

**STRESS CORROSION CRACKING BEHAVIOR OF
AUSTENITIC STAINLESS STEELS IN NATRIUM
CHLORIDE SOLUTIONS**

SAMIR MILAD ELSARITI

© This item is protected by original copyright

UNIVERSITI MALAYSIA PERLIS

2013



Stress Corrosion Cracking Behavior of Austenitic Stainless Steels in Natrium Chloride Solutions

By

Samir Milad Elsariti

(0931410408)

A thesis submitted in fulfillment of the requirements for the degree of
Master of Science (Mechanical Engineering)

**School of Mechatronic Engineering
UNIVERSITI MALAYSIA PERLIS**

Year
(2013)

UNIVERSITI MALAYSIA PERLIS

DECLARATION OF THESIS

Author's full name : SAMIR MILAD ELSARITI

Date of birth : 10th September. 1982

Title : STRESS CORROSION CRACKING BEHAVIOR OF AUSTENITIC
STAINLESS STEELS IN NATRIUM CHLORIDE SOLUTIONS

Academic Session : 2012/2013

I hereby declare that the thesis becomes the property of Universiti Malaysia Perlis (UniMAP) and to be placed at the library of UniMAP. This thesis is classified as :

CONFIDENTIAL (Contains confidential information under the Official Secret Act 1972)*

RESTRICTED (Contains restricted information as specified by the organization where research was done)*

OPEN ACCESS I agree that my thesis is to be made immediately available as hard copy or on-line open access (full text)

I, the author, give permission to the UniMAP to reproduce this thesis in whole or in part for the purpose of research or academic exchange only (except during a period of _____ years, if so requested above).

Certified by:

SIGNATURE

SIGNATURE OF SUPERVISOR

(NEW IC NO. / PASSPORT NO.)

NAME OF SUPERVISOR

Date : _____

Date : _____

NOTES : * If the thesis is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization with period and reasons for confidentiality or restriction.

ACKNOWLEDGEMENTS

I would not have been able to complete this thesis without the support of many individuals.

First of all, I highly appreciate the opportunity that I have got from University Malaysia Perlis (UniMAP) to further my studies in Mechanical Engineering field and lots of thanks for vice chancellor Y. Bhg. (B) Jen. Dato' Prof. Dr. Kamarudin Hussin.

I would like to thank Dr. Haftirman, our lead supervisor, for his continuous guidance, understanding and patience. Dr. Haftirman taught me how to approach problems from different directions, which broadened my flexibility when confronted with new challenges. I am enormously grateful for his guidance, and the time he takes to listen to my endless questions, to provide advice and insight, and to motivate and encourage.

Many thanks to Dr. Mazlee for supporting me by sharing his thoughts, and for providing ideas to resolve problems I have encountered. Thank you for the motivation that you have provided by demonstrating how to succeed through persistence and hard work.

Special thanks to our School of Mechatronic Engineering's Dean at the university, and the Dean of Materials Engineering School who allowed a flexible work schedule; without this I would not be able to complete the required laboratory tests for this graduate degree as a full-time student. We are particularly thankful for the help of the technical staff in the School of Mechatronic Engineering and School of Materials Engineering.

And special thanks to our Center of Graduate Studies (CGS), University Malaysia Perlis for their support and kindness all the time from first registration to pre-registration every semester beside providing us student activity fund to attend conferences.

Finally, I would like to thank my parents and my siblings for their love, unconditional support and encouragement, and for listening to my complaints and frustrations.

TABLE OF CONTENTS

	PAGE
THESIS DECLARATION	i
ACKNOWLEDGMENT	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	vi
LIST OF FIGURES	vii
LIST OF ABBREVIATION	xi
LIST OF SYMBOLS	xiii
ABSTRAK	xiv
ABSTRACT	xv
CHAPTER 1 INTRODUCTION	
1.1 Research Background	1
1.2 Problem Statement and Research Scope	8
1.3 Objectives	9
1.4 Thesis Organization	9
CHAPTER 2 LITERATURE REVIEW	
2.1 Background on Stainless Steel	11
2.2 Stress corrosion cracking history and significance in Austenitic Stainless Steels	14
2.3 Definition and Mechanism	20
2.3.1 Essential Conditions for Occurrence	20

2.3.2	Stress Corrosion Cracking in 304, 310 & 316 Austenitic Stainless Steels	22
2.3.3	General Nucleation Mechanism	26
2.3.4	General Propagation Mechanisms	31
2.3.5	Stages of Stress corrosion cracking	39
2.4	Stress Corrosion Cracking Test Methods	41
2.5	Difficulties in Testing	46
2.5.1	Chloride Stress corrosion cracking Influencing Factors	46
2.5.2	Inconsistency and Intricacy of Laboratory Results	62
2.5.3	Importance in Research	66
2.6	Summary	68
CHAPTER 3 RESEARCH METHODOLOGY		
3.1	Introduction	69
3.2	Experimental Method	69
3.2.1	Material and Specimen	69
3.2.2	Test Solution	73
3.2.3	Constant Load Test	75
3.2.4	Constant Load Application Device	77
3.2.5	Test Chamber	79
3.2	Test Setup	82
3.3.1	Tensile Test	84
3.3.2	Constant Load Test of Stainless Steel types	84

CHAPTER 4 RESULTS AND DISCUSSION

4.1	Introduction	87
4.2	Results	87
4.2.1	Crack Growth	87
4.2.2	Crack Growth Comparison between 304, 310 & 316 in 3.5wt% & 9.35wt% NaCl	97
4.2.3	Weight Lost of 304, 310 & 316 Austenitic Stainless Steels in 3.5wt% & 9.35wt% NaCl Solutions	99
4.2.4	The relationship between the Stress Corrosion Cracking and the Weight Lost	
4.3	Discussion	104
4.3.1	Morphology by Scan Electronic Microscopy (SEM)	104
4.4	Summary	128

CHAPTER 5 CONCLUSIONS AND SUGGESTIONS FOR FUTUER WORK

5.1	Conclusions	130
5.2	Suggestions for Future Work	134

REFERENCES	137
-------------------	-----

APPENDIX A	145
-------------------	-----

LIST OF PUBLICATIONS	147
-----------------------------	-----

LIST OF TABLES

NO		PAGE
2.1	Examples of SCC level Environment in Austenitic Stainless Steel.	24
3.1	Mechanical Properties.	70
3.2	Chemical Composition wt%.	70
4.1	The results Summary of Stress Corrosion Cracking Tests in Lab Environment (Room Temperature).	100
A.1	Research Schedule.	145
A.2	Crack Length (μm) of 304, 310 & 316 Austenitic Stainless in 3.5wt% NaCl Solution.	145
A.3	Crack Length (μm) of 304, 310 & 316 Austenitic Stainless in 9.35wt% NaCl Solution.	146
A.4	Weight Lost (g) of 304, 310 & 316 Austenitic Stainless Steels in 3.5wt% NaCl Solution.	146
A.5	Weight Lost (g) of 304, 310 & 316 Austenitic Stainless Steels in 9.35wt% NaCl Solution.	146

LIST OF FIGURES

NO		PAGE
2.1	Composition and Property Linkages in the Stainless Steel Family.	13
2.2	First Pipeline Failure Caused by SCC in Natchitoches, Louisiana.	15
2.3	Percentage of Materials in SCC Cases.	17
2.4	SCC Time-to-Cracking (Chlorides Environment).	18
2.5	SCC Time-to-Cracking vs. Temperature (Chlorides Environment).	19
2.6	Necessary Conditions for SCC in Austenitic Stainless Steel.	21
2.7	A Schematic of Transition in SCC Morphology.	25
2.8	Generalized Chain of Events in Stress Corrosion Cracking.	27
2.9	Evans Diagram and Possible Occurrence of Pitting.	29
2.10	Pipeline Steel Exposed to Carbonate-Bicarbonate Solution.	31
2.11	Commonly Known Proposed SCC Propagation Mechanisms.	32
2.12	Schematic Representation of Corrosion Elongation Curve.	40
2.13	Variation of Stress Corrosion Cracking Susceptibility with Strain Rate.	43
2.14	Effect of Chlorides and Oxygen on the Susceptibility of Stainless Steel to Stress Corrosion Cracking at 550°F.	60
2.15	Copson Curve—Effect of Ni Content on Time-to-Failure of Fe-Ni-Cr Alloy Wires Exposed Under Stress to Boiling 42wt% MgCl ₂ Solutions.	61
2.16	Effect of Ni Content on Stress Corrosion Cracking Resistance, KISCC of Fe-Ni-Cr Alloys in Aerated 22wt% NaCl Solution at 105°C.	61
3.1	The basic geometry and dimensions of the tension specimens.	72
3.2	Sodium Chloride.	74
3.3	Constant-Load Stress Corrosion Cracking Test Chamber.	76

3.4	Constant Load Fixture.	77
3.5	Effect of Spring Constant for Applied Load.	78
3.6	Spring & UTM Test Result.	79
3.7	Tensile Test Graph for SS304.	82
3.8	Tensile Test Graph for SS310.	83
3.9	Tensile Test Graph for SS316.	83
3.10	Scan Electronic Microscopy (SEM).	86
4.1	Crack Growth of Austenitic Stainless Steel 304 in 3.5wt% & 9.35wt% NaCl Solutions.	94
4.2	Crack on the surface of type 304 with 0.9 yield strength in natrium chloride concentration of 3.5Wt% at room temperature (x1000).	95
4.3	Crack Growth of 310 Austenitic Stainless Steel in 3.5wt% & 9.35wt% NaCl solutions.	95
4.4	Crack on the surface of type 310with 0.9 yield strength in Natrium Chloride concentration of 3.5Wt% at room temperature(x1000).	96
4.5	Crack Growth of 316 Austenitic Stainless Steel in 3.5wt% & 9.35wt% NaCl solutions.	96
4.6	Crack on the surface of type 316 with 0.9 yield strength in Natrium chloride concentration of 3.5wt% at room temperature (x1000)	97
4.7	Crack Growth Comparison of SS304, 310 &316 in 3.5wt%NaCl.	98
4.8	Crack Growth Comparison of SS304, 310 &316 in 9.35wt%NaCl.	99
4.9	Comparison of Weight Lost between the three Austenitic Stainless Steels Types in 3.5wt% NaCl Solution.	102
4.10	Comparison of Weight Lost between the three Austenitic Stainless Steels Types in 9.35wt% NaCl Solution.	102
4.11	The crack length in initial stage SCC of SS304 in 9.35wt% NaCl in 404 hours.	105
4.12	The crack length in 1678 hours SCC of SS304 in 9.35wt% NaCl solution.	106
4.13	SCC appears on the notch side of SS304 in 838 hours 3.5wt% NaCl Solution.	106

4.14	SCC of SS304 at the notch side in 838 hours in 3.5wt% NaCl Solution.	107
4.15	SS304 surface and no crack observe in 404 hours in 3.5wt% NaCl solution.	108
4.16	SS304 surface in 404 hours 3.5wt% NaCl & no cracks.	109
4.17	Corrosive surface of SS304 in 9.35wt% NaCl solution.	109
4.18	SCC of SS304 appears on the notch in 1244 hours 3.5wt% NaCl solution.	110
4.19	Deep SCC of SS304 appears on the surface in 9.35wt% NaCl solution.	110
4.20	Appearance of SCC on the surface of SS304 notch area in 9.35wt% NaCl solution.	111
4.21	SCC of SS304 specimen in 3.5wt% NaCl solution.	111
4.22	Corrosive surface of SS304 during the test time.	112
4.23	Corrosive surface and cracking shows in SS304 at the last stage in 3.5wt% NaCl solution.	113
4.24	Cracked surface of SS304.	113
4.25	Cracks appearance on the surface SS304 in the finale stage in 9.35wt% NaCl solution.	114
4.26	Initial Crack length in 838 hours on the notch area of SS310 in 9.35wt% NaCl solution.	115
4.27	Crack length of SS310 in 1678 hours in 9.35wt% NaCl solution.	115
4.28	Cracks appearance on SS310 surface in 838 hours 9.35wt% NaCl solution.	116
4.29	Deep cracking appears on SS310 surface in 1244 hours 3.5wt% NaCl solution.	117
4.30	Corrosive surface of SS310 during the test time.	117
4.31	Corrosive surface of SS310 in 9.35wt% NaCl solution.	118
4.32	Corrosive surface of SS310 shows some initial cracks in 3.5wt% NaCl solution.	119
4.33	Corrosive and no cracks were observed in this stage of the test of SS310 in 3.5wt% NaCl solution.	119
4.34	SCC appearance of SS310 in 9.35wt% NaCl solution.	120

4.35	Corrosive on SS310 surface and no cracks in first stage in 3.5wt% NaCl solution.	121
4.36	No cracks on SS310 surface during second stage in 3.5wt% NaCl solution.	121
4.37	SS310 surface shows No cracks at first stage of 404 hours in 9.35wt% NaCl.	122
4.38	Another notch side of polished surface of SS310 at 404 hours in 9.35wt% NaCl solution.	122
4.39	Corrosive notch side of SS310 during the test.	123
4.40	Initial cracking length was observed on the surface of SS316 in 9.35wt% NaCl solution in 838 hours.	124
4.41	The length of crack was observed on SS316 surface 9.35wt% NaCl solution in 1678 hours.	124
4.42	Cracks appearance on the surface of SS316 in third stage in 3.5wt% NaCl solution in third stage.	125
4.43	Cracks appearance on SS316 surface in 1244 hours 3.5wt% NaCl solution.	126
4.44	Crack appearance along the surface of SS316 in finale stage in 3.5wt% NaCl solution.	126
4.45	No cracks on the surface of SS316 at 404 hours in 3.5wt% NaCl solution.	127
4.46	Scratches on polished surface of SS316 and no cracks at 404 hours in 9.35wt% NaCl solution.	128

LIST OF ABBREVIATIONS

SS	Austenitic Stainless Steel
ASTM	American Society for Testing and Materials
CT	Compact Tension
EAC	Environmentally Assisted Cracking
EDS	Energy Dispersive Spectroscopy
FSS	Ferritic Stainless Steel
HE	Hydrogen Embrittlement
HIC	Hydrogen Induced Cracking
ISCC	Intergranular Stress Corrosion Cracking
LME	Liquid Metal Embrittlement
LTS	Low Temperature Sensitization
LVDT	Linear Variable Differential Transducer
MSS	Martensitic Stainless Steel
NACE	National Association of Corrosion Engineers
NGPSA	Natural Gas Pipeline Safety Act
PHSS	Precipitate Hardening Stainless Steel
PREN	Pitting Resistance Equivalent Number
PC	Polyvinyl Chloride
PWHT	Post Weld Heat Treatment
SCC	Stress Corrosion Cracking

SEM	Scanning Electronic Microscopy
SFE	Stacking Fault Energy
SSRT	Slow Strain Rate Test
TSCC	Transgranular Stress Corrosion Cracking
SCE	Saturated Calomel Electrode
OPS	Office of Pipeline Safety
UTM	Universal Testing Machine

© This item is protected by original copyright

LIST OF SYMBOLS

F	Applied force from spring
K	Spring constant
δ	Spring displacement
ϕ	Diameter of specimen circular hole.

© This item is protected by original copyright

Kelakuan Retakan Kakisan Tegasan Keluli Tahan Karat Beraustenit dalam Larutan Natrium Klorida

ABSTRAK

Retakan Kakisan Tegasan merupakan kegagalan yang berbantu persekitaran yang tercetus kesan daripada tindak balas terhadap kakisan di bawah tegasan tegangan yang dikandung. Retakan Kakisan Tegasan lazimnya berlaku pantas dalam keadaan yang tidak diduga serta mendatangkan kesan yang buruk. Kegagalan boleh berlaku dalam masa beberapa jam atau bertahun-tahun. Kebanyakan aloi rentan terhadap Retakan Kakisan Tegasan dalam satu atau lebih daripada satu persekitaran yang memerlukan pertimbangan yang teliti dari aspek jenis aloi dalam reka bentuk komponen. Keluli tahan karat beraustenit dan aloi berasaskan nikel biasanya tidak berfungsi dengan baik dalam persekitaran klorida yang berair. Salah satu daripada persekitaran ini ialah natrium klorida yang mengandungi natrium klorida dengan kepekatan NaCl sebanyak 3.5wt% NaCl dan 9.35wt%. Keluli tahan karat beraustenit biasanya digunakan dalam pembinaan tangki penyulingan dan saluran paip dalam banyak industri yang berbeza, khususnya industri petroleum. Oleh itu, keluli tahan karat beraustenit telah digunakan bagi menggantikan keluli karbon dalam persekitaran yang berkakis. Walau bagaimanapun, kegagalan jenis rapuh didapati berlaku kesan daripada retakan kakisan tegasan. Retakan Kakisan Tegasan dalam larutan natrium klorida merupakan salah satu daripada bentuk Retakan Kakisan Tegasan yang paling kerap berlaku pada Keluli Tahan Karat Beraustenit. Ramalan hayat komponen memerlukan tahap permulaan daripada Retakan Kakisan Tegasan dan tempoh kegagalan daripada data yang pernah diterbitkan. Namun begitu, data sebegini agak terhad. Dalam kajian ini, peralatan bereksperimen digunakan bagi memperoleh data tentang tempoh inkubasi dan masa retak yang mengambil masa 70 hari bagi jenis Keluli Tahan Karat Beraustenit 304, 310 & 316 yang direndam dalam 3.5wt% & 9.35wt% larutan NaCl pada suhu bilik yang sama dengan air garam dan Sabkha (tanah datar garam). Penggunaan peralatan ini disahkan dengan menggunakan ujian yang standard. Eksperimen ini menggunakan jenis lekapan pegas berbeban dan berdasarkan ASTM G49 untuk kaedah eksperimen dan E292 untuk spesimen geometri. Retakan kakisan tegasan bagi keluli tahan karat beraustenit bagi jenis 304, 310 dan 316 dalam larutan natrium klorida pada suhu bilik diselidiki sebagai variasi fungsi kepekatan klorida. Retakan ini diuji dengan menggunakan kaedah beban tekal dengan satu tegasan tegangan awal serta 90% memperlihatkan kekuatan. Imbasan potensi Keluli Tahan Karat Beraustenit yang terpilih dilakukan bagi menentukan Retakan Kakisan Tegasan dan ujian dilakukan bagi menentukan sifat-sifat mekanikal dan kimia dengan menggunakan mesin Pengimbas Elektron Mikroskop dan Ujian Universal. Perincian tentang peralatan yang diguna pakai serta pewajaran keputusan uji kaji yang diperolehi diterangkan secara mendalam dalam tesis ini. Dalam proses penghasilan, kepekatan natrium klorida dalam air laut dan sabkha (tanah mendatar garam) menjadi lebih efektif kepada industri, terutamanya kerana persekitaran industri mengandungi kepekatan sebegini. Atas dasar ini, eksperimen dilakukan dengan kepekatan natrium klorida seperti 3.5wt% dan 9.35wt%. Kakisan yang berlekuk-lekuk berlaku pada permukaan kawasan takuk spesimen pada peringkat yang berbeza dan jenis berbeza Keluli Tahan Karat Beraustenit yang dipilih. Keluli Tahan Karat 304 lebih terdedah kepada semua bentuk keadaan. Semua spesimen tidak memperlihatkan sebarang retakan pada tahap pertama masa uji selama 404 jam apabila kepekatan larutan natrium klorida ialah sebanyak 3.5wt%. Kepekatan natrium klorida yang lebih tinggi dan aras tegasan yang sama menunjukkan peningkatan kelajuan retakan dengan masa kegagalan yang sama. Saranan untuk kajian eksperimen yang akan datang turut dikemukakan dalam kajian ini.

Stress Corrosion Cracking Behavior of Austenitic Stainless Steels in Sodium Chloride Solutions

ABSTRACT

Stress Corrosion Cracking is an environmentally assisted failure caused by contact to a corroding while under a sustained tensile stress. Stress Corrosion cracking is most often rapid, unpredictable and catastrophic. Failure can occur in as little as a few hours or take years to happen. Most alloys are susceptible to Stress Corrosion Cracking in one or more environments requiring careful consideration of alloy type in component design. In aqueous chloride environments austenitic stainless steels and many nickel based alloys are known to perform poorly. One of environment is Sodium Chloride. This contains sodium chloride with concentration 3.5wt% NaCl and 9.35wt% NaCl. Austenitic stainless steel is usually used in distillation construction tank and pipe line in many different industries especially petroleum. So, Austenitic stainless steel has been used as a substitute for carbon steel in corrosive environments, however, brittle type failures were encountered due to stress corrosion cracking. Stress Corrosion Cracking in sodium chloride solution is one of the most prevalent forms of Stress Corrosion Cracking in Austenitic Stainless Steels. Component life prediction requires Stress Corrosion Cracking initiation and failure time from published data, however, such data are limited. In this research, experimental equipments were used for gathering data on the incubation period and the crack time about last of 70 days for types 304, 310 & 316 Austenitic Stainless Steels immersed in 3.5wt% & 9.35wt% NaCl solutions at room temperature which is similar to Sea water and Sabkha (salt-flat). The use of the equipment was verified by conducting a standardized test. The experiment uses a spring loaded fixture type and is based on ASTM G49 for experiment method, and E292 for geometry of specimen. The stress corrosion cracking of the austenitic stainless steels of types 304, 310 and 316 in sodium chloride solution at room temperature is investigated as a function variation of chloride concentration, using a constant load method with one of initial tensile stress as 90% yield strength. Potential scans of selected types of Austenitic Stainless Steels were performed in an attempt to determine the Stress Corrosion Cracking and also they were tested to conduct their mechanical and chemical properties by using such as Scanning Electronic Microscopy and Universal Testing Machine. Detail equipment being used and justification of results obtained are explained in full details in this thesis. In production process, concentration of sodium chloride in sea water and sabkha (salt-flat) become more effective to those industries since those are the surrounded environment. And that reason is that the experiment is conducted in sodium chloride concentration such as 3.5wt% and 9.35wt% NaCl. Pitting corrosion occurs on the surface of specimen's notch area in different stages on different types of those selected Austenitic Stainless Steels. Austenitic Stainless Steel 304 was more susceptible for all conditions. In sodium chloride solution with concentration of 3.5wt%, all specimens do not show any cracking for first stage of 404 hour of test time. The higher concentration sodium chloride and the same stress level, the crack speed increase with same time failure. And recommendations for future experimental work are presented herein.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Austenitic stainless steels are widely used for construction of nuclear power and chemical plant components and in marine construction due to the combination of mechanical properties, fabric-ability, weld-ability and corrosion resistance.

Stainless steel is often perceived as the backbone of current industry (Khatak & Baldev, 2002). Stainless steel has achieved extensive applications in a wide range of industries and has been in use as a reliable substitute for carbon steel in corrosive environments ever since (Oberndorfer et al., 1999). Stainless steel was generally recognized as being an expensive, high-technology alloy (Khatak & Baldev, 2002). As material manufacturing and fabrication technology advanced, large-scale production of stainless steel components occurred. This made stainless steel more cost-effective and affordable (Marshall, 1984). All of these mentioned factors, including cost of corrosion, economical feasibility, and the need to operate in more severe environments, have encouraged the wide-spread use of stainless steel.

The touchstone element accountable for the statelessness is chromium. At least 12 wt% of chromium is necessary to make steel appropriate to be classified as "stainless steel" (Brown, 1977). Of all types of stainless steel, austenitic stainless steel (300 series) is regarded as the most important group (Balk et al., 1974). Austenitic stainless steel is highly corrosion resistant in many different corrosion conditions without the need for additional

protective measures. It has excellent work-hardening characteristic and excellent mechanical ductility, which makes it suitable for many manufacturing processes (Balk et al., 1974; Truman, 1977) and is not susceptible to breakable fracture in classical applications (Tyzack, 1972). The use of Austenitic stainless steel is highly diversified and it is frequently used in demanding applications such as steam power plants, chemical plants, petrochemical facilities, nuclear applications, pulp and paper industries, fossil fuel electric power plants, gas turbines, jet propulsion units, heat exchanges, surface piping, vessel cladding, and miscellaneous components in equipment used for various purposes (Marshall, 1984; Alloy Digest Source Book, 2000; Bruce, 2009).

Stress Corrosion Cracking (SCC) is a form of failure of material having specific characteristics. This is a represent able cause of dominant damage at one particular component or material structure, so that it is considered in design at a construction industry. Stress Corrosion Cracking behavior in austenitic stainless steels in solution has been extensively investigated using a constant load method.

Wen stated that the material 2205 duplex stainless steel is resistant to Stress Corrosion Cracking in near neutral NaCl solution at concentrations up to 26 wt% in the temperature range from 25°C to 908°C. Pitting corrosion has assisted the initiation and the elective dissolution was involved in the propagation of Stress Corrosion Cracking in concentrated NaCl solution at 908 °C (Wen et al., 2000).

Li had claimed that the contagion of the water with Sulphate acid has increased the Stress Corrosion Cracking susceptibility of the weld by both decreasing the minimum potential for cracking and by increasing crack growth rate at the same potential (Li & Congleton, 2000).

Nishimura reported that the relationships between applied stress and the three parameters were divided into three regions that are dominated by either stress corrosion cracking or corrosion. Sulphate ions were found to become more aggressive than chloride ions for the Stress Corrosion Cracking susceptibility of the specimens with the most severe sensitization (Nishimura et al., 2003). Thus, Stress Corrosion Cracking on austenitic steel in chloride solution with various concentration of chloride at room temperature has not been clarified completely.

As many other topics of research in material science were pursued and resolved a impossibility exists for austenitic stainless steels. Breakable type failures were unavoidably encountered in austenitic stainless steels from time to time despite its excellent general corrosion resistance and expected durability in practice. Many of the unpredicted failures occurred as a result of combined effects of corrosion and stress, in an environment that is normally classified as non-critically corrosive or moderate (Truman, 1977; Tyzack, 1972). This type of defect was later referred to as stress corrosion cracking. It is one of the most restrained forms of localized corrosion attack. Of the various causes of failure, Stress Corrosion Cracking has probably drawn the most attention and effort from researchers due to its unclear and mysterious nature (Truman, 1977).

Stress Corrosion Cracking refers to the environmentally assisted cracking (EAC) process as a result of the conjoint, simultaneous interaction of tensile stress and corrosion. Stress Corrosion Cracking is material environment specific, its occurrence requires the exposure of a susceptible material to its specific Stress Corrosion Cracking causing substances with the presence of tensile stress (Russell, 1992). The amount of this tensile stress is relatively low, and failure can be in some cases induced by a small amount of

residual stress remaining as a result of the manufacturing process (Tyzack, 1972; Greenfield, 1971).

Not all stress corrosion cracking susceptible environments and material combinations are known (Truman, 1977), and the list of specific environments that cause Stress Corrosion Cracking continues to expand (Parkins, 1972). Detection of Stress Corrosion Cracking at its initial stage for in-service equipment is very difficult, and its incubation period is unpredictable. In practice, Stress Corrosion Cracking failures are often unannounced and can be disastrous. Engineering designs are mostly based on the yield strength criteria, for example, Working-Stress Approach, except for specific applications where a Reliability-Base Approach may be justified to maximize the utilization of materials.

Nevertheless, the operating conditions during Stress Corrosion Cracking failures are often within the design criteria, resulting in unanticipated failures (Tyzack, 1972). For austenitic stainless steels, even though it is generally agreed that a hot chloride environment is notorious for causing failures, a clear relationship of chloride to Stress Corrosion Cracking is still lacking, and failures without prior warning from apparently safe environments are sometimes surprisingly encountered (Denny, 1996). One example of such an accident is the failure of a concrete ceiling in a swimming pool at Uster, Switzerland, that was suspended from a main structure by rods made of type 304 Austenitic Stainless Steel (Oldfield & Todd, 1990).

Stress corrosion cracking susceptibility is sensitive to material composition and surface preparation. Even though material may put up with the same name or is classified under the same material group, with the ever improving techniques of material

manufacturing processes and advances in quality control procedures, newer materials may contain slightly different constituents than materials made in earlier days, such as less impurities or better alloying capability which may change Stress Corrosion Cracking resistance of the material. The quality of surface preparation may be different depending on workmanship and quality control.

As a result, the susceptibility of Stress Corrosion Cracking for the same class of products made in a different time, or material made from different groups of production, or components from different manufacturing facilities, may be conflicting. When older equipment, piping or components that were constructed earlier to the mid-1960s are involved, there can be a higher chance for Stress Corrosion Cracking to result in disastrous failures. The term fracture mechanics was not introduced until 1954 by Irwin, and presented theories related to the plastic zone sizes, R-curve and sub-critical crack growth in 1965. The elastic plastic and J-integral approaches were introduced by Rice in 1968 (Shaw, 2002; Ceriolo & Tommaso, 1998). The understanding of cracked components and the use of fracture mechanics in design was not included in common industrial codes until later years. Factors such as toughness and crack growth resistance are probably not integrated in designs completed preceding to the introduction of fracture mechanics. Although the argument of possible increased risk as a result of overlooking fracture mechanics consideration for austenitic stainless steels components in early designs may not be entirely valid as austenitic stainless steels is a material that has good ductility and toughness, consideration of cracks and fracture may still be important depending on component geometry and application. Since Stress Corrosion Cracking is a crack-type

defect, it is clear that knowledge of fracture mechanics assists in further explanation of the phenomenon that are still not clarified and fully understood.

Stress Corrosion Cracking causes enormous challenges in engineering design and integrity management, including life prediction, defect detection, and maintenance scheduling for implementation of preventive measures. A dependable tool for austenitic stainless steels selection for a given operating environment is also missing (Oberndorfer et al., 1999). Component life prediction for in-service equipment and for new designs based on theoretical understanding is not possible as general agreement amongst available Stress Corrosion Cracking initiation and propagation mechanisms is not yet reached (Puiggali et al., 1987), and a systematic explanation of why specific environments promote Stress Corrosion Cracking in certain materials while other materials are immune is unknown (Parkins, 1972). Experimental life prediction requires crack initiation and failure time from either actual failure data or laboratory tests at many different operating conditions. Unfortunately, such data are scarce or even unavailable. When limited test data are obtained, they are often very spotted and may be conflicting (Congleton & Sui, 1982). It would be handy if simple design charts were available that could make easier problem identification of complex designs, at least during the initial design stage. Fig. 2.1 is an example of graphical representation of failure data that is useful in engineering design, such homogenous data is extremely rare in this field (Brown, 1977). Stress Corrosion Cracking in chloride solution remains the most prevalent form of Stress Corrosion Cracking in austenitic stainless steels (Brown, 1977), and is one that gives the most concern in the oil and gas industry (Oberndorfer et al., 1999).

Boiling concentrated MgCl solutions are the most widely used test medium for laboratory experimentations for studying susceptibility of chloride Stress Corrosion Cracking in austenitic stainless steels (Bibala & Hehemann, 1984). The commonly used concentration of MgCl solution ranges between 42 to 45wt% (Balk et al, 1974), and tests are usually conducted at elevated temperature above 150°C. Fig. 2.1 was generated within the extent of this test range. Testing with boiling MgCl solution is popular both because it is a standardized test procedure (ASTM G36) and that the effect can be observed within a few hours.

Accelerated tests are helpful serving as a viewing test for material selection, based on the concept that if a material is acceptable in a highly destructive environment, it is likely to perform satisfactorily in actual operating conditions with a less accurate environment. However, questions arise as to the degree of applicability of time-to-failure data obtained in accelerated tests due to the increased intensity of test environment and the way load is being applied. In addition, the time required to generate a localized critical environment resulting in Stress Corrosion Cracking from a macroscopically mild environment may not be reflected in accelerated tests, yet the incubation period of Stress Corrosion Cracking is believed to represent the longest portion within the total time-to-failure duration from the start of operation to fracture of the component. Detection of the incubation period, where the component spent most of its life, is very difficult both in practical situations and during laboratory tests.