***Dedicated** to*

*My parents, **Ghulam Nabi** and **Khursheed Banu**,*
*My wife, **Arshi Khattak**,*
*My son(s), **Rokhan & Ryan**,*
*My siblings, **Nadia & Asim***
All my family and friends for their immensurable support and love

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ABSTRACT

Accurate quantification of the current accumulated material damage in the steel wall of a reactor vessel is essential in assessing the safety and integrity of the structure. In this study, a framework for mechanism-based structural life monitoring and assessment procedure is proposed and examined. The methodology is based on the competition between damage evolution and continual strength degradation of the material throughout the design life of the component. In this respect, damage evolution characteristics of the welded vessel steel are established through controlled laboratory experiments. Two types of steels, type-316 austenitic stainless steel and A516 Gr70 pressure vessel steel are used in this research. The samples (SS316 austenitic stainless steel) were heat treated (HT) at 500°C, 800°C and 1000°C followed by furnace cooling. This work examines the effect of different microstructures of austenitic stainless steel on both static and fatigue responses of the alloy. Type A516 steels are commonly used in welded construction of pressure vessels and boilers. Prolonged exposure to high operating temperature and fluctuating pressure could induce undesirable microstructure evolution, particularly in the vicinity of the welded connection. This in turn, modifies the long-term mechanics response of the structure and affects structural reliability prediction. This research attempts to quantify the effects of absorbed hydrogen and thermal aging on crack-tip plastic zone, impact toughness and fatigue crack growth response of the Type A516 Gr70 steel plate and the associated heat affected zone (HAZ). Ductile-to-brittle transition temperature (T_{DBTT}) values of Base Metal (BM) and Weld Metal (WM) are -26°C and -20°C respectively, while T_{DBTT} value of HAZ is -32°C. Results show that a crack continuously grows in the base metal or HAZ with increasing applied crack tip driving force, ΔK_a. The threshold stress intensity factor range, ΔK_{th} for HAZ (13.2 MPa√m) is lower than that for the base metal (15.3 MPa√m). Prolonged thermal exposure further lowers ΔK_{th} of HAZ to 11.4 MPa√m.

ABSTRAK

Ketepatan penaksiran bagi kerosakan dinding keluli reaktor adalah penting dalam menilai keselamatan dan integriti struktur bahan. Dalam kajian ini, satu rangka kerja bagi mengawasi struktur mekanisme dan penilaian prosedur dicadangkan dan diperiksa. Kaedah adalah berdasarkan perbandingan di antara kerosakan evolusi dan degradasi kekuatan abadi bahan sepanjang hayat rekabentuk komponen. Ciri-ciri kerosakan evolusi bagi keluli terkimpal telah dilakukan melalui eksperimen di dalam makmal yang terkawal. Dua jenis keluli, iaitu 316 keluli tahan karat austenitik dan A516 Gr70 keluli bertekanan digunakan dalam penyelidikan ini. Asas fizik keretakan lesu mekanisme-mekanisme keluli austenitik dengan mikrostruktur yang berbeza diperkenalkan secara ringkas. Sampel (keluli tahan karat SS316 austenitik) dipanaskan pada 500°C, 800°C dan 1000°C diikuti oleh pendinginan di dalam relau. Ini bagi mengkaji kesan perbezaan mikrostruktur keluli tahan karat austenitik pada dua keadaan tindak balas aloi iaitu statik dan lesu. Keluli A516 kerap digunakan di dalam pembinaan kimpalan bagi bekas bertekanan dan pendidih. Pendedahan yang berterusan terhadap suhu tinggi operasi dan turun naik tekanan boleh menyebabkan evolusi mikrostruktur yang tidak dikehendaki terutamanya pada bahagian sambungan kimpalan. Ini menyebabkan perubahan struktur mekanik bahan pada jangka masa panjang dan memberi kesan kebolehpercayaan ramalan kepada struktur. Kajian ini juga menilai kesan serapan hidrogen dan penuaan terma pada retak hujung zon plastik, keliatan hentaman dan pertumbuhan keretakan kelesuan yang bertindak balas pada plat keluli A516 Gr70 dan kawasan suhu yang terlibat. Nilai suhu peralihan mulur kepada rapuh (T_{DBTT}) bagi kawasan keluli asas (BM) dan keluli kimpal (WM) adalah pada -26°C dan -20°C, manakala nilai T_{DBTT} HAZ adalah -32°C. Keputusan menunjukkan keretakan yang berterusan pada logam asas atau HAZ dengan pertambahan retak yang dikenakan pada daya penggerak hujung, ΔK_a. Faktor keamatan tegasan ambang julat, ΔK_{th} untuk HAZ (13.2 MPa$\sqrt{m}$) berada lebih rendah daripada logam asas (15.3 MPa$\sqrt{m}$). Pendedahan terma yang berterusan akan merendahkan ΔK_{th} HAZ kepada 11.4 MPa$\sqrt{m}$.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

σ_{YS}	Yield strength (MPa)
υ	Poisson ratio
a	Crack length (mm), includes notch plus fatigue pre-crack
Å	Atomic radius
B	Specimens thickness (mm)
BM	Base Metal
C(T)	Compact Tension
CH_4	Methane
CTOD	Crack tip opening displacement
E	Young’s Modulus
EPFM	Elastic plastic fracture mechanics
F	Frequency
Fe	Ferrum
Fe_3C	Cementite
H_2	Hydrogen gas
HAZ	Heat affected zone
K_I	Stress intensity factor $(\mathrm{MPa}\sqrt{\mathrm{m}})$
K_{IC}	Plane strain fracture Toughness $(\mathrm{MPa}\sqrt{\mathrm{m}})$
K_Q	Critical stress intensity factor $(\mathrm{MPa}\sqrt{\mathrm{m}})$
LEFM	Linear elastic fracture mechanics
P	Load (N)
Pmax	Ultimate Load
P_Q	5% secant line to elastic loading slope (N)

R	Load ratio
r_ρ	Radius of the plastic zone
S	Span (mm)
SAW	Submerged arc welding
W	Specimen width
WM	Weld metal

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Today's business sector economics compel industrial units, such as petro-chemical, fertilizers and oil and gas industries to attain ever-higher capacity factors. Materials aging and other form of degradation increases the potential for component failures, outages and higher operation and maintenance costs. Managing materials degradation and aging is one of the major technical and economic challenges facing today's industry in general and oil and gas sector in particular. For oil and gas plants approaching the license renewal stage, assuring regulators of the continuing reliability and safety of in-service materials adds another dimension to this challenge. The rate of materials degradation, and consequently plant component or system availability, are strongly affected by a plant's environment-fatigue loading, including temperatures and corrosiveness. Thus, a comprehensive, integrated understanding of materials characterization with respect to their resistance to load, temperature and corrosive environment is a fundamental consideration in the development of overall plant business and operating strategies in oil and gas industries.

1.2 Background and Rationale

Pressure vessel (Figure 1.1) and piping system form a class of components for which particularly high levels of integrity and reliability are required. This is due to the potential hazards which are associated with many industrial processes combined with their high capital value. In oil and gas industries and chemical processing plants, the reactor pressure vessel often operates in aggressive environment. The loading consists of high pressure with fluctuating as in services operation and shut down. Such condition leads to environment-fatigue interaction of the material. The vessel provides the integrity of the reactor pressure boundary and function as a barrier for preventing the leakage of isolated chemical. In addition, the continued safety of the reactor pressure vessel is a key factor in ensuring the feasibility of implementing plant life extension program.

Figure 1.1 A 405 ton, hydro treatment reactor vessel for ConocoPhillips refinery project in Billings (Lakes superior warehousing, 2008).

Chemical reactor vessels and pipelines are commonly constructed using welded C-Mn (A516) steels and stainless steel (SS304) liners. In oil refineries and chemical plants these steel vessels operate in corrosive environments where high concentration of hydrogen sulphide is present. The operating temperature typically ranges from -29 to

427 °C. C-Mn and Cr-Mo low-alloy ferritic steels are widely used in power and petrochemical industries because of its susceptibility to HIC and high toughness at lower operating temperatures respectively. Unfortunately, prolonged exposure of these steels to intermediate service temperatures (thermal aging), could lead to deleterious effects such as embrittlement, loss of toughness and creep rupture of the steel (Spence and Nash, 2004) and a shift in ductile-to-brittle transition temperature (DBTT) to higher temperatures. Previous research showed that DBTT increases with increase in thermal aging temperature (Song et al, 2008). All these conditions could lead to failures of pressure vessels and pressure piping related accidents, which are often fatal and involved loss of capital investment (Tesman, 1973 and Challenger et al, 1995).

The majority of pressure vessels are made from joining parts or subassemblies, which have been previously sub fabricated into segments, such as cylinders and hemispheres by welding to form the base vessel. Welding joint used to produce the pressure vessel are mainly longitudinal joint and circumference joint (figure 1.2).

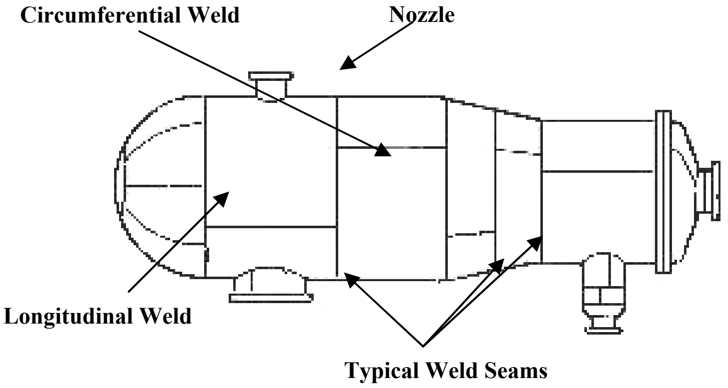

Figure 1.2 Type of welded joints in construction of a pressure vessel

The application of immense heat in a welded joint of a pressure vessel steel, to fuse the base plate and weld metal (electrode) for strong permanent joint results in a mechanical and metallurgical inhomogeneity due to the weld thermal cycle in the base metal (BM), the heat affected zone (HAZ) and the weld metal (WM). These changes often lead to a decrease in toughness of the weld and HAZ resulting in different microstructures throughout the HAZ and the associated residual stresses.Weldments are identified as a particular concern because they are often a life-limiting feature in the construction of pressure vessels.

During service, reactor pressure vessel is subjected to moderately high pressure and temperatures, neutron irradiations and cyclic fatigue. The most likely degradation sites are typically weldments. Various studies showed that cracks have been found in different regions of the weld with different orientation in the weld zone, such as centerline cracks, transverse cracks and micro-cracks in the underlying WM or HAZ (Zhu et al, 1992; Brooks and Thompson, 1991; Pandey, 2004 and Bullough et al, 2007), thus rendering this region to be the most susceptible for crack initiation and growth. The most severe and significant degradation mechanism is neutron irradiation embrittlement, which may be exacerbated by thermal aging. The accumulated effects over a long period of time due to irradiation and thermal aging causes range of mechanical properties, most significantly an increase in the DBTT.

Reactor pressure vessel failures have caused extensive damage to the industry, people and environment. The explosion of boiler/pressure vessel on-board the Mississippi steamship 'Sultana' in 1965 have claimed 1238 lives, although more souls were lost when a ship sank within 20 min after the explosion. The explosion of Union Oil amine absorber pressure vessel in 1984 has resulted in causing 17 fatalities and extensive property damage (Challenger et al., 1995). In 1999, 23 percent of a total of 138 explosion and 82 percent of a total of 150 accidents involved failure of boilers, resulting in 21 fatalities (Spence et al*.,* 2004). The situation worsened in 2001 where 158 people died and 342 were injured in boilers, pressure vessel and pressure piping related accidents. Many of these reported mishaps were due to non-conforming design and fabrication of pressurized vessels and components and inadequate in-service inspection.

This research is aimed at quantifying the progressive damage of welded steel in the combined loading conditions of pressure, pressure fluctuation and hydrogen absorption, typical of a reactor pressure vessel environment. An improved methodology for assessment of damage and structural integrity of the vessel based on the critical heat affected zone of the weld is proposed.

1.3 Research Objective

Following are the objectives of this research;

1. To develop a mechanism-based life prediction methodology for welded A516 Grade 70 pressure vessel steel under environment-fatigue loadings.
2. Establish baseline mechanical properties and fatigue crack growth behavior (FCG) of A516 Grade 70 steel.
3. Quantify the effect of thermal aging and hydrogen absorption on fatigue crack growth (FCG) behavior of welded A516 steel.

1.4 Scope of Work

The scope of this research work is to review the followings:

1 Methodology for assessment of damage in welded connections of carbon manganese steel reactor vessels.
2 Metallurgical and microstructural evaluation of welded A516 steels.
3 Impact toughness of thermally aged welded A516 steels.
4 Effects of absorbed hydrogen and thermal aging on crack-tip plastic zone in welded A516 steels.
5 Fatigue fracture mechanism of welded austenitic steel inlay.
6 Effects of absorbed hydrogen on fatigue crack growth behavior of thermally aged welded A516 steels.

1.5 Significance of Research

This research addresses various industrial sectors' strategic objectives. It includes achieving maximum plant useful life and cost/risk-focused decision making in regulation, operation, and design. This research also focuses on developing a methodology to address materials degradation/aging.

1.6 Organization of Thesis

The thesis comprises of nine chapters. Chapter one, the introduction overviews the application and importance of pressure vessel and highlights it as an important element of the oil and gas industries. It discusses the background of welded pressure vessel, research objectives, scope and significance of research.

Chapter two covers the literature review on methodology for assessment of damage in welded connections of carbon-manganese steel reactor vessel. Literature covering different aspects of pressure vessels, its types, geometry, working loads, material employed for construction of pressure vessels, design and constructional codes and aspects of assessment of damage and structural integrity with respect to fracture mechanics approach has been discussed in detail.

Chapter three narrates in detail the research methodology adopted in this research. It proposed improvement for life prediction methodology by discussing a research frame work employed in this research and presenting step by step process in accomplishing the results in the form of research methodology flow chart. This chapter gives adequate details regarding welded steel A516 plates, its different microstructure in as-received and corrosive environment, chemical analysis and detailed experimental procedures carried out throughout this research work.

Chapter four details the metallurgical and microstructure evaluation of welded A516 steel. Welding process, chemical composition and microstructure of A516 steel, J-factor, hardness variations across the welded A516 steel for as-received, thermally and hydrogen charged specimen and its tensile properties are the main focus in this chapter.

Chapter five discusses the impact toughness of thermally aged welded A516 steels. This chapter discusses in adequate detail on the aging procedures. Results are discussed in terms of impact energies for thermally aged specimen, ductile-to-brittle transition temperature (DBTT) and fractographic analysis.

Chapter six illustrates effects of absorbed hydrogen and thermal aging on crack tip plastic zone in welded A516 steels. This chapter discusses the fracture mechanics aspects of the materials and the corresponding fracture mechanisms.

Chapter seven reports on the fatigue behavior of cladding material (SS316) of the pressure vessel in terms of fatigue fracture mechanism of welded austenitic stainless steel inlay. Focus is placed on stainless steel liner functions and types. Effects of aging on mechanical behavior and fatigue fracture mechanisms are discussed in detail in this chapter.

Chapter eight narrates the fatigue crack growth behavior of welded A516 steels in the reactor vessel corrosive environment. This includes the Paris equation, threshold stress intensity factor and fatigue crack growth mechanisms.

Finally, Chapter nine notes the conclusion of the study and recommendations for future work in this area.