Ultrasonic Attenuation of Bridge Steels and Narrow-gap Improved Electroslag Welds

Bridget M. Crowley

Purdue University

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ULTRASONIC ATTENUATION OF BRIDGE STEELS AND NARROW-GAP IMPROVED ELECTROSLAG WELDS

by

Bridget M. Crowley

A Thesis

Submitted to the Faculty of Purdue University

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# TABLE OF CONTENTS

LIST OF TABLES .................................................................................................................. viii
LIST OF FIGURES ................................................................................................................ ix
ABSTRACT .............................................................................................................................. xii

1. INTRODUCTION .............................................................................................................. 1
   1.1 Background .................................................................................................................. 1
   1.2 Research Objectives ................................................................................................... 2
   1.3 Organization ............................................................................................................... 2

2. CRITICAL REVIEW OF LITERATURE ........................................................................... 3
   2.1 Introduction into Ultrasonic Inspection Techniques ................................................... 3
   2.2 Effects of Paints on Ultrasonic Inspection .................................................................. 4
   2.3 Ultrasonic Attenuation in Common Bridge Steels ......................................................... 4
       2.3.1 Introduction .......................................................................................................... 4
       2.3.2 E. Papadakis ......................................................................................................... 4
       2.3.3 C. Gür and Y. Keleş ............................................................................................ 5
       2.3.4 P. Prasad and S. Kumar ....................................................................................... 5
       2.3.5 K. Iba ................................................................................................................... 6
       2.3.6 N. Rattanasuwannachart, C. Miki, S. Hirose, and H. Shirahata ......................... 7
       2.3.7 Current Reference Standards ................................................................................ 8
   2.4 Ultrasonic Inspection of Narrow-Gap Improved Electroslag Welds ............................. 10
       2.4.1 Introduction .......................................................................................................... 10
       2.4.2 J. Chambers and R. Medlock .............................................................................. 11
       2.4.3 M. Gray ............................................................................................................... 12
       2.4.4 A. Prchlik, R. Mertz, J. Gramlick, K. Hoffman, N. Choy ................................. 12
   2.5 Summary ..................................................................................................................... 13

3. SPECIMEN CONFIGURATIONS AND MATERIALS ....................................................... 14
   3.1 Introduction ................................................................................................................. 14
   3.2 Effects of Paint Systems on Phased Array Ultrasonic Testing .................................. 14
       3.2.1 Specimen Properties .......................................................................................... 14
       3.2.2 Specimen Fabrication and Configuration .......................................................... 16
<table>
<thead>
<tr>
<th>Section</th>
<th>Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>Ultrasonic Attenuation of Common Bridge Base Metals</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Specimen Properties</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Specimen Fabrication and Configuration</td>
</tr>
<tr>
<td>3.4</td>
<td>Ultrasonic Inspection of Narrow-Gap Improved Electroslag Welds</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Specimen Properties</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Specimen Fabrication and Configuration</td>
</tr>
<tr>
<td>4.</td>
<td>EXPERIMENTAL PROCEDURES</td>
</tr>
<tr>
<td>4.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>4.2</td>
<td>Equipment</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Ultrasonic Equipment</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Calibration and Reference Blocks</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Probe Apparatus</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Couplant</td>
</tr>
<tr>
<td>4.3</td>
<td>Equipment and Material Calibration</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Shear Wave Calibration</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Compression Wave Calibration</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Material Reference Calibration</td>
</tr>
<tr>
<td>4.4</td>
<td>Ultrasonic Evaluation</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Paint Systems</td>
</tr>
<tr>
<td>4.4.2.1</td>
<td>Experimental Design</td>
</tr>
<tr>
<td>4.4.2.2</td>
<td>Evaluation Procedures</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Bridge Base Metals</td>
</tr>
<tr>
<td>4.4.3.1</td>
<td>Experimental Design</td>
</tr>
<tr>
<td>4.4.3.2</td>
<td>Evaluation Procedures</td>
</tr>
<tr>
<td>4.4.4</td>
<td>Narrow-Gap Improved Electroslag Welds</td>
</tr>
<tr>
<td>4.4.4.1</td>
<td>Experimental Design</td>
</tr>
<tr>
<td>4.4.4.2</td>
<td>Evaluation Procedure</td>
</tr>
<tr>
<td>5.</td>
<td>EXPERIMENTAL RESULTS</td>
</tr>
<tr>
<td>5.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>5.2</td>
<td>Paint Systems</td>
</tr>
</tbody>
</table>
5.3 Base Metals............................................................................................................................................. 42
  5.3.1 Test Sequence 1 – Probe Frequencies with Shear Wave ................................................................. 43
  5.3.2 Test Sequence 2 – Probe Frequencies with Compression Wave ....................................................... 46
  5.3.3 Test Sequence 3 – Difference in Reference Blocks ........................................................................... 47
  5.3.4 Test Sequence 4 – Thermo-mechanical Control Processed Plates ..................................................... 54
5.4 Narrow-Gap Improved Electroslag Welds ................................................................................................. 62
  5.4.1 Specimen P1 ....................................................................................................................................... 63
  5.4.2 Specimen P2 ....................................................................................................................................... 67
  5.4.3 Specimen P3 ....................................................................................................................................... 69
  5.4.4 Specimen P4 ....................................................................................................................................... 72
  5.4.5 Summary ........................................................................................................................................... 77
6. CONCLUSIONS AND FUTURE RESEARCH ........................................................................................... 78
  6.1 Conclusions ........................................................................................................................................... 78
    6.1.1 Paint Systems ................................................................................................................................... 78
    6.1.2 Base Metals .................................................................................................................................... 79
    6.1.3 Narrow-Gap Improved Electroslag Welds ....................................................................................... 81
  6.2 Future Research ..................................................................................................................................... 82
REFERENCES ................................................................................................................................................. 84
APPENDIX A. DRAWINGS ........................................................................................................................... 86
LIST OF TABLES

Table 2.1: Attenuation due to Thermal Treatment ................................................................. 6
Table 2.2: Material Attenuation Summary Table ................................................................. 8
Table 2.3: Probe Frequency Summary Table ........................................................................ 9
Table 3.1: Bridge Component Specimens ............................................................................ 14
Table 3.2: Steel Specimens ................................................................................................. 19
Table 3.3: Shear Wave Acoustic Velocities of Steel Specimens ........................................ 20
Table 3.4: ASTM Grain Size Classifications ...................................................................... 21
Table 3.5: NGI-ESW Specimen ......................................................................................... 25
Table 4.1: Equipment Specifications ................................................................................... 27
Table 4.2: Base Metal Tests ................................................................................................. 35
Table 4.3: NGI-ESW Tests ................................................................................................. 36
Table 5.1: Paint System Statistics ....................................................................................... 40
LIST OF FIGURES

Figure 2.1: NGI-ESW Grain Structure (Chambers & Medlock, 2015) .......................................................... 11
Figure 3.1: Bridge Component Specimens ........................................................................................................ 15
Figure 3.2: Typical Specimen Configuration ....................................................................................................... 17
Figure 3.3: Poorly Adhered Paint Systems ......................................................................................................... 17
Figure 3.4: Drill Setup .......................................................................................................................................... 18
Figure 3.5: Microstructure for Specimens at 100X (perpendicular to rolling direction) ...................................... 22
Figure 3.6: Typical Fabrication Details for Steel Plate Specimens ...................................................................... 23
Figure 3.7: Steel Plate Specimens ..................................................................................................................... 24
Figure 3.8: Specimen P1 Weld and HAZ Boundaries ........................................................................................ 25
Figure 3.9: Typical Fabrication Details for NGI-ESW Specimens .................................................................... 26
Figure 3.10: NGI-ESW Specimens .................................................................................................................... 26
Figure 4.1: Scanning Equipment ......................................................................................................................... 28
Figure 4.2: Probe Apparatus and Weight ........................................................................................................... 30
Figure 4.3: Scanning Process ............................................................................................................................... 33
Figure 4.4: Typical NGI-ESW Sound Path Schematic ....................................................................................... 37
Figure 5.1: Change in Indication Signal - Compression Wave without Wedge .................................................. 39
Figure 5.2: Change in Indication Signal - Compression Wave with Wedge ....................................................... 39
Figure 5.3: Change in Indication Signal - Shear Wave ....................................................................................... 40
Figure 5.4: Bridge Component Surface Roughness .......................................................................................... 41
Figure 5.5: Change in Attenuation Per Inch of Sound Path – 2.25 MHz Conventional UT ......................... 44
Figure 5.6: Change in Attenuation Per Inch of Sound Path– 2.25 MHz PAUT ............................................. 45
Figure 5.7: Change in Attenuation Per Inch of Sound Path – 5 MHz PAUT ................................................... 45
Figure 5.8: Change in Attenuation Per Inch of Sound Path– 2.25 MHz PAUT Compression .......................... 46
Figure 5.9: Change in Attenuation per Inch of Sound Path– 5 MHz PAUT Compression ............................ 47
Figure 5.10: Change in Attenuation per Inch – A36 IIW-type Reference Block 5 MHz PAUT ................. 48
Figure 5.11: Change in Attenuation per Inch – 1018 IIW-type Reference 5 MHz PAUT ....................... 48
Figure 5.12: AWS D1.5 Acceptance Criteria and Reference Blocks A36 Steel 5 MHz PAUT .................. 50
Figure 5.13: AWS D1.5 Acceptance Criteria and Reference Blocks HPS A709 Gr. 100W Steel with 5 MHz PAUT ......................................................................................................................... 51
Figure 5.14: AWS D1.5 Acceptance Criteria and Reference Blocks A36 Steel with 2.25 MHz PAUT.................................................................52
Figure 5.15: AWS D1.5 Acceptance Criteria and Reference Blocks HPS A709 Gr. 100W Steel with 2.25 MHz PAUT.................................................................53
Figure 5.16: Recorded Flaw Depth at 70° Incidence Angle .................................................................54
Figure 5.17: A-Scan & S-Scan at an Equivalent Gain with 70° Incidence Angle............................55
Figure 5.18: Change in Signal Intensity Per Inch of Sound Path between Incidence Angles – 2.25 MHz Conventional UT .................................................................59
Figure 5.19: Change in Signal Intensity Per Inch of Sound Path between Incidence Angles – 5 MHz PAUT.................................................................59
Figure 5.20: Change in Signal Intensity between Incidence Angles – 1.0” deep hole, 2.25 MHz Conventional UT.................................................................60
Figure 5.21: Change in Signal Intensity between Incidence Angles – 1.0” deep hole, 5 MHz PAUT.................................................................60
Figure 5.22: Specimen TMCP 2 Change in Signal Intensity Per Inch of Sound Path – 2.25 MHz Conventional UT.................................................................61
Figure 5.23: Specimen TMCP 2 Change in Signal Intensity Per Inch of Sound Path – 5 MHz PAUT.................................................................61
Figure 5.24: Specimen P1 Sound Path Schematic – 0.6” deep SDHs ......................................................64
Figure 5.25: Specimen P1 Attenuation per inch – 0.6 deep hole 2.25 MHz ........................................65
Figure 5.26: Specimen P1 Attenuation per inch – 0.6 deep hole 5 MHz ..............................................65
Figure 5.27: Specimen P1 Attenuation per Inch Overall Scatter – 2.25 MHz.................................66
Figure 5.28: Specimen P1 Attenuation per Inch Overall Scatter – 5 MHz..........................................66
Figure 5.29: Specimen P2 Sound Path Schematic – 0.6” deep SDHs ......................................................67
Figure 5.30: Specimen P2 Attenuation per inch – 0.6 deep hole 2.25 MHz ........................................68
Figure 5.31: Specimen P2 Attenuation per inch – 0.6 deep hole 5 MHz ..............................................68
Figure 5.32: Specimen P2 Attenuation per Inch Overall Scatter – 2.25 MHz.................................69
Figure 5.33: Specimen P2 Attenuation per Inch Overall Scatter – 5 MHz..........................................69
Figure 5.34: Specimen P3 Sound Path Schematic – 0.6” deep SDHs ......................................................70
Figure 5.35: Specimen P3 Attenuation per inch – 0.6 deep hole 2.25 MHz ........................................71
Figure 5.36: Specimen P3 Attenuation per inch – 0.6 deep hole 5 MHz ..............................................71
Figure 5.37: Specimen P3 Attenuation per Inch Overall Scatter –2.25 MHz ........................................... 72
Figure 5.38: Specimen P3 Attenuation per Inch Overall Scatter –5 MHz ............................................... 72
Figure 5.39: Specimen P4 versus Specimen TMCP 1 Indication Signal of 0.6” deep hole – 2.25 MHz .................. 73
Figure 5.40: Specimen P4 Attenuation Per Inch of Sound Path – 0.6 deep hole 2.25 MHz ............ 75
Figure 5.41: Specimen P4 Attenuation Per Inch of Sound Path – 0.6 deep hole 5 MHz ............... 75
Figure 5.42: Specimen P4 Attenuation per Inch Overall Scatter –2.25 MHz ................................. 76
Figure 5.43: Specimen P4 Attenuation per Inch Overall Scatter –5 MHz .............................. 76
ABSTRACT

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Degree Received: May 2018
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Major Professor: Robert J. Connor

Ultrasonic testing is a nondestructive inspection technique currently required during the inspection of complete joint penetration bridge welds. Ultrasonic testing utilizes sound wave reflections to find and characterize internal features and defects. Inspection with ultrasound is readily used in both fabrication shops and in the field to detect and locate critical defects detrimental to the safety and performance of bridges. Current inspection guidelines and acceptance criteria for bridge welds are found in the 2015 American Welding Society (AWS) D1.5 Bridge Welding Code.

Variables such as frequency, modes of wave propagation, velocity, grain structure, and equipment calibration all separately impact ultrasonic inspection. When ignored or improperly accounted for, these variables lead to inconsistent detection and classification of defects. Experimental data collected on six bridge components revealed an unanticipated difference in material attenuation between various grades of steel. As a result, the objective of the study was to characterize the difference in ultrasonic attenuation in a variety of hot-rolled steels, including heat-treated and controlled-rolled plates. The impacts of frequency, modes of wave propagation, and equipment calibration on the magnitude of ultrasonic attenuation were all evaluated. Additionally, the difference in attenuation between base metal, the heat-affected zone, and weld metal of narrow-gap improved electroslag welds was examined.

The experimental data collected confirmed a difference in ultrasonic attenuation between different grades of steel and throughout electroslag welds. The variation in attenuation was sometimes very significant. The frequency of the probe used during inspection had a direct impact on the magnitude of the attenuation found. The findings were used to evaluate possible implications of the current AWS D1.5 guidelines and acceptance criteria for both conventional and phased array ultrasonic testing.
1. INTRODUCTION

1.1 Background

Ultrasonic inspection is a nondestructive testing method that utilizes sound wave reflections to find and characterize internal features or defects. Two types of ultrasonic evaluation are currently used within the bridge industry, conventional ultrasonic testing (UT) and phased array ultrasonic testing (PAUT). Along with radiography, UT is a required nondestructive inspection technique for complete joint penetration (CJP) bridge welds. Inspection with UT is readily used in both fabrication shops and the field to detect and locate critical defects detrimental to the safety and performance of bridges. Inspection guidelines and acceptance criteria for bridge welds are found in the 2015 American Welding Society (AWS) D1.5 Bridge Welding Code.

The findings from ultrasonic inspection can be significantly influenced by differences in ultrasonic behavior, inspection material, and calibration. The behavior of ultrasound alone is heavily dependent upon frequency, modes of wave propagation, and velocity. Additionally, a specimen’s material properties such as grain structure, ultrasonic velocity, and material attenuation are crucial for proper inspection. In addition to the influence from ultrasonic characteristics and material properties, equipment setup and calibration also greatly impacts the findings from ultrasonic inspection. When ignored or improperly accounted for, these variables lead to inconsistent detection and classification of defects. To assure adequate inspection and detection, AWS D1.5 sets parameters and/or procedures to control most, but not all, of these variables.

Experimental data collected during an investigation of different paint systems on six bridge components revealed an unanticipated and at times significant difference in material attenuation between grades of steel. During an initial literature review, the difference in ultrasonic attenuation of hot-rolled and heat-treated steels became apparent as other researchers have also made the same observations. If neglected, a difference in attenuation between grades of steel could adversely affect ultrasonic inspection with the current AWS D1.5 guidelines. As a result, laboratory testing investigating the ultrasonic behavior of a variety of hot-rolled steels, including heat-treated and controlled-rolled plates, was conducted. Additionally, the performance of ultrasonic inspection of narrow-gap improved electroslag welds was assessed.
1.2 Research Objectives

The research objectives for this project are as follows:

- Evaluate the effects of different bridge paint systems on PAUT and compare the behavior of ultrasound through the painted and unpainted surfaces.
- Compare the material attenuation of different common bridge base metals.
- Investigate the effect of different variables, such as ultrasonic frequency, modes of wave propagation, velocity, and microstructure, on the magnitude of material attenuation.
- Determine the limitations of ultrasonic inspection on acoustically anisotropic steel plates.
- Examine the abilities of ultrasonic inspection on narrow-gap improved electroslag welds by comparing the attenuation of sound through base metal, the heat affected zone, and weld metal.

1.3 Organization

This document is organized into six chapters plus appendices. All subsequent chapters will have information and data split into three phases of experimental testing. The three phases of experimental testing required to accomplish the outlined research objectives were, (1) effects of paint systems on PAUT, (2) ultrasonic attenuation of common bridge steels, and (3) ultrasonic inspection of narrow-gap improved electroslag welds.

Chapter 2 presents a summary of current reference standards and previous research relevant to ultrasonic inspection and the influence of different variables on the behavior of ultrasonic testing. The configurations and materials of all specimens used during each phase of experimental testing is provided Chapter 3. Chapter 4 outlines the experimental equipment, setup, and procedures. Experimental results are presented in Chapter 5 for all three phases of testing. Chapter 6 summarizes and draws final conclusions from the experimental results, as well as providing recommendations for future research.
2. CRITICAL REVIEW OF LITERATURE

A literature review related to ultrasonic testing is presented in the following section. This review begins with a brief introduction of conventional ultrasonic testing and phased array ultrasonic testing. A summary of previous research relevant to the three phases of testing: effects of paint systems on PAUT, ultrasonic attenuation of common bridge steels, and ultrasonic inspection of NGI-ESW welds, follows.

2.1 Introduction into Ultrasonic Inspection Techniques

Current nondestructive inspection practices come from the 2015 American Welding Society (AWS) D1.5 Bridge Welding Code. Chapter 6 outlines the procedures and acceptance criteria for conventional ultrasonic testing and Annex K does the same for phased array ultrasonic testing.

Conventional UT transmits high frequency sound waves from a single element. Conventional UT can produce longitudinal waves or shear waves as part of an assembly with a wedge. Shear waves can only be produced at a single refracted angle determined by the selected wedge, the AWS standards are 45°, 60°, and 70°. Conventional UT can be conducted in either a pulse-echo method or pitch-catch method. An amplitude scan (A-Scan) is produced with conventional UT as a signal versus time plot; that is the time it takes for the sound to initiate and travel back to the probe.

PAUT transmits high frequency sound waves using multi-element transducers composed of anywhere from 16 to 256 individual elements. These elements can be pulsed individually, in groups, or all at once. PAUT transducers are designed for direct contact use, as an assembly with a wedge, or water immersion. Due to delays in pulse timing, PAUT has the unique ability to sweep a sound beam through different refracted angles, anywhere from 30° to 70°, or along a linear path and the ability to focus at a desired depth within a test specimen. PAUT can be conducted in either a pulse-echo method or pitch-catch method. Similar to conventional UT, PAUT will produce an A-Scan, but in addition due to its ability to sweep a sound beam through different refracted angles, PAUT can produce a sectorial scan (S-Scan). S-Scans are two-dimensional, cross-sectional views resulting from the A-Scans produced at different refracted angles with respect to time. (Nelligan & Kass, 2018)
2.2 Effects of Paints on Ultrasonic Inspection

Currently, there is no previous research specifically studying the ultrasonic properties of different paint systems currently being used on bridges or the effect of these paints on the propagation of sound. The reason is rather simple, since AWS D1.5 currently requires paint systems to be removed and the inspection surface carefully prepared. Paint removal and surface preparation before ultrasonic inspection is a standard procedure across many inspection communities. However, removal of coating systems in existing structures can be costly and time-consuming. Hence, it was desired to investigate some of the possible effects typical coating systems have on defect detection and signal amplitude.

2.3 Ultrasonic Attenuation in Common Bridge Steels

2.3.1 Introduction

A review of literature related to the ultrasonic attenuation of common bridge steels has been conducted within the following section. The main topics discussed below include the influence of microstructure, grain size, and heat-treatment on the behavior or ultrasound in steel plates. A summary of relevant national and international code previsions associated with ultrasonic inspection are presented at the end.

2.3.2 E. Papadakis

Predominant factors known to influence ultrasonic attenuation in steel plates are grain scattering and the austenitic grain size before cooling. Grain scattering is dependent upon the size and elastic moduli of a grain’s substructure and carbon content. Prior to this study, grain scattering had been observed to be the greatest in lamellar pearlite and the least in tempered martensite.

This research study set to investigate the influence of these two factors on ultrasonic attenuation. Experimental data were collected on the ultrasonic attenuation of steel plates at different austenitization temperatures. Five specimens of SAE 52100 steel were evaluated, all austenitized at five different temperatures from 1454 °F to 1850 °F, before all were quenched and tempered. Data for both compression and shear wave ultrasonic testing were gathered.

The major conclusion was that an increase in austenitizing temperature led to an increase in attenuation. At greater austenitizing temperatures, a larger, coarser martensite grain structure...
formed which increased the attenuation. The one exception was the specimen austenitized at 1454 °F. This specimen was austenitized at what was thought be at the austenite – austenite + eutectic boundary line on the phase diagram but as a result did not fully harden. The incomplete austenitization of this specimen resulted in a large-grain body centered cubic iron which caused an increase in attenuation to occur at higher frequencies. All other specimens austenitized at temperatures greater than 1454 °F formed tetragonal martensite grain structure. Two trends always remained the same between all specimens: shear wave always attenuated more than compression wave and higher frequencies had greater attenuation. (Papadakis, 1970)

2.3.3 C. Gür and Y. Keleş

Hot-rolled steel specimens of SAE 1020 and SAE 1050 were inspected using 10 MHz compression waves. The specimens underwent different heat treatment procedures such as furnace cooling, air cooling, and oil quenching after austenitization at two different temperatures. Similar attenuation between grades of steel, regardless of the difference in carbon content, were found between the two furnace cooled specimens, the two air cooled specimens, and the two quenched specimens. Results did show the attenuation varied significantly whether the specimens were austenitized at 1580 °F or 1940 °F. The austenitization temperature directly determined the grain size. The larger prior austenite grains found at the higher austenitization temperature had higher ultrasonic attenuation. The orientation and shape of the grains also impacted the degree of attenuation to some extent. However, effect from cooling rate impacts attenuation very little in comparison to the prior austenite grain size. (Gür & Keleş, 2003)

2.3.4 P. Prasad and S. Kumar

Experimental data on the ultrasonic attenuation of heat treated steel plate specimens was collected during this research study. As-forged steel specimens with a thickness of 2” were subject to annealing, normalizing, quenching alone, and quenching and tempering. Specimens were tested with 2.5 MHz compression wave. Hot forging of the material developed internal stresses due to the rolling and cooling. Annealing the as-forged specimens reduced the internal stresses. Normalizing the as-forged specimens also removed these internal stresses, but additionally produced a finer grain distribution. Quenching the as-forged specimens introduced internal stresses from lattice deformation as the microstructure transformed into martensite. The addition
of tempering after hardening reduced internal stresses but also decreased the hardness resulting in increased ductility. The least attenuating specimen was subject to normalizing, followed by hardening, hardening and tempering (392 °F), annealing, and as-forged. Hardening was consistently done at 1508 °F, but three different tempering temperatures of 392 °F, 752 °F, and 1112 °F were evaluated. An increase in tempering temperatures led to an increase in attenuation.

Using the attenuation data presented by Prasad and Kumar, Table 2.1 lists differences in attenuation given as the change in decibels (dB) between a particular specimen and the as-forged specimen. Less attenuation is indicated by a negative change in dB as gain was removed to achieve identical amplitude signals. (Prasad & Kumar, 1994)

<table>
<thead>
<tr>
<th>Thermal Treatment</th>
<th>ΔdB from As-forged</th>
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<tbody>
<tr>
<td>As-forged</td>
<td>0.0</td>
</tr>
<tr>
<td>Annealed</td>
<td>-1.7</td>
</tr>
<tr>
<td>Normalized</td>
<td>-2.6</td>
</tr>
<tr>
<td>Hardened</td>
<td>-2.4</td>
</tr>
<tr>
<td>Hardened/Tempered (392°F)</td>
<td>-2.2</td>
</tr>
<tr>
<td>Hardened/Tempered (752°F)</td>
<td>-1.4</td>
</tr>
<tr>
<td>Hardened/Tempered (1112°F)</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

2.3.5 K. Iba

Elastic anisotropy has been observed in thermo-mechanical controlled process (TMCP) steel plates. Ultrasonic evaluation on these plates using shear wave resulted in a reduction of signal sensitivity in certain directions causing the inability to detect flaws. Numerous TMCP steel plates have been investigated in the rolled and cross-rolled direction for the influence of ultrasonic anisotropy on flaw detection.

The direction of ultrasonic wave propagation in anisotropic steel has a profound effect on the amplitude and angle of refraction. The specimens were tested with nominal 45°, 60°, 65°, and 70° probes in three propagation directions: the rolled direction, 45° to the rolled direction, and the cross-rolled direction. The actual angle of refraction was found to have a higher incidence angle in the rolled direction and lower incidence angle in the cross-rolled direction for all nominal angles
of refraction larger than 60°. At nominal angles of 45° and 60°, the transmitted pulse amplitude is nearly the same in all propagation directions. However, at 70° the transmitted pulse amplitude is greatest in the cross-rolled direction and gradually decreases as the probe is turned 90° to the rolled direction. Currently, ultrasonic testing of welds occurs perpendicular to the weld or along the rolled direction. Therefore, the decrease in signal along the rolled direction is a serious concern in the detection and sizing of flaws.

Scanning specimens with side-drilled holes, Iba found anisotropic steel plates have a substantial effect on the accuracy of locating flaws. In the rolled direction a flaw on average was reported to be 0.25 inches deeper than its actual location, whereas in the cross-rolled direction the average flaw depth was reported to be exactly where the known flaw was located.

Ultimately, it was suggested during the ultrasonic evaluation of anisotropic steel plates the nominal refracted angle be limited to 65° or less. It was recommended to also calculate the actual angle of refraction to correctly locate and size a flaw. (Iba, 1987)

2.3.6 N. Rattanasuwannachart, C. Miki, S. Hirose, and H. Shirahata

Acoustical anisotropy within steel plates has been found to profoundly affect the use of ultrasonic inspection. It was found when ultrasonic inspection is used on anisotropic steel plates, inaccuracies are produced in location, shape, and size of flaws detected. In a survey of 900 acoustically anisotropic steel plates, almost all had been fabricated with TMCP. Of these 900 plates, thinner plates, those less than 0.75”, have a higher anisotropic ratio than thicker ones. An anisotropic ratio is a measure of acoustic velocity in the rolled direction divided by the acoustic velocity in the cross-rolled direction minus a constant of one. The effects of acoustical anisotropy become weaker in plate thicknesses of 2.0” or greater.

It has been observed that TMCP plates have different cooling rates at the surface versus the center. Different size grains along the thickness of the steel plate are produced as a result, with fine grains along the surface and coarse grains in the central region. Due to rolling at lower temperatures, near surface grains elongate along the rolling direction in TMCP plates. The anisotropic ratio calculated at the surface was found to be different than that of the center. Shear wave velocities longitudinal to the rolling direction increased drastically in the surface layer of the steel plates. Shear wave velocities transverse to the rolling direction remained constant throughout. (Rattanasuwannachart, Miki, Hirose, & Shirahata, 2004)
2.3.7 Current Reference Standards

A collection of reference standard provisions, both national and international, related to ultrasonic testing have been summarized below. Specifically, a comparison of each standard’s policy on material attenuation and probe frequency have been presented, see Table 2.2 and Table 2.3.

Table 2.2: Material Attenuation Summary Table

<table>
<thead>
<tr>
<th>Specification</th>
<th>Accounts for the material attenuation due to varying grade or microstructure</th>
<th>If so, how?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Conventional UT</td>
</tr>
<tr>
<td>AWS D1.5</td>
<td>NO</td>
<td>n/a</td>
</tr>
<tr>
<td>CSA W59</td>
<td>NO (UT) / YES (PAUT)</td>
<td>n/a</td>
</tr>
<tr>
<td>EN ISO</td>
<td>YES</td>
<td>Requires a calibration block. If the calibration block and test object are not acoustically the same, a transfer correction is to be applied.</td>
</tr>
<tr>
<td>ASME BPVC</td>
<td>YES</td>
<td>Requires a calibration block of the same product form and material specification of the material being examined. If any acoustic differences remain between the calibration block and test object, a transfer correction is to be applied.</td>
</tr>
<tr>
<td>JIS Z 3060</td>
<td>YES</td>
<td>Requires all calibration blocks to be of a steel material with equivalent acoustic characteristics to the test object.</td>
</tr>
</tbody>
</table>

AWS D1.5:2015 Annex K is the only code which does not require PAUT technicians to account for differences in material attenuation between the calibration block and the test specimen. (AASHTO/AWS, 2015) For conventional UT, AWS D1.5 and CSA W59 account for attenuation in the test specimen by the application of an attenuation factor and use of an International Institute of Welding (IIW) "type” reference block to set reference amplitude. No background on the development of this attenuation factor could be found. However, CSA W59 requires PAUT technicians to develop a calibration procedure on a case-by-case basis as part of a written procedure. (CSA, 2013) The ISO and ASME Codes specifically state that modifications to calibration are required if the material attenuation differs between the calibration block and the test object, including both base metal and weld metal. This is typically in the form of a transfer correction. ISO requires a transfer correction be applied when a difference of 2 dB to 12 dB is
observed at the longest inspection sound path. Any difference less than 2 dB is negligible and any difference greater than 12 dB is a cause for reevaluation of the calibration procedures. (ISO, 2010) ASME states, if “the block material is not of the same product form or has not received the same heat treatment, it may be used provided it meets all other block requirements and a transfer correction for acoustical property differences is used”. (ASME, 2017) ASME does not provide limitations on the use of a transfer correction but leaves it up to an inspector’s discretion. JIS Z 3060 provides five different calibration blocks to be used in different circumstances. Each reference block is required to be of a steel material with equivalent acoustic characteristics to the test object. (Japanese Standards Association, 2015)

A single, unanimous definition of the phrases *acoustic characteristics* or *acoustic properties* does not exist. ISO defines acoustical properties as the characteristics of a material which control the propagation of sound in a material. (ISO, 2017) In ultrasonic testing these principal characteristics are ultrasonic velocity and attenuation. For example, ASTM E114 states “the reference standard material and production material must be acoustically similar (in velocity and attenuation)”. (ASTM, 2013b) ISO 2400, the standard for the IIW calibration block, imposes strict requirements on the material, heat treatment, and surface finish of the IIW reference block. Following fabrication with these guidelines, the acoustic velocity of the block must be checked and fall within ±0.2% of the prescribed wave velocities. Ultrasonic velocity and attenuation may be the two material characteristics to have the biggest impact on ultrasonic evaluation, but grain size, grain structure, material composition, and surface roughness are all factors determining the velocity and attenuation of a material.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Probe Shear Wave Frequency Range (MHz)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional UT</td>
<td>PAUT</td>
</tr>
<tr>
<td>AWS D1.5</td>
<td>2-2.25</td>
<td>1-6</td>
</tr>
<tr>
<td>CSA W59</td>
<td>2-2.25</td>
<td>No stipulation</td>
</tr>
<tr>
<td>EN ISO</td>
<td>2-5</td>
<td>No stipulation</td>
</tr>
<tr>
<td>ASME BPVC</td>
<td>1-5</td>
<td>1-5</td>
</tr>
<tr>
<td>JIS Z 3060</td>
<td>2-5</td>
<td>2-5</td>
</tr>
</tbody>
</table>
AWS D1.5 and CSA W59 are both restrictive for shear wave conventional UT probe frequency due to the previously mentioned attenuation factor which is only valid for a specific probe size, shape, and frequency. (Holloway, 2017) The other codes allow a wider range of probe frequencies but also require that a calibration be performed to take into account material attenuation. The ISO code states that lower frequencies are recommended for conventional UT where flaw characterization and sizing is not required and the evaluation is carried out according to acceptance levels based on length and amplitude. (ISO, 2010) JIS Z 3060 allows 3.5 to 5 MHz probes be used on sound paths that are 100 mm (3.9”) or less. At a 45° incidence angle this would be a thickness of 1.4” and at a 70° incidence angle this would be a thickness of 0.7”. The longer the sound path, the lower the allowed frequency. Anything over 250 mm (9.8”) is only allowed to be inspected using 2 MHz. (Japanese Standards Association, 2015)

2.4 Ultrasonic Inspection of Narrow-Gap Improved Electroslag Welds

2.4.1 Introduction

A review of relevant literature on the ultrasonic inspection of narrow-gap improved electroslag welds has found accounts of difficulty locating and sizing flaws. Narrow-gap improved electroslag welding (NGI-ESW) was developed to resolve the shortcomings of conventional electroslag welding. Researchers have cited the main source of these difficulties in conventional electroslag welds was large grain sizes found in the weld metal and heat affected zone (HAZ). (Gray, 1978; Mudge, 1982) The large grain sizes was a deficiency of conventional ESW which has been thought to have been resolved following the development of NGI-ESW. However, still many researchers cite the problems with flaw location and sizing in NGI-ESW welds is still caused by large grain sizes in the weld metal and HAZ. (Malin, 1996; Prchlik, Mertz, Gramlick, Hoffman, & Choy, 2015; Prine, Oleksy, & Malin, 1996) No previous research directly comparing the ultrasonic attenuation between base metal, the HAZ, and the weld metal of electroslag welds has been found. However, studies investigating the ultrasonic inspection of electroslag welds and different variables affecting it follows. First, an introduction to NGI-ESW and the properties of the weld’s microstructure is presented.
2.4.2 J. Chambers and R. Medlock

Narrow-gap improved electroslag welding (NGI-ESW) was developed to replace conventional electroslag welding and as a result enhanced manufacturing speed, weld toughness, and reliability in weld fabrication. NGI-ESW welds join plates 1” to 6” thick and are fabricated in a single pass. Two plates are positioned with a 3/4” gap and a sump is attached at the base where welding will begin. Flux is deposited within the sump, an electric arc ignites forming a pool of slag which then extinguishes the arc. An electrode is continuously fed into the slag pool generating an electric current which provides the thermal energy needed to melt the welding consumables and fuse the joint. Strict geometric and procedural requirements must be followed during the fabrication of NGI-ESW welds to prevent lack of fusion or inclusions along the weld.

Multiple zones of differing grain structures can be found in the HAZ and weld metal of NGI-ESW welds. Two different grain structures can be found within HAZ, fine grains alongside the base metal and coarse grains along the fusion line. Within the weld, coarse columnar grains form alongside the edges of the weld with equiaxed grains forming in the central region of the weld. The manufacturing speed at which NGI-ESW is performed has increased the coarse columnar grain structure within the weld when compared to conventional ESW. Also, the addition of nickel and molybdenum to the NGI-ESW electrodes has stimulated the growth of equiaxed grains within the central region of the weld. See Figure 2.1 for a visual representation of the different grain structure zones. (Chambers & Medlock, 2015)

![Figure 2.1: NGI-ESW Grain Structure](Chambers & Medlock, 2015)
2.4.3 M. Gray

This study illustrates the concerns with using ultrasonic evaluation of conventional electroslag welds prior to the development of NGI-ESW. An investigation examining the ultrasonic testing of conventional ESW welds was conducted using shear wave. Flat-bottom holes were placed at various depths throughout the thickness of the plate and perpendicular to the weld axis. Holes were drilled on one side of the weld and scanning occurred on the opposite side. 2 MHz and 4 MHz single shear wave probes were used to evaluate the flat-bottom holes. This evaluation required the sound beam to travel entirely through the HAZ and the weld metal to find the reflectors. Due to the attenuation in the weld metal and fusion zone, the flat bottom holes were unable to be found during inspection. In response, a new scanning procedure using lower frequency and a pitch-catch scanning technique was developed to adequately detect flaws within ESW welds. With the use of two 2 MHz shear wave probes, reflectors were able to be accurately located and sized. Using this procedure, in-service ESW welds were rescanned and new, never found centerline shrinkage cracks were discovered. Additionally, ESW weld specimens were tested with radiography and appeared clean, however they were re-tested with the new UT pitch-catch scanning procedure and similar shrinkage cracks were also found throughout these specimens. (Gray, 1978)

2.4.4 A. Prchlik, R. Mertz, J. Gramlick, K. Hoffman, N. Choy

This study illustrates the concerns with the ultrasonic evaluation of welds fabricated with the NGI-ESW procedures. Challenges associated with the ultrasonic inspection of NGI-ESW welds were found and assessed. NGI-ESW fabrication produces a large columnar grain structure within the weld. Subsequently, a higher probability of planar defects within the weld or along the fusion face is likely in these welds. The inspection of 20 field-welded NGI-ESW welds found that once thought to be acceptable indications per AWS D1.5 were in reality large, linear defects transverse along the weld. These planar defects were found in all 20 welds tested. Due to the planar characteristics and orientation of these defects, during investigation the sound beam was directed away from the pulse-echo probe. Since the reflected sound signal never made its way back to the probe, the indications were undetectable.

In response to these defect misclassifications, an assessment of the current AWS D1.5 prescribed pitch-catch scanning technique for planar type defects was conducted. Currently,
problems arise in AWS D1.5 due to geometric constraints and misinterpretations of attenuation factors. Therefore, a new combination of pulse-echo and pitch-catch scanning techniques were produced and shown to locate and classify defects in NGI-ESW welds. Ultimately, the current shortfalls of AWS D1.5 associated with ultrasonic inspection of NGI-ESW welds could unknowingly affect proper evaluation by ultrasonic inspectors. (Prchlik et al., 2015)

2.5 Summary

This brief literature review has provided a basic introduction to conventional UT and PAUT, an assessment of the effects of heat treatment and controlled-rolling on attenuation and flaw detection in steel plates, and outlined the complications encountered during the ultrasonic inspection of NGI-ESW welds.

From the literature review, the concerns regarding a difference in attenuation between steels and the large grain structures within NGI-ESW welds have been supported. However, no experimental data specific to “normal” and high-performance grade steel plates currently being used within the bridge industry is available. Likewise, no experimental data on the attenuation of sound between base metal, the HAZ, and weld metal of NGI-ESW welds is available. While observations and trends have been previously reported, additional data are needed to properly evaluate the magnitude of attenuation differences found in base metal and welds. Only then can the impact of these differences on the ultrasonic inspection of bridge components be assessed.
3. SPECIMEN CONFIGURATIONS AND MATERIALS

3.1 Introduction

To facilitate the three phases of testing, (1) effects of paint systems on PAUT, (2) ultrasonic attenuation of common bridge steels, and (3) ultrasonic inspection of NGI-ESW welds, three sets of specimens were fabricated. The following section will outline the selection, properties, and configurations of all specimens.

3.2 Effects of Paint Systems on Phased Array Ultrasonic Testing

3.2.1 Specimen Properties

Six specimens were selected based on their paint systems and the condition of their paint systems. Table 3.1 and Figure 3.1 illustrate the bridge components and their respective properties. The specimens tested were located at Purdue University’s Center for Aging Infrastructure (CAI) Steel Bridge Research, Inspection, Training, and Engineering (S-BRITE) Center. All specimens tested were either out-of-service bridge components or standard practice bridge fabrications.

<table>
<thead>
<tr>
<th>Bridge Name</th>
<th>Original Location</th>
<th>Year Built</th>
<th>Last Painted</th>
<th>Lead Test</th>
<th>Steel Specification(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lafayette Bridge</td>
<td>St. Paul, MN</td>
<td>1968</td>
<td>1986</td>
<td>Positive</td>
<td>A441</td>
</tr>
<tr>
<td>&quot;New&quot; Girder</td>
<td>S-BRITE Center</td>
<td>2009(1)</td>
<td>2009(1)</td>
<td>Negative</td>
<td>A709 Gr. 50</td>
</tr>
<tr>
<td>Virginia Avenue Bridge</td>
<td>Indianapolis, IN</td>
<td>1973</td>
<td>2003</td>
<td>Positive</td>
<td>A36</td>
</tr>
<tr>
<td>I-35W Bridge</td>
<td>Minneapolis, MN</td>
<td>1964</td>
<td>1999</td>
<td>Positive</td>
<td>A36</td>
</tr>
<tr>
<td>Pennsylvania Railroad</td>
<td>Jersey City, NJ</td>
<td>1956</td>
<td>Unknown</td>
<td>Positive</td>
<td>A373</td>
</tr>
<tr>
<td>Dresbach Bridge</td>
<td>Dresbach, MN</td>
<td>1967</td>
<td>1993</td>
<td>Positive</td>
<td>A441</td>
</tr>
</tbody>
</table>

(1) This is the fabrication date as the girder was never placed into service
(2) This is the steel specification corresponding to the specific member used in testing
The presence of lead was checked for in each paint system using 3M Lead Check swabs on both the paint and primer systems. The instructions per the 3M LeadCheck Instruction Manual were followed with each specimen. Disinfection of tools, preparation of surfaces, and storage of swabs were all carefully conducted in order to eliminate the possibility of cross contamination between bridge parts. The results of the lead tests can be found in Table 3.1. Many of the paint systems reacted differently to the 3M LeadCheck swabs. Within the user instruction 3M specifies, ‘Red Lead Primer applied to steel structures typically has a lead content greater than 50%. This instantly turns the 3M LeadCheck Swab tip a bright cherry red color.’ This effect was seen in 2 of the 6 bridges, I-35W and Pennsylvania Railroad. The instruction manual also states, ‘…industrial paints as well as other materials may contain lead chromate (CR +6). Lead chromate paints are typically red, yellow, green, or orange in color. 3M LeadCheck swabs will indicate the presence of lead in these paints. However, since lead chromate is virtually insoluble in water, it can take up to 18 hours for the pink color to appear on the swab tip and/or surface tested.’ This effect was seen in 2 of the 6 bridges, Virginia Avenue and Dresbach with each turning pale pink 3-5 hours after application. The surface of Lafayette Avenue turned red at application, but the
swab itself did not. This is still recognized by 3M as a positive indication. ‘New’ girder is the only bridge component that had no effect on the swabs.

The presence of lead may be surprising in some of the bridge components, especially given most have been repainted sometime during its in-service life. After speaking with a coating expert, it is normal to find lead within industrial paints up until the early 1990’s. Residential paints banned the use of lead in 1978, however the industrial paint industry took much longer to dissipate or ban the use of lead in their paints.

During removal of the paint systems, some key observations were made. First, I-35W was repainted green, but instead of removing the initial paint system, they decided to repaint directly on top of it. The initial paint system was a typical orange, high lead content paint. Second, Virginia Avenue was recently repainted in 2003, which caused questions to arise when it tested positive for some unknown amount of lead. However, while removing the new paint, red paint residuals were found sprinkled below the primer coat which could have caused the positive indication.

3.2.2 Specimen Fabrication and Configuration

Following the selection and characterization of the bridge components, reflectors were placed into all six specimens. The reflectors were 5/64” diameter side-drilled holes (SDH) and extended approximately 1.25” deep into the side of each specimen’s flange. All SDHs were placed at a depth of 0.5” below the scanning surface, see Figure 3.2 for the typical fabrication. Placing reflectors at the same depth within all members allowed for each paint system be assessed against each other. Six reflectors, one in each specimen, was placed at a location where the paint system was deemed “well adhered” based on visual inspection. An additional three reflectors were placed into Lafayette, Virginia Avenue, and Dresbach at locations where the paint systems were deemed “poorly adhered”, see Figure 3.3. The paint on Lafayette was very uneven with built-up corrosion below the section tested. Virginia Avenue had a bumpy surface which turned out to be remains of an older paint system that was not fully removed prior to repainting. Dresbach had areas of chipped topcoat exposing the primer coat, which appeared to be in good condition. Thus, all together nine reflectors were tested.
Figure 3.2: Typical Specimen Configuration

Figure 3.3: Poorly Adhered Paint Systems
(left to right) top row: Lafayette, Virginia Avenue
bottom row: Dresbach
All nine reflectors were fabricated through the side of the flange using a Hougen Magnetic Drill. To adequately secure the drill, a portable drill jig was developed using a steel plate, steel angle, and two large clamps. See Figure 3.4 for the drilling configuration.

Figure 3.4: Drill Setup

3.3 Ultrasonic Attenuation of Common Bridge Base Metals

3.3.1 Specimen Properties

In response to results found during the investigation of different paint systems, a controlled experimental setup was devised to study the ultrasonic attenuation in different base metals typically used in bridge construction. Nine steel specimens were fabricated and tested using conventional UT and PAUT. Table 3.2 outlines the samples tested and their properties. Two specimens, Virginia Avenue (ID 36) and “New” Girder (ID 50), from the initial testing looking at the effects of bridge paints on PAUT were reused during this portion of the study. These specimens represented the least and most attenuating specimens previously tested within the field. To fully evaluate these differences in a more controlled setting, samples were cut from the girders and brought into the laboratory. ID 36 was a “historical” A36 steel, ID 50 was a modern A709 Gr. 50 steel. Further, additional seven “modern” high performance steels (i.e., HPS) were added to further extend the evaluation. The addition of these new specimens set out to further evaluate if there were differences in the ultrasonic attenuation characteristics in difference plates. Three of the new specimens were of the quenched and tempered (QT) variety at the mill, while four of the new specimens were produced using the thermo-mechanical control process (TMCP).
Table 3.2: Steel Specimens

<table>
<thead>
<tr>
<th>ID</th>
<th>Steel Properties</th>
<th>Fabrication Year</th>
<th>Thickness (in)</th>
<th>Width (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>A36</td>
<td>1973(1)</td>
<td>1.25</td>
<td>1.87</td>
</tr>
<tr>
<td>50</td>
<td>A709 Gr50</td>
<td>2013</td>
<td>1.25</td>
<td>1.87</td>
</tr>
<tr>
<td>70</td>
<td>HPS 70W QT</td>
<td>2000</td>
<td>1.50</td>
<td>1.87</td>
</tr>
<tr>
<td>101</td>
<td>HPS 100W QT</td>
<td>circa 2000s</td>
<td>2.00</td>
<td>1.87</td>
</tr>
<tr>
<td>102</td>
<td>HPS 100W QT</td>
<td>circa 2000s</td>
<td>1.50</td>
<td>1.87</td>
</tr>
<tr>
<td>TMCP 1</td>
<td>HPS 70W TMCP</td>
<td>2009</td>
<td>1.57</td>
<td>1.87</td>
</tr>
<tr>
<td>TMCP 2(2)</td>
<td>HPS 70W TMCP</td>
<td>2014</td>
<td>1.25</td>
<td>1.87</td>
</tr>
<tr>
<td>TMCP 3</td>
<td>HPS 70W TMCP</td>
<td>2011</td>
<td>2.00</td>
<td>1.87</td>
</tr>
</tbody>
</table>

(1) Date the bridge was put into service
(2) Two specimens, one in the rolled direction and one in the cross rolled direction, were fabricated with this steel plate

The acoustic velocities of the high performance steel samples were measured using an Electro Magnetic Acoustic Transducer (EMAT). Using a shear wave, acoustic velocity was measured in the rolled and cross rolled direction. It is important to note these are average acoustic velocities over the thicknesses of the plates. Pervious research has reported the velocity of TMCP plates varies through the thickness of the plates, however the EMAT probes did not capture this variation, if there is any. (Rattanasuwannachart et al., 2004) The acoustic velocities and birefringence are listed below in Table 3.3. Acoustic birefringence is the measured difference between the acoustic velocities in the rolled and cross rolled directions, which is the same as the acoustic anisotropic ratio defined by JIS Z 3060. The quenched and tempered specimens, specimens 70, 102, and 101, have a very low birefringence. In comparison, the thermo-mechanical processed specimens have a high birefringence. The Japanese JIS Z 3060 UT code specifies when the birefringence ratio is greater than 2%, the test object is considered an anisotropic material. (Japanese Standards Association, 2015) All three TMCP specimens used during this study were classified as acoustically anisotropic in accordance with the Japanese code.
Table 3.3: Shear Wave Acoustic Velocities of Steel Specimens

<table>
<thead>
<tr>
<th>ID</th>
<th>Acoustic Velocity (in/µsec)</th>
<th>Birefringence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rolled Direction</td>
<td>Cross Rolled Direction</td>
</tr>
<tr>
<td>70 (QT)</td>
<td>0.1271</td>
<td>0.1272</td>
</tr>
<tr>
<td>101 (QT)</td>
<td>0.1272</td>
<td>0.1274</td>
</tr>
<tr>
<td>102* (QT)</td>
<td>0.1280</td>
<td>0.1280</td>
</tr>
<tr>
<td>TMCP 1</td>
<td>0.1338</td>
<td>0.1266</td>
</tr>
<tr>
<td>TMCP 2</td>
<td>0.1304</td>
<td>0.1241</td>
</tr>
<tr>
<td>TMCP 3</td>
<td>0.1293</td>
<td>0.1255</td>
</tr>
</tbody>
</table>

*Velocity was measured with a normal incidence shear wave probe instead of the EMAT

The literature review also revealed that as expected, chemical composition, grain size, and microstructure have all been found to affect the acoustic properties and propagation of sound through material. The chemical composition of each specimen was obtained and found to meet the requirements of its respective ASTM steel standard. For each specimen, a metallurgical analysis of the grain size and microstructure was also performed by an outside consultant (Chicago Spectro Service Laboratory). Figure 3.5 shows the grain structure perpendicular to rolling for each specimen magnified at 100X with Nital etchant.

Specimen 36 consisted of a Widmanstätten pattern of ferrite and pearlite. Specimen 50 consisted of ferrite and pearlite. Specimen 70 had a general structure of fine acicular ferrite with small spherical carbides, but also visible were bands of ferrite and low-carbon martensite and bainite. Specimen 101 and 102 consisted of quenched and tempered martensite. The TMCP specimens all had a variation in grain structure near the surface in comparison with the central regions. Specimen TMCP 1 had acicular ferrite with elongated pearlite and long bands of pearlite in the central region. On the near surface region, a fine acicular ferrite and short bands of pearlite were seen. Specimen TMCP 2 had elongated ferrite with bands of pearlite and bainite in the central region. On the near surface region, elongated ferrite and short bands of pearlite and bainite existed. Specimen TMCP 3 had a fine acicular ferrite with patches of pearlite in the central region. On the near surface region, a more refined structure of fine acicular ferrite and patches of pearlite were seen. Specimen TMCP 2 was further analyzed parallel to the rolling direction. Parallel to rolling, the central region and near surface regions both consisted of elongated ferrite with bands of pearlite and bainite.
Grain size measurements were made in accordance with ASTM E112-13 Standard Test Methods for Determining Average Grain Size. Per ASTM E112, grain size measurements can be conducted numerous ways, but all methods include counting the number of grains or number of grain boundaries along a specified line within a known area. A table is provided in ASTM E112 to rate the grain size from 00 up to 14.0, 00 having the largest average grain size and 14.0 having the smallest average grain size. (ASTM E112, 2013) Table 3.4 presents the grain sizes measured for the group of specimens. It should be noted, for Specimens 101 and 102, the prior austenite grain size is measured and presented in Table 3.4. In this case, the prior austenite grain size was that of the steel before quenching and tempering occurred.

Table 3.4: ASTM Grain Size Classifications
(perpendicular to rolling direction unless noted otherwise)

<table>
<thead>
<tr>
<th>ID</th>
<th>Grain Size</th>
<th>ASTM Grains per Unit Area (in²) at 100X&lt;sup&gt;(1)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>ASTM 2-1/2</td>
<td>2.83</td>
</tr>
<tr>
<td>50</td>
<td>ASTM 7</td>
<td>64.0</td>
</tr>
<tr>
<td>70</td>
<td>ASTM 10</td>
<td>512.0</td>
</tr>
<tr>
<td>101</td>
<td>ASTM 8</td>
<td>128.0</td>
</tr>
<tr>
<td>102</td>
<td>ASTM 8</td>
<td>128.0</td>
</tr>
<tr>
<td>TMCP 1</td>
<td>ASTM 11 (central)/ ASTM 11 (surface)</td>
<td>1024.0</td>
</tr>
<tr>
<td>TMCP 2</td>
<td>ASTM 11 (central)/ ASTM 11 (surface)</td>
<td>1024.0</td>
</tr>
<tr>
<td>TMCP 2 (parallel to roll)</td>
<td>ASTM 10 (central)/ ASTM 10 (surface)</td>
<td>512.0</td>
</tr>
<tr>
<td>TMCP 3</td>
<td>ASTM 8 (central)/ ASTM 12 (surface)</td>
<td>128.0/2896.3</td>
</tr>
</tbody>
</table>

<sup>(1)</sup>ASTM E112, 2013
Figure 3.5: Microstructure for Specimens at 100X (perpendicular to rolling direction)
3.3.2 Specimen Fabrication and Configuration

The samples were machined into uniform steel blocks. The thickness of the part varied between 1.25” to 2.00” with a consistent width of 1.87” to ensure beam spread did not skew results. The length of the specimen varied based on the available size of steel samples. All specimens were fabricated along the rolling direction with one exception. For TMCP 2, two specimens were fabricated. One specimen in the rolled direction and one in the cross rolled direction. A CNC machine was used to place four 1/16” diameter SDHs through the full width of each specimen. Two sets of holes, one at 0.6” and one at 1.0” from the top surface to the center of the hole, were centered in each block at 4” apart. See Figure 3.6 for typical fabrication details and Figure 3.7 for the final specimens.

![Figure 3.6: Typical Fabrication Details for Steel Plate Specimens](image-url)
3.4 Ultrasonic Inspection of Narrow-Gap Improved Electroslag Welds

3.4.1 Specimen Properties

The variability in ultrasonic inspection of NGI-ESW welds was then assessed following the evaluation of base metal. Unlike the consistent microstructure of base metal, welding produces different zones of varying grain structures. From the electroslag welding process, the HAZ consists of two grain structure zones. The portion of the HAZ bordering the base metal is comprised of fine grains and the inner portion is comprised of coarse grains. The weld may have an additional two or three zones itself of coarse columnar and/or equiaxed grains. Specimens were fabricated to facilitate the comparison of attenuation between base metal, HAZs, and weld metal. The electroslag weld samples were donated by the Federal Highway Administration (FHWA) and supplied by two different fabricators. Table 3.5 outlines the sample information and their material properties.
Table 3.5: NGI-ESW Specimen

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Fabricator</th>
<th>Base Metal</th>
<th>Fabrication Year</th>
<th>Thickness (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Fabricator A</td>
<td>HPS 70W (QT)</td>
<td>HPS 70W (QT)</td>
<td>2015</td>
</tr>
<tr>
<td>P2</td>
<td>Fabricator A</td>
<td>50W</td>
<td>50W</td>
<td>2015</td>
</tr>
<tr>
<td>P3</td>
<td>Fabricator A</td>
<td>50W</td>
<td>HPS 70W (QT)</td>
<td>2015</td>
</tr>
<tr>
<td>P4</td>
<td>Fabricator B</td>
<td>HPS 70W (TMCP)</td>
<td>HPS 70W (TMCP)</td>
<td>2013</td>
</tr>
</tbody>
</table>

3.4.2 Specimen Fabrication and Configuration

Upon receiving the samples, all four were cleaned, polished, and etched to expose the welds and HAZs. The specimens were sanded starting with 40 grit sand paper and worked up to 600 grit. 5% Nital was then used to etch the weld. Cross-sections of the weld and HAZs were exposed on both side faces (side 1 and side 2) of the sample as well as the top surface to document how the weld width and shape varies between the two side faces. After exposing the boundaries of the welds and HAZs, proper placement of the reflectors could be determined to achieve the desired sound paths. Figure 3.8 shows this process for one sample.

Figure 3.8: Specimen P1 Weld and HAZ Boundaries
The four specimens were then individually fabricated using a CNC machine. Eight 1/16” diameter SDHs were placed through the width of the specimen, two in the base metal, two in each HAZ, and two in the weld metal. Holes were placed at 0.6” and 1.0” from the top scanning surface to the center of hole. See Figure 3.9 for typical fabrication details and Figure 3.10 for the final specimens.

Figure 3.9: Typical Fabrication Details for NGI-ESW Specimens

Figure 3.10: NGI-ESW Specimens
(top to bottom) P1, P2, P3, P4
4. EXPERIMENTAL PROCEDURES

4.1 Introduction

The following section will outline the details of all experimental procedures carried out for each of the three phases. First, an overview of the equipment used to facilitate the material testing will be presented followed by the equipment and material calibrations utilized. To finish, the ultrasonic evaluation for each of the individual three phases will be presented.

4.2 Equipment

4.2.1 Ultrasonic Equipment

Specimens were tested using conventional UT and PAUT. A number of probe and wedge combinations were used to facilitate the testing. Table 4.1 and Figure 4.1 show the equipment and specifications. The probes used for testing were 2.25 MHz and 5 MHz and ranged in size. All PAUT testing was performed firing 16 elements unless otherwise specified. The conventional UT wedges were formed of plexiglass while the PAUT wedges were formed of Rexolite. These materials are very similar but do have a small difference in acoustic velocity.

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Phased Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flaw Detector</td>
<td>Olympus OmniScan MX2</td>
<td>Olympus OmniScan MX2</td>
</tr>
<tr>
<td>Probe + Wedge</td>
<td>GE AWS 2.25MHz 0.63” x 0.63” +</td>
<td>Olympus 5MHz 5L64-A12 +</td>
</tr>
<tr>
<td>Combination 1</td>
<td>45° SF-AWS, 60° SF-AWS, 70° SF-AWS</td>
<td>SA12-N55S</td>
</tr>
<tr>
<td>Probe + Wedge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probe + Wedge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combination 3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.1: Scanning Equipment
4.2.2 Calibration and Reference Blocks

AWS D1.5 Bridge Welding Code requires the use of a reference standard for calibration of all ultrasonic testing. An International Institute Welding (IIW) type reference block was used to facilitate calibration and selected testing. Per AWS D1.5, an IIW-type reference block should conform to the material specifications of ASTM A709 Gr. 36 or acoustically equivalent. (AASHTO/AWS, 2015) It is important to note that AWS currently refers to this reference block as an ‘IIW block’ but it is truly an ‘IIW-“Type”’ block. IIW-“Type” reference blocks are formed similar to a “True” IIW block but do not conform to the material requirements of the International Organization for Standardization (ISO) 2400 specification. A true IIW reference block in accordance with ISO 2400 is of steel grade S355J0 and is subject to a very strict heat treatment process. The steel is to be austenitized at 1688 °F for 30 minutes, rapidly quenched in water, tempered at 1184 °F for 3 hours, and air cooled. The measured acoustic velocity of these blocks is required to be 0.233 in/µs ± 0.0012 in/µs for compression wave and 0.128 in/µs ± 0.0006 in/µs for shear wave. An additional margin of error of ±0.2% is allowed for both the compression and shear wave acoustic velocities. (ISO, 2012) Therefore, throughout this study and as required per AWS D1.5 an IIW-type reference block has been used. Two different IIW-type 1 reference blocks were used and had material specifications of ASTM A36 and AISI 1018.

4.2.3 Probe Apparatus

Preliminary testing was conducted manually, and the effect of inconsistent and uneven pressure was observed. As a result, consistent and constant pressure was obtained by the construction and use of a 10-pound steel weight and support jig, see Figure 4.2. The support jig was constructed using two pieces of plexiglass and four 3/8” diameter threaded rods. The threaded rods were placed and cut such that multiple probe and wedge combinations would fit within the apparatus. The 10-pound weight was secured to the top of the jig using Scotch Rubber Mastic tape. The Mastic tape secured the weight throughout testing for any given configuration, but as configurations changed the Mastic tape allowed the weight to be readjusted. The weight was always readjusted for a given configuration in order to ensure that the weight was distributed evenly along the length of the probe. To do this, the probe was centered between two scales, the scales were zeroed, and the weight was placed upon the jig. The steel block was adjusted above the probe until both scales read the same value within ±0.1-pound.
4.2.4 Couplant

As required, the roughness of the scanning surface was prepared during the specimen fabrication such that couplant would adequately transmit sound across the probe-steel interface. Gel and motor oil couplants were both used during testing in a series of measurements to compare any differences. It was found that each yielded very similar results. Therefore, a gel couplant was used during the evaluation of different paint systems in the field, and a medium weight Castrol GTX SAW 10W-40 motor oil was used for all remaining testing that took place in the laboratory. During the laboratory testing, motor oil produced a consistent layer of coupling below the wedge and the scanning surface. Gel couplant tended to disperse and thin between the wedge and steel block under the weight of the probe which led to increased variability in amplitude.

4.3 Equipment and Material Calibration

4.3.1 Shear Wave Calibration

Shear wave calibrations for conventional UT and PAUT are performed differently. For conventional UT shear wave, the flaw detector, probe, and wedge combination were calibrated by performing a velocity/zero calibration and verifying the refracted angle. Velocity/Zero calibration was performed using the A36 IIW-type reference block to compensate for the portion of sound that forms and travels through the wedge. Velocity/Zero calibration also adjusted for small differences between the calibration block’s acoustic properties and the standard setup of the machine and probe being used. Using the 4” radius on the IIW-type reference block, the wedge exit point was placed on the zero mark and the peak signal off of the radius was calibrated such
that the machine interpreted it as a 4” sound path. The 9” sound path was then checked for accuracy. This process was repeated until the 4” and 9” sound paths were satisfactory.

For PAUT, sensitivity and wedge delay calibrations were performed. Time corrected gain (TCG) was not used during testing. Sensitivity and wedge delay were both standard calibrations facilitated by the Olympus OmniScan equipment. Sensitivity was calibrated off of the 1/16” diameter SDH in the A36 IIW-type reference block for 0.6” depth SDHs and a chosen test specimen for the 1.0” depth SDHs. Sensitivity was always calibrated off a SDH at the same depth of the data being collected, hence the reason TCG was ignored and not required. The probe was swept through all angles along the scanning surface. This was repeated until the results were ±1 dB of each other. Wedge delay was calibrated also using the 4” radius. Wedge delay was checked by verifying the 4” sound path at all angles. After calibrations were performed, prior to each test sequence, and at the beginning of each day, the setups were verified.

4.3.2 Compression Wave Calibration

Compression wave required little calibration. When a 0° wedge was used during testing, verification of the wedge delay was required. Beyond this calibration, appropriate setup of the equipment was sufficient.

4.3.3 Material Reference Calibration

The material reference calibration was set prior to the beginning of every ultrasonic evaluation by setting a standard sensitivity level. Similar to the scanning instructions found in ASTM D1.5 Annex K ‘Advanced Ultrasonic Examination’, the standard sensitivity level was set off of a 1/16” diameter SDH. (AASHTO/AWS, 2015) The standard sensitivity level used for this testing was 80% full-screen height (FSH) and the respective gain was set as the primary reference level. The primary reference level was then used as the baseline for all subsequent evaluations with a given setup.

4.4 Ultrasonic Evaluation

4.4.1 Introduction

Three phases of testing took place investigating three significant variables effecting ultrasonic evaluation. Experimental testing began investigating the effects of paint systems on
ultrasonic evaluation. Following observations from these tests, a more in-depth look at the attenuation between common bridge steels was investigated. Lastly, the ultrasonic evaluation and attenuation of narrow-gap improved electroslag welds were inspected.

4.4.2 Paint Systems

4.4.2.1 Experimental Design

To investigate the effects of paint systems on ultrasound, six existing bridge components were tested. All testing occurred in the field at Purdue University’s CAI S-BRITE Center. Tests were conducted using PAUT with compression and shear wave. A typical scanning procedure and plan was used throughout the entirety of this evaluation.

4.4.2.2 Evaluation Procedures

Each of the 9 reflectors placed within the 6 specimens were scanned with PAUT using three different setups. The Olympus OmniScan along with a 5 MHz 5L64-A12 probe was used for scanning. Measurements were taken using compression wave with a SA12-0L wedge, compression wave without a wedge, and shear wave with a SA12-N55S wedge. Shear wave was only evaluated at a 55° incidence angle. Each method was conducted three times on each specimen: (1) through the paint system, (2) with the paint removed, and (3) with paint removed and a ground smooth surface. Paint systems were removed using an aerosol aircraft paint remover. The surfaces were ground smooth using a Dremel rotary tool with a stone and sanding bit.

The scanning procedures for all three methods were similar. As mentioned above, SDHs were placed at the same distance below the scanning surface. Therefore, in order to directly compare indication signals between all 9 SDHs, a reference hole was chosen to set the primary reference level. The primary reference level was set off the unpainted, smooth indication reading from the “New” Girder SDH. The SDHs located in all specimens and for all trials were evaluated against this baseline.

Scanning procedures first took place on the painted surface of each specimen. Two compression wave readings, one with and one without the wedge, and two shear wave readings, one from the right side and one from the left side of the SDH, were taken. Data was collected at least twice to ensure results were repeatable. The specimens were first scrubbed to peak the amplitude signal and the position of the probe was then marked. The bounds of the marked
position were extended and the paint around the bounds of the probe was removed. The initial steel roughness was kept once the paint was removed and scanning occurred once more. As expected, variation in surface roughness was found between the different steel bridges. Again, scanning occurred and the indication signal was peaked. Although the ultrasonic technician did not limit the scrubbing to the confines of the marked boundary, in most cases the probe remained within or nearby the confines. The probe was never expected to match the original position from the first trial due to change in thickness after removal of paint. The surface was then ground smooth and special attention was given to attaining consistency between all specimens. Once more, the amplitude signal was peaked. Figure 4.3 shows a typical scanning sequence from the painted, to the unainted, and to the unainted with a ground smooth surface.
4.4.3 Bridge Base Metals

4.4.3.1 Experimental Design

To investigate the ultrasonic properties of different bridge steels, an experimental study was setup with several steel samples within a controlled laboratory setting. The purpose of this study was to reveal whether when evaluated against some universal acceptance criteria a given indication located within two different grades of steel would produce different results. That is, would the same indication in one grade of steel be classified as acceptable but rejectable for a different grade of steel.

4.4.3.2 Evaluation Procedures

It is common practice in the inspection of butt welds to use a shear wave to fully capture the extents of the weld. Therefore, minimal testing was conducted using compression wave and the ultrasonic inspection primarily focused on using shear waves.

The specimens listed above in Table 3.2 were evaluated in a number of different sequences using a combination of different flaw detectors, probes, and wedges. Table 4.2 outlines four test sequences, the number of tests performed within each sequence, the specimens evaluated, the calibration reference, and the equipment used. Sequence 1 evaluated the attenuation of common bridge steels, grades ranging from 36 ksi to 100 ksi, using a 5 MHz PAUT probe, a 2.25 MHz PAUT probe, and a 2.25 conventional UT probe. Sequence 2 evaluated these same specimens using a 5 MHz and 2.25 MHz PAUT probe with compression wave. Due to the observed results in sequence 1, sequence 3 was carried out to assess the difference in the A36 and 1018 IIW-type reference blocks using the same probes. The evaluation of ultrasonic attenuation of base metal concluded with sequence 4 inspecting thermo-mechanical processed (TMCP) steels using a 5 MHz PAUT probe and a 2.25 MHz conventional UT probe.

The primary reference level was first set from the reference listed in Table 4.2. Evaluation then took place for each specimen by peaking the indication signal to 80% FSH. This was done by increasing or decreasing the gain from primary reference level. The increase or decrease in gain revealed whether a specimen was attenuating more or less, respectively. This evaluation occurred for each hole, in every specimen, and with the probe/wedge combinations outlined below. Shear wave was investigated at 45°, 60°, and 70° incidence angles when using PAUT and
conventional UT. Each scan of a given SDH was performed a minimum of two times before moving on to ensure the data were repeatable.

Table 4.2: Base Metal Tests

<table>
<thead>
<tr>
<th>Test Sequence-Number</th>
<th>Evaluated Specimens</th>
<th>Reference</th>
<th>Flaw Detector and Probe+Wedge Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>0.6” + 1.0” deep holes of Block 36, 50, 70, 101, 102</td>
<td>Block 50 (Side A)</td>
<td>OmniScan MX2 with 5MHz 5L64-A12 + SA12-N55S</td>
</tr>
<tr>
<td>1-2</td>
<td>0.6” deep holes of Block 36, 50, 70, 101, 102</td>
<td>Block 50 (Side A)</td>
<td>OmniScan MX2 with 2.25MHz 2.25L64-A2 + SA2-N55S</td>
</tr>
<tr>
<td>1-3</td>
<td>0.6” + 1.0” deep holes of Block 36, 50, 70, 101, 102</td>
<td>Block 50 (Side A)</td>
<td>OmniScan MX2 with AWS 2.25MHz 0.63” x 0.63” + 45°, 60°, and 70° SF-AWS</td>
</tr>
<tr>
<td>2-1</td>
<td>1.0” deep holes of Block 36, 50, 70, 101, 102</td>
<td>Block 50 (Side A)</td>
<td>OmniScan MX2 with 5MHz 5L64-A12</td>
</tr>
<tr>
<td>2-2</td>
<td>1.0” deep holes of Block 36, 50, 70, 101, 102</td>
<td>Block 50 (Side A)</td>
<td>OmniScan MX2 with 2.25MHz 2.25L64-A2</td>
</tr>
<tr>
<td>3-1</td>
<td>0.6” deep holes of Block 36, 50, 70, 101, 102</td>
<td>IIW A36</td>
<td>OmniScan MX2 with 5MHz 5L64-A12 + SA12-N55S</td>
</tr>
<tr>
<td>3-2</td>
<td>0.6” deep holes of Block 36, 50, 70, 101, 102</td>
<td>IIW 1018</td>
<td>OmniScan MX2 with 5MHz 5L64-A12 + SA12-N55S</td>
</tr>
<tr>
<td>4-1</td>
<td>0.6” + 1.0” deep holes of Block TMCP 1, TMCP 2, TMCP 3</td>
<td>Block 50 (Side A)</td>
<td>OmniScan MX2 with 5MHz 5L64-A12 + SA12-N55S</td>
</tr>
<tr>
<td>4-2</td>
<td>0.6” + 1.0” deep holes of Block TMCP 1, TMCP 2, TMCP 3</td>
<td>Block 50 (Side A)</td>
<td>OmniScan MX2 with AWS 2.25MHz 0.63” x 0.63” + 45°, 60°, and 70° SF-AWS</td>
</tr>
</tbody>
</table>
4.4.4 Narrow-Gap Improved Electroslag Welds

4.4.4.1 Experimental Design

To investigate the NGI-ESW process and the variation in microstructure throughout a welded specimen, a similar experimental setup to the base metal evaluation was used. Concerns about grain size have long been reported with conventional electroslag welding, thus NGI-ESW was evaluated to validate or refute these concerns.

4.4.4.2 Evaluation Procedure

The specimens listed in Table 3.5 were assessed with two tests, one evaluating the welds using a 5 MHz PAUT probe and one evaluating the welds using a 2.25 MHz conventional UT probe. Table 4.3 outlines the two tests, the specimens evaluated, the calibration reference, and the equipment used. All tests were conducted using shear wave at 45°, 60°, and 70° incidence angles.

The primary reference level was first set from the reference listed in Table 4.3. Similar to the base metal procedure above, evaluation took place by peaking the indication signal to 80% FSH. A scan plan was created to ensure the specimens were tested at all incidence angles with sound passing through the base metal, HAZs, and weld metal. A total of 14 data points was collected from the 8 SDHs located within each specimen. Evaluation first began by scanning the two SDHs located in the base metal from one side. The SDHs located within the HAZs were then scanned from either side. By scanning the SDHs from either side, sound initiated in base metal from one side and either in weld metal or the HAZ on the other side depending on the incidence angle. The last holes to be scanned are those located within the weld metal. Again, these holes were scanned from both sides. Due to geometric limitations, scanning took place on the top and bottom surface of the specimens to ensure each SDH was scanned with all incidence angles. Table 4.3 provides a typical schematic of the different sound paths of interest.

<table>
<thead>
<tr>
<th>Test Sequence-Number</th>
<th>Evaluated Specimens</th>
<th>Reference</th>
<th>Flaw Detector and Probe+Wedge Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>0.6” + 1.0” deep holes of P1, P2, P3, P4</td>
<td>Block 50 (Side A)</td>
<td>OmniScan MX2 with 5MHz 5L64-A12 + SA12-N55S</td>
</tr>
<tr>
<td>1-2</td>
<td>0.6” + 1.0” deep holes of P1, P2, P3, P4</td>
<td>Block 50 (Side A)</td>
<td>OmniScan MX2 with AWS 2.25MHz 0.63” x 0.63” + 45°, 60°, and 70° SF-AWS</td>
</tr>
</tbody>
</table>
Figure 4.4: Typical NGI-ESW Sound Path Schematic

Note: 45° and 60° sound paths from bottom scanning surface not shown for the 1.0” deep SDHs for clarity.
5. EXPERIMENTAL RESULTS

5.1 Introduction

The following section will present the results and the corresponding analysis of the three phases of experimental testing: (1) effects of paint systems on PAUT, (2) ultrasonic attenuation of common bridge steels, and (3) ultrasonic inspection of NGI-ESW welds.

5.2 Paint Systems

The ultrasonic evaluation conducted during this phase compared the ultrasonic behavior of: (1) painted, (2) unpainted, and (3) unpainted and ground smooth bridge components. Section 4.4.2 fully details the experimental testing information. The objective of these tests was to assess the performance of PAUT through bridge paints to determine if the time and costs of paint removal were essential.

Results using a 5 MHz frequency PAUT probe have been presented below as change in indication signal, that is the difference in decibels (dB) between the peak signal amplitude of a SDH and the primary reference level. Again, the primary reference level was set off the ground smooth SDH indication located in “New” Girder. Each of the three plots below, Figure 5.1, Figure 5.2, and Figure 5.3, present the change in dB along the y-axis and the sequential three phases of testing along the x-axis. Figure 5.1 and Figure 5.2 show the results using a 5 MHz compression wave, one without a wedge and one with a wedge, respectively. Figure 5.3 shows the results using a 5 MHz shear wave. In all figures, positive values indicate an increase in signal loss compared to reference and negative values indicate a decrease in signal loss compared to reference. Finally, Table 5.1 summarizes the mean change in indication signal, the standard deviation, and statistical range of all SDHs for both compression and shear waves during all three phases.
◆ in painted data indicates “poor adhesion” of the paint coating

Figure 5.1: Change in Indication Signal - Compression Wave without Wedge

Figure 5.2: Change in Indication Signal - Compression Wave with Wedge
in painted data indicates “poor adhesion” of the paint coating.

* Data for one hole was unable to be collected due to a complete loss of signal at the surface.

Figure 5.3: Change in Indication Signal - Shear Wave

Table 5.1: Paint System Statistics

<table>
<thead>
<tr>
<th>Change in Indication Signal</th>
<th>Painted</th>
<th>Unpainted</th>
<th>Unpainted, Smooth</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compression Wave</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>without Wedge (ΔdB)</td>
<td>Mean</td>
<td>-2.8</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>4.0</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>Statistical Range</td>
<td>11.6</td>
<td>3.4</td>
</tr>
<tr>
<td><strong>Compression Wave</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with Wedge (ΔdB)</td>
<td>Mean</td>
<td>-4.1</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>3.9</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Statistical Range</td>
<td>11.4</td>
<td>2.3</td>
</tr>
<tr>
<td><strong>Shear Wave (ΔdB)</strong></td>
<td>Mean</td>
<td>10.1</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>3.9</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>Statistical Range</td>
<td>14.7</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Paint systems had a clear impact on the ultrasound. With compression wave, whether it be with or without a wedge, a significant amount of scatter was seen through a variety of paint systems. Overall, 11.4 to 11.6 dB was seen between the highest and lowest indication signals through the paint. Once the paint was removed, scatter was still present but at a smaller magnitude of 2.3 to 3.4 dB. This scatter was regarded as reasonable due to significant variation of the surface...
roughness found once the paint was removed, see Figure 5.4. However, whether a wedge was used or not used should not have impacted the scatter seen during a given phase of testing, thus the difference of 0.9 ΔdB between the use of a bare probe or a wedge was likely induced by user error, calibration, or environmental changes. However, the reduction in scatter was still very apparent. After data was collected with the paint removed, the components’ surfaces had all been ground smooth. After removing key factors responsible for the scatter, paint coatings and surface roughness, the scatter was expected to diminish. However, Figure 5.1 and Figure 5.2 show a scatter of 3.2 and 2.8 ΔdB remained. An unexplainable trend with compression wave was also seen in Figure 5.1 and Figure 5.2. Seven of the nine SDHs were less attenuating when scanned through the painted surface than when scanned through the unpainted, ground smooth surface. The two SDHs that attenuated more were located at location where the paint was deemed ‘poorly adhered’. Thus, this would indicate paints and coatings amplified the transmission of compression waves. This amplification led to mean 5.6 dB decrease in indication signal when scanning through the paint system.

Figure 5.4: Bridge Component Surface Roughness
Similar trends in scatter between the three phases were seen with the use of shear wave. The reduction in scatter between the painted and the unpainted, smooth surfaces were just as apparent with a decrease from 14.3 $\Delta dB$ to 4.2 $\Delta dB$. Again, scatter of 4.2 $\Delta dB$ was unexpected once the paint and surface roughness were both removed. The overall scatter and magnitude of shear wave attenuation in the bare steel specimens is slightly larger than that with compression wave, corroborating observations made in previous research from Papadakis. (Papadakis, 1970) The amplification of sound transmission through the paint system was not observed when using shear wave.

The remaining scatter found during the last phase of testing with both compression and shear wave came as a surprise for two reasons. First, currently the bridge inspection community and specifications, namely AWS D1.5, do not explicitly take into account a difference in attenuation in common bridge steels. Second, existing research specifically looking at attenuation in various grades of C-Mn steel plates concluded that, ‘for [the] plate samples, attenuation did not appear to be a problem and only when large or grossly anisotropic grains are encountered, such as unnormalized electroslag welds, does attenuation become significant’. (Mudge, 1982) The remaining scatter found during this phase ultimately led to a more in-depth and controlled experimental evaluation of the attenuation in common bridge steels. These findings are presented in the next section.

The key takeaway from this evaluation is that various paint systems all behave differently under ultrasonic inspection. There is no way to account for this variability and therefore scanning should not occur through the painted surface. Although time consuming and costly, removing the paint and grounding the surface smooth is the best solution to adequately inspect and detect flaws consistently within bridge components and welds.

5.3 Base Metals

The ultrasonic evaluation conducted during this phase evaluated different variables including probe frequency, for both compression and shear wave, code approved reference standards, and grade of steel, including processing. Section 4.4.3 and Table 4.2 fully detail experimental testing information. The objective of these tests was to assess the attenuation found in various grades of steel and evaluate the impact it may have on the inspection and detection of flaws.
The results have been presented below as the change in attenuation per inch of sound path, that is the difference in decibels (dB) between the peak signal amplitude of a SDH and the primary reference level divided by the sound path of the compression or shear wave, see Equation 5-1. Three different incidence angles were used during evaluation, therefore dividing by the sound path allowed for a direct comparison of experimental results. The change in dB per inch thickness is shown along the y-axis and the base metal evaluated during a given test sequence is along the x-axis. Again, positive values indicate an increase in attenuation from reference and negative values indicate a decrease in attenuation from reference.

\[
\frac{\Delta dB}{in} = \frac{Indication\ Signal\ (dB) - Primary\ Reference\ Level\ (dB)}{Beam\ Sound\ Path\ (in)} \quad \text{Equation 5-1}
\]

### 5.3.1 Test Sequence 1 – Probe Frequencies with Shear Wave

During the first test sequence of this phase two probe frequencies were compared, 2.25 MHz and 5 MHz. Data collected with two separate 2.25 MHz probes, one conventional UT and one PAUT, and one 5 MHz PAUT probe are presented in Figure 5.5, Figure 5.6, and Figure 5.7, respectively. For all figures, a marker indicates the average change in dB per inch for each specimen. Error bars for each marker displays the variation of indication signals measured between the four holes in each block at the three different incidence angles.

Figure 5.5 and Figure 6.6 comparing a 2.25 MHz conventional UT probe with a 2.25 MHz PAUT probe yielded very similar results. Specimens 36, 70, 101, and 102 all attenuated 0.1 dB/in more with the 2.25 MHz conventional UT probe when compared to the 2.25 MHz PAUT probe. This was a negligible difference. The variation between the two probes was likely credited to the difference in probe aperture and size.

Further comparing Figure 5.5 and Figure 6.6 to Figure 5.7, a noticeable difference between the attenuation per inch with a 2.25 MHz and 5 MHz probe was observed. All five specimens only varied at most by an average of 0.3 dB/in with a probe frequency of 2.25 MHz, but with a 5 MHz this increased to 1.3 dB/in. This was a more than 300% increase in the average attenuation between all specimens in terms of dB/in. At 2.25 MHz specimens 36 and 50 behaved almost the same, but at 5 MHz they differ by an average of 0.7 dB/in. The QT (i.e., high performance steel) specimens
attenuated less compared to specimen 50 by 0.3 dB/in with a 2.25 MHz probe to 0.6 dB/in with a 5 MHz probe. Probe frequency played a critical role in attenuation with shear wave. Higher frequencies resulted in larger differences in attenuation between grades of steel.

While frequency amplified the differences observed between various grades of steel, trends between material properties and attenuation were present regardless. The findings of this evaluation coincide with previous research from Papadakis which established an evident relationship between grain size and grain scattering with attenuation. (Papadakis, 1970) The QT steels, which have undergone heat treatments, attenuated less than those that have not. From the analysis of the microstructure presented in Section 3.3.1, the refined grain size of specimens 70, 101, and 102 promoted the transmission of sound and reduced attenuation.

Figure 5.5: Change in Attenuation Per Inch of Sound Path – 2.25 MHz Conventional UT
Figure 5.6: Change in Attenuation Per Inch of Sound Path – 2.25 MHz PAUT

Figure 5.7: Change in Attenuation Per Inch of Sound Path – 5 MHz PAUT
5.3.2 Test Sequence 2 – Probe Frequencies with Compression Wave

A comparison between compression wave probe frequencies was also investigated. A 2.25 MHz PAUT and 5 MHz PAUT probe were used to inspect five different steel specimens. Similar to above, a marker indicates the average change in dB per inch for each specimen. Error bars for each marker displays the variation of indication signals measured between the two holes in each block. Figure 5.8 and Figure 5.9 again showed a clear difference in attenuation per inch of sound path between the two different frequencies. All five specimens only vary 0.6 dB/in with a probe frequency of 2.25 MHz and 1.5 dB/in with a 5 MHz probe frequency. This was a more than 150% increase in attenuation between specimens. Therefore, the effect of probe frequency on attenuation was also seen in compression wave. Again, regardless of frequencies the quench and tempered high performance bridge steels attenuated less.

![Figure 5.8: Change in Attenuation Per Inch of Sound Path– 2.25 MHz PAUT Compression Wave](image-url)
5.3.3 Test Sequence 3 – Difference in Reference Blocks

AWS D1.5 requires an IIW-type reference block for evaluation using both conventional UT and PAUT to be used as the standard for distance and sensitivity. AWS D1.5 states that the IIW-type reference block should conform to the A709 Gr. 36 specification or acoustically equivalent. Two IIW-type reference blocks conforming to two different material specifications, A36 and AISI 1018, were used to facilitate this phase of testing and would be acceptable references under the lax guidelines of AWS.

Figure 5.10 and Figure 5.11 illustrate the results collected using a 5 MHz PAUT probe with the two different reference blocks. In comparing the results, it is visible that different results were measured depending on which reference block was used. The A36 calibration block was more attenuating than all specimens, 0.7 dB/in more attenuating than specimen 36 and 2.1 dB/in more attenuating than specimen 102. The 1018 calibration block was similar to the average value of the specimens. While the 1018 block was less attenuating than specimens 36 and 50, it was more attenuating than the high performance steels, specimens 70, 101, and 102. The behavior still varied by 0.7 dB/in from specimen 36, but this time only 0.5 dB/in from specimen 102.
Figure 5.10: Change in Attenuation per Inch – A36 IIW-type Reference Block
5 MHz PAUT

Figure 5.11: Change in Attenuation per Inch – 1018 IIW-type Reference
5 MHz PAUT
Concerns arise when the current AWS D1.5 code and its guidelines for IIW-type calibration blocks are considered. Limits on the ultrasonic properties are not defined and ‘acoustically equivalent’ can be very open to interpretation. For example, ISO defines acoustically equivalent as a difference of less than 2 dB over the inspection sound path. Even exclusively specifying A709 Gr. 36 could warrant different results if the acoustic attenuation and velocity varies as a result of differences in the chemical composition, grain structure, or rolling. Two IIW-type references blocks were tested, one grade A36 and one grade AISI 1018, and the averaged difference in attenuation between the two blocks was of 1.5 dB/in with 5 MHz PAUT. It is unlikely these two specimens account for the extreme maximum and minimum of IIW-type reference blocks currently being used to facilitate ultrasonic inspections, thus this apparent difference could be even larger.

The acoustic characteristics of the IIW-type reference block plays a key role in the acceptance or rejection of flaws during inspection. AWS D1.5 Annex K defines the disregard level (DRL) as 6 dB under the standard sensitivity level (SSL) and the automatic reject level (ARL) as 5 dB above the standard sensitivity level. For example, consider an inspection with a 5 MHz PAUT probe in first leg of a plate with the average acoustic properties of specimen 36. When the 1018 IIW-type reference block is used to set the SSL and primary reference level, a flaw with the same reflective characteristics as the SDH located 3” below the inspection surface or deeper would automatically fall below the DRL at all incidence angles. Next, consider the A36 IIW-type reference block is used to set the primary reference level prior to scanning. The exact same reflector located 3” below the inspection surface, that was automatically acceptable with the 1018 IIW-type block, would now be classified as automatically rejectable with the A36 IIW-type block. Figure 5.12 shows a visual representation of this. The depth of the flaw below the inspection surface is along the x-axis and the change in gain from reference in decibels is along the y-axis. When reference is set off the A36 IIW-type block, the average acoustic attenuation of specimen 36 was -0.7 dB/in with a 5 MHz probe, see Figure 5.10. When reference is set off the 1018 IIW-type block, the average acoustic attenuation of specimen 36 was 0.7 dB/in with a 5 MHz probe, see Figure 5.11. From this, the required change in gain from reference in decibels for different sound paths and flaw depths were propagated. Per AWS D1.5 when an indication falls within the area between the DRL and ARL length-sizing is required for evaluation.
Conducting this same comparison with a steel plate with the average acoustic properties of specimen 102 is illustrated in Figure 5.13. From Figure 5.10, the average acoustic attenuation used was -2.1 dB/in with the A36 IIW-type block. From Figure 5.11, the average acoustic attenuation used was -0.5 dB/in with the 1018 IIW-type block. Inspection of a plate with the same acoustic properties as specimen 102 with a 5 MHz PAUT probe would again produce different results with the two different IIW-type reference blocks. If the A36 IIW-type reference block was used to set the primary reference level, a flaw with the same reflective characteristics as the SDH located deeper than 1.0” below the inspection surface would automatically fall above the ARL at all incidence angles. If the 1018 IIW-type reference block was used to set the primary reference level, the exact same reflector, which was automatically rejectable at a depth of 1.0” with the A36 IIW-type block, would now need to be located at a depth of 3.5” below the inspection surface or deeper to be automatically rejectable. The consequences of these differences could be excessive rejection of noncritical indications. When a reference block with large attenuation is used for calibration of a steel plate with comparably lower attenuation, small indications could result in automatically rejectable amplitude levels and lead to numerous repairs, some being unnecessary.
The figures above clearly illustrate completely different conclusions regarding acceptance and rejection when two different IIW-type reference blocks are used to inspect a single plate. Figure 5.12 illustrates how the same reflector can be acceptable with one reference standard but rejectable with a different reference standard. Figure 5.13 illustrates how the same reflector can be classified automatically rejectable at one depth but with a different reference standard the reflector could have to be almost four times deeper to achieve the same classification of automatically rejectable. Not only can you obtain two different answers in one material, but these differences also vary with material, i.e. the different responses between a plate with the acoustic properties of specimen 36 versus specimen 102.

The same analysis and comparison of different IIW-type references blocks with a 2.25 MHz PAUT probe is presented below. Figure 5.14 shows the analysis of a plate with the same acoustic properties as specimen 36. Figure 5.15 shows the analysis of a plate with the same acoustic properties as specimen 102. As expected, the same trends are seen with a 2.25 MHz PAUT probe when compared with the 5 MHz PAUT probe. However, using a 2 would need to be placed deeper than 10” from the scanning surface for it to classified rejectable with the A36 IIW-type block and acceptable with the 1018 IIW-type block. With 5 MHz this reflector only needed
to be placed deeper than 3”. A depth of 10” will likely never be examined in the bridge industry with AWS D1.5. The thickest probable member has been determined to be 8”, which is the inspection of a 4” thick steel plate in second leg. Figure 5.15 shows a reflector in a plate with the acoustic properties of specimen 102 would need to be deeper than 5.5” to be automatically rejectable with A36 IIW-type block as reference. This would likely reduce the probability of noncritical indications being found and automatically rejectable. It is clear 2.25 MHz does not fix the differences in material attenuation, but for depths commonly found in the bridge industry it does minimize the magnitude of difference. 25 MHz probe reduces the variation in acoustic attenuation between the A36 and 1018 IIW-type block to 0.3 dB/in, whereas this was 1.5 dB/in with a 5 MHz probe. For example, in Figure 5.14 a reflector

![Diagram of attenuation data](image)

**Figure 5.14: AWS D1.5 Acceptance Criteria and Reference Blocks**

A36 Steel with 2.25 MHz PAUT
Evident implications arise when something as simple as the selection of an IIW-type reference block greatly affects the acceptance or rejection results. In a perfect world calibration would be set off a material that has the same acoustic properties as the test object. Concerns regarding inspection arise when standard sensitivity and primary reference levels are set from a material with different acoustic properties, namely acoustic attenuation and velocity, then the test material. This is especially evident with 5 MHz scanning frequency. This difference is not only critical to IIW-type reference blocks but time corrected gain (TCG) calibration blocks, too. AWS D1.5 Annex K requires the use of a TCG calibration block but does not specify nor limit any material properties or geometric constraints for these blocks. TCG blocks are fabricated with three or more SDHs to facilitate a depth sensitivity calibration. That is, following a TCG calibration reflectors will all have the same approximate amplitude regardless of a variation in depth. (AASHTO/AWS, 2015) Figure 5.12 through Figure 5.15 all have a depth sensitivity calibration applied based on the attenuation properties of the IIW-type reference block, i.e. standard sensitivity remains constant at all depths. However, this is likely not always the case since AWS D1.5 does not require inspectors to have all calibration blocks formed of the same material, which in turn introduces additional error not seen in the above analysis. Overall, if any reference material differs
from the test material, and no correction is taken into account, inconsistency and inaccuracies in detection and characterization of flaws will occur.

### 5.3.4 Test Sequence 4 – Thermo-mechanical Control Processed Plates

A separate evaluation of plates from three different heats of high performance steel has been conducted in this section. The steel specimens in this section are all HPS A709 Gr. 70W and have underwent a thermo-mechanical control process (TMCP) treatment. The three specimens have been obtained by three different steel mills in order to look at possible differences in rolling techniques. Again, two different probe frequencies were used to conduct the ultrasonic inspection. Furthermore, one steel sample was used to fabricate a specimen in the rolled direction and cross-rolled direction in order to compare the apparent differences in grain structure and ultrasonic velocity.

During the first round of testing noticeable differences between the behavior of a TMCP specimen and a quenched and tempered (QT) specimen, both HPS A709 Gr. 70W, were observed. In the TMCP specimen, at higher incidence angles the location of the SDH registered deeper than the actual known position. Figure 5.16 graphically shows a steel block specimen, the four SDHs located within it, and the recorded flaw depths for specimens QT and TMCP 1. PAUT accurately measured depth of the flaw in the QT specimen while in comparison the TMCP specimen always indicated the SDH was deeper than it actually was. Furthermore, the indication signal became very weak in TMCP specimens. Figure 5.17 shows data screenshots of the QT and TMCP 1 specimens at an equivalent gain. The amplitude of the QT specimen measured at 80% FSH while the amplitude of the TMCP 1 specimen measured only 20% FSH. Also comparing the two S-scans, note the change in color intensity of the signal amplitude between specimens QT and TMCP 1.

![Figure 5.16: Recorded Flaw Depth at 70° Incidence Angle](image.png)
At first, the significant decrease in signal strength was attributed to ultrasonic attenuation in the TMCP specimens. However, after further evaluation and additional research the cause was not a result of attenuation but instead due to the acoustic velocity of the TMCP steel specimens. Accounts of both weakened signals and inaccuracy in locating defects in steel plates have been reported in previous research studies as a result of acoustic anisotropy, or the variation of acoustic velocity in the rolled and cross-rolled directions. From these studies, the vast majority of plates characterized as acoustically anisotropic were manufactured using TMCP. (Iba, 1987; Rattanasuwannachart et al., 2004) The unique behavior observed in these steels has been explained by the increase in the steel’s ultrasonic velocity in the rolled direction. This increase in ultrasonic velocity was measured by Rattanasuwannachart et al. to vary through the thickness of a steel plate, being greater at near-surface region versus the central region. The metallurgical reports of specimens TMCP 1, TMCP 2, and TMCP 3 noted the regions adjacent to the surfaces consisted of
a different grain structure when compared to the central region. It must be noted that this observation is typical of TMCP plates and does not indicate a problem or abnormality with these specific plates (i.e., the mechanical properties and chemistry meet ASTM A709). Rather, it is simply inherent of the processing associated with TMCP. The near-surface grain structure has been found to cause an increase in ultrasonic velocity. When the shear wave velocity of a given material is significantly faster than the assumed shear wave velocity, sound cannot transmit into the steel plate but instead forms surface waves at the exterior of the plate. (Rattanasuwannachart et al., 2004) Therefore, a portion of the total sound expected to transmit into the steel is unknowingly and immediately lost along the surface of the test material causing a sometimes significant loss in signal strength reflected back from internal reflectors.

During this experimental investigation, it became apparent that this reflection of sound at the surface is much more critical at higher incidence angles. Rattanasuwannachart et al. has established a relationship between incidence angle and what they refer to as ‘critical shear wave velocity’. The critical shear wave velocity is the velocity that causes refraction along the surface to occur. When a material’s shear wave velocity is less than the critical shear wave velocity, the sound beam can form within the material. Conversely, when a material’s shear wave velocity is greater, refraction of the sound wave along the surface will occur. (Rattanasuwannachart et al., 2004) This is a result of Snell’s Law and beam spread. In anisotropic plates along the rolled direction, the angle of refraction is always larger than the assumed incidence angle due to the increase in velocity. This difference is amplified at larger incidence angles. The Japanese JIS Z 3060 code uses a variation of Snell’s Law to calculate the angle of reflection when the actual velocity and assumed velocity differ:

$$\theta = \sin^{-1}\left(\frac{V}{V_{assumed}} \times \sin(\theta_{search})\right)$$

Equation 5-2

From Equation 5-2, a smaller incidence angle (e.g., 45°) impacts the angle of refraction less than a larger incidence angle (e.g., 70°). Also, at lower incidence angles the deviation between the actual material velocity and the assumed velocity can deviate much more before the angle of refraction causes surface reflection of the beam or issues with defect depth location. A 70° sound beam inherently forms and propagates closer to the surface and therefore even a slight increase in
the angle of refraction will cause a greater loss in signal due to the increase formation of surface wave.

An evaluation of the three TMCP specimens evaluated using 2.25 MHz and 5 MHz shear waves is seen in Figure 5.18 and Figure 5.19, respectively. Due to the influence of ultrasonic velocity and grain structure on different incidence angles and sound paths, the data has been separated by incidence angle and reflector depth along the x-axis. The difference between the indication level and the primary reference level, or the change in dB, per inch thickness is plotted along the y-axis.

Figure 5.20 and Figure 5.21 show the collected data for the 1.0” deep holes in the three TMCP specimens evaluated with a 2.25 MHz and 5 MHz probe, respectively. Similar to Figure 5.18 and Figure 5.19, the data has been separated by incidence angle along the x-axis. The difference between the indication level and the primary reference level, or the change in dB, is plotted along the y-axis. Figure 5.20 and Figure 5.21 directly show the adjustment in gain required to peak signal amplitude of the SDH signals compared to reference. For specimens TMCP 1 and TMCP 2, an average 10.5 dB was added to peak the signal with a 2.25 MHz probe at 70° and an addition of 9.5 dB was required with a 5 MHz probe at 70°. This is a substantial increase compared to specimen 70 (QT) where 1.0 dB was subtracted to peak the signal with a 2.25 MHz probe at 70° and 1.9 dB was subtracted with a 5 MHz probe at 70°.

Trends noted during the ultrasonic evaluation of the three different TMCP specimens are as follows:

- From Figure 5.18 and Figure 5.19, it is apparent that the three specimens, all of which were from different heats, had differences in their behavior at different incidence angles and sound paths. The differences were small at 45° and 60° but increase significantly at 70°. Figure 5.20 and Figure 5.21 also show this trend.
- All SDHs, at all angles, and with both frequency probes attenuated more than the HPS A709 Gr. 70W QT steel specimen (with the exception of the TMCP 2 0.6” deep SDH at 45° with 2.25 MHz).
- Signal amplitude was most comparable to the HPS A709 Gr. 70W QT specimen at a 45° incidence angle. A weakened signal was observed in all three specimens when compared to the QT specimen at a 60° incidence angle and even more so at 70°.
• The acoustic velocity of specimens TMCP 1 and TMCP 2 in the rolled direction were higher than specimen TMCP 3. As a result, a larger reduction in signal amplitude at 70° was noticed in TMCP 1 and TMCP 2. Only one plate was obtained from the steel mill of TMCP 3, but further testing on additional plate samples would be required to prove or disprove if the manufacturing practices of this mill was the source of dissimilarity.

• At 60° and 70° incidence angles, the signal amplitude of the 0.6” deep hole was smaller than the 1.0” hole for all specimens. This was unexpected and unusual because the sound path for a 1.0” deep hole is longer than a 0.6” hole. Longer sound paths usually result in an increase reduction of signal amplitude due to material attenuation. However, material attenuation was not the cause of these findings but instead ultrasonic velocity. Thus, this would indicate that the near-surface layer impacted the evaluation of the 0.6” deep SDHs more than the 1.0” deep SDHs.

• The use of a 2.25 MHz probe instead of a 5 MHz probe showed no advantage and instead both behaved similarly. Probe frequency was not the cause of the weakened signal amplitudes.
Figure 5.18: Change in Signal Intensity Per Inch of Sound Path between Incidence Angles – 2.25 MHz Conventional UT

Figure 5.19: Change in Signal Intensity Per Inch of Sound Path between Incidence Angles – 5 MHz PAUT
Figure 5.20: Change in Signal Intensity between Incidence Angles – 1.0” deep hole, 2.25 MHz Conventional UT

Figure 5.21: Change in Signal Intensity between Incidence Angles – 1.0” deep hole, 5 MHz PAUT
The acoustic anisotropy commonly reported in TMCP plates has been attributed to a variation in cooling rates between the surface and central regions and the low temperature used during rolling and fabrication. These variables cause differences in the grain sizes and orientations throughout the thickness of the plates. (Rattanasuwannachart et al., 2004) To further evaluate these claims, two specimens were fabricated from specimen TMCP 2, one in the rolled direction and one in the cross-rolled direction. The preceding figures all show the data collected in the rolled direction for specimens TMCP 1, TMCP 2, and TMCP 3. Therefore, the rolled direction data for TMCP 2 is reiterated below but with the addition of data collected in the cross-rolled direction.

Figure 5.22 and Figure 5.23 show the comparison between the rolled and cross-rolled direction of specimen TMCP 2 with a 2.25 MHz and 5 MHz probe, respectively. Again, the data has been separated by incidence angle and reflector depth along the x-axis and change in dB per inch of sound path along the y-axis. From the figures, it was clear the two directions behave very differently. The cross-rolled direction behaved almost identical to specimen 70 (QT) at all incidence angles and with both a 2.25 MHz and 5 MHz frequency probe. The acoustic anisotropy within TMCP steels poses a substantial problem to ultrasonic evaluation, especially if inspectors are unaware of the fabrication practices or material properties of a member being inspected.
The ultrasonic evaluation conducted during this phase investigated the ultrasonic inspection of narrow-gap improved electroslag welds. Four specimens from two different fabricators were tested with two different probe frequencies. Section 4.4.4 and Table 4.3 fully detail experimental testing information. The objective of these tests was to determine if the narrow-gap improved fabrication process results in reduced ultrasonic attenuation and increased flaw detectability due to the reported reduction in grain size.

The following sections have been divided by specimens. Each specimen has eight holes total, four at 0.6” from the center of the hole to the top of the scanning surface and four at 1.0”. All eight holes were scanned with a 2.25 MHz conventional UT and 5 MHz PAUT probe at 45°, 60°, and 70°. The figures below all present the data similarly, the hole identification number is along the x-axis along with the different sound paths and change in attenuation per inch of sound path is along the y-axis. Defined in Section 5.3 by Equation 5-1, the change in attenuation per inch of sound path is the change in decibels required to peak the signal of a SDH from the primary reference level divided by the sound path of the shear wave at a given incidence angle. The data
were grouped this way because the sound path to each hole varied substantially with different incidence angles thus grouping them all together hid the effects of the HAZ and weld metal. For example, at a 45° incidence angle the sound beam would pass entirely through heat-affected base metal, at a 60° incidence angle the sound beam would pass through weld metal and heat-affected base metal, and 70° incidence angle the sound beam would pass through an even larger amount of weld metal and heat-affected base metal. This variation had a considerable impact on attenuation and should be noted in the below figures. Two figures will show the change in attenuation per inch of sound path of the 0.6” deep holes and two figures will show the overall scatter produced when data of the 0.6” and 1.0” deep holes are combined.

Each section will show a schematic of the weld with the average HAZ and weld boundaries and the paths the sound took to each SDH. The sound path to hole 1 was solely through base metal (BM). The sound path to hole 2 was base metal to HAZ from the left and solely HAZ or weld metal (WM) to HAZ from the right. The sound path to hole 3 was solely weld metal or HAZ to weld metal. Finally, the sound path to hole 4 was solely HAZ or weld metal to HAZ from the left and base metal to HAZ from the right. The figures below designate whether the direction of the sound path came from the right (R) or from the left (L).

5.4.1 Specimen P1

Figure 5.25 and Figure 5.26 show the attenuation per inch of sound path for specimen P1 using a 2.25 MHz and 5 MHz probe, respectively. The overall attenuation of hole 1, hole 2 from the left, and hole 4 from the right were all very similar with both frequency probes. The magnitude of the change in attenuation was larger with a 5 MHz probe than with a 2.25 MHz probe, but from previous experimental results this was expected. The overall attenuation for hole 2 from the right and hole 4 from the left, where the sound path initiated in the HAZ or weld metal, was more inconsistent at different incidence angles and was more attenuating in comparison to when sound initiated in the base metal. The overall attenuation for hole 3 was the most unpredictable and most attenuating.

Figure 5.27 and Figure 5.28 show the overall scatter in attenuation per inch of sound path for all 8 holes located in specimen P1 using 2.25 MHz and 5 MHz probes, respectively. The intention of these two figures is to illustrate the variation observed between scanning through base metal, the HAZ, and weld metal. Very minimal scatter was seen when both the 0.6” and 1.0” deep
holes were inspected at all incidence angles with a sound beam initiating and propagating in solely base metal or base metal (BM) into the HAZ. The average attenuation per inch of sound path was also consistent across the three holes, holes 1, 2, and 4. The scatter increased when hole 2 and hole 4 were inspected at all incidence angles with a sound beam initiating and propagating in solely the HAZ or weld metal (WM) into the HAZ. With a frequency of 2.25 MHz the overall scatter was an average of 1.7 dB/in for holes 2 and 4. With a frequency of 5 MHz the overall scatter increased to an average of 2.6 dB/in. The largest scatter in attenuation per inch of sound path was observed in hole 3 where the sound beam initiated and propagated solely in weld metal or the HAZ into the weld metal. With a frequency of 2.25 MHz the scatter was 4.4 dB/in and for 5 MHz it was 4.0 dB/in.

Figure 5.24: Specimen P1 Sound Path Schematic – 0.6” deep SDHs
Figure 5.25: Specimen P1 Attenuation per inch – 0.6 deep hole 2.25 MHz

Figure 5.26: Specimen P1 Attenuation per inch – 0.6 deep hole 5 MHz
Figure 5.27: Specimen P1 Attenuation per Inch Overall Scatter – 2.25 MHz

Figure 5.28: Specimen P1 Attenuation per Inch Overall Scatter – 5 MHz
5.4.2 Specimen P2

Similarly, Figure 5.30 and Figure 5.31 show the attenuation per inch of sound path for specimen P2 using a 2.25 MHz and 5 MHz probe, respectively. Similar trends in attenuation between base metal, the HAZ, and weld metal were seen between specimens P1 and P2. Overall, the base metal of P2 attenuated more than the base metal of P1 which substantiates the differences in attenuation between A709 Gr. 50 and HPS A709 Gr. 70 QT found earlier. However, with both the 2.25 MHz and 5 MHz frequency probes the average attenuation per inch of sound path in the weld was less in specimen P2 than in P1. Again, the overall attenuation of hole 1, hole 2 from the left, and hole 4 from the right were the same. In almost all cases, attenuation of hole 2 and hole 4 increased due to the sound initiating and propagating from solely the HAZ or weld metal into the HAZ. Again, attenuation through weld metal for hole 3 varied, but overall the attenuation of the sound traveling through solely weld metal or the HAZ into weld metal was the largest.

Figure 5.32 and Figure 5.33 show the overall scatter in attenuation per inch of sound path for all 8 holes located in specimen P2 using 2.25 MHz and 5 MHz probes, respectively. Again, the average attenuation per inch of sound path was consistent across holes 1, 2, and 4 where sound was initiated in the base metal. Scatter increased when holes 2 and 4 were shot with sound initiating in solely in the HAZ or weld metal. The overall scatter in attenuation per inch of sound path increased to 1.1 dB/in with a frequency of 2.25 MHz and 2.5 dB/in with 5 MHz. In comparison, the overall scatter in attenuation per inch of sound path for hole 3 was 2.6 dB/in with a 2.25 MHz probe and 1.7 dB/in with a 5 MHz frequency.

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![Figure 5.29: Specimen P2 Sound Path Schematic – 0.6” deep SDHs](image-url)
Figure 5.30: Specimen P2 Attenuation per inch – 0.6 deep hole 2.25 MHz

Figure 5.31: Specimen P2 Attenuation per inch – 0.6 deep hole 5 MHz
Figure 5.32: Specimen P2 Attenuation per Inch Overall Scatter – 2.25 MHz

Figure 5.33: Specimen P2 Attenuation per Inch Overall Scatter – 5 MHz

5.4.3 Specimen P3

Specimen P3 was fabricated by the same fabricator as specimens P1 and P2 and was a combination of the two different heats of steels used to fabricate P1 and P2. Therefore, P3 should
mimic the results shown above. The left side of P3 was of the same heat of steel as P1 and the right side was of the same heat of steel as P2. Figure 5.35 and Figure 5.36 show the attenuation per inch of sound path for specimen P3 using a 2.25 MHz and 5 MHz probe, respectively. Attenuation for hole 1 and hole 2, where sound initiated in the base metal, matched perfectly between specimens P1 and P3 for both frequency probes. Attenuation for hole 4 where sound initiated in the base metal matched very similar between specimens P2 and P3 for both frequency probes. Similar variations in attenuation were seen in holes 2 and 4 where sound was initiated in the HAZ or weld metal for specimens P1, P2, and P3.

Figure 5.37 and Figure 5.38 show the overall scatter in attenuation per inch of sound path for all 8 holes located in specimen P3 using 2.25 MHz and 5 MHz probes, respectively. Again, results for holes 1, 2, and 4 correlated well with the results of specimens P1 and P2. Scatter in attenuation for hole 3 was broken up into side A and side B. The average attenuation per inch of sound path recorded for side A matched specimen P1 within 0.4 dB/in and side B matched specimen P2 within 0.3 dB/in. However, the overall scatter associated with hole 3 in specimens P1, P2, and P3 varied between specimens. Overall, P3 validated the findings and analysis of specimens P1 and P2 above.

Figure 5.34: Specimen P3 Sound Path Schematic – 0.6” deep SDHs
Figure 5.35: Specimen P3 Attenuation per inch – 0.6 deep hole 2.25 MHz

Figure 5.36: Specimen P3 Attenuation per inch – 0.6 deep hole 5 MHz
Figure 5.37: Specimen P3 Attenuation per Inch Overall Scatter –2.25 MHz

Figure 5.38: Specimen P3 Attenuation per Inch Overall Scatter –5 MHz

5.4.4 Specimen P4

Specimen P4 was fabricated by a different fabricator than the other three specimens above. While performing the ultrasonic inspection it appeared the base metal of specimen P4 was
behaving acoustically anisotropic. A mill report provided for the base metal of this specimen specifically stated it was manufactured as QT. The velocity of this plate was measured using a normal incidence angle shear probe and in the rolled direction was found to be 0.132 in/µs and 0.126 in/µs in the cross-rolled direction. It is the belief of the RT team that this plate was manufactured using TMCP but at some time was mislabeled. Therefore, not only in the field is it possible for inspectors to be ignorant to the types of steels they are inspecting but even within a shop setting this is possible if the material tracking is not adhered to rigorously.

Figure 5.39 compares the results from the 0.6” and 1.0” deep holes in the base metal of specimen P4 to specimen TMCP 1 from Section 5.3.4. It was clear the base metal of specimen P4 behaved acoustically anisotropic due to the gradual loss of signal sensitivity at higher angles. While this should not affect the weld or behavior of the weld, it was expected to increase the variability in attenuation found in hole 1, hole 2 from the left, and hole 4 from the right.

![Graph showing comparison between specimen P4 and specimen TMCP 1](image)

Figure 5.39: Specimen P4 versus Specimen TMCP 1
Indication Signal of 0.6” deep hole – 2.25 MHz

Figure 5.40 and Figure 5.41 show the attenuation per inch of sound path for specimen P4 using a 2.25 MHz and 5 MHz probe, respectively. Again, unlike the trends observed in specimens P1, P2, and P3, the attenuation of hole 1, hole 2 from the left, and hole 4 from the right was inconsistent across different incidence angles and a loss of signal was observed at higher angles.
As a result, the attenuation found in hole 2 and hole 4 where the sound path initiated in the weld was more consistent, but still more attenuating than an acoustically isotropic HPS A709 Gr. 70W QT base metal. Similar statements can be said for hole 3 located in the weld metal.

Figure 5.42 and Figure 5.43 show the overall scatter in attenuation per inch of sound path of all 8 holes located in specimen P4 using 2.25 MHz and 5 MHz probes, respectively. The average attenuation per inch of hole 2 and hole 4 inspected with the sound beam initiating in the weld metal mirrored data collected for specimens P1 and P2 for these holes within ±0.3 dB/in with a 2.25 MHz probe and ±0.5 dB/in with a 5 MHz probe. The average attenuation per inch for hole 3 when compared to specimens P1 and P2 as well with a maximum deviation of ±0.5 dB/in with a 2.25 MHz probe and ±1.3 dB/in deviation with a 5 MHz probe. Overall, when the sound beam initiated and propagated from weld metal and the HAZ less scatter was seen in comparison to the anisotropic base metal.
Figure 5.40: Specimen P4 Attenuation Per Inch of Sound Path – 0.6 deep hole 2.25 MHz

Figure 5.41: Specimen P4 Attenuation Per Inch of Sound Path – 0.6 deep hole 5 MHz
Figure 5.42: Specimen P4 Attenuation per Inch Overall Scatter –2.25 MHz

Figure 5.43: Specimen P4 Attenuation per Inch Overall Scatter –5 MHz
5.4.5 **Summary**

From the data collected above, the coarse grain structure found in the weld and parts of the HAZ of the developed NGI-ESW procedure obviously still impacts ultrasonic inspection. While there was a subtle difference in attenuation due to probe frequency, the microstructure of the weld itself plays too big of a role for the use of a 2.25 MHz or 5 MHz probe to make an abundant difference. It is recommended to scan NGI-ESW welds along both sides of the weld. If scanning is performed only along a single side of the weld the sound beam is required to pass entirely through the weld and back. As a result, the attenuation observed in the weld metal could limit the detection of critical flaws.

In addition, previous research found a concerning number of planar defects due to in-field fabrication of NGI-ESW. Due to the NGI-ESW fabrication setup and the inherit grain structure, planar defects are more likely to form along the fusion face of the weld. (Prchlik et al., 2015) Between the orientation of these defects and the increase in ultrasonic attenuation of the HAZ and weld metal, revisions to the current scanning guidelines is necessary. First, Prchlik et al. has provided an updated pitch-catch scanning procedure shown to enhance the detection and characterization of planar defects in NGI-ESW welds. (Prchlik et al., 2015) However, the current AWS D1.5 code only requires pitch-catch to be used on NGI-ESW welds when a defect is found at the fusion line of the weld. (AASHTO/AWS, 2015) If no indication is initially found, pitch-catch is never employed. Therefore, similar to the current AWS D1.5 prescribed acceptance-rejection criteria for CJP double groove welds, NGI-ESW welds should be evaluated at a minimum of 4 dB more sensitive than scanning level. This will help overcome the losses in signal due to attenuation and increase the detectability of planar flaws.
6. CONCLUSIONS AND FUTURE RESEARCH

6.1 Conclusions

6.1.1 Paint Systems

The evaluation of the effects of paint systems on phased array ultrasonic testing yielded the following conclusions:

- With compression wave scanning through well adhered and poorly adhered paint systems, a maximum difference of 11.6 dB was seen between nine reflectors. Ignoring the poorly adhered paint systems, a maximum difference of 6.9 dB was seen for six reflectors. When the paint was removed and the surface was ground smooth, a maximum difference of 3.3 dB was seen for all nine reflectors.

- With shear wave scanning through well adhered and poorly adhered paint systems, a maximum difference of 14.7 dB was seen for nine reflectors. Ignoring the poorly adhered paint systems, a maximum difference of 7.2 dB was seen for six reflectors. When the paint was removed and the surface was ground smooth, a maximum difference of 4.2 dB was seen for all nine reflectors.

- The scatter remaining between specimens after the paint was removed and the surface ground smooth was unexpected because it was believed that typical carbon steels used in bridge fabrication all behave the same.

- With compression wave, the average indication signal was less attenuating when compared to scanning on a ground, smooth steel surface – the paint amplified the sound. Contradictory, when scanning through paint with shear wave the average indication signal was more attenuating in comparison to scanning on a ground, smooth steel surface.

- No definitive trend was observed to account for the difference in ultrasonic behavior between all painted and unpainted steel surfaces. The type, thickness, and condition of paint coatings varied widely and affected the ultrasonic inspection differently.

- The time and cost of removing paint and prepping the surface of a component before inspection is the best solution for proper inspection.
6.1.2 Base Metals

The evaluation of the ultrasonic attenuation of common bridge base metals yielded the following conclusions:

**Test Sequence 1 and 2**

- Currently the AWS D1.5 Bridge Welding Code procedures (for conventional UT and Annex K) explicitly assume that all carbon bridge steels possess the same attenuation characteristics and no correction or consideration is needed to be taken during the inspection of bridge welds.
- In common bridge base metals ranging from 36 ksi to 100 ksi, an average measured difference in attenuation per inch with shear wave was 0.3 dB/in with a 2.25 MHz frequency probe and 1.3 dB/in with a 5 MHz frequency probe.
- With compression wave, an average measured difference in attenuation per inch in common base metals was 0.6 dB/in with a 2.25 MHz frequency probe and 1.5 dB/in with a 5 MHz frequency probe.
- The change in attenuation between common base metals was magnified at higher frequencies. Therefore, the differences in attenuation noticed between 2.25 MHz and 5 MHz frequency probes will result in discrepancies using the current AWS D1.5 Annex K PAUT acceptance criteria.
- Lower frequencies, 2.25 MHz for example, should be required in ultrasonic testing when an amplitude and length only acceptance criteria are employed unless the material attenuation is specifically considered during calibration.

**Test Sequence 3**

- The ultrasonic properties of calibration materials, such as an IIW-type reference block or TCG block, have a significant impact on the evaluation and classification of bridge components and defects.
- Two IIW-type reference blocks, one of grade A36 and one of AISI 1018, were used to calibrate and evaluate the base metal specimens. A difference in attenuation of 1.5 dB/in was observed between the two reference blocks using a 5 MHz frequency shear wave probe. This difference was only 0.3 dB/in with 2.25 MHz.
Due to differences in attenuation, using the current AWS D1.5 acceptance criteria to evaluate components with sizable differences in ultrasonic properties will lead to a discrepancy in flaw classification. For example, when a reference block used for TCG calibration was more attenuating than the test object, an indication could be characterized as \textit{automatically rejectable}. If a different reference block was used for calibration and was less attenuating than the test object, the \textit{exact same} indication could be characterized as \textit{automatically acceptable}.

Two solutions to this problem are:
1) Calibration must occur off a material with the same acoustic properties (acoustic attenuation and velocity) as the test object
2) Stringent guidelines for calibration materials and their ultrasonic properties should be outlined in an evaluation code and correspond with the intent of the provided acceptance criteria.

**Test Sequence 4**

- TMCP steel plates are susceptible to acoustic anisotropy. Acoustic anisotropy affects the detection of flaws at higher incidence angles due to additional refraction of the sound beam and a reduction in signal amplitude. When flaws are detected, accurately locating and sizing the flaws becomes difficult.

- Inspection of TMCP plates should be limited to small incidence angles. Previous research suggests limiting the incidence angle to 63° or less. (Iba, 1987) However, experimental testing suggested there is an average 2 dB increase in signal amplitude at 60° than at 45°. 2 dB is minimal compared to an average 10 dB increase in signal amplitude at 70° than at 45°. Regardless, the increase in signal amplitude at higher incidence angles must be considered during evaluation.

- Probe frequency was not a cause of the large variation in signal amplitude found during the evaluation of TMCP plates. In TMCP plates, the 2.25 MHz probe attenuated the same, if not more, as the 5 MHz probe at higher incidence angles.

- The strength of the signal per inch of sound path for the 0.6” deep SDH was consistently lower than the 1.0” deep SDH at higher angles. Therefore, flaws
within or closer to near-surface refined grain structure seen in TMCP plates are affected more by the velocity change.

- Obvious differences in ultrasonic properties between the rolling and cross rolling directions were found in a TMCP specimen. The cross roll direction behaved very similar to a quenched and tempered plate of the same grade, while the rolled direction demonstrated all the characteristics of an anisotropic plate listed above.
- The current AWS D1.5 code does not provide guidance on TMCP or anisotropic plates. The Japanese Industrial Standard’s *Method for Ultrasonic Testing for Welds of Ferritic Steel* and the American Petroleum Institute’s *Recommended Practices for Ultrasonic and Magnetic Examination of Offshore Structural Fabrication and Guidelines for Qualification of Technicians* both acknowledge and make recommendations with regards to TMCP plates.

### 6.1.3 Narrow-Gap Improved Electroslag Welds

The ultrasonic inspection of NGI-ESW welds yielded the following conclusions:

- The ultrasonic attenuation of the holes located within the HAZ when shot with sound initiating in the base metal produced very similar results to the holes located solely in base metal. These holes also had very little scatter associated with them.
- The average ultrasonic attenuation and the scatter in results increased when the holes located in the HAZ were shot with the sound initiating in the HAZ or weld metal. The ultrasonic attenuation increased by an average of 0.7 dB/in with a 2.25 MHz probe and 1.3 dB/in with a 5 MHz probe when compared to plain base metal.
- The ultrasonic attenuation was the most inconsistent for the hole located within the weld metal. The ultrasonic attenuation also increased by an average of 1.3 dB/in with a 2.25 MHz probe and 2.3 dB/in with a 5 MHz probe when compared to plain base metal.
- The coarse grain structure of the weld had a clear impact on signal amplitude and attenuation. The inconsistency of results between the two SDHs at the different incidence angle indicated there is a clear variation of the microstructure in the weld, as well.
• The microstructure of the weld impacted the attenuation of sound through NGI-ESW welds too much for probe frequency to make an abundant difference. Therefore, even 2.25 MHz frequency probes still displayed a significant sound loss due to attenuation through the weld metal.

6.2 Future Research

Recommendations for future research are as follows:

• The ultrasonic evaluation of common bridge base metals was limited by the number of specimens and depths of the SDHs.

  1. Additional normal strength steel specimens, (e.g., 50 ksi), from different mills should be investigated. The production and fabrication of A709 Gr. 50 steel is more open to variation than are quench and tempered HPS steels (e.g., HPS 70W and HPS 100W). While Gr. 50 steels can alone be manufactured in a number of ways, per ASTM A709 it can also be produced as HPS Gr. 50W. HPS Gr. 50W can be as-rolled, controlled-rolled, TMCP, or QT. Therefore, “high-performance steels” can be manufactured different ways and each may produce different acoustic properties.

  2. Additional TMCP steels should be evaluated and their acoustic velocities measured. While, three TMCP specimens from two different mills all maintained similar acoustic velocities, a fourth TMCP specimen from a third mill had lower acoustic velocity in comparison. It may be of interest to investigate additional plates from these fabricators to establish if the mill’s manufacturing process had an impact on this difference. Furthermore, it is unknown at this time what the typical acoustic velocity range is for TMCP steels and also how that may vary in different plate thicknesses.

  3. Longer sound paths than those examined during this study should be investigated. It is common practice to evaluate welds by skipping to second leg and as a result verification of attenuation at these sound paths should take place.

• An ultrasonic inspection and analysis of additional complete joint penetration (CJP) weld specimens common within the bridge industry. While NGI-ESW welds were
investigated during this study, the fabrication process is much different for other CJP welds. The effects of different variables such as weld geometry, grain structure, and fabrication process on flaw detection and attenuation should all be studied further.
REFERENCES


APPENDIX A. DRAWINGS
ROLLING DIRECTION

STEEL PLATE LAYOUT

TOP SCANNING SURFACE

STEEL PLATE ELEVATION

MACHINE TOP SURFACE SMOOTH

MACHINE BOTTOM SURFACE SMOOTH

1/16" SIDE-DRILLED HOLE
DRILL ALL THE WAY THROUGH

NOTES:
1. TOTAL (9) PLATES PROVIDED
2. STEEL GRADES: A36, A709 Gr. 50, A709 Gr. HPS 70W, A709 Gr. HPS 100W
3. PLATE THICKNESS VARIES BETWEEN 1/2" - 2"

PROJECT: NCHRP 14-35
FABRICATION NOTES:
1. MILL TOP AND BOTTOM SURFACES SMOOTH
2. MILL THE SIDES SMOOTH
3. DRILL (4) HOLES 0.6" FROM THE TOP SMOOTH SURFACE TO THE CENTER OF THE HOLE
4. DRILL (4) HOLES 1.0" FROM THE TOP SMOOTH SURFACE TO THE CENTER OF THE HOLE

PROJECT: NCHRP 14-35
REVISIONS:

SHEET TITLE: NGI-ESW ULTRASONIC INSPECTION SPECIMEN
SHEET NOTES:

1040 SOUTH RIVER ROAD WEST LAFAYETTE, IN 47906 P: 765-494-2227 F: 765-494-6986

Specimen P1

2 of 5
FABRICATION NOTES:
1. MILL TOP AND BOTTOM SURFACES SMOOTH
2. MILL THE SIDES SMOOTH
3. DRILL (4) HOLES 0.6" FROM THE TOP SMOOTH SURFACE TO THE CENTER OF THE HOLE
4. DRILL (4) HOLES 1.0" FROM THE TOP SMOOTH SURFACE TO THE CENTER OF THE HOLE
STEEL PLATE TOP VIEW

TOP SCANNING SURFACE

HAZ BOUNDARY
WELD BOUNDARY

EL

STEEL PLATE ELEVATION

MACHINE BOTTOM SURFACE SMOOTH

STEEL PLATE TOP VIEW NTS

MACHINE TOP SURFACE SMOOTH

WELD METAL
HAZ

1/8" SIDE-DRILLED HOLE
DRILL ALL THE WAY THROUGH
(4 SETS - 6 HOLES TOTAL)

FABRICATION NOTES:
1. MILL TOP AND BOTTOM SURFACES SMOOTH
2. MILL THE SIDES SMOOTH
3. DRILL (4) HOLES 0.6" FROM THE TOP SMOOTH SURFACE TO THE CENTER OF THE HOLE
4. DRILL (4) HOLES 1.0" FROM THE TOP SMOOTH SURFACE TO THE CENTER OF THE HOLE

PROJECT: NCHRP 14-35
REVISIONS:

SHEET NOTES:

FREEZE FRAME
FABRICATION NOTES:
1. MILL TOP AND BOTTOM SURFACES SMOOTH
2. MILL SIDES SMOOTH
3. DRILL (4) HOLES 0.6" FROM THE TOP SMOOTH SURFACE TO THE CENTER OF THE HOLE
4. DRILL (4) HOLES 1.0" FROM THE TOP SMOOTH SURFACE TO THE CENTER OF THE HOLE