EFFECTS OF ABSORBED HYDROGEN ON FRACTURE TOUGHNESS OF WELDED SA516 GRADE 70 STEEL

MOHAMAD HAIDIR BIN MASLAN

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Dedicated to
my parents, Maslan bin Isa and Kaujah binti Yahok,
my wife, Noraini binti Kurdi,
my daughter, Nazurah Hana,
and all my family and friends
for their immensurable support and love.

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ABSTRACT

Effects of absorbed hydrogen on structure and properties of welded A516 Grade-70 steel are investigated. Emphasis is placed on ductility measure of the crack-tip plastic zone under Mode I loading. Specimens are cathodically charged in a cell with dilute sulphuric acid and corrosion inhibitor with uniform charging current density of 20 mA/cm^2 and at different exposure time. Results indicate a change from coarse- to fine-grained microstructures in the weld region and heat affected zone (HAZ) of hydrogen-charged specimen. Well-defined ferrite-pearlite bands in the base metal are transformed into coarse-grain structure. Hardness variation along radial distance indicates higher values towards the center of the bar, possibly due to faster diffusion rate but limited solubility of hydrogen. Load-COD responses indicate that slow, stable crack propagation occurred in both base metal and HAZ. The measured provisional fracture toughness, K_Q is higher for HAZ than that for the base metal. The toughness values decreases significantly for the initial three hours of hydrogen charging. The tensile fracture region in the immediate fatigue pre-crack tip forms a triangular (rough) zone due to limited constraint to free surface deformation in the thin specimen. Fracture surface of HAZ is dominated by intergranular fracture with localized cleavage facets.

ABSTRAK

Kesan penyerapan hidrogen ke atas struktur dan sifat bahagian kimpalan pada besi A516 Gred 70 adalah dikaji. Penekanan diberikan kepada pengukuran kemuluran pada bahagian plastik di hujung retak dengan pembebanan mod 1. Spesimen dicaj pada bahagian katod dalam sel elektrolisis yang menggunakan cecair campuran asid sulfurik dan perencat kakisan, dengan arus caj malar 20 mA/cm^2 dan tempoh mengecas yang berbeza. Keputusan mendapati terdapat perubahan dari mikrostruktur kasar kepada mikrostruktur berbijian halus di bahagian kimpalan dan bahagian kesan pemanasan bagi spesimen yang dicaj dengan hidrogen. Jalus ferit pearlit pada logam asas bertukar kepada struktur bijian yang kasar. Variasi kekerasan pada jarak sepanjang jejarian didapati nilainya meningkat ke arah pusat rod. Berkemungkinan ianya disebabkan oleh kadar serapan yang pantas tetapi dengan keterlarutan hidrogen yang terhad. Bebanan perubahan pembukaan retak mendapati berlakunya perambatan retak yang perlahan dan stabil berlaku pada kedua-dua logam asas dan bahagian kesan pemanasan. Pengukuran kekuatan patah sementara, KQ bagi bahagian kesan pemanasan adalah lebih tinggi berbanding bahagian logam asas. Nilai kekuatan berkurangan dengan ketara selepas tiga jam pertama dicaj hidrogen. Bahagian permukaan patah pada pra-retak lesu berbentuk segitiga akibat dari kekurangan pergantungan kepada perubahan bentuk permukaan bebas di dalam spesimen nipis. Permukaan patah bahagian kesan pemanasan di dominasi oleh patah antara bijian dengan celah segi setempat.

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 Test
CH_4	Methane
CTOD	Crack tip opening displacement
E	Modulus Young
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 $(MPa\sqrt{m})$
K_{IC}	Plane strain fracture Toughness $(MPa\sqrt{m})$
K_Q	Critical stress intensity factor $(MPa\sqrt{m})$
LEFM	Linear elastic fracture mechanics
P	Load (N)
Pmax	Ultimate Load
PQ	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 ONE

INTRODUCTION

1.1 Introduction

Today business sector economics compel industrial units to attain ever-higher capacity factors, yet materials aging and the other forms of degradation are increasing the potential for components failure, derating or outages and higher operation and maintenance costs. Thus managing materials degradation and aging is one of the major technical and economic challenges facing today industry. For 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 operating environment, including temperatures and corrosiveness. Thus, a comprehensive, integrated understanding of materials characterization with respect to their resistance to load, temperature and corrosive environment are a fundamental consideration in the development of overall plant business and operating strategies.

1.2 Background

Pressure vessel and piping system form a class of components for which particularly high levels of integrity and reliability are required. This is due the potential hazards which are associate with many industrial processes combined with their high capital value. In oil and gas industries, and chemical processing plants, the reactor pressure vessel often operate in aggressive environment. In this study, the environment is focusing the presence of corrosive gases. The loadings constitutes 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.

Reactor pressure vessel failures have caused extensive damage to the plant, people and environment. 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). The explosion of boiler/pressure vessel on-board the Mississippi steamship ‘Sultana’ in 1965 have claimed 1238 lives, although more souls were lost when ship sank within 20 min after the explosion. 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.

Pressure vessel are often used in the temperature range 480-565^{o}C with the stresses about 15-30 MPa over time periods of some 30 years. The main factor responsible for the good creep resistance of this low alloy steel is the formation of fine and highly stable dispersions of alloy carbides, although a significant contribution also comes from solid solution strengthening (Tsai, 2003). In heavy-wall vessels operating in similar service environment, it is common to apply welded austenitic steel inlay to low carbon steels, Thereby, taking advantage of the high strength and low cost of the base metal while retaining the superior corrosion resistance of the stainless steel weld inlay(Nasman, 1982). The low carbon steel and stainless steel inlay of the vessel is primarily constructed by welding resulting in different microstructure in the welded zone(Krisnan et al., 2005). The application of heat for the fusion process greatly transforms the microstructure; induce phase changes and mechanical properties of the steel in the vicinity of the welded region. These changes often lead to a decrease in toughness of the weld and heat affected zone (HAZ) resulted in different microstructures throughout the HAZ and the associated residual stresses.

Several commercially available steel have been studied for applications in reactor pressure vessel. Although these studies have contributed to better understanding of the microstructures of these welded joints, little information is available in correlating the observed microstructures with the mechanical responses of the alloy.

An experimental research, establishing the processing, heat treatment-structure-properties relationship of the alloy is therefore necessary. The result is essential in generating relevant failure data and quantifying factors that can explain fracture mechanism for both static and fluctuating load at elevated temperatures and in corrosive environment.

This research is aimed at discovering and understanding the underlying fracture mechanism with environment interaction of welded connection and to examine the effect of the HAZ in both static and fatigue responses of the welded ASTM SA516 Grade 70 steel connection.

1.3 Research Problem And Hypothesis

1.3.1 Statement of Research Problem

How does the material damage evolve in the process zone of welded ASTM SA 516 Grade 70 steel subjected to hydrogen absorption?

1.3.2 Research Questions

1. What are the damage parameters for the HAZ of welded ASTM SA516 Grade 70 steel under hydrogen environment?
2. What are the evolution characteristics of these parameters and its limiting values?

3. What type of hydrogen concentration sequence that should be applied to test specimens in accelerated tests for a given operative conditions?
4. What are mechanism-base of life prediction models are proposed to represent the Hydrogen interaction failure of welded ASTM SA516 steel?

1.3.3 Hypothesis

Physical-based damage parameters for the HAZ include the different microstructural features of the zone, resulting from steep temperature gradient during the fusion process. These range from grain size, types of microstructures and surface defects. Hardness measurements may also indicated the material damage. In addition, initiation of microcracks may be quantified in terms of crack density (crack length per unit area sampled)

Non-linear or logarithmic-type evolution characteristic is expected for the chosen damage parameter. For example, hardness measures decreases rapidly after half design-life of the vessel has been reached. This is expected due to synergistic environment effect especially at elevated temperature when creep might be present.

Typical operating conditions for hydrocracking pressure vessel are 380^{o}C-455^{o}C along with hydrogen pressure of 17 MPa. This condition has cause critical point in the wall to experience increasing of hydrogen concentration up to 4.28ppm. Temperature is set at ambient temperature as a control process, and different hydrogen concentration will be applied to get the relation of material degradation to the hydrogen concentration.

Two approaches are proposed for the mechanics-based life prediction models. In the damage mechanics approach, damage will be plotted against component life(years) throughout designed life of the component. Damage parameters in this approach are hardness variation and microstructure degradation. In the fracture mechanics approach, damage parameters are fracture toughness (K_{IC}) and stress intensity factor (K_I). K_I can be calculated through non-destructive testing (NDT) during in-service conditions and curve for K_{IC} will be established through experimental setup.

1.4 Research Objectives

The objectives of this research are to quantify the effect of absorb hydrogen on crack tip ductility in welded SA516 grade 70 steel

1.5 Research Scope

Scope of this research is:

- Critical literature review on welded ASTM SA516 Grade 70 steel, hydrogen embrittlement of steel, and fracture mechanics
- Development accelerated hydrogen absorption test cell. Establish absorption characteristics.
- Mechanical test of ASTM SA516 Grade 70 steel- Tension and fracture toughness tests, fractographic and metallurgical analysis on welded samples and base metal samples.
- Establish damage evolution characteristics of ASTM SA 516 Grade 70 steel in prolonged hydrogen environment. Damage parameters include fracture toughness, hardness and microstructure.

1.6 Significance of Study

This research directly addresses and ensures safety and integrity of vessel throughout desired life. Moreover this research will help to avoid any expected pressure vessel failure events thereby improving plant capacity, realibility and availability. Last but not least, life-extension program can successfully be achieved through this research.