Defect Detection in Friction Stir Welding by Measureable Signals

Johnathon Bryce Hunt
Brigham Young University

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Defect Detection in Friction Stir Welding
by Measurable Signals

Johnathon Bryce Hunt

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

Yuri Hovanski, Chair
Michael P. Miles
Carl D. Sorensen
Brian A. Mazzeo

Department of Manufacturing Engineering
Brigham Young University

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ABSTRACT

Defect Detection in Friction Stir Welding by Measurable Signals

Johnathon Bryce Hunt
Department of Manufacturing Engineering, BYU
Master of Science

Friction stir welding (FSW) is an advantageous solid-state joining process, suitable for many materials in the energy, aerospace, naval and automotive industries. Like all other welding processes, friction stir welding requires non-destructive evaluation (NDE). The time and resources to preform NDE is expensive. To reduce these costs, nontraditional NDE methods are being developed for FSW. Spectral based defect recognition uses the forces during the welding process to validate weld quality. Although spectral NDE methods have shown promise as an alternative NDE processes, many research welding speeds do not correspond to manufacturing speeds, nor do they explain the relationship between the spectral data and the process. The purpose of this work is to explore the possibility of acquiring additional information about the defect. Namely the defect’s type, location, and magnitude. In this study, welds with “wormhole” defects were produced at 2000, 2500 and 3000 mmpm in 5754 aluminum. The welding process forces and torque were measured and analyzed spectrally. The welded plates were then imaged with x-ray photography, a validated NDE method. It was found that low frequencies (0 – 4 Hz) in the y & z force signals correlate with defect presence in high speed FSW. In addition, the strong correlation between the spectral data and the presence of a defect allowed for defect magnitude predictions. Linear fits were applied to the defect measurements and the spectral data. Large error inhibits the wide use of this prediction method.

Keywords: friction stir welding, FSW, nondestructive examination, NDE, defects
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1 INTRODUCTION

1.1 Introduction to the Problem

Friction stir welding (FSW) is an advantageous material joining process that is used in aerospace, automotive, navel, energy and other industries [1]. The process includes two work pieces that have a seam between them. A FSW tool, comprising of a cylindrical shoulder and a concentric pin, often threaded, is plunged down into the seam while rotating. Once the shoulder engages with the workpiece, the tool will advance along the seam while rotating, see Figure 1-1.

![Figure 1-1: A schematic of the friction stir welding process and the coordinate system used in this thesis.](image)

The friction between the tool and work piece creates heat and plastic deformation which results in a consolidated joint between the two sheets. Like all other welded joints, many industries require non-destructive evaluation (NDE) to ensure weld quality. Currently there are many types
of NDE that are used to verify joints: acoustic emission analysis, thermal image analysis, eddy current probe analysis, ultrasonic & phased array evaluation, liquid penetrant evaluation, and x-ray analysis [2-9]. Although these NDE methods have strengths detecting certain type of defects in friction stir welds most of them are preformed after the welding process. Post welding processes increase the time, machinery, training, labor or force manufactures to send large batches for testing. These production costs are very expensive. Other NDE methods have been researched to reduce these costs. Among these developing methods is spectral analysis based NDE. Spectral based NDE for FSW has been researched for the past sixteen years [10]; however, it is not widely used in industry. Possible reasons for the lack of implementation are: 1) industry welding speeds are three times faster than any of the current researched welding speed, 2) spectral based NDE has not been validated in enough materials, thicknesses, tool geometries, or other welding environments, or 3) the method to implement spectral based NDE is not clear. In order to push the use of spectral based NDE technology this study had three objectives in the beginning of this work.

1. Validate that spectral based NDE can locate defects in friction stir welds at industry welding speeds.

2. Explore the use of spectral based analysis to infer the magnitude of a defect.

3. Explore the use of spectral based analysis to infer the type of friction stir weld defect.

The company that sponsored the welding material and friction stir welding tools wanted more emphasis given to the first two objectives. This focus limited the time and resources to create different kinds of defects. Thus, the third objective was left for future study and was not addressed in this thesis.
1.2 Thesis Summary

To address the first objective related to spectral based NDE, this thesis includes a study that is presented in chapter 2. This study was submitted to the Journal of Manufacturing Processes and is currently under review. It focuses on the ability to detect defects along a weld at high speed friction stir welding using a novel approach. In addition, it contains: a review of the literature, an explanation of the experiments and methodology used to investigate high speed defect detection, a discussion regarding the results of the experiments, and the conclusions reached. Chapter 3 elaborates more on using spectral data to infer defect cross-sectional location. The method, results, and discussion for the inference of magnitude and defect type are also included in chapter 3. Lastly, chapter 4 of this thesis summarizes the conclusions presented in chapters 2 and 3 and provides the author’s recommendations for future work on this topic.

1.3 Methodology

Four sets of data were required to answer the three questions in section 1-1:

1. Friction stir welds and their raw data
2. Spectral analysis of raw data
3. Radiographic images
4. Cross-sectional images

The method used to acquire these four data sets will be explained in the following sections of this thesis. The friction stir welds and the raw data were the base of the thesis. This data allowed the possibility for spectral analysis to develop NDE for FSW, specifically at high speed and in work hardenable alloys. The spectral data provided the first half of the correlation between spectral data and FSW defects. Lastly, the radiography and cross-sectional images
provided quantified defect location and magnitude information on the defects that were produced across all of the welds.

1.3.1 Friction Stir Weld Set & Raw Data

The TWB Company, LLC provided the FSW tool and work materials for this thesis. The FSW tool was made from H13 tool steel. Its geometry included a flat, two start scrolled shoulder, 12 mm in diameter and a threaded pin that included three flats 120 degrees apart, a base diameter of 6 mm and a length of 3.1 mm with a 10-degree taper. The shaft of the tool was 0.95 inches in diameter. The workpieces were 3.8 mm thick sheets of 5754-O aluminum [11] whose dimensions were 3x2 feet.

![Figure 1-2: A schematic of the friction stir welding process and the working coordinate system of this thesis.](image)

All the welds were made on the TTI manufactured FSW machine on BYU campus. However, a few preparations were needed to ready the material for welding. The larger sheets were sheared to 4 inch wide strips 20 inches long (+1 inch, −0 inch). The length of the welding strips was not critical to hold to a tight tolerance because the determined weld length was 19.5
inches long. Prior work had performed much shorter welds, near 7 inches in length [12, 13]. Once the sheets were sheared to size, the welding edges were cleaned on a CNC mill to ensure square intimate seams between welding strips. Prior to welding the FSW machine was prepared with dowel pins that aligned the weld seam to the material seam within 0.004 inches. Side loading was provided by these dowels and blocks with set screws to hold the seam together. To have more uniform side load small 0.25 in square bars were set between the workpieces and the dowels or the set screws. Loading in the z direction, see Figure 1-2 for coordinate system, was provided by three toe clamps on top of 1x0.5 inch steel bar. A picture of the welding table is included in Figure 1-3. The FSW tool was inserted with a drawbar and a CAT50 taper shank end mill holder. All welds were performed with this set up.

![Figure 1-3: A picture of the friction stir welding table.](image)

Once the welding table was, sample welds were performed to learn what parameters would yield defects. Once a myriad of parameters were tested, the resulting welds were cross sectioned using the method in section 1.3.3. The welds that included defects were noted and the
final test set was chosen. The parameters used are found in Table 1-1. Five welds were produced in each of the six parameter sets resulting in thirty total welds.

<table>
<thead>
<tr>
<th>Set Number</th>
<th>Transverse Speed (mmpm)</th>
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<td>6</td>
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Table 1-1: The parameters for the FSW test set.

The raw data was sampled at 1250 Hz, however the data acquisition is not perfectly spaced between samples. Often there is an inconsistent time step of 0.0012 sec instead of 0.0008 sec. Thus, the average sample rate is closer to 1.05 kHz. In-between welds there was a waiting time for the tool to return to 30 C. This prevented the table and the tool to become hotter than another weld. This waiting practice prevented large changes between weld of the same parameter due to temperature.

1.3.2 Spectral Analysis

The inconsistent sampling frequency required that the spectral analysis be approached by one of two ways. First, the analysis could be done with the assumption that the data was sampled at the averages sample frequency or second, data points would be added in between the inconsistent time steps to make each time step equal. The first approach would include error in the frequency content because the points are not actually equally separated. Thus, additional time or less time would change the frequency power slightly. The second method could introduce some error because it assumes that the actual system matches a linear, or higher order, trend
between points. In addition, because of the periodic nature of the force, torque and other signals, if the interpolation occurs near an inflection point then there could be loss of curvature. This loss of curvature could lead to a change in the periodicity of the signal.

The author decided to use the second option and interpolate between points. The reason for this decision was that the original time step was small to begin with, 0.0008 sec. Thus, the additional points would need to be on the order of 0.0004 sec. This time step was sufficiently small enough to follow the original data without adding inconsistencies. A linear fit was used to interpolate between points. A higher order interpolation would not have resulted in a more accurate curve because of the small time step in-between points. The Matlab [14] function interp1 was used to add the additional points. The interpolated data was then used in the Matlab function spectrogram [14]. To acquire the most detailed frequency and time fidelity multiple runs of the spectrogram function was executed. The parameters that yielded the best fidelity were a bin size of 2500 data points and an 85% overlap with the sample frequency of 2.5 kHz. The frequency bins were 1.22 Hz wide and the time bins were .12 seconds wide. This fidelity assured that the spectral data represented at least 6 mm of weld length. Adjusting the parameters for the spectrogram function is essential to have high fidelity in the x position of a weld because the defect location prediction is only as precise as the spectral data.

1.3.3 Radiographic & Cross Sectional Images

The workpiece thickness provided difficult to image radiographically. Companies were researched and tested to secure images that had the resolution to display defects. The company that could provide good quality images was Avonix Imaging, MN. All the welds were sent there to be imaged by their custom built M2 system which used the following components: Nikon 225kv microfocus x-ray tube; and a Varex 1621 amorphous silicon flat panel detector. After the
images were taken, their team processed them in ImageJ. Then the author used photoshop to stitch, straighten and adjust the brightness levels to make one image for each weld.

Cross sections at points of interest were cut out with a waterjet. Then the samples were placed in backlight looking into the welding direction. A fine surface finish was not necessary because the defects were on the order of mm. Thus, Leco 1200F paper was the finishing step for all samples. The Olympus SZX12 optical microscope on campus with Leco Paxit 2 software provided the cross-sectional images.

The next chapter will discuss how these four datasets were used to create a threshold using the z force spectral data. The format of chapter 2 follows the article style writing guidelines from the Journal of Manufacturing Processes.
2 STUDY: SPECTRAL BASED DEFECT RECOGNITION IN FRICITION STIR WELDING

2.1 Abstract

Friction stir welding (FSW) is an advantageous solid-state joining process, suitable for many materials in the energy, aerospace, naval and automotive industries. Like all welding processes, friction stir welding requires non-destructive evaluation (NDE). The time and resources used to perform NDE are expensive. To reduce these costs, other NDE methods are being developed for FSW. These include force-based analysis, thermal imaging, acoustic emission analysis and others. Spectral-based defect recognition uses the generated forces during the welding process to validate weld quality. Developing this technology could lead to real-time process defect detection and potential control methods. Although new spectral based NDE methods have shown promise as alternative NDE processes, the welding speeds in many research studies do not correspond to relevant manufacturing speeds. The purpose of this work is to: first, validate that low frequencies correlate to defects at manufacturing production speeds, and second, to introduce a novel spectral NDE method using the axial force. In this study, welds with “wormhole” defects were produced at 2000, 2500 and 3000 mmpm to validate spectral NDE methods in work hardenable aluminium, specifically 5754-O. During the welding process forces and torque were measured, and these signals were post processed using a spectral technique. The welded plates were then imaged with radiography, a validated NDE method. It was found that
low frequencies (0.6-1.8 Hz) in the y & z force signals correlate with defect presence in high speed FSW in thin sheet 5754-O aluminum.

2.2 Introduction

2.2.1 Current Industry Standard Nondestructive for Friction Stir Welding

Friction stir welding (FSW) is an advantageous solid-state material joining process used in the automotive, naval, aerospace and energy industries that was invented by The Welding Institute [1, 15]. The process includes two work pieces that have a seam between them. A FSW tool, comprising of a cylindrical shoulder and a concentric pin, often threaded, is plunged down into the seam while rotating. Once the shoulder is engaged with the workpiece, the tool will advance along the seam while rotating, see Figure 2-1. The friction between the tool and work piece creates heat and plastic deformation which results in a consolidated joint between the two sheets. There are three main advantages of FSW: first, the energy required to produce a friction stir weld regularly is less than the energy required to produce a fusion weld[16]; second, friction stir welded joints can have superior material properties in comparison to traditional fusion welded joints [17]; finally, FSW can be less expensive because it is more environmentally friendly due to the lack of consumable products during the process, such as shielding gas, electrodes, or other materials [18].

Industries that use welding often require a non-destructive evaluation (NDE) method, or a method to verify that defects are not present, to validate welds [19]. Many researchers have investigated different NDE methods to locate defects in FSW including: acoustic emission analysis, thermal image analysis, eddy current probe analysis, ultrasonic & phased array evaluation, liquid penetrant evaluation, and radiographic analysis [2-9]. Each of these NDE methods have specific strengths in detecting certain defects. Liquid penetrant most readily
detects a lack of penetration while ultrasonic and radiographic methods detect sub surface wormholes and internal voids. Ultrasonic and radiography NDE are used as the standard for many industries [20]. Currently, no NDE methods exist that can detect all the different defects that could occur in a friction stir [21]. In addition, the NDE methods listed above are all secondary manufacturing processes and increase the cost to manufacture products because of additional time, machinery, training, labor, or costs associated with evaluation by a third-party company.

2.2.2 Researched Spectral Nondestructive Examination

Other NDE methods, using measured signals from the FSW process, have been studied in order to reduce these secondary process costs. These methods have been able to identify volumetric FSW defects. Morihana used discrete fast Fourier transforms on the x & y forces and found a correlation between subharmonic amplitude peaks and defects in friction stir welds for which the spindle speed was defined as the fundamental frequency [10]. Boldsaikhan continued this work by developing a program that used a neural network designed to identify spectral

Figure 2-1: A schematic of FSW and the coordinate system used in this work.
patterns that were related to defects [22, 23]. Later, a validation of Boldsaikhan’s program was performed by Britos. Britos made a comparison between radiography and ultrasound NDE methods to the neural network method. It was found that the neural network was more sensitive in detecting smaller voids than the other NDE methods and was 92.7% accurate overall [24]. However, both groups reported the use of a neural network required training for every combination of material, welding machine, thickness of material, and parameters. Additionally, statistical neural networks limit the understanding of why certain spectral data are related to defects. Balasubramanian demonstrated that feedback forces in the x and y directions are periodic in nature and striations of material flow match peaks of the process forces [25]. Franke studied the influence that tool geometry has on the spectral data. This study showed that if a tool’s pin was not aligned with the axis of rotation then larger oscillations occurred in the force signals. In addition, if the shoulder was not orthogonal to the axis of rotation then extra shifts in the force data would occur each revolution with the changing shoulder depth [26]. Finally, Franke noted how the machine compliance would affect how the force signals are measured.

Shrivastava developed a physics-based method to predict the volume of a void. This method used the volume of the probe and shoulder of the tool and associated them to the resulting forces [12]. The model significantly overpredicted the volume of a void, though, the prediction was proportional to the actual volume of the void. Shrivastava later developed another method to detect a defect and predict its volume. This second method was comprised of calculations from the frequency amplitudes in the x force, based on the schematic in Figure 2-1. Then the third harmonic amplitudes from the spindle speed frequency were divided by the spindle speed frequency amplitude. If these values were greater than 0.2 his correlation predicted a defect was present. The volume of the defect could be predicted by subtracting the absolute
value of the quantity of third harmonic amplitude divided by the average y force from 0.1005.
The result was then multiplied by the advance per revolution, probe height and diameter, and 1.1.
The third harmonic was used because the tool used in the study had three flats [13]. This method showed the capability to detect defects in welds and presented a preliminary evaluation for predicting the actual volume of a void. Additionally, the process was fast enough that it could be used in real-time to detect defects and predict their volume. However, some limitations to this method include: the tool needs to have at least two flats on the pin of the tool, and the model did not accurately predict the volume when process parameters were changing, such as table or spindle speed adjustments required during temperature control welding. Additionally, Shrivastava was only able to verify this prediction in a single alloy & welding environment, and other attempts to validate the predictions in other alloys were not successful.

2.2.3 Objective

The studies cited above have built a foundation that recognizes how spectral force analysis could be used to detect defects in industrial FSW. However, the fastest welding speed in the experiments from the cited studies above was 650 mmpm in heat treatable aluminum alloys including: AA7075 – T6 & T7, AA2024 – T3 and AA6061 – T6 with thickness ranging from 4 mm to 6.35 mm[10, 12, 13, 22, 24]. To increase the usability of spectral NDE, research needs to parallel current industry standards [27]. This effort would need to encompass more materials, thicknesses, clamping methods, heat treatments, dissimilar material welds, dissimilar thickness welds, and different tool designs in the experiments at relevant welding speeds.

The purposes of the current study are: first, to validate that subharmonic frequencies, lower than the spindle speed frequency, correlate with defects at speeds from 2000 to 3000 mmpm. Second, to introduce a novel post-weld use of spectral data to detect defects in friction
stir welds. Third to validate that low frequency correlations are useable in work hardenable aluminum alloys.

2.3 Methods

2.3.1 Material and Tools

Friction stir “butt” welds, produced from work hardenable aluminum 5754-O [11] with dimensions of 525 mm x 50 mm x 3.8 mm, were evaluated for this work. Figure 2-2 depicts an example weld. Position control was used for all welding with a constant spindle speed of 1600 RPM (26.67 Hz). The weld set was manufactured on a TTI model RM-2 FSW machine with an B&R controller and a 68kW Siemens compact induction motor, model 1PH8166-1TF23-2LA2. The traverse speed and welding tilt varied throughout the experiments and are included in Table 2-1. Five welds were made in each parameter set, resulting in 30 total butt welded panels. The welding tool was made from H13 tool steel with a flat, two start scrolled shoulder, 12 mm in diameter. The threaded pin had three flats 120 degrees apart, a base diameter of 6 mm and a length of 3.1 mm with a 10 degree taper. A drawbar system was used with a CAT-50 tool holder to fit the FSW tool in the machine. Temperature was measured using a bluetooth Lord MicroStrain TC-Link, model 1CH-LXRS, with a K type thermocouple. The thermocouple hole was drilled 50 thousandths from the FSW tool shoulder.

Figure 2-2: An example of a friction stir weld produced for spectral analysis.
Table 2-1: Welding parameters for data set.

<table>
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2.3.2 Data Acquisition and Process Algorithm

The x, y and z force as well as torque data were prepared to be sampled at a frequency of 1250 Hz to avoid aliasing possible significant high frequencies in each signal. These measurements were obtained from three Kistler tri-directional load cells that are placed 120 degrees apart in between the frame of the machine and the tool. The raw measured data included inconsistent time steps that averaged to 1 kHz. Therefore, linear interpolation between points was done to create a dataset that had a consistent time step of 0.0004 seconds, as if all signals were sampled at 2.5 kHz. It is essential that a FSW machine possesses the capability to measure y forces in order to execute most spectral NDE methods that have been developed. To avoid aliasing, data would need to be sampled, at a minimum, two times faster than the spindle speed frequency. However, higher sampling rates may be required to secure high fidelity spectral data along a weld. The raw steady state data was analyzed after the force and torque signals were truncated and binned.

There were two parts to the data truncation, these are displayed in Figure 2-3. The first part includes truncating the start of the data until the weld has reached a steady state condition.
This occurs when the first index of the traverse speed has reached the commanded velocity. Then the second part of the truncation occurs at the end of the weld, when the final traverse position command had been reached. Next the truncated data was binned. The purpose of binning the signal is to create small enough data sets so each bin acts as a stationary signal or nonvariant in that time period.

The binned data sets would then be used in a discrete Fourier transform calculation which, outputs a set of complex values that represent the frequency content in the time domain data. These complex values provide the input to calculate amplitudes. All previous spectral NDE methods have used amplitude data to detect defects in friction stir welds, some used binned force data sets and others used the whole force signal. This work used binned force sets to calculate the power spectral density (PSD) of the signal, which is the squared amplitude. PSD values were used, instead of amplitude, to eliminate the effect of noise that occurs when different bin sizes

Figure 2-3: An example of the data truncation used in this study.
are used and provides a simpler way to compare how the spectral characteristics change through the length of a weld.

To perform spectral analysis on periodic data each sample is required to have an equal time step. The data acquisition on the machine used to produce welds, occasionally included an inconstant time step. To rectify this irregular sampling, additional points were interpolated between samples to create a dataset that represented data as if it had been sampled at 2500 Hz. Then the spectrogram function in MATLAB calculated the one-sided PSD, data [14]. The parameters used in this function were a bin size of 2500 data points and an 85% overlap, to obtain high x position fidelity. These parameters yielded time bins that were 0.12 seconds apart and frequency bins that were 1.2 Hz apart, or a PSD value every 6 mm at the fastest traverse speed. If the bin size had been larger the frequency bins would have been finer, but the time steps between PSD values would have been larger, resulting in increased distance between PSD values. In addition, if the sampled rate was lower than 1250 Hz then there would have been lower time fidelity. For the application of locating a defect along a friction stir weld, high time fidelity is required to convert to a high position fidelity.

2.3.3 X-Ray Images and Cross Sections

Two-dimensional radiographic images for 29 out of the 30 welds were acquired from Avonix Imaging, MN. The following equipment was used to image the samples: M2 system, internally designed and built; Nikon 225kv microfocus x-ray tube; and a Varex 1621 amorphous silicon flat panel detector. Image J and Adobe Photoshop were the two programs used to equate grey scales and stitch the images of a single weld together. Logical vectors that represented defect locations were manually extracted from each image and converted from pixels to millimeters. After radiographic imaging, cross sectional metallography quantified the area of a defect. An
optical microscope; Olympus SZX12 running Leco Paxit software provided the cross-sectional images. These images were used to measure the defect magnitude.

2.4 Results

2.4.1 Weld Data

The measured data from all thirty welds were mapped to understand how the different parameter sets affected the resulting forces. Figure 2-4 includes example plots for the y and z forces. In general, the z force decreased as the transverse speed increased and as the tilt angle decreased, the greatest difference in z force was 3.5 kN. The y forces increased as the transverse speed increased. The greatest y force difference between parameter sets was 1.3 kN.

![Figure 2-4](image)

Figure 2-4: Example of welding forces across all of the parameters used in this study. a) z forces b) y forces.

2.4.2 X-Ray Data

A comparison between the 29 images confirmed that the data set included welds that were defect free, that had defects that grew and diminished and that included a wormhole defect throughout the length of the entire weld see Figure 2-5. In addition, the images confirmed the repeatability of each parameter set and their resulting weld quality. Once a defect location along
the weld was known, cross sections were made to measure the area of the defect, similar to the cross-sectional optical micrograph shown in Figure 2-6. Defect ranged from 0.003 - 0.6 mm$^2$.

Figure 2-5: a) An example of a non-defective weld. b) An example of a partially defective weld. c) An example of a completely defective weld.
Figure 2-6: An example of defect size produced in this study.

2.4.3 Spectral Data

The MATLAB spectrogram function outputs three data sets: first, an array that lists the midpoint of each time bin; second, an array that lists the midpoint of each frequency bin and

Figure 2-7: A spectral map from a weld ranging from 0 to 600 Hz along the length of a weld.
third, a matrix of PSD values that corresponds to the time and frequency bins arrays. The raw data was used to convert time to x position. This conversion made the comparison between the spectrograms to the radiographic images simpler. These three outputs create a three-dimensional plot that renders the spectral changes of the welding forces for the entire weld. An example spectral map is found in Figure 2-7.

Each force and torque signal, from each weld, yielded 120 spectral maps. Once both the logical defect vectors and the spectral maps were made, a correlation coefficient was calculated between each of the 29 weld’s defect logic vector and each PSD vector for every frequency bin (0 – 600 Hz). The correlation coefficients were calculated using the corrcoef function in Matlab. Correlation maps, Figure 2-8, were then created to identify which frequency bins consistently correlated to defect. A correlation coefficient could not be calculated for welds that did not have a defect, or logical value of 0 along the weld. Therefore, a correlation of 0 was given between the logical vector and the PSD data.

Only two frequency bins that consistently related with a correlation coefficient value higher than 0.5. These bins were the lowest two frequency bins from the z and y PSD data, Figure 2-8 b & c. There was not a consistent correlation between defect presence and the x force or torque PSD datasets, Figure 2-8 a & d, therefore they are not included in the analysis herein. The first bin corresponds to 0 Hz, or the non-oscillating value of the signal or the DC portion of the signal. This represents a squared moving average of the respective force. The second bin includes how prevalent frequencies from 0.7 to 1.7 Hz are in the force data. The author would like to note that a study that subtracts the DC gain out of the signal, or eliminates the moving average of the signal if the correlations still exist.
2.5 Discussion

2.5.1 Weld Data

Numerous authors have demonstrated that a reduction of heat in a friction stir weld may yield wormholes or void defects in the stir zone [12, 22]. Although AA5754-O is commercially welded using FSW at speeds above 2000 mmpm [28], for the purposes of this work, defects were
necessary to examine the spectral data associated with them. As such, a reduction of the weld temperature was sought by increasing transverse speed to yield defects in the weld. A temperature map can be found in Figure 2-9.

![Temperature Map](image)

**Figure 2-9: A temperature map across the different welding parameters used in this study.**

In addition, a lower tilt was used to decrease the pressure on the trailing side of the tool, which reduces the necessary downward force required to consolidate the material and avoid weld defects [29]. These two changes to the welding parameters assured defects in the stir zone for several of the welding parameters evaluated herein. Through this discussion weld 11 from the dataset will serve as an example. Figure 2-5b displays that a defect opens, near 60 mm, then closes at 250 mm. Another defect later opens near 350 mm and closes at 470 mm.

One note about the temperature in this data includes the fact that because of the fast velocities the temperature did not reach a saturated point. The dynamics of the temperature could affect the flow stresses throughout the weld. These changes of flow stress would then affect the
measured forces that are used as a bases for spectral NDE. A more rigorous approach would be to define “steady state welding” once the temperature has become essentially static. For this data set that would occur roughly at 300 mm. This would not be applicable for many current FSW manufacturer who only trim the first and last 10 mm of their welds, but defining the steady state welding at that point would be more rigours.

2.5.2 Spectral Data

The logical defect presence vector, for a given weld, provided the defect locations and allowed a comparison between defects and spectral data. The two lowest frequency bins were analyzed to observe the differences between a defective weld and a non-defective weld. The negative correlation between defect presence and z force spectral data suggested that defect free welds resulted in higher spectral values than defective welds. In addition, the positive correlation between y force spectral data and defect presence suggested the opposite trend. Defect free welds resulted in lower spectral values than defective welds. These trends were used to find a threshold that could predict defect presence along a weld such as Figure 2-10.

![Figure 2-10: An example threshold of z force PSD data.](image-url)
As an example, weld 11 is the top blue triangle curve in Figure 2-10. The example z PSD threshold in this plot is $2.25 \times 10^7$. In the beginning of the weld the z PSD value is greater than the threshold until close to 100 mm, thus the threshold would predict a defect free weld from the start of the weld until 100 mm. The z PSD value stays beneath the threshold until 230 mm, predicting a defect in that portion of the weld. From 230 mm until 350 mm the threshold suggests no defect in the weld. Near 350 mm the z PSD values cross the threshold again, assuming a defect again through the remainder of the weld. These predictions closely align with the defect location found in the radiographic image Figure 2-5b. There is some error where the PSD predictions do no match exactly the defect location, however, increasing or decreasing the threshold would reduce the error.

To find the best threshold, the minimum and maximum PSD values from all 30 welds were found for both the y & z datasets. One hundred even steps between them were generated. Next, each of the one hundred threshold’s predictions and the actual defect logical vector for each weld, were used to calculate a confusion matrix for each threshold. A receiver operating characteristic, ROC, curve was created, Figure 2-11, from this data.

The ROC plot provides a guide to understand the performance of the 100 thresholds. A perfect threshold would be where the sensitivity is one and one minus specificity is zero, which is the top left corner of the ROC plot. This perfect threshold would define every defect as a defect, 100% true positive rate, without any false positives. In most real-world applications, it is difficult to achieve a perfect threshold. Thus, many applications will choose the threshold that is closest to the upper left-hand corner in a ROC plot. Figure 2-11 displays that the z ROC curve is more ideal than the y ROC curve with a performance of 93.3% true positive rate and 9.7% false negative rate. The most ideal threshold for the y PDS data preforms with 88.6% true positive rate.
and 8.4% false negative rate. However, for applications where a zero-defect tolerance is required, a threshold that gives 100% true positive rate would be necessary. In this instance, the best z PSD threshold that offers no false negative would incorrectly label defect free welds defective 32.6% of the time. The y PSD threshold preforms worse with a 0% false negative rate with a 40.6% false positive rate. The trade off with reducing the false positive rate is the true positive rate also decreases. This trade off can be understood in Figure 2-11. To compare the performance of these ROC curves to another spectral NDE method, Brito’s study of Boldsaikhan’s neural network resulted in 92.8% true positives and 3.6% false positives.

The author noted that there were two location in the force data that consistently changed through all the welds, near 180 & 400 mm in Figure 2-4. The change was most prevalent in the z force measurements, the largest decrease was 200 N. The author hypothesized that this change in force could be a result of the clamping method for this weld set. Direct toe clamps, on top of a

![Figure 2-11: An ROC plot for predicting a defect along a friction stir weld using y & z force PSD data. The y axis displays the true positive rate and the x axis displays the false positive rates.](image)
rectangular steel bars, were located near the locations of the force drops. These direct clamps could have restricted the thermal expansion that the workpiece would have exerted at welding temperatures, near 400 degrees C. This reduction of thermal expansion would have reduced the force in those locations. This factor does not affect the PSD thresholds as seen in Figure 2-11. The PSD data for defect free welds follow a similar curve at those locations, but all the values are still significantly greater than the defective welds. In addition, welds that had defects were processed at faster traveling velocities. These velocities reduced the temperatures in these welds and limited the time for a location to be at a peak temperature. These shorter peak temperature times would have limited the thermal expansion and therefore the forces would have been less variant. This trend can be observed in Figure 2-4 by the darker markers representing the faster velocity welds. However, this finding would suggest that further experiments should be done with a variety of clamping methods to validate spectral based thresholds.

This is the first work that has related the z force to defects. This finding is valuable to many manufactures who may not have the ability to measure the x and y forces currently on their welding machines. However, because the workpiece material was thin it is hypothesized that this phenomenon occurs when the defect size is a significant portion of the material thickness. This NDE method may not hold for thicker materials with similar defect sizes. In addition, the threshold method applies to a particular tool and work piece material. However, the threshold holds true even with different parameter settings such as welding speed or machine tilt. Other developed spectral NDE methods required that any changes to the welding environment require additional training. This NDE method could be applied to other welding environments after in-house testing. A particular weld, with a specific tool and material, would need to be repeated to have good and bad welds. Images of this batch would be required to synthesize the second to
lowest bin of spectral data to build a threshold. Once this threshold is set, a post process NDE of a weld’s data would yield whether that weld has a defect or is defect free. This threshold would then qualify for a similar weld that is made with the same material and tool.

2.6 Conclusions

To decrease the cost of NDE for FSW in many industries, a spectral-based defect recognition method was studied in this work. Experiments were performed to capture force measurements during defective and non-defective FSW in work hardenable aluminum, specifically 5754-O. These force measurements were used as the input for post process PSD calculations. Radiography imaging, a validated NDE method, located defects in the weld dataset. Correlation coefficients could then calculate between defect location and the PSD data for the process forces and torque. The use of PSD data allows a more complete understanding of how the spectral nature of the welding forces changes throughout a weld. The results of this work conclude three items:

1. Low frequency spectral data (0.6-1.8 Hz) captured from the y and z axis forces during high speed FSW are correlated to volumetric defects at speeds up to 3000 mmpm. The author’s findings validate that approaches previously demonstrated at welding speeds at or below 650 mmpm may be extended to much faster welding speeds.

2. While previous studies have focused on correlations of the y-axis force, the author has demonstrated that both the y-axis and z-axis forces may be correlated with internal defects. This work is the first time that z-axis force data has been correlated to defects. The best z force threshold for aluminum 5754-O was 93.3% true positive rate and 9.7% false positive rate. The best y force threshold was 88.6% true positive rate and 8.4% false positive rate. These thresholds were consistent in all the 30 welds in this study even across variable welding velocities and tilts.
3. Spectral methods of NDE can be used with work hardenable aluminum alloys. Previously reported studies have only demonstrated defect correlations with precipitation strengthened alloys.

2.7 Future Work & Acknowledgements

2.7.1 Future Work

To improve the usefulness of spectral analysis to detect defects in friction stir welds two main points should be studied.

1. What the fundamental connection between low frequencies, near 1 Hz, and volumetric defects is physically.

2. The application of thresholding with different tools, materials and material thicknesses, specifically in thickness larger than 6.35 mm.

2.7.2 Acknowledgments

Funding for this project was provided by BYU Technology & Engineering seed projects and supported in part through the Utah NASA Space Grant Consortium, NASA Grant #80NSSC20M0103.

Materials and tooling were donated by TWB, LLC in Monroe, MI.
3 ADDITIONAL DEFECT INFORMATION

3.1 Cross Sectional Location

3.1.1 Methods

The author hypothesized that the cross-sectional location of a defect could be inferred by the combination of the measured $x$ and $y$ forces. The combination of $x$ and $y$ forces are a result of the transverse movement and the torque that the tool exerts on the material. The torque can be modelled as a force at a distance that rotates at a point. This representation of the torque would allow for a summation of forces through one rotation of the tool. An average could be taken of discrete locations through a rotation to represent the force that the tool exerts on the material in steady state friction stir welding. This force would be measured in $x$ and $y$ components; however, a polar conversion would extract the direction and magnitude of the tool’s average force per revolution. In normal welding conditions, or a weld with a defect present, the author hypothesized that this average tool force would remain consistent, and that when a defect is present the average force would move away from the normal magnitude, location, or both.

To test this hypothesis the measured data from the thirty 5754-O [11] aluminum butt weld set was used to covert $x$ and $y$ forces into angle and magnitude. Then average forces and directions were taken when defects were present and when they were not present.

Cross sections were cut from the welds using the waterjet. Bakelite pucks were then used to hold the samples during Leco sandpaper grinding. Fine surface finish was not required to
measure the defect dimensions, so all samples were grinded only to Leco 1200 fine paper. Images were then taken on the Olympus SZX12 optical microscope running Leco Paxit 2 software. Cross sectional images allowed the author to verify where in the cross section the defect was located.

3.1.2 Results & Discussion

Looking in the negative z direction, Figure 2-1, on the friction stir welding processes, the resulting average welding force for this tool set and material point about 216 degrees angle away from the welding transverse direction. However, when a defect opens the angle increases closer to 225 degrees, see Figure 3-1 below.

![Figure 3-1: A top down view of the average welding forces plotted in polar coordinates. The red markers are average forces when a weld had a defect. The blue markers are average forces when a weld was defect free.](image)

The weld cross section images indicated that all the defects produced in this data set were on the advancing side, see an example cross section in Figure 3-2. From section 2.4.3 the
correlation coefficient between y force and defect presence were positively correlated, R value of 0.793. The angle of the average force and defect presence were also positively correlated, R value of 0.697. This correlation would suggest that as the y force is higher there is a better chance that there is a defect. Relating this correlation to the cross sections; it could be hypothesized in this tool and material, that as the y force increases, a defect on the advancing side opens. The same prediction would be made by using the theta correlation.

![Figure 3-2](image.png)

*Figure 3-2: An example cross section view of a defect in this data set. The horizontal red line marks the shoulder's footprint and the vertical red line signifies the midpoint of the tool. The weld direction is into the page.*

The opposite could be hypnotized as well; if the angle or the y force decreases, a defect would open on the retreating side of the weld. However, in this data set all of the defects were located on the advancing side of the weld, according to the cross sections. Thus, a comparison was not possible to test if a reduction in y force or in resultant angle that a defect would open on the retreating side. In addition, there are three points where a defect free weld’s average resultant force had an angle of 225 degrees or greater. These three points were from the welds that had a traverse speed of 1500 mmpm and a tilt angle of one degree. These three points are not very precise either, with a spread of 13 degrees. The reason of these point’s high variance is unknown.
3.2 Defect Magnitude

3.2.1 Methods

The strong correlation between the first and second bins of the z & y force PSD data and the defect logical vectors, from chapter 2, led the exploration to see if the PSD values could be used as a method to determine the magnitude of the defect. Welds that included defects were cross sectioned so a measurement of the defect area could be taken. The method to create the cross-sectional images are explained in 3.1.1. Once the images were created, the Matlab [14] “boundary” function was used to bound and calculate the defect area, as well as, height and width from the optical images. Values from both y and z PSD data that corresponded to the x position to the cross sections were then used to create a linear fit with the defect areas. The author hypothesized that the z PSD force would provide a better fit for the height prediction because the z force is in the same direction as the height of the defect. The y force PSD values were also used in this experiment to see if it could predict the width of the defect, because the y force is parallel to the width of the defect.

3.2.2 Results & Discussion

The best $R^2$ value from applying the linear fit to the PSD and defect dimensions was 0.54, and the worst was 0.26 across the z and y PSD data and defect size. Due to the spread in defect size the resultant error is significant in many instances. The estimated defect dimensions, actual defect dimensions and the associated error for welds 24 and 28 are tabulated in Table 3-1:4. The fit of the data is also plotted in Figure 3-3:8.
Figure 3-3: The y PSD data from the second bin (.7 to 1.2 Hz) and the width of six defects.

Figure 3-4: The y PSD data from the second bin (.7 to 1.2 Hz) and the height of six defects.

Figure 3-5: The y PSD data from the second bin (.7 to 1.2 Hz) and the area of six defects.
Table 3-1: Estimates of width, height, and area using the second bin y PSD data for weld #24. Percent error for each estimate is given as well.

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<th>Error (%)</th>
<th>Height Estimates (mm)</th>
<th>Actual Height (mm)</th>
<th>Error (%)</th>
<th>Area Estimates (mm$^2$)</th>
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Table 3-2: Estimates of width, height, and area using the second bin y PSD data for weld #28. Percent error for each estimate is given as well.

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<th>Error (%)</th>
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Figure 3-6: The z PSD data from the second bin (.7 to 1.2 Hz) and the width of six defects.
Figure 3-7: The z PSD data from the second bin (.7 to 1.2 Hz) and the height of six defects.

Figure 3-8: The z PSD data from the second bin (.7 to 1.2 Hz) and the area of six defects.

Table 3-3: Estimates of width, height, and area using the second bin z PSD data for weld #24. Percent error for each estimate is given as well.

<table>
<thead>
<tr>
<th>Width Estimates (mm)</th>
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<th>Actual Height (mm)</th>
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Table 3-4: Estimates of width, height, and area using the second bin z PSD data for weld #28. Percent error for each estimate is given as well.

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<th>Actual Height (mm)</th>
<th>Error (%)</th>
<th>Area Estimates (mm²)</th>
<th>Actual Area (mm²)</th>
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</table>

The second bin of the y PSD values did not yield the least amount of error in the width predictions as was hypothesized; however, the average percent error was 13%. The second bin of the z force PSD values yielded low error width estimates, average of 10%. A possibility for the low error using z PSD data could be because the thickness of the material used in these welds. Most of the defects in this sample set were not very tall, but they grew out. Therefore, as a defect grew the z force would change because of the lack of material.

The predictions of height and area were not as accurate. The average percent error of the z PDS data and the height predictions, was 20%, and the area predictions was 58%. The average percent error of the y PSD data and the height predictions was 35%, and the area predictions was 197%. The 197% error for area predictions are greatly pulled by the middle prediction that was an order of magnitude higher. The area predictions from both the y and z PSD data sets were the worst out of the three-dimensional predictions. The author hypothesis that the error could be due to the squared nature of a length measurement. However, the width and height predictions for the z PSD data would allow for a rough idea of defect magnitude in a production setting, but not accurate enough to develop a criterion for this tool and material.
3.3 Defect Type

The 30 welds that supplied the data for this thesis did not include multiple types of FSW defects. Only “wormhole” defects were evident in the x-ray images. Additional defects were not studied to provide more results for the first two objectives based off of the corporate sponsor’s request to find defects at industry speeds.
CONCLUSIONS AND FUTURE WORK

4.1 Defect Location

Spectral NDE for FSW can be very useful for many industries. Once developed, spectral NDE could save time, money and other resources for manufacturers. In addition, understanding the spectral nature of FSW will push the ability to find parameter sets easier in hard to weld material. In the future, developing spectral NDE may lead to controls for FSW that would make FSW a very superior joining process with low risk of failure. This thesis focused on pushing spectral NDE in two ways: 1) using spectral data in high speed FSW and 2) exploring the possibility that spectral data can infer the magnitude of a defect.

4.1.1 Defect Position Along the Weld

This thesis does provide an additional method using spectral data for NDE in FSW. Using the second bin of low frequencies in the z & y PSD data thresholds can be made to detect defects in high speed friction stir welding of Al 5754-O. The performance measures of this threshold are:

Y PSD Thresholds
88.6% True Positive Rate 8.4% False Negative Rate
100% True Positive Rate 40.6% False Negative Rate

Z PSD
93.3% True Positive Rate 9.7% False Negative Rate
100% True Positive Rate 32.6% False Negative Rate
This finding is important to this field of research in three different ways.

1. No training is required. This allows for flexibility for users to change parameters and save time and resources to not train for a different set of parameters, such as welding speed or tilt.

2. The threshold can be developed using z force measurements. This allows for machines that do not currently measure x or y forces to develop spectral methods of NDE without upgrading to accommodate past researched methods.

3. This thesis validates that spectral NDE can be used for industry welding speeds, up to 3000 mmpm.

4.1.2 Cross Section Location

Cross sectional location was not able to be rigorously studied in this thesis. However, a hypothesis to predict whether a defect is on the advancing or retreating side was created. This hypothesis includes a combination of the x & y forces during a weld. If the angle of this force vector is point more in the advancing side, then the defect will reside in the advancing side. The opposite would be true as well. If the angle of the combined force vector points more to the retreating side, then the defect will reside on the retreating side. In the weld dataset that supplied this thesis included welds with defects that were all on the advancing side of the tool. A trend was found that the combined force vector pointed farther to the advancing side. The test of this hypothesis was incomplete because there were not any defects on the retreating side of the weld in this thesis.

4.1.3 Final Defect Location Conclusion

The two conclusions in 4.1.1 and 4.1.2 provided additional insight for spectral data to be used in high speed FSW. Defects can be located along a high-speed friction stir weld using a z
PSD threshold. These thresholds were validated with defects that were made at high speeds, 2000 mmpm to 3000 mmpm. However, cross section location was not able to be rigorously studied due to the lack of defect location in the cross section.

4.2 Defect Magnitude

This thesis was not able to produce accurate defect magnitude predictions as desired as one of the main objectives of this work. However, for this tool and material reasonable defect widths could be predicted by using the second y PSD bin or z PSD bin data using a linear fit. The predictions had an average of 11% error. Height and area predictions were not as reliable, with an average of 38% error. Possible reason why the y PSD data can predict the width of the defect is because of the y force is parallel to the width measurement. The z PSD could be used as a predictor of defect width because the defect shape grew outward decreasing the material underneath the tool. This decrease in material would change the z force allowing the z PSD data to be a width predictor. In summary, the null hypothesis that spectral cannot be used as a predictor of defect magnitude can be partially rejected, however more research in developing this method could yield more accurate predictions.

4.3 Defect Type

As discussed in Chapter 3, the data set produced in this thesis did not contain different defects. Therefore, it was not possible to study if PSD data can be used to identify different friction stir welding defects. However, the author noted, while working on other research projects, how to acquire welds with different defects. To produce a lack of penetration defect, LOP, a tool that replicated the original tool but with a short pin could be used. To produce a “lazy s” defect a similar tool, without flats and a smaller pin diameter could be used. One
difficulty that would need to be addressed in creating these two defects are that different tools are required. An important question with using different tools would be if the comparison of spectral or other data justified? This would need to be researched further.

4.4 Connection Between the FSW Process & Subharmonic Frequencies

Many cited studies, of spectral data and FSW defects, and this thesis have correlated low frequencies to defects[10, 13]. However, an in-depth study of why this is the case has not been explored. To increase the value of this thesis’s defect detection, as well as others, an understanding why low frequencies are related to defects would be necessary. The author’s current hypothesis is that while welding a non-defective weld the process forces are very consistent. However, once a defect starts to open the average forces start to drift away from the steady state values. This small drifting would reveal itself as low frequency changes to the spectral data. However, an understand the effect of the DC portion of the data could provide insight since it also correlates to defect presence.

4.5 Additional Experiments

Low frequency based spectral defect detection in friction stir welds has been done in many materials of the same thicknesses. Thicknesses range from 3.8-6.5 mm and materials range from 7075 T6&T7, 2024-T3, 6061-T6 and 5754-O. To increase the efficacy of these methods more experiments with different material thicknesses, tools (without flats), dissimilar material thicknesses and more materials such as steels would need to be executed. The data from these experiments would further the readiness of this technology to be widely used in many applications in different industries.
REFERENCES


A.1 Weld Information

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B.1 First Imaged Group

Eighteen welds were sent for radiography before spectral data was investigated or cross sections were taken.

Figure B-1: X-ray image number 1.

Figure B-2: X-ray image number 2.
Figure B-3: X-ray image number 3.

Figure B-4: X-ray image number 4.

Figure B-5: X-ray image number 5.

Figure B-6: X-ray image number 6.
Figure B-7: X-ray image number 7.

Figure B-8: X-ray image number 8.

Figure B-9: X-ray image number 9.

Figure B-10: X-ray image number 10.
Figure B-11: X-ray image number 11.

Figure B-12: X-ray image number 12.

Figure B-13: X-ray image number 13.

Figure B-14: X-ray image number 14.
Figure B-15: X-ray image number 15.

Figure B-16: X-ray image number 16.

Figure B-17: X-ray image number 17.

Figure B-18: X-ray image number 18.
B.2 Second Imaged Group

The other eleven welds were sent to validate the PSD thresholds from chapter 2. These welds have the cross-sectional pieces missing.

Figure B-19: X-ray image number 2.1.

Figure B-20: X-ray image number 2.2.

Figure B-21: X-ray image number 2.3.
Figure B-22: X-ray image number 2.4.

Figure B-23: X-ray image number 2.5.

Figure B-24: X-ray image number 2.6.

Figure B-25: X-ray image number 2.7.
Figure B-26: X-ray image number 2.8.

Figure B-27: X-ray image number 2.9.

Figure B-28: X-ray image number 2.10.

Figure B-29: X-ray image number 2.11.