Axial and Torsion Deformation and Fatigue Behaviors and Estimation Methods for a Steel Weld Metal

Tarek Diab

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AXIAL AND TORSION DEFORMATION AND FATIGUE BEHAVIORS AND ESTIMATION METHODS FOR A STEEL WELD METAL

by

Tarek Diab

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of
Master of Science

Major: Mechanical Engineering

The University of Memphis

August 2022
Abstract

Steel alloys are commonly used as weld metal and widely used for welded steel constructions such as automobile components, pipelines, and pressure vessels. However, fatigue is a significant factor in weldments due to the flaws presented in the welds that act as stress concentrations, facilitating the development of fatigue cracks which may lead to catastrophic failure. This investigation utilized the use of ER70S-3 filler metal supplied by Hyundai Motor Company for fatigue performance investigation. Monotonic tests were performed to determine the monotonic axial and shear properties. Likewise, fatigue tests were conducted under fully-reversed loading conditions to assess the axial and shear fatigue properties. Additionally, prediction models are used to estimate weld metal’s fatigue life and cyclic properties and the outcomes are evaluated by comparing to the obtained experimental data. Furthermore, fractography of the weld steel specimens were analyzed to determine the fatigue initiation mechanism and advancement throughout the specimen gage section when subjected to cyclic axial and torsion loads.
Acknowledgment

This study would not have been possible without the help of my supervisor, Dr. Ali Fatemi. Furthermore, I'd like to appreciate my committee members, Dr. Gladius Lewis, and Dr. Amir Hadadzadeh, for their assistance and suggestions for improvement. In addition, I would like to sincerely appreciate, Matthew, who performed the tests. I would like to thank Hyundai Motor Company for sponsoring this study and providing test specimens. Also, I would like to thank my colleagues in Fatigue and Fracture Research Laboratory for their assistance and support. Moreover, I would want to express my gratitude to my brothers for their constant love, care, and motivation during my educational journey. Furthermore, I want to thank my mother, the one and only person who has always been there for me, for her love and care during this experience. Finally, this thesis is dedicated to my father's memory. Even though you were not here to witness my adventure, I believe you are proud of me.
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List of Abbreviations

ASTM .... American Society for Testing and Materials

BSI .......... British Standards Institution

CMT ...... Cold Metal Transfer

DIC......... Digital Image Correlation

FEA....... Finite Element Analysis

IST........ Instron Structural Testing
List of Symbols

\( A \) ................................ Intercept of the best fit line to the stress amplitude \((\sigma_a)\) versus cycles to failure \((N_f)\) data in log-log scale

\( A_f \) ..............................Cross-sectional area at fracture \([\text{mm}^2]\)

\( A_i \) ..............................Initial cross-sectional area \([\text{mm}^2]\)

\( B \) ..............................Slope of the best fit line to the stress amplitude \((\sigma_a)\) versus cycles to failure \((N_f)\) data in log-log scale

\( b \) ..............................Fatigue strength exponent

\( b_o \) ..............................Shear fatigue strength exponent

\( c \) ..............................Fatigue ductility exponent

\( c_o \) ..............................Shear fatigue ductility exponent

\( D_{\text{min}} \) ........................Diameter of the cross-section in the thinnest part of the neck \([\text{mm}]\)

\( E \) ..............................Modulus of elasticity \([\text{GPa}]\)

\( e \) ..............................Engineering axial strain

\( e_x \) ..............................Transverse strain

\( G \) ..............................Modulus of rigidity \([\text{GPa}]\)

\( HB \) ..............................Brinell hardness

\( K \) ..............................Strength coefficient \([\text{MPa}]\)

\( K' \) ..............................Cyclic strength coefficient \([\text{MPa}]\)

\( K_o \) ..............................Shear strength coefficient \([\text{MPa}]\)

\( K'_o \) ..............................Cyclic shear strength coefficient \([\text{MPa}]\)

\( L \) ..............................Specimen’s length \([\text{mm}]\)

\( \Delta L \) ..............................Change in length \([\text{mm}]\)
$l_f$ Specimen final length [mm]

$l_i$ Specimen initial length [mm]

$n$ Strain hardening exponent

$n'$ Cyclic strain hardening exponent

$n_o$ Shear strain hardening exponent

$n'_o$ Cyclic shear strain hardening exponent

$N_f$ Number of cycles to failure [Cycles]

$2N_f$ Number of reversals to failure [Reversals]

$N_{Pa}$ Number of cycles recorded near the midlife cycle at which load amplitude was obtained in axial fatigue test [Cycles]

$N_{Ta}$ Number of cycles recorded near the midlife cycle at which torque amplitude was obtained in torsion fatigue test [Cycles]

$2N_t$ Fatigue transition life [Reversals]

$P$ Axial load [kN]

$P_f$ Axial load at fracture [kN]

$P_{max}$ Maximum axial load [kN]

$r$ Radius of specimen [mm]

$R$ Neck radius [mm]

$RA$ Reduction in area [%]

$R_\delta$ Minimum to maximum displacement ratio in fatigue tests

$R_\theta$ Minimum to maximum rotational angle ratio in fatigue tests

$S$ Engineering stress [MPa]

$S_f$ Fatigue limit defined as fatigue strength at $10^6$ cycles [MPa]
$S_{ult}$ .......................Ultimate tensile strength [MPa]

$S_y$ ..........................Yield strength [MPa]

$T$ ..............................Torque [N.m]

$\frac{dT}{d\theta}$ ..................Slope of torque versus rotation angle curve $\left[\frac{N.m}{\circ}\right]$

$\Delta T$ ..........................Torque range [N.m]

$\frac{d\Delta T}{d\Delta \theta}$ ........Slope of the tip of midlife $T - \theta$ hysteresis loops $\left[\frac{N.m}{\circ}\right]$

$T_{max}$ ..........................Maximum torque [N.m]

$v$ ..............................Poisson’s ratio

$\sigma$ ..............................True stress [MPa]

$\sigma_a$ ..........................Stress amplitude [MPa]

$\sigma_f$ ..........................True fracture stress [MPa]

$\sigma'_f$ ..........................Fatigue strength coefficient [MPa]

$\sigma'_y$ ..........................Cyclic yield strength [MPa]

$\tau$ ..............................Shear stress [MPa]

$\Delta \tau$ ..........................Shear stress range [MPa]

$\tau'_f$ ..........................Shear fatigue strength coefficient [MPa]

$\tau_{ult}$ ..........................Ultimate shear strength [MPa]

$\tau_y$ ..............................Yield shear strength [MPa]

$\tau'_y$ ..........................Cyclic shear yield strength [MPa]

$\varepsilon$ ..........................True strain

$\varepsilon_a$ ..........................Total strain amplitude

$\varepsilon_e$ ..........................Elastic strain
\( \varepsilon_f \) ................. True fracture strain

\( \varepsilon'_f \) ................. Fatigue ductility coefficient

\( \varepsilon_p \) ................. Plastic strain

\( \gamma \) ...................... Shear strain

\( \gamma_a \) .................... Total shear strain amplitude

\( \gamma_e \) ..................... Elastic shear strain

\( \gamma'_f \) ..................... Shear fatigue ductility coefficient

\( \gamma_p \) ..................... Plastic shear strain

\( \frac{\Delta \varepsilon_e}{2} \) .............. Elastic strain amplitude

\( \frac{\Delta \varepsilon_p}{2} \) .............. Plastic strain amplitude

\( \frac{\Delta \gamma_e}{2} \) .............. Elastic shear strain amplitude

\( \frac{\Delta \gamma_p}{2} \) .............. Plastic shear strain amplitude

\( \delta_a \) ..................... Displacement amplitude [mm]

\( \theta \) ....................... Rotation angle [°]

\( \Delta \theta \) ...................... Rotation angle range [°]
1. Introduction

This chapter explains the significance of fatigue and how it relates to weldments. Additionally, the distinctions between monotonic and fatigue behaviors, as well as their importance, will be discussed along with the study objective of this thesis.

1.1 Importance of Fatigue of Welds

Fatigue failures typically occur suddenly and often without warning. Fatigue is a localized failure that refers to the fact that the fatigue process occurs in specific sections of the component or structure. These local regions may undergo considerable stresses and strains because of external loads, geometry changes, temperature differentials, residual stresses, and material flaws. As a result, fatigue cracks begin at discontinuities that act as a stress concentration in the material and continue to spread through the thickness until they reach a critical size at which fracture occurs. Fatigue failure is responsible for about 90% of all failures in engineering components as claimed by T. R. Gurney [1].

Welds will always contain macro or microdiscontinuities or even both macro and micro flaws that act as stress concentrations in the weldments, creating areas for cracks to initiate, advance, and break unexpectedly. As a result, fatigue is a well-known feature of weldments and it is an important aspect to consider when designing welds in components. Generally, there are butt welds, fillet welds, and spot welds which come in a variety of forms and combinations. Improving fatigue resistance of a weld metal may be accomplished by minimizing geometrical discontinuities in the weld and carefully grinding unnecessary reinforcement, as well as stress relief procedures that create desired compressive residual stresses, including processes such as shot peening, hammer...
peening, and surface rolling. Fatigue of weldments design for various weld configurations can be found in handbooks and standards such as BSI BS7608 [2].

The I-40 Mississippi River Bridge which is connecting Memphis with Arkansas is an illustration showing the fatigue crack initiation and propagation through the weldment. It was closed in May 2021 after inspectors discovered a crack in one of the horizontal steel beams. Investigators reported that a crack developed during the manufacturing of the bridge in a weld between two plates that was originally undetectable by conventional inspection and was not detected by an ultrasonic examination in 1982. A crack had been visible in 2016, which was developed because of the welding procedure and the type of steel used during the fabrication of the bridge, as a result welded plates were more vulnerable to cracking by time [3]. This example illustrates that fatigue is an essential aspect to consider when designing welds since fatigue cracks can cause major safety concerns and inconveniences.

1.2 Importance of Axial and Torsion Deformation and Fatigue Behaviors

Tensile testing is a fundamental test that involves subjecting a sample to a monotonically increasing tension load up to fracture of the specimen. Tension test results may be used to understand a material's axial deformation behavior, assisting in the design process, reducing material costs, achieving production objectives, and ensuring compliance with international and industry standards. Tensile testing is used by filler metal manufacturers to develop and maintain filler metal product classifications. Tension test results are critical in determining whether a weld metal is suitable for a certain application.
Torsion tests are performed by twisting a material to a specified degree by applying a torque load until the material breaks and fail. Many components are subjected to torsional loads that result in shear stresses during their operation, such as in motor spindles, machine tool spindles and vehicle transmission shafts. Shear mechanical properties measured from a torsion test are critical in the computation of mechanical analysis, engineering design, for any welded material exposed to torsion deformation or shear stress.

For the first time, Bauschinger [4] observed that monotonic deformation differs significantly from cyclic deformation. Cyclic application of plastic strain to a metal can cause continuous changes until cyclic stability is reached. This means that the metal becomes more or less deformable, and the material exhibits cyclic hardening or softening behavior. These processes may be recognized in a deformation-controlled test by displaying the stress amplitude as a function of reversals to failure. The material will experience hardening mode if the load is increasing, however softening mode will be achieved if the load is decreasing over time. Furthermore, material may also experience a mixed-mode behavior, which combines the hardening and softening behaviors by increasing and decreasing applied load amplitude over time.

Fatigue is a process of localized failure characterized by the breaking of materials and structural components as a result of applied cyclic stresses. One of the most fascinating aspects of fatigue damage development is that it may initiate and propagate at stress levels much below the material's yield strength. As a result, understanding the fatigue deformation behavior of materials is crucial because they it can occur at stresses less than yield strength. Fatigue damage process can be divided into three stages, the first
stage is crack initiation, where under cyclic stresses slip bands are formed because of intrusions and extrusions which act as stress concentrators, allowing a crack to develop and grow. The second stage is crack growth, where the formed microcrack(s) advances through the material due to cyclic plastic strain at the crack tip. The third stage is the fatigue failure phase, where fracture occurs due to crack reaching a critical size [5].

1.3 Thesis Objectives

This study investigates monotonic and fatigue properties of steel weld metal ER70S-3. Monotonic tension and torsion tests were performed under displacement and rotation angle control to obtain monotonic axial and shear properties. Axial and torsion fatigue experiments were also conducted under constant amplitude displacement ($R_δ = -1$) and rotation angle amplitude control ($R_θ = -1$) to generate the axial and shear fatigue properties of the weld metal. Prediction models are used to estimate weld metal’s monotonic torsion behavior, axial and shear cyclic deformation properties, as well as axial and shear fatigue properties. Predicted data are then evaluated and compared with the determined experimental data. Additionally, fracture surfaces under axial and torsion fatigue tests are analyzed to explain the fatigue phases and how the fatigue failure process developed and progressed through the gage section of the specimen.

Chapter 1 provided an overview of the relevance of axial, torsion, and fatigue behaviors, as well as the study's purpose. Chapter 2 details the manufacturing process of specimens and the testing equipment used to test them. Chapters 3 and 4 discuss axial and torsional monotonic and cyclic deformation tests and properties, respectively. Chapters 5 and 6 discuss axial and torsion fatigue tests and properties, respectively. A summary of this work along with the conclusions are presented in Chapter 7.
2. Experimental Program

This chapter focuses on the weld metal used for investigation, along with the manufacturing process of the specimens and their preparation. Explanations of experimental setup and equipment used for monotonic tests as well as fatigue tests are also included.

2.1 Material and Specimens Manufacturing Process

ER70S-3 weld metal was used for investigation to obtain deformation and fatigue properties of the weld metal under axial and torsion loads. Ordinary Hull Structure Steel AH36 was the base metal with an equivalent carbon content of 0.44% according to ASTM standard A6/A6M [6] which shows a good welding compatibility. Chemical composition of the weld metal as well as the base metal provided by manufacturer are summarized and given in Table 2.1.

Manufacturing process of the specimens started with a plate of the base metal with a v-groove cut at 90° through the center of the plate to create a butt weld through the plate. The weld metal ER70S-3 was then deposited by Fronius CMT welding machine, and a fully penetrated butt weld was formed through the center of the plate which was grinded to remove reinforcement with respect to the surface plate. The welded plate was then cut into 15 mm bars, and the extracted bars were annealed to remove tensile residual stresses from the weld caused during the welding process. Specimens were machined from the annealed bars. Manufacturing steps are summarized and shown in Figure 2.1 and schematic presentation of the specimen is shown in Figure 2.2.

2.2 Testing Equipment

An IST closed-loop servo-controlled hydraulic axial and torsion load frame shown in Figure 2.3 was used to conduct both the monotonic tests under displacement and rotation angle
control, while fatigue tests were performed under displacement amplitude and rotation angle amplitude control. It has a load capacity of $\pm 100$ kN with an axial actuator stroke of 150 mm and a torque capability of $\pm 1000$ N.m with a rotary stroke of 90° [7].

Digital Image Correlation (DIC) was utilized to determine the full-field strain over the specimen's surface. It is a noncontact optical device for sensing deformation in three dimensions. One linked device camera can detect two-dimensional deformations, while two coupled device cameras can recognize three-dimensional surface contours and strain distributions by taking the depth displacement into account. DIC analysis can recognize an object's surface properties in digital camera photos and assigning coordinates to the image pixels. Then, DIC measurement captures additional pictures throughout the object's loading and compares them to the reference image. Recently, DIC has been used widely over actual extensometers in material testing because strains can be directly observed by using DIC, and greatly increasing the amount of data that can be gleaned from the testing of materials. In this study, GOM Correlate software was used particularly to evaluate strains in monotonic and cyclic deformation tests. Additional information is available in the GOM user handbook catalog [8]. DIC setup with IST is shown in Figure 2.4. Specimens were polished using Morrison Specimen polishing machine presented in Figure 2.5 prior to fatigue testing. Fractography of the specimens’ was conducted by using a Keyence ultra high accuracy digital microscope VHX Series with a VHX-E100 lens [9] and a magnification range of up to x500, as shown in Figure 2.6.
Table 2.1: Chemical composition. (a) Base metal AH36, (b) Weld metal ER70S-3.

<table>
<thead>
<tr>
<th>Chemical Composition (wt.%)</th>
<th>Carbon (C)</th>
<th>Silicon (Si)</th>
<th>Manganese (Mn)</th>
<th>Phosphorus (P)</th>
<th>Sulfur (S)</th>
<th>Equivalent Carbon (C_{eq})</th>
</tr>
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<tr>
<td>(a)</td>
<td>0.18</td>
<td>0.10-0.50</td>
<td>0.7-1.60</td>
<td>0.035</td>
<td>0.035</td>
<td>0.44</td>
</tr>
</tbody>
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<tr>
<th>Carbon (C)</th>
<th>Chromium (Cr)</th>
<th>Copper (Cu)</th>
<th>Manganese (Mn)</th>
<th>Molybdenum (Mo)</th>
<th>Nickel (Ni)</th>
<th>Phosphorus (P)</th>
<th>Silicon (Si)</th>
<th>Sulfur (S)</th>
<th>Vanadium (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.073</td>
<td>0.027</td>
<td>0.16</td>
<td>1.14</td>
<td>0.003</td>
<td>0.010</td>
<td>0.013</td>
<td>0.66</td>
<td>0.009</td>
<td>0.003</td>
</tr>
</tbody>
</table>
Figure 2.1: Manufacturing process of the specimens. (a) Base metal plate with a 90° V-groove, (b) Fully penetrated butt weld of weld steel ER70S-3, (c) Grinding butt weld to remove reinforcement
Figure 2.2: (a) Specimen machined from 15 mm x 15 mm cross section bar, (b) Schematic presentation of specimen with weld region.

Figure 2.3: IST hydraulic axial and torsion load frame.
Figure 2.4: DIC Setup with IST machine.

Figure 2.5: Morrison Specimen polishing machine.
Figure 2.6: Keyence ultra high accuracy digital microscope VHX Series.
3. Axial Deformation Behavior and Properties

This chapter explains the monotonic tension test experimental methods, determination of tensile properties, as well as the cyclic axial step test procedure, and cyclic deformation properties of the weld metal. Additionally, a prediction method of cyclic deformation properties for the weld metal based on monotonic deformation properties is evaluated and compared with the experimental axial fatigue deformation curve.

3.1 Monotonic Tension Test and Properties

Ductile materials will fail by yielding if the applied stress is greater than the material's yield strength. By estimating the force required to yield a material, designers may forecast how materials and products will function in their intended applications. This is accomplished by evaluating material's axial mechanical deformation behavior.

Monotonic tension test was performed according to ASTM standard E8/E8M [10] under displacement control for one specimen to generate the axial monotonic properties of the weld metal. DIC was used to determine axial strain on a specimen by selecting an appropriate surface component on the specimen at the reference stage, as shown in Figure 3.1. The first deformation picture was synchronized with the IST load frame such that the first deformation picture had an axial load value of \( P_i = 0.6 \text{kN} \) and the DIC was recording pictures for the deformed specimen every five seconds.

In a monotonic tensile test, engineering stress is calculated by:

\[
S = \frac{P}{A_i}
\]  

(3.1)

Engineering strain is defined as the following:
\[ e = \frac{\Delta L}{l_i} = \frac{l_f - l_i}{l_i} \quad (3.2) \]

True stress is calculated based on:

\[ \sigma = S(1 + e) \quad (3.3) \]

True strain is expressed in terms of engineering strain as:

\[ \varepsilon = \ln(1 + e) \quad (3.4) \]

Monotonic axial properties of the weld metal obtained from the tension test include; Modulus of elasticity \((E)\), Poisson’s ratio \((\nu)\), yield strength \((S_y)\), ultimate tensile strength \((S_{ult})\), reduction in area \((\%RA)\), true fracture strain \((\varepsilon_f)\), true fracture stress \((\sigma_f)\), strength coefficient \((K)\), and strain hardening exponent \((n)\). Axial mechanical properties of the weld metal are summarized and reported in Table 3.1.

Axial load versus displacement up to fracture is shown in Figure 3.2. Axial monotonic stress-strain behavior is shown in Figure 3.3(a) as expressed by using Ramberg-Osgood in Figure 3.3(b). The Ramberg-Osgood equation is given by:

\[ \varepsilon = \varepsilon_e + \varepsilon_p = \frac{\sigma}{E} + \left( \frac{\sigma}{K} \right)^{\frac{1}{n}} \quad (3.5) \]

Modulus of elasticity was determined based on the linear relationship between axial stress and axial strain in the elastic region, as shown in Figure 3.4 where:

\[ E = \frac{\sigma}{e} \quad (3.6) \]

Poisson’s ratio was calculated on the basis of transverse strain and axial strain as shown in Figure 3.5 expressed by:

\[ \nu = -\frac{\varepsilon_x}{\varepsilon_y} \quad (3.7) \]
Poisson’s ratio was calculated to be 0.28 for elastic regime and increasing to approximately 0.5 for fully plastic region.

The ultimate tensile strength was calculated from:

\[ S_{\text{ult}} = \frac{P_{\text{max}}}{A_i} \]  

(3.8)

The true fracture stress is corrected for necking in ductile materials by using Bridgeman correction factor [11] and calculated by:

\[ \sigma_f = \frac{P_f}{A_f} \frac{1}{(1 + \frac{4R}{D_{\text{min}}}) \ln (1 + \frac{D_{\text{min}}}{4R})} \]  

(3.9)

\( D_{\text{min}} \) was calculated to be 3.27 mm by carefully combining the two fracture surfaces and the thinnest cross section was measured by using caliper. Neck radius, \( R \) was 1.79 mm based on the average of four different neck radius measurements, as shown in Figure 3.6.

Reduction in area represents the ductility of the material and it is expressed by:

\[ (\%) RA = \frac{A_f - A_i}{A_i} \times 100 \]  

(3.10)

Initial cross-section of the specimen, \( A_i \) was 27.8 mm\(^2\) and the final cross-section, \( A_f \) was 8.42 mm\(^2\).

The true fracture strain was calculated based on:

\[ \varepsilon_f = \ln \left( \frac{A_i}{A_f} \right) = \ln \left( \frac{1}{1 - RA} \right) \]  

(3.11)

In the plastic region, there is a linear relationship between true stress and true plastic strain in log-log scale, to determine strength coefficient (\( K \)) and strain hardening exponent (\( n \)) according to ASTM standard E646 [12] by selecting ten data points with approximately equal data spacing, as shown in Figure 3.7, given by:
The specimen failed on the maximum shear stress plane under monotonic tension load. Typical ductile behavior can be seen in Figure 3.8(a), which is known as cup and cone failure. Furthermore, Figure 3.8(b) shows the strain distribution in the gage region, which represents the 45° line more clearly corresponding to maximum shear plane.

3.2 Cyclic Axial Deformation Test and Properties

Cyclic axial step test was performed under displacement amplitude control. The purpose of the axial step test was to generate a relationship between displacement amplitude and strain amplitude to calculate strains in axial fatigue tests. Displacement amplitude was correlated with strain amplitude measured from DIC by using best fit lines for elastic and plastic regions, as shown in Figure 3.9. The axial cyclic step test had eight cyclic steps. The first three steps were elastic and the other steps were plastic. The surface component used to measure cyclic axial strain on the specimen was the same length as the monotonic axial test, 4 mm, with the same pixel size (29x16).

A straight-line results from fitting stress amplitude versus plastic strain amplitude in a log-log plot represented by:

$$\sigma_a = K'\left(\frac{\Delta\varepsilon_p}{2}\right)^{n'}$$

(3.13)

Axial cyclic properties of the weld metal can be determined from this plot shown in Figure 3.10. These include cyclic strength coefficient ($K'$) and cyclic strain hardening exponent ($n'$). Cyclic yield strength ($\sigma'_y$) can then be determined from: $\sigma'_y = K'(0.002)^{n'}$. Cyclic properties are reported in Table 3.2.
Cyclic stress vs. strain was generated from axial fatigue test data because material did not reach stabilization in the cyclic axial step test. It is shown in Figure 3.11 by using Ramberg-Osgood relationship, which is given by:

\[ \varepsilon_a = \frac{\Delta \varepsilon_e}{2} + \frac{\Delta \varepsilon_p}{2} = \frac{\sigma_a}{E} + \left( \frac{\sigma_a}{K'} \right)^{1/n'} \]  \hspace{1cm} (3.14)

Superimposed plot of cyclic stress-strain curve with the monotonic stress vs. strain curve is shown in Figure 3.12. It can be observed that the material is experiencing cyclic softening under cyclic axial load until 1.5% strain amplitude.

### 3.3 Prediction of Cyclic Axial Deformation Properties

Prediction of cyclic axial deformation from monotonic tensile properties of the weld metal was made according to Lopez and Fatemi estimation method for steels [13]; They proposed prediction of cyclic strength coefficient \((K')\) based on ultimate tensile strength \(S_{ult}\) from:

\[ K' = 3 \times 10^{-4} (S_{ult})^2 + 0.23(S_{ult}) + 619, \text{for} \frac{S_{ult}}{S_y} < 1.2 \] \hspace{1cm} (3.15)

They proposed prediction of cyclic strain hardening exponent \((n')\) from:

\[ n' = -0.33 \left( \frac{S_y}{S_{ult}} \right) + 0.40 \] \hspace{1cm} (3.16)

The ratio \(\frac{S_{ult}}{S_y}\) for the weld steel is 1.18. Predicted values of \((K')\) and \((n')\) are shown in Table 3.3. Predicted axial cyclic curve is compared to the experimental axial cyclic curve in Figure 3.13. Predicted axial cyclic curve from ultimate tensile strength \((S_{ult})\) is close to the experimental axial cyclic curve. The ability to predict the axial cyclic stress-strain curve from a steel's ultimate tensile strength is important where cyclic material properties may not be available, but needed for fatigue design. If a material's ultimate tensile strength is unknown, it can be predicted from hardness from Equation
(5.11) given in Chapter 5. Cyclic stress-strain relation is required when using FEA or any other analysis to predict the fatigue life of a steel component.
Table 3.1: Summary of monotonic axial properties of weld metal.

<table>
<thead>
<tr>
<th>Monotonic property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>210.3 GPa</td>
</tr>
<tr>
<td>$v$</td>
<td>0.28</td>
</tr>
<tr>
<td>$S_y$ (0.2% offset)</td>
<td>470 MPa</td>
</tr>
<tr>
<td>$S_{ult}$</td>
<td>557 MPa</td>
</tr>
<tr>
<td>$\sigma_f$</td>
<td>930.4 MPa</td>
</tr>
<tr>
<td>$RA$</td>
<td>70%</td>
</tr>
<tr>
<td>$\epsilon_f$</td>
<td>1.2</td>
</tr>
<tr>
<td>$K$</td>
<td>719.2 MPa</td>
</tr>
<tr>
<td>$n$</td>
<td>0.0803</td>
</tr>
</tbody>
</table>

Table 3.2: Summary of axial cyclic properties of weld metal.

<table>
<thead>
<tr>
<th>Cyclic property</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E'$</td>
<td>206 GPa</td>
</tr>
<tr>
<td>$\sigma'_y$</td>
<td>376.1 MPa</td>
</tr>
<tr>
<td>$K'$</td>
<td>831.2 MPa</td>
</tr>
<tr>
<td>$n'$</td>
<td>0.1276</td>
</tr>
</tbody>
</table>
Table 3.3: Summary of axial cyclic curve properties estimated by using Lopez and Fatemi prediction method [13].

<table>
<thead>
<tr>
<th>Cyclic property</th>
<th>Experimental</th>
<th>Based on $S_{ult}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K'$</td>
<td>831.2 MPa</td>
<td>840.2 MPa</td>
</tr>
<tr>
<td>$n'$</td>
<td>0.1276</td>
<td>0.1215</td>
</tr>
</tbody>
</table>
Figure 3.1: DIC selected 4 mm x 5.95 mm surface component (29x16 pixels) under monotonic tension test.

Figure 3.2: Axial load versus displacement recorded during monotonic tension test up to failure.
Figure 3.3: (a) Monotonic axial stress-strain curve, (b) Superimposed plot of engineering stress-strain curve up to ultimate tensile strength and the Ramberg Osgood curve.
Figure 3.4: Modulus of Elasticity determination from initial part of stress-strain data.

\[ y = 210314x + 0.2912 \]

\[ R^2 = 0.9983 \]
Figure 3.5: (a) Superimposed strain components during tensile test, (b) Poisson’s ratio versus axial true strain up to ultimate tensile strength.
Figure 3.6: Determination of the neck radius by using Keyence digital microscope.

Figure 3.7: True stress versus true plastic strain from yield stress up to ultimate tensile strength.
Figure 3.8: (a) Specimen’s failure surface under monotonic tension test, (b) Strain distribution at the beginning of strain hardening stage.

Figure 3.9: Displacement amplitude versus strain amplitude for elastic and plastic steps under axial cyclic step test.
Figure 3.10: Determination of cyclic strength coefficient ($K'$) and cyclic strain hardening exponent ($n'$) from stress amplitude versus plastic strain amplitude in log-log plot.

$$K' = 831.2 \text{ MPa}$$
$$n' = 0.1276$$
$$\sigma'_y = 831.2(0.002)^{0.1276} = 376.1 \text{ MPa}$$

Figure 3.11: Cyclic stress-strain deformation curve.
Figure 3.12: Axial cyclic stress-strain curve compared to monotonic stress-strain curve.

Figure 3.13: Experimental cyclic axial stress-strain curve compared to predicted stress-strain curve by using Lopez and Fatemi prediction method based on ultimate tensile strength [13].
4. Torsion Deformation Behavior and Properties

This chapter highlights the monotonic torsion test technique, determination of monotonic shear properties, cyclic shear test procedure, and the determination of cyclic shear deformation properties. Also, estimations of monotonic and shear stress-strain curves were made using Tresca and von-Mises criteria based on axial properties.

4.1 Monotonic Torsion Test and Properties

Monotonic torsion test was performed for one solid specimen to generate the torsion monotonic properties of the weld metal. DIC was used to determine shear strain on the specimen by selecting an appropriate surface component, as shown in Figure 4.1. The reason for selecting a larger element size in monotonic torsion test was because the element becomes smaller by continuous shear deformation and the camera can no longer detect the elements. Thus, a larger element size is needed in monotonic torsion test. DIC was synchronized with IST frame such that the first deformation picture was at \( T_i = 5 \text{ N.m} \) and the deformation pictures were recorded every ten seconds. A plot between torque and actuator rotation angle up to fracture recorded by IST is shown in Figure 4.2.

In order to calculate the shear stress for solid specimens in torsion tests, Miller and Chandler equation [14] was followed, given by:

\[
\tau = \frac{1}{2\pi r^3} \left[ 3T + \theta \frac{dT}{d\theta} \right] \quad (4.1)
\]

where \( \frac{dT}{d\theta} \) represents the slope of torque versus rotation angle curve. Figure 4.3 shows the slope determination in order to calculate for shear stress in monotonic torsion test.

Shear strain is defined as:

\[
\gamma = \frac{R\theta}{L} \quad (4.2)
\]
Shear properties such as modulus of rigidity \((G)\), shear yield strength \((\tau_y)\), ultimate shear strength \((\tau_{ult})\), shear strength coefficient \((K_o)\), and shear strain hardening exponent \((n_o)\) were determined as monotonic shear properties, which are reported in Table 4.1.

Monotonic shear stress-shear strain curve is provided in Figure 4.4. It is also represented by Ramberg-Osgood equation given by:

\[
\gamma = \gamma_e + \gamma_p = \frac{\tau}{G} + \left(\frac{\tau}{K_o}\right)^{\frac{1}{n_o}}
\]  
(4.3)

The ultimate shear strength was calculated according to the following equation:

\[
\tau_{ult} = \frac{3T_{max}}{2\pi r^3}
\]  
(4.4)

Modulus of rigidity was calculated based on the linear relationship between shear stress and shear strain in the elastic regime, as shown in Figure 4.5 as follows:

\[
G = \frac{\tau}{\gamma}
\]  
(4.5)

A plot of shear stress versus plastic shear strain in log-log scale is shown in Figure 4.6 to determine shear strength coefficient \((K_o)\) and shear strain hardening exponent \((n_o)\) in the following equation:

\[
\tau = K_o(\gamma_p)^{n_o}
\]  
(4.6)

Specimen failed on the shear stress plane under monotonic torsion load as can be seen in Figure 4.7 where failure plane is perpendicular to specimen axis.

**4.2. Prediction of Monotonic Shear Deformation Properties**

Tresca and von-Mises criteria were used to predict monotonic torsional behavior from axial monotonic properties [15]. This was done on the basis of Ramberg-Osgood relationship, from:
According to Tresca criterion:

\[
K_o = \frac{K}{2} \left(\frac{2}{3}\right)^n , \text{ and } n_o = n
\]  

(4.7)

And, based on von-Mises criterion:

\[
K_o = K \left(\frac{1}{3}\right)^{\frac{n+1}{2}} , \text{ and } n_o = n
\]  

(4.8)

Modulus of rigidity, \( G \) was calculated from the axial test properties by using the equation below:

\[
G = \frac{E}{2(1 + \nu)}
\]  

(4.9)

Modulus of rigidity calculated from the axial test was found to be 82 GPa, with a difference of 0.6% compared to the measured modulus of rigidity from monotonic torsion test which was 81.5 GPa.

It was observed that von-Mises criterion better estimates the experimental monotonic torsion curve, compared to Tresca criterion, as shown in Figure 4.8. Also, results of monotonic torsion behavior predictions are reported in Table 4.2.

### 4.3 Cyclic Torsion Deformation Test and Properties

Cyclic torsion step test was conducted under rotation angle amplitude control in order to establish a correlation between rotation angle amplitude and shear strain amplitude for the purpose of determining shear strains in rotation-controlled torsion fatigue tests. The torsion cyclic step test was performed at six cyclic steps. The first step was elastic, while the other five steps were inelastic. The surface component utilized to quantify cyclic shear strain on the specimen was 4 mm in length and had the same pixel size (40x40) as the monotonic torsion test. Depending on the controlled rotation angle amplitude for each step, shear strain amplitude was measured by DIC. The relationship
between rotation angle amplitude and shear strain amplitude measured from the DIC is shown in Figure 4.9.

Cyclic shear stress range was calculated using the Chandler and Miller approach [14], where \( T \) and \( \theta \) are substituted by \( \Delta T \) and \( \Delta \theta \), respectively, in Equation (4.1), as shown below:

\[
\Delta \tau = \frac{1}{2\pi r^3} \left[ 3\Delta T + \Delta \theta \frac{d\Delta T}{d\Delta \theta} \right] 
\] (4.10)

and \( \frac{d\Delta T}{d\Delta \theta} \) is the average slope of the tips of the loading and unloading parts of the midlife \( T - \theta \) hysteresis loop. Equation (4.10) is reduced to: \( \Delta \tau = \frac{2(\Delta T)}{\pi r^3} = \frac{(\Delta T)r}{j} \) in the elastic region and \( \Delta \tau = \frac{3(\Delta T)}{2\pi r^3} = \frac{3(\Delta T)r}{4j} \) for the fully plastic torque. The midlife \( T - \theta \) hysteresis loops in the cyclic shear incremental step test and torsion fatigue test are shown in Figures 4.10 and 4.11, respectively. Cyclic shear stress calculations in both tests are summarized in Table 4.3. Values of \( \gamma_a \) in Table 4.3(a) were measured from DIC system, while in Table 4.3(b) they were calculated from the \( T - \theta \) relation in Figure 4.9.

A linear relationship between shear stress amplitude and plastic shear strain amplitude in a log-log scale to determine cyclic shear strength coefficient \( (K'_{\circ}) \) and cyclic shear strain hardening exponent \( (n'_{\circ}) \) as shown in Figure 4.12 given by:

\[
\tau_a = K'_{\circ} \left( \frac{\Delta \gamma_p}{2} \right)^{n'_{\circ}}
\] (4.11)

Cyclic shear properties were determined from the torsion fatigue data. In the torsion fatigue tests, Inelastic tests were used to determine the cyclic shear strength coefficient \( (K'_{\circ}) \) and cyclic shear strain hardening exponent \( (n'_{\circ}) \) of the weld metal. Cyclic shear yield strength \( (\tau'_{\circ}) \) can then be determined from: \( \tau'_{\circ} = K'_{\circ}(0.002)^{n'_{\circ}} \).

Cyclic properties are reported in Table 4.4. A comparison between generating cyclic
shear properties from the cyclic shear incremental step test and torsion fatigue test data is shown in Figure 4.12. Figure 4.12(a), which represents the cyclic shear properties obtained from the cyclic torsion step test compared to cyclic shear properties obtained from the torsion fatigue test data as shown in Figure 4.12(b). Comparison of the cyclic shear stress-strain curve from the two methods is shown in Figure 4.12(c). The experimental curves generated from the two methods were close.

Cyclic shear stress vs. shear strain curve was generated from torsion fatigue data and it is shown in Figure 4.13 by the means of Ramberg-Osgood equation:

\[ \gamma_a = \frac{\Delta \gamma_e}{2} + \frac{\Delta \gamma_p}{2} = \frac{\tau_a}{G} + \left( \frac{\tau_a}{K'_o} \right)^{\nu} \]

(4.12)

A superimposed plot comparing cyclic torsion deformation and monotonic shear stress-strain curves are shown in Figure 4.14. It can be observed that the material experiences significant softening behavior under cyclic shear load.

4.4 Prediction of Cyclic Shear Deformation Properties

Predictions of cyclic shear deformation properties were made based on axial cyclic deformation properties by using Tresca and von-Mises criteria [15], as shown in Figure 4.15. The results are summarized in Table 4.5. This was done by using the Ramberg-Osgood equation based on the following:

Tresca criterion:

\[ K'_o = K' \left( \frac{2}{3} \right)^{n'} \text{, and } n'_o = n' \]

(4.13)

von-Mises criterion:

\[ K'_o = K' \left( \frac{1}{3} \right)^{\left( \frac{n'_{+1}}{2} \right)} \text{, and } n'_o = n' \]

(4.14)
It can be observed that cyclic deformation curve generated by Tresca and von-Mises criteria are near to the experimental cyclic shear stress-strain curve. However, von-Mises criterion was closer to the experimental cyclic shear curve up to the cyclic shear yield strength and Tresca criterion was closer to the experimental cyclic shear curve when the cyclic plasticity increased.
Table 4.1: Summary of monotonic shear deformation properties of weld metal.

<table>
<thead>
<tr>
<th>Monotonic shear property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$</td>
<td>81.5 GPa</td>
</tr>
<tr>
<td>$\tau_y$ (0.2% offset)</td>
<td>280 MPa</td>
</tr>
<tr>
<td>$\tau_{ult}$</td>
<td>425 MPa</td>
</tr>
<tr>
<td>$K_o$</td>
<td>403.7 MPa</td>
</tr>
<tr>
<td>$n_o$</td>
<td>0.0648</td>
</tr>
</tbody>
</table>

Table 4.2: Summary of results obtained from Tresca and von-Mises criteria to predict shear properties from monotonic axial properties.

<table>
<thead>
<tr>
<th>Shear property</th>
<th>Experimental</th>
<th>Tresca</th>
<th>von-Mises</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_o$</td>
<td>403.7 MPa</td>
<td>348.1 MPa</td>
<td>397.3 MPa</td>
</tr>
<tr>
<td>$n_o$</td>
<td>0.0648</td>
<td>0.0803</td>
<td>0.0803</td>
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</tbody>
</table>
Table 4.3: Calculation of cyclic shear stress. (a) In cyclic torsion incremental step test, (b) In torsion fatigue test.

(a)

<table>
<thead>
<tr>
<th>Step</th>
<th>$D_{\text{min}}$ [mm]</th>
<th>$T_a$ [N.m]</th>
<th>$\theta_a$ [$^\circ$]</th>
<th>$Y_a$</th>
<th>$\Delta T$ [N.m]</th>
<th>$\Delta \theta$ [$^\circ$]</th>
<th>$\frac{d\Delta T}{d\Delta \theta}$ $^\text{[N.m]}$</th>
<th>$\Delta \tau$ [MPa]</th>
<th>$\tau_a$ [MPa]</th>
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<tbody>
<tr>
<td>1</td>
<td>5.88</td>
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<td></td>
<td>0.0016</td>
<td>9.9</td>
<td>1.00</td>
<td>248.01</td>
<td>124.01</td>
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<td>5.88</td>
<td>-</td>
<td>1</td>
<td></td>
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<td>-</td>
<td>-</td>
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<td>-</td>
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<td>3</td>
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<td>-</td>
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</table>

(b)

<table>
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<tr>
<th>Spec. ID</th>
<th>$D_{\text{min}}$ [mm]</th>
<th>$T_a$ [N.m]</th>
<th>$\theta_a$ [$^\circ$]</th>
<th>$Y_a$</th>
<th>$\Delta T$ [N.m]</th>
<th>$\Delta \theta$ [$^\circ$]</th>
<th>$\frac{d\Delta T}{d\Delta \theta}$ $^\text{[N.m]}$</th>
<th>$\Delta \tau$ [MPa]</th>
<th>$\tau_a$ [MPa]</th>
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<td>0.0024</td>
<td>13.6</td>
<td>1.35</td>
<td>8.86</td>
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<td>1</td>
<td>0.0037</td>
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</tr>
<tr>
<td>21</td>
<td>5.87</td>
<td>9.99</td>
<td>1.5</td>
<td>0.0070</td>
<td>19.98</td>
<td>3</td>
<td>2.67</td>
<td>427.75</td>
<td>213.87</td>
</tr>
<tr>
<td>17</td>
<td>5.88</td>
<td>10.98</td>
<td>2</td>
<td>0.0103</td>
<td>21.96</td>
<td>4</td>
<td>1.67</td>
<td>454.44</td>
<td>227.22</td>
</tr>
<tr>
<td>22</td>
<td>5.94</td>
<td>11.26</td>
<td>2</td>
<td>0.0103</td>
<td>22.52</td>
<td>4</td>
<td>1.67</td>
<td>451.01</td>
<td>225.51</td>
</tr>
<tr>
<td>18</td>
<td>5.88</td>
<td>12.4</td>
<td>3.75</td>
<td>0.0219</td>
<td>24.8</td>
<td>7.5</td>
<td>0.264</td>
<td>478.36</td>
<td>239.18</td>
</tr>
</tbody>
</table>
Table 4.4: Summary of cyclic shear properties of the weld metal.

<table>
<thead>
<tr>
<th>Cyclic shear property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau'_y$</td>
<td>205.1 MPa</td>
</tr>
<tr>
<td>$K'_o$</td>
<td>316.1 MPa</td>
</tr>
<tr>
<td>$n'_o$</td>
<td>0.0696</td>
</tr>
</tbody>
</table>

Table 4.5: Summary of results obtained from Tresca and von-Mises criteria to predict cyclic shear properties from cyclic axial properties.

<table>
<thead>
<tr>
<th>Cyclic shear property</th>
<th>Experimental</th>
<th>Tresca</th>
<th>von-Mises</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K'_o$</td>
<td>316.1 MPa</td>
<td>394.6 MPa</td>
<td>447.4 MPa</td>
</tr>
<tr>
<td>$n'_o$</td>
<td>0.0696</td>
<td>0.1276</td>
<td>0.1276</td>
</tr>
</tbody>
</table>
Figure 4.1: Surface component 5.95 mm x 4 mm (40x40 pixels) used under monotonic torsion test to measure shear strain.

Figure 4.2: Torque vs rotation angle during monotonic torsion test up to fracture.
Figure 4.3: Slope of torque versus rotation angle determination to calculate shear stress.

Figure 4.4: Superimposed plot of monotonic shear stress-strain curve and the curve represented by Ramberg Osgood equation.
Figure 4.5: Modulus of rigidity determination from the initial part of shear stress-shear strain curve.

\[ y = 81520x + 0.2392 \]
\[ R^2 = 0.9988 \]

Figure 4.6: Shear strength coefficient and shear strain hardening exponent determination.

\[ K_o = 403.7 \text{ MPa} \]
\[ n_o = 0.0648 \]

\[ y = 403.73\gamma_p^{0.0648} \]
\[ R^2 = 0.895 \]
Figure 4.7: Specimen’s failure surface under monotonic torsion test indicating shear failure plane.

Figure 4.8: Predictions of monotonic shear stress-strain curve based on Tresca and von-Mises criteria from monotonic tension stress-strain curve.
Figure 4.9: Correlation of shear strain amplitude measured by DIC with rotation angle amplitude controlled by IST frame and fittings for elastic and plastic torsion steps.
Figure 4.10: Slopes of torque vs. rotation angle hysteresis loops used for calculations of shear stress range in torsion incremental step test.
Figure 4.11: Slopes of torque vs. rotation angle hysteresis loops used for calculations of shear stress range in torsion fatigue tests.
Figure 4.12: Comparison of generated cyclic shear properties. (a) From cyclic torsion step test, (b) from torsion fatigue test data, (c) Cyclic shear curves generated from cyclic torsion step test and torsion fatigue test data.
Figure 4.13: Cyclic shear stress-strain deformation curve.

Figure 4.14: Superimposed plot comparing cyclic and monotonic shear stress-strain behaviors.
Figure 4.15: Predicted cyclic shear stress-strain curve from cyclic axial properties by using Tresca and von-Mises criteria.
5. Axial Fatigue Behavior and Predictions

This chapter covers the fatigue behavior of the weld metal when subjected to cyclic axial loading. The experimental procedures are shown, along with the results and axial fatigue life properties of the weld metal. Specimens fractography was used to analyze how fatigue damage initiated and advanced through specimen gage section under cyclic axial load. Additionally, predictions of axial fatigue behavior is made based on tensile properties and predicted hardness of the weld metal.

5.1 Axial Fatigue Experimental Methods

Fully-reversed \((R_\delta = -1)\) axial fatigue tests were performed under displacement amplitude control according to ASTM standard E606 [16], where failure was defined as 50% load drop for thirteen polished specimens to determine strain-life curve and axial fatigue properties. Basquin-Manson-Coffin model for predicting the fatigue life was adopted to generate the weld metal strain-life curve and axial fatigue properties where total strain amplitude is divided into elastic and plastic strain components as follows:

\[
\varepsilon_a = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \tag{5.1}
\]

Based on Basquin’s equation stress-life approach equation is given by:

\[
\sigma_a = A(N_f)^b \tag{5.2}
\]

The fitting constants based on the best fit equation of (5.2) are related by:

\[
B = b \tag{5.3}
\]

\[
A = (2)^b \sigma'_f \tag{5.4}
\]

The point at which elastic strain amplitude and plastic strain amplitude intersects is called the transition life, \(2N_t\). Transition life divides the strain-life curve into low cycle region
and high cycle region. At low life cycles ($N_f < N_t$) plastic strains are dominant and at high life cycles ($N_f > N_t$) elastic strains are dominant. It is represented by the following equation:

$$2N_t = \left( \frac{\varepsilon'_f E}{\sigma'_f} \right)^{\frac{1}{b-c}}$$  \hspace{1cm} (5.5)

### 5.2 Experimental Results and Axial Fatigue Properties

Axial fatigue test data are summarized in Table 5.1 which are determined based on the midlife $P - \delta$ hysteresis loops for each specimen, as shown in Figure 5.1. Stress amplitude was calculated based on $P/A_1$. Strain amplitude was calculated based on the relationship between displacement amplitude and strain amplitude as described in Figure 3.9, where:

$$\varepsilon_a = 0.0171(\delta_a), \text{for} \ 0.03 \text{ mm} \leq \delta_a \leq 0.09 \text{ mm}$$  \hspace{1cm} (5.6)

$$\varepsilon_a = 0.0897(\delta_a) - 0.0073, \text{for} \ 0.12 \text{ mm} \leq \delta_a \leq 0.35 \text{ mm}$$  \hspace{1cm} (5.7)

The weld metal experienced cyclic softening under axial cyclic load, as shown in Figure 5.2.

Strain amplitude and stress amplitude are the independent variables and fatigue life is the dependent variable according to ASTM standard E739 [17] when fitting fatigue test data to obtain fatigue properties. In other words, strain amplitude and stress amplitude are the controlled parameters and fatigue life is the measured parameter. Axial strain-life properties of the weld metal are determined by linear fitting stress amplitude and plastic strain amplitude data against reversals to failure in log-log plots shown in Figures 5.3 and 5.4, respectively. The experimental axial strain-life curve of the weld
metal is shown in Figure 5.5 and axial fatigue properties are summarized and reported in Table 5.2.

Specimen failure surfaces under fatigue axial test are shown in Figure 5.6. Specimens 3 and 5 had surface defects in gage section before fatigue testing, as shown in Figure 5.7, which act as a stress concentration in the weld metal. It was observed that fatigue failures occurred at the center of the specimen's gage section, where cracks nucleated from the surface as a result of slip bands dislocation movement because of intrusions and extrusions under cyclic axial load. However, fatigue failure initiated from defects for specimens 3, 8 and 9, as shown in Figure 5.8. This is characterized by fish-eye fracture pattern. The fish-eye is composed of two regions in the center; the inner region is the pupil, which has the defect, and the outer region is the iris, which fractures in a pattern extending away from the pupil. Specimen 11 was not included in fits because of a larger than expected defect, as shown in Figure 5.9.

5.3 Prediction of Axial Stress-Life and Strain-Life Curves

Experimental stress-life curve was generated from the axial fatigue data and compared to the predicted stress-life curve based on the ultimate tensile strength of the weld metal, by knowing that for steels, fatigue limit [5] can be estimated usually at \( N_f = 10^6 \) cycles, where:

\[
S_f = 0.5 S_{ult} \text{, for } S_{ult} \leq 1400 \text{ MPa}
\]  

(5.8)

Correction factors based on ultimate tensile strength were applied to the predicted fatigue limit for size correction factor due to tension loading \( K_l = 0.85 \) [5]. Predicted fatigue limit based on ultimate tensile strength was found to be 236.7 MPa which was close to the experimental fatigue limit of the weld metal which was 241.5 MPa. Using
\[ \sigma_a = S_{ult} = 557 \text{ MPa at } N_f = 1 \text{ and } \sigma_a = (0.85)(0.5)(557) = 236.7 \text{ MPa at } N_f = 10^6 \]
in equation (5.2) results in:

\[ S_{N_f} = 557(N_f)^{-0.062} \] (5.9)

Comparison of this predicted line with the experimental line is shown in Figure 5.10.

Muralitharan and Manson [18] have approximated Equation (5.1) for metals with their method of Modified Universal Slopes, where the strain life curve is given by:

\[ \varepsilon_a = 0.623 \left( \frac{S_{ult}}{E} \right)^{0.832} (2N_f)^{-0.09} + 0.0196 \left( \varepsilon_f \right)^{0.155} \left( \frac{S_{ult}}{E} \right)^{-0.53} (2N_f)^{-0.56} \] (5.10)

Roessle and Fatemi [19] proposed a method for predicting strain-life curves from Brinell hardness of steels by modeling the correlation between fatigue strength coefficient and Brinell hardness, using 69 pieces of fatigue test data, and determined that:

\[ \varepsilon_a = \left( \frac{4.25 \left( \frac{HB}{E} \right) + 225}{E} \right)\left( 2N_f \right)^{-0.09} + \left( \frac{0.32(HB)^2 - 487(HB) + 191000}{E} \right) \left( 2N_f \right)^{-0.56} \] (5.11)

Hardness was not experimentally measured in this investigation. Thus, hardness was predicted to be 161.45 based on ultimate tensile strength of the weld metal [5] using the following equation:

\[ S_{ult} = 3.45 \text{ HB} \] (5.12)

Results of the two methods of predictions are compared with the experimental axial strain-life curve in Figure 5.11. It can be observed that both methods gave close predictions to experimental results with a close range between each other.
Table 5.1: Summary of axial fatigue test data under fully-reversed ($R_\delta = -1$) displacement amplitude control.

<table>
<thead>
<tr>
<th>Spec ID</th>
<th>$\delta_a$ [mm]</th>
<th>$D_{min}$ [mm]</th>
<th>Frequency [Hz]</th>
<th>$P_a$ [kN]</th>
<th>$\sigma_a$ [MPa]</th>
<th>$\varepsilon_a$</th>
<th>$\Delta \varepsilon_e / 2$</th>
<th>$\Delta \varepsilon_p / 2$</th>
<th>$N_{P_a}$ [Cycles]</th>
<th>$N_f$ [Cycles]</th>
<th>$2N_f$ [Reversals]</th>
<th>Defect [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.32</td>
<td>5.82</td>
<td>0.25</td>
<td>13.56</td>
<td>509.7</td>
<td>0.0214</td>
<td>0.0025</td>
<td>0.0189</td>
<td>80</td>
<td>163</td>
<td>326</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>0.32</td>
<td>5.88</td>
<td>0.25</td>
<td>13.40</td>
<td>493.5</td>
<td>0.0214</td>
<td>0.0024</td>
<td>0.0190</td>
<td>90</td>
<td>170</td>
<td>340</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.2</td>
<td>5.81</td>
<td>1</td>
<td>12.02</td>
<td>453.4</td>
<td>0.0106</td>
<td>0.0022</td>
<td>0.0084</td>
<td>200</td>
<td>457</td>
<td>914</td>
<td>0.7</td>
</tr>
<tr>
<td>15</td>
<td>0.2</td>
<td>5.89</td>
<td>0.5</td>
<td>12.18</td>
<td>447.0</td>
<td>0.0106</td>
<td>0.0022</td>
<td>0.0085</td>
<td>300</td>
<td>545</td>
<td>1,090</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.14</td>
<td>5.72</td>
<td>2</td>
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<td>409.4</td>
<td>0.0053</td>
<td>0.0020</td>
<td>0.0033</td>
<td>2,000</td>
<td>3,844</td>
<td>7,688</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.125</td>
<td>5.81</td>
<td>5</td>
<td>10.03</td>
<td>378.3</td>
<td>0.0039</td>
<td>0.0018</td>
<td>0.0021</td>
<td>2,000</td>
<td>3,427</td>
<td>6,854</td>
<td>0.7</td>
</tr>
<tr>
<td>5</td>
<td>0.125</td>
<td>5.82</td>
<td>1</td>
<td>9.92</td>
<td>372.9</td>
<td>0.0039</td>
<td>0.0018</td>
<td>0.0021</td>
<td>300</td>
<td>5,515</td>
<td>11,030</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.085</td>
<td>5.67</td>
<td>5</td>
<td>7.69</td>
<td>304.6</td>
<td>0.0015</td>
<td>0.0015</td>
<td>0.0000</td>
<td>52,000</td>
<td>104,609</td>
<td>209,218</td>
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<tr>
<td>13</td>
<td>0.085</td>
<td>5.90</td>
<td>5</td>
<td>8.04</td>
<td>294.1</td>
<td>0.0015</td>
<td>0.0015</td>
<td>0.0000</td>
<td>54,000</td>
<td>106,866</td>
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</tr>
<tr>
<td>7</td>
<td>0.067</td>
<td>5.74</td>
<td>20</td>
<td>6.65</td>
<td>257.0</td>
<td>0.0012</td>
<td>0.0012</td>
<td>0.0000</td>
<td>5,000,000</td>
<td>10,000,000</td>
<td>20,000,000</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.67</td>
<td>5.86</td>
<td>40</td>
<td>6.59</td>
<td>244.3</td>
<td>0.0012</td>
<td>0.0012</td>
<td>0.0000</td>
<td>5,000,000</td>
<td>10,000,000</td>
<td>20,000,000</td>
<td></td>
</tr>
<tr>
<td>11*</td>
<td>0.06</td>
<td>5.79</td>
<td>5-10</td>
<td>5.73</td>
<td>217.6</td>
<td>0.0010</td>
<td>0.0011</td>
<td>0.0000</td>
<td>150,000</td>
<td>297,697</td>
<td>595,394</td>
<td>0.85</td>
</tr>
<tr>
<td>12</td>
<td>0.045</td>
<td>5.79</td>
<td>10-30-40</td>
<td>4.27</td>
<td>162.2</td>
<td>0.0008</td>
<td>0.0008</td>
<td>0.0000</td>
<td>2,550,000</td>
<td>5,057,804</td>
<td>10,115,608</td>
<td></td>
</tr>
</tbody>
</table>

* Data not included in fits due to larger than expected defect
Table 5.2: Summary of axial fatigue properties of the weld metal.

<table>
<thead>
<tr>
<th>Fatigue property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma'_f$</td>
<td>770.8 MPa</td>
</tr>
<tr>
<td>$b$</td>
<td>-0.080</td>
</tr>
<tr>
<td>$\varepsilon'_f$</td>
<td>0.782</td>
</tr>
<tr>
<td>$c$</td>
<td>-0.644</td>
</tr>
</tbody>
</table>
Figure 5.1: Hysteresis loops at midlife cycle \((P - \delta)\) under fully-reversed \((R_\delta = -1)\) displacement amplitude control.

Figure 5.2: Load amplitude versus cycles for axial fatigue tests under fully-reversed \((R_\delta = -1)\) displacement amplitude control.
Figure 5.3: Stress amplitude versus reversals to failure under fully-reversed ($R_δ = -1$) displacement amplitude control to determine fatigue strength coefficient and fatigue strength exponent.

\[ \sigma'_f = 770.8 \text{ MPa} \]
\[ b = -0.08 \]
\[ S_f = 770.8(2 \times 10^6)^{-0.08} = 241.5 \text{ MPa} \]

Figure 5.4: Plastic strain amplitude versus reversals to failure in fully-reversed ($R_δ = -1$) displacement amplitude control test to determine fatigue ductility coefficient and fatigue ductility exponent.

\[ \epsilon'_f = 0.782 \]
\[ c = -0.644 \]

\[ y = 0.782x^{0.644} \]
\[ R^2 = 0.842 \]
Figure 5.5: Experimental axial strain-life curve of the weld metal under fully-reversed ($R_\delta = -1$) displacement amplitude control.
Figure 5.6: Specimen fracture surfaces under fully-reversed \( R_\delta = -1 \) axial fatigue test.
Figure 5.7: Initial defects in the gage section before axial fatigue testing. (a) Specimen 3 after polishing defect, (b) Specimen 5 initial defect.

Figure 5.8: Fish-eye surface defects. (a) Specimen 3, (b) Specimen 8, (c) Specimen 9.
Figure 5.9: Specimen 11 defect under fully-reversed \( R_\delta = -1 \) axial fatigue test.

Figure 5.10: Experimental stress-life curve compared to predicted stress-life curve from ultimate tensile strength of the weld metal.
Figure 5.11: Experimental axial strain-life curve compared to strain-life curves predicted from monotonic axial properties by using Modified Universal Slopes [18] and Roessle and Fatemi methods [19].

\[ \varepsilon_a = 0.0043 (2N_f)^{-0.09} + 0.574 (2N_f)^{-0.56} \]

\[ \varepsilon_a = 0.0045 (2N_f)^{-0.09} + 0.468 (2N_f)^{-0.56} \]

\[ \varepsilon_a = 0.0037 (2N_f)^{-0.080} + 0.782 (2N_f)^{-0.644} \]
6. Torsion Fatigue Behavior and Predictions

This chapter covers the fatigue behavior of the weld metal when subjected to cyclic torsion loading. The experimental procedures are presented and shear fatigue life properties of the weld metal are determined. Additionally, predictions of shear fatigue properties are made based on axial fatigue properties by using Tresca and von-Mises criteria.

6.1 Torsion Fatigue Experimental Methods

Fully-reversed \( R_\theta = -1 \) torsion fatigue tests were conducted for seven polished specimens where failure was defined as 50% torque drop to determine shear strain-life curve of the weld metal under rotation angle amplitude control. Total shear strain amplitude is composed of elastic shear strain amplitude and plastic shear strain amplitude as given in the following equation:

\[
\gamma_a = \frac{\Delta \gamma_e}{2} + \frac{\Delta \gamma_p}{2} = \frac{\tau'_{f}}{G}(2N_f)^{b_o} + \gamma'_{f}(2N_f)^{c_o}
\]  

(6.1)

According to stress-life approach, shear stress-life curve is generated by substituting \( \sigma_a \) and \( N_f \) by \( \tau_a \) and \( 2N_f \) respectively, in Equation (5.2), represented by:

\[
\tau_a = A(2N_f)^{B}
\]

(6.2)

where \( A \) is the Intercept of the best fit line to the shear stress amplitude \( (\tau_a) \) versus reversals to failure \( (2N_f) \) data and \( B \) is the slope of the best fit line.

6.2 Experimental Results and Shear Fatigue Properties

Torsion fatigue test data are summarized in Table 6.1 which were determined based on the midlife \( T - \theta \) hysteresis loops for each specimen, as shown in Figure 6.1. Shear stress amplitude was calculated according to Chandler and Miller approach [14], as shown in Figure 4.11. Shear strain amplitude was calculated based on the relationship
between rotation angle amplitude and shear strain amplitude, as shown in Figure 4.9, where:

\[ \gamma_a = 0.0032(\theta_a), \text{for } 0 \leq \theta_a \leq 0.5^\circ \]  

(6.3) \[ \gamma_a = 0.0066(\theta_a) - 0.0029, \text{for } 1^\circ \leq \theta_a \leq 3.75^\circ \]  

(6.4)

The weld metal experienced a significant softening behavior under cyclic shear load, as shown in Figure 6.2.

Shear strain-life properties are determined by linear fitting shear stress amplitude and plastic strain amplitude versus reversals to failure in log-log plots. Shear strain amplitude and shear stress amplitude are the independent variables and fatigue life is the dependent variable in these fits. The fits to generate the shear fatigue properties of the weld metal are shown in Figures 6.3 and 6.4. Shear strain-life curve of the weld metal is shown in Figure 6.5 and shear fatigue properties are determined and reported in Table 6.2.

Failure surfaces of specimens under cyclic torsion loading are shown in Figure 6.6. It is characterized by a star shaped pattern failure. Fatigue cracks nucleated and propagated at a 45° angle from the surface where higher shear stress exist due to the stress gradient effect of the solid specimens, where the center of the solid specimen behaves elastically and the outer surface behaves inelastically [15].

6.3 Prediction of Shear Strain-Life and Shear Stress-Life Curves

Shear fatigue properties were predicted based on the axial fatigue life properties of the weld metal by using Tresca and von-Mises failure criteria [15], where:

According to Tresca:
\[ \tau'_{f} = \frac{\sigma'_{f}}{2}, \quad \gamma'_{f} = 1.5\varepsilon'_{f}, \quad b_{o} = b, \quad \text{and} \quad c_{o} = c \]  \hspace{1cm} (6.5) \\

And, based on von-Mises:

\[ \tau'_{f} = \frac{\sigma'_{f}}{\sqrt{3}}, \quad \gamma'_{f} = \sqrt{3}\varepsilon'_{f}, \quad b_{o} = b, \quad \text{and} \quad c_{o} = c \]  \hspace{1cm} (6.6)

The experimental shear strain-life curve is compared to the shear strain-life curves predicted from axial fatigue properties of the weld metal based on Tresca and von-Mises criteria. Results of the predictions are shown in Figure 6.7 and summarized in Table 6.3.

As shown, predicted shear strain-life curves did not produce satisfactory fits compared to the experimental fatigue torsional behavior. However, predicted shear strain-life curve by von-Mises criterion was close to the experimental shear strain-life curve. Shear stress-life curve is compared to the predicted shear stress-life curves in Figure 6.8, where it is shown that the predicted shear-stress life curve based on von-Mises criterion was closer to the experimental shear stress-life curve, as compared to Tresca criterion.
Table 6.1: Summary of torsion fatigue test data under fully-reversed ($R_\theta = -1$) rotation angle amplitude control.

| Spec. ID | $\theta_a$ $D_{min}$ $|$ Frequency $|$ $T_a$ $|$ $\tau_a$ $|$ $Y_a$ $|$ $\Delta Y_e/2$ $|$ $\Delta Y_p/2$ $|$ $N_{\tau a}$ $|$ $N_f$ $|$ $2N_f$ |
|----------|-----------------|-------------|----------------|--------------|--------------|--------------|--------------|--------------|--------------|
|          | $[°]$ $[mm]$ $|$ $[Hz]$ $|$ $[N.m]$ $|$ [MPa] $|$          |              |              |              |              |              |              |
| 18       | 3.75            | 5.88        | 1              | 12.40        | 239.18       | 0.0219       | 0.0029       | 0.0189       | 1,000        | 1,912        | 3,824        |
| 22       | 2               | 5.94        | 2              | 11.26        | 225.51       | 0.0103       | 0.0028       | 0.0075       | 6,000        | 11,567       | 23,134       |
| 17       | 2               | 5.88        | 2              | 10.98        | 227.22       | 0.0103       | 0.0028       | 0.0075       | 4,000        | 7,783        | 15,566       |
| 21       | 1.5             | 5.87        | 3              | 9.99         | 213.87       | 0.0070       | 0.0026       | 0.0044       | 10,000       | 21,263       | 42,526       |
| 19       | 1               | 5.88        | 4-6            | 8.8          | 200.85       | 0.0037       | 0.0025       | 0.0012       | 100,000      | 216,867      | 433,734      |
| 20       | 1               | 5.90        | 6              | 8.69         | 196.77       | 0.0037       | 0.0024       | 0.0013       | 64,000       | 128,303      | 256,606      |
| 27       | 0.675           | 5.86        | 8              | 6.8          | 166.92       | 0.0024       | 0.0020       | 0.00034      | 950,000      | >1,890,000   | >3,780,000   |

Table 6.2: Summary of shear fatigue properties of the weld metal.

<table>
<thead>
<tr>
<th>Fatigue shear property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau'_f$</td>
<td>342.7 MPa</td>
</tr>
<tr>
<td>$b_o$</td>
<td>-0.044</td>
</tr>
<tr>
<td>$\gamma'_f$</td>
<td>3.003</td>
</tr>
<tr>
<td>$c_o$</td>
<td>-0.611</td>
</tr>
</tbody>
</table>
Table 6.3: Summary of predicted shear fatigue properties estimated from axial fatigue properties based on Tresca and von-Mises criteria.

<table>
<thead>
<tr>
<th>Fatigue shear property</th>
<th>Experimental</th>
<th>Tresca</th>
<th>von-Mises</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau'_f$</td>
<td>342.7 MPa</td>
<td>385.4 MPa</td>
<td>445 MPa</td>
</tr>
<tr>
<td>$b_o$</td>
<td>-0.044</td>
<td>-0.080</td>
<td>-0.080</td>
</tr>
<tr>
<td>$\gamma'_f$</td>
<td>3.003</td>
<td>1.173</td>
<td>1.355</td>
</tr>
<tr>
<td>$c_o$</td>
<td>-0.611</td>
<td>-0.644</td>
<td>-0.644</td>
</tr>
</tbody>
</table>
Figure 6.1: Hysteresis loops at midlife cycle \((T - \theta)\) under fully-reversed \((R_\theta = -1)\) rotation angle amplitude control.

Figure 6.2: Torque amplitude versus cycles presented on log-log plot under fully-reversed \((R_\theta = -1)\) rotation angle amplitude control.
Figure 6.3: Shear stress amplitude versus reversals to failure under fully-reversed ($R_\theta = -1$) rotation angle amplitude control to determine shear fatigue strength coefficient and shear fatigue strength exponent.

Figure 6.4: Plastic shear strain amplitude versus reversals to failure under fully-reversed ($R_\theta = -1$) rotation angle amplitude control to determine shear fatigue ductility coefficient and shear fatigue ductility exponent.
Figure 6.5: Experimental shear strain-life curve of the weld metal under fully-reversed ($R_\theta = -1$) rotation angle amplitude control.

The equation for the experimental data is:

$$\gamma_a = 0.0042(2N_f)^{-0.044} + 3.003(2N_f)^{-0.611}$$
Specimen 18

\[ N_f = 1,912 \text{ cycles} \]

Specimen 22

\[ N_f = 11,567 \text{ cycles} \]

Specimen 17

\[ N_f = 7,783 \text{ cycles} \]

Specimen 21

\[ N_f = 21,263 \text{ cycles} \]

Specimen 19

\[ N_f = 216,867 \text{ cycles} \]

Specimen 20

\[ N_f = 128,303 \text{ cycles} \]

RUNOUT

Specimen 27

\[ N_f = 1,890,000 \text{ cycles} \]

Figure 6.6: Specimen fracture surfaces under fully-reversed (\( R_\theta = -1 \)) torsion fatigue tests.
Figure 6.7: Experimental shear strain-life curve compared to predicted shear strain-life curves from axial fatigue properties by using Tresca and von-Mises criteria.

Figure 6.8: Comparison between experimental shear stress-life curves and predicted shear stress-life curves based on Tresca and von-Mises criteria.
7. Summary and Conclusions

The purpose of this study was to evaluate monotonic and fatigue deformation behaviors under axial and shear loads for ER70S-3 steel weld metal. Tension test was done for one specimen under displacement control to determine the axial mechanical properties of the weld metal, while torsion test was conducted on one specimen under rotation angle control to obtain the shear deformation properties of the weld metal. Axial fatigue tests were performed on thirteen specimens under fully-reversed \((R_\delta = -1)\) displacement amplitude control to determine the axial fatigue properties and strain-life curve of the weld metal. Similarly, torsion fatigue tests were conducted for seven specimens under fully-reversed \((R_\theta = -1)\) rotation angle amplitude control to determine shear fatigue properties and shear strain-life curve of the weld metal.

Prediction of axial cyclic curve was obtained from the tensile strength of the weld metal by using Lopez and Fatemi prediction method. Also, estimations were made to predict monotonic shear behavior from the monotonic axial properties by using Tresca and von-Mises criteria. Again, Tresca and von-Mises criteria were used to estimate cyclic shear deformation properties from the cyclic axial properties of the weld metal. In addition, stress-life curve was predicted from the ultimate tensile strength of the weld metal and it was compared to the experimental axial stress-life curve. Moreover, estimations were made to predict axial strain-life curve from the tension properties of the weld metal by using Modified Universal Slopes and Roessle and Fatemi prediction methods. Lastly, shear strain-life curve was predicted based on axial fatigue properties by using Tresca and von-Mises criteria. Based on the collected data and investigations from earlier chapters, the following can be concluded:
1) Predictions of the axial cyclic stress-strain curve from ultimate tensile strength of the weld metal by using Lopez and Fatemi method fits the experimental cyclic axial curve well.

2) When estimating the monotonic shear behavior from the monotonic axial properties of the weld metal by using Tresca and von-Mises criteria, von-Mises criterion was observed to be closer to the experimental shear deformation curve.

3) When predicting the cyclic shear properties from the axial cyclic properties of the weld metal, von-Mises criterion was found to fit the experimental cyclic shear stress-strain curve. Tresca criterion became closer to the experimental cyclic shear stress-strain curve as the cyclic plasticity increased.

4) Predicted stress-life curve estimated from the ultimate tensile strength of the weld metal was close to the experimental stress-life curve.

5) Under fully-reversed ($R_\delta = -1$) displacement amplitude control axial fatigue tests fatigue failure was at the middle of specimen’s gage section. Cracks initiated from the surface because of slip bands dislocation motion. On the other hand, Fatigue damage nucleated from defects in some specimens, characterized by fish-eye defects.

6) Predicting axial fatigue behavior from the monotonic axial properties of the weld metal by using Modified Universal Slopes and Roessle and Fatemi methods produced satisfactory predictions.

7) Under fully-reversed ($R_\theta = -1$) rotation angle amplitude control torsion fatigue tests, fatigue failure initiated from the surface of the specimens because of higher
shear stresses due to the stress gradient effect of solid specimens and the failure was characterized by a star shaped pattern.

8) When predicting the torsional fatigue behavior of the weld metal from the axial fatigue properties by Tresca and von-Mises criteria, predicted shear-strain life curves did not produce satisfactory predictions, but von-Mises criterion was closer to the experimental shear strain-life and shear stress-life curves compared to Tresca criterion. However, predictions by von-Mises criterion were still about an order of magnitude in terms of fatigue life shorter than the experimental curves (i.e. conservative predictions).
References


[9] KEYENCE, VHX-7000 Series Digital Microscope. USA.


