UNIVERSITI TEKNIKAL MALAYSIA MELAKA

THE INVESTIGATION ON THE FATIGUE CRACK GROWTH ON WELDED PRESSURE VESSEL STEEL

This report is submitted accordance with requirement of Universiti Teknikal Malaysia Melaka (UTeM) for Bachelor Degree of Manufacturing Engineering (Engineering Material) with Honours.

by

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I hereby, declared this thesis entitled "The Investigation on the Fatigue Crack Growth on Welded Pressure Vessel Steel" is the results of my own research except as cited in references.

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6 April 2009

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APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of UTeM as partial fulfillment of the requirements for the degree of Bachelor of Manufacturing Engineering (Engineering Materials) with Honours. The members of the supervisory committee are as follow:

(Signature of Supervisor)

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ABSTRACT

This project (*Projek Sarjana Muda*) studied the fatigue crack growth (FCG) of commonly industry used welded pressure vessel steel. In the oil and gas industries, the welded pressure vessel steel was affected by the welding heat output that causes many changes to the mechanical and metallurgical properties on near as-welded region (HAZ) effecting fatigue crack growth (FCG) rate on its interface. This leads to many accidents involving failure of pressure vessels. The objective of this project is to investigate and study about the fatigue crack growth (FCG) on the base metal (BM) region, and heat affected zone (HAZ) region of the welded pressure vessel steel. The type of tested steel is ASTM 516 Grade 70 of thickness 12mm. The steel was welded using submerged arc welding, and undergone post weld heat treatment. Then, it is fabricated to compact tension C(T) specimen according to ASTM E647-03. Two different notch location of compact tension specimens were fabricated relatively according to the heat affected region, and base metal region. The microstructure analysis was done and resulted ferrite-pearlite in BM region, and ferrite, austenite and cementite in the HAZ, while the WM has ferrite, widmanstatten ferrite and bainite. The hardness test was also done using Rockwell Hardness testing and found HAZ region had the highest value than BM region. These two specimens were fatigue cyclic loaded according ASTM E 647-03 and found that the HAZ region had the highest FCG rate compared to the BM FCG rate because of the brittle structures of the HAZ regions. Finally, the ruptured surface of the specimens was done fractograph analysis under scanning electron microscope (SEM) and found that modes of fracture formations involved in both HAZ and BM regions are the same and slightly differences that are transgranular-mixed and equiaxed dimples, quasi and mixed modes fracture, and fine cleavage and transition from large to small dimples of fracture on pre-crack, FCG and rupture regions respectively.

ABSTRAK

Projek Sarjana Muda ini mengkaji pemanjangan keretakan kelesuan pada besi yang digunakan untuk besi tangki bertekanan di industri. Didalam industri minyak dan gas, kesan haba dari kimpalan menyebabkan perubahan sifat mekanikal dan metallurgi kepada kesan haba kimpalan yang memberikan kesan kepada pemanjangan keretakan kelesuan yang membawa kepada banyak letupan berlaku. Objektif projek ini untuk mengkaji pemanjangan keretakan kelesuan pada bahagian kesan haba kimpalan dan besi utama besi tangki bertekanan yang telah dikimpalkan. Jenis besi yang diuji adalah ASTM A516 gred 70 berketebalannya 12 milimeter. Kepingan besi dipateri menggunakan ark kimpalan automatik dan menjalani proses rawatan haba. Kemudian, besi tadi di fabrikasi mengikut bentuk mampat-tegangan spesimen mengikut panduan ASTM E647-03. Dua bentuk mampat-tegangan spesimen dibentuk mengikut kedudukan bahagian kesan haba kimpalan dan besi utama. Analisis mikrostuktur dilakukan dan mendapati mikrostruktur “ferrite-pearlite” in besi utama (BM), “ferrite, austenite dan cementite” di kawasan kesan haba kimpalan, dan besi kimpalan, (WM) ada “ferrite, widmanstatten ferrite dan bainite”. Ujian kekerasan dilakukan melalui Mesin Ujian Kekerasan Rockwell mendapati nilai kekerasan kesan haba kimpalan tinggi berbanding besi utama. Kedua spesimen dijalankan ujian pemanjangan keretakan kelesuan mengikut “Pengukuran Kadar Pemelajaran Kelesuan Keretakan” (ASTM E647-03) mendapati kesan haba kimpalan (HAZ) mempunyai kadar pemelajaran keretakan tinggi berbanding besi utama (BM) disebabkan rapuhnya kesan haba kimpalan (HAZ). Selepas itu, spesimen yang sepenuhnya retak dijalankan analisis fractograf dibawah mesin Misroskop Imbasan Elektron mendapati mod keretakan sama dan tidak banyak berbeza di dalam kesan haba kimpalan dan besi utama iaitu campuran antara-granular, campuran mod keretakan, perubahan unjuran besar ke kecil pada pra-retak, kelesuan keretakan, dan kawasan gagal masing-masing.

DEDICATION

To my beloved parents and grandmother

Hajah Normah Bte Sulaiman

Mohd Zin Bin Mohd Amin

Hajah Halijah Bte Md. Don

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LPG	-	Liquefied petroleum gas
Psig	-	pound-force per square inch gauge
ASTM	-	American Society for Testing and Materials
WM	-	Weld metal
HAZ	-	Heat affected zone
BM	-	Base metal
MPa	-	Mega Pascal
SAW	-	Submerged arc welding
DC	-	Direct current
AC	-	Alternating current
SS	-	Stainless steel
σ_x	-	Longitudinal stress
σ_y	-	Transverse stress
σ_m	-	Maximum stress
f	-	Residual stress
LEFM	-	Linear elastic fracture mechanics
EPFM	-	Elastic-plastic fracture mechanics
K_1	-	Stress intensity factor
G	-	Energy release rate
γ_s	-	Specific surface energy

γ_p	-	Plastic deformation energy
α	-	Applied stress
a	-	Crack length
E	-	Modulus of elasticity
$a*$	-	Effective crack length
r_p	-	Circular plastic zone of radius
θ	-	Angular coordinate
t_{xy}	-	Torque stress
σ_{xy}	-	Elastic-plastic boundary
r	-	Radius
r_y	-	Plain stress and plain strain
K_{eff}	-	Effective stress intensity factor
c	-	Internal crack length
t	-	Thickness
K_{IC}	-	Fracture toughness
K_C	-	Maximum fracture toughness
CTOD	-	Crack-tip opening displacement
d	-	Crack-tip opening displacement (changes)
d_{el}	-	Crack-tip opening displacement (elastic)
d_p	-	Crack-tip opening displacement (plastic)
SENB	-	Single edge notch bend
ESIS	-	The European Structural Integrity Society
CCT	-	Centre-cracked tension (CCT)
SENT	-	Single edge notch tension
da/dN	-	Crack growth rate per cycle of loading
DK_I	-	Stress-intensity factor at the tip of the crack
FCG	-	Fatigue crack growth
JLF-1	-	Reduced activation steel type
Cr	-	Chromium
AISI	-	American iron and steel institute
$\propto$	-	Alpha designation ferritic grains
CGB	-	Coarse-grained bainitic
FGB	-	Fine-grained bainitic
ICR	-	Inter-critical region

CGHAZ- Coarse-grained heat affected zone

FGHAZ- Fine-grained heat affected zone

PWHT - Post weld heat treatment

FCAW-S- Self shielded flux-cored arc-welding

Al - Aluminium

Ti - Titanium

Zr - Zirconium

EDM - Electric discharge machining

GDS - Glow Discharge Spectrometry

CHAPTER ONE

INTRODUCTION

1.1 Introduction

In the revolution of oil and gas in our industrial world, it involves the applications of pressure vessel. Pressure vessels is used to hold gases or liquids at a pressure different from the ambient pressure or designed as a closed container. For fundamental uses, pressure vessel is used as a vessel, tanks, and pipelines that carry, store, or receive fluids. In the industry world, pressure vessels are used in a variety of applications such as industrial compressed air receivers and domestic hot water storage tanks. Other examples of pressure vessels are diving cylinder, recompression chamber, distillation towers, autoclaves and many other vessels in mining or oil refineries and petrochemical plants, nuclear reactor vessel, habitat of a space ship, habitat of a submarine, pneumatic reservoir, hydraulic reservoir under pressure, rail vehicle airbrake reservoir, road vehicle airbrake reservoir and storage vessels for liquefied gases such as ammonia, chlorine, propane, butane and Liquefied petroleum gas (LPG).

1.2 Background

Pressure vessels are built with good tensile properties that is chemically stable in the chosen application can be employed. The mechanical properties of steel are increased by forging, but welding can sometimes reduce these desirable properties. In case of welding, in order to make the pressure vessel meet international safety standards, carefully selected steel with a high impact resistance & corrosion resistant material should also be used. Some pressure vessels are made of wound carbon fibre held in place with a polymer. Due to the very high tensile strength of carbon fibre these vessels can be very light, but are much trickier to manufacture.

However, there are many accidents involving pressure vessel steel and boilers. And it had become a common problem in the uses of these pressure vessels. For example, the accident on July, 2002, an Enbridge 34-inch-diameter-steel pipeline ruptured in a marsh west of Cohasset, Minnesota, America. Approximately 6,000 barrels (252,000 gallons) of crude oil were released from the pipeline as a result of the rupture. No deaths or injuries resulted from the release. The cost of the accident was approximately $5.6 million, which includes the cost of cleanup and recovery, value of lost product, and damage to the property of the pipeline operator and others. The National Transportation Safety Board determines that the probable cause of the July 4, 2002, pipeline rupture near Cohasset, Minnesota, was inadequate loading of the pipe for transportation that allowed a fatigue crack to initiate along the seam of the longitudinal weld during transit. After the pipe was installed, Cavaney (2004) found that fatigue crack grew with pressure cycle stresses until the crack reached a critical size and the pipe ruptured.

Another example, January 20, 2004, after an explosion at Algeria's largest refinery and principal oil exporter in the port city of Skikda. Rescue workers searched through rubble for missing worker on Tuesday after a huge explosion at its key gas installations killed 23 people on Monday evening, official media said. It caused by a defective, high pressure, steam boiler ruptured, high vibrations just before the boiler ruptured. The resultant explosion on rupture damaged nearby vessels containing flammables. The flammable Loss of Containment resulted in further fires and explosions. (Anonymous, 2004)

1.3 Problem statement

This behaviour crack growth has become an undesired phenomenon that occurs to the pressure vessel steel. Pressure vessel steel was widely been used in pipings, storage tanks or container that is that operated at pressures above 15 *psig* or etc. This presence of crack can cause many safety hazards. This cyclic fatigue growth is a phenomenon in structures subject to cyclic actions involving progressive localized damage, with cracks and crack propagation. Crack may initiate originally undamaged areas and propagate afterwards, and already existing cracks and crack-like defects propagate. The process eventually leads to a reduction of cross-sectional areas to such an extent that rupture occurs under an action of a magnitude that has been withstood satisfactory before. Zeman *et al.* (2006) stated that final structure will be ductile or brittle.

Recently, safety organizations have discovered during inspections that there are a number of welded pressure vessels that are cracked and damaged in workplaces. When pressure vessels have cracks or damage, they become unsafe. The cracks or damage may result in leakage or rupture failures. Failure, when dealing with pressure vessels and such high *psig*, can present major safety issues. The commonly used pressure vessel steel type is ASTM SA516 Grade 70 steel, the interested argument in this research is;

"How does the fatigue crack growth rate of the welded pressure vessel ASTM A516 Grade 70 of the heat affected zone and base metal regions?"

1.4 Research objectives

In this project, there are two main objectives that have to be achieved in order to fulfil the requirements of the project. These objectives are identified and analyzed from series of discussion and references made regarding the problem statement;

1) To investigate the fatigue crack growth on welded pressure vessel steel in two different crack propagation regions that are the base metal (BM) region, and heat affected zone (HAZ) region.
2) To compare the fatigue crack growth rate and behaviour on each region studied.

1.5 Scope of the project

The joining process of welding two or more pressure vessel steels will affect or vary along with the properties of the pressure vessel steels. The welded pressure vessel steel is composed to several of heterogeneous microstructural regions composed to base metal (BM), heat affected zone (HAZ), and weld metal (WM). Variations in the properties may due to the high heat input during welding, slag inclusions, chemical reactions of the metal to the atmosphere of flux or filler material, disproportionate heating or cooling rates (Sindo *et al.*, 1987). These microstructural regions of its microstructure and properties are altered by welding heat from the welding process and subsequent re-cooling causes this change in the area surrounding the weld.

The extent and magnitude of property change depends primarily on the base metal (BM), the weld filler metal, and the amount and concentration of heat input by the welding process. The extent and magnitude of property change gradually from WM to HAZ to BM. The property changes include changes in chemical reactions, mechanical properties, microstructures, grain size, and etc. having each regions have different yield strength, tensile strength, and fracture toughness. The grains near the weld are coarser gradually changing finer towards the base metal. This change of property is most discussed at weld interface, which is the boundary separating the WM from the HAZ. Thus when crack develops in the weld metal or outside the weld metal in the heat affected zone and starts propagating, it encounters different set of properties as it advances. In particular, when it encounters the weld interface, its behaviour changes according to its orientation and point of initiation in weldment relative to the interface.

Thus, the scope of this project are to compare the fatigue crack propagation of welded ASTM 516 Grade 70 steel plate on different regions of base metal (BM) and heat affected zone (HAZ). The microstructure analysis is done to identify the micro structural surface of the welded ASTM 516 Grade 70 steel plate. The hardness test is conducted to analyze the hardness distribution of the welded ASTM 516 Grade 70 steel plate. Also the tensile test is done to obtain the yield point, and the tensile strength. And lastly, the fractograph analysis is done to analyze its ruptured surface.

1.6 Design of the project

The aim of this work is the analysis of fatigue crack propagation in the sample material on two different regions of base metal, and heat affected zone of the ASTM 516 Grade 70 steel plate. These tests were done in compact tension specimen according to the ASTM E647 standard test procedure. The cyclic loading was done by the Instron Cyclic Fatigue Loading Machine. Finally, fracture surfaces morphology (fractograph analysis) was conducted by scanning electron microscope (SEM) on each of sample regions after completely plasticity failure in regions of the pre-crack, fatigue crack growth, and rupture regions respectively.

CHAPTER TWO

LITERATURE REVIEW

2.1 Pressure vessel steel

Chattopadhyay (2005) defines pressure vessel as a closed container with a pressure differential between inside and outside. Pressure vessel like vessels, tanks, and pipelines that used to carry, store, or receive fluids. Pressure vessels often have a combination of high pressures together with high temperatures and in some cases flammable fluids of highly radioactive materials. Because of such hazards it is imperative that the design be such no leakage can occur. In addition, these vessels have to be designed carefully to cope with the operating pressure and pressure. The rupture of a pressure vessel has a potential to cause extensive physical injury and property damage.

The pressure vessels steels usually are fabricated from carbon and alloys. The standard specifications for general requirements according to the American Society for Testing and Materials (ASTM) for steels plates for pressure vessels of carbon types are listed in the in the Table 2.1.