UNIVERSITI PUTRA MALAYSIA

EFFECT OF DWELL PERIOD ON FATIGUE LIFE OF 316L STAINLESS STEEL TUBE AT HIGH TEMPERATURE UNDER CREEP CONDITION

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By

KHAIRUL AZHAR BIN MOHAMMAD

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

EFFECT OF DWELL PERIOD ON FATIGUE LIFE OF 316L STAINLESS STEEL TUBE AT HIGH TEMPERATURES UNDER CREEP CONDITION

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December 2014

Chairman : Professor Mohd Sapuan Salit, PhD, P. Eng
Faculty : Engineering

Components of engineering structures that operate at high temperatures, such as jet engines, pressure vessels, nuclear reactors, oil and gas plants, and steam and gas turbines, are subjected to significant thermal and mechanical loadings. As the external surfaces of structures always maintain contact with the environment and are exposed to weather, surface cracks may form due to imperfections during product fabrication. The main purpose of this study was to characterize and examine the relative importance of the mechanism of fatigue damage in tubular structures, which occur at high temperatures, and to develop an adaption equation of creep-fatigue life prediction based on failure mechanisms at high temperatures.

In this study, a 316L stainless steel grade tubular structure was employed to characterize the prediction fatigue lifetime of plant industry components at operating temperatures in the range of 500-650°C and in creep-fatigue loading conditions. Fatigue tests were performed in the finite life region of a rounded specimen with a constant load amplitude, a constant frequency of 5 Hz and the stress ratio R of 0.1 at room temperature. A constant load and high temperature of 565°C were imposed on the specimen during the creep test. The nature of a hold period (tensile or compressive) affects fatigue life and surface crack patterns. The creep-fatigue test, which is similar to the fatigue test, with five hold times at maximum tensile stress, was conducted using a rounded specimen of “Type 316L stainless steel” at 565°C. Optical and scanning electron microscopy was performed to characterize the metallurgical damage and explain the microscopic damage mechanics.

Fatigue tests with and without hold periods were performed to assess the influence of creep-fatigue interaction on fatigue life. The results of the tests indicated that creep and temperature significantly impact fatigue behaviour. In several cases, fatigue lives were significantly reduced with an applied

hold time at high temperatures. Hold times are most damaging at high stress ranges and low fatigue lives. Many parameters affect the fatigue performance of structural components. Fatigue life is influenced by a variety of factors, such as the geometries and properties of specimens, stress, temperature, surface finish, direction of loading, presence of oxidizing or inert chemicals. Fatigue with a hold time and fatigue without a hold time at the fatigue limit were determined to be 39.2 MPa and 87.8 MPa, respectively, in this research.

The fatigue life of the 316L stainless steel was estimated by approaching the mean stress using a continuum damage mechanism (CDM). The continuum damage mechanism provides a reasonable prediction of fatigue response for high conditions. Based on the observation and characterization of fatigue life tubular steel pipes, the adaption equation for creep fatigue life prediction was proposed. Its simplicity gives it credibility and the adjustable use of alloy metal, which incorporates a number of cycles, applied stress and temperature, enables a power plant to predict the fatigue life of engineering components. The adaption equation can facilitate the damage tolerance design, which is the best design approach for reducing the cost and weight of heavy applications in the manufacturing process. A damage tolerant design philosophy for creep has been previously developed to improve the creep properties and elevated temperature fatigue crack growth resistance without sacrificing tensile strength and Low Cycle Fatigue (LCF) crack initiation life relative to the conventional microstructure (CM). Understanding the fatigue behaviour of steel pipes, which are derived from this study, are also useful in the design stage.

To validate the experimental results, the fatigue life prediction using finite element analysis (FEA) via Abaqus was employed. The simulation was performed by applying different stress levels to predict the stress of operation to measured life at the measured operation stress. The focus of the simulation is the importance of characterizing the fatigue limit using a comparison with experimental data. The fatigue limits for the simulation and the experiment are 150 MPa and 161 MPa, respectively, which correspond in terms of accuracy prediction; various aspects should be considered in the simulation. Additional developments in the analysis of creep-fatigue prediction test data are discussed, and expression for estimating fatigue life at high temperatures in stress-controlled tests are derived. To check the validity of adaption model proposed in this study, the assessment for creep fatigue interaction tests of austenitic 316L stainless steel under stress control at 565^{o}C has been conducted. The life prediction results are within a factor of $\pm \times 1.5$, which indicates that the model is suitable for stress-controlled fatigue or creep fatigue life prediction of ductile material. The predicted results correspond with the experimental data.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KESAN TEMPOH MASA PADA JANGKA HAYAT KELESUAN TIUB 316L KELULI TAHAN KARAT DI SUHU TINGGI DALAM KEADAAN RAYAPAN

Oleh

KHAIRUL AZHAR BIN MOHAMMAD

Disember 2014

Pengerusi : Professor Mohd Sapuan Salit, PhD, P. Eng
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Komponen struktur kejuruteraan yang beroperasi pada suhu tinggi seperti enjin jet, kontena/ bejana tekanan, reaktor nuklear , loji minyak dan gas, dan gas turbin dan wap adalah tertakluk kepada muatan haba dan bebanan mekanik yang tinggi. Sejak permukaan luaran struktur sentiasa bersentuhan dengan persekitaran dan terdedah kepada cuaca dan terkena keretakan dan juga kerana ketidaksempurnaan semasa pembuatan produk, retak permukaan mungkin wujud. Tujuan utama kajian ini adalah untuk mencirikan dan memeriksa kepentingan relatif mekanisme kerosakan keletihan dalam struktur silinder berlaku pada suhu yang tinggi dalam usaha untuk membangunkan satu formula adaptasi rayapan-keletihan ramalan kehidupan berdasarkan mekanisme kegagalan pada suhu tinggi.

Dalam kajian ini masa ini, struktur berbentuk tiub 316L keluli tahan karat gred digunakan untuk mencirikan meramalkan jangka hayat kelesuan terutamanya bagi komponen industri loji dengan suhu operasi dalam lingkungan 500-650°C menjalani bebanan rayapan-kelesuan. Ujian kelesuan telah dijalankan dengan amplitud malar beban, kekerapan malar 5 Hz dan nisbah tekanan, R bersamaan dengan 0.1 pada suhu bilik untuk spesimen berbentuk tiub di kawasan hayat komponen. Sementara itu beban tetap dan suhu tinggi sebanyak 565^{o}C akan dikenakan to spesimen untuk ujian rayapan. Sifat tahan lama (tegangan atau mampatan) mempengaruhi hayat kelesuan dan corak permukaan retak. Ujian rayapan-kelesuan adalah sama dengan ujian kelesuan dengan masa lima minit pada tegasan tegangan maksimum telah dijalankan menggunakan spesimen berbentuk tiub "Jenis 316L keluli tahan karat" pada suhu 565^{o}C. Ujian optik dan imbasan mikroskop elektron akan dijalankan untuk mencirikan kerosakan metalurgi dalam memahami mekanik kerosakan mikroskopik.

Ujian kelesuan dengan dan tanpa tempoh pegangan telah dijalankan untuk menilai pengaruh interaksi rayap -kelesuan pada hayat lesu. Ia telah mendapati bahawa rayapan dan suhu memberi kesan yang utama ke atas tingkah laku kelesuan. Dalam beberapa kes, hayat kelesuan menyusut terutamanya dengan masa tegasan pada suhu yang tinggi. Ia telah mendapati

bahawa masa tegasan adalah paling merosakkan pada tekanan tinggi dan hayat kelesuan berkurang. Banyak parameter mempengaruhi prestasi kelesuan komponen struktur. Hayat kelesuan dipengaruhi oleh pelbagai faktor, seperti geometri dan sifat-sifat spesimen, tekanan, suhu, kemasan permukaan, arah bebanan, kehadiran pengoksidaan atau lengai bahan kimia dan lain-lain. Kelesuan dengan dan tanpa masa tegasan untuk daya ketahanan kelesuan didapati sebanyak 39.2 MPa dan 87.8 MPa masing-masing dalam kajian ini.

Hayat Kelesuan daripada keluli tahan karat 316L dianggarkan dari penghampiran tekanan separa menggunakan Continuum Damage Mechanism (CDM). Continuum Damage Mechanism menyediakan ramalan yang respon munasabah kelesuan untuk keadaan yang tinggi. Berdasarkan pemerhatian dan pencirian hayat lesu paip keluli berbentuk tiub, formula adaptasi rayapan kelesuan ramalan hayat telah dicadangkan. Ia adalah kesederhanaan memberikan ia kredibiliti, penggunaan laras untuk logam aloi yang menggabungkan bilangan kitaran, tekanan di kenakan dan suhu dan boleh membenarkan loji kuasa untuk menerima / adaptasi pakai dan hanya menggunakannya untuk meramal hayat lesu komponen kejuruteraan. Formula adaptasi boleh memudahkan reka bentuk toleransi kerosakan, yang mana merupakan pendekatan reka bentuk terbaik untuk kekal kos dan mengukuhkan simpanan untuk aplikasi berat dalam proses pembuatan. Falsafah reka bentuk toleransi kerosakan untuk rayap sebelum ini dibangunkan dengan tujuan untuk memperbaiki sifat-sifat rayapan dan rintangan kelesuan pertumbuhan retak suhu tinggi tanpa mengorbankan kekuatan tegangan dan LCF retak permulaan hidup berbanding dengan mikrostruktur konvensional (CM). Pemahaman dan pengetahuan tentang tingkah laku kelesuan paip keluli yang diperolehi daripada kajian ini juga berguna dalam peringkat reka bentuk.

Untuk keputusan pengesahan eksperimen, ramalan hayat lesu menggunakan Analisis Unsur Terhingga (FEA) melalui Abaqus telah digunakan. Simulasi dilakukan dengan tahap tekanan yang berbeza untuk meramalkan tekanan operasi untuk mengukur hayat di tekanan operasi. Penekanan simulasi memberi tumpuan kepada kepentingan mencirikan had kelesuan berbanding dengan data uji kaji. Perbandingan had kelesuan antara simulasi dan eksperimen adalah 150 MPa dan 161 MPa, masing-masing yang akan menyediakan pertalian baik dari segi ketepatan ramalan walaupun pelbagai aspek perlu diambil kira dalam perkembangan simulasi. Pembangunan selanjutnya dalam analisis data ujian ramalan rayap-kelesuan dibincangkan dan ungkapan yang diterbitkan untuk menganggarkan hayat lesu pada suhu yang tinggi dalam ujian tekanan terkawal. Dalam usaha untuk memeriksa kesahihan model adaptasi yang dicadangkan dalam kajian ini, penilaian bagi ujian interaksi kelesuan rayapan 316L keluli tahan karat di bawah kawalan tekanan pada 565^{o}C telah dijalankan. Hasil ramalan hayat berada dalam factor $\pm\times1.5$ dan model dapat di kaitkan untuk tekanan terkawal kelesuan atau kelesuan rayapan ramalan hayat bahan mulur. Keputusan meramalkan berada dalam pertalian yang baik dengan data uji kaji.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

AGR	Advanced gas cooled reactor
AISI	American Iron and Steel Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
Ω	Atomic volume
Au	Gold
C	Carbon
^{o}C	Celcius
CDM	Continuum Damage Mechanisms
CM	Conventional Microstructure
Cl	Chlorine
Co	Cobalt
Cr	Chromium
CTOD	Crack Tip Opening Displacement
DLDR	Double Linear Damage Rule
EDX	Energy Dispersive X-ray
Fe	Ferum
FEA	Finite element analysis
F	Fluorine
FS	Frequency Separation Technique
FSW	Friction Stir Welding
HCF	High Cycle Fatigue
HTHP	High Temperature High Pressure
HTLCF	High Temperature Low Cycle Fatigue
HCL	Hydrogen chloride
kN	Kilo Newton
LDR	Linear Damage Rule
LEFM	Linear Elastic Fracture Mechanics
LCF	Low Cycle Fatigue
Mn	Manganese
MPa	Mega Pascal
T_M	Melting Temperature
Mo	Molybdenum
Na	Natrium
N	Newton
HNO_3	Nitric acid
O	Oxygen
PSB	Persistent Slip Band
SEM	Scanning Electron Microscopy
Si	Silicon
SEFS	Strain Energy Frequency Modified Approach
SIF	Stress Intensity Factor
S-N	Stress Life
S	Sulphur
TNBR	Tenaga Nasional Berhad Research
wt%	Weight Percentage
Yb	Ytterbium

YS	Yield Strength

LIST OF SYMBOLS

T	Absolute Temperature
ΔF	Activation Energy
Q_g	Activation Energy Of Grain Boundary Diffusion
D	An Allowable Damage Value
σ	Applied Stress
R	Bolztmann's Constant
b	Burgers Vector's Magnitude Of The Dislocation
l	Cavity Spacing
P	Coefficient Of The Second Stage Of The Fatigue Life
$\Delta\varepsilon_{pc}$	Compressive Creep Strain
$\Delta\varepsilon_{cc}$	Compressive Creep Strain
$\Delta\varepsilon_{PP}$	Compressive Plastic Strain
$\Delta\varepsilon_{cp}$	Compressive Plastic Strain
α	Constant Of Order Unity
t_r	Creep Rupture Time At The Same Stress Level In Static Creep Tests
ε_{cr}	Creep Strain
$1/n_c$	Creep Strain Hardening Exponent
N_I	Damage Caused By Crack Initiation,
N_{II}	Damage Caused By Crack Propagation.
E_{mod}	Elastic Modulus

ε_{el}	Elastic Strain,
$\Delta\varepsilon_e$	Elastic Strain Range
σ_e	Endurance Limit
$\dot{\varepsilon}_{cr}$	Equivalent Creep Strain Rate
σ_v	Equivalent Saturation Creep Stress.
c	Fatigue Ductility Exponent
b	Fatigue Strength Exponent
$\dot{\varepsilon}_t$	Fatigue Ductility Coefficient
$\dot{\sigma}_f$	Fatigue Strength Coefficient
$\dot{\tau}$	Flow Stress At 0 K
v	Frequency
GPa	Giga Pascal
D_g	Grain Boundary Diffusivity
$\sigma(t)$	Instantaneous Tensile Relaxation Stress During Hold Time
F_{max}	Maximum Strength
$M_{23}C_6$	Metal Carbide
N_f	Number Of Cycles To Failure
N_f^{Hold}	Number Of Cycles To Failure At A Given Strain Range For Fatigue Tests With Hold Periods
N_f^{NoHold}	Number Of Cycles To Failure At The Same Strain Range For Continuous Fatigue Tests
ε_{pl}	Plastic Strain

$\dot{\varepsilon}$	Secondary Creep Strain Rate,
μ	Shear Strength
$\varepsilon - N$	Strain Life
$\dot{\varepsilon}$	Strain Rate
σ_a	Stress Amplitude
A_o	Stress Co-Efficient,
n	Stress Exponent
σ_{FL}	Stress of Fatigue Limit
$\Delta\varepsilon_p$	Sum of a Plastic Strain Range
T	Temperature
T_a	Absolute Temperature
Q	Thermal Activation Energy Of Creep
δ	Thickness Of A Grain Boundary
t	Time
m	Time Exponent
ε_{tot}	Total Strain
t	Total Time In Fatigue Hold-Time Tests At A Given Stress Level
$\Delta\varepsilon_t$	Total Width Of The Loop
ε_f	True Fracture Strain,
σ_f	True Fracture Strength,

$\Delta\varepsilon_t$	Total Range Of Strain
$\Delta\sigma$	Total Stress Range
F_{yield},	Yield Strength
E	Young's Modulus

CHAPTER 1

INTRODUCTION

1.1 Scenario of Fatigue Life in Heavy Industries at High Temperatures

Creep-fatigue life prediction is a complex and essential criterion in the design of components that operate at high temperatures and are subjected to alternate loadings. The mechanical properties of most materials are dependent on the temperature. The ultimate tensile strength, yield strength and modulus of elasticity usually decrease with increasing temperature. The effect of high temperature on mechanical properties is associated with transformations of the material structure due to diffusion processes, ageing, dislocation restructuring (softening), and recrystallization. These processes imply that plastic deformation can easily occur at an elevated temperature. For high temperature applications in the melting point temperature range of 1400-1500°C, with the introduction of hold time, creep deformation can occur if favourable stress and temperature combinations are maintained. At elevated temperatures that span one-third to two-thirds of the melting point and at low-imposed stresses, the majority of metals, alloys and ceramics exhibit creep deformation grain boundary cavitations. In many engineering alloys, creep cavities nucleate below the nominal stress level of 100 MPa. Creep deformation with the introduction of hold time can occur if favourable stress and temperature combinations are maintained for high-temperature applications in the melting point temperature range of 1400-1500°C.

At high temperatures, the majority of metals show damage in the form of grain boundary voids and wedge cracks. A grain boundary cavity may nucleate as a result of either sliding or slip impingement and is sustained by either a stress-assisted diffusion, additional grain boundary sliding or a combination of these factors (Sandhya et al., 2005). Creep damage, which is a time-dependent process, is primarily dependent on the history of the stress and temperature that was applied to the component, whereas fatigue damage is generated by the cyclic stress and is primarily dependent on time-independent plastic strain (Gaoa et al., 2005).

A few decades ago, the prevailing viewpoint was that brittle material did not undergo fatigue (as brittle materials have limited dislocation motion); however, brittle materials do exhibit both mechanical fatigue and thermal fatigue under repetitive loading (Bhowmik et al. 2007; Wachyman et al. 2009).
Engineering components that are employed in oil, gas, aviation and nuclear industries usually involve high-temperature environments; in these conditions. As creep-fatigue is a significant failure mechanism, the life of these components should be adequately predicted before they are fabricated and implemented. Therefore, existing damage tolerant life prediction methods need to incorporate the creep phenomenon in high-temperature applications.

1.2 Issues Concerning of High-Steel Industries

Many researchers have performed studies on the type of steel that is applied for the global transmission of oil and gas. Defects that occur over the lifetime of a pipeline are problematic to engineers, researchers and manufacturers. Similar to any engineering structure, pipelines occasionally fail. In numerous cases, the only significant load in a pipeline's breakdown is the internal pressure (Cosham and Hopkins, 2004). Circumstances in which additional loads are possible include high temperature high pressure (HTHP), environmental damage (corrosion fatigue), elevated temperatures (creep fatigue) or sliding/physical contact (fretting and rolling contact fatigue) (Ritchie, 1999).

Different types of failure scenarios may occur on a pipeline, in which the failure of fittings (flanges and valves) are not considered.

i. failure of a defect-free pipe,

ii. failure of a pipe, which consists of a 'workmanship' imperfection (i.e., an imperfection in the pipe body or the possibility of a careless weld that is satisfactory to the relevant specifications or standards), and

iii. failure of a pipe, which consists of a defect/flaw that is not tolerable at the workman-ship level (such as a crack or a dent on a weld) (Cosham et al., 2008).

In addition, the damage/blow of steel is also categorized by the interaction between a defect (which causes a reduction in the burst strength) and a defect in the pipe fitting (pipework, fitting, and elbows). Thus, a study of Type 316L stainless steel is conducted to identify the mechanism that is susceptible to failure under temperature and variable stress. Continuous research and development are required to understand the causes and cures of cracking in steel.

A general tendency towards severe operating conditions is observed, i.e., higher mechanical loadings and temperatures to increase the efficiency of gas and steam turbines, internal combustion engines, heat exchangers, conventional and nuclear electric power generation equipment and other engineering components and devices. This trend has caused the initiation, growth and interaction of complex damaging processes within the materials of these components. They can cause the failure of a component and an entire structure, which limits their lifetime. Therefore, the safe assessment of the lifetime of a component is important for the prevention of failures, which may have disastrous consequences. Conservative predictions, however, may unnecessarily increase the cost of production and maintenance of systems.

1.3 Significance of Service Lifespan Prediction

Service lifespan prediction techniques are important in any industry that involves the daily use of metal components to assess its service damage, which is caused by high pressure and elevated temperature creep. A precise life prediction methodology that focuses on metal life is essential to ensure that the hot section component can be rejuvenated and to minimize irreparable damage and replacement costs associated with steel components.

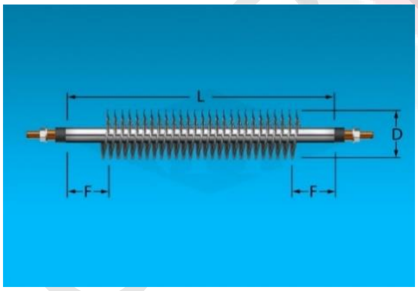
The main failure mode for tubular steel is known as high temperatures at low cycle fatigue as their utilization has experienced high global demand. Many researchers have focused on the service life prediction and extension of tubular steel, which is challenging due to the geometric shapes of specimens and the complexity of the phenomena. To determine and characterize the accuracy of a life prediction, both the upper bound and the lower bound are main aspects of engineering components at elevated temperatures. A material will be more unsafe and dangerous when it is overpredicted, whereas m will affect the inherent risk of damaged components or offset the economic benefits (Bernstein, 1982). No specific life prediction model has gained global acceptance among the majority of plant industries. Each industry performs a separate life prediction according to the situation and application. The foremost difficulty in the prediction on any material is accounting for the contributions by creep and/or environmental attack of the fatigue process.

Seamless Steel Tubes for
Heat Exchanger and
Condensers

UHT treatment of milk

stainless steel pipes

Food grade and sanitary
grade applications



Finned Tubular Heater
Construction Styles

Finned Tubular Heaters with Copper,
Stainless Steel and Incoloy Sheaths

Figure 1.1: Applications of Stainless Steel

1.4 Problem Statement

Life prediction is a complex and essential aspect of designing a component that is subject to high temperatures and alternative loading. Many researchers have focused on tolerate design to determine the life of a heavy-duty pipe that operates at high mechanical pressures and temperatures due to the repeated usage of cylindrical components and the extensive usage of this type of geometry. A main feature for industry is the provision of a high-strength material, which is challenging due to unknown compositions of industrial materials and the inevitable presence of defects in their substructures, such as holes, cavities and cracks. As a result, the consideration of fracture mechanics in the design of metallic structures is crucial. Both fatigue and creep can cause a structure to fail. Numerous efforts to understand why and how materials fail have been achieved. An increased demand for stainless steel products can be attributed to the increased use of stainless steel in the automotive industry (which uses stainless steel liners for auto exhaust systems), the maintenance an upgrading of oil refining and chemical plants, and the extensive use of stainless steel equipment in the pulp and paper industry and fast food service industry. The consumption of stainless steel that is used to fabricate kitchen utensils and appliances and the decorative use of coloured stainless steel on building facades by the construction industry has also increased.

The designer/analyst requires information about the stress concentration factor that is created by axial wall misalignment of adjacent tubular sections. This misalignment is usually caused by a change in wall thickness, oversized cross-sections and/or imprecise fabrication controls (Connelly and Nettlemoyer, 1993) Tubular components such as pressure vessels, pipes, borers, and driving shafts are common and useful parts of engineering structures. Due to an extensive range of usage for this type of structure, such as the transmission or storage of fluid produced in pipes and high-pressure vessels, these structures should be assessed under different conditions, such as various material, temperature and loading conditions. These conditions are conducive to combination creep-fatigue, which is a major mechanism for these components (Becker et al., 1986).

In the safety consideration of the mode of failure of pressure vessels and pipes, crack initiation, crack propagation and fracture, as well as fatigue failure, should be considered. Pipes that are subjected to high temperatures will have a shorter life than those with creep damage and fatigue damage that are separately incurred. In a safety assessment of pressure vessels and pipes, fatigue crack propagation and fracture should be considered among the possible modes of failure. The geometry of the component and the load conditions are the two most important parameters that affect the mechanisms of failure and crack propagation. The combination of temperature and loading fatigue causes more damage and life reduction in engineering components. Many researchers have noted that the application of fatigue and creep at high temperatures in the estimation of life and safety in a component is an essential part of design and application in heavy industries. The mechanism of the parameter in life prediction for a tubular structure under different conditions, such as creep, fatigue or creep-fatigue, is not well understood.

Therefore, this study investigated the fatigue life due to creep-fatigue and the estimation of life and verifies effective parameters and factors for tubular structures regarding certain parameters that can be published to improve the development of this modern arena.

1.5 Research Objectives

The objectives of this research are as follows:

- To characterize the fatigue life and endurance limit of tubular steel 316L stainless steel at high temperatures.
- To determine the mechanism of fracture, which is associated with creep-fatigue that is induced by temperature and hold time.
- To investigate the metallographic microstructural characterization of the metal in terms of the microstructure's fractured surface based on the results of fatigue and creep fatigue tests.
- To suggest the simple constitutive models of creep-fatigue interaction, which can be used to predict the lifetime for complicated situations of creep-fatigue, using simple creep and fatigue test data.

1.6 Thesis Layout

This thesis is divided into five chapters. Following this introductory chapter, which consists of the background of the research, chapter two provides a critical review of relevant literature based on an overview of fatigue, creep, fracture mechanics and creep-fatigue. A review of fatigue studies that have explored topics such as the historical background and creep fatigue life prediction models, is also presented in chapter two. Chapter three outlines the underlying theory and the experimental techniques that are employed in this study. Chapter 3 describes the experimental work, including the utilized materials, the testing techniques and the equipment. Chapter four is a placeholder to present the results of the current study and discuss the correlation between the obtained results and the existing theory. Observations of crack initiation sites and details of the transition from Stage I to Stage II and the transition from Stage II to Stage III using scanning electron microscopy are provided. The microstructural and chemical composition study that employs SEM are discussed. The test results are analysed in Chapter 5, which also presents the conclusion and recommendations for future studies.

1.7 Scope of Study

The scope of this study focuses on stainless steel grade 316L, which is extensively used in the petrochemical and construction industries and for power generation in pressure vessels, boilers, and steam turbines; its application in the oil and gas industries, such as pipe lines for carrying natural gas and sour gas, was not addressed in this study. The specimen preparation and fatigue tests were conducted in accordance to ASTM E606-92 and ASTM E466-96, respectively. The fatigue tests were performed under constant amplitude cyclic stress fluctuation loadings. A push-pull fatigue test was conducted to develop a stress-life curve for the hourglass of stainless steel specimens. In the creep test, which was conducted in accordance with ASTM E-139, specimens were subjected to high-temperature conditions and constant stress. The environment design was created to mimic the real scenario of actual piping in plant industries; thus, a combination of fatigue and creep tests have been performed to examine the mechanism of creep fatigue interaction on steel subjected to stress and elevated temperature. A simulation using Abaqus was performed to compare and validate the experimental data. In this study, a new contribution has been achieved by discovering the adaption of the equation from the continuum damage mechanism (CDM), which can be employed to predict the fatigue life of the engineering components of 316L stainless steel at high temperatures. Scanning electron microscopy (SEM) was employed to analyse the variations in the microstructure pattern and the fracture surface of the steel fatigue specimen and a macrostructure analysis was employed to identify the basic stages crack development using optical microscopy. The composition elements of the specimen fatigue of the structure were analysed by energy dispersive X-ray (EDX) analysis.

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