and minimum stress per cycle in an every cyclic loading which is defined with S1 and S3 stresses. Every cyclic load scenario has also a mean stress effect and it must be determined. On the other hand, material tests are completed with uniaxial loading and ignoring the mean stress effect. To be able to use material fatigue test curves, multiaxial stresses are converted into an equivalent uniaxial stress. Empirical formulas are improved to convert multi-axial stresses into an uniaxial stress to use material tests SN curves. In this regard, NASA Life methodology use Manson Mc-Knight and SWT (Smith Watson Topper) methodologies to evaluate an uniaxial equivalent stress. This method uses following equation. [10]

$$\sigma_m = SIGN(\sigma_{xm} + \sigma_{ym} + \sigma_{zm}) \quad (3.11)$$

$$\sigma_a = \frac{\sqrt{2}}{2} \sqrt{(\sigma_{xa} - \sigma_{ya})^2 + (\sigma_{ya} - \sigma_{za})^2 + (\sigma_{za} - \sigma_{xa})^2 + 6(\tau_{xya}^2 + \tau_{yza}^2 + \tau_{zxa}^2)}$$

The presence of positive mean stresses negatively affects LCF life times. LCF Material curves are evaluated with specific R values. It is hard to evaluate fatigue curves for every R ratio. So, it is need to be reflected mean stress effect to fatigue life calculations. Smith-Watson-Topper (SWT) Method and Walker Method are used in NASA Life procedure. SWT uses R= -1 test curves. Stress results which have different

R ratio are reflected to the $R = -1$ fully reversed S-N curves. This method uses following equation, m material constant is used 0.5 according to SWT Equation.

$$\sigma_{aw} = 0.5 \sigma_{max}(1 - R)^m \quad (3.12)$$

On the other hand, Walker method uses $R=0$ test curves. Stress results which have different R ratio are reflected to the $R=0$ material curves, m material constant change with temperature. So, it can be said SWT equation is a special form of Walker Equation. SWT Correlation is more conservative method than Walker Correlation and Walker Method is more close to the test results that is in **Figure 25**.

$$\sigma_{aw} = \sigma_a(1 - R)^{m-1} \quad (3.13)$$

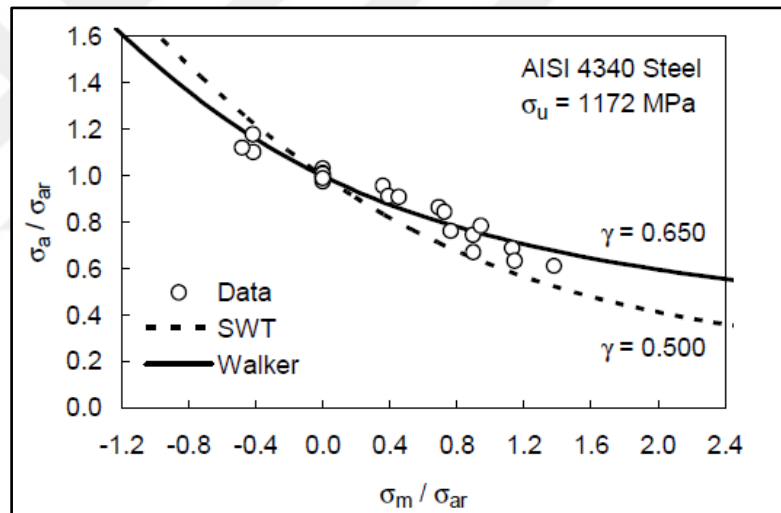


Figure 25. SWT-Walker and Test Data Comparison [10]

3.2 Fundamentals of the Creep Fatigue Behavior

Creep is a time dependent phenomenon that elongation of a structure occurs under a constant load and high temperature ambient conditions even if it is less than the elastic limit of the material. This phenomenon, which is a time dependent function, causes the total elongation values to reach the critical value and part failure. Creep is associated with time-dependent plasticity under a fixed stress at an elevated

temperature. The temperature condition is generally defined greater than roughly $0.4-0.5T_m$, where T_m is the absolute service temperature of the material. According to this phenomenon, material deforms continuously with time and it is exposed to plasticity or rupture. Due to the fact that, material plasticity behavior is need to be investigated. With this effect, parts are exposed to permanent plastic deformations which affects not only durability, but also clearances with other parts in terms of engine performance and assembly- disassembly conditions.

There are 3 stages of creep mechanism which can be classified as primary, secondary and tertiary regions respectively. First region is called as primary creep stage where the creep rate is decreasing with increasing plastic strain. Dislocations are effective on the material in primary stage. The fatigue life of material is related with the slope of the primary stage curve [11]. The hardening and softening effects caused by the change of grain boundaries are tried to be modeled with hardening material models the primary region of creep and shown in **Figure 26**. The plasticity is described in a graph for constant stress (a) and constant strain rate (b)

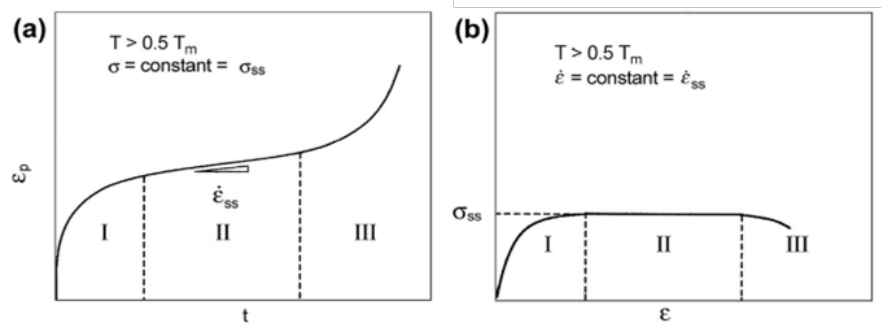


Figure 26. Constant Stress Rate(a) vs Constant Strain Rate(b) Creep Behavior [12]

In secondary creep stage, pile up of dislocations is equilibrated with dislocation glides. During this steady-state region, strain increases linearly with time while creep strain rate is constant. Due to the fact that, deformation continue for a long time. Generally, cruise regions throughout a flight cycle is corresponds this long time period.

In tertiary region, an abrupt change is seen as exponential curve. Some type of vacancies occur in material microstructure in tertiary region and it leads to the fracture of the component.

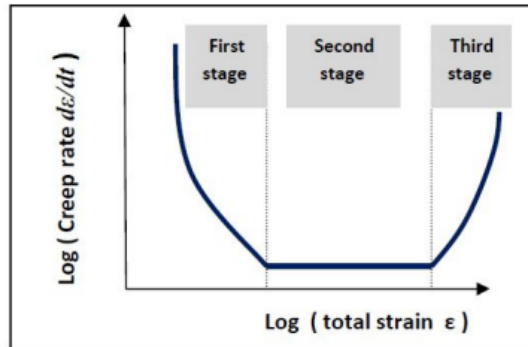


Figure 27. Creep Strain Rate versus Total Strain in a log-log scale [11]

3.3 Creep Mechanism and Macroscopic Relationship

Creep effects the material structure with rearrangement of atoms and may cause fracture finally. From primary stage to tertiary stage, slips of the grain boundaries cause dislocation motions under high stresses, by thermal activation energy, dislocation piles up and material hardens. Then, some vacancies may occur and result with fracture.

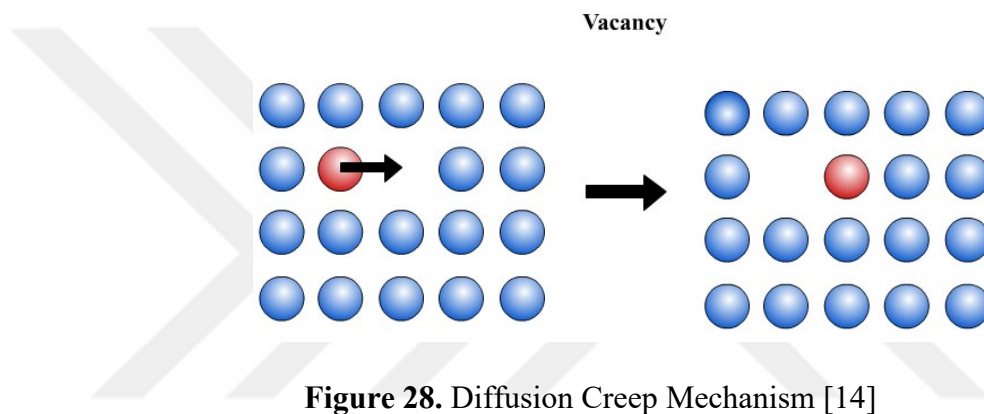
Creep mechanisms are take place during creep of the material which are dislocation creep (glide), diffusional creep and grain boundary sliding (GBS). [13]

3.3.1 Diffusion Creep

According to perfect lattice with no defects so the atoms cannot move from site to site. All the atoms have thermal energy and therefore vibrate about their stable positions. In a real material there will be defects, such as the vacancies shown in **Figure 28**. These allow atoms within the structure to move from one atomic site to another. However, the atoms cannot move freely into the vacancies. They must 'push' other atoms out of the way to move from one site to another. This means that there is

an energy barrier which must be overcome when an atom changes site. If an atom has enough thermal energy ($> Q$), then it can cross over the energy barrier. [14]

At high temperatures, the tensile stress gives direction and speed to the event of moving of the atoms at the edges of the grains. Then, atoms act in the direction of this tension and fill the grain spaces above and below. Thus, the grain size grows in the direction of the tensile stress and in this direction cause the material plasticity. This process is used to create spaces between the grains, contributes to the shifting of grain boundaries. [14]



3.3.1.1.1 Interstitial Diffusion

In this case, the diffusing atom is not on a lattice site but on gap between atoms (interstice) as it is shown in **Figure 29**. The diffusing atom is free to move throughout the gap. This is when a smaller atom on an interstitial site diffuses through the lattice. There is still an energy barrier to overcome with this mechanism, but it is lower due to the smaller atom, and there are also lots of vacant sites for it to diffuse.

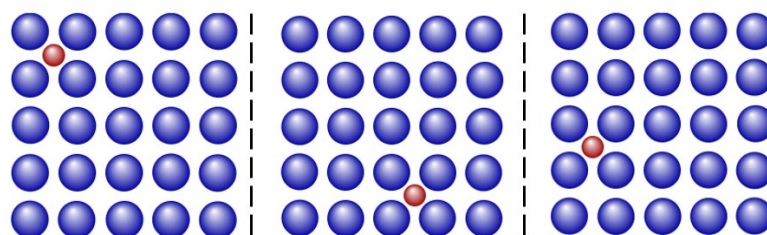


Figure 29. Interstitial Diffusion [14]

3.3.1.1.2 Substitutional Diffusion

Atoms move from one atomic site to another atomic site in substitutional diffusion mechanism as it is shown in **Figure 31**. High energy is required to swap atoms from one place to another place. Vacant site of the lattice gives permission to atoms to change their places with others. Because, occurrence of the vacant site requires less energy barrier for movement of atoms. More vacancies effect and increase the rate of diffusion [15]. This type of vacancies may occur after casting process of materials. Due to the fact that, substitutional diffusion mechanism effect the creep behavior of casting parts. In **Figure 30**, the substitutional diffusion mechanism is observed.

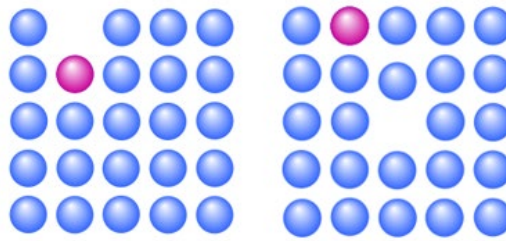


Figure 30. Substitutional Diffusion [15]

3.3.2 Dislocation Creep

Dislocation creep mechanism is explained, when edge dislocations encounter obstacles in material, dislocations start to climb with the thermal energy. Thus, ascending dislocations get the opportunity to progress by getting rid of the limiting obstacles and cause plastic deformation. [15]

Dislocation creep is a mechanism which involves motion of dislocations. This is the mechanism that high stresses and low temperatures cause the dislocation motions [15]. With higher stresses, it is common for a type of creep to occur that involves

motion of dislocations, particularly in metals, where dislocation densities tend to be high. Provided the stress is below the yield stress, macroscopic plasticity, occurring predominantly via dislocation glide. However, with stresses start to approach the yield stress, and are maintained for extended periods, progressive dislocation motion, and hence macroscopic plastic deformation may occur.

According to **Figure 32**, as the temperature is increased the formation of vacancies becomes more favorable and so at higher temperatures more vacancies are present in crystal structure. As stress is increased there is a greater force for diffusion parallel to the shear stress and hence dislocation shows net motion (glide). For higher values of stress and temperature, the dislocation moves further in the same time period and hence deformation via dislocation creep occurs a greater strain rate. [15]

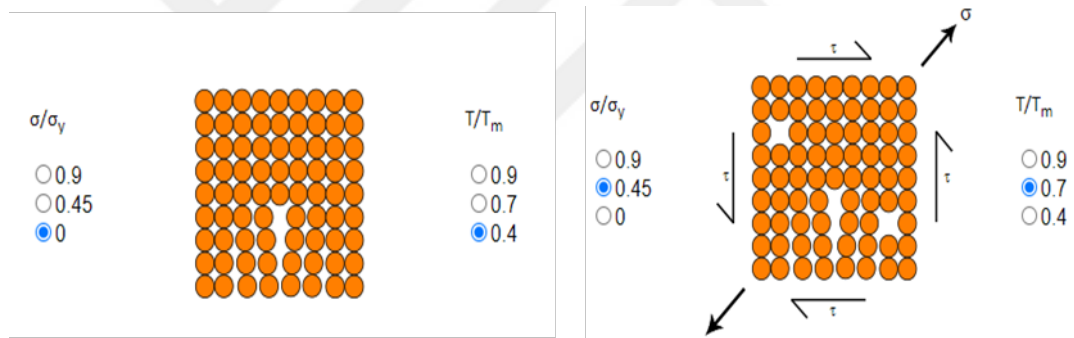


Figure 31. Dislocation Creep Mechanism [15]

3.3.3 Coble Creep Mechanism

Mechanisms of the creep tend to be complex. However, creep mechanisms almost always involve diffusion of some sort. Diffusional mechanisms are progressive with time. Due to the fact that, it is about how the time dependence occurs. Creep deformation is caused by shape changing (deviatoric) component of the stress or Von Mises. Because, hydrostatic component has no effect, creep deformation occurs at constant volume. [15]. Dislocation cores or grain boundaries play an important role of the speed of the diffusion paths. Atoms are redistributed and shape changing is

occurred. When this redistribution occurs on the scale of the grain with the diffusion occurring throughout the grain boundaries, it is named as Coble Creep. **Figure 32** shows the temperature and stress effect how the creep mechanism work. According to this, when σ is increased, there is a greater driving force for diffusion towards the "polar" regions from the "equatorial" regions and so, for a given T , the grain deforms faster at higher stress. [15]

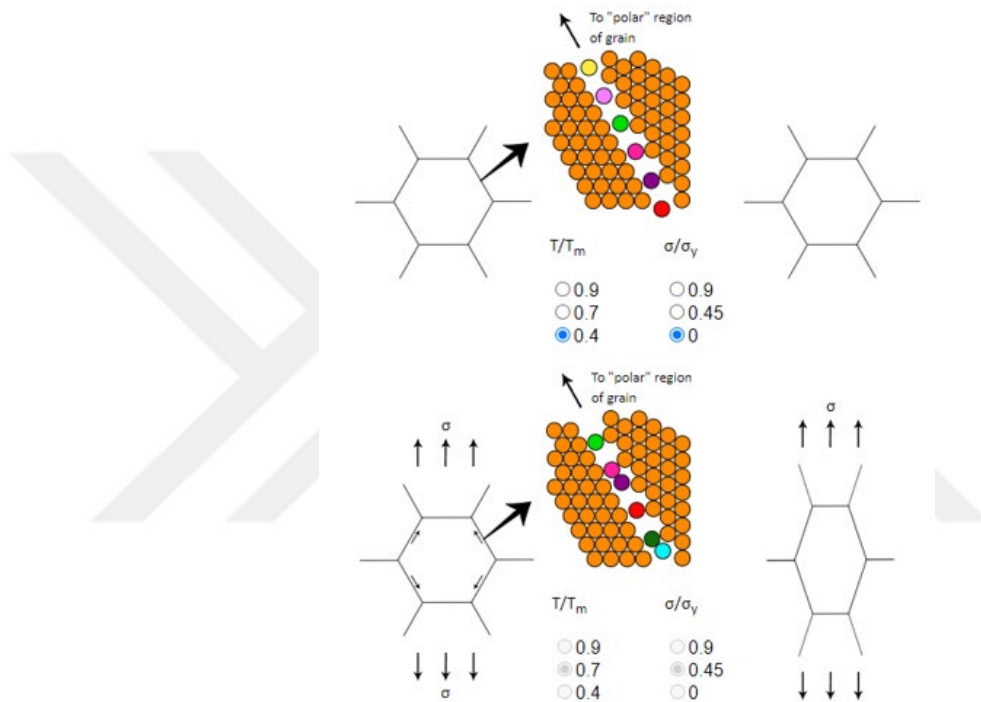


Figure 32. Coble Creep Mechanism [15]

Applied higher stress increase the deformation. The driving force cause a migration of the material from equatorial region to polar region and it creates hydrostatic compression stresses on equatorial region and hydrostatic tensile stresses on polar region. Longitudinal extensions and lateral contractions show the effect of tensile and compressive hydrostatic force in **Figure 32**. As a result of the extensions and contradictions, atoms try to move more crowded regions to open regions. Hence diffusive flux is considered as a migration of vacancies in the opposite direction to the

motion of atoms. Diffusion which is on the grain boundaries require low activation energy. Due to that, Coble creep mechanism is seen low temperatures and fine grain size.

3.3.4 Nabarro - Herring Creep Mechanism

This type of creep mechanism is seen as diffusion within the interior (lattice) of the grain rather than the grain boundaries. If the grains are relatively large, there is a considerably greater sectional area available via lattice paths. Due to that, N-H type creep mechanism require higher activation energy. This type of creep mechanism is seen large grains or single grains at higher temperature. High pressure turbine working environment may correspond or cause N-H Creep mechanism. [15]

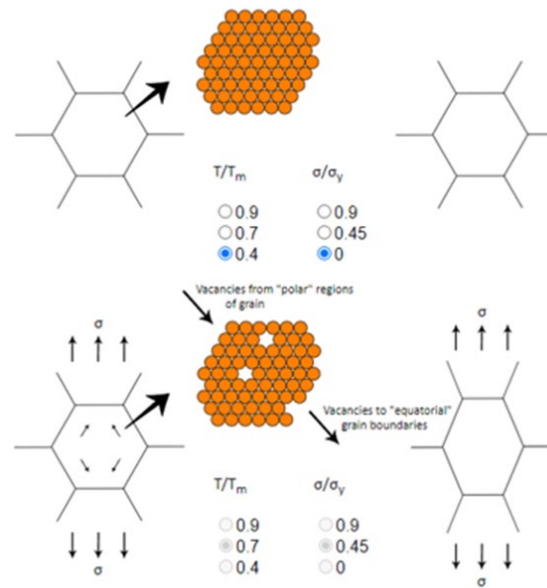


Figure 33. N-H Creep Mechanism [15]

As the temperature is increased, the formation of vacancies becomes more favor, and so at higher temperatures more vacancies are present in the crystal structure. As the σ is increased the driving force for diffusion increases towards the top of the grain and so the rate of deformation increases as it is shown in **Figure 33**.

3.4 Rheological Material Models of Plasticity and Viscoplasticity

Material plasticity, viscoelasticity and viscoplasticity behaviors are explained with Rheological models. These models help to understand material behaviors under cyclic loadings. Rheological models consist from spring element, friction element and damping element. Material plasticity models are grouped with rate dependent and rate independent models and separated isotropic-kinematic-combined hardening material models and viscous material behaviors.

3.4.1 Isotropic and Kinematic Hardening Rheological Models

Gas turbine components work under compulsory thermal environment. Especially, high and low pressure turbine parts exposure heat up and cool down cycles which cause cyclic thermal stresses. When thermal stresses reach yield strength and this cause dislocation movements and plasticity.

Atomic bonds behave as a spring. During the plasticity, material stretch and energy is stored. Load should be increased to evaluate more strain on parts. Because, dislocations get stuck and plastic deformation increase dislocation density and generate more obstacles. This is the hardening effect of plasticity on materials.

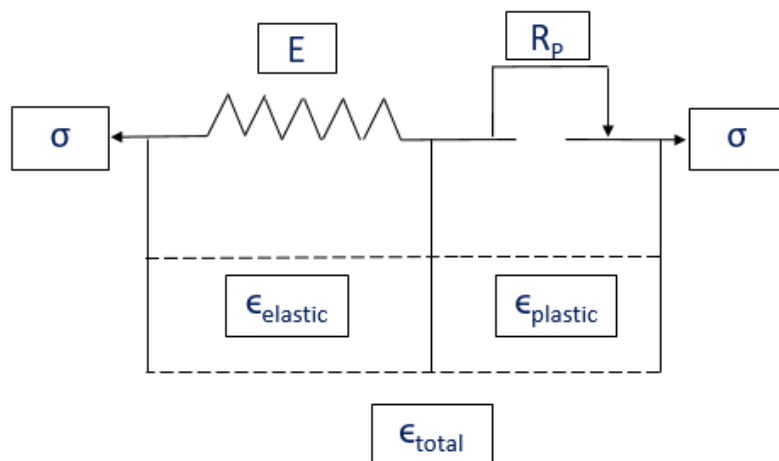


Figure 34. Rheological Model of Isotropic Hardening [16]

According to Rheological model of Isotropic Hardening rule which is shown in **Figure 34**, R_p is defined as a function of equivalent plastic strain. It means that applying cyclic loads, increase plastic strain in tension and decrease in compression. This quantity measures the material experienced strain. R_p is corresponded as friction element in Rheological model. It means that it must be overcome some friction stress until there is a sliding motion of element that gives us plastic deformation.

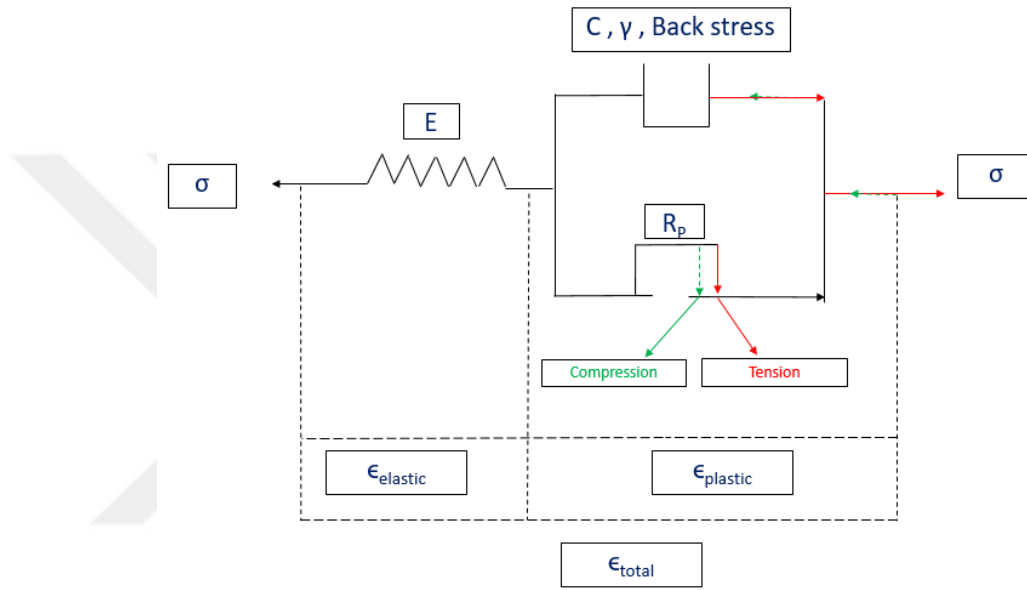


Figure 35. The Rheological Model of Kinematic Hardening [16]

According to the Rheological model of kinematic hardening which is shown in **Figure 35**, the difference is seen with a damping element when it is compared with isotropic hardening rheological model. When applied stress is bigger than the yield strength, R_p element is shifted to the right side, yield strength is overcome and plasticity is occurred. On the other hand, damping element stores the energy during the tension loading. Then the loading way reversed and compression loading is applied, stored energy on damping element give us as back stress which makes it easier to get back yielding. In this respect, isotropic hardening is independent from loading direction. If the stress increases in tension, it does the same in compression. As a result

of this effect, isotropic hardening increases the elastic domain. On the other hand, the nature of material is different from isotropic hardening rule.

In the structure of material, dislocations move when it is faced with plasticity. If it is assumed such a dislocation moving through crystals, it may end up at a grain boundary. It will not easy to move further to other grain. Because, next grain has different crystal orientation. Dislocations pile up at boundaries in front of the obstacles. Residual stress fields of dislocations superimposed during piling up. It comes to yielding, residual stress exert a back stress that makes it easier lower stresses that the dislocation move again in the reverse direction. Yielding is occurred below the yield strength under reverse loading and it is the explanation of the Bauschinger effect. Kinematic and Isotropic hardening rules differ in this point. As it is shown in **Figure 36**, kinematic hardening model shift the center of elastic domain up in loading direction. When both hardening models are compared, kinematic hardening model reflect the dependency of loading direction in cyclic loads.

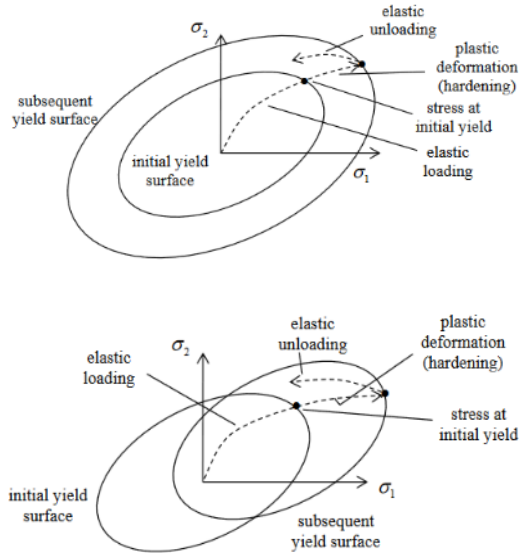


Figure 36. Isotropic Hardening vs. Kinematic Hardening [17]

The hardening rule states that the yield criterion changes with work hardening and/or with kinematic hardening. The main difference between isotropic and kinematic hardening model is dependency to the load direction. Kinematic hardening material models reflect Bauschinger effect better than isotropic hardening models. The main reason is that back stress term α contribute to reverse yielding and the yield surface shift. Back stress α term consist of linear hardening modulus and dynamic recovery constant according to Armstrong and Frederick Equation. Due to that, back stress terms has linear behavior that means increasing of the stress cause more plastic strain. On the other hand, dynamic recovery constant of the back stress term cause nonlinear behavior. It is the explanation of that the dislocations are not only locked but also recovered along the grain boundary.

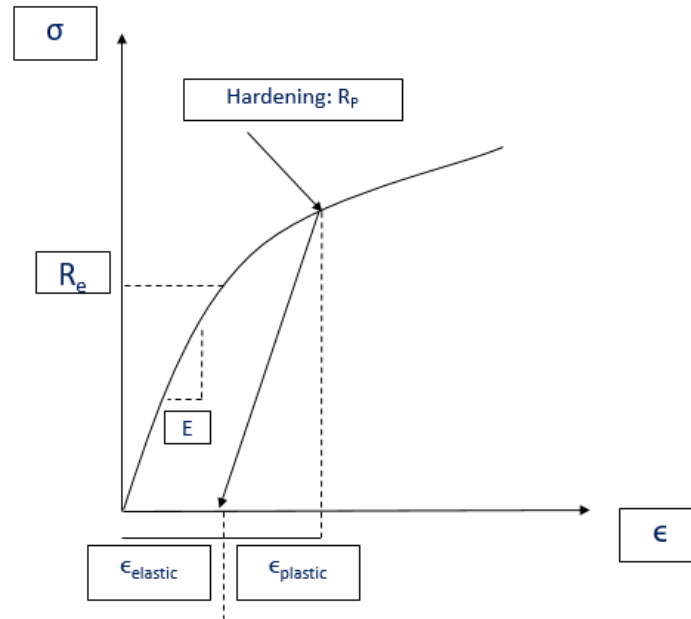


Figure 37. Plasticity with Isotropic Hardening

$$\sigma = E \cdot \epsilon_e = E (\epsilon - \epsilon_p) \quad (3.14)$$

$$\emptyset = |\sigma| - R_e < 0 \text{ (elastic loading)} \quad (3.15)$$

$$\emptyset = |\sigma| - R_e = 0 \text{ (plastic loading)} \quad (3.16)$$

$$\text{Yield function: } \emptyset = |\sigma| - R_p \leq 0 \quad (3.17)$$

$$\text{Isotropic Hardening Rule : } R_p \bar{\epsilon}_p \quad (3.18)$$

$$\text{Accumulated Plastic Strain : } \bar{\epsilon}_p = \int \epsilon_p dt \quad (3.19)$$

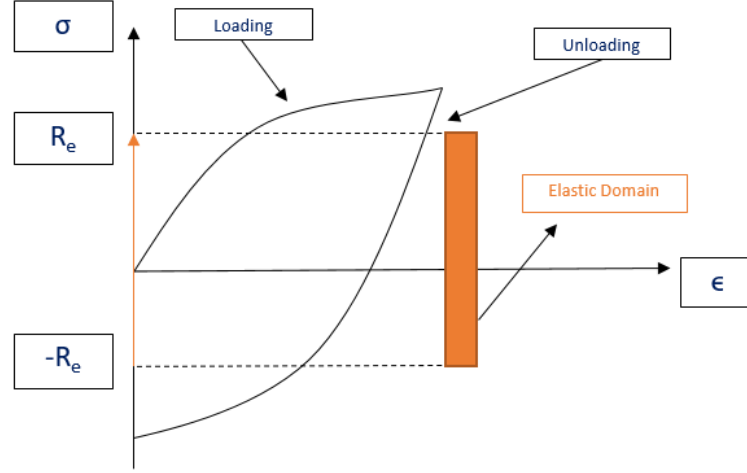


Figure 38. σ - ϵ graph (Isotropic Hardening Material Model)

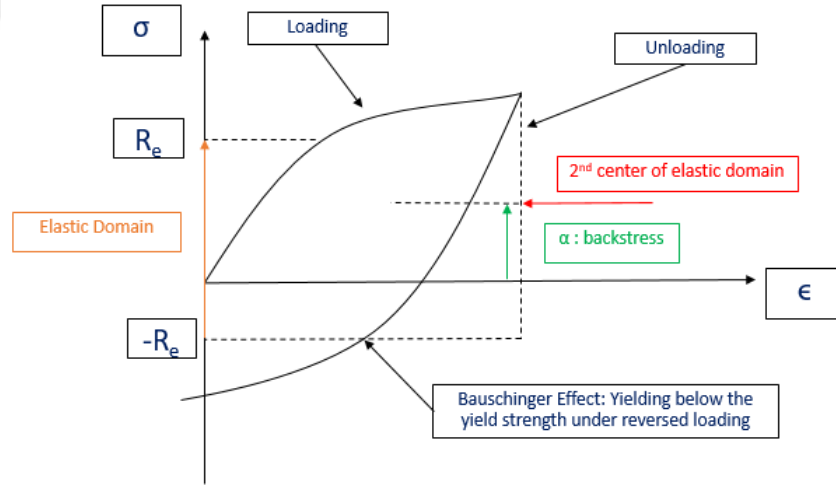


Figure 39. σ - ϵ graph (Kinematic Hardening Material Model)

$$\sigma = E \cdot \epsilon_e = E (\epsilon - \epsilon_p)$$

$$\emptyset = |\sigma| - R_e < 0 \text{ (elastic loading)}$$

$$\emptyset = |\sigma| - R_e = 0 \text{ (plastic loading)}$$

$$\text{Yield function: } \emptyset = |\sigma - \alpha| - R_e \leq 0 \quad (3.20)$$

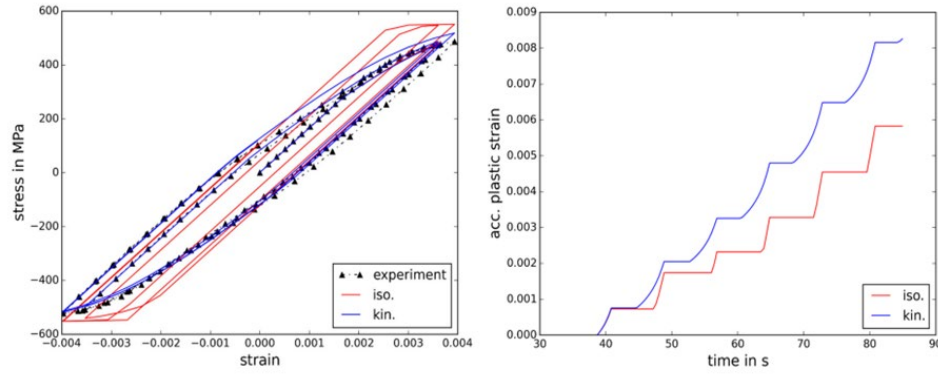


Figure 40. Comparison of Isotropic and Kinematic Hardening for SiMo51 Material

[18]

According to comparison of the hardening rules, it is shown in **Figure 40** that kinematic hardening material models reflect material behavior better than isotropic hardening material models. It is also explained with **Figure 38**, while isotropic hardening models increases elastic domain and low plastic strains are evaluated, kinematic hardening model is already start to yield and more plastic strain is evaluated, but isotropic hardening model is just on elastic domain.

3.4.2 Viscoelasticity and Viscoplasticity Rheological Models

In high temperature conditions, additional mechanisms occur in material. Due to the creep phenomenon, rate dependent material models are need to be established to evaluate more plastic strain and reach the real material behavior. Creep phenomenon differs from time-independent plastic models. The elongation on the material increases with time under constant load and high temperature working environment. Because of that, creep phenomenon is a time dependent event and strain values increase under constant load with time. Time or rate dependent term is the reflection of the material viscous behavior. Because, additional mechanisms within the material counteract the rate at which plastic effects occur with their viscous behavior. Viscoelastic material behavior is explained with another rheological model. As it is shown in **Figure 41**,

viscoelasticity rheological model shows the damper element just strain depending on stress and it is independent from the hardening effects of material.

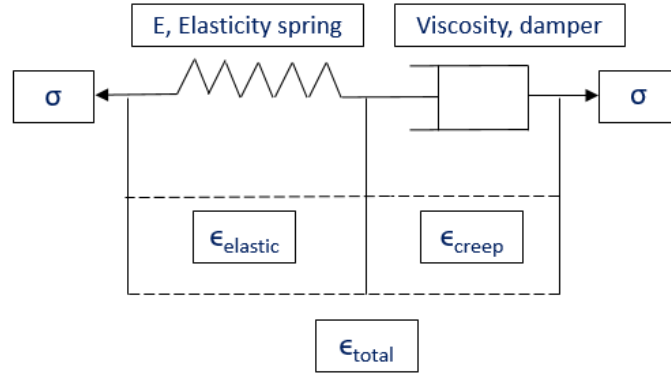


Figure 41. Viscoelasticity Rheological Model [16]

Under cyclic loading condition, there is not any connection between plasticity hardening effects and creep. To reflect the hardening effects with creep strains, viscoplasticity rheological models are improved. As it is seen in **Figure 42**, by connecting the damper element in series with the plastic part, creep strains can be associated with hardening effects. It is a compromise from the real coupled material behavior of time dependent and time independent effects. But it provides better prediction than the decoupled solution viscoelastic models.

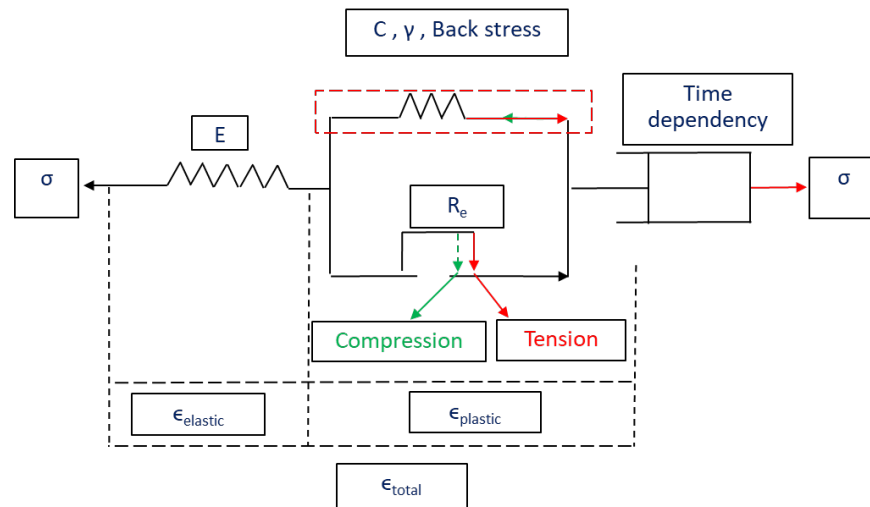


Figure 42. Viscoplasticity Model-1

According to viscoplasticity rheological model-1, there is not any interaction between creep and plasticity. Damper element just creeps depending on stress level but it is independent from hardening effects. In this model, recovery of hardening with time due to dislocation climbs can not be reflected. On the other hand, viscoplasticity model-2 (Chaboche type material models, TMF Curves) reflect the recovery effect. At high temperature level, thermal activation contribute diffusing vacancies into the compressive region. The stucked dislocations upward an atomic plane, new dislocation planes are occurred and dislocations are able to move freely again.

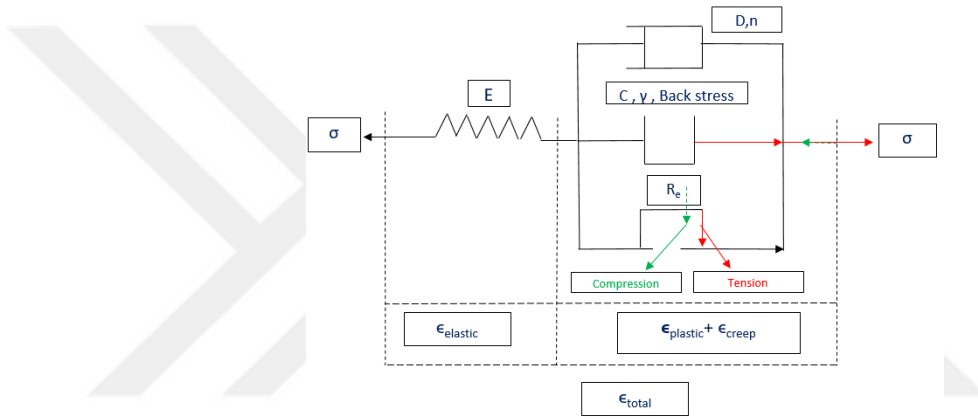


Figure 43. Viscoplasticity Rheological Model-2 [16]

Stress ;

$$\sigma = E \cdot \epsilon_{el} = E (\epsilon - \epsilon_{vp}) \quad (3.21)$$

Yield Function;

$$\phi = |\sigma - \alpha| - R_p \leq 0 \quad (3.22)$$

Viscoplastic Flow Rule;

$$\dot{\epsilon}_{vp} = \overline{\epsilon}_{vp} \cdot \frac{\sigma - \alpha}{|\sigma - \alpha|} \text{ and } \dot{\epsilon}_{vp} = \left(\frac{\phi}{K} \right)^n \quad (3.23)$$

Isotropic Hardening;

$$R_p = R_e + Q_\infty (1 - e_{vp}^{-be}) \quad (3.24)$$

Kinematic Hardening;

$$\dot{\alpha}_i = C_i \dot{\epsilon}_{vp} - \gamma_i \dot{\epsilon}_{vp} \alpha_i + \frac{\partial C_i}{\partial T} \frac{1}{C_i} T \cdot \alpha_i \quad (3.25)$$

3.5 Creep Test Procedure

Creep tests are performed according to ASTM C1291, ASTM C1337, ASTM D2990 and ASTM E139 standards and specimen as it is shown in **Figure 44**. ASTM E139 creep tests are carried out by applying a constant load to a tensile specimen under a constant temperature environment. Test specimens are manufactured according to the ASTM E139 Standard and performed different creep tests with different stress and strains for each temperature. At the end of the test procedure, isothermal creep curves and equations which are typical and valid between the defined stress and temperature ranges are evaluated. Creep tests are completed with constant load under a constant temperature condition for defined stress - temperature ranges and these tests are not involved any stress relaxation. In a constant temperature environment, constant load is changed until getting the targeted creep strain value at this specific temperature. Creep tests give us isothermal curves and isothermal equations. By using isothermal equation, other isothermal curves are evaluated and interpolated for different constant loads which are not used as stress-temperature ranges in tests.

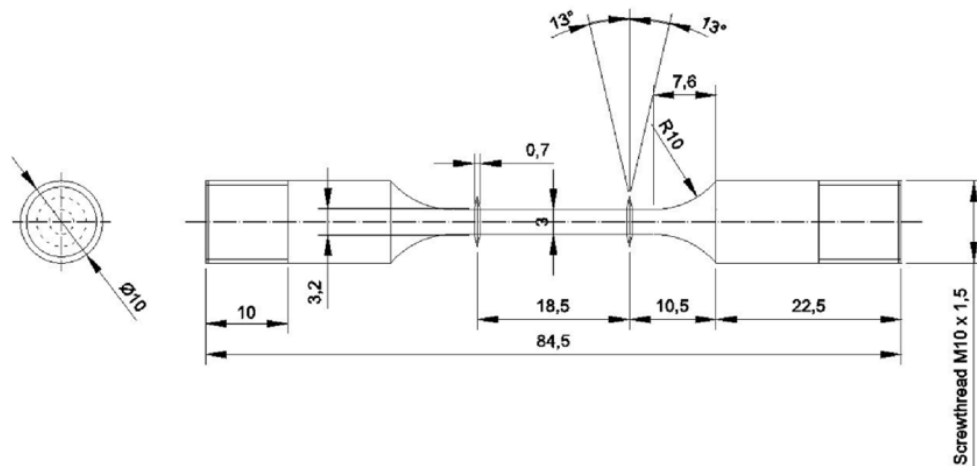


Figure 44. Standard Creep Test Specimen according to ASTM E139 [19]

Creep tests are performed by different types of machines. These are dead weight creep test machine, spring loaded test machine and electromechanical devices. Creep

test machines resemble standard tensile test machine but temperature is a new additional input when it is compared with a tensile test machines.

In creep testing, standard test specimen is heated constant temperature. In this thermal environment, constant load is applied to the standard test specimen while extensometer measure the percent strain depending on time parameter.

As it is shown in **Figure 45**, the standard design of test specimen as established by the American Society for Testing and Materials (ASTM) is clamped in the grips. The load applied from the hanger through the load beam is transmitted to the material through the upper test piece. When a force is applied to the specimen, strain occurs and relative movement between the gripping points is transmitted through the load beam to the dial gauge. The dial gauge is calibrated in steps equivalent to an extension of 0.001mm and the maximum amount of extension measured is 2.5mm. [20]

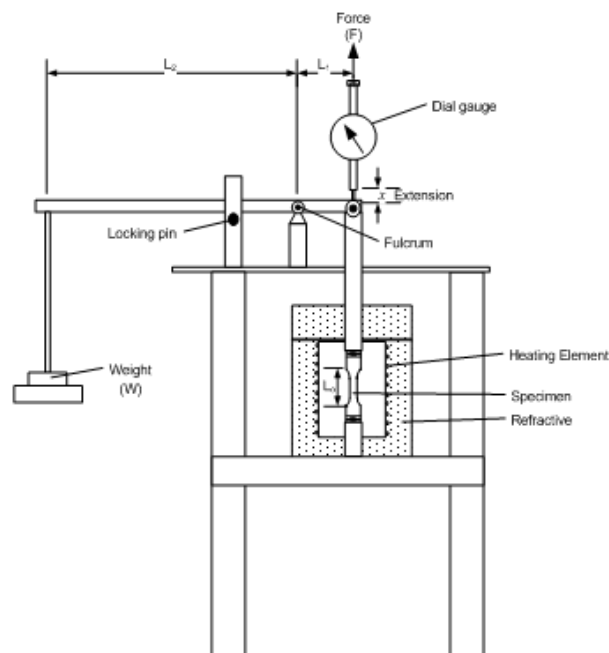


Figure 45. Creep Testing Machine [20]

3.6 Isothermal Equation and Larson Miller Parameter

Creep tests are completed for defined stress - temperature ranges. In a constant temperature environment, constant load is changed until getting the targeted creep strain value at this specific temperature. At the end of the test, the creep time is calculated for every constant load under the specific temperature environment. Tests are completed for every stress-temperature binaries to evaluate reaching time of targeted % creep strain. Isothermal equation is the expression of the creep material behavior and it gives creep constants with respect to the %strain values. As it is shown in **Figure 46**, isothermal curves express the arrival time of % strain values changing the load under constant temperature.

$$\begin{aligned} \text{Log } t = & b + m_1 \frac{1}{T} + m_2 \frac{X}{T} + m_3 \frac{X^2}{T} + m_4 \frac{X^3}{T} + m_5 Y_1 + m_6 Y_2 + m_7 Y_3 + m_8 Y_4 + \\ & m_9 Y_5 + m_{10} Y_6 + m_{11} Y_{\text{Rupture}} \end{aligned} \quad (3.26)$$

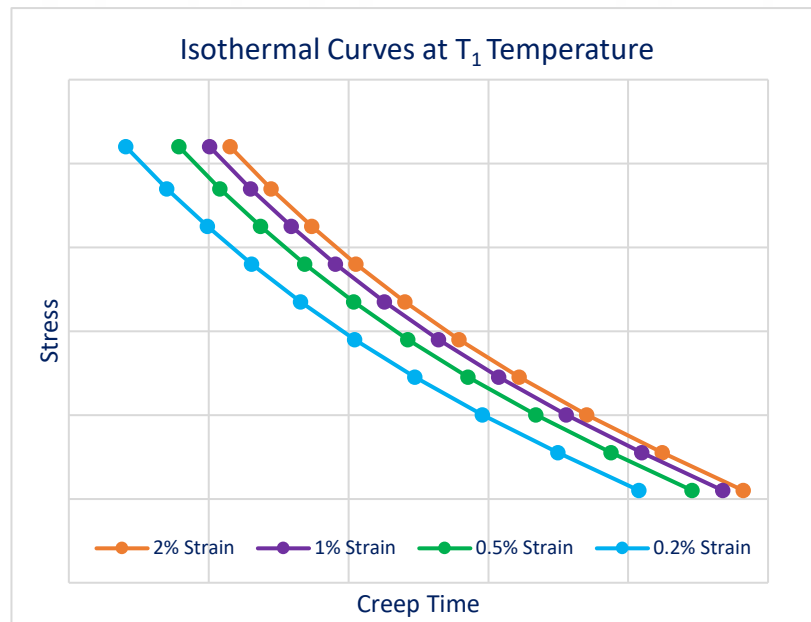


Figure 46. Isothermal Curves at T₁ Temperature

Y₁: %0,1 Creep strain limit

Y₂: %0,2 Creep strain limit

Y₃: %1 Creep strain limit

Y₄: %2 Creep strain limit

Y₅: %5 Creep strain limit

Y_{Rupture}: Rupture Creep strain limit

X : Log (σ) : Log Stress

t: time (hr)

T: Temperature

There is a extrapolation necessity for creep data especially for long-term creep conditions that is often not possible to obtain from normal laboratory experiments. To remedy this situation, creep rupture tests are performed at a comparable stress level, at much higher temperatures than necessary, for shorter processing times. Larson-Miller is a methodology which is used to extrapolate the operating conditions from the test data [21]. Briefly, Larson Miller parameter is used to calculate creep life at elevated temperatures using results from tensile rupture tests for real service conditions. The Larson-Miller Parameter (LMP) is often used to describe the creep force (at a given strain) as a function of time and temperature. Larson-Miller parameters follows that;

$$t_R = \frac{1}{A \cdot \sigma^n \cdot \exp \frac{Q}{RT}} \quad (3.27)$$

$$-\ln(t_R) = \ln(A \cdot \sigma^n) - \frac{Q}{RT} \quad (3.28)$$

$$\frac{Q}{RT} = T[\ln(A \cdot \sigma^n) + \ln(t_R)] \quad (3.29)$$

$$P = LMP = T[k + \ln(t_R)] \quad (3.30)$$

$$LMP = T(\text{Kelvin}) \cdot (20 + \log_{10}(t)) \cdot 10^{-3} \quad (3.31)$$

where T in K, t in hours, C is often assumed to be 20 but it can be experimentally determined. [21]

3.7 Review of The Power Law

The power law is a combination of Arrhenius Equation and Norton's Law. While Arrhenius equation ensure a relationship between temperature and creep rate, Norton's Law does it between stress and creep rate. The backbone of creep is the using of the Arrhenius equation to define the activation energy.

The Arrhenius equation is an empirical relationship that describes the effect of temperature on a rate constant, R is the gas constant and T is the absolute temperature and Q is the activation energy for creep. As the temperature increases, the value of the K constant increases. The factor A is called the frequency constant and is an indicator of successful collisions. According to the Arrhenius equation, a straight line relation is obtained with increasing in temperature. [13]

$$\dot{\epsilon} = A \exp\left(-\frac{Q}{RT}\right) \text{ and } \dot{\epsilon} \propto \exp\left(-\frac{Q}{RT}\right) \quad (3.32)$$

Norton's law gives us a linear relationship and obtained another straight line between stress and creep rate ; $\dot{\epsilon} \propto \sigma^n$

Combining of these two laws give us power law to understand steady state creep behavior.

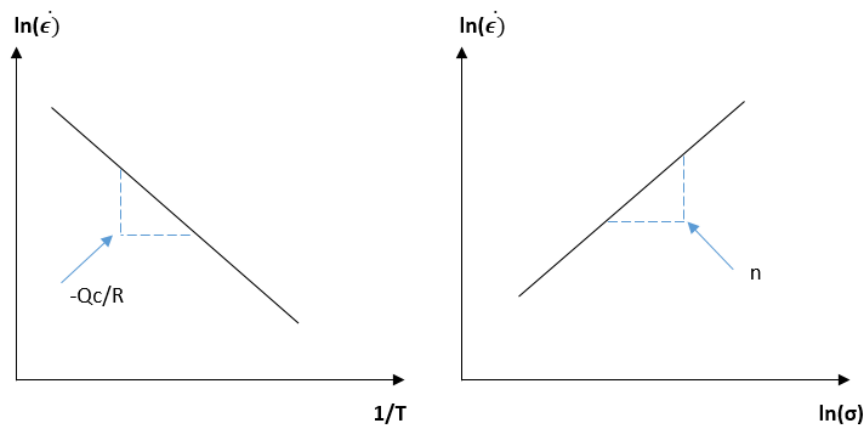


Figure 47. The secondary creep rate dependence of temperature and stress [13]

$$\dot{\epsilon} = A\sigma^n \exp\left(-\frac{Q}{RT}\right) \quad (3.33)$$

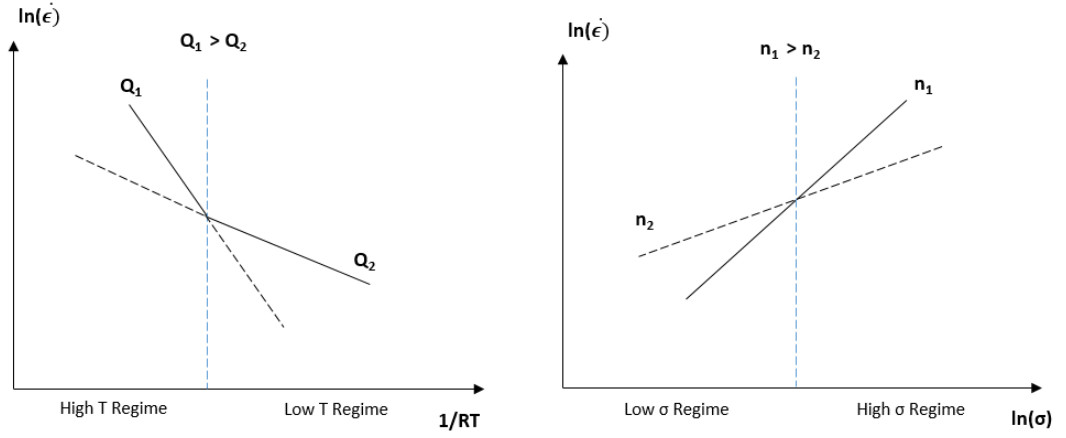


Figure 48. Transition of Q and n , relative to temperature and stress [13]

According to the Power Law, changing of the creep rate has relationship between temperature, stress, activation energy (Q) and stress exponent n . It is seen in **Figure 48** that increasing of temperature and stress cause the increasing of creep rate in same time. On the other hand, activation energy and n is material constant has inverse proportion with creep rate. Increasing of the activation energy tells the higher energy requirement to increase creep strain rate in same time. [13]

3.8 Creep Material Models

Creep material models are generally classified implicit and explicit creep material models. It is shown with a comparison table in **Table 1**. It is the explanation why implicit creep models are recommended and used. According to this comparison, implicit models can reflect isotropic and kinematic hardening effects in addition to the pure creep effect. Beside that, implicit material models does not require small time steps and it gives more accurate and efficient properties.

Table1. Comparison of the explicit and implicit creep material models [22]

	Explicit	Implicit
1	Forward Euler Method	Backward Euler Method
2	useful for cases involving very small time steps, such as in transient analyses	Does not require a small time step as explicit creep model (much faster and efficient way)
3	combine explicit creep with other plasticity options using superposition	define the combined effects of more than one type of creep using the implicit equations / problems involving large creep strain and large deformation
4	plasticity correction is performed first followed by creep correction	can model pure creep, creep with isotropic hardening plasticity, and creep with kinematic hardening plasticity, using both von Mises and Hill potentials
5	Two corrections occur at different stress values	the creep and plasticity are modeled simultaneously (no superposition), not independently
6	Because of the matter 4&5, it is less accurate than implicit model	Because of the matter 4&5, it is more accurate than explicit model

Creep hardening rules assumes that the creep strain rate depends on time and strain rate. If the parameter is time, it is called as time hardening. If the parameter is strain, it is called as strain hardening. If this issue is explained with a graph, the curves shift up/down as stress change from σ_1 to σ_2 in time hardening. On the other hand, the creep rate depends on strain rate and the curves shift left/right as stress change from σ_1 to σ_2 , the different creep strain rates are calculated point A to B in strain hardening as it is shown in **Figure 49**. [22]

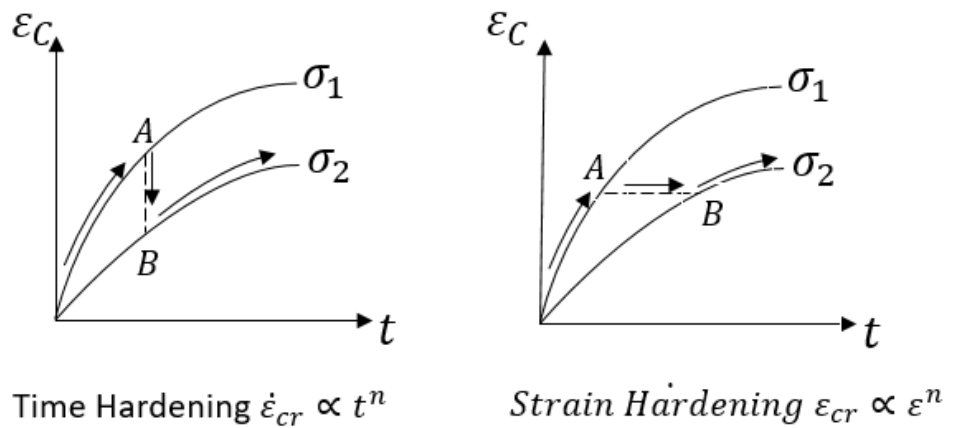


Figure 49. Time Hardening vs. Strain Hardening [22]

Determination of the using appropriate creep model based on material data availability. In other words, strain hardening tends to approximate primary creep region more accurately. Because, primary creep region shows either time or strain hardening while secondary region creep rate is constant. In this respect, there are lots of material models which are improved and shared in literature. These are shown in below as creep material models and equation description. The main target of this equation is trying to evaluate a single curve. This equations transforms all stress-temperature binaries (which are calculated from creep testing and reduced as a isothermal equation) to one curve with curve fitting methodology. While doing that, some equations can reflect primary stage, the other reflect secondary stage. On the other hand, there are other equations which try to reflect both time and strain hardening.

As it is seen in **Figure 50**, strain hardening and time hardening equations are used in primary region. However, some other equations can describe only secondary region like Norton or Garofalo equations. In addition to that, the other equation forms try to define both primary and secondary effects. These are seen as mathematical equations in below.

		$\dot{\epsilon}$: Creep Strain t : time σ : Stress T : Temperature				
Creep Equation Description	Type	creq	dcreq	time	seqv	temp
Strain Hardening	Primary	x	x		x	x
Time Hardening	Primary		x	x	x	x
Generalized Exponential	Primary		x	x	x	x
Generalized Graham	Primary		x	x	x	x
Generalized Blackburn	Primary		x	x	x	
Modified Time Hardening	Primary	x		x	x	x
Modified Strain Hardening	Primary	x	x		x	x
Generalized Garofalo (Hyperbolic Sine)	Secondary		x		x	x
Exponential Form	Secondary		x		x	x
Norton	Secondary		x		x	x
Time Hardening	Both	x		x	x	x
Rational Polynomial	Both		x	x	x	x
Generalized Time Hardening	Primary	x		x	x	x
User Creep						

Figure 50. Types of Creep Material Models

In this thesis, Norton and Combined Time Hardening models are used and compared. It is aimed to evaluate hardening effects on creep behavior with using Norton and Combined Time Hardening material models. To do that, material creep test is completed for a specific material and isothermal curves and equations are evaluated. All final test durations are calculated for every temperature and stress ranges. Besides that, a specimen fea model is established and creep constants are calculated according to Norton and CTH Material models which is explained in detail in ‘Creep Test and FEA Parametric Analysis Procedure’ Section

Strain Hardening:

$$\dot{\epsilon}_{cr} = C_1 \sigma^{C_2} \epsilon^{C_3} e^{-C_4/T} \quad (3.34)$$

Time Hardening:

$$\dot{\epsilon}_{cr} = C_1 \sigma^{C_2} t^{C_3} e^{-C_4/T} \quad (3.35)$$

Modified Strain hardening:

$$\dot{\epsilon}_{cr} = \{C_1 \sigma^{C_2} [(C_3 + 1) \epsilon]^{C_3}\}^{\frac{1}{(C_3+1)}} e^{-C_4/T} \quad (3.36)$$

Modified Time Hardening:

$$\epsilon_{cr} = \frac{C_1 \sigma^{C_2} t^{C_3+1} e^{-C_4/T}}{(C_3+1)} \quad (3.37)$$

Norton:

$$\dot{\epsilon}_{cr} = C_1 \sigma^{C_2} e^{-C_3/T} \quad (3.38)$$

Generalized Garofalo:

$$\dot{\epsilon}_{cr} = C_1 [\sinh (C_2 \sigma)]^{C_3} e^{-C_4/T} \quad (3.39)$$

Combined Time Hardening:

$$\epsilon_{cr} = \frac{C_1 \sigma^{C_2} t^{C_3+1} e^{-C_4/T}}{(C_3+1)} + C_5 \sigma^{C_6} t e^{-C_7/T} \quad (3.40)$$

3.9 Norton Creep Law and Combined Time Hardening Models

Creep is a time dependent phenomenon that occurs when a material is subjected to stress at high temperatures. In general case, creep strain rate depends on stress, temperature and time that can be explained generally in equation (3.41). It is also possible to separate these effects which is shown in equation (3.42)

$$\epsilon_{cr} = F_{cr} \cdot (\sigma, T, t) \quad (3.41)$$

$$F_{cr} \cdot (\sigma, T, t) = f_1(\sigma) f_2(T) f_3(t) \quad (3.42)$$

Experiments show there are generally 3 stages of creep mechanism which can be classified as primary, secondary and tertiary regions. First region is called as primary creep stage where the creep rate is decreasing with increasing plastic strain or time. Primary creep stage is transient creep and the dislocations are effective on the material. The fatigue life of material is related with the slope of the primary stage curve.

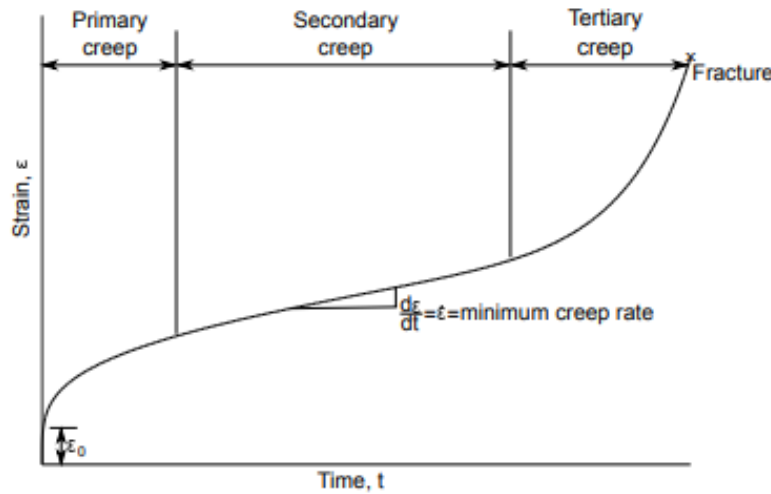


Figure 51. Typical Creep Curve showing three stages of creep [23]

Primary stage is high initial rate but decreases with time. It is a shorter period than secondary stage. This period reflect strain hardening effects on material. Secondary stage is called as state-state region and strain rate is constant in this region. Tertiary region reflect increasing strain rate to rupture and it is not modelled in

mechanical modul. As it is seen **Figure 51**, Norton Creep Law work in secondary creep region while CTH can reflect both primary+secondary creep stage. If the equation of Norton Creep Law and CTH law is examined, the difference between two material models are evaluated.

Considering that the fixation of the creep material test is performed, it can be predicted that the C_7 value, which is dependent on temperature, converges to zero in Norton calculations. In this case, the Norton equation will turn into an equation such as $y=mx$. This explains that the creep elongation of the Norton equation has a linear relationship with time. If the same situation is examined for combined time hardening, it is seen that the coefficients C_4 and C_7 will converge to zero. In this case, the equation takes its form in 3.40. The second part of this equation parallels the Norton equation, while the first part becomes a quadratic equation and reflects the primary stage. In reality, the plasticity effects that the material will be exposed to cannot be neglected and this situation is explained with Rheological material models. For this reason, studies are conducted between the CTH material model and the Norton material model.

4. METHODOLOGY

As it is shown in **Figure 52** and **Figure 53**, a flow chart is defined that shows the methodology and road map. It is aimed to search the durability and fatigue behavior of a rotor blade under highly energetic aero-thermal condition of an engine mission profile. In this respect, a mission profile is selected. Creep time duration and aerothermal loads are applied according to the selected mission profile.

Since it is known that the motor will be exposed to these loads as a cyclic load, the hardening effects are compared over a literature material test data at the beginning of the study. In this context, material properties are defined on the 1d fea element. The elongation values which are obtained during the test are defined as the boundary condition for the nodes of the 1d element. The isotropic and kinematic hardening material properties were compared with the test data using the obtained stress and elongation values. In this way, the material properties that best reflect the hardening effects in a cyclic loading were determined. Material models include material plasticity behaviors, viscoelasticity and viscoplasticity effects.

Secondly, the creep testing process of a material is modeled with a 2d fea analysis model. The isothermal curves which are obtained from the Creep tests compared with the curves obtained using the Norton and CTH material models. The final material model is decided by using the hardening effects caused by cyclic loadings.

Finally, the obtained material model is reflected in the analysis model of the 3d blade geometry. In the post processes, permanent deformations are calculated at the un-load step and it is compared with scanned test data. Stress and strain results are used to calculate the life of the design.

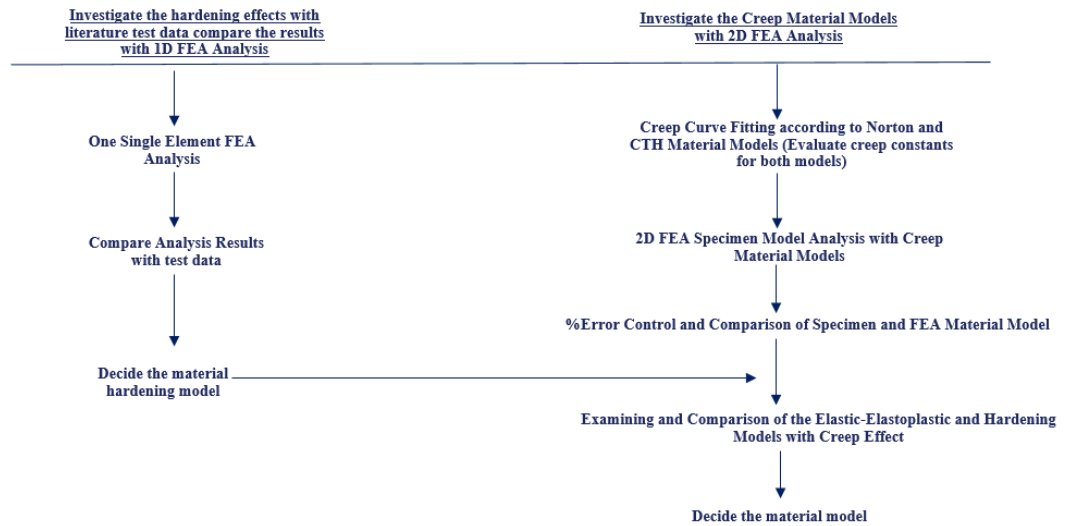


Figure 52. Methodology and Road Map-1

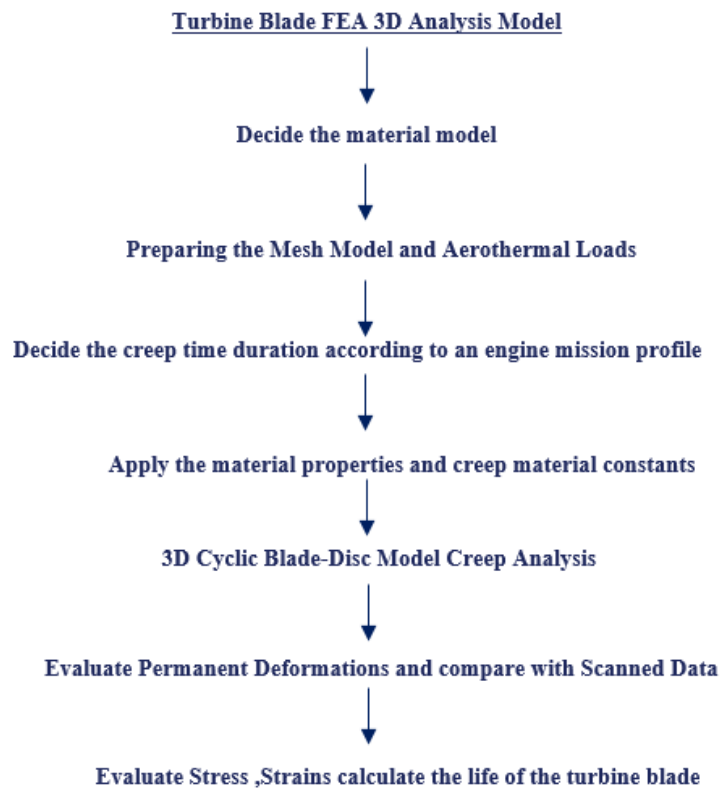


Figure 53. Methodology and Road Map-2

4.1 Gas Turbine Engine Mission Profiles

In a gas turbine engine design, mission profile definition consists of parameters. A mission profile is a scenario that is required to establish the weight, fuel, payload, range, speed, flight altitude, any other operations that the platform must be able to accomplish. The requirements are specific for any other mission. In other words, mission profile is a scheme of a platform's detailed description of activities in flight. The mission can be related with medical evacuation, offshore, PCT (personal cargo transport), CVP (Corporate Vip Transportation), DH (Dead Heading), HHH (Hot and High Hoge). These are examined in terms of strength and life assessments. On the other hand, missions can be very different in terms of take off time, cruise time, soakage or shutdown time. Because of then, all missions are investigated and all parts of a gas turbine engine ensure the strength and life requirements throughout mission profiles. A basic mission that is shown in **Figure 54** includes which are called as ground idle, flight idle, cruise, descend, HIGE and HOGE, cruise to descend, descend HOGE or HIGE and Cool down periods.

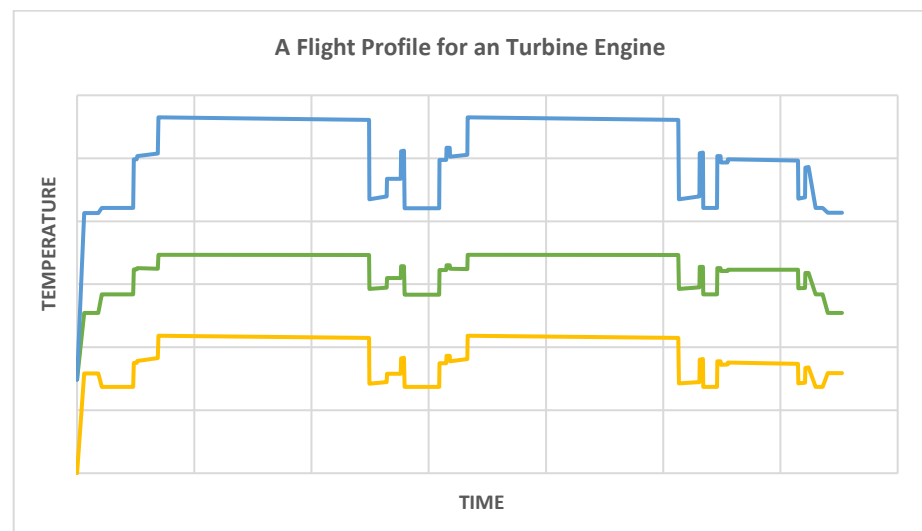


Figure 54. A Mission Profile for a Gas Turbine Engine

A basic mission profile show the heating and cooling regions as abrupt temperature increasing and decreasing. On the other hand, turbine parts hold in a long time regions which called as cruise time. In cruise, rotor blades reaches the maximum metal temperature and rotational velocity. Rotational velocity gives a constant centrifugal loads on blades throughout this period. In other words, while centrifugal loads gives us the constant load, metal temperature reach the top and constant value. It includes all thermo-mechanical fatigue effects in this hold time regions. So, hold time regions complete the parameters of the creep phenomenon. Due to the fact that, mission analysis, mission tests, endurance tests are important to see whether or not the parts ensure the engine requirements. Methodology requires to establish 2D-3D Mission models to investigate the LCF and creep behavior of turbine parts. The important thing is the determination of the major and minor cycles for components. Rainflow counting and Miner's damage rule contribute the fatigue calculation. On the other side, cruise time is the most damaging interval in terms of the creep nature.

4.2 Critical Time Points of Mission Profiles

The fatigue life of a gas turbine engine part is determined according to their working environment and condition. Turbine side of a gas turbine engine are especially effected from thermal gradients. Thermal gradients means cyclic thermal loads on parts. Permanent deformations and total strain values are need to be controlled with respect to the engine requirements. All engine parts must ensure the determined overall cycle. The main purpose is to investigate assembly-disassembly status of parts, investigate whether or not a possible crack initiation.

Mission profiles start from a point and complete with a shut down. Profiles are generally long periods and consist of many take off and cruise regions that create thermal cyclic loadings. Every gas throttle points called as corner points and a practical

way is used as decreasing time point numbers. To select important time points of a mission profile, thermal gradient regions on a part are determined. Thermal differences give peak points which are the main object for sorting out of the mission all points.

In rotor parts, the most critical time points are mission corner points. Corner points corresponds the accelerated and decelerated throttle regions. As engine accelerated, rpm and thermal loads increase with pressure loads. To capture the effect, corner points are added to time point selection method that is shown in **Figure 55**.

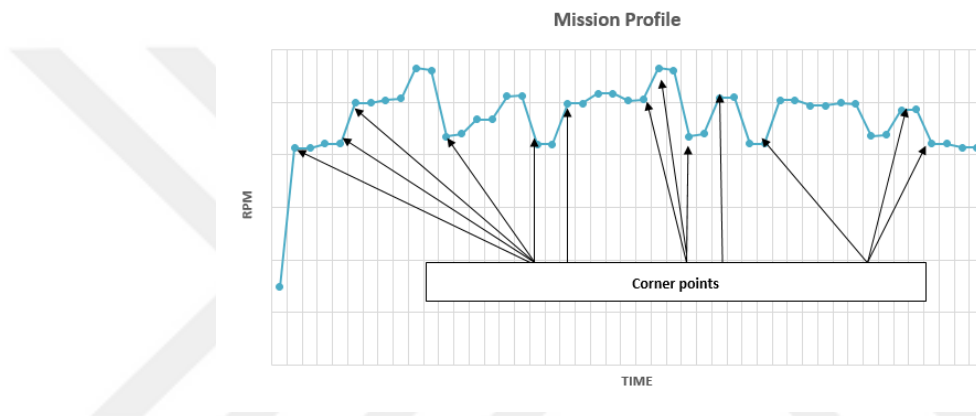


Figure 55. Corner Points of a Mission Profile

Each mission has own thermal history and each of them effect the behavior with different thermal stresses. **Figure 56** illustrate a mission temperature vs. time graph. Each time point has identical temperature differences for engine parts. Due to excessive thermal history data, time point selection method is used as a practical way. In addition to gas throttle regions, some extra points need to be selected before and after corner points. The reason is that metal temperature reach the stable value some points before or after then corners.

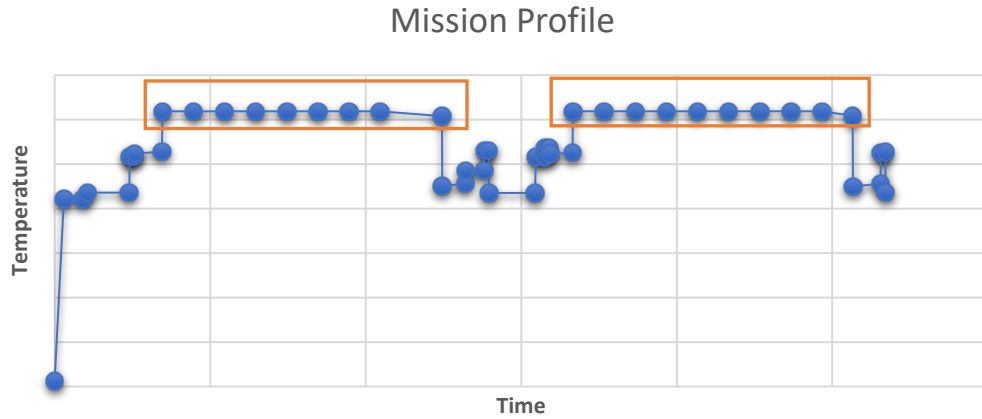


Figure 56. A Mission Profile

As it is shown in **Figure 56**, cruise times make up 60% of a mission profile. It indicates that engine parts operate at constant load and highest temperature for long periods of time and then quickly cool from high to low temperatures until the engine shut down. This situation is reflected with a shut-down unload step in 3d blade fea analysis.

4.3 Effect of Creep on Design and Post-Processing Items in Methodology

Parts should be designed to have a creep margin for the following reasons;

- Maintaining compatibility between adjacent parts for integrity and rotor balance
- Defining the suitability of seal spaces to control secondary flows
- Maintaining blade end clearance with static structure to ensure durability and engine performance and lifetime effect

Possible situations where creep can affect the design can be classified as follows;

- Bulk residual stress may trigger buckling in blades

- Deformations in Rabbets and other contact areas – affect local stress and tight fit which can affect assembly/disassembly conditions
- Deformations in dovetail tangs can change load sharing
- Excessive creep can initiate creep rupture (time-dependent crack initiation)
- Conformity between adjacent parts required for integrity and rotor balance may not be maintained
- Providing blade end clearance with a static part can negatively affect engine durability and performance. The effect of creep results on this situation should be examined



Figure 57. Fractured and Damaged Turbine Blade [24]

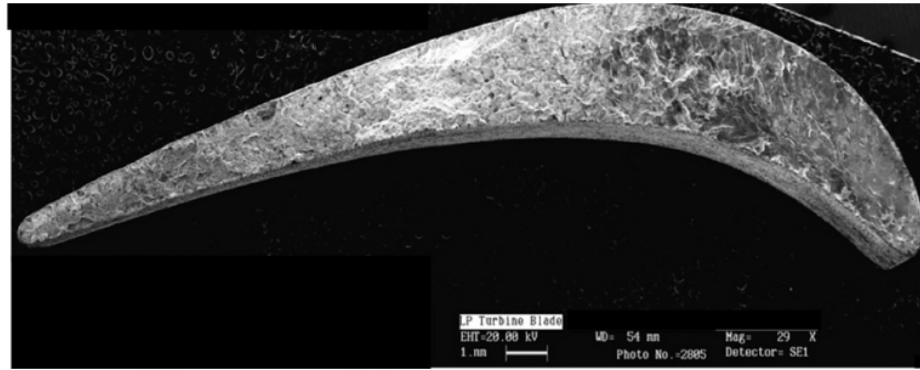


Figure 58. Low Magnification (29X) SEM Image of the Fracture Surface of Turbine Blade [24]

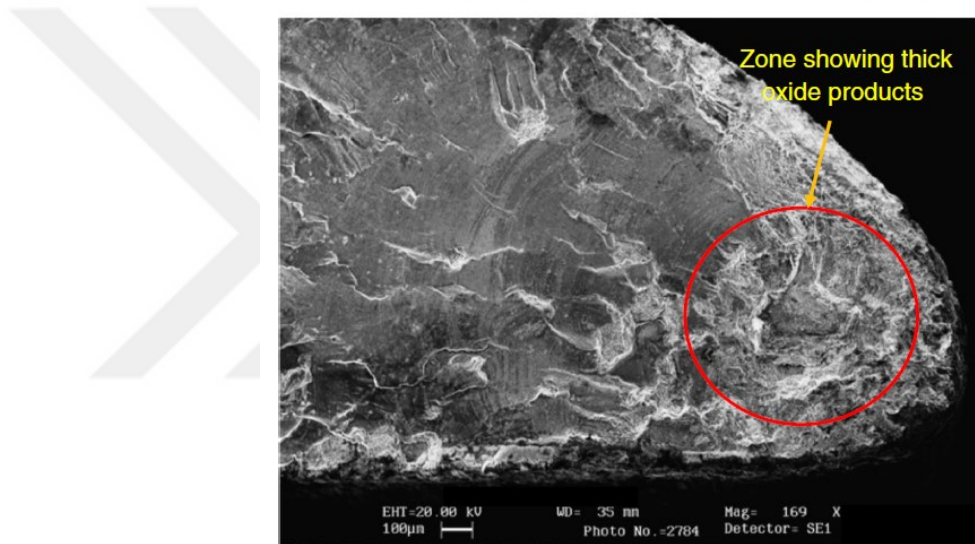


Figure 59. High Magnification of SEM Image Captured at the Leading Edge [24]

Turbine rotor blades mostly fail from stress locations concentrated in the fir tree regions, tip root radius and cracks starting from a certain height of the blade. **Figure 57** is an example of this situation. The blade design fails as a result of a crack that starts at the leading edge at $\frac{2}{3}$ the height of the blade. The crack initiation point is determined by electron microscopy is shown in **Figure 59**. From the orientation of the striations, it appeared that fatigue failure had originated from the leading edge of the blade. [24]

5. FINITE ELEMENT METHOD

5.1 Finite Element Method Definition

Analytical solution is convenient when the geometry, loading and boundary conditions are simple. Otherwise, finite element method using which is apply numerical methods, differential equations or integral expressions are inevitable. The finite element method is an approximation numerical analysis of complex engineering problems. In this method, the structure is divided into a finite number of parts (elements) that can be determined by a number of parameters and all the system is considered as the sum of all elements.

In fea methodology, forces and displacements are calculated at nodes. Stresses and strains are calculated at Gaussian (integration) points. Then, these are extrapolated to the corner nodes using the shape functions of elements. Therefore, each node receives a stress value from each element it is connected to. One node is shared by several elements and each element report different stresses. Reported values are averaged to obtain a single value. The most important thing is that averaged and unaveraged values should be closed to the each other. It means small stress and strain gradients evaluation is an obligation to reach a mesh converged finite element analysis model. Some methods are used to control to ensure a mesh converged model.

5.2 Discretization of the Geometry

Geometries are discretized into elements and nodes which is called as meshing, finite element models are established. Due to the sensitivity across the stress and thermal distribution, creep models need to established by using brick elements or second order tetra elements. Solid186 quadratic element type which is higher order 3D 20-node solid elements with mid-side nodes are used in the analysis. For root fillet regions, Solid187 type quadratic tetrahedron elements can be used in the model.

SOLID186 is a higher order 3-D 20-node solid element that exhibits quadratic displacement behavior. The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. The element supports plasticity, hyper elasticity, creep, stress stiffening, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper elastic materials. SOLID187 element is a higher order 3-D, 10-node element. SOLID187 has a quadratic displacement behavior and is well suited to modelling irregular meshes. The element is defined by 10 nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, hyper elasticity, creep, stress stiffening, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper elastic materials. In this thesis work, cyclic symmetric modelling technique is used. Ansys Space claim and 19.2 Version Workbench interfaces are used for geometrical simplification and discretization.

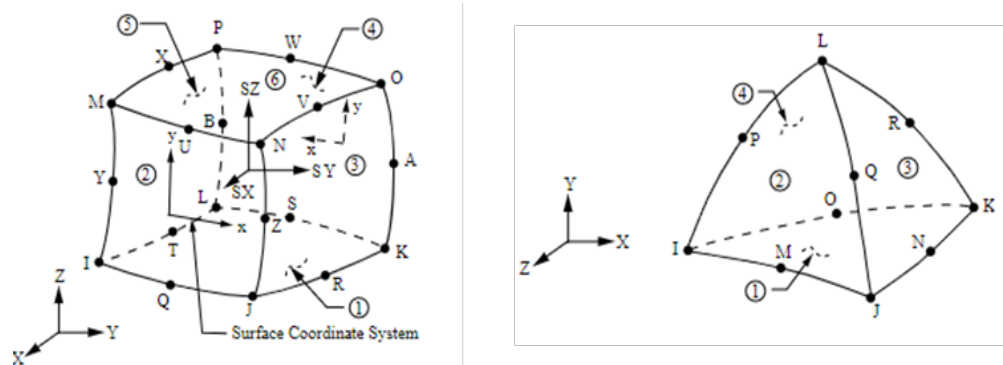


Figure 60. Solid 186 and Solid187 Element Types

6. 1D and 2D FEA ANALYSIS PROCEDURE

In order to compare the 3D turbine rotor geometry analysis results with the test measurement results, the actual material behavior is investigated with 1D and 2D fea models within the scope of mechanical modeling of the material. In this context, first of all, the plasticity behavior of the material against cyclic loading is examined with a 1d analysis model. On the other hand, creep material model is examined with 2d fea models that include curve fitting procedures separately for Norton and CTH models and take into account the real test specimen design.

6.1 Comparison of the Single Element 1D FEA Material Model and Material Test Results

Material hardening has critical effect on fatigue assessment in a cyclic load condition as the Bauschinger effect tells that material behavior changes under tension-compression load scenarios. In this respect, complex low cycle fatigue material test literature data (CLCF) is used to investigate hardening effects.

CLCF test data is used as boundary conditions on one single fea element nodes. Isotropic hardening, kinematic hardening, kinematic hardening + creep combined time hardening material models are selected and applied respectively. Stress and strain results in normal direction are compared with test results. Comparisons are normalized and then compared in graphics.

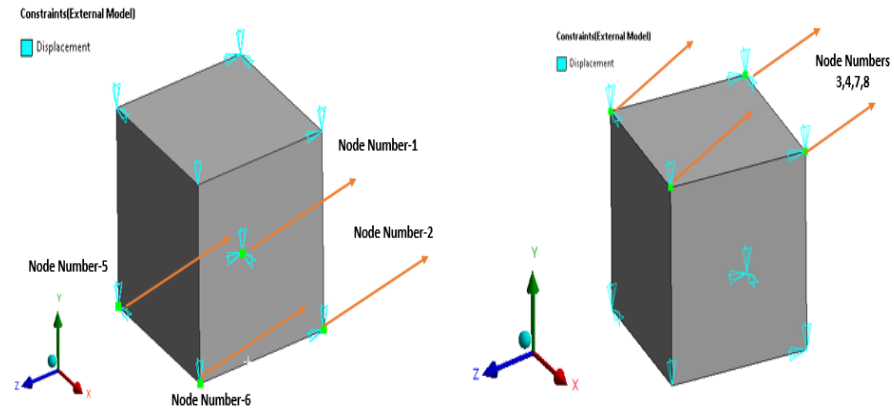


Figure 61. Single Element FEA Model

As it is seen in **Figure 61**, single element nodes are used to define displacement boundary condition. Displacements are taken from material tests and defined to the nodes with commands [18]. It is shared in **Figure 62** that test outputs are defined as displacement boundary condition on each nodes. It is expanded and defined to reflect whole test time. At the end of the analysis, stress, strain values are taken as an output.

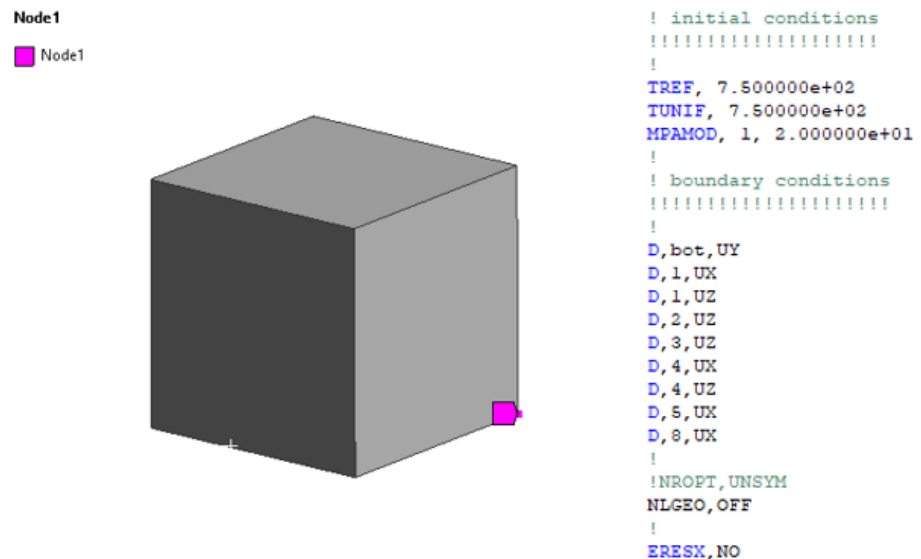


Figure 62. Test Outputs as 1D FEA Model Boundary Conditions

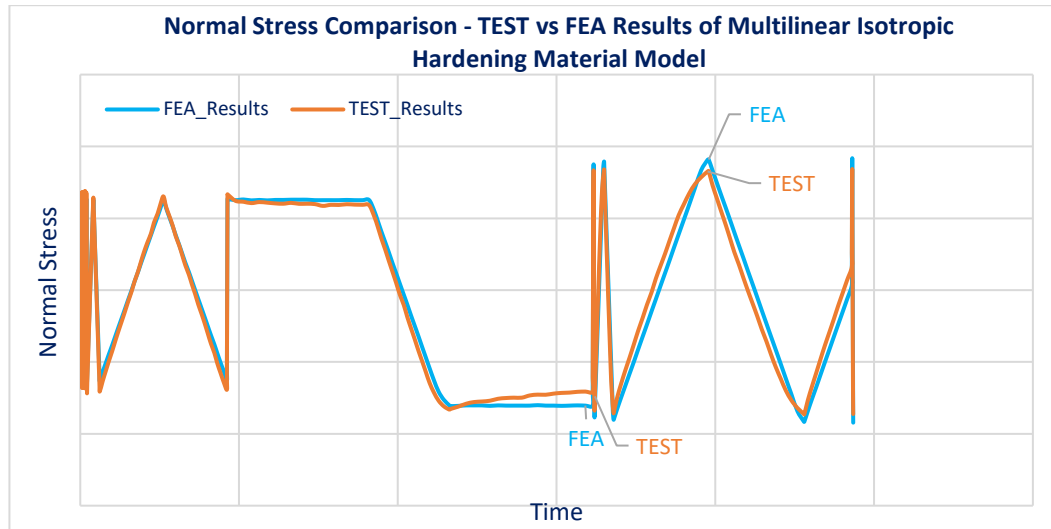


Figure 63. S_y Stress Comparison (Isotropic Hardening vs Test)

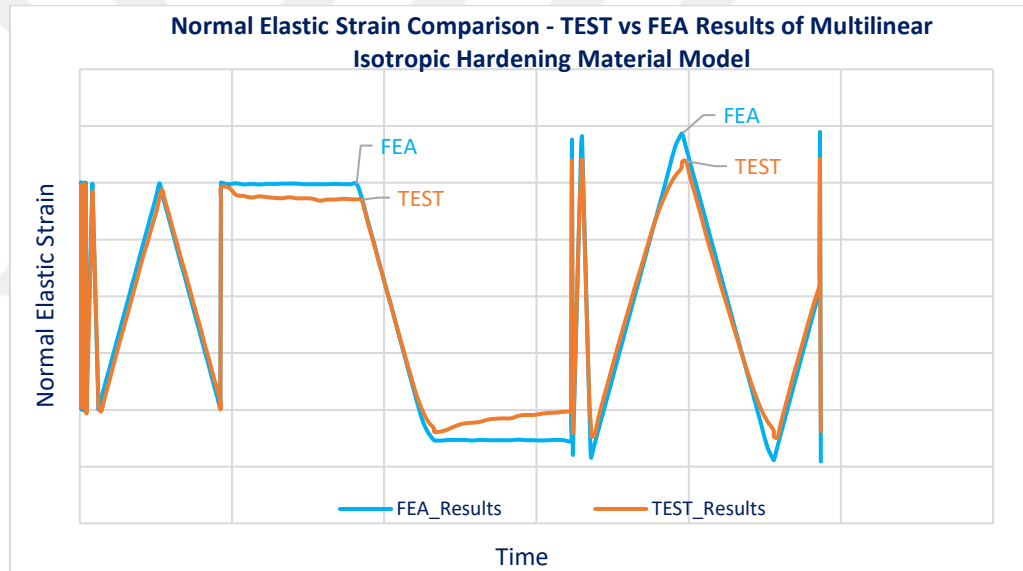


Figure 64. Elastic Strain (ϵ_{ye}) Comparison (Isotropic Hardening vs Test)

As shown in the comparison charts of the test and analysis results, the use of the isotropic hardening material model alone does not reflect the actual behavior of the material. As it is shown in **Figure 64**, %error increase and more elastic strain is calculated with isotropic hardening model which is shown with Rheological Models.

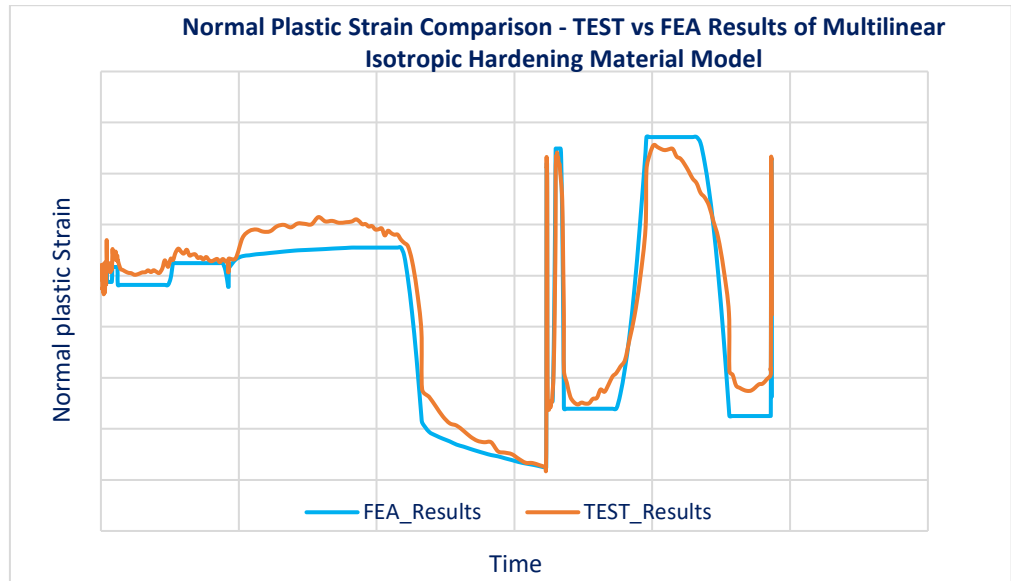


Figure 65. Plastic Strain (ϵ_{yp}) Comparison (Isotropic Hardening vs Test)

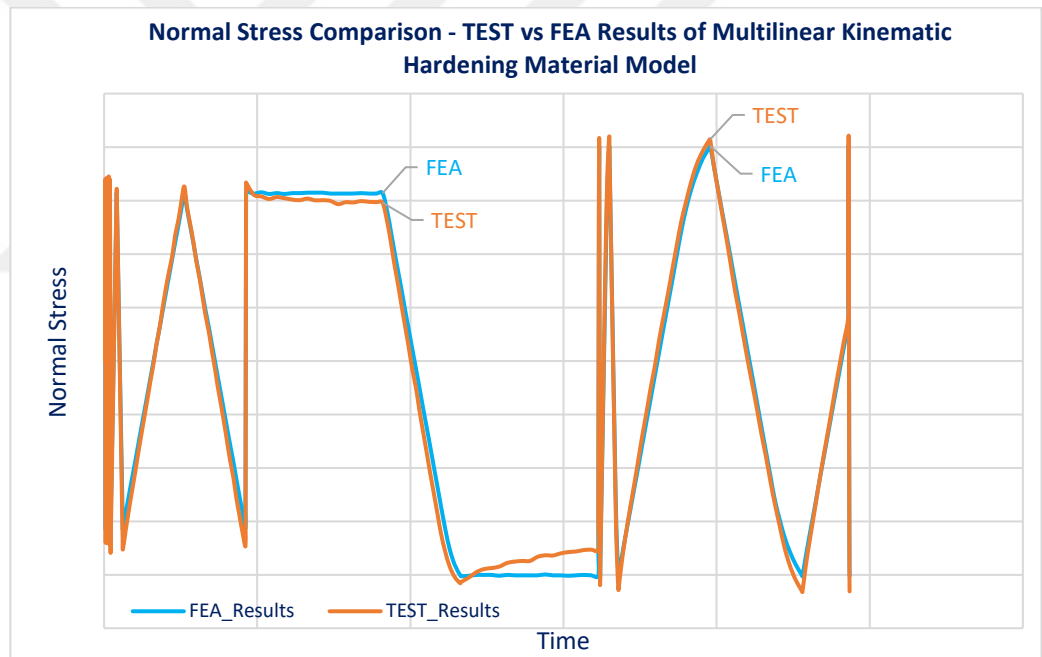


Figure 66. S_y Stress Comparison (Kinematic Hardening vs Test)

As shown in the comparison charts of the test and analysis results, the use of the kinematic hardening material model reflect the actual behavior of the material better than the isotropic hardening model. As it is shown in **Figure 66**, %error increase but it is better than isotropic hardening material model.

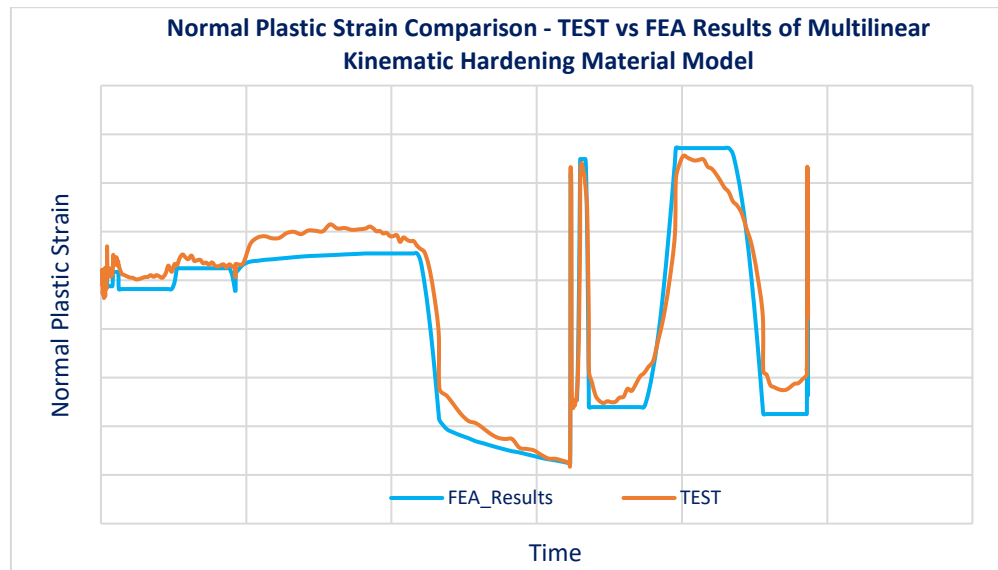


Figure 67. Plastic Strain (ϵ_{yp}) Comparison (Kinematic Hardening vs Test)

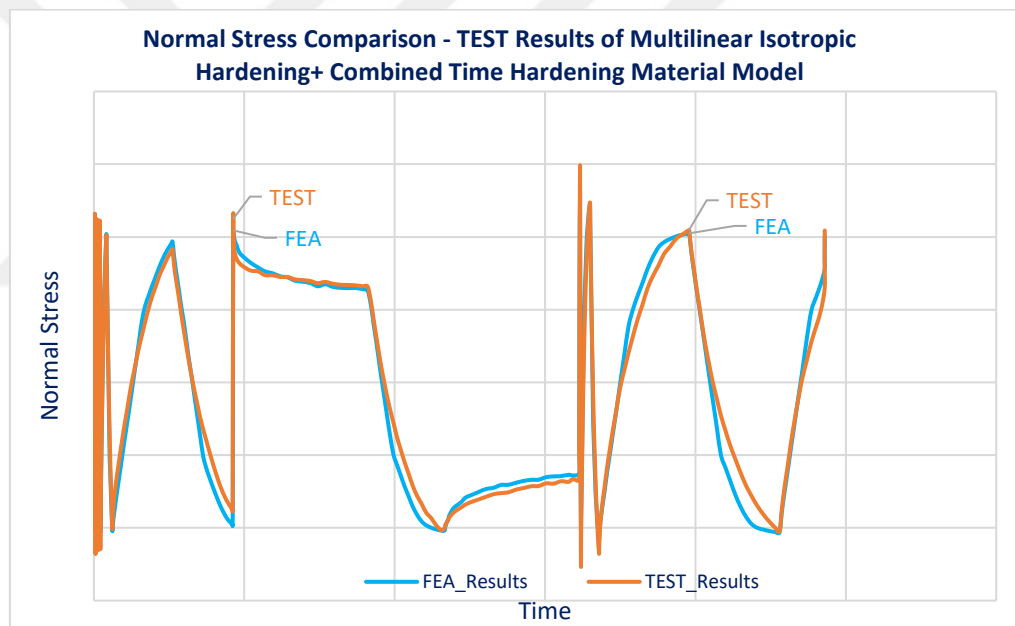


Figure 68. Sy Stress Comparison (Kinematic Hardening + Combined Time Hardening vs Test) at 2nd Temperature Condition

As shown in the comparison charts of the test and analysis results, the use of the kinematic hardening material model with combined time hardening model reflect the actual behavior of the material better than the other material models. As it is shown

in **Figure 68**, %error decrease and calculated peak stresses converge with test results which is also shown with Rheological Models.

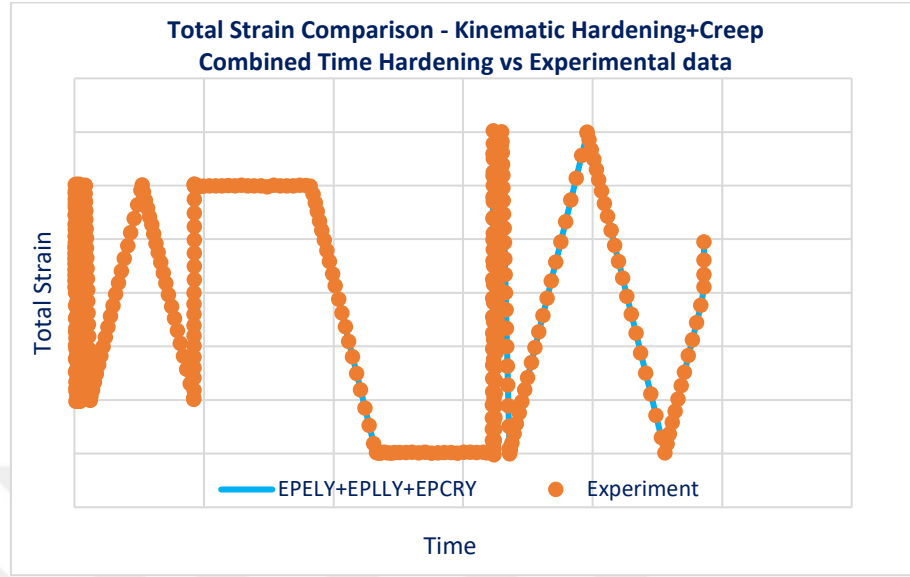


Figure 69. Total Strain Comparison (Kinematic Hardening + Combined Time Hardening vs Test) at 2nd Temperature Condition

As it is shown in **Figure 63** and **Figure 66**, using only isotropic or kinematic hardening material models create large deviation when they are compared with test results. On the other hand, using hardening material models with combined time hardening models ensure a convergence with material test results as it is shown in **Figure 68** and **Figure 69**.

6.2 Control of The Creep Curve Fitting Procedure with Parametric 2D FEA model

Creep is a time dependent phenomenon and corresponds when the targeted % creep strain value is reached at the specific load and temperature condition. These values are used to drawn isothermal curves (stress vs time for every temperature-load ranges). In order to reduce these tests using different temperature and constant load pairs to a single curve, the curve fitting procedure is applied using different creep

material models such as Norton or CTH material models. As a result of curve fitting procedure, constants are obtained which vary depending on temperature reflect the selected material models.

In parametric 2D analysis, The accuracy of the curve fitting procedure and the % margin of error are examined. In this respect, standard test specimen is modelled which is shown in **Figure 70**. As the creep tests are carried out in a certain temperature and stress range, 2d analysis models are also carried out by considering these temperature and stress pairs. As a result of the analyzes, the time to reach the same elongation values of the real specimen and the numerical analysis model is compared on the graphs and these are shown from **Figure 77** to **Figure 82**.

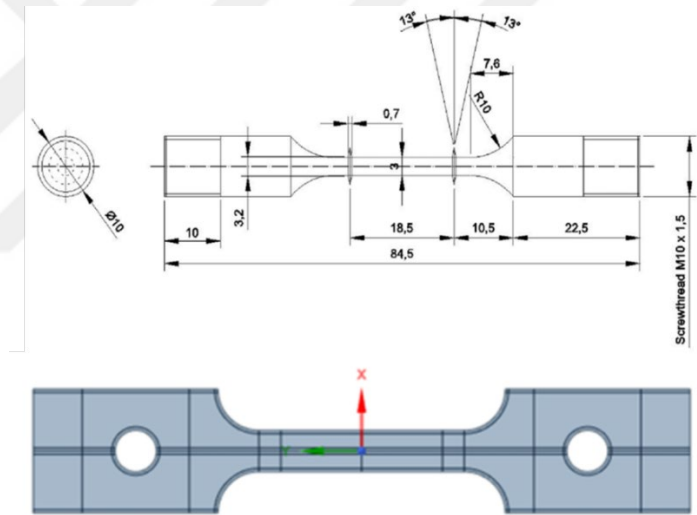


Figure 70. %Creep Strain Calculation

6.3 Parametric FE Analysis with Creep Test Specimen Geometry

% creep strain calculation is performed from gauge bottom side to top side. In this respect, if-do loop commands are implemented to the parametric analysis. Gauge location is defined where the gauge is located in test. In the loop command, parameter values are defined as % creep strains (%0.2 / %0.5 / %1 creep strain etc.). When the material model reached these targeted % creep strain values, total time is calculated

for every creep strain and written as creep time output result of the fea specimen analysis model. In **Figure 71**, the critical area on the specimen model is shown and gauge top-bottom displacement result is calculated for this region. For instance, the specimen is heated up the constant temperature and the constant load is applied which ensure to reach the targeted stress value. The test is finished when the targeted strain value is evaluated.

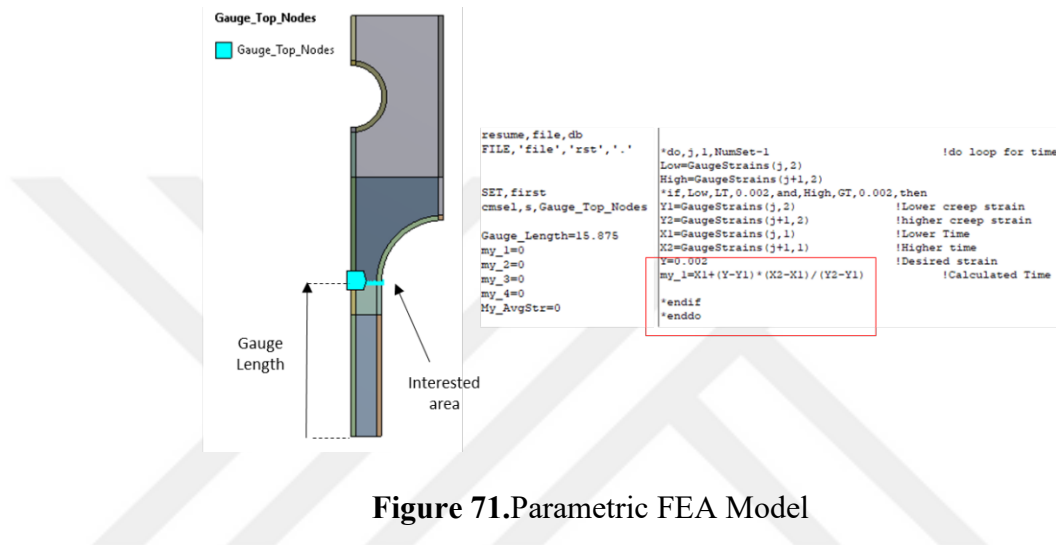


Figure 71.Parametric FEA Model

Parametric FE analysis of test specimen geometry is a way that is the control mechanism of the curve fitting methodology. Percent error or the accuracy of the curve fitting methodology is controlled with this models which is shown in **Figure 71** and **Figure 72**.

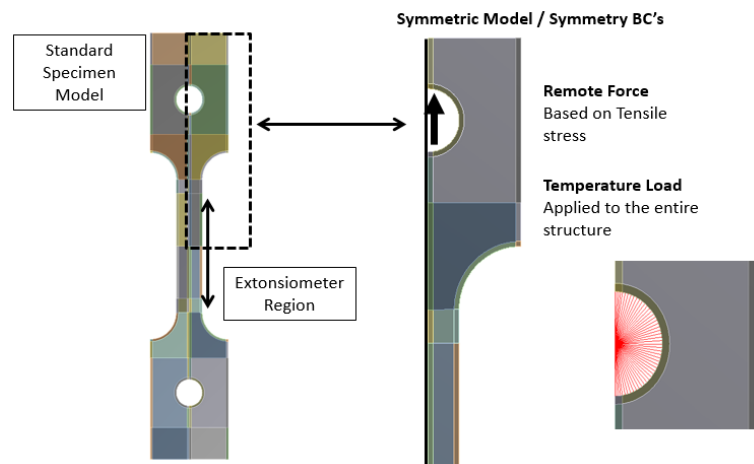


Figure 72. 1st phase of the FEA Parametric Analysis

The specimen geometry is established as a symmetric model in ANSYS-Spaceclaim module as it is shown in **Figure 73**.

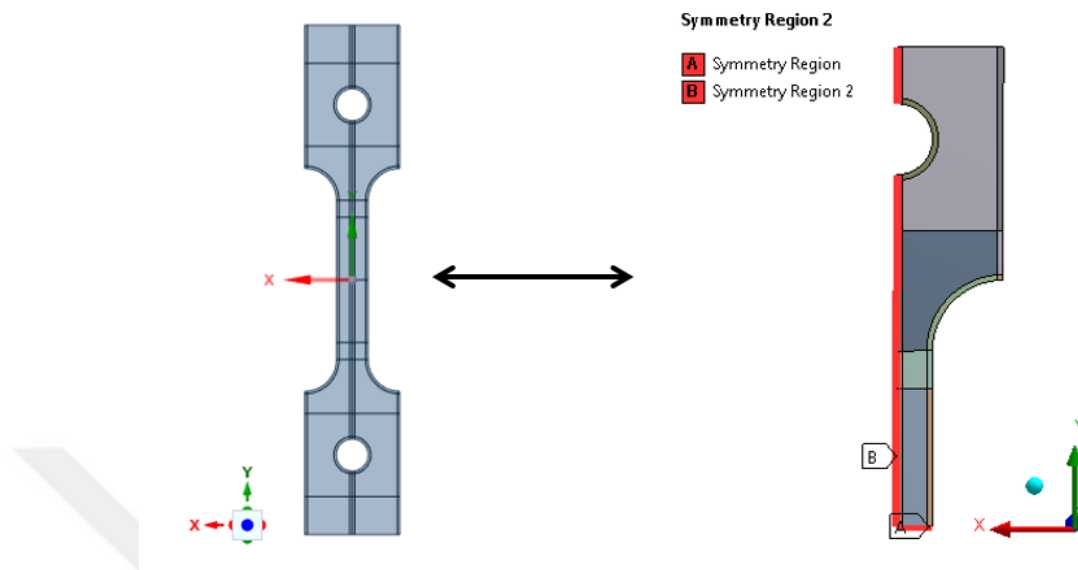


Figure 73. Analysis Model with Symmetric Boundary Condition

According to the creep test, constant temperature and constant load is applied to the specimen geometry as it is shown in **Figure 74**.

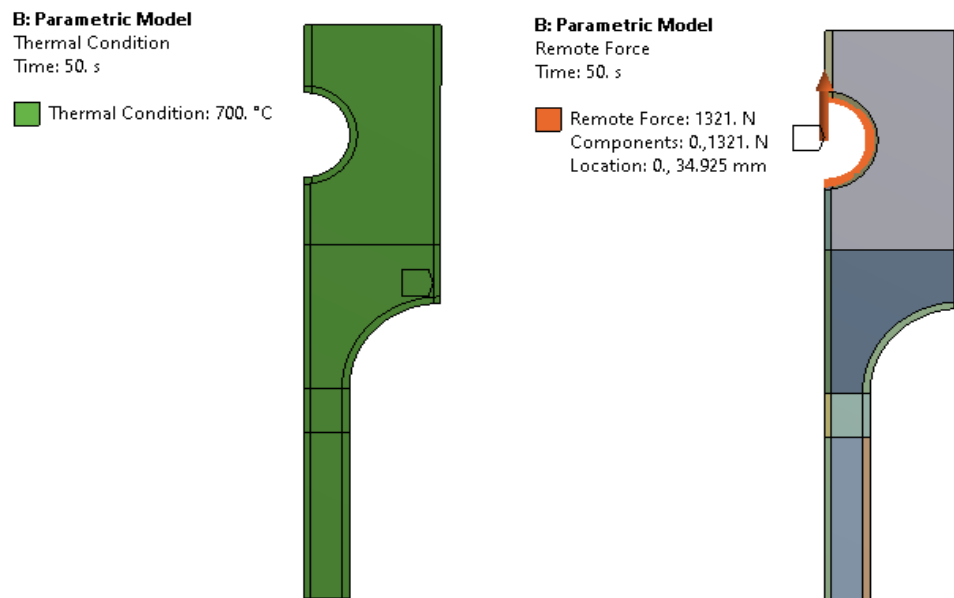


Figure 74. 1st Test Temperature and Load Binary

The applied temperature and constant loads are the input parameters of the analysis. The remote force is applied to the specimen hole surfaces and it is aimed to evaluate the first stress value at the first thermal condition.

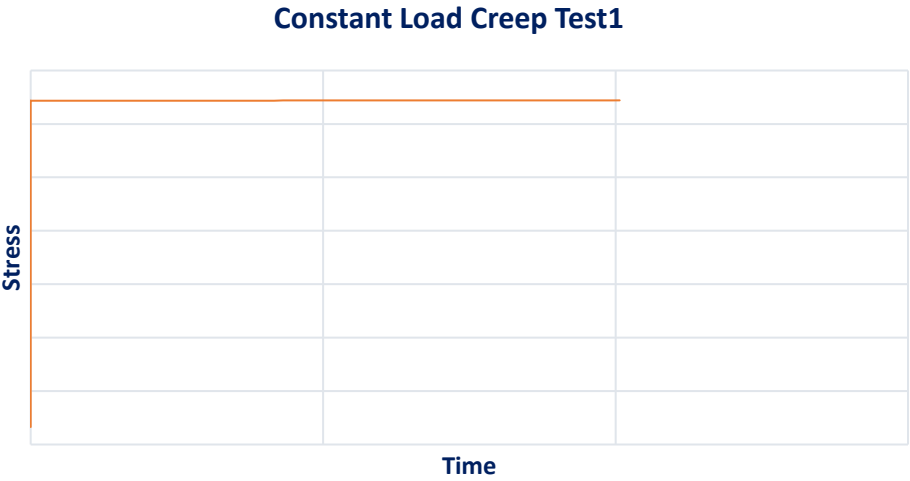


Figure 75. Constant Load Creep Test-1-Stress Result (σ_1 - T_1)

Different creep tests are completed with FEA Analysis specimen model. As it is shown in **Figure 75**, stresses reach a constant value throughout creep time as it is done in material tests. On the other hand, creep strain increases with time as it is shown in **Figure 76**.

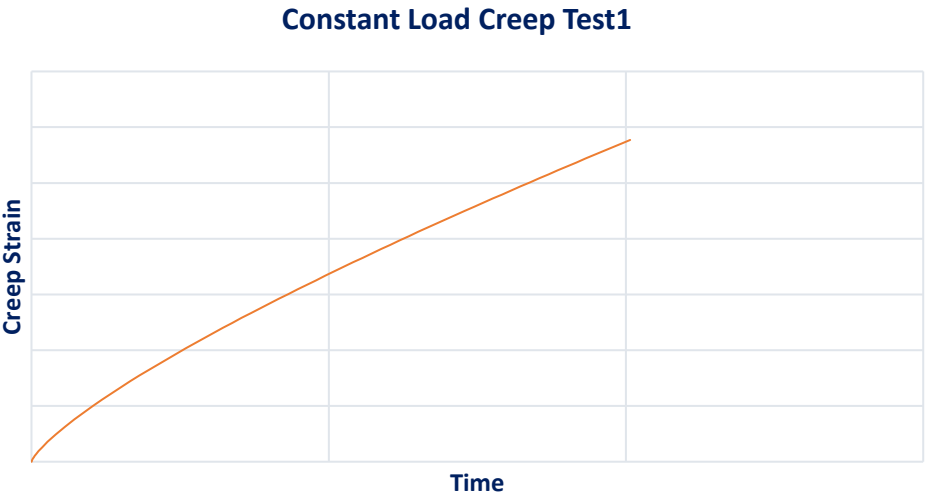


Figure 76. Constant Load Creep Test-1-Strain Result

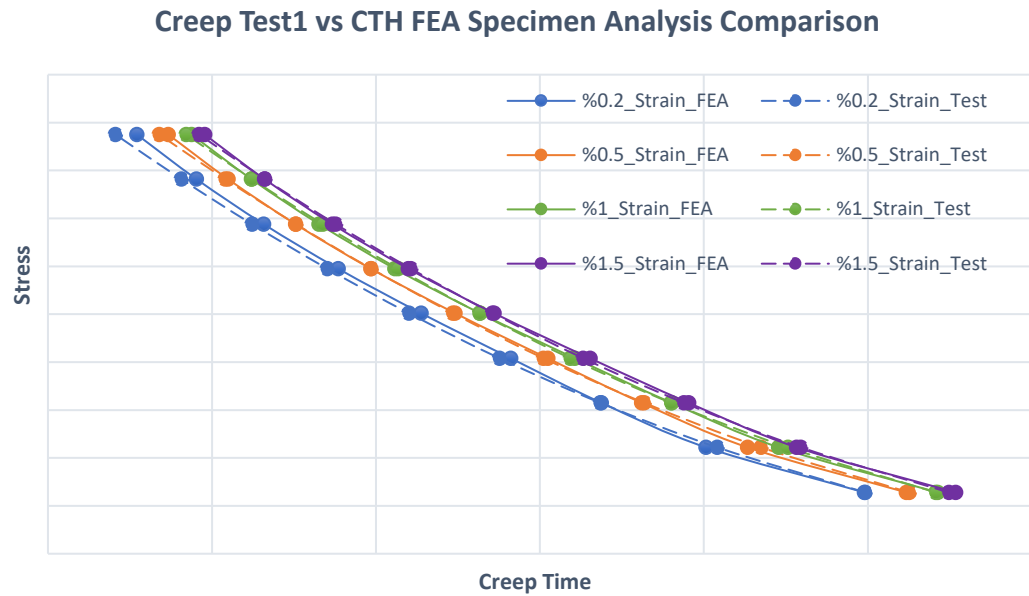


Figure 77. Comparison of the Creep Test-FEA Specimen Analysis Results at T_1

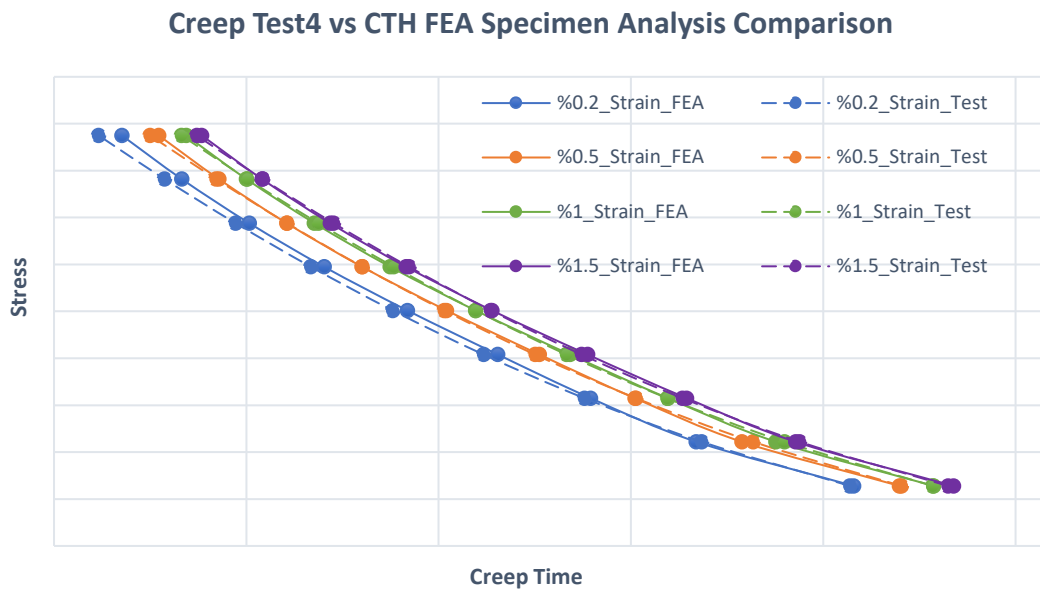


Figure 78. Comparison of the Creep Test-FEA Specimen Analysis Results at T_2

Test and Fea Specimen Analyses are compared as it is shown in **Figure 77** and **Figure 78**. These graphs reflect the accuracy of the curve fitting method and the error rate between the actual material behavior and the combined time hardening material model.

Test and analysis comparisons are also completed with Norton and Combined Time Hardening material models creep coefficients. As it is shown in **Figure 79** and **Figure 81** and **Figure 82**, it is seen that Norton material model ignore the plasticity hardening effects of creep primary region.

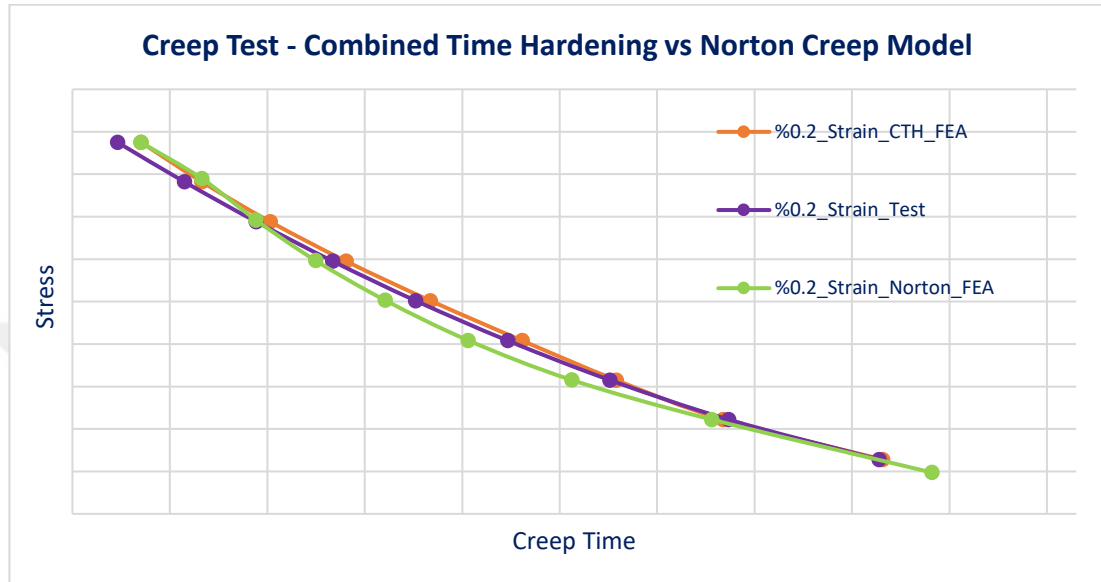


Figure 79. Comparison of the Combined Time Hardening vs Norton Creep Model with Material Test Results (%0.2 Creep Strain)

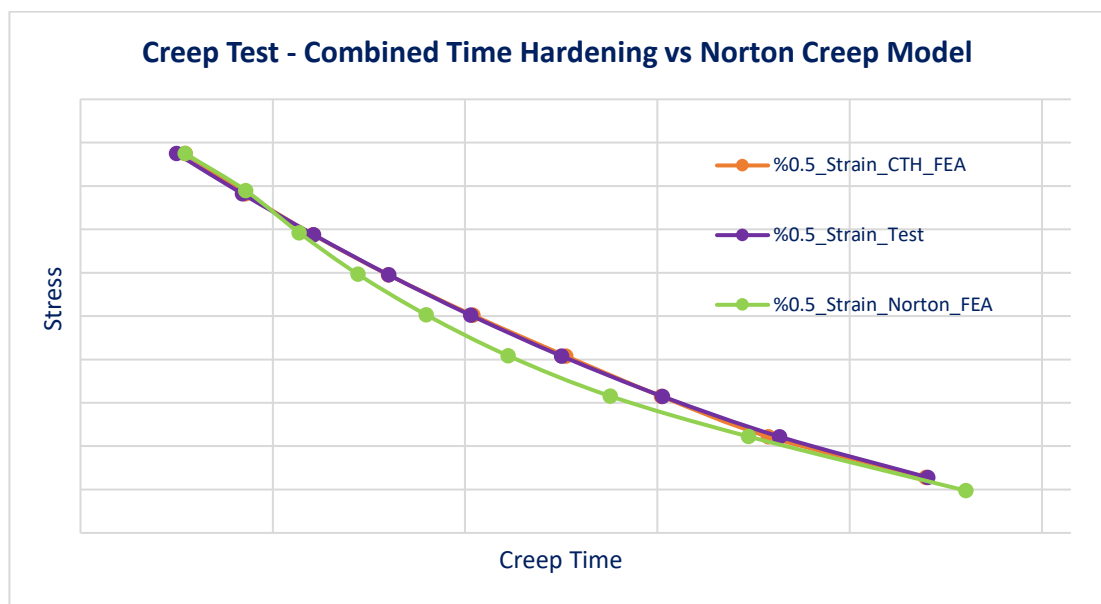


Figure 80. Comparison of the Combined Time Hardening vs Norton Creep Model with Material Test Results (%0.5 Creep Strain)

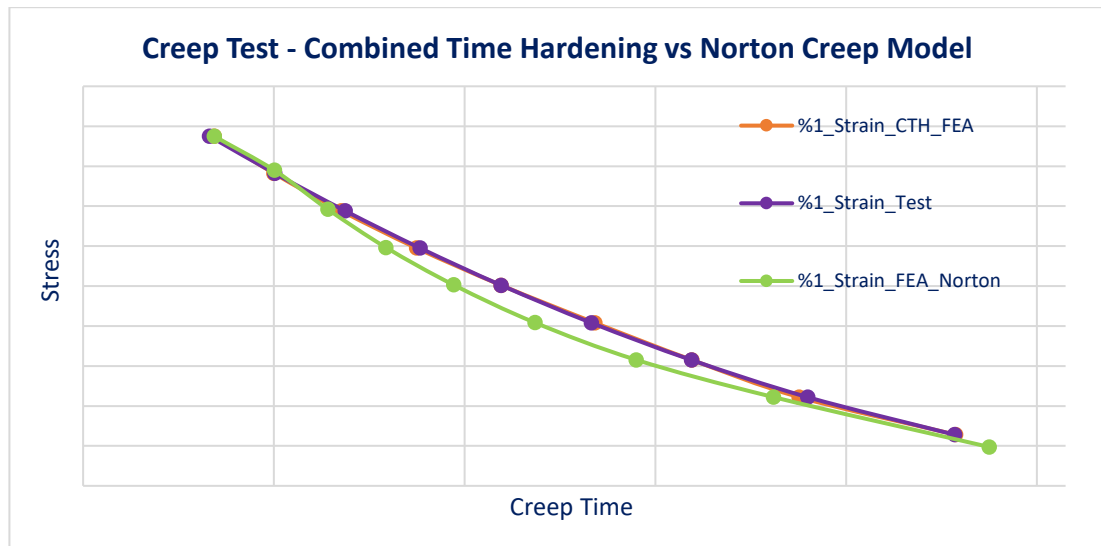


Figure 81. Comparison of the Combined Time Hardening vs Norton Creep Model with Material Test Results (%1 Creep Strain)

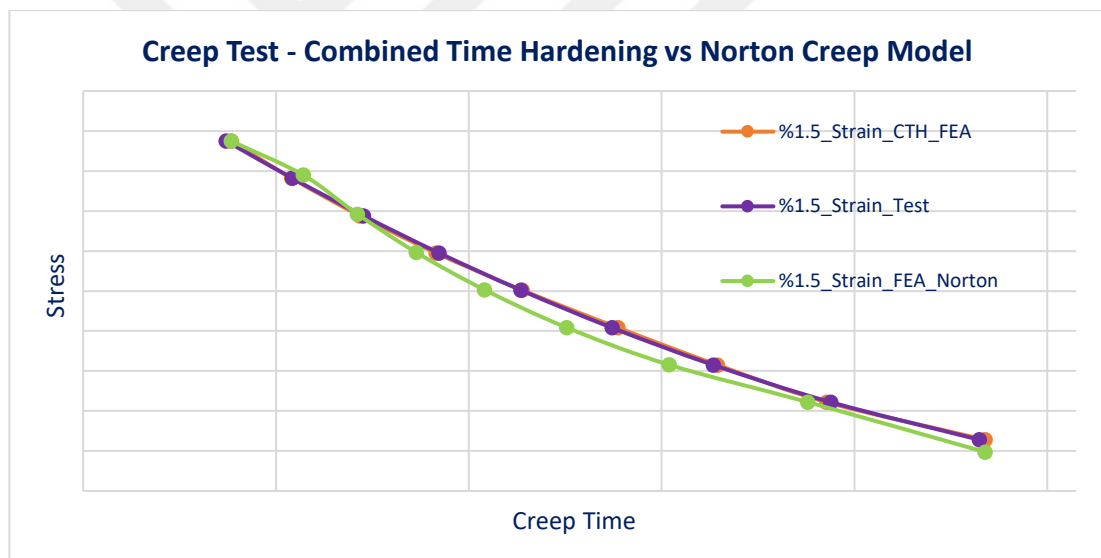


Figure 82. Comparison of the Combined Time Hardening vs Norton Creep Model with Material Test Results (%1.5 Creep Strain)

It is possible to say that more elongation occurs in the same time with the Norton material model definition and it stay more conservative material model than Combined Time Hardening model. Not only in graphics but also the mathematical equation of Norton show that it only reflect creep secondary region with ignoring primary region hardening effects.

6.4 Numerical Simulation Results of a Turbine Blade

After one-dimensional and two-dimensional investigations of the mechanical behavior of the material, the creep damage and life prediction of a 3D rotor blade geometry is investigated with respect to the engine mission profile that is shown in **Figure 83**. The main target is to compare the elongation measurements of the blade geometry in an engine running during the maintenance interval with the results of the finite element analysis performed with the selected material model. Secondly, considered critical creep elongation value and the time to reach this value is compared with the compliance of the maintenance interval.

The mission profile shows the amount of time the engine repeats during the maintenance interval, including time intervals such as ground idle, flight idle, cruise time, and soak back. Since the creep behavior of the material is directly related to the time factor, the total cruise times are taken as the time parameter in the creep function. While the cruise time to be reached during the maintenance interval is reflected as the total time, each engine on-off situation and its plastic effects may occur due to this can be reflected in a single cycle. This situation causes a difference between the total elongation measured after the test and the total elongation calculated after the analysis.

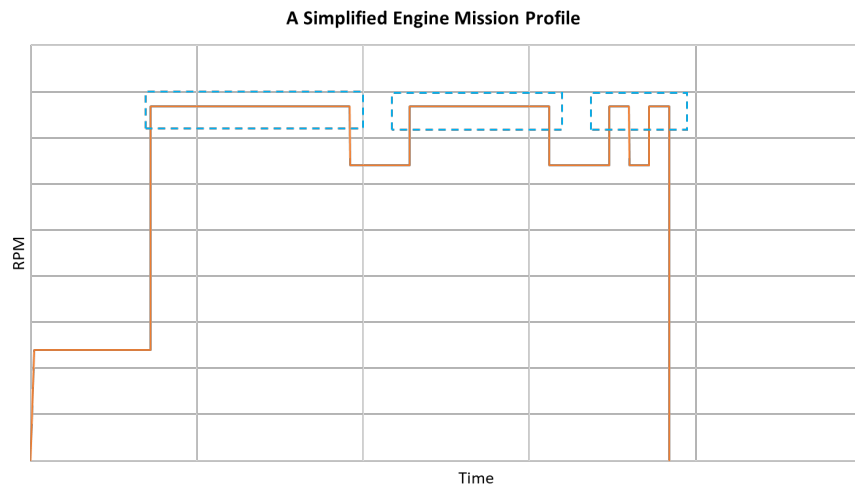


Figure 83. A Simplified Mission Profile and Cruise Regions

As it is shown in **Figure 84**, engine rotor part reach the maximum working condition in first load step without creep effect. Second load step continue during total cruise time with maximum rotational velocity and aerothermal condition while material creep properties are reflected. At the last load step the shutdown condition and all loads and creep effects removed.

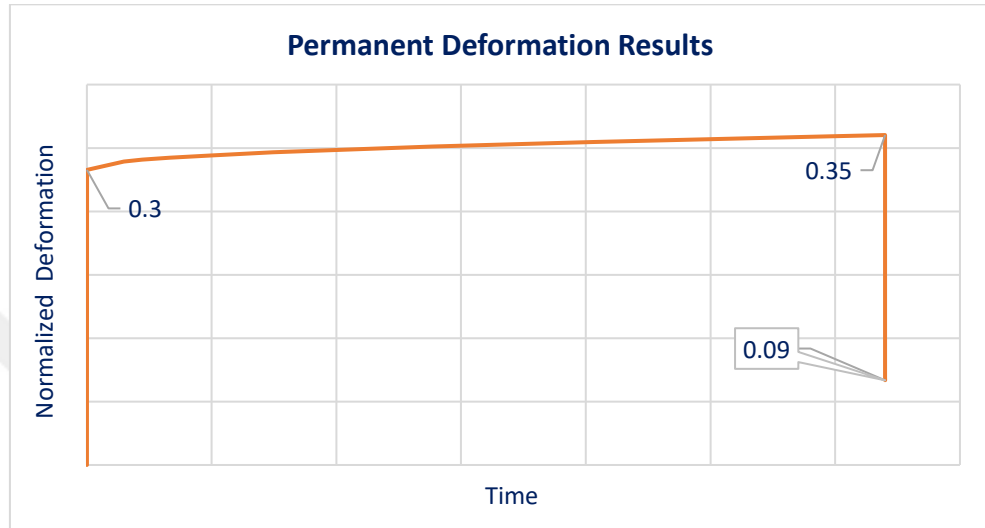


Figure 84. Analysis Results (Total Deformation)

As it is shown in total deformation results, rotor blade end point gets longer with creep effect. At the end of the analysis, close permanent deformation is calculated with % 12 error. It is also shown in **Figure 85**.

Scanned test results are taken from blade end points and it is seen in Figure 85 that deformation distribution change throughout 360°. This is a result of the effects of what is called the overall temperature distribution factor, which causes the thermal effects to vary over 360°. The reason is that the hot gas coming out of the combustion chamber does not show a smooth distribution to each rotor blade and it affects the permanent deformation values. For this reason, it can be said that an average elongation value of 170 micron is obtained for the whole structure.

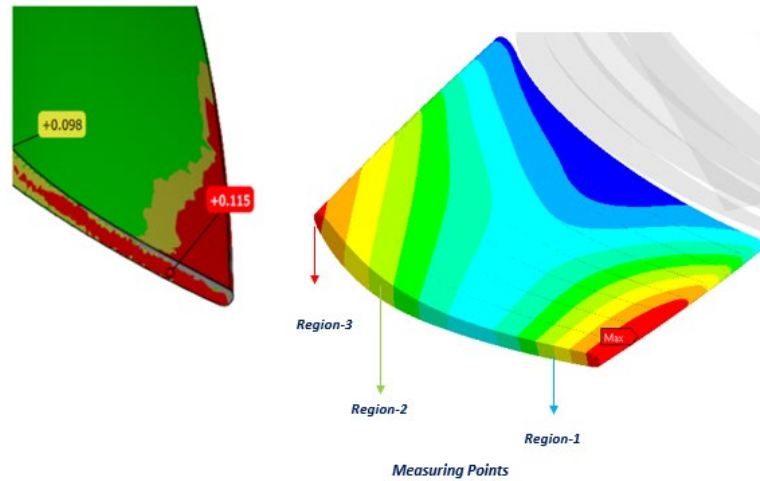


Figure 85. Test Result vs FEA Result (Permanent Deformation)

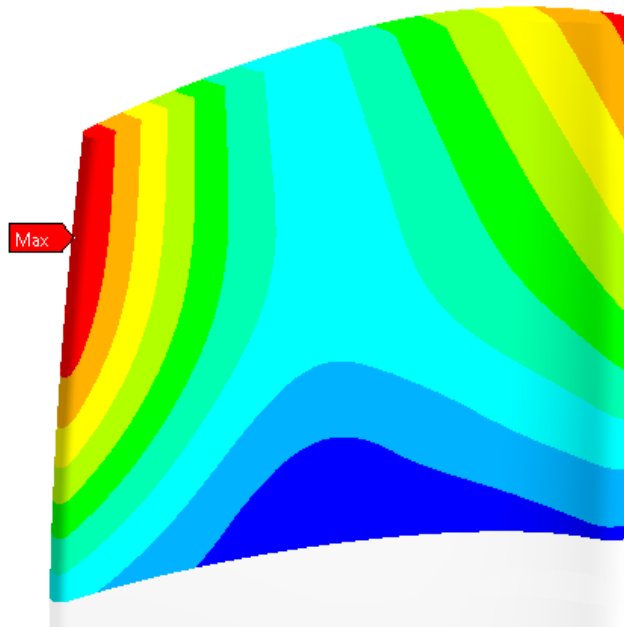


Figure 86. FEA Result (Permanent Deformation)

As it is shown in **Figure 87**, creep strain potential critical value is obtained approximately in %54 span region of the design. In addition, Similar points encountered when examining damage reports are shown in **Figure 57** that is an intergranular crack example on a rotor blade geometry mid-span region. Although the relevant reference work includes oxidative effects, it is similar to the crack initiation points obtained in the finite element analysis.

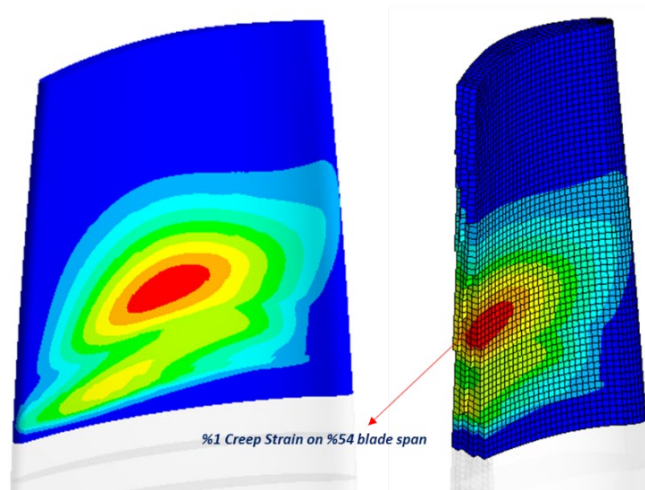


Figure 87. %1 Creep Strain on Blade Span

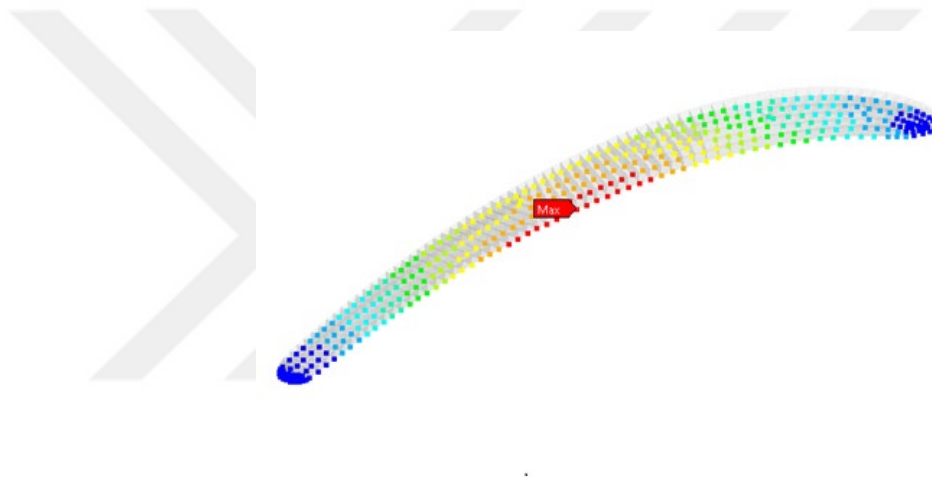


Figure 88. Stress and Strain Result on Critical Region

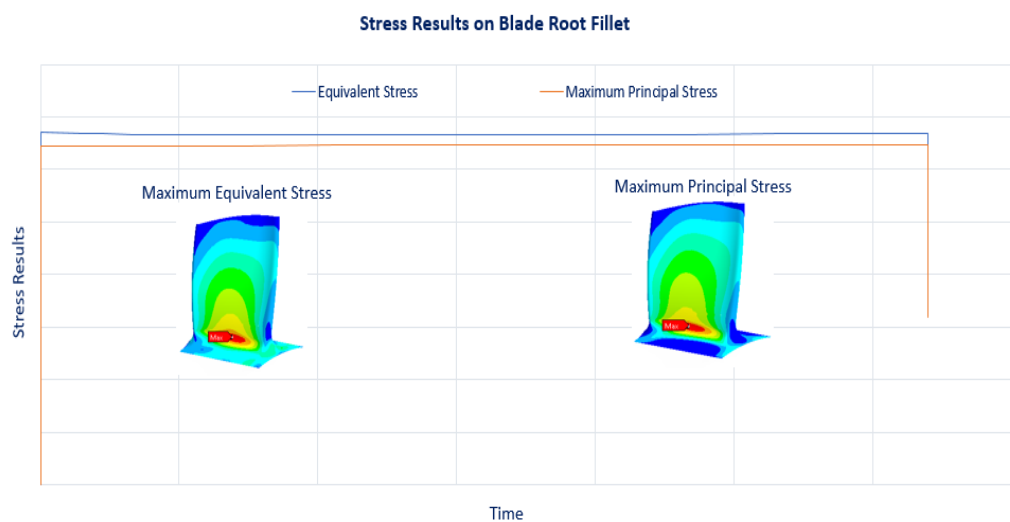


Figure 89. Equivalent and Maximum Principal Stress Results

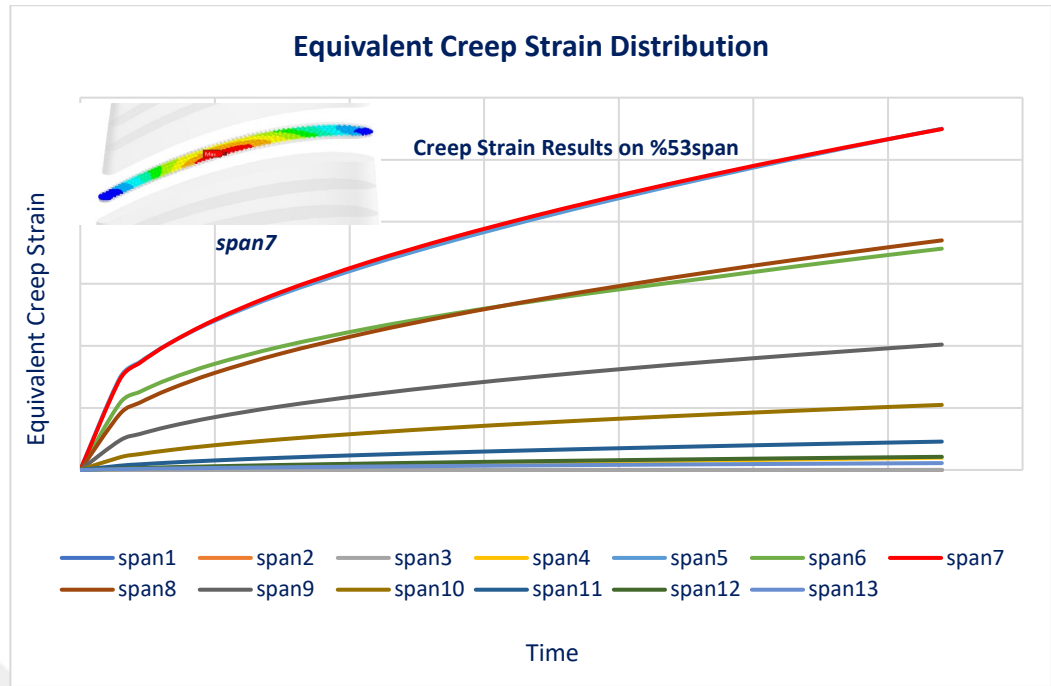


Figure 90. Creep Strain Distribution According to % span

As it is shown in **Figure 90** and **Figure 91**, maximum principal stress results and maximum equivalent stress results show that loads on blade cause purely tensile stress distribution. While the disk is supported on the shaft, the blade is subjected to high velocity, temperature and pressure loads. As a result of the centrifugal loads blade extends, stresses intensify in the root radius regions which are the disc-blade connection face. As the 4th parameter, the time effect increases the elongation from the blade span regions. When the creep elongation percentages obtained in the span regions are examined, it is seen that the stress values decrease towards the 53% span region and the creep elongation reaches the critical creep elongation value. It is similar to the rupture of the specimen that is used in material tests from the part called necking or reduced section. In addition, oxidative and corrosive effects that occur over time cause the blade to complete its working life much earlier than expected that is shown in **Figure 57**.

7. CONCLUSION

In this study, the behavior of a rotor blade is investigated under pressure, temperature and centrifugal loads to which it will be exposed throughout engine maintenance interval. Since the exposed loads involve cyclic effects, firstly, the mechanical behavior of the material under cyclic loads is determined with rate independent material models in 1d fea simulations. Analysis results are compared with test results and shared with σ - ϵ graphics.

Creep effects, which is a time-dependent phenomenon, are investigated since engine parts operate under these heavy loads for a long time and their duty profiles include long dwell times. In order to accurately modelling the creep effects, two different creep models in the literature are compared and the combined time hardening model is selected for 3d analysis. The results can be listed as follows;

- Isotropic and kinematic hardening models can not reflect by itself the real material behavior under cyclic loads. Kinematic hardening models are better than the isotropic hardening models due to the back stress term. However, creep is a time dependent phenomenon and dislocation pile up and recovery effects include material viscous behavior and it requires viscoplasticity material models usage.
- Under creep condition, the Norton material model is able to reflect the secondary region. It can not reflect the hardening effects of the primary region which are caused by plasticity especially in long transition time.
- On the other hand, Combined time hardening material model reflects primary and secondary regions better than Norton material model. This is shown by mathematical equations and graphics of both 1d and 2d fea models.

- When the test measurement results are compared with the studies carried out within the scope of finite elements, 40micron difference emerges in the permanent deformation values. While the cruise time of the operating profile is reflected to the analysis as the total creep time in the creep analysis, the shutdown-start steps that the engine actually encounters are reflected once. This reveals that the primary zone plastic effects occurring in the real case cause additional elongation and thus additional permanent deformations. The load unload scenario in which creep effects are neglected and causes a permanent elongation of 3 microns in total confirms this situation.
- The difference between the motor test measurement results and the simulations shows that the combined time hardening material models cannot model the real situation with 100% accuracy. It is seen that with the combined time hardening material models, the error rate is up to 12%. This difference is due to disc behavior and elongation being ignored during the cruise flight. By extending the finite element model and incorporating creep effects into the disk geometry, the error rate will decrease. In addition, we encounter different mechanisms within the material at high temperatures. The use of Chaboche type material models or curves obtained with TMF reflects better the recovery effects we encounter at high temperatures. These types of materials show better that the stucked dislocations are opened with the recovery effect as in the real situation, therefore more permanent deformation is obtained. In order to reduce the margin of error, it is considered to use TMF curve usage or Chaboche type material.

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