PROJECT REPORT

CONSTRUCTION OF A CRACK GROWTH TESTING APPARATUS ASSOCIATED WITH STRESS CORROSION CRACKING (SCC) STUDY

P. KHIDMAT MAKLUMAT AKADEMIK
UNIMAS

PETER ANDERSON ANAK JOSEPH

This project is submitted in partial fulfillment of the requirement for the Degree of Bachelor (Honours) of Mechanical Engineering and Manufacturing System

Report Submitted To
Faculty of Engineering
UNIVERSITY MALAYSIA SARAWAK (UNIMAS)
2005
DEDICATE TO MY LOVING FAMILY, SISTER AND BROTHER
AND ALL MY FRIENDS WHO HAS SUPPORTED AND
ENCOURAGED ME THROUGH GOOD TIME AND HARD TIME

THANK YOU AGAIN FOR YOUR SUPPORT AND
ENCOURAGEMENT.
ACKNOWLEDGEMENT

First of all, the author would like to take this opportunity to express his sincere and thousand of appreciation to all the individuals who contributed to the production of this thesis through their moral support, advice, guidance and participation.

I would like to thank both of my supervisors, Dr. Mohammad Omar Bin Abdullah and Madam Mahshuri Yusuf for giving guidance, valuable advice and continuous support during the development of this project. Their idea and methods had clearly guided the author to work even better and objective oriented. The author is grateful to the staffs of Asean Bintulu Fertilizer (ABF) especially Mr. Jamuri Zen and Mr. Martin Allin Sayan for their industrial expertise and advice.

Special thanks also go to Dr Shahril, Dr Andrew Rigit A.R and Mr. Liew Fui Kiew who has giving good advice and explanation on the fabrication of the prototype in Designing and Construction of Crack Growth Apparatus and other technical approach.

All in all, the author would like to thank the lecturers, friends, lab technician, Mr. Masri, Mr. Rhyer, Mr. Sabriman, Mr. Aiman, Mr. Zaidi, Madam Miza and relatives who had helped directly or indirectly in the project. It’s been great pleasures for all who had give their point of view in good comment, critics and advice which actually drive the author to think positive and understand better the existing problem.

Finally, the author would like to thank his beloved parents especially Mr. Joseph Ak Geraman and Seri Ak Jugah for supporting in financial, guidance and moral support. Not forgotten to his brother and sister who give an inspiration and encouragement, this research would not be possible without their continuous support and encouragement.
ABSTRACT

A case study of Stress Corrosion Cracking or SCC is a part of this project title. Ammonia tank always related with the SCC problem especially at -33°C. Stress corrosion cracking (SCC) can be divided into three important keywords to differentiate the mechanism which is tending to cause the fracture mechanism over the metallic material. SCC is caused by three conditions such types of environment, types of materials and types of stress. Continuous research was encouraged to solve this problem from time to time in order to recognize main problem in obtaining the best solution. Hence, various design of the prototype had been carrying out to study the material with concerning the major problem, condition, material used in the study and etc. The methodologies used for development of the proposed project were selection of the crack growth apparatus, determining apparatus or equipment and resulting from the testing to the fabrication of the prototype. The testing is a must to carry out in order to detect a failure or defect on the prototype. From the result obtained, the data will be analyzed and the discussion is carrying out to discuss the defect of the prototype.
ABSTRAK

Kajian kes tentang “Stress Corrosion Cracking” atau juga dikenali sebagai SCC adalah sebahagian daripada tajuk ini. Tangki ammonia sering dikaitkan dengan permasalahan yang dikaitkan dengan SCC terutama pada suhu -33°C. SCC terbahagi kepada tiga kekunci yang penting bagi membezakan mekanisma yang menyebabkan kegagalan pada bahan logam. SCC disebabkan oleh tiga keadaan seperti keadaan persekitaran, jenis-jenis bahan dan jenis tekanan. Kajian yang berterusan amat digalakkan bagi menangani masalah ini dari semasa ke semasa dan juga bagi mengenal pasti masalah utama yang membawa kepada penyelesaian yang amat diperlukan. Oleh sebab itu, pelbagai jenis rekabentuk atau model telah direka dan diguna pakai bagi menjalankan kajian bahan berpandukan permasalahan utama, keadaan, bahan yang ingin dikaji dan sebagainya. Metodologi yang digunakan semasa perkembangan projek ini adalah pemilihan rekabentuk model yang sesuai untuk “Crack Growth Apparatus”, penentuan alat dan software, diikuti lukisan berskala and pembinaan rekabentuk model tersebut. Pengujian terhadap rekabentuk model ini adalah dikehendaki bagi mengetahui kecacatan yang dijangka akan berlaku. Daripada keputusan pengujian yang diperolehi, data tersebut akan dianalisa bagi membincangkan permasalahan terhadap rekabentuk model tersebut. Sejurus itu, rekomen akan diberi bagi memperbaiki model tersebut.
LIST OF CONTENT

CHAPTER 1 INTRODUCTION

1.0 Introduction 1
1.1 Tank inspection procedure 3
1.2 General description of ammonia storage tank 4
  1.2.1 Design of ammonia storage tank 5
1.3 Comprehensive view 6
1.4 Objective of project 7

CHAPTER 2 LITERATURE REVIEW

2.0 Introduction 8
2.1 Various models of SCC test apparatus 9
  2.1.1 Model of crack growth apparatus 9
  2.1.2 Model for electrochemical test apparatus 12
  2.1.3 Magnetic nondestruction inspection method 14
  2.1.4 Model for sulphide stress corrosion cracking test 18
  2.1.5 Compact tension specimen (CT) 21

CHAPTER 3 BACKGROUND STUDY

3.0 Nature of corrosion 25
3.1 Stress corrosion cracking (SCC) 29
  3.1.1 Mechanism of stress corrosion cracking 32
3.2 Corrosion fatigue 34
  3.2.1 Mechanism of fatigue and corrosion fatigue growth 34
    3.2.1.1 Fatigue 34
    3.2.1.2 Corrosion fatigue 35
3.3 Crevice corrosion 36
CHAPTER 4 RESEARCH METHODOLOGY

4.0 Introduction 38
4.1 Methodology approaches 38
4.2 Study and Selection of Crack Growth Apparatus Design 39
4.3 Identifying methods and materials 40
  4.3.1 Testing equipment 40
  4.3.2 Torque wrench 42
  4.3.3 Stainless steel 304 42
  4.3.4 Compact tension specimen preparation 43
4.4 Prototype design of crack growth apparatus 45
4.5 Fabrication of the Prototype and Commissioning 46
4.6 Testing the prototype 46
  4.6.1 Procedure for Strain measurement in relation to Strain-Torque Characteristic Testing of Prototype 47
4.7 Observation and data collection 49
4.8 Data analysis 49
4.9 Discussion and Recommendation for Future Work 50

CHAPTER 5 RESULT AND DISCUSSION

5.0 Introduction 52
5.1 Testing results 52
  5.1.1 Data collection 52
  5.1.2 Data analysis 57
5.2 Discussion 59
  5.2.1 Discussion of the test result and the study limitation 59
  5.2.2 Limitation 61
5.3 Discussion of ammonia storage tank 63
CHAPTER 6 CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

6.0  Introduction 70
6.1  Achievement from the fabrication of crack growth prototype 70
6.2  Conclusion 71
6.3  Recommendation for future research/work 73

REFERENCES 78
APPENDIX I (Detail drawing in 2D) 1
APPENDIX II (Fabrication Process) 1
APPENDIX III (Test Implementation) Initial Test 1
APPENDIX IV (Storage Inspection Procedure) 1
LIST OF TABLES

Table 2.1 Materials with chemical composition and mechanical properties.

Table 2.2 Nominal composition of electrodes.

Table 2.3 (a) Chemical composition of Inconel 600 alloy studied.

Table 2.3 (b) Chemical composition of type 304 stainless steel studied.

Table 2.4 Chemical analysis (wt %) of the duplex stainless steel Pipes used.

Table 2.5 Chemical composition of Types 304SS used for the tests.

Table 5.0 Data collected from the testing.

Table 5.1 Data collected from the testing.

Table 5.2 Inspection of the tanks performed.
LIST OF FIGURES

Figure 1.1 (a)  Design of 10,000 tones of ammonia storage tank.
Figure 1.1 (b)  Design of 30,000 tones of ammonia storage tank.
Figure 2.1     A typical equipment for crack growth studies.
Figure 2.2     A typical equipment for electrochemical studies.
Figure 2.3 (a) Setup of magnetic nondestructive inspection method.
Figure 2.3 (b) Magnetic nondestructive inspection methods.
Figure 2.4 (a) Model for sulphide stress corrosion cracking test.
Figure 2.4 (b) Three dimensional representation of the microstructure of the as-received materials.
Figure 2.5 (a) A Schematic representation of the experimental set-up.
Figure 2.5 (b) Dimensions for the CT specimen.
Figure 2.5 (c) Schematic diagram of CT specimen in clevis.
Figure 3.1 (a) Atoms structure bonding.
Figure 3.1 (b) Atoms structure bonding.
Figure 3.2     Stress corrosion cracking.
Figure 3.3     Stress application over the material.
Figure 3.4 (a) Mechanism of stress corrosion cracking.
Figure 3.5     Film Rupture mechanism of intergranular SCC in sensitized stainless steel.
Figure 4.1     Flow process of works in fabricating the crack growth apparatus.
Figure 4.2     Application of strain gauge to the CT Specimen.
Figure 4.3     Torque Wrench.
Figure 4.4     Stainless steel 304 plate.
Figure 4.5 (a)  ASTM Standard Dimension of Specimen.
Figure 4.5 (b)  Dimension of Specimen.
Figure 4.6     The prototype.
Figure 5.1     Effect of torque (every 25 Nm) increment to the strain.
Figure 5.2     Effect of torque (every 5 Nm) increment to the strain.
Figure 5.4     The illustration of the defect over the holder.
Figure 5.5     Bending specimen.
Figure 5.6 (a) Initiated bending over the specimen.
Figure 5.6 (b) The illustration of the bent specimen.
Figure 5.7 (a) Initiated bending over the specimen.
Figure 5.7 (b) Initiated bending over the specimen.
Figure 6.1     Specimen setup on the holder.
Nomenclature

\( \varepsilon \) Strain

\( dF_s \) Electrical resistance

\( F \) Strain gauge factor

\( R_s \) tensile strain pulse increase

\( R_b \) Ballistic resistor

\( V_s \) Potential difference of strain gauge

\( E \) Voltage supply

\( n \) Constant

\( k \) Strain constant
CHAPTER 1

INTRODUCTION

1.0 General Introduction

Oil and gas industry is becoming one of the main incomes for the oil-producing country beside the other sectors of manufacturing industrial. The development of this industry between the oil-producing countries had been helping much and beneficial for their economic supports. Thus, large petroleum and petrochemical manufactures is spending large amount of money to build process plant to process the products from the offshore raw materials such as oil and gas.

Most chemical plant needs storage facilities for feedstock and products which are able to store large quantities of the products produce. Therefore, various risks are involved in storing and handling large quantities of flammable liquids and liquefied gases. Hence the developer has to develop highly sophisticated safety concepts to counteract such risks especially for tank terminals with long operating periods. Beside the purpose of storage, the tank is most useful to keep the liquid product temporarily before its loading to shipping and exported out.
Due to this situation, the tank is to be inspected at certain period which is recommended by authorities and recommendations by special codes and internal recommendations (companies). According to D. Schirmer, besides the regulation and recommendations technical aspect are the reasons for the tank inspection. This will lead to the shut down activities for the overall of plant operation once there are found that all the equipments, instruments, valves, piping materials, electrical materials and so on are in worst and in improper condition. Generally, from the inspection through technical aspect, the related causes to the inspection implementation are because of following factors:

1. Corrosion caused by medium
2. Corrosion caused by atmosphere, water, ground water
3. Cracks caused by high strength of deformation by unequal foundation settlement
4. Crack caused by high strength of un normal operating condition
5. Crack cause by stress concentration (SCC)
6. Safety reasons
7. Damages from outside
8. Lack of maintenance

To overcome these problems, the management of the petroleum or petrochemical industrial specially has to spend a large sum of costs annually on mitigating the effects of chemical and environment that was induced the failure of materials used over the storage tank and other equipments in process plant. Their
have to spend a cost in anti corrosion mechanism, materials selection and modern
fracture mechanics before construct the tank.

1.1 Tank Inspection Procedure

To inspect the tank, it must following certain procedure and regulation which is
outline to guide the process of inspection. The main objective is to keep the
shutdown time of the storage as short as possible and preplanning is required to
determine the date and duration will be taken to implementing the inspection and
overhaul works. Time frame is presented which are including the whole activities
during the shutdown.

Site survey is the continuous task to be implemented before the shutdown
operation is proceeding. The tank and others facilities are to be inspected when they
are still in service. The conditions of all the components or equipments are stated and
reported, any malfunction or damages methods of equipments are evaluated for the
next actions. Daily report will help much in cope up the problem of malfunction and
damage components through the process.

From the survey and the inspection report it is the basis for the scope of
inspection of all components. The report from the investigation will brought to the
meeting room of knowing further action should be overhaul or renewal or
replacement. All required jobs are to determine and the time demand is to be
evaluated by preparing the time frame and planning for scheduling. All the
requirements such as manpower, mobilisation and demobilisation, materials are
summarized in the planning and scheduling. The decommissioning procedure must be prepared together. For the proper planning step, it is shown in Appendix IV.

1.2 General Description Of Ammonia Storage Tank

Through the case study, the author found that almost all of the ammonia storage tanks are atmospheric refrigerated type. The capacity of ammonia storage tank is designed according to the manufacturer request. Based on D. Schirmer (June, 1987), ammonia is design for 41.6m diameter x 12.9 straight shell height with flat bottom and rafter supported domed roof of spherical radius 30m. It is contained within a full height pre-stressed concrete bund. The design pressure is 800mmWG/-50mmWG. The refrigeration unit is 2x275000Kcal/h. The flare capacity is 750Nm³/h gas. The tank is design to contain 10,000 tones of liquid ammonia tank at -33.4°C and a maximum filling height of ammonia (NH₃) to 12.3 as shown in Figure 1.1 a and Figure 1.1 b.

The second example of ammonia tank design is a “double integrity tank (cup-in-tank), 40m diameter, 36.225m high; the outer tank is 42.3m, externally insulated with a spherical roof, and stands on a piled, insulated, concrete foundation about 600mm clear of the ground. The installation is refrigerated and operates at the normal boiling point of ammonia of -33°C and has a design pressure of 14kPa. The tank materials is specified low temperature impact properties and has a thickness of 32mm at the lowest strake and a minimum thickness of 10mm in the upper one third of the tank. (http://www.needaus.org/peter3.htm)
1.2.1 Design of Ammonia Storage Tank

10,000 t Ammonia Storage Tank, FACT, Cochin, India

Design pressure: 800 mm WG/- 50 mm WG
Refrigeration unit: 2 x 275,000 Kcal/h
2 x 93,000 Kcal/h
Flare capacity: 750 Nm³/h gas

Figure 1.1a Design of 10,000 tonnes of ammonia storage tank.
(Source: D. Schirmer 1987)

Figure 1.1b Design of 30,000 tonnes of ammonia storage tank.
(Source: http://www.needaust.org/peter3.htm)
Aluminum and zinc metal spray both prevented cracking. Aluminum spray has a low potential margin and high consumption rate. Zinc spray has a large potential margin and low consumption rate in range 0.02 mm/year, which it allowing about 10 years lifetime.

1.4 Objective of Project

In this final year project, the author reviewed the case study of the fracture mechanism which always occurred in metallic material in petrochemical process plants. Stress corrosion cracking of ammonia storage tank is the study that will involve in this topic where author have to study how does it occurred in the beginning and how does the environment influence the mechanism. The main project objectives are as follows.

1. To study and review SCC and other potential hazards associated with commissioning of ammonia tank.
2. To design and fabricate a prototype which is used to study the crack growth.
3. The commission and do conduct initial test on the prototype constructed to investigate the prototype’s performance.

In order to obtain those objectives mentioned above, the testing was carried out using Compact Tension (CT) specimen. The testing procedure is mentioned in chapter four in details. Lastly the author will do some recommendation and suggestion on the prototype built.
2.0 Introduction

Stress corrosion cracking (SCC) is the most serious corrosion problem for metallic materials encountered in service. Recently experimental study had been carried out and it is found that SCC can be defined as the failure mechanism in metallic structure initiate cause of the weakness of the bonding structure affected by the environment and the others factors and wherever finally turn to cracking.

Lunde and Nyborg (1989) carried out their study in stress corrosion cracking (SCC) by using two types of methods which are by using of Compact Tension (CT) specimens and the other one is by electrochemical study. The purpose of their study is to study the crack growth and means to prevent cracking in carbon steels in ammonia solution. The study is considered the characteristic of the SCC mechanism which from the theoretical study SCC can be understand as a mechanism that is occurring under active passive electrochemical condition. The absence of corrosion
cause by the protective film will performs a corrosion rather than cracking. Cracking is occurred while the stress or stress intensity is applied.

Thus combination of these three mechanisms hence it will equivalent to a stress corrosion cracking. If one of stress and corrosion does not absence it will not perform as SCC.

2.1 Various Models of SCC Test Apparatus

2.1.1 Model for Crack Growth Apparatus

![Diagram](image)

Figure 2.1: A typical equipment for crack growth studies.
The studied of stress corrosion cracking (SCC) growth of carbon steel in ammonia had been done by Lunde and Nyborg (1989) by using the method as show in Figure 2.1. The objective of their study is to study the crack growth upon the pre-crack specimens and means to prevent cracking. The construction of the SCC crack growth equipment is based on their experience before proceed the experiment by using the Compact Tension (CT) specimens.

The compact tension specimens were fabricated with standard dimension and 1.5mm deep side grooves with thickness 25mm. Firstly the specimens were fabricated with Chevron Notch and a fatigue pre-crack. Later specimens made with straight notch without fatigue pre-crack. In addition, the experiment also carry out the specimens with the heat affected zone where welding plates was performed both with X-formed weld and K-formed weld. CT specimens were made with through-thickness notch located either in the weld metal or in the line heat affected zone. Table 2.1 shows the different types of materials used by comparing the chemical composition and mechanical properties. Liquid ammonia is used for chemical reaction; the ammonia will flow in and out of the tank.
Table 2.1: Materials with chemical composition and mechanical properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical Composition %</th>
<th>Mechanical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Mn</td>
</tr>
<tr>
<td>St. 52.3 plate DIN 17100 ASTM A537 Grade 1</td>
<td>0.17</td>
<td>1.57</td>
</tr>
<tr>
<td>St. 52.4 tube</td>
<td>0.18</td>
<td>1.43</td>
</tr>
<tr>
<td>RAEX 266 P ARC/350</td>
<td>0.08</td>
<td>1.03</td>
</tr>
<tr>
<td>BS 150: 224 490 B-LT50</td>
<td>0.18</td>
<td>1.14</td>
</tr>
<tr>
<td>Weld metal Norweld electrode Baso 120</td>
<td>0.06</td>
<td>0.9</td>
</tr>
</tbody>
</table>


Based on the data analysis and result, Lunde and Nyborg (1989) summarize that stress corrosion cracking does not occur in steel specimens with a fatigue crack because of the existent of crevice corrosion attack occurred in the outer part of the fatigue crack specimens. Their just find that stress corrosion cracking (SCC) just occurred easily in specimens with machined notch only.

Based on the experiments with increasing of stress intensity factor or crack opening/displacement it was found that maximum stress corrosion crack growth rate increased with the increasing of stress intensity factor. Their obtained the rates of crack growth in the experiments were 2mm/year at stress intensity factor of 40MPa√m and 6mm/year at 60MPa√m. Just a very small amount of SCC was found at
30MPa√m. The experiments with increasing of stress intensity factor had shown the higher crack growth rates than with the constant load.

The experiments with welded specimens showed that residual stresses in welds are important for SCC of carbon steel in ammonia, while microstructure variations in the weld and the heat-affected zone (HAZ) seem to have a little effect.

2.1.2 Model for Electrochemical Test Apparatus

![Diagram of electrochemical test apparatus](image)

Figure 2.2: A typical equipment for electrochemical studies.

Electrochemical studies also had been carried out by Lunde and Nyborg (1989) with the Model as show in Figure 2.2. This method is built up to study either
stress corrosion cracking (SCC) is occurred under electrochemical potential or not. Lunde and Nyborg (1989) found that SCC of carbon steel in ammonia was prevented by cathodic polarization. The condition is when anodic polarization is high, it tends to affect SCC occurred in ammonia with 2000 ppm water and with ammonia without an Oxygen (O₂). The materials used to implement the experiment are shown in Table 2.2.

Table 2.2: Nominal composition of electrodes

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Al</th>
<th>Mg</th>
<th>Mn</th>
<th>Si</th>
<th>Fe</th>
<th>Zn</th>
<th>Cu</th>
<th>Zr-Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-wire</td>
<td>99.8</td>
<td>-</td>
<td>-</td>
<td>&lt;0.15</td>
<td>&lt;0.15</td>
<td>-</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>Al-plate</td>
<td>99.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AlMn</td>
<td>-</td>
<td>0.3</td>
<td>0.9-1.5</td>
<td>0.5</td>
<td>0.7</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>AlMg₃</td>
<td>-</td>
<td>2.6-3.6</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>AlMg 4.5Mn</td>
<td>-</td>
<td>4-5</td>
<td>0.4-1</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Mg</td>
<td>-</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Zn</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>


Lunde and Nyborg (1989) conclude that SCC of carbon steel in ammonia is strongly dependent on the electrochemical potential. The SCC was prevented by cathodic polarization at about +300mV vs. Al and below, while SCC was easily obtained by anodic polarization at +500mV vs.