Determination of Chemical Notch, $K_{\text{chem}}$ on Aluminum and Steel When Subjected Under Slow Strain Rate Test in Corrosive Environment

Joshua Teo Lee Kuok

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DETERMINATION OF CHEMICAL NOTCH, $k_{\text{chem}}$ ON ALUMINUM AND STEEL WHEN SUBJECTED UNDER SLOW STRAIN RATE TEST IN CORROSIVE ENVIRONMENT

by

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A thesis submitted to the Graduate College in partial fulfillment of the requirements for the degree of Master of Science

Mechanical Engineering

Western Michigan University

April 2018

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DETERMINATION OF CHEMICAL NOTCH, $k_{\text{chem}}$ ON ALUMINUM AND STEEL WHEN SUBJECTED UNDER SLOW STRAIN RATE TEST IN CORROSIVE ENVIRONMENT

Joshua Teo Lee Kuok, M.S.E

Western Michigan University, 2018

When designing for any mechanical components or system, the question would arise as to how the material would react to the loads subjected on it? Would the component survive its service load? How would it react to environmental corrosion? To answer these questions, the technique used in this thesis paper is the Slow Strain Rate Test (SSRT) method. Aluminum and steel were chosen as the material to be tested in this paper. Al 7075-T651, and Al 6061-T651 was chosen due to its wide range of application, high strength to weight ratio and ease of machinability. It is highly used in the aerospace industry, for fuselage and wings of airplanes. AISI 4130 steel was chosen for its high strength and low cost. It is highly used in the automotive industry for components such as, chassis and cab A pillar, where high strength is needed for the safety of passengers.

In this thesis paper, when failure occurs due to corrosion, the high stress concentration will be termed as “chemical notch”, $k_{\text{chem}}$. Chemical notch is derived by conducting SSRT, subjecting specimens with various physical notched under corrosive environment of 3.5% NaCl with a pH of 2.5. Chemical notch is then used to predict the corrosion stress-life (S-N) curve of the individual material. S-N curves are generally used in the industry when evaluating the service life of a component. In order to generate an S-N curve, several specimens would be required for testing, and at various stress amplitude with multiple specimen runs for higher accuracy. These are all lengthy processes. This thesis paper seeks to use $k_{\text{chem}}$ estimation line in predicting corrosion S-N curve. By using this new and novel approach, it would not only save time but also cost, as the number of specimens needed for testing is far less.
ACKNOWLEDGMENTS

First and foremost, I offer my sincerest gratitude to my professor and advisor, Dr. Daniel Kujawski who has supported me all the way through my thesis with his patience and knowledge. It would not have been possible to make this dissertation a reality without his vision.

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Joshua Teo Lee Kuok
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1 INTRODUCTION

1.1 Motivation

When designing for a new component or modifying design changes, engineers would ensure that the design changes on the component could withstand the external applied load on it during their service life. Tensile test which would generate a stress-strain curve is used for identifying the mechanical properties of the material; it is a good approach when only static load is present. However, most mechanical components in industrial applications such as automotive, aerospace and heavy-duty machines are subjected under cyclic loading instead of just a static load; these repeated loading can also be termed as fatigue.

Fatigue is the weakening of a material caused by cyclic loading over a period of time. When predicting the fatigue life of a mechanical component, engineers would rely on the stress-life curve (S-N). However, these S-N curves often do not take corrosion into account. Results of a study done by McLean, V.A. in conjunction with the Federal Highway Administration (FHWA) [1] showed that the total annual estimated corrosion cost in the U.S. is a staggering $276 billion in the year 2002, approximately 3.1% of the nation’s Gross Domestic Product (GDP). It reveals that, although corrosion management has improved over the past several decades, the U.S. must find more efficient and better ways to encourage, support, and implement optimal corrosion control practices.

Significant amount of time and cost is required in order to generate an S-N curve for a single material. Furthermore, the S-N curve data are usually very scattered, because of the variability in specimen material and corrosive solution, thus requiring a high number of test specimens for it to be accurate. Instead of running several fatigue test specimens in a corrosive environment to generate an S-N curve, this thesis paper conducted seeks to provide an alternative solution in generating the S-N curve, which is the chemical notch, $k_{chem}$ estimation line method. Using $k_{chem}$ estimation line in predicting corrosion S-N curve would not only save
time but also cost, as the number of specimens needed for testing is far less.

1.2 Background

Mechanical components are designed to endure a certain amount of external applied loads during their service life. Ideally, it is designed to withstand its service load without any mechanical failures. But when components fail, they tend to fail under excessive load, thus causing deformation. Component fails under excessive force, which is caused by deformation passed yielding. Yield strength $\sigma_0$, is defined as the stress at which a material begins to deform plastically, it usually occurs at 0.2% of its plastic strain as shown in Fig. 1.

When designing for any mechanical components or system, the question would arise as to how the material would react to the loads subjected on it? Would the component survive its service load or would it fail? To answer these questions, engineers have developed several experimental techniques for mechanical testing of engineering materials. Among them are, tensile test. Tensile test is the simplest technique that would reveal the load-displacement behavior of the material.

Tensile test has been widely adopted and used when testing a material to failure to determine its mechanical properties. Because of its varies method and reporting, a standard reporting practice has been established, where the results are reported in terms of engineering
stress, $\sigma$ and engineering strain, $\varepsilon$. Engineering stress, $\sigma$ is the applied load divided by the initial cross-sectional area of a specimen, Eq. 1.1.

$$\sigma = \frac{P}{A_i} \tag{1.1}$$

Where $\sigma$ is stress, $P$ is load and $A_i$ is initial cross-sectional area. Engineering strain $\varepsilon$ is calculated as the ratio of change in gage length over the initial gage length, Eq. 1.2.

$$\varepsilon = \frac{\Delta L}{L_i} \tag{1.2}$$

Where $\varepsilon$ is strain, $\Delta L$ is the change in gage length and $L_i$ is initial gage length.

From the stress-strain graph shown in Fig. 1, certain fundamental mechanical properties can be determined. Young’s modulus, $E$ is defined as the slope of the stress-strain curve within the linear range representing the fact that the stresses in this elastic region follow the same path back during unloading. Yield stress, $\sigma_o$ occurs when the curve deviates from the linear path at a certain stress level. After the stress level crosses the yield strength, the material is said to undergo elastic-plastic deformation. Yield stress can be determined by drawing a parallel line with the elastic slope $E$, using an offset of 0.2% strain as shown in Fig 1. Ultimate strength, $\sigma_u$ is the maximum stress that a material can withhold before failure occurs. The strain at fracture is term as fracture strain, $\varepsilon_f$. Equation 1.3 shows the relationship between stress, strain and Young’s modulus.

$$\sigma = E\varepsilon \tag{1.3}$$

It is usually assumed that when the applied stress is below yield stress or in the elastic region that no damage would occur. This assumption however would not hold true if a material is subjected to repeated stresses over a long period of time although below yield stress. These repeated stresses are term as cyclic stresses and would cause microscopic damage and finally failure of component. These microscopic damages are termed as fatigue of material. Fatigue in any mechanical component is considered dangerous due to its possible failure which may vary from a few cycles to a few million cycles.
1.3 Traditional Fatigue

Besides considering static loading onto a component, fatigue in a material is a critical consideration when cyclic loading is present. Fatigue occurs in material when subjected under cyclic stresses that are below ultimate strength $\sigma_u$, or even below yield strength $\sigma_y$. Fatigue has been a major concern in various applications, because it is very difficult to detect or predict when the material would fail. It was Wohler [2] who in 1860s performed laboratory fatigue tests under cyclic stresses and introduced the concept of stress amplitude vs. number of cycles to failure or S-N diagram/curve. The S-N curve is generated by subjecting a specimen under constant cyclic stress amplitude, and the cycles to failure $N_f$ are recorded.

![Figure 2: S-N graph proposed by Wohler [2].](image)

A series of tests are recorded at different stress amplitude to form an S-N diagram as shown in Fig 2. In general, for metallic material, at $10^7$ cycles with its corresponding stress amplitude level it is treated as the fatigue endurance limit, where the specimen is supposed to survive without failure.
1.4 Endurance Limit

Endurance limit is defined as the safe stress amplitude applied on one material where it is supposed to survive without failure. Endurance limits are commonly estimated at the horizontal part of the S-N curve as seen in Fig. 3. Corrosion of the material can have huge impact on the endurance limit, as shown in Fig. 4. Figure 4 shows how the endurance limit of the same material changes from air to corrosive environment. The change in endurance limit when tested in corrosion is due to the fact that corrosive environments reduces the stress resistance of the material, weakening its endurance to high loads, thus lowering the endurance limit.

*Figure 4: Comparing endurance limit with air and corrosion.*
Each material has its own endurance limit, particularly when comparing ferrous and non-ferrous alloys. Ferrous alloy such as steel exhibits stress amplitude to be asymptotic up to the high cycles of loadings where material will not meet failure below the asymptotic curve. For non-ferrous alloys such as aluminum, stress amplitude decreases with the cycles of loading, and it will eventually fail at very low stress amplitude. For non-ferrous alloys the endurance limit is generally defined as long life usually at \( N_{EL}=10^7 \) cycles, as illustrated in Fig. 5.

![Diagram showing endurance limit for steel and aluminum](image)

*Figure 5: Comparing endurance limit of different materials.*

1.5 Stress Concentration Effects

Most mechanical components are designed in such a way that it involved variable cross sections, and are often designed with stress concentrating features such as holes, notches, grooves, flanges, tapers, etc. Most of the time, such features are there to serve an important purpose, so they cannot be eliminated. These discontinuities are referred to as stress raiser, which causes a localized stress concentration on the boundary of the area. For this paper, stress raisers will be labeled as notch.

For most components, when subjected under cyclic loading with a geometric discontinuity, it is observed that failure takes place because of initiation of fatigue crack at the root of the notch. In order to produce a safe design, the root radius of the notch would be a major designing factor. Notches with a small radius would result in higher stress concentration when compared to notches with a larger radius. This is because a sharper notch would initiate crack initiation and thus propagate much faster even at a lower stress level. Figure 6 shows two
different specimens with different degrees of notches. The sharper notch specimen has a higher $k_t$ value versus the blunt notch.

![Figure 6: Different stress concentration factor.](image)

Stress concentration factor $k_t$ is defined as the maximum elastic stress at the notch tip to the nominal stress. Nominal stress is the average stress calculated on the basis of the net cross section of a specimen without taking into account the effect of geometric discontinuities such as holes, grooves, fillets, etc. $k_t$ is based on the theoretical assumption that stress level that lies within the elastic range without considering plasticity.

$$k_t = \frac{\sigma_{\text{max}}}{\sigma_{\text{nom}}} \quad (1.4)$$

The fatigue notch concentration factor $k_f$ is defined as the ratio of the endurance limit of a smooth specimen $\sigma_{\text{EL}}$, to the endurance limit of a notch specimen $S_{\text{EL}}$, which as previously discussed is taken at $N_f = 10^7$ cycles or greater.

$$k_f = \frac{\sigma_{\text{EL}}}{S_{\text{EL}}} \quad (1.5)$$

Now there are several methods to estimate $k_f$, one of the methods which were proposed by Peterson in 1974 is listed in equation 1.6:

$$k_f = 1 + \frac{k_t - 1}{1 + \frac{\alpha}{\rho}} \quad (1.6)$$
Where $\alpha$ is a material constant having dimension of length and $\rho$ is a notch tip radius. For a sharp notch, it can be seen that $\rho < \alpha$, $k_f < k_t$ and a notch that is blunt $\rho > \alpha$, $k_f = k_t$.

1.6 Corrosion Fatigue

Corrosion fatigue is a combination of accumulated damage from cyclic load and corrosion in an aggressive environment [2]. It is an environmentally assisted damage of a material. Nearly all engineering structures experience some form of alternating stress, and are exposed to harmful environments during their service life. The environment plays a significant role in the fatigue of high-strength structural materials like steel, aluminum alloys and titanium alloys. The S-N curve in figure 7 depicts a significant decrease of fatigue lives and fatigue strength in corrosive environment. When comparing the S-N curve of a vacuum and air environment, the deviation seems to be small, but when comparing the corrosive environment with air and vacuum, a large deviation can be seen. Also, the S-N curve for corrosion fatigue shows absence of the fatigue endurance limit, plateau at high fatigue life, which is present in air and vacuum.

Figure 7: Schematic showing comparison of S-N diagram for vacuum, air and corrosive environment.
Corrosion is known to be a time dependent process which is affected by the type of materials and the environments. When generating the S-N curve, it is assumed that the material is free from cracks or internal flaws. But internal flaws are always present at a microscopic level, and different specimen although with the same material will present different severity of microscopic cracks. Thus, even with the advancements of research in corrosion fatigue, the effects of cyclic stresses and electromechanical nature of corrosion on metals is not fully understood and is hard to predict. The practical way to determine a material’s susceptibility to corrosion assisted cracking is through experimental testing.

Within the last few decades, extensive investigation of test procedure has been developed for standardizing procedures for corrosion testing. The procedures are frequently reexamined for further improvement. In this thesis paper, slow strain rate will be used as the experimental technique to evaluate the environmental effect on a material under monotonic loading.

1.7 Literature Review

In 1960s, Frost and Dugdale [3] contributed many experimental efforts to understand the difference between crack initiation and crack propagation on notch specimens with varying root radii. Figure 8 shows the relationship between crack initiation and non-propagating cracks on vee-notch specimens in ambient air.
Figure 8: Frost diagram for crack initiation and propagation versus stress concentration factor [3].

According to Fig. 8, line ABC is a theoretical crack initiation stress curve shown in Eq. 1.7.

\[ \sigma_{in} = \frac{\sigma_{EL}}{k_t} \]  

(1.7)

On the other hand, the horizontal curve BD represents the minimum propagation stress required to cause complete fracture of the specimen. Between line BD and BC is a region of non-propagating cracks in notch. This region corresponds to crack arrests when applied nominal stress is not high enough to propagate the crack further. Complete fracture will only occur when the applied stress is above line BD of crack propagation.

Frost and Dugdale [3] also correlated the stress concentration factors of \( k_t \) and \( k_f \) as shown in Fig. 9. Frost explained that the fatigue strength of the materials for blunt notches is controlled by crack initiation where all cracks grow to failure, and \( k_f \equiv k_t \). However as seen in Fig. 9, for sharp notches, where \( k_t < k_f \) the minimum propagation stress remains constant and is independent of the notch root radius. Therefore, decreasing the notch radius will also decrease the stress to initiate cracks.
Meng [4], which tested 7075 aluminum under corrosive environment combined with cyclic loading found that fatigue crack growth rate increased with increasing the corrosion solution concentration, raising the temperature, or lowering the pH value. The above three factors could be simply expressed by the surface current intensity, $I_{corr}$ [4].

To determine a material’s behavior under stress, experimental testing of metals must be tested in a controlled condition. The reason for controlled conditions is to isolate the material’s behavior under specific conditions. Understanding the material’s behavior would help in optimizing the design and accurately predicting the service life of the component.

1.8 Slow Strain Rate Test (SSRT) Method

The most common and well-established test procedure to evaluate the fundamental properties of metals is the tension test procedure, this has been widely used. This test is relatively quick and simple but it does not take into consideration the environmental effects. Because of the relatively short duration in the tension test, the component is not sufficiently exposed to the environment. To understand the effect of environment on the fundamental properties of a material, slow strain rate test (SSRT) method has been developed [5]. The SSR test was designed
to provide sufficient time for the environment to affect the material during tests, while the mechanical properties are evaluated.

The tests are done by subjecting a uniaxial tension specimen under a slow constant rate elongation, along with the presence of aggressive environment until failure occurs, while measuring load and displacement. A schematic of SSR test setup is shown in Figure 10.

![Figure 10: Schematic of tensile or slow strain rate test setup.](image)

By comparing the failure of stress and strain levels in corrosive environment to that in laboratory air or vacuum, relative susceptibility of environment on the material may be evaluated. When comparing a standard tensile test, SSR test in air and SSR test subjected under corrosive environment, the elongation to failure, $\varepsilon_f$ is higher in standard tensile test, followed by SSR test in air and lastly SSR test in corrosive environment as shown in Fig. 11.
SSR testing is heavily influenced by the strain rate in which the test is carried out, and is also dependent on the material and environment system. Too high of a strain rate during a SSR test would fail to capture the environmental effects on the material since the reaction of the material with the environment may proceed at a much slower rate than the ductile cracking mechanism. While too low of a strain rate would result in long and inefficient test duration. The strain rate that captures the influence of environmental effects within a reasonable testing time is usually found experimentally by trial and error, this is called critical strain rate. In this thesis paper, for common materials like steel and aluminum, the critical strain rate is within the range of $10^{-4} - 10^{-7}/s^{-1}$. This results in two to three orders of magnitude slower than a traditional tensile test [6].

According to Lee et. al [7], when carrying out a series of SSR test with varying strain rate from $1 \times 10^{-5}/s^{-1}$ to $8 \times 10^{-8}/s^{-1}$, with a material of Al 2024-T351 in 3.5% NaCl, the test performed at a strain rate of $8 \times 10^{-8}/s^{-1}$ showed the most noticeable influence of environment on the material properties, with approximately 70% reduction in tensile elongation compared to air, while only 10% reduction in area was reported for a strain rate of $1 \times 10^{-5}/s^{-1}$. These results indicate and proof that there is existence of a critical strain rate for a given material and environment that it is subjected under. Hence in this thesis paper, a strain rate of $8 \times 10^{-7}/s^{-1}$ was chosen when testing Al 7075-T651, Al 6061-T651 and AISI 4130 steel.
SSRT method is generally used to generate the material’s mechanical properties when subjected under corrosion, but not it is not used for generating an S-N curve or fatigue properties. This thesis paper seeks to use the slow strain rate test (SSRT) method to estimate the stress-life (S-N) curve of corrosion. This is done by using the chemical notch, \( k_{chem} \) line estimation method to generate a corrosive S-N curve, and from the S-N curve fatigue properties can be determined. These properties are critical inputs in Finite Element Analysis (FEA) simulation software. By using this new approach, engineers would not have to run several fatigue tests in order to generate a corrosion S-N curve, instead, this new approach with its \( k_{chem} \) line estimation would save time and cost for engineers.
2 EXPERIMENTAL DETAILS

This thesis paper was conducted to investigate the environmental effects, when subjecting different notch sharpness specimens under SSR test method. The aim is to see how the different notch sharpness and different test environment effects the engineering fracture strain, $\varepsilon_f$. The following materials were chosen: 7075-T651 aluminum, 6061-T651 aluminum and AISI 4130 steel. The chemical composition and mechanical properties of these materials are given in Table 1, it was provided by Schupan & Sons and Metal Depot.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Chemical Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum 7075-T651</td>
<td>Si 0.4%, Ti 0.2%, Zn 6.1%, Others 0.15%, CR 0.28%, Mg 2.9%, Mn 0.3%, Cu 2%, Fe 0.5%</td>
</tr>
<tr>
<td>Aluminum 6061-T651</td>
<td>Cr 0.04%, Cu 0.15%, Fe 0.7%, Mg 0.8%, Mn 0.15%, Si 0.4%, Ti 0.15%, Zn 0.25%</td>
</tr>
<tr>
<td>AISI 4130 Steel</td>
<td>Fe 97.03%, Cr 0.8%, C 0.28%, Si 0.15%, S 0.04%, P 0.035%</td>
</tr>
</tbody>
</table>

There are several reasons in choosing aluminum. In general, most aluminum alloys offer a wide range of application in varies industry because of its ease of machinability. Aluminum is also known for its superior strength to weight ratio when compared to many similar strength steels [7]. Thus, it is widely used in the aerospace industry, from the wings of the aircraft all the way to its fuselage. Secondly, aluminum alloys provide a high resistance to corrosion under varies environmental conditions combined with varies loading conditions. This self-protecting characteristic forms an invisible oxide film which protects itself from further oxidation.

These materials were subjected to SSR testing at a constant elongation rate until failure. The tests were carried out in accordance with the procedure specified in the ASTM standard G129 [4]. As mentioned previously, a strain rate of $8 \times 10^{-7}/s^1$ was chosen from V. Raja and T. Shoji in their literature [7]. The corrosive environment used was a solution of 3.5% NaCl with pH of 2.5; this was achieved by adding concentrated HCl to 3.5% NaCl solution. The acidity of this solution
helps to dissolve to oxide layer that is form from the specimen material and NaCl reaction, thus exposing a fresh layer of metal surface to the corrosive solution all throughout the test.

2.1 Comparing 7075-T651, 6061-T651 Al and AISI 4130 Steel

In the 1930’s, because of the bourgeoning aircraft industry, it caused a rapid development of new alloys, in particular aluminum because it was extremely light and strong, perfect for airplanes. Among the most common alloys were 6061 and 7075. They each have their unique characteristics, understanding the differences is important for industry decision makers who are tasked with finding the perfect material for their applications.

6061 was first introduced in 1935 and was one of the first commercially available alloys. The main two elements in its chemical makeup are magnesium and silicon. Magnesium is added to aluminum to increase its strength. Silicon is used to reduce the melting temperature. When combining both, 6061 responds well to heat treatment. 6061 is known for its good surface finish, while offering excellent corrosion resistance. It is also considered to have good machinability and can be easily welded and joined.

7075 was developed in 1936 by Sumitomo Metal Industries [8]. They were looking for solutions to build cheaper and lighter aircraft. Its main alloying agent is zinc. 7075 is known to be one of the highest strength to weight ratios of the aluminum alloys. It is perfect for applications when high strength is the critical factor. It is not as resistant to corrosion as 6061. In general, it does not offer good weldability. But its strength is very comparable to most steels like 4130, without the substantial weight when compared with steel.

4130 steel was chosen as a benchmark to both aluminum 6061 and 7075 to observed its differences between them. Steel is an alloy of iron and carbon and other elements. Because of its high tensile strength and low cost, it is a major component used in buildings, infrastructure, automobiles and machines. When compared to aluminums, steel is more susceptible to corrosion and has a much lower strength to weight ratio.
2.2 Specimen

Test specimens were machined in WMU and the raw materials were obtained from Schupan & Sons and Metal Depot as 1”x 1”x 6” blanks cut from plate in the longitudinal transverse (LT) direction as shown in Fig. 12. The blanks were machined by turning of the bar into a cylindrical shape. This is further machined into a standard test specimen with 1” gage length and approximately 2.5” gripping length.

*Figure 12: Schematic of machining process for SSR testing specimen.*
2.3 Corrosion chamber

To submerge the gage length of the specimen into the corrosive environment of 3.5% of NaCl, a corrosion chamber was designed. This chamber was designed using a plexi-glass so that it is both transparent and corrosive resistant. It is important for it to be transparent so that the water level of the corrosion chamber can be observed to be at the same level all throughout the test. Figure 13 shows the corrosion chamber, with a center through hole to hold the specimen using O-rings to prevent leaking. Two holes were drilled, one on the bottom, another towards the middle-top. A pump was used to pump NaCl from a reservoir up into the corrosive chamber, and to keep the amount of corrosive solution to be constant, a middle-top hole was drilled in order to allow the excess corrosive solution of NaCl to flow back into the reservoir, keeping the level of the corrosive solution the same.

![Figure 13: Picture of corrosion chamber.](image)

This is done to expose the specimen to both corrosive environment and air simultaneously. Where part of the specimen gage length would be immersed in corrosion solution and part of it is exposed to air as shown in Fig. 14. Consider this as a material that is the hull of a ship. Part of the hull of the ship is submerged in water while the upper part above water is interacting with air. Where the hull meets the water surface is called waterline or liquid-air interface. This is because the point of concern is specifically at the liquid-air interface instead of the whole specimen.
In summary for this test setup, aluminum was chosen mainly because of its strength to weight ratio and steel because of its wide range of application in the automotive and heavy equipment industry and as a bench line comparison for aluminum. The dog-bone specimen was shaped according to ASTM standard for testing in tensile, where the stresses are isolated at the strength gage instead of the whole specimen. Lastly, the corrosive chamber was made out of plexi-glass to prevent reaction with the corrosive solution poured into it, so that only the reaction between the corrosive solution and material is isolated and considered.
3 TEST PROCEDURE FOR SMOOTH SPECIMENS

All three materials were first tested in air or normal lab environment to create a benchmark for the material properties without any influence of the corrosive environment shown in Fig. 15.

![Smooth specimen tested in air.](image)

Next, the smooth specimen is tested in a corrosive environment as can be seen in Fig. 13. The level of the corrosive environment is maintained constant, such that the liquid-air interface is roughly at the center of the gage length. For the corrosive environment test, it was performed in displacement control since an extensometer could not be mounted on the gage length. The test was performed at a displacement control of $3.34 \times 10^{-5}$ mm/s, so that the strain rate is maintained at $8 \times 10^{-7}$ sec$^{-1}$. This was achieved by utilizing the displacement vs. time data recorded from strain-controlled tests in air. A uniaxial servo hydraulic MTS machine 810 was used, with a maximum load capacity of 80 KN and maximum actuator displacement of 100mm. Load, displacement and strain values were recorded using an automated computer program called Station Manager. It interfaces with MTS 810 machine as shown in Fig. 16.
3.1 SSR test Results and Discussion

From the test in air with a strain rate of $8 \times 10^{-7}$ sec$^{-1}$ the mechanical material properties are obtained and presented in table 2-4 for 7075Al-T651, 6061Al-T651 and 4130 steel.

*Table 2: Mechanical Properties of Al 7075-T651.*

<table>
<thead>
<tr>
<th>Al 7075-T651</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength, $\sigma_u$</td>
<td>554 MPa</td>
</tr>
<tr>
<td>Yield Strength, $\sigma_o$</td>
<td>490 MPa</td>
</tr>
<tr>
<td>Young’s Modulus, $E$</td>
<td>68 GPa</td>
</tr>
<tr>
<td>Fracture Strain, $\varepsilon_f$</td>
<td>31 %</td>
</tr>
</tbody>
</table>
Table 3: Mechanical properties of Al 6061-T651.

<table>
<thead>
<tr>
<th>AL 6061-T651</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength, $\sigma_u$</td>
<td>352 MPa</td>
</tr>
<tr>
<td>Yield Strength, $\sigma_o$</td>
<td>343 MPa</td>
</tr>
<tr>
<td>Young’s Modulus, E</td>
<td>73 GPa</td>
</tr>
<tr>
<td>Fracture Strain, $\varepsilon_f$</td>
<td>37 %</td>
</tr>
</tbody>
</table>

Table 4: Mechanical properties of AISI 4130 Steel.

<table>
<thead>
<tr>
<th>AISI 4130 steel</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength, $\sigma_u$</td>
<td>622 MPa</td>
</tr>
<tr>
<td>Yield Strength, $\sigma_o$</td>
<td>530 MPa</td>
</tr>
<tr>
<td>Young’s Modulus, E</td>
<td>20.3 GPa</td>
</tr>
<tr>
<td>Fracture Strain, $\varepsilon_f$</td>
<td>32 %</td>
</tr>
</tbody>
</table>

Figure 17 to 19 shows a comparison of material response between a slow strain rate test of $8 \times 10^{-7}$ sec$^{-1}$ in air, and in corrosive environment test.

Considering 7075Al-T651, it can be observed that when comparing the SSR test in air and corrosive environment of its strain to fracture, the strain to fracture was reduced from 31% in air to 3.5% in 3.5% NaCl as seen in Fig. 17. Giving the total change of strain to fracture of 28.5%. While the yield strength and young’s modulus remain unaffected.
When looking at 6061 Al-T651, we can compare and see that the SSR test in air and NaCl of its strain to fracture has reduced from 35% to 30% as seen in Fig. 18. When comparing 6061Al with 7075Al, the difference of strain to fracture is only 5% for 6061Al, instead of 28.5%. From this inference, it can be concluded that 7075Al is more susceptible to corrosion because of its larger change in strain to fracture, $\Delta \varepsilon_f$. The reduction in strain values overall also indicates that both the materials tend to show brittle behavior in the presence of corrosive environment.

Lastly, observing Fig. 19, for 4130 steel, it can be seen that the percentage in reduction of its strain to fracture comparing SSR test in air and NaCl went from 32% to 18%, a difference of 14% in strain fracture. When comparing its strength to weight ratio with 7075Al, 7075Al has a higher ratio, and thus it is more advantageous to be using 7075Al in applications where both its strength and weight are important factors in design.
Figure 18: Test results of SSR testing of Al 6075-T651 in air, 3.5% NaCl solution and normal tensile test in air.

Figure 19: Test results of SSR testing of 4130 steel in air, 3.5% NaCl solution and normal tensile test in air.
When examining all the smooth specimens tested in corrosion, the specimens showed failed at the center of the gage length, most of them would fail in a 45-degree shear as shown in Fig. 20. This will be further explained later in the chapter.

Figure 20: 45-degree failure of specimen.

Also, when considering specimens tested in NaCl for smooth specimens, the specimens failed at the center, which corresponds to the liquid-air interface. In order to confirm that failure occurs in the at the liquid-air interface, for each material, two more specimens were tested. For these two specimens the liquid-air interface was maintained such that, for one specimen the liquid-air interface was 0.25 inches above the center of the gage, and the other 0.25 inches below the center of the gage, this can be illustrated in Fig. 21. All the specimens failed at the liquid-air interface.

Figure 21: Schematic of test setup (a) NaCl half of gage length, (b) NaCl 0.25” above the middle of gage length (c) NaCl 0.25” below the middle of gage length. Reprinted from “Modeling of Environmentally Assisted Fatigue Crack Growth Behavior,” by Sree Phani., WMU 2015.
3.2 Chemical Corrosion Reaction

Corrosion is the deterioration of a metal as a result of chemical reactions between it and the surrounding environment. Both the type of metal and the environmental conditions, particularly gasses that are in contact with the metal, determine the form and rate of deterioration. The chemical reaction of aluminum and steel when encountered with any corrosive solution reacts differently. In this thesis paper, a 3.5% of NaCl with a pH of 2.5 was used as the corrosive solution to mimic seawater.

Aluminum is a very reactive metal, but when it reacts with oxygen or water, it forms a coherent surface oxide which impedes further reaction of aluminum with the environment as shown in the equation 3.1. This would help in preventing corrosion if it is only in contact with oxygen or water.

$$2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2$$  \hspace{1cm} (3.1)

In most applications for aluminum, the components would react with rain water which is acidic, or salt water in sea applications. In these cases, the thin film aluminum oxide layer that was form would dissolve away when reacting with NaCl, oxygen and water. These chemical reactions would form hydrogen which would then join with chloride, finally becoming hydrochloric acid as shown in Eq. 3.2.

$$NaCl + H_2O \rightarrow NaOH + HCl$$  \hspace{1cm} (3.2)

This reaction of hydrochloric acid and Al$^{3+}$ would continue to dissolve the aluminum oxide that was initially form between the reaction of aluminum and water, and subsequently the aluminum metal itself. This would cause microscopic pits and holes in the metal, thus having a higher stress concentration in that affected area.
The corrosion of steel can be considered as an electrochemical process that occurs in stages. Initial attack occurs at anodic areas on the surface, where ferrous ions go into solution. Electrons are released from the anode and move through the metallic structure to the adjacent cathodic sites on the surface, where they combine with oxygen and water to form hydroxyl ions. These react with the ferrous ions from the anode to produce ferrous hydroxide, which itself is further oxidized in air to produce hydrated ferric oxide. The sum of these reactions is shown in Eq. 3.3.

\[
Fe + 3O_2 + 2H_2O = 2Fe_2O_3H_2O
\] (3.3)

The hydrated ferric oxide that is formed can also be commonly identified by the red color compound formed on the steel metal component. This corrosion process requires the simultaneous presence of water and oxygen. In the absence of either, corrosion does not occur. Whereas for aluminum, corrosion would only take place if all three, water, oxygen, and NaCl, is present.

3.4 Microscopic Observation of Fracture Surface

The differences between SSRT in air and in corrosion can be seen in Fig. 22-24 below. For 7075 Al-T651 SSRT in air in Fig. 22(a), it is observed that the crack occurs uniformly, showing the same colors and roughness. But when looking at Fig. 22(b), two distinct areas can be observed.

![Figure 22: 7075Al-T651 (a) SSRT in air (b) SSRT in 3.5% NaCl.](image)

One region shows a flat-like surface shear indicating a brittle fracture, where another region shows a ductile failure of 45 degrees. The outline area in red shows that it was affected by corrosion, thus producing a ring-like shape around the circumference of the specimen, where the
inner region highlighted in yellow was due to the stress concentration created by the corrosive solution of 3.5% NaCl. This phenomenon is called microscopic corrosion pits, where it would act as notches thus creating stress raisers or concentration around the area. Due to these microscopic corrosion pits acting as stress raisers, the notch-tip experiences higher stresses than any other part of the gage length.

Figure 23: 6061Al-T651 (a) SSRT in air (b) SSRT in 3.5% of NaCl.

Chapter 4 would answer the question as to how can we predict the stress concentration factor, \( k_t \) caused by corrosion. As shown in section 1.2.3, stress concentration factor is a dimensionless quantity and geometry dependent, it describes the stress in the presence of notch when compared to unnotched specimens. According to Eq. 1.4, we can see that stress concentration factor is defined by taking the maximum stress, divided by the nominal stress. A
stress concentration factor, $k_t$ of 1 is said to be a unnotched smooth specimen. Any $k_t$ greater than 1 is defined to have some discontinuities in the geometry, thus causing higher stresses within the notch region.
In this thesis paper, when failure occurs due to liquid-air interface, the created stress concentration will be termed as “chemical notch”, $k_{\text{chem}}$. To investigate further on the assumption of chemical notch, slow strain rate test was repeated on several specimens with machined notch, having different stress concentration factors. The notches were machined on the gage length of the specimen. The stress concentration factor, $k_t$ can be change by changing the notch-tip radius ($\rho$), depth of the notch ($t$), and angle of notch ($2\theta$). In this thesis, the graph taken from N.A. Noda from his paper stress concentration factors for round and flat test specimens with notches [11] was used in determining the value of $k_t$. The graph can be seen in Fig. 25.

A sharper notch-tip indicates a higher $k_t$, and generally when increasing the depth of the notch ($t$), it would result in higher $k_t$, but only up to a certain value which is also dependent on the notch-tip radius as can be seen in Fig. 25. In order to test the assumption of chemical notch, two specimens with the same $k_t$ were machined. To be certain that the notch machined was

![Graph](image)

*Figure 25: V-shaped circumferential notched round bar under tension finding $k_t$. Reprinted from Stress Concentration Factors for Round and Flat Test Specimens with Notches," by Noda, N., 1995[11].*

30
according to specifications and that there are no strain hardening or softening at notch-tip radii, an optical comparator was used to ensure that the notch depth and root radii is accurate after machining, this can be seen in Fig. 26. An optical comparator is a device that applies the principles of optics to the inspection of component parts. The magnified silhouette of a part is projected upon the screen, and the dimensions and geometry of the part are measured against prescribed limits. The simplest way of measurement is the graduations on the screen, being superimposed over the silhouette, allowing the viewer to measure, as if a clear ruler were laid over the image. From this, the user would be able to tell the sharpness and radius of the notch machined.

Figure 26: Optical comparator.
The position of the notch was machined about 0.25” from the center of the gage length, allowing one of the notch on the specimen to be submerged in corrosive solution and another to be in the air. The test ran was such that one of the notch will be in the air and another will be submerged in corrosive environment for the same $k_t$. The idea is to observe and identify the fracture location of the specimen given the same stress concentration factor. If failure occurs at the liquid-air interface, it would mean that the chemical notch has a higher effect than the machined notch. If failure occurs at the machined notch, it means the machined notch has a higher stress concentration factor than the chemical notch. This is illustrated in Fig. 27.

4.1 Test Result for Notch Specimen in Corrosive Environment

Three different tests were conducted as can be seen in Fig. 28, half of the gage length for all three specimens were submerged in corrosive solution. Figure 28(a) shows a smooth specimen where half of its gage length is submerged in 3.5% NaCl, Fig. 28(b) shows a notched specimen with its circumferential machined notch and half of its gage length submerged in NaCl. Lastly, Fig. 28(c) depicts a notched specimen with a circumferential machined notch in air and the bottom half of its gage length is submerged in NaCl.
4.2 Chemical Notch

Chemical Notch in this paper is defined when failure occurs at the liquid-air interface caused by microscopic damages that is an apparent stress concentration factor from the corrosive solution that is presumably higher than the machined notch stress concentration factor. Figure 29 shows a schematic of a specimen and its relation to stress concentration factor, $k_t$. The value of $k_t$ is dependent on the notch root radius, $\rho$, notch depth, $t$, and notch-tip angle, $2\theta$.

Figure 29: Schematic of specimen with its relationship to $k_t$.

The corrosive solution at the liquid-air interface act as a stress raiser as seen in Fig. 30, because of the interaction between the corrosive solution and the metal tested, the corrosive solution
causes a ‘virtual’ stress concentration right at the liquid-air interface. However, if the stress concentration of the chemical notch is higher than the machined notch stress concentration factor, $k_t$, the specimen would fail at the liquid-air interface and vice-versa.

![Diagram of Chemical Notch and Liquid-Air Interface](image)

*Figure 30: Chemical notch and liquid-air interface.*

From Chapter 3, the results for Fig. 28(a) were already discussed, where the specimen would always fail in the liquid-air interface independent on the material tested. Test results for notched specimens are summarized in Figures 31-33. On Fig. 31-33, the x-axis is categorized by stress concentration factor, $k_t$, this is the stress concentration factor of the physical machined notched on the specimen, instead of the virtual chemical notched. The two black dashed lines indicates the location in which the failure occurs, either at the liquid-air interface indicated by the top-black dashed line, or at the physical notched of the specimen at the bottom-black dashed line. The red cross symbol indicates that the physical notched on the specimen was exposed to air when tested as seen in Fig. 28 (c). The blue circular symbol indicates that the physical notched on the specimen was submerged in corrosive solution when tested which was illustrated in Fig 28 (b). The highlighted blue background indicates failure due to corrosion, and the green background indicates that the failure was due to the physical notched. The white space in the middle between the blue and green background would be identified as the range of chemical notch, $k_{chem}$ for the material tested.
Consider Fig. 31 of Al 7075-T651, the specimen was first tested with a high $k_t = 3.8$, when the physical notched of the specimen was tested in air and in corrosive solution, it was observed that the specimens both failed at the physical notch. A lower $k_t$ of 3.2 was tested, and the same observation occurred as at $k_t = 3.8$. When a specimen of $k_t = 3$ was tested, the failure of the specimens now failed at the liquid-air interface instead of the physical notched. It can be concluded that for notched specimens with $k_t \leq 3$, failure occurs at the liquid-air interface independent of the location of the machined notch. It shows that for Al 7075-T651, any $k_t$ that is below 3, the effect of liquid-air interface is greater than the effect of machined notch, even if the notched is tested in air or in NaCl. With $k_t$ of 3.2 and above, it is observed that the failure always occurs at the machined notched. The machined notched has a greater effect than the liquid-air interface when $k_t$ is at or above 3.2. Thus, it can be concluded that the chemical notched is apparent for Al 7075-T651, and it ranges from $3.0 \leq k_t \leq 3.2$.

When considering Al 6061-T651, the test results from Fig. 32 concluded that for notch specimens with $k_t \leq 1.65$, failure occurs at the liquid-air interface, even when the machined notch is submerged in NaCl. From this we can conclude that when $k_t \leq 1.65$, the liquid to air interface
has a higher effect than the machined notch stress concentration factor. Results tested at \( k_t = 1.85 \) gave conflicting results, one of the specimen with notch in the air failed at the liquid-air interface, and another failed at the machined notch. Because of this anomaly, specimens were tested with machined notch of \( k_t = 2.0 \) and 3.0. The test results show that for \( k_t \geq 2.0 \), the failure occurs at the machined notch, indicating that when \( k_t \geq 2.0 \) the effect of the machined notch is greater than the liquid-air interface. The test can also be concluded that chemical notch for Al 6061-T651 is within the range of \( 1.65 \leq k_t \leq 2.0 \).

**Figure 32: Al 6061-T651 failure for notched specimens.**

Lastly, AISI 4130 steel and its effect of chemical notch is considered when compared to machined notch. Fig. 33 shows a very similar pattern as Fig. 32 of Al 6061-T651. When considering notch of \( k_t = 1.85 \), the notch in air failed at the machined notch interface, whereas the notch submerged in NaCl failed at the liquid-air interface. When \( k_t \geq 2.0 \), failure occurs at the machined notch, signifying that the machined notch has a greater effect on the specimen than the liquid-air interface. When \( k_t \leq 1.65 \), failure occurs at the liquid-air interface. Thus, from these results it
can be concluded that the chemical notch for AISI 4130 steel is within the range of $1.65 \leq k_t \leq 2.0$, which is the same as Al 6061-T651.

![AISI 4130 steel failure location with respect to $k_t$]

In summary, it can be concluded that Al 7075-T651, Al 6061-T651 and AISI 4130 steel all has a defined chemical notch range. The chemical notch for Al 7075-T651, Al 6061-T651 and AISI 4130 steel can be summarized in table 5. These results show that chemical notch for these materials can be quantifiable. In chapter 5, the results of the chemical notch will then be used to predict the S-N curve of the material.

![Figure 33: AISI 4130 steel failure for notched specimens.]

Table 5: Chemical notch for different materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>Chemical Notch, $k_{chem}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al 7075-T651</td>
<td>3.0 – 3.2</td>
</tr>
<tr>
<td>Al 6061-T651</td>
<td>1.65 – 2.0</td>
</tr>
<tr>
<td>AISI 4130 steel</td>
<td>1.65 – 2.0</td>
</tr>
</tbody>
</table>
5 ANALYSIS OF CHEMICAL NOTCH, $k_{\text{chem}}$

The common practice in the industry when wanting to find the service life of a component, is to reference the S-N curve of the material used. The data for the S-N curve is obtained by cycling specimens at different stress amplitudes until failure. The usual procedure is to test the first specimen at a high peak stress where failure is expected in a fairly short number of cycles. The test stress is decreased for each succeeding specimen until one or two specimens do not fail in the specified numbers of cycles, which is usually around $10^6$ or $10^7$ cycles. However, with S-N curve it often produced a considerable amount of scatter in fatigue data even when carefully machined standard specimens out of the same lot of material. Also, it requires a very high number of specimens tested at different cyclic stress amplitude to obtain an accurate S-N curve. Thus, the whole process in obtaining an S-N curve for a new material is costly and very time consuming.

With the advancement of technology and simulation tools, many of these simulation tools would require inputs of fatigue properties to accurately predict the fatigue life of a component under consideration. Fatigue properties can be extracted from the S-N curve and S-N curves are usually drawn in a log-log or semi-log graph as shown in Fig. 34. Equation 5.1 is used for approximating a straight line on a log-log plot found in Norman Dowling’s book [2].

$$\sigma_a = \sigma_f'(2N_f)^b$$

(5.1)

where, fatigue strength exponent, b is the slope of the log-log graph of stable stress amplitude, $\sigma_a$ vs. reversals to failure, $2N_f$. Fatigue strength coefficient, $\sigma_f'$ is the stress corresponding to $\log(2N_f) = 1$.

With $k_{\text{chem}}$ identified for materials with 7075-T651, 6061-T651 and AISI 4130 steel in chapter 4, the question would arise as to how $k_{\text{chem}}$ could be used to predict the S-N curve for an individual material in corrosion? S-N curve data were curated from several sources such as journals, websites and from Tyng Tyng’s thesis done in 2009 [10].
Figure 34 shows a SAE 1015 steel in a log-log S-N curve. The reversal to failure and cycles to failure is depicted in Fig. 35, where two reversals to failure would form one cycle.

5.1 Discussion of Material Tested with S-N Curve

**7075-T651 Aluminum**

Figure 36, shows a stress-life curve with fatigue data of air and corrosion. The best fit line was drawn for the air data. The $k_{chem}$ line estimation method was used. $k_{chem(lower)}$ and $k_{chem(upper)}$ line estimation was compared with the best fit line of air. By taking $N_f = 1E3$ cycles as the first point of reference, and comparing it with the equation from the best fit line of air, the first coordinates of $k_{chem}$ line estimation was obtained. $N_f$ of 1E3 cycles was chosen as the initial point, because the difference between the initial slope of air and corrosion at $N_f$ of 1E3 cycles is small.
as can be seen in Fig. 7, and it gradually increases as the number of cycles increases. The second coordinate for \( k_{\text{chem(lower)}} \) was taken when \( N_f = 1E6 \) cycles, and for \( k_{\text{chem(upper)}} \) when \( N_f = 1E7 \) cycles. \( N_f \) of 1E6 and 1E7 was chosen because for both aluminum and steel, engineers would usually set that as the endurance limit.

Consider \( k_{\text{chem(lower)}} \), using Eq. 5.2, which is an adaptation of Eq. 1.5 as previously discussed in chapter 1, and taking \( N_f = 1E6 \), finding the respective stresses for both stresses in air and it corrosion, it can be concluded that \( k_{\text{chem}} = 3.0 \), which is within the range of \( k_{\text{chem}} \) of Al 7075 as shown in Table 5.

\[
k_{\text{chem}} = \frac{\sigma_{\text{air}}}{S_{\text{corrosion}}}
\]  

(5.2)

**Figure 36 S-N data of 7075-T651 [10].**

\( k_{\text{chem(upper)}} \) line estimation is the same as \( k_{\text{chem(lower)}} \) line estimation except this time, the number of cycles to failure is taken at \( N_f = 1E7 \) instead. Figures 37 and 38 shows extra data taken from journals, in both instance, the corrosive solution was 3.5% NaCl, but the pH level was not stated in the journals[12][13]. It can be concluded from Fig. 37 and 38, that the \( k_{\text{chem}} \) is also 3.0. This
proves that the $k_{\text{chem}}$ line estimation method provides a very good estimation of predicting the corrosive S-N curve.

Figure 37 S-N data of 7075-T651 [12].

Figure 38 S-N data of 7075-T651 [13].
6061-T651 Aluminum

Fig. 39-41 shows data of air and corrosion of S-N curve taken from Tyng Tyng’s thesis and journal papers. Figure 39 is fatigue data taken from Tyng Tyng’s thesis, where the specimen was in a short transverse direction, and corrosive solution was 3.5% NaCl with pH 2.5. Although in this paper, the specimens taken was in a longitudinal transverse direction, it still provided a very good $k_{chem}$ line estimation. Both $k_{chem(lower)}$ and $k_{chem(upper)}$ provided a $k_{chem}$ of 1.825, which lays within the range of $k_{chem}$ from 6061-T651 Al as seen in table 5.

![Figure 39 S-N data of 6061-T651](image)

Figures 40 and 41 shows data taken from Mutombo, F. K. [14] and Weber, M [15] respectively. Both of these data, the specimen rolling direction was longitudinal, with its corrosive environment remaining the same which is 3.5% NaCl, the pH level was not stated in the journals. Both resulted in a $k_{chem}$ of 1.825 which also lays within the range of $k_{chem}$ tested in chapter 4, as seen in table 5.
Finally, when considering AISI 4130 steel, Fig. 42 is data taken from Tyng Tyng’s thesis, and Fig. 43 is data taken from a textbook which uses a third-party data, of which the author of
the data was not cited. $k_{\text{chem(lower)}}$ and $k_{\text{chem(upper)}}$ is now slightly different from aluminum. Where in aluminum, the first coordinate point was taken at $N_f=1E3$ cycles, but for steel the first coordinate point is taken when $N_f = 1E4$ cycles instead. Taking $N_f = 1E4$ cycles provided a better estimation line in steel. It can be observed that both figures resulted in the same $k_{\text{chem}}$ of 1.825, which also lays within the range of the $k_{\text{chem}}$ tested as seen in Table 5.

![Image of S-N data of AISI 4130 steel](image)

*Tyng Tyng, (2009)*

*Figure 42 S-N data of AISI 4130 steel [10].*
In conclusion for this section, the $k_{chem}$ line estimation method provided a very good estimation of the S-N curve when compared with the $k_{chem}$ tested in Chapter 4. Table 6 summarizes the results concluded.

*Table 6: Comparison between chemical notch and chemical line estimation method*

<table>
<thead>
<tr>
<th>Materials</th>
<th>Chemical Notch, $k_{chem}$</th>
<th>Chemical Line Estimation, $k_{chem}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al 7075-T651</td>
<td>3.0 – 3.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Al 6061-T651</td>
<td>1.65 – 2.0</td>
<td>1.825</td>
</tr>
<tr>
<td>AISI 4130 steel</td>
<td>1.65 – 2.0</td>
<td>1.825</td>
</tr>
</tbody>
</table>
5.2 Additional Materials Comparison using $k_{chem}$ Line Estimation Method

To validate the $k_{chem}$ line estimation method, a few more materials were taken and analyzed, as shown from Fig. 44 to 49.

**E690 Steel**

Fig. 44 shows air and corrosion data taken from Tian Ling Zhao (2017) [16]. The corrosive environment used is hydrochloric acid, the rolling grain direction of the specimen was not specified in the journal. $k_{chem(estimation)}$ line in green is defined by taking the best fit line of the corrosive data, and setting its number of cycles to failure at $N_f = 1E4$ cycles for the first point and $N_f = 1E6$ cycles as the second point. $k_{chem(lower)}$ line is defined where first coordinate was taken at $N_f = 1E4$ cycles, and the second coordinate was $N_f = 1E6$ cycles. Both compared with the power law equation of air and setting $k_{chem} = 2.0$. Using Eq. 5.1, with $k_{chem}$ and $\sigma_{air}$ known, $S_{corrosion}$ can be identified. When comparing $k_{chem(lower)}$ with $k_{chem(estimation)}$, it can be seen that $k_{chem(lower)}$ line provides a more conservative line, which is always desirable in most design cases.

![Figure 44 E690 S-N curve data of E690 [16].](image)
**Mg Alloy**

Figure 45 presents S-N curve data of air and corrosion of AZ31 Mg alloy. The specimen was tested at a frequency of 30 Hz, at a stress ratio of $R = -1$, in 3.5% of NaCl. It can be observed that the $k_{chem(lower)}$ line estimation provided yet again a more conservative line when compared to $k_{chem(estimation)}$ which is the best fit line of the corrosion data.

![Mg Alloy S-N curve data](image)

Figure 45 Mg alloy S-N curve data [17].

**A1N Railway Steel**

Figure 46 displays a material of A1N Railway Steel. The test ran at a frequency of 30 Hz, and its corrosive environment is 0.9 % NaCl, which is supposed to mimic rainwater. $k_{chem(lower)}$ line estimation again provides a more conservative S-N line when compared with $k_{chem(estimation)}$ line.
Carbon Steel

Figure 47 shows a material of carbon steel test in both air and corrosion solution. The carbon steel material has a tensile strength of 610 MPa, yield strength of 375 MPa and elongation of 18%. The corrosion solution is artificial seawater of 3.5% NaCl, pH of 5. Frequency tested was at 22 Hz. $K_{chem(lower)}$ line estimation provides a more conservative line also for carbon steel.
To summarized, based on Fig. 36-43 a fairly accurate estimation for $k_{\text{chem}}$ line can be seen when considering mainly aluminums and steels of 7075-T651 Al, 6061-T651 Al and AISI 4130 steel. $k_{\text{chem}}$ line estimation can be used to predict the S-N curve of the material with a good conservative prediction. When comparing the $k_{\text{chem}}$ tested and $k_{\text{chem}}$ line estimation, it can be concluded that the $k_{\text{chem}}$ line estimation lies within the range of the chemical notch tested in chapter 4, of which the comparison can be seen in table 6. Hence, using $k_{\text{chem}}$ line estimation in generating the S-N curve would be possible for 7075-T651 Al, 6061-T651 Al and AISI 4130 steel.

In order to validate this method to be applicable for more materials, few more materials and its S-N curve was selected as shown from Fig 44-47. Figures 44 to 47 shows materials that were not physically tested for its $k_{\text{chem}}$ but taking a $k_{\text{chem}}$ of 2.0 for steel and comparing it with the best fit line of corrosion data, it can be seen that the $k_{\text{chem(lower)}}$ line from Fig. 44 to 47 would always provide a more conservative line when compared to the best fit line of $k_{\text{chem(estimation)}}$. It can therefore be concluded that the $k_{\text{chem}}$ line estimation method would always provide a conservative prediction of the S-N curve for the steel material tested in section 5.1.2.
CONCLUSION

- Experimental testing using SSRT for Al 7075-T651, Al 6061-T651 and AISI 4130 steel showed the influence of 3.5% NaCl solution on the strain at fracture, $\varepsilon_f$ when compared with specimens tested in air.

- For smooth specimens using SSRT, the strain at fracture when comparing specimens tested in air and in corrosion are very different depending on the material chosen. Al 7075-T651 showed a large change in strain to fracture, followed by AISI 4130 steel and lastly Al 6061-T651.

- Slow Strain Rate Technique was used to identify the chemical notch, $k_{chem}$ of each material. It also led to the understanding of chemical notch effect at the liquid-air interface and the ranges of chemical notch for each specimen.

- The chemical notch, $k_{chem}$ line estimation method was verified with fatigue data in air and corrosive environment. $k_{chem}$ line estimation can be used to predict the S-N curve of corrosion. By doing so, it will save time and cost, because less specimens have to be tested in order to predict the S-N curve of a material subjected under corrosion.

- Different steels material fatigue data was used in conjunction with $k_{chem}$ line estimation method. For these materials, it can be concluded that the $k_{chem}$ line estimation would always provide a more conservative S-N curve when compared with best fit line of the corrosion data on a log-log plot.
**FUTURE WORK**

- The three materials analyzed are 7075-T651, 6061-T651 and 4130 steel. All 3 of them are taken in a longitudinal rolling direction. Further analyses could be done by taking a short transverse direction as this is usually the weakest orientation in any given material.

- This thesis paper was conducted in a constant $8 \times 10^{-7}/s$ slow strain rate. It would be recommended to test it in different strain rate in order to identify how it would change when subjected to corrosive environment as we know corrosion is a time dependent process.

- Running a test with different corrosive solution and different pH level would be an interesting study. Lastly, it would be important to have more materials of different alloys, tested under constant slow strain rate in order to identify its kchem, to further prove the application for kchem line estimation within the S-N curve.
REFERENCES


10. Tyng Lee, 2009, Master’s Thesis


