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

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UNIVERSITI MALAYSIA PERLIS

2013

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

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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

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Academic Session : 2012/2013

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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.

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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

LIST OF SYMBOLS

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

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 diperoleh 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 Natrium 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 Natrium Chloride. This contains natrium 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 natrium 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 natrium 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 natrium 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 natrium 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 natrium 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 natrium 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 25ºC to 908ºC. 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 ºC (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.